NBS TECHNICAL NOTE 1069

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

VOR Calibration Services

Neil T. Larsen
Dominic F. Vecchia
George R. Sugar

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NBS Technical Note
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Neil T. Larsen

Electromagnetic Technology Division
Center for Electronics and Electrical Engineering
National Engineering Laboratory
National Bureau of Standards
Boulder, Colorado 80303

Dominic F. Vecchia

Statistical Engineering Division
Center for Applied Mathematics
National Engineering Laboratory
National Bureau of Standards
Boulder, Colorado 80303

George R. Sugar

Retired (formerly with the Electromagnetic Technology Division, National Bureau of Standards)

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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EVALUATION OF THE STANDARDS

VOR Calibration Services

Neil T. Larsen, Dominic F. Vecchia, George R. Sugar

National Bureau of Standards
Boulder, Colorado 80303

The National Bureau of Standards has designed, constructed, and evaluated a standard for the support of very-high-frequency omnidirectional range (VOR) air navigation aids. The standard consists of two instruments: (1) a digital waveform signal generator for the composite VOR audio waveform, and (2) a standard phasemeter based on time series analysis of this waveform. Experimental results, a statistical analysis of them, and the principal software listings are included.

Key Words: air; calibration standard; navigation; omnidirectional; range; very-high frequency; VOR

SYSTEM OVERVIEW

1. Introduction

1.1 History

The origins of the air navigation system now known as Very high frequency Omnidirectional Range (VOR) go back to about 1928, in England, when work was started on a phase-comparison system. About 1940, the Civil Aeronautics Administration examined and developed the technique, and finally presented it to the Radio Technical Commission for Aeronautics in 1945. In 1946, it was offered by the U.S. Government to what is now the International Civil Aviation Organization (ICAO). It was accepted as part of ICAO's Standards and Recommended Practices, where it is stated:

> "In localities where conditions of traffic density and low visibility necessitate a short-distance radio aid to navigation for the efficient exercise of air-traffic control, the standard aid shall be VOR (vhf omni-range) of the CW phase-comparison type conforming to the Standards contained in Paragraph 3.4 of Chapter III of this Annex [1]."

Since that time, more than 1,000 stations have come into use around the world. However, in spite of its use by commercial, military, and private aircraft, there has until now been no standard or technique by which VOR instruments could be calibrated, either directly or indirectly, at the National Bureau of Standards. Reference 2 is a very good overview of the VOR system. It describes the origins and evolution of the system in considerable detail and is recommended to those interested in the history of VOR.

1.2 Organization of Report

This report comprises four main parts. They are:

I. A general overview of the VOR system and the calibration services designed to support it (sections 1 through 4).

II. A detailed description of the NBS VOR generator, including specifications, operating procedures, and theory of operation and maintenance (sections 5 through 12).

III. A similar description of the VOR phasemeter (sections 13 through 15).

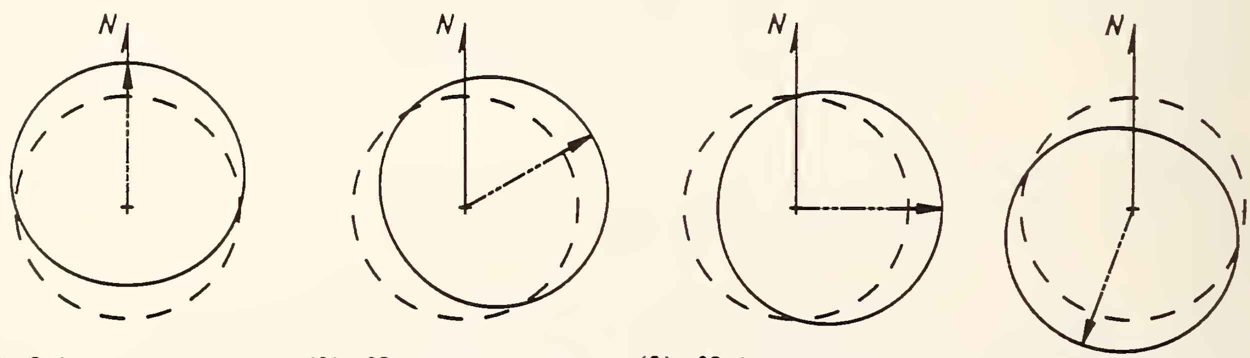
IV. A statistical evaluation of the VOR generator and VOR phasemeter when they are used together as a system (sections 16 through 18). A large amount of both simulated and measured data is abstracted and discussed. The statistical theories used in the analysis are given. Finally, a provisional statement of uncertainty is made.

The appendices provide graphical and tabular illustrations of the actual measurement results. The software listings for the NBS phasemeter and for some of the statistical work are included. Throughout this report, the terms phasemeter and generator appear many times. In every case, a VOR phasemeter or a VOR generator is meant, but for brevity, the modifier will often be omitted.

Throughout this report, the terms phasemeter and generator appear many times. In every case, a VOR phasemeter or a VOR generator is meant, but for brevity, the modifier will often be omitted. Areas where the designs of the generator and phasemeter have influenced each other are noted. Since there exists no independent means of checking either the phasemeter or the generator, the two must be regarded as a system, and, of necessity, there is a strong interdependence when it come to the evaluation of each.

2. Technical Basics

The VOR signal is radiated from a transmitter that produces a spinning pattern. The spin may be produced by a mechanically driven goniometer or other means. The antenna field pattern is not omni-directional; a contour of constant intensity follows a curve known as a "limacon." The shape is nearly circular, as shown in figure 2-1. As the pattern turns at 1800 rpm, the field intensity at a remote receiver fluctuates sinusoidally at 30 Hz. The 30 Hz signal obtained by demodulating the VHF carrier is called the "variable phase" signal. If a timing reference were available to determine when the peak of lobe passed magnetic north, then the phase of the 30 Hz signal measured relative to that reference would vary in space as the bearing angle between magnetic north and the receiver, measured at the transmitter.



(1) 0 degrees rotation (2) 60 degrees rotation (3) 90 degrees rotation (4) 200 degrees rotation

Figure 2-1. The rotating VOR horizontal field pattern. A dashed circle is shown for comparison.

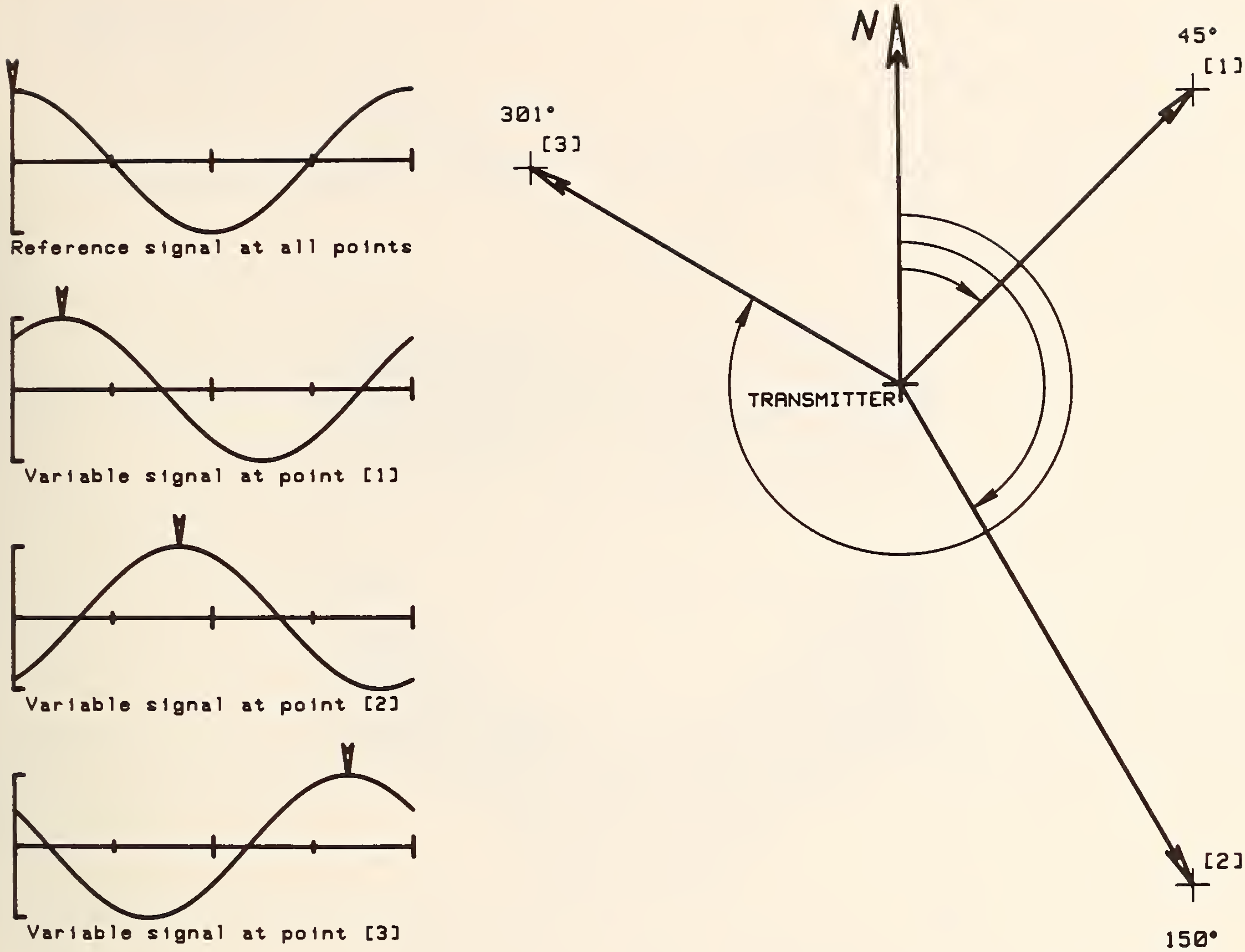


Figure 2-2. Reference and variable phase signals as received at three typical locations.

The required reference is transmitted by means of a 9960 Hz subcarrier that amplitude modulates the same VHF carrier. The 9960 Hz is frequency modulated at 30 Hz. The subcarrier is obtained by demodulating the VHF carrier, and the 30 Hz "reference phase" signal is then extracted from the subcarrier. The reference phase signal does not change in phase as the receiver moves in space. It is therefore possible to determine the bearing angle simply by measuring the phase angle between the two 30 Hz signals. The antenna spin is phased such that the field intensity at a receiver due north of the transmitter peaks at the same time as the 30 Hz reference phase signal. Due north corresponds to a bearing angle of 0 degrees.

Typical signals received at three different locations are shown in figure 2-2. Note that the reference signal, derived from the 9960 Hz subcarrier, is the same at all points. At point [1], the variable phase signal lags the reference by 45 degrees, which is also the bearing angle from magnetic north. Proportional phase lags are seen at the other two points.

Figure 2-3 is a representation of the audio signals from which the bearing angle information is obtained. The top waveform is one fundamental period of the reference signal. The second waveform represents the 9960 Hz subcarrier. Note that the peak positive frequency deviation occurs at the

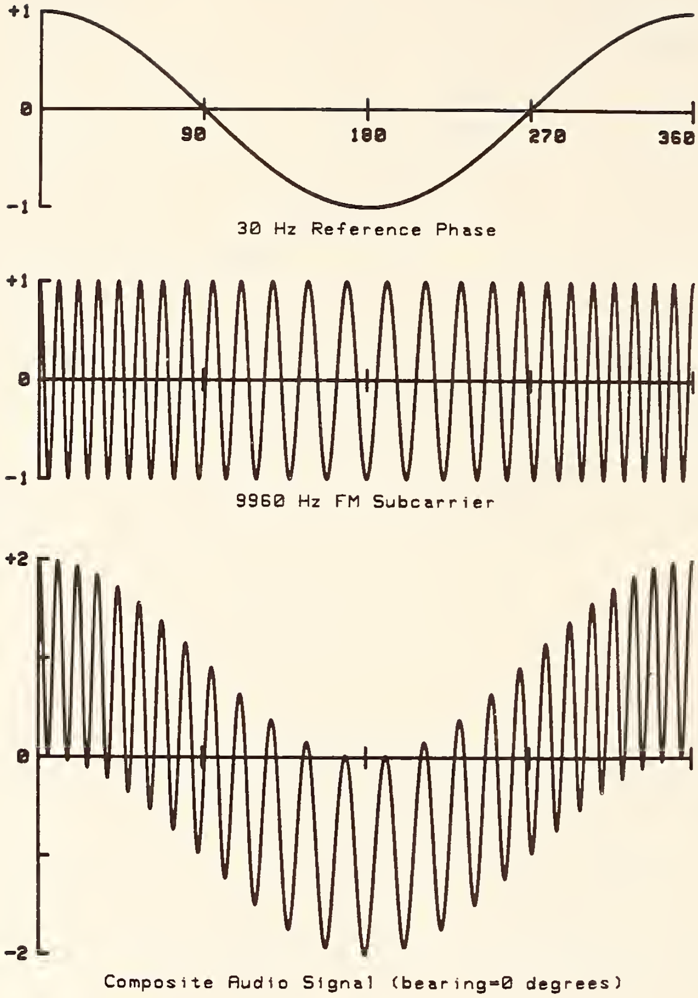


Figure 2-3. Simulated 30 Hz and 9960 Hz waveforms. Time is distorted for clarity.

positive peak of the reference signal. The sum of reference and variable phase signals is known as the "composite audio" signal, shown in the bottom curve. This is the signal that is obtained at the output of the am detector of a remote VHF receiver. It is the signal produced by the NBS standard generator and measured by the NBS standard phasemeter.

Note that the time dimension in figure 2-3 has been greatly distorted to make the frequency modulation of the subcarrier visible; however, the phase relationships are correct for a bearing angle of zero degrees. The figure is intended only as an aid to visualization.

The composite signal shown above can also be described by a mathematical model. This model is discussed in much more detail beginning in section 16. It consists of two parts: the variable phase waveform and the frequency modulated 9960 Hz waveform.

The variable phase waveform is

$$v(t;\underline{\theta}) = \alpha_1 \cos[2\pi f_1 t + \theta_1 + \theta_2].$$

The FM waveform is

$$s(t;\underline{\theta}) = \alpha_2 \cos[2\pi f_2 t + \theta_3 + \beta \sin[2\pi f_1 t + \theta_2]].$$

The composite waveform is defined by the sum of these two functions. The variables are as follows:

t = time
$\underline{\Theta}$ = a vector of unknown three unknown phase angles
α_1 = amplitude of variable phase signal
f_1 = frequency of variable phase signal (30 Hz)
Θ_1 = VOR bearing angle; i.e., the quantity to be measured
Θ_2 = an arbitrary phase offset included in the model for generality
α_2 = amplitude of the FM subcarrier
f_2 = frequency of the FM subcarrier (9960 Hz)
Θ_3 = an arbitrary phase offset included in the model for generality
β = the modulation index of the FM subcarrier (nominally = 16)

It is the purpose of the VOR generator to generate a signal that conforms to this model, and it is the purpose of the VOR phasemeter to determine the actual value of Θ_1 from measurements on the signal. The hardware aspects of the generation and measurement are described at length in sections 4 through 15; the statistical aspects of the measurement system are covered in section 16.

3. Description of the VOR Calibration Services

Two services are offered to support the calibration of VOR instruments. NBS has designed and built a standard VOR audio generator, which is used to calibrate unknown VOR phasemeters, and a standard VOR phasemeter for the calibration of unknown generators. Both of these services are for audio generators and phasemeters; direct generation or measurement of standard rf signals is not a part of this service, although some effort is being made in that direction. To avoid confusion, each of these services is discussed separately.

3.1 VOR Phasemeter Calibration Service

An unknown phasemeter is calibrated by connecting its input to the output of the NBS standard generator. The generator provides a composite audio signal that is the sum of two signals, each 1 V rms (±1 percent) in amplitude. The first is simply a 30 Hz sinusoid, and represents the variable phase signal as it would be recovered from the original vhf signal. The second is the frequency-modulated 9960 Hz subcarrier. Most commercial VOR phasemeters cover the entire 0° to 360° range, and so does the standard. It is possible to set the standard, by means of digital thumbwheel switches, to any bearing angle from 0° to 399.99° in steps of 0.01°.

Calibrations of VOR phasemeters are documented with a report containing the following statement:

The assigned values of VOR phase angles are the nominal bearing from 0 to 360° in increments of 0.01°. The overall uncertainty of these values has been estimated from test data at bearings from 0° to 360° at 30° increments. Thus, each of the nominal bearings has been assigned a provisional overall uncertainty of +/- 0.0028°, based on estimated bounds of +/- 0.0022° on the systematic error and a computed standard error of 0.0002°.

It appears that the NBS generator is more accurate than presently available generators by about a factor of 10, and better by an even larger factor than the needs of operational systems. It is not possible to fly an aircraft, using VOR, to 0.25°, even with an autopilot. Ground effects perturb the field of the transmitter enough that more typical uncertainties in the air are on the order of 1° or 2°.

At present, the most suitable transfer standard appears to be a commercially made phase meter. Neither the NBS generator nor phasemeter are portable. Another possibility is a generator that has recently been developed at the National Physics Laboratory, England, by White, Clark, and Yell [3]. We do not yet know its properties, although one intercomparison with their portable generator has been made. There appear to be no commercial generators that are suitable for use as a transfer standard in connection with the NBS standards. The problem is mainly with short-term jitter and noise. This may change; however, any commercial phase meter used as a transfer standard must demonstrate shipability.

3.2 VOR Generator Calibration Service

An unknown generator is calibrated by the NBS standard phasemeter. The output of the generator is connected to the phasemeter. In addition, a digital timing reference signal must be provided by the generator to the phasemeter. Some commercial instruments provide such a signal internally; others do not. Of those that do, only two have been found suitable for calibration, so far. This is because the operating principles of the NBS phase standard require good short-term phase stability in the timing signal. This is discussed further in section 13.1.

Because of the short term (30 μs) phase jitter of most commercial generators, they cannot be calibrated by the NBS standard phasemeter. Instead, a transfer must be made through a commercial phasemeter that has been calibrated against the NBS standard generator. Commercial phasemeters do not show the sensitivity to short term fluctuations that the NBS phasemeter does. This is usually due to the use of analog phase-locked loops and averaging circuits that reduce sensitivity to this type of noise. The price paid is that the commercial phasemeter is not reliable as a primary standard and must be calibrated against the NBS generator immediately before use as a transfer standard, to minimize the degradation of the accuracy of the NBS generator. Hopefully, industry will design stable generators which provide a timing reference for the NBS phasemeter.

Because of the complementary nature of these two services and the limitations of commercial generators, the best transfer standard for either a generator or a phasemeter calibration is a commercial phasemeter, as discussed in section 3.1, above.

A sample report of calibration appears in appendix E.

4. Design Philosophy

At the beginning of the standards development effort, it was decided that it would be necessary to design both a standard signal source and a standard phasemeter, since otherwise there would be no independent way of checking either one. Two instruments working on different principles, that agree closely with each other, give some assurance that they are both performing as desired. This agreement, of course, must not require any adjustments or "twiddling" of either instrument. This condition has been achieved. In addition, other objective means can be used for evaluating the performance of each instrument independently of the other, up to a point. For example, a common signal sampled by the phasemeter through a single-pole double throw switch should result in a zero phase difference, which it does, to within a standard deviation of less than 0.0005°. For the generator, precise matching of differential time delays between the various signals, extending through the digital-to-analog converters (DACs) is possible. This is discussed in more detail in section 10.3.

It was also decided at the outset that it would be necessary to minimize the number of linear circuit elements in the signal paths, such as capacitors, amplifiers, resistors, and filters. In order to attain the desired ±0.01° uncertainty objective, elements with significant time or temperature drifts could not be used. This requirement suggested the heavy use of digital circuits. It resulted in a design in which the remaining essential analog components have very little effect on the phase integrity of either the generator or the phasemeter (see sections 10.3 and 10.4).

As above, the generator and phasemeter are discussed separately.

4.1 Generator Design

The generator comprises three digital waveform synthesizers, all driven by the same crystal-controlled clock. It produces three digital outputs, 16 bits wide, reset every 0.01° (about 925 ns). Only 14 bits of data are actually generated, because of present DAC resolution and speed limitations. Binary numbers from -8188 decimal to +8188 decimal are generated. This comprises 16377 different codes, or $2^{14}-7$. These codes are used to drive three 13-bit digital-to-analog converters (DACs). The lowest bit is not used. The converters are made as nearly identical as possible and are designed in such a way that differential time delays between them can be made negligible (less than 10 ns). The analog outputs represent the 30 Hz variable phase signal, the 9960 Hz subcarrier, and the 30 Hz signal that is, in principle, frequency modulating the subcarrier. Actually, there is no frequency modulator in the generator, as this would require unstable analog circuitry. Instead, the subcarrier is synthesized directly as the modulated waveform. Note that the subcarrier waveform does not change with bearing angle settings. The 30 Hz reference phase is not needed in a calibration but is useful for other purposes; e.g., a 30 Hz phase angle standard.

Normally, the composite audio signal used for calibrating phasemeters is obtained by combining the variable phase and subcarrier signals in a passive linear resistive adding network, which introduces insignificant phase shifts. This network is followed by a 7-section linear-phase LC filter with a 100 kHz cutoff frequency, to remove residual digital switching noise and higher harmonics present in the waveform due to the quantization in the DACs. The filter measurement and evaluation techniques are discussed in more detail in section 10.4.

4.2 Phasemeter Design

As with the generator, analog circuitry is avoided as much as possible. The phasemeter consists of three main elements, all of which are commercially available: a 16-bit analog-to-digital converter (ADC), a programmable time delay generator (TDG), and a desktop computer-controller.

The critical consideration in the phasemeter, as in the generator, is to avoid differential time delays between the variable phase signal and the reference phase signal present as modulation on the subcarrier. Most methods of analog FM demodulation cause unacceptable instabilities. More importantly, they require at least some adjustments. Adjustability would defeat the objective of a truly independent phasemeter. A sampling technique provides a solution, since a sampling ADC gives constant time offsets, to a first order approximation [4]. The phase angle of the variable phase signal relative to the reference phase signal can then be computed via a fast Fourier transform (FFT).

VOR GENERATOR

5. Generator Details

An aircraft determines its magnetic azimuth relative to a ground-based VOR transmitter by measuring the phase difference between the two modulation components of the received signal. The generator described in this report was developed to serve as the phase angle standard for these modulation components. It consists of three separate audio generators, arranged to function with controllable phase relations among them. There are two 30 Hz sine-wave generators and one frequency-modulated-wave generator. The FM signal is a 9960 Hz carrier, modulated by a 30 Hz sine wave at a modulation index of 16. The nominal deviation is thus ±480 Hz.

The phase relation between the two 30 Hz signals, which are called the 30 Hz reference phase signal and the 30 Hz variable phase signal, can be set for a lag of 0.00° to 399.99° in steps of 0.01°. The phase of the FM signal is fixed relative to the 30 Hz reference signal such that maximum frequency of the 9960 Hz signal occurs at the positive peak (90° point) of the 30 Hz reference signal (see fig. 5-1).

The unique characteristics of the generator are low distortion of the outputs and the highly accurate control of the phase relations among the three signals. These features were accomplished through the use of synchronous (clocked) logic as much as possible within the instrument. This design minimized the number of analog circuits used.

All three generators use similar circuits; they generate digital representations of the desired waveforms. The output data are then converted from the periodic numerical sequences to varying voltages which are filtered to provide the desired sine and FM waveforms. In each generator, a new digital value is produced each 0.925925... μs for every 0.01° of a 30 Hz waveform. A 13-bit representation is used, giving a numerical resolution of almost 1/4096 of the peak value. An output filter serves to interpolate between the discrete voltage steps, changing the stairstep output to a smoothly varying one.

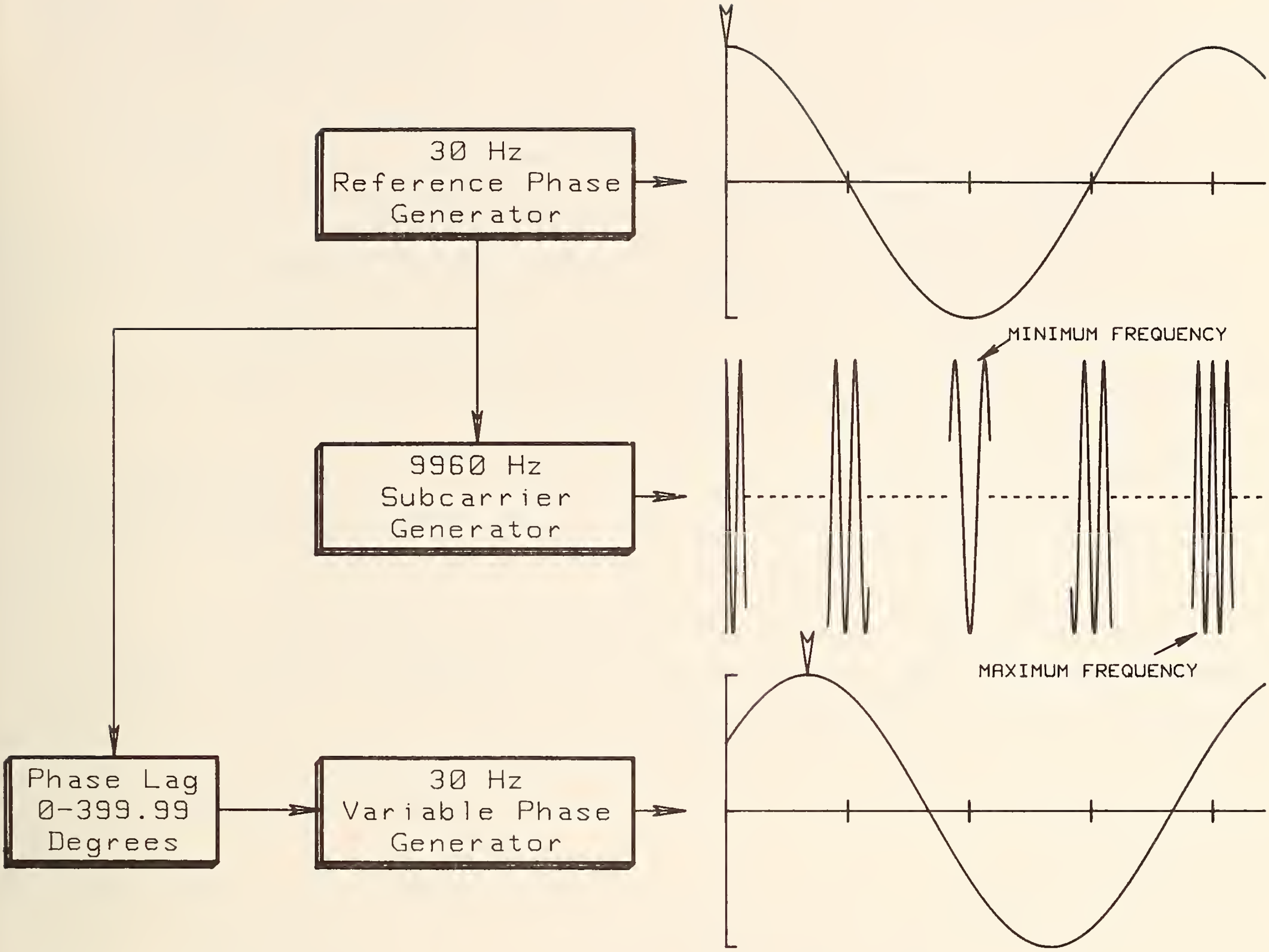


Figure 5-1. Simplified block diagram of generator.

The general principle is illustrated in figure 5-2. The output of the counter changes each 0.9259... μs and repeats after 36,000 counts, or 1/30 sec. The output of the Programmable-Read-Only-Memory (PROM) changes accordingly, and gives a 36,000 point digital approximation to the desired waveform. The exact form is ideally a staircase with a 1.08 MHz step rate. This signal is smoothed with a 100 kHz low-pass linear-phase filter to achieve the required accuracy. See section 10.4 for a discussion of the filter.

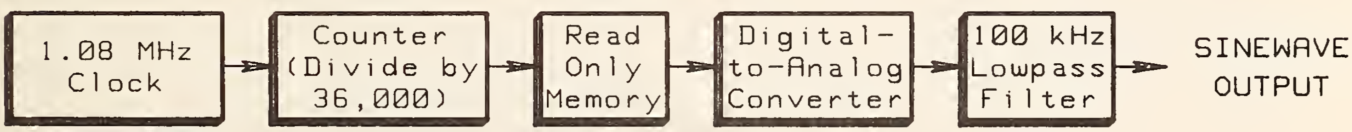


Figure 5-2. A waveform synthesis technique.

The actual implementation differs somewhat from the above simplified version, primarily to reduce the cost of the PROM tables that store the waveforms. When this design was frozen, the cost of the memory alone for a direct sine lookup table was about $10,000. Since then, there have been large reductions in the cost of PROMs; this factor should be considered if this type of instrument is built again. Four techniques were used to reduce the required memory size without loss of accuracy:

1. The symmetry of the desired waveforms has been used to reduce memory size by a factor of 4 for the 30 Hz generators. Only one-fourth of a 30 Hz cycle is stored; i.e., 0° to 90°. These data are used 4 times, with appropriate address changes, to produce each 30 Hz cycle.
2. In the 9960 Hz generator, one-half cycle of the desired waveform is stored and used twice per 30 Hz output cycle.
3. Both 30 Hz generators share the same PROMs through multiplexing. The 4-phase clock permits this approach without introducing phase offsets.
4. The PROMs do not store the actual waveform amplitudes; instead, they store the second or third difference between each steps. With this method, only two bits are required for each 30 Hz step, and only 4 bits are needed for each 9960 Hz step. Simple digital accumulators sum the successive incremental changes to obtain full 14-bit representations for the DACs (only the top 13 bits are used).

These techniques are, of course, not free of side costs. Their use, particularly the use of incremental values, has added significant complexity to the remainder of the circuits. However, a substantial net saving in overall size and complexity has resulted. We now see where further simplification is possible and discuss this in section 12.

6. Specifications

6.1 Audio Signal Outputs

6.1.1 Individual and Composite Signal Outputs

Amplitude: 1 V rms at filter output

Output impedance: 600 Ω, unbalanced to ground at filter output

Load capacitance: Not more than 100 pF; larger values may cause nonlinear phase shifts.

6.1.2 30 Hz Reference and Variable Phase Outputs at Filter Output

Purity: Total harmonic distortion less than 0.01%

Noise: Less than 0.5 mV rms from 0 to 300 kHz

Phase lag setting: Variable phase output relative to reference phase, adjustable from 0.00 to 399.99° in steps of 0.01°, lagging.

Phase lag uncertainty: ± 0.002°

6.1.3 FM Output

Carrier frequency: 9960 Hz

Modulating frequency: 30 Hz

Modulation index: 16

Purity: The differences between the measured and computed amplitudes of the various lines in the spectrum are too small to measure. Harmonic distortion components were below the spectrum analyzer sensitivity of -75 dB.

Noise: Noise, as determined by measuring the amplitude of selected lines, is too small to to measure accurately.

Spectrum: See figure 10-1.

6.2 Other Outputs

Synchronizing Pulses--0° Reference (Reference Phase [RP] 0°, Variable Phase [VP] 0°, 9960 0 DET)

Timing: 30 Hz channels--pulse occurs 0.00324° (110 ns) before the positive-going zero crossing of the output signal. Note that this time offset, which is fixed, does not enter into the phasemeter uncertainty estimate, because it affects all time samples equally.
FM channel--pulse occurs 0.00324° before the positive-going zero crossing at the maximum positive frequency excursion.

Duration: 0.9 μs

Amplitude: Nominal 3 V

Source characteristics: Unloaded TTL output with 100 Ω series resistor added.

Synchronizing Pulse--90° Point of 30 Hz Reference Channel (RP 90°)

Timing: Pulse occurs 0.00324° (110 ns) before the 90.00° point of the 30 Hz sine wave

Other characteristics: As above

Master Clock Pulse (ϕ_1)

Timing: 1.08 MHz repetition rate, 4-phase

Other characteristics: As above

Square-Wave Outputs--RP Cycle, VP Cycle, FM Scan

Timing: 30 Hz square waves with rising edge occurring at the fall of the corresponding 0° reference pulse

Other characteristics: As above

6.3 Frequency and Phase Stability

All signals are derived from a single 4.32 MHz temperature-controlled quartz master oscillator

Nominal uncertainty: 1×10^{-7}

Short term stability: 5×10^{-10} rms

Aging rate: 3.5×10^{-8}/week

Output timing jitter: Less than ± 1 ns

6.4 Error Detection Circuits

An audible alarm sounds when any of the three generators loses synchronism with the other two or when an erroneous output value is computed by the digital circuits. Indicator lamps show which error condition has occurred. These comparison circuits are indicated by the circled letter "C" in figure 6-1. All comparisons are made 30 times per second.

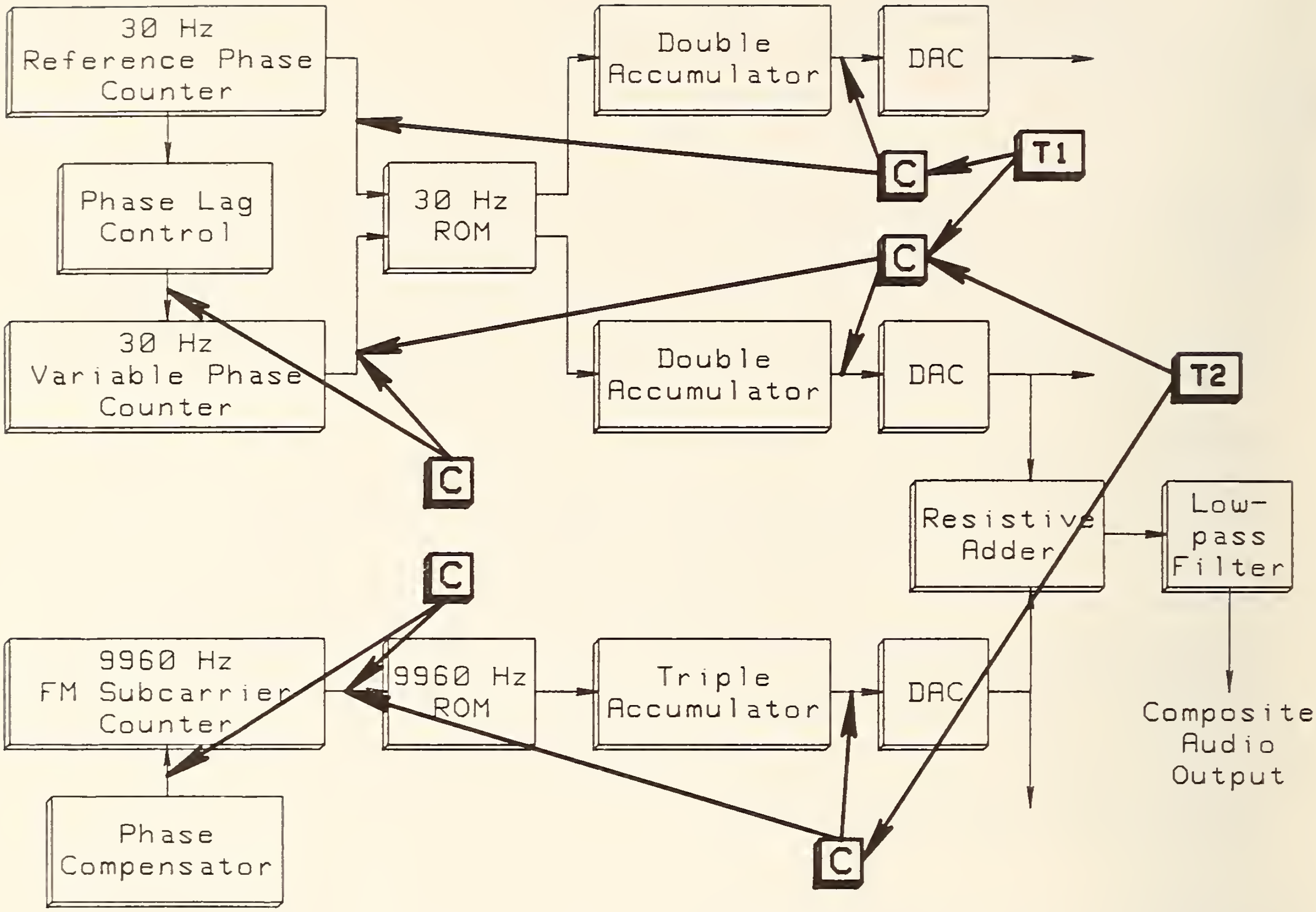


Figure 6-1. Error detection circuits. Digital comparisons are made between the pairs of digital signal paths as indicated by the heavy arrows. Clock is not shown.

6.5 Built-in-Test Circuits

6.5.1 Circuit T1 in Figure 6-1

This circuit compares the two 30 Hz generators at 0 and 360° phase lags and lights an error lamp if they disagree. This test is made manually from the front panel.

6.5.2 Circuit T2 in Figure 6-1

This circuit compares the FM generator with the 30 Hz variable phase generator at 90° phase lag and indicates an error if they disagree. This test is made manually, from the front panel.

6.6 Controls

Power switch.

Connectors (6) to select the components of the composite signal and timing references

Phase lag--5 decade lever switch, 0 to 399.99°

Error indicator reset pushbutton

Built-in-test operate pushbutton

6.7 Indicators

Power on: 1 lamp
Error indicators: 5 lamps, 1 audible alarm. Indicator latch ON if tripped
Test indicators: 2 lamps

6.8 Other Characteristics

Power input: 117 VAC ± 10%, 350 W
Size: 58 cm high by 50 cm wide by 46 cm deep
Ambient temperature: Normal laboratory environment, 22 ± 5°C
Signal connectors: BNC

7. Operating Procedures

7.1 Normal Operation

Turn on ac power and wait one hour for warmup. Connect short (1 m) shielded cables to the 30 Hz and 9960 Hz outputs. Connect the two cables to the resistive summing network. Connect the output of the network to the input of the linear-phase low-pass filter. The composite signal is then available at the filter output (see fig. 7-1). Set the lever switches to the desired bearing angle. Proceed with measurements. It is normal for the error alarm to sound briefly and for the phase lag error indicator to glow briefly whenever the bearing angle switch setting is changed. There is a problem only if the alarm continues to sound. See sections 8.5 and 11.3.

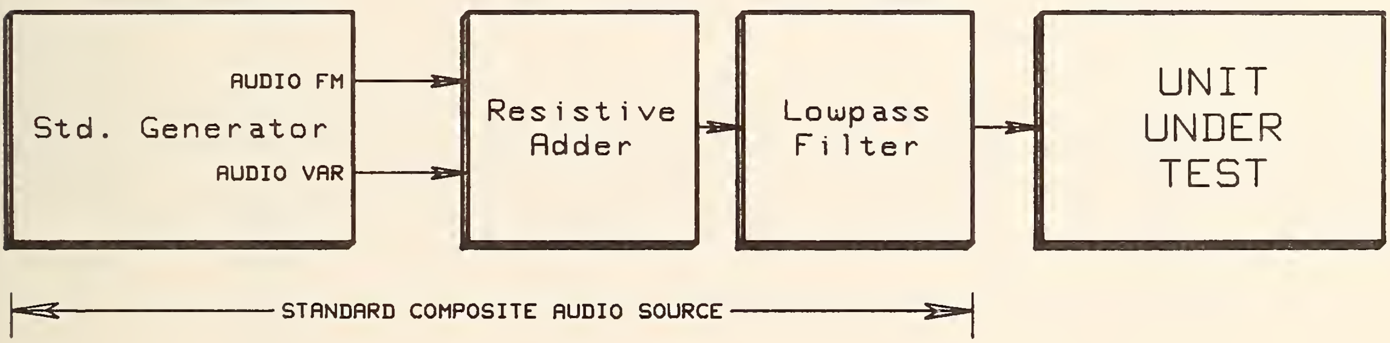


Figure 7-1. Connecting the standard VOR generator, adder, and filter to a unit under test.

7.2 Error Conditions

Continuous sounding of the alarm after a phase lag change, or momentary sounding of the alarm at any other time during operation, indicates that an error has occurred. The indicator lamps show which circuits are involved. The RESET button turns off all error indications but does not affect any other circuits. An automatic power-on reset circuit clears all error indicators five seconds after power turn on. Since the generator circuits are self correcting (as described in section 8.5), an occasional error indication is of no consequence unless it occurs during a measurement. Any error lamp that is lit during a phasemeter calibration means that the run should be repeated, as the data may be invalid. This is a rare occurrence, and is usually due to a static discharge between the operator and the system. Frequent errors or a continuous alarm are reasons for concern, and their cause must be determined and corrected.

7.3 Testing Bearing Angle Settings

Set the bearing angle settings successively to 0.00° and 360.00° and press the TEST button. The respective indicator labeled 0° or 360° LAG should light. It should not light for other nearby values. Indications that differ from these result from faulty 30 Hz generator circuits or faulty test circuits.

Set the bearing angle to 90.00° and press the TEST button. The correspondingly labeled indicator should light. It should not light for other nearby bearing angle settings. Any other indication shows a circuit failure. Note that the indicators will also light for a few settings well removed from the prescribed settings. This condition is normal and is of no concern.

8. Generator

8.1 General Approach

The overall design concept was to reproduce the desired waveforms from internally stored tables of numbers which are associated with the waveform. The last stage is signal generation by means of a DAC and filter. In the actual implementation, a number of steps were taken to reduce the required amount of programmable read-only memory, the most expensive part, by a factor of 14.

In this section, the basic scheme is described first. Then, the various techniques used to reduce ROM size are discussed.

It should be noted that this design does not attempt to minimize the number of samples per cycle required to represent the required signals. The 1.08 MHz sampling rate used is well above the Nyquist rate of about 22000 samples per second. In fact, the design approach was to use the highest sampling rate that could be readily implemented, in order to minimize the generation of unwanted signals.

See section 12 for possible future improvements.

8.2 Generating the 30 Hz Sine Waves

8.2.1 Basic Method

The 30 Hz signals were generated from stored numeric representations by fetching each successive value from a table and sending it through digital-to-analog converters. In order to get a phase resolution of 0.01°, it was convenient to work with 36,000 values, one for each 0.01° of a complete cycle. Portions of a sine table, based on a full scale amplitude of ±8188, are shown in table 8.1.

It is readily seen that the size of such a table can be reduced by a factor of 4 by using the symmetry properties of the sine wave, as follows:

Table 8.1. Selected values of 8188 sin θ and its first and second differences.

θ degrees	$\Delta^2 A$	$\Delta^1 A$	f
0.00	1	1	0
0.01	-1	2	1
0.02	1	1	3
0.03	-1	2	4
0.04	1	1	6
0.05	-1	2	7
0.06	0	1	9
0.07	1	1	10
0.08	-1	2	11
0.09	1	1	13
89.99	0	0	8188
90.00	0	0	8188
90.01	0	0	8188
179.91	1	-2	13
179.92	0	-1	11
179.93	-1	-1	10
179.94	1	-2	9
179.95	-1	-1	7
179.96	1	-2	6
179.97	-1	-1	4
179.98	1	-2	3
179.99	0	-1	1
180.00	-1	-1	0
180.01	1	-2	-1
180.02	-1	-1	-3
180.03	1	-2	-4
180.04	-1	-1	-6
180.05	1	-2	-7
180.06	0	-1	-9
180.07	-1	-1	-10
180.08	1	-2	-11
180.09	-1	-1	-13
269.99	0	0	-8188
270.00	0	0	-8188
270.01	0	0	-8188
359.91	-1	2	-13
359.92	0	1	-11
359.93	1	1	-10
359.94	-1	2	-9
359.95	1	1	-7
359.96	-1	2	-6
359.97	1	1	-4
359.98	-1	2	-3
359.99	0	1	-1

The table is used directly for angles (θ) between 0° and 90°. For θ between 90° and 180°, the values for (180-θ)° are used, scanning the table backward from 90° to 0°. For angles between 180° and 270°, the entry for (θ-180)° is used but with the sign of the value changed to minus. For angles between 270° and 360°, the entry for (360-θ)° is used, again with a negative sign for the value. Thus the size of the table is reduced by 4 with no loss of information.

The scanning of the table is readily controlled with the aid of a digital counter which is changed by one count each 0.93 μs (1/36000 x 1/30 s). The count is incremented for the first 9000 counts, decremented for the next 9000, then incremented for 9000 counts, then decremented for 9000 counts for four scans of the PROM. During the second half of this cycle, the sign of the number is negated, thus producing a normal sine wave output.

8.2.2 Use of Differences to Reduce ROM Size

When the 30 Hz sine wave generators are implemented as just described, the minimum size of the lookup table is 9001 13-bit words. However, it can be seen from table 8.1 that the changes (the "Δ^1_A") between successive words are small. If the function is generated from its stored differences, the length of each word in the table is substantially reduced. This reduction is shown in table 8.2 in the column labeled "First difference."

Table 8.2. Sine function and differences.

θ Degrees	8188 Sin(θ)	First difference (Δ^1)	Second difference (Δ^2)
0.00	0	1	1
0.01	1	2	-1
0.02	3	1	1
0.03	4	2	-1
0.04	6	1	1
0.05	7	2	-1
0.06	9	1	0
0.07	10	1	1
0.08	11	2	--
0.09	13	--	--
.	.	.	.
.	.	.	.
.	.	.	.

Since sin(θ) changes most rapidly around 0°, the first differences at other angles will not be any larger than those near 0°. A thorough examination, in fact, shows that the range of first differences is 0 to 2 for θ between 0° and 90°. By using a conventional binary number representation, this range could be covered by using two bits per entry, instead of the 13 bits required to represent 8188 sin(θ). In the actual system, we chose to carry this one step further and use second differences[1] that is, the differences between first differences. In that case, the number range is -1 to +1. This approach still requires two bits to represent all required values.

When differences are used instead of the actual function, the circuits must be modified to generate the function from the differences read from the table. This is done by providing two accumulators, as shown in figure 8-1. The first accumulator adds the successive values of Δ^2, the second differences read from the table, and forms Δ^1, the first difference. The second accumulator adds successive values of Δ^1 to get the desired function, 8188 sin θ, which supplies the input to the DAC. Additional circuits are required to insert the appropriate initial values into the accumulators at 0° and to change from addition to subtraction when the table is scanned in the reverse direction.

[1]This decision was made early in the design process, before it was recognized that there is no advantage in using second differences in the 30 Hz generators. Indeed, upon examining a complete computer printout of the occurrences of all first differences, it was discovered that the 30 Hz memory could have been cut in half again by the addition of a single flip-flop. With such an arrangement, only a single bit is required in the lookup table for each value of the sine function first difference. See section 12.1.

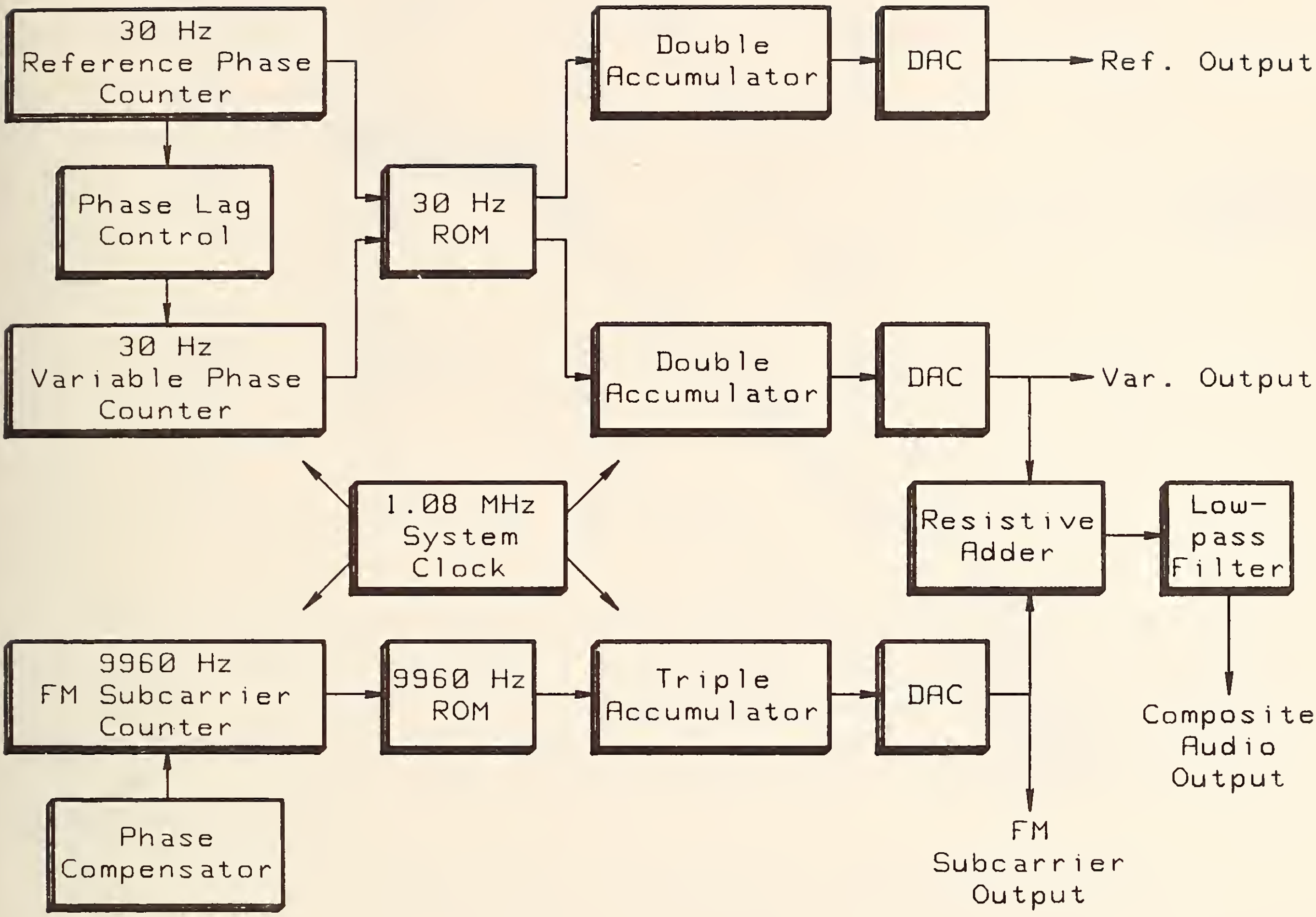


Figure 8-1. Overall generator block diagram.

8.3 Generation of the Frequency-Modulated 9960 Hz Signal

8.3.1 Basic Method

The method used here is similar to that used for 30 Hz generation. The values corresponding to the third differences of the desired frequency-modulated signal, computed at intervals of 0.93 μs, are stored in a table, integrated appropriately, and reproduced through a DAC. The 9960 Hz generator is driven from the same clock as the 30 Hz generators; this approach maintains synchronism among all signals. The 9960 Hz FM signal has only a two-fold symmetry, in contrast to the four-fold symmetry of a sine wave.

The function represented in the table is

$$F(\phi) = 8188 \sin \left[332\, \phi + \frac{360}{2\pi} \sin \phi\right]$$

where ϕ is the phase of the 30 Hz signal relative to its 90° point. This function, when interpreted as a sine wave of slowly varying frequency, sweeps ±480 Hz around 9960 Hz. The computed spectrum is a

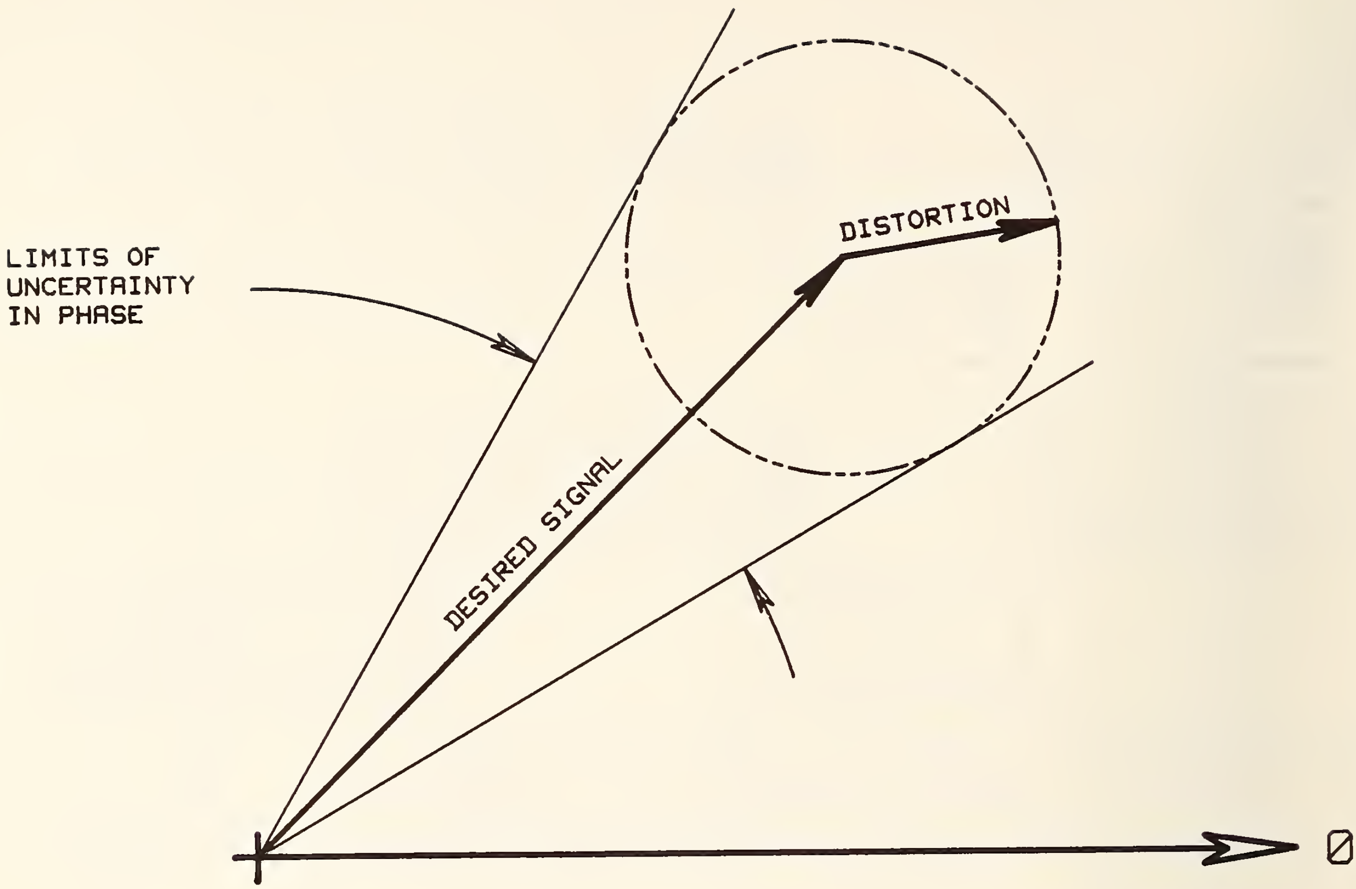


Figure 8-2. Relationship between amplitude distortion and phase uncertainty.

set of discrete lines spaced every 30 Hz around 9960 (there is further discussion of the spectrum in sections 10.2 and 16.1). The -80 dB points of the spectrum are at ±810 Hz relative to 9960 Hz. This means that almost all of the information contained in the composite VOR signal appears in the line at 30 Hz and the band between 9150 and 10770 Hz. For purposes of the standard generator and the standard phasemeter, it can be shown [5] that sufficient information to perform a calibration to an uncertainty of less than 0.01° can be obtained from the 30 Hz line and those between 9420 Hz and 10,500 Hz.

The PROM table stores half of this FM waveform, using 18000 locations to do so. The other half is obtained by reading the table backwards.

8.3.2 Use of Differences to Reduce PROM Size

As in the case of 30 Hz signal generation, a table storing the function $F(\phi)$ would be quite large, 18001 13-bit words. Again, because the function changes relatively little between successive entries in the table, it is feasible to use differences to reduce the required word length. The use of third differences reduces the word length to 4 bits, as indicated in table 8.3.

Table 8.3. 9960 Hz FM signal function and its first three differences.

ϕ Degrees	$F(\phi)$	First diff. (Δ^1)	Second diff. (Δ^2)	Third diff. (Δ^3)
0.00	0	497	-2	-1
0.01	497	495	-3	-3
0.02	992	492	-6	-1
0.03	1484	486	-7	-3
0.04	1970	479	-10	0
0.05	2449	469	-10	-2
0.06	2918	459	-12	--
0.07	3377	447	--	--
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
179.93	-3083	423	8	-2
179.91	-2660	431	6	0
179.95	-2229	437	6	-1
179.96	-1792	443	5	-3
179.98	-1349	448	2	-1
179.99	-451	451	--	--
180.00	0	--	--	--

There is a priori reason to assume that the higher order differences will have numerically smaller values. The design approach was to select the lowest order differences that had reasonably small absolute values. Table 8.4 shows that for $F(\phi)$, the maximum magnitude of the differences decreases up to Δ^3 but then increases again. Accordingly, Δ^3 was chosen as the function to be stored in the table. This optimum approach was ascertained by a computer algorithm that tested the zero through fifth differences.

Table 8.4. Maximum value of the first through fourth differences for the 9960 Hz FM waveform.

First difference:	$\lvert\Delta^1\rvert \leqslant 496$
Second difference:	$\lvert\Delta^2\rvert \leqslant 31$
Third difference:	$\lvert\Delta^3\rvert \leqslant 5$
Fourth difference:	$\lvert\Delta^4\rvert \leqslant 7$

The circuit arrangement required to implement this approach is also shown in figure 8-1. Three digital accumulators are required to determine the values of Δ^2 from Δ^3, Δ^1 from Δ^2 and $F(\phi)$ from Δ^1. The accumulators are initialized to correspond to the values given in table 8.3 for $\phi = 0.00°$, namely $F(0.00) = 0$, $\Delta^1(0.00) = 497$, and $\Delta^2(0.00) = -2$ since this information is not stored in the PROM. A similar initialization, but with different numeric values, is also used at 180.00°.

8.4 Accuracy Considerations

The general design goal has been to achieve an overall uncertainty of ±0.01° in the various outputs of the signal source. This goal affects the design in three critical areas:

a. The short- and long-term accuracy of the output frequencies;
b. the short- and long-term accuracy of the phase differences between the three output signals; and
c. distortion and noise at the three signal outputs.

8.4.1 Frequency Accuracy

All outputs are derived from a single 4.32 MHz quartz crystal oscillator with an aging rate of less than 3.5×10^{-8}/week and a short-term stability of 5×10^{-10} rms. After allowing for temperature and voltage effects, the estimated frequency accuracy is about 1×10^{-7}. The frequency error required to produce 0.01° error would be 1/36000 or 2.8×10^{-5}. Thus, errors from the crystal oscillator frequency instability should not exceed $(0.01)(10^{-7})/(2.8 \times 10^{-5})$ or 0.000035°, a clearly negligible amount. This oscillator, and that in the phasemeter time-delay generator, are conveniently calibrated directly against the NBS atomic clock. Routine calibrations have resulted in corrections of less than 5×10^{-10}, which is still negligible.

The second potentially significant source of uncertainty is the short-term variations in timing of the circuits that use the clock signals. The system design uses synchronous logic so that variations in time delays will accumulate over only a few logic elements. The short-term variations in delay through the critical path from the clock oscillator to the inputs of the digital-to-analog converter are less than 5 ns (54 microdegrees). This is well below the 926 ns clock period and therefore could contribute at most a negligible uncertainty.

8.4.2 Phase Setting Accuracy

The desired phase shifts between the various outputs are produced by delaying the 30 Hz variable phase generator in increments of the clock period, 926 ns. At any delay setting, the actual delays have a variation of less than 5 ns, a negligible amount. The clock signals are distributed in a manner which ensures that significant fixed differential delays are not present. Residual delays that appear at the analog outputs are reduced to less than 5 ns, as noted below.

The composite signal is obtained by adding the 9960 Hz FM and 30 Hz variable phase signals in a passive resistive network. A passive low-pass filter follows the adding network. The filter has a cutoff frequency of 100 kHz, well below the 1.08 MHz clock frequency. It has a Bessel (maximally linear phase) response and contains seven sections. It is designed to work between 600 Ω source and load impedances and is terminated by a 600 Ω load. This design provides a fixed output level of 1 V rms for each of the two components of the composite signal. It was found that most commercially available 600 Ω "T-pad" attenuators were not sufficiently phase linear to provide for an adjustable output. Such an attenuator could be added at the price of a slight increase in the phase uncertainty.

A Bessel filter with seven sections closely approximates the ideal. In such a filter, the time delay (phase shift divided by frequency) is nearly the same for all frequencies. This is another way of stating that the filter has low group-delay distortion. Obviously, if all of the significant components of the spectrum are equally delayed in time, there is no effect on the VOR bearing angle. Computer simulations of the effects of the actual filter, with its measured imperfections, have shown that the differential time delays from 30 Hz to 10,770 Hz (a band that includes virtually all of the composite signal power) are negligible in so far as the bearing angle is affected. See section 10.4 for measurement details.

A third potential source of uncertainty in the bearing angle is the instability of the filter characteristics due to component drift. The filter is passive, with no operational amplifiers. Bessel filters tend to have a low sensitivity to component drift; inductor "Q"s for a 7-section filter need not exceed about 1.1. Finally, since the first-order errors have been found negligible, certainly higher-order errors are also.

8.4.3 Amplitude Distortion and Noise

Noise and distortion are introduced into the output signals in a number of ways. These include quantizing noise, digital-to-analog converter nonlinearity, switching spikes (so-called glitches), nonlinearity in the amplifiers that follow the converters, and digital signals that find their way into the analog signal outputs through subtle paths. All of these have an explicit effect on the design of the system. All are discussed below.

8.4.3.1 Quantizing Noise

The unfiltered output from the digital-to-analog converter is nominally in the form of a staircase with a step size equal to 2^{-N} times the peak-to-peak output voltage, where N is the number of bits used in the converter. This means that the maximum uncertainty in reproducing any waveform will be 1/2 the step size. In terms of the peak value of a sine wave with unit amplitude, the maximum uncertainty is $1/(2^N-1)$.

A useful interpretation of the 0.01° uncertainty requirement is that amplitude distortion of a signal must not shift the time position of a zero crossing, with respect to an ideal 30 Hz sinusoid, by more than 0.01°. The amount of distortion that produces this phase shift is easily deduced from the phasor diagram of figure 8-2.

The maximum value of $\Delta\theta$ is related to ΔE by the expression $\Delta E = A \sin(\Delta\theta)$. Thus, for $\Delta\theta = 0.01°$, $\Delta E/A = \sin(0.01) = 1.7 \times 10^{-4}$. Thus, 0.017 percent is the maximum allowable distortion for a phase uncertainty of ±0.01°.

Setting 2^{-N} = 0.017 percent, we obtain $N \geqslant 13$. If quantizing noise in one channel were the only source of error, a 13-bit converter would be adequate. However, since there are other sources of error, a more conservative design must be used. Converters that will operate at the required speed are not readily available for $N > 13$. Accordingly, 13-bit converters are used, followed by a low-pass filter to further reduce the quantizing noise. Assuming that the principal quantizing noise component is at 1.08 MHz, a 7-section Bessel low-pass filter with a cutoff frequency at 100 kHz will reduce this noise component by more than 80 dB. The quantizing noise from a 13-bit converter followed by this filter should then be 1.2×10^{-6} percent. Note that the total harmonic distortion figures given above include the effects of quantizing noise, along with other noise sources, hum, and harmonic distortion. It is apparent that the quantizing noise is very small compared to the maximum allowable value of 0.017 percent, and in fact is too small to be measured.

8.4.3.2 Converter Nonlinearity

The DACs used have a specified maximum nonlinearity of ±1/2 of the least significant bit (LSB) relative to a straight line connecting the largest and smallest output values. Thus, the amplitude uncertainty at a nominal zero-crossing point could be as great as 1/2 LSB, or 6.1×10^{-5}. The change in the zero-crossing time that this uncertainty would produce can be estimated by assuming that the slope of the waveform is constant in this region and equal to $2\pi f$ for a unit amplitude sinusoid. There, the offset Δt for an amplitude uncertainty of Δv is given by

$$\Delta t = \frac{\Delta v}{2\pi f} = \frac{6.1 \times 10^{-5}}{2\pi \cdot 30} = 0.324\ \mu s,$$

or

$$\frac{0.324\ \mu s}{0.926\ \mu s \text{ per } 0.01 \text{ deg}} = 0.0035 \text{ deg.}$$

This result, taken alone, indicates a marginal design. However, the uncertainties caused by converter nonlinearity are only significant to the extent that the resulting distortion components appear at the output of the filter described above. All three converters are interchangeable. The harmonic distortion for all three was measured at 30 Hz, at the filter output, using a twin-T notch filter with a fundamental rejection of more than 100 dB at 30 Hz. This technique allowed direct measurement of the total noise and distortion products of the DACs. In all cases, the total was less than the fundamental by more than 85 dB.

8.4.3.3 Converter Switching Spikes

Switching spikes (or "glitches") occur in digital-to-analog converters because of small differential delays in the digital input signals for different bits. The glitches are always present to some degree, because the current switches turn on in less time than they turn off. The converters used in the VOR generator are "de-glitched;" that is, they contain circuits that prevent the glitches from reaching the analog output. This is accomplished by following the digital portion with a track-and-hold amplifier and providing appropriate timing signals. The amplifier is in the "hold" mode while the digital currents settle, and is then switched to "track" until just before the next digital word arrives. This technique significantly reduces the spike energy.

8.4.3.4 Amplifier Noise and Nonlinearity

The current-to-voltage output amplifiers in the converters were supplied by the manufacturer. The characteristics of these amplifiers are included in the total specifications of the converters. Actual performance was determined by the total harmonic distortion measurements.

8.5 Error-Detection and Built-in-Test Circuits

8.5.1 Overview

In order to maintain this system as a national standard, it is essential to provide a means of routinely checking for slight degradations in its performance. Major failures will be immediately obvious when attempting to use the system. However, minor malfunctions, such as a single bit changing in ROM, might never be detected without repeating the full system validation. Therefore, the digital subsystems were designed to include error-detecting circuits, as described in section 6.4. It was relatively simple to augment this inherent capability and provide the ability to detect a large variety of permanent or transient malfunctions in the digital circuitry. Two types of checking are provided. The circuits which function without special attention from the user are called error-detection circuits. Those that require operator manipulation are called built-in-test circuits (see fig. 6-1).

8.5.2 Inherent Error-Detecting Capabilities

Using the method of differences to generate the output functions provides an inherent capability for error detection. Any single error in the ROM output data or in any accumulator will continue to distort the output signal until the start of a new cycle. When this occurs in other than the final accumulator (the "f-accumulator"), the distortion increases continually throughout the cycle. The result is that consistent single errors are likely to produce a severe distortion of the output signal. This distortion results in a major degradation of performance and would probably be noticed immediately by the user. It is immediately apparent on an oscilloscope. However, errors that occur close to the end of a cycle may not produce enough distortion to be obvious to the user.

8.5.3 Error-Detection Circuits

Three error-detection circuits, one for each of the three channels, provide a continuous check on the internal functioning of the digital elements of each channel. They operate by verifying that the outputs of the 30 Hz channels are correct at their 359.99° points and that the 9960 Hz channel output is correct just preceding its 0° and 180° points. Two additional error-detection circuits check the 9960 Hz counter and the 30 Hz phase-lag counter, at times just prior to their initialization, to ascertain whether a miscount occurred during the current cycle (see fig. 6-1). The five self checks are denoted by the letter "C" and the two tests by "T". When an error is detected by any of the five "C" circuits, an indicator lights, and an alarm sounds briefly. The phase-lag-counter error light automatically resets after 1/10 s, since this error occurs each time the phase-lag setting is changed by the user. The other four error indicators must be reset manually. This arrangement allows an extended measurement to be made without an operator present; if one or more of these lights is on at the end of the measurement, it must be assumed that bad data may have been taken. Over a period of several months of use, the only times that these lights have been lit have been when static discharges have taken place either nearby or into the instrument itself. There have been no "hard" failures. A power-on reset circuit resets all indicators 5 s after power is first applied.

8.5.4 Built-In-Test Circuits

These circuits (described in section 6.5) compare time delays introduced by the phase-lag circuits with fixed delays in the generator control circuits, thus providing a means of cross-checking the various digital delays. Checks are performed at 0°, 90°, and 360° lags. In operation, the tests are performed by setting the phase-lag switch to one of these three lags and seeing if the appropriate indicator lamp lights when the TEST push-button is depressed.

9. Power Supplies

The digital logic that generates the data presented to the digital-to-analog converters is powered by a single 5 V, 16 A supply. The nominal drain is 12.5 A. The logic is protected by a 6.8 V crowbar circuit. Heavy copper distribution buses and remote sensing are used.

Each of the three analog channels has its own power supplies, to reduce the possibility of crosstalk that could contaminate the output signal. Each channel uses a plus and minus 15 V, 350 mA supply for the analog circuits and a 5 V, 500 mA supply for the DAC logic.

10. Verification of Performance

In this section, we discuss the methods that verify that the digital and analog circuits are, in fact, performing as intended.

10.1 Memory Pattern Verification

The VOR "standard," in a certain sense, exists in the bit pattern of the programmable read-only memory chips. Therefore, considerable attention was given to assuring that the patterns were correct. This was done as follows:

1. A BASIC program was written for a desktop computer to prepare magnetic tapes containing the binary values for all of the PROM addresses for both the 30 Hz and 9960 Hz memories.
2. A second program was written to read the binary patterns from the magnetic tapes to a paper tape punch. The PROM vendor required such tapes to perform the programming operations. The PROMs are of the fusible-link type, nonerasable. This choice was dictated by the speed requirements.
3. A third program was written to read back the paper tape and compare the punched pattern with the original magnetic record. Punching errors were found and corrected.
4. A test jig and interface was designed and a program written to read the programmed PROM patterns and compare them directly with the original magnetic tape. Programming errors were corrected; defective PROMS were replaced by the vendor.
5. The PROMS were installed in the generator, and a special interface was designed to allow the computer to drive the system in place of the normal system clock. Programs were written to allow rapid access to any part of the waveform cycle (36,000 PROM addresses). This allowed examination of the bit patterns in the three channels at such critical points as sign changes, memory address turnaround, and so forth. Memory could be stepped one address at a time for debugging.
6. When all appeared normal, a program was written to step the logic through all 36,000 addresses and read out to the computer all three 16-bit words appearing at the DAC inputs. These were compared with the proper words computed at the same time, rather than comparing with the magnetic tape, so that the patterns were compared directly with the algorithm that generated them in the first place. This test, which involved the computation and comparison of 108,000 16-bit words, required about 10.5 hours to run. This may be compared with the time required for the generator to produce them normally, that is, about 33 milliseconds. No discrepancies were found, and it was concluded that the digital portion of the generator was indeed performing as required.
7. Two other points were considered in this verification. First, the question of whether the computer used to generate the PROM patterns had sufficient precision was answered by generating the same patterns using a large digital computer capable of maintaining 24 decimal digit precision. The files were identical, which is not surprising, since the small computer was capable of 12 decimal digit precision. Second, the algorithm used to generate the data was derived independently by several persons, to ensure that it accurately represented the VOR waveform.

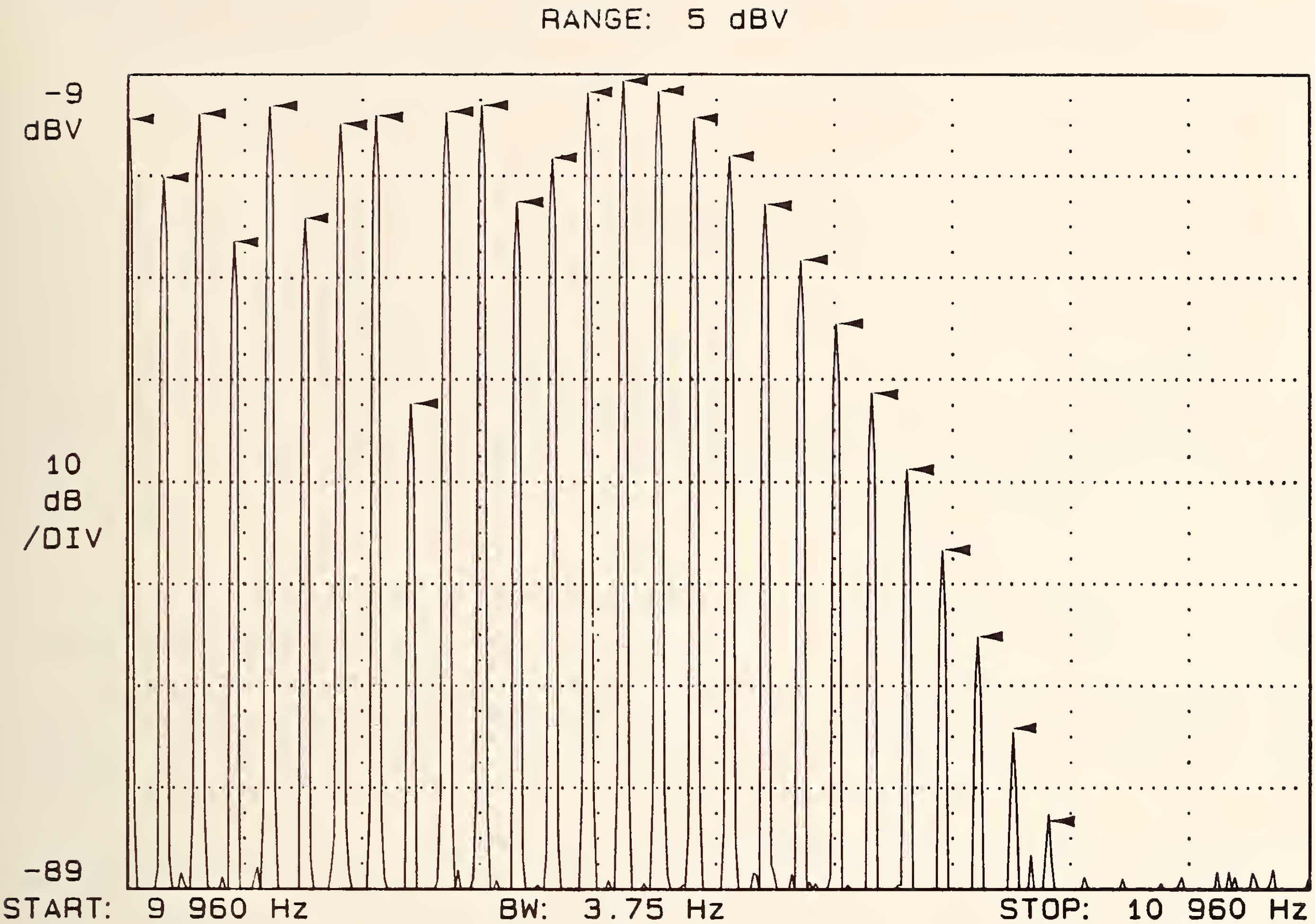


Figure 10-1. Partial 9960 Hz spectrum. Arrows indicate computed amplitude.

10.2 Analog Performance Verification

Some discussion of the methods used to verify the analog performance was given in section 8. For completeness, this discussion will be expanded here.

Initially, until the completion of the phasemeter, it was not possible to make an overall test of the generator. However, the individual components of the analog circuits were tested. Each of the DACs, in turn, was driven by the digital data from the 9960 Hz data lines. The output of each DAC was examined with a spectrum analyzer. Figure 10-1 is a typical result. Plots were made that showed that the spectra of the output were in close agreement with the theoretical and that harmonic components were below the minimum detectable level (about -70 dBc for the FM waveform). Errors such as missing codes in the DACs, or excessive non-monotonicity, show as unwanted sidebands. The outputs were also examined across an entire cycle, using an oscilloscope with an expanded sweep, to ensure that the DAC deglitching circuits were performing properly.

A second set of tests was made on each DAC using the digital input from the 30 Hz reference phase generator. Since the analog output contained only a single frequency, it was possible to measure harmonic distortion directly by suppressing the fundamental. It was at least 85 dB below the fundamental.

Finally, the analog filter was tested to the extent possible before the completion of the phasemeter. In the end, the definitive tests on the filter were made with the help of the phasemeter, as described in section 10.4.

10.3 Digital-to-Analog Circuit Timing Verification

Ideally, there would be zero differential time delay and jitter between the three analog signals at the outputs of the DACs. The three DACs are nominally identical, and all are clocked by the same clock phase. They are provided with two timing adjustments each. Data is presented to each DAC on the falling edge of clock phase 1. When the clock falls, the first of two cascaded monostable multivibrators is triggered. The time delay to its falling edge is adjustable over a small range. Its falling edge, in turn, triggers the second monostable, which produces a pulse with a fixed 50 ns width. During the period of the first delay, the digital data settle at the DAC input. The rising edge of the second delay enables the DAC, and the data are latched into the DAC registers. At the same time, the DAC deglitching amplifier is placed in the "hold" mode, so that the DAC switching impulses do not reach the output.

The DAC contains a second adjustable delay internally, that determines when the deglitching amplifier is returned to the "track" mode. This adjustment allows optimization of the DAC speed while allowing switching transients to die out. To match the three DAC time delays, each, in turn, was driven by the 9960 Hz data. Since there are only, on the average, about 108 samples per cycle in this waveform, the transitions may be clearly seen on an oscilloscope. If the oscilloscope is triggered by the transition of the sign bit of the reference 30 Hz DAC, at a sweep speed of 20 ns/division, all of the DACs may be adjusted to equality to within 10 ns or less. The delay from the falling edge of clock phase 1 to the rising edge of the DAC enable pulse was set to 110 ± 2 ns. Then, the delay from the falling edge of the clock to the beginning of the analog output transition was set to 300 ± 5 ns. A mismatch of 7 ns corresponds to a phase uncertainty of about 76 microdegrees, a negligible amount.

10.4 Analog Filter Characteristics

The actual characteristics of the output filter were measured as follows. A single-pole double-throw reed relay was placed at the input to the NBS standard phasemeter. The relay, in effect, permitted time-sharing the phasemeter between two inputs, simulating a conventional two-input phasemeter. A programmable frequency synthesizer was connected to the filter input, with appropriate padding to present a 600 Ω source resistance. The filter was also terminated in 600 Ω. The signal at the filter input was connected to one of the two phasemeter inputs, and the filter output was connected to the other. Thus, the phaseshift through the filter was simply the phase angle between the two phasemeter inputs.

The synthesizer was stepped at 30 Hz intervals from 30 Hz to 10,770 Hz. At each frequency, 256 amplitude samples were taken on each channel, covering precisely one cycle at the signal frequency. A discrete Fourier transform then allowed the computation of the filter phase shift at that frequency. The reduced data (phase versus frequency) were then fitted to a second-degree polynomial. The phase linearity was very good, but the conclusive determination was made by using the fitted phase function with simulated data, as described next.

A complete measurement of the composite signal was simulated by computing 1024 amplitude samples in which the only noise was due to the 14-digit precision of the computer used for this purpose. When these data were reduced, by the same machine, there was a offset of only about 54 microdegrees. Then the partially reduced simulated data were perturbed, using the filter function discussed above, to simulate very closely the effects that the actual filter would have produced. There was an insignificant change in the 54 microdegrees offset. The conclusion is that the filter does not degrade the phase integrity of the standard.

11. Maintenance Procedures

Three areas of maintenance are discussed here: adjustments, performance checks, and trouble shooting. There is no preventive maintenance as such for the system. The section on adjustments mainly covers the analog elements of the system and describes the procedures originally used to set the circuits to their design values. The trouble shooting section is quite brief, dealing mainly with getting started toward finding malfunctions in the digital elements of the system.

11.1 Adjustments

Run the system for at least 30 min to stabilize internal temperatures, then perform the following adjustments, in order.

5 Volt Power Supply. The main power supply contains an output-voltage adjustment. Connect a suitable dc voltmeter to the +5 V test-output receptacle. Set the adjustment (labelled 5 ± 5 percent VDC) for 5.0 V ± 0.1 V.

Oscillator. Connect a frequency counter to the ϕ_1 test-output receptacle. Use the adjustment on the oscillator (labelled FREQ. ADJ.) to set the frequency to 1,080,000 ± 1 Hz. Note that this oscillator is more accurate than the time bases in some frequency counters, and caution should be exercised in readjusting its frequency. An external standard may be required.

DAC Adjustments. See section 10.3. Adjust the time delays as noted. Final adjustment is best accomplished by using the following procedure:
Connect the cable carrying the 9960 Hz FM data to a "T" cable that allows driving two DACs simultaneously with that signal. Connect a two-channel oscilloscope to the unfiltered DAC outputs and trigger the oscilloscope with the sign bit of the 30 Hz reference phase. Set the sweep speed to 10 ns per division. Superimpose the two traces vertically, using the oscilloscope controls. Superimpose them in time by adjusting the time delay on either DAC. Only very minor adjustment should be needed. Reverse the connections to the oscilloscope to ensure that the channels have a negligible differential delay. If they do not, compensate accordingly. Replace either of the DACs with the third DAC and adjust the third DAC in the same manner. In this way, all three DACs have been adjusted to have the same overall time delays, and differential phase errors are made negligible at the output ports of the generator.

Low-Pass Filter. There are no adjustments available on the low-pass filter.

Phase Compensation. The phase compensation switches provide a means of advancing (or delaying) the start of the 9960 Hz signal to ensure that its principal zero crossing occurs exactly 90.00° after the corresponding point of the 30 Hz reference signal. This circuit was included early in the design under the assumption that it might be necessary to compensate for phase nonlinearity in a low-pass filter. This has since been found to be unnecessary, and, in fact, undesirable. The switches should all be set to provide zero compensation (all switches closed). If any switch is open, the 90.00° test will fail. The test will pass if the thumbwheel front panel switches are set to the value programmed by the phase compensation switches. This feature has been allowed to remain in the instrument for possible future experiments, but is never used for calibration purposes. The "untweaked" status of the generator is thus maintained.

11.2 Performance Checks

In addition to the parameters covered in section 11.1, a few other measurements can be made to verify that overall performance has not deteriorated. There are no specific adjustments associated with these measurements. If performance has deteriorated, the reasons must be determined through troubleshooting procedures. However, the performance will be affected by the adjustments of section 11.1, and these performance measurements should be made after final adjustments have been made. It is assumed that the error-detection circuits show no errors and that the internal (built-in) tests have been performed and passed.

Phase-Lag Tests. Certain failures in the phase-lag setting circuits could go unnoticed in normal operation. In particular, some switch settings could give erroneous values of lag. It is not feasible to check each of the 39,999 settings. However, it is straightforward to check each digit over its full range. Proceed as follows. Connect a two-channel oscilloscope to the generator, with one 30 Hz signal to each input. Trigger externally, using the sign bit of the reference signal. Set the sweep speed at 1 or 2 μs per division. Starting with a phase-lag of zero on the thumbwheel switches, advance slowly to 0.09° while watching the relative phase of the two signals. They should begin perfectly in phase (less than 10 ns offset) and move apart in nine equal steps of 926 ns, one for each new step on the 0.01° switch. This verifies that the 0.01° delay is functioning properly. Repeat for all of the higher order switches, decreasing the sweep speed by a factor of 10 for each successively higher order digit. The 100° switch, of course, can be tested only to 300°.

Spectrum Measurements. The overall performance of all three channels can be observed by measuring the spectra of the three signals. By comparing these spectra with the data obtained in the original tests of the system, any serious departure from the original state can be detected.

There are two approaches that may be used. In the first, a commercial low frequency spectrum analyzer with a plotter output can provide a comparison spectrum. Figure 10-1 was made in this way. If the output amplitude is the same as for the original test, the later plot can simply be laid over the original to detect deviations. Of course, the 30 Hz spectra should show only a single line at 30 Hz.

The second method involves the use of the NBS standard phasemeter. This is the best method for checking the performance of the 9960 Hz circuits. The relative amplitudes of the lines from 9420 through 10,500 Hz are compared to the fundamental at 9960 Hz. These amplitudes should follow closely the predicted values [3].

11.3 Trouble Shooting

The main requirements for finding other than obvious troubles are a reasonable understanding of the system design principles and circuits and a good oscilloscope. The principles and circuits have already been covered. The oscilloscope should have a pass-band of at least 20 MHz, a two- (or four-) trace input capability, and a dual time-base. A digitally-delayed sweep is useful but is not essential.

A number of points should be kept in mind.

1. The three channels are independent of each other except for their phase relationships. Any one channel can fail while the other two still function.
2. The only elements that affect all channels are the 5 V power supply and the clock circuits.
3. The error-detection circuits may not indicate a gross failure in a channel.
4. The simplest test of overall operation is to observe the individual channel outputs on the oscilloscope. Triggering the scope from the variable phase sign bit permits examination of the individual cycles of the 9960 Hz output by changing the phase-lag setting. The 30 Hz outputs should be perfectly clean sine waves, and the 9960 Hz output should have uniform amplitude everywhere. Any small part of it should appear to be a clean sine wave.
5. A ROM or accumulator failure, no matter how minor, usually results in an output signal that bears no resemblance whatsoever to the desired signal. If the signal appears normal over only part of the cycle, noting the precise point of failure helps to localize the trouble.
6. The three DAC cards may be interchanged with each other to localize faults.
7. The ϕ_1 signal is the main clocking signal for all channels. Nearly all clocked flip-flops are triggered by the trailing edge of ϕ_1. The other three clock signals are used as synchronizing and strobe signals in the phase-lag control, phase-compensation, ROM-multiplexing, error-detection, and built-in-test circuits.
8. The internal control signals always lead the actual 0° point of the analog output signals. Do not assume that these signals are at the zero crossing points of the sine or FM signals.

12. Suggestions for Future Designs

During the development of this system a number of design simplifications became apparent. For the most part, we chose not to incorporate these simplifications into the present system, since doing so would have delayed its completion. However, it will probably be cost-effective to incorporate these into a future system if one is to be constructed.

12.1 30 Hz ROM and Accumulators

In the 30 Hz channels a 14-bit value of the sine function is computed, but only the 13 most-significant bits are used. The size of the 30 Hz ROM can be cut in half, using only one bit per word. Examination of a complete printout of all 9001 first differences reveals that the present precision of 8188 can be maintained with half the present memory by supplying a 1 or 0 from a flipflop. It changes state from 1 to 0 at some point away from the zero crossing. The pattern shows only "1"s and "2"s in the region of rapid change, and only "0"s and "1"s near the peak of the wave, where the slope is zero. Thus, only one bit per word is sufficient, if the flipflop is added.

12.2 Reduced Sampling Rate

In the present system there are 36000 samples per 30 Hz cycle and about 108.3 samples per 9960 Hz cycle. If these numbers can be reduced without degrading overall performance, then the size of ROM can be reduced correspondingly. In the limit, the sampling theorem requires just two samples per 30

Hz cycle or per nominal 9960 Hz cycle.[2] In principle, the sampling rate could be reduced by a factor of about 50 and still be fast enough for the 9960 Hz generator. However, if this were done, the low-pass filters at the analog outputs would need to have much sharper cutoff, so much so that conventional analog filters would no longer be practical. The optimum tradeoff between number of samples per cycle and filter complexity is not apparent, particularly in view of the need for low group-delay distortion of the 9960 Hz FM signal. However, if adequately stable filters with accurately known characteristics can be constructed, then the 9960 Hz FM signal can probably be predistorted to compensate for amplitude and phase distortion introduced by the filter. Such an approach might permit a major reduction in the sampling rate and a corresponding reduction in ROM size.

VOR PHASEMETER

13. Phasemeter Details

This section describes the hardware and software developed to allow measurements of the composite audio signal generated by the NBS standard VOR generator discussed above. A general discussion of the VOR system was given in sections 1 and 2. For a complete analytical description of the mathematical model used for the VOR waveform, and for an analysis of the phasemeter measurement principle, see Vecchia [5].

13.1 Phasemeter Design Principles

The phasemeter is very simple in comparison to the generator. It was assembled completely from commercial off-the-shelf modules and instruments. By far the most complexity lies in the software that runs it.

In the development of both the standard generator and the standard phasemeter, the approach was to avoid analog circuitry as much as possible. The design objective for the phasemeter was a bearing angle uncertainty of not more than 0.01°. The design of filters and an FM demodulator capable of this uncertainty did not appear feasible. Instead, a sampling approach was used. A block diagram of the phasemeter is shown in figure 13-1.

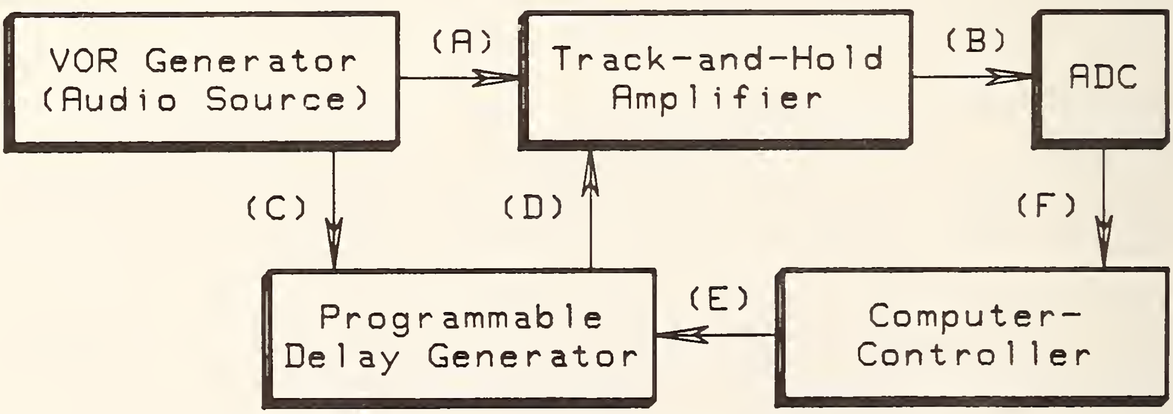


Figure 13-1. Simplified block diagram of the phasemeter.

[2]Note that a "band-pass" version of the sampling theorem indicates that the sampling rate need only provide two samples per cycle for the bandwidth of the 9960 Hz signal. Since the -80 dB bandwidth of this signal is about 1620 Hz, the sampling limit is about 3240 Hz, as compared with the requirement for roughly 20,000 samples/s based on the 9960 Hz carrier frequency itself. However, it is not apparent how to construct a highly accurate system based on the band-pass interpretation of sampling and data reconstruction.

The composite analog waveform from the VOR generator under test is applied to the analog-to-digital converter (ADC), which contains a track-and-hold amplifier at its input. A timing reference signal, such as the 30 Hz reference DAC sign bit in the NBS generator, is obtained from the source under test. It provides an arbitrary point from which all sample delays are measured. Its phase relative to the fundamental 30 Hz signal is unimportant, but it must be stable over the length of time required to take the data (about 6.5 min per set). The controller programs the delay generator for an initial delay of 0 and arms it to output one trigger pulse to the ADC upon the arrival of the next timing signal from the source. Upon receipt of the trigger from the delay generator, the track-and-hold amplifier switches to the hold mode and the 16 bit analog-to-digital conversion is completed. The controller reads the digital data from the ADC, causes the programmed delay time to be incremented, and re-arms the delay generator. This cycle is repeated until 1024 samples, equally spaced in time, have been acquired. The effective spacing is, of course, 1/(30*1024) s, or about 32.55 μs. The delay generator used has a time resolution of 10 ps, a jitter of 200 ps rms maximum, and an absolute uncertainty of ±1 ns ± (time base uncertainty). These specifications are critical to the application; a delay generator with ±100 ns uncertainty or jitter is inadequate. Note that the peak jitter of 282 ps corresponds only about 3 microdegrees at 30 Hz.

Following the acquisition of the amplitude samples, the data are processed by the same computer that controls the system. A fast Fourier transform (FFT) is used to compute the frequency-domain spectrum of the composite signal. The fundamental is the 30 Hz variable-phase component. The phase angle of the fundamental and the phases of all of the other harmonics are relative to the arbitrary timing reference. By appropriate manipulation of this phase information [5], the VOR bearing angle can be computed. This computation is discussed in more detail in section 15.

14. Hardware Details

The hardware components used to assemble the phasemeter are listed in table 14.1. At the time of the original design, all items were available commercially. Since then, however, the manufacturer of the 16-bit ADC used has discontinued it. Therefore, another unit must be selected if one wishes to duplicate the system. Since replacements for the original unit are not available, we plan to replace the ADC in the NBS system as well. Specifications of the units used are also given in table 14.1 to assist in identifying suitable substitute components.

It is imortant to understand that the commercial equipment listed in table 14.1 is not necessarily the only equipment suitable for this application; indeed, it may not even be the best suited. Mention of specific items does not constitute an endorsement of the product by the National Bureau of Standards; NBS has made no attempt to evaluate all of the various possible choices. Such mention is made here only to facilitate the duplication of the phasemeter by interested parties.

Finally, it should be noted that NBS, after examining VOR audio generators from four different companies, has found none that are suitable for use as transfer standards, for various reasons. This situation, unfortunately, reduces the incentive to build in-house standard phasemeters. The problems seen in commercial VOR audio generators include excessive time jitter (short term) in the timing signal, inaccurate or unstable deviation of the 9960 Hz signal, and noise. Most generators are not crystal controlled, and even those that are appear to provide insurmountable problems to the NBS phasemeter approach. Consequently, the principal value of the NBS phasemeter lies in providing the assurance that the NBS generator is, in fact, an accurate generator of the VOR composite waveform.

Table 14.1. Critical component specifications.

1. Analog-to-digital converter, including track-and-hold amplifier	
Resolution	16 bits (as tested, 14 may be adequate)
Accuracy	
Linearity	1/2 LSB in laboratory environment
Offset	Unimportant if stable and less than 10 mV
Gain	Unimportant if stable over measurement time
Noise	Less than 1 LSB (153 μV for 16 bits)
Stability	
Gain	±7 ppm/°C
Nonlinearity	±2 ppm/°C
Power supply sensitivity	±0.002%/%
Conversion time	Unimportant if less than 10 ms (see note 1)
Input range	±5 V
Input impedance	1000 MΩ (see note 2)
Output coding	(see note 3)
2. Time delay generator	
Mode	Externally triggerable, single cycle
Range	0 to 33.333333... ms
Step size	50 ps minimum
Absolute uncertainty	±1 ns ± time base uncertainty
Jitter	200 ps rms maximum between ext. trigger and output pulse
External trigger input	Positive slope, threshold at about 2 V, TTL compatible
Output pulse	TTL compatible, or as required by ADC
Time base:	(see note 4)
Aging	$<5 \times 10^{-10}$ per day
Short term	$<1 \times 10^{-11}$ for 1 s average
Temperature	$<7 \times 10^{-9}$ for 0° to 55°C
Line voltage	$<1 \times 10^{-10}$, ± 10% of nominal

Note 1. The conversion time interacts with the track-and-hold droop specification to determine the overall accuracy of the ADC. For this reason, it is desirable to obtain an integrated module that is specified overall by the manufacturer.

Note 2. The input impedance is not critical unless the converter is to be capacitively coupled to the VOR generator. The 1000 MΩ specification applies to the NBS unit used.

Note 3. The output coding is not important except to the extent that NBS-provided software is used. It is designed to accept complemented 2s complement binary, because this code requires the least conversion by the computer.

Note 4. These specifications apply to the unit used by NBS and represent what has been tested and evaluated, not necessarily what is absolutely required.

The computer used in the NBS system is the Hewlett-Packard 9845B, with 186 kbytes of user memory. The software requires ROM extensions for I/O operations, graphics (optional), IEEE-488 bus operations, and a real-time clock (optional, but recommended for documenting measurement runs). The software uses statements in extended BASIC that are not available on the older 9845A. The software presumably will run on the 9845C.

15. Software Details

15.1 General

The program listing in appendix A is the complete code for the phasemeter. It contains all of the instrument drivers for acquiring the data, and the processing routines for computing the VOR bearing angle. If more than one measurement at a given bearing is taken, it will compute statistics on the set of measurements. It also contains some subroutines which are used primarily for diagnostic purposes, such as evaluating the quality of an unknown generator, or testing the accuracy of the phasemeter ADC.

All of the variables in this program are global. Subprograms are not used. Since variable names and labels may have up to 15 characters in this extended BASIC, variable names can be made mnemonic to a high degree. Therefore, there was no attempt to partition the code into independent subprograms with local variables.

In several places in the sample printouts to follow, the term "dtg" is used. This refers to a date-time group, coded as a 10-digit number, that identifies when a particular event occurred. It is a numerical representation of the date and time in the form YYMMDDHHMM; for example, "8210071430" refers to October 7, 1982, at 2:30 p.m. The year information is input by the operator at the beginning of each session; the remainder of the data come from the computer real-time clock. This results in a unique number that identifies every measurment, software revision, and flexible disk. It is also the means of tracing any printout output back to the original raw data, and provides the time dimension on the quality control charts.

The interactive initialization portion of the program will be discussed first, then data acquisition and storage, and finally data processing. All line number references are for code revision date "8207140822." See line 100, appendix A.

15.2 Initialization

This portion begins at line 2700. All arrays are dimensioned in lines 2720 through 2840. Line 2860 is used only on certain occasions, as discussed in section 15.4.

The printer specifier, Printer, and the mass storage unit specifier, Disk$, are supplied by the user. It is not necessary to store the data on the same disk as the program, but it is often a good idea. This practice avoids confusion as to which code revision was used to process the data.

The program asks, in line 3120, what the nominal bearing angle is, Nom_bearing. This information is used only to compute deviations between the measured value and the nominal value; it is not used in any other way.

Next, the user tells the program whether old data is to be processed, or new data is to be taken. This provision allows data to be taken at one time and then processed or reprocessed when convenient. Unless the program is interrupted, all new data are processed in the run in which taken. Also, all new data are automatically stored on disk for future reference.

If new data are to be taken, subroutine Check_files checks the disk to see if there is enough space for the number of measurements specified earlier by No_measmnts. If not, it tells the operator and suggests alternatives.

This routine completes the initialization process.

15.3 Data Acquisition

If new data are to be taken, the loop beginning at line 3340 is executed. Three subroutines are nested within it, and they have further routines nested within them.

"Setup_5359" initializes the time delay generator by sending command strings over the IEEE-488 interface to define the operating parameters needed, including the delay step size. This string is fixed in this program because the fundamental frequency is always 30 Hz and 1024 samples are always taken.

"Take_data" begins at line 3940. It prints a date-time group from the real-time clock to identify the printout. It initializes the array, Integer__data, in which the ADC output will be stored. Then it begins the loop that arms the generator, reads the ADC, tests for ADC overload, puts the sample in the array, increments the delay, and re-arms the generator. The WAIT statements in this loop are required to allow the delay generator to become "unbusy" after being incremented. In the aggregate, these delays account for almost 2 min of the 6.5 min required to acquire 1024 samples.

"Store_data," starting at line 5020, is used next to put the data array on disk, along with certain pieces of housekeeping information, such as the date-time group. It names the file, after examining the files already on the disk, and prints the data to the disk. The file name itself also becomes a part of the file. A list of the housekeeping items that accompany every data file is given in lines 1020 through 1400.

This portion of code completes the acquisition and storage of one measurement. This data acquisition loop is repeated No_measmnts times. It is then processed by going to subroutine Retrieve_data, which is discussed under the next section.

15.4 Data Processing

Data processing begins with Retrieve_data, line 5300. If old data is to be processed, the operator enters the number of the first file in the set and the number of measurements in the set. Various items are checked by the program, and if the file is valid and unprocessed, the actual processing begins at line 6460, where the routine Fft_driver is called. This routine puts the 1024 data points into two arrays, R(*) and I(*), 512 points in each, alternating. Subroutine Fft is then called, and the transform is computed in lines 10320 through 11680. Arrays R(*) and I(*) now contain the real and imaginary parts of 512 spectral lines.

Following the transform, the signs of the elements in R(*) and I(*) are corrected from a table of Bessel functions, Jn(*). The phases of each line are computed and the proper quadrant assigned.

The phase angles progress uniformly from spectral line to line, the difference between the phases of adjacent lines depending on the bearing angle. At most settings, the phase difference exceeds 360°, and it is necessary to add or subtract multiples of 360° to order the lines correctly. This processing is done in the section labelled Order_lines, beginning at program line 8500.

The remainder of the Fft_driver routine, lines 9240 through 10300, does two linear regressions on the ordered phase angles. The first regression covers only the lines -7 through +7, i.e., 9750 through 10170 Hz. Its purpose is to determine the slope of the phase versus line number plot in order to best determine the value for the -8th and +8th lines. This regression done, a second regression covers the entire range from the -18th through the +18th lines.

Subroutine Estimation (line 11700) is called next. It is based on the analysis by Vecchia [5]. The subroutine uses the results of the preceding step to compute three phase angles, and from these the VOR bearing angle is found. The three angles result from the generality of the waveform model and allow an arbitrary phase relationship between the timing reference signal used in data acquisition and the fundamental. As part of the Estimation routine, an estimate is made of the standard deviation that would be expected if the measurement were to be repeated a large number of times. This estimate is based on the assumption that noise in the data is random in nature. In fact, it is not, and consequently the estimate of the standard deviation tends to be too high (conservative) by about a factor of 3 to 10. This estimate is, nevertheless, a useful measure of the validity of the measurement and can be used to flag a bad one. This flagging is done by the program automatically if the estimated standard deviation exceeds a rather arbitrary threshold that was set to 0.005° after making a large number of measurements on the NBS standard generator.

If there is more than one measurement in the set, routine Statistics (line 4320) is called. This routine computes the variance, standard deviation, and mean of the set. It prints these results and the difference between the mean and the nominal value. If there is only one measurement in the set, only the result and the difference are printed.

15.5 Utility Subroutines and Programs

Two utility subroutines are contained in the program, but are only used for diagnostic purposes, by calling from the keyboard. The first routine is "Meas_print" (line 13520). It prints in tabular form the real and imaginary parts of the fundamental and 37 harmonics. It also prints the line amplitudes, unordered phase angles in radians, and ordered phase angles in degrees. This routine is useful for determining whether there was a misordering of the lines, due to noisy data, for example (see fig. 15-1).

The second routine, Plot, plots the phase angles of the 314th through 350th lines as a function of harmonic number, both before and after ordering. With experience, it can be used to determine whether there was excessive time jitter in the unknown signal or in the timing reference (see fig. 15-2).

Code dtg: 8207140822. Disk dtg: 8204231351. Filename: VOR1
DAT027:F8,0 Nominal bearing angle= 300

Corr sign	Real part	Corr sign	Imag part	Bess sign	Line ampl	Rad-ians	Deg-rees	Line no.	Row no.	Row -20
0	1.2369	0	.7162	0	1.4293	.5249	30.07	1	1	-19
0	.0363	0	-.0879	1	.0951	-1.1788	-1507.54	314	2	-18
0	.1511	0	.0628	-1	.1636	.3939	-1417.43	315	3	-17
0	-.0972	0	.2331	1	.2526	1.9659	-1327.36	316	4	-16
0	-.3151	0	-.1317	-1	.3415	-2.7457	-1237.32	317	5	-15
0	.1500	0	-.3576	1	.3878	-1.1736	-1147.24	318	6	-14
0	.3107	0	.1307	-1	.3371	.3981	-1057.19	319	7	-13
0	-.0622	0	.1474	1	.1600	1.9700	-967.13	320	8	-12
0	-.0894	0	-.0381	1	.0972	-2.7389	-876.92	321	9	-11
0	.1149	0	-.2701	-1	.2936	-1.1687	-786.96	322	10	-10
0	.2482	0	.1058	1	.2698	.4029	-696.91	323	11	-9
0	-.0038	0	.0093	-1	.0100	1.9605	-607.67	324	12	-8
0	-.2387	0	-.1027	-1	.2599	-2.7355	-516.73	325	13	-7
0	.0940	0	-.2180	1	.2374	-1.1639	-426.68	326	14	-6
0	.0751	0	.0326	1	.0819	.4102	-336.50	327	15	-5
0	-.1148	0	.2646	-1	.2884	1.9802	-246.54	328	16	-4
0	-.0573	0	-.0250	1	.0625	-2.7310	-156.48	329	17	-3
0	.1063	0	-.2430	1	.2652	-1.1585	-66.38	330	18	-2
0	.1177	0	.0517	-1	.1285	.4137	23.70	331	19	-1
0	-.1004	0	.2277	-1	.2489	1.9859	113.78	332	20	0
0	-.1177	0	-.0519	1	.1287	-2.7262	203.80	333	21	1
0	.1073	0	-.2423	1	.2650	-1.1539	293.89	334	22	2
0	.0570	0	.0255	-1	.0625	.4205	384.09	335	23	3
0	-.1175	0	.2634	-1	.2884	1.9906	474.05	336	24	4
0	-.0747	0	-.0333	-1	.0818	-2.7223	564.03	337	25	5
0	.0974	0	-.2164	1	.2373	-1.1481	654.22	338	26	6
0	.2368	0	.1067	1	.2598	.4232	744.25	339	27	7
0	-.0043	0	.0090	-1	.0100	2.0126	835.32	340	28	8
0	-.2456	0	-.1116	-1	.2697	-2.7151	924.44	341	29	9
0	.1216	0	-.2671	-1	.2935	-1.1437	1014.47	342	30	10
0	.0884	0	.0402	-1	.0971	.4269	1104.46	343	31	11
0	-.0668	0	.1453	1	.1599	2.0016	1194.68	344	32	12
0	-.3061	0	-.1408	1	.3369	-2.7104	1284.71	345	33	13
0	.1623	0	-.3519	1	.3875	-1.1387	1374.76	346	34	14
0	.3098	0	.1432	1	.3413	.4331	1464.82	347	35	15
0	-.1062	0	.2289	1	.2523	2.0051	1554.88	348	36	16
0	-.1482	0	-.0690	1	.1635	-2.7056	1644.98	349	37	17
0	.0403	0	-.0861	1	.0950	-1.1330	1735.08	350	38	18
0	-.0064	0	-.0000	0	0.0000	0.0000	0.00	0	39	19

Theta1= 300.000079135
Theta2= 90.0716559148
Theta3= 113.759060751

Figure 15-1. Sample diagnostic output of routine "Meas_print".

```
DAT027:F8,0    Code revision dtg:8207140822              Ordered angles.
Rmin=               -2.74571086303      Rmax=              2.01263088195
Dmin=               -1507.54289148      Dmax=              1735.08402433
```

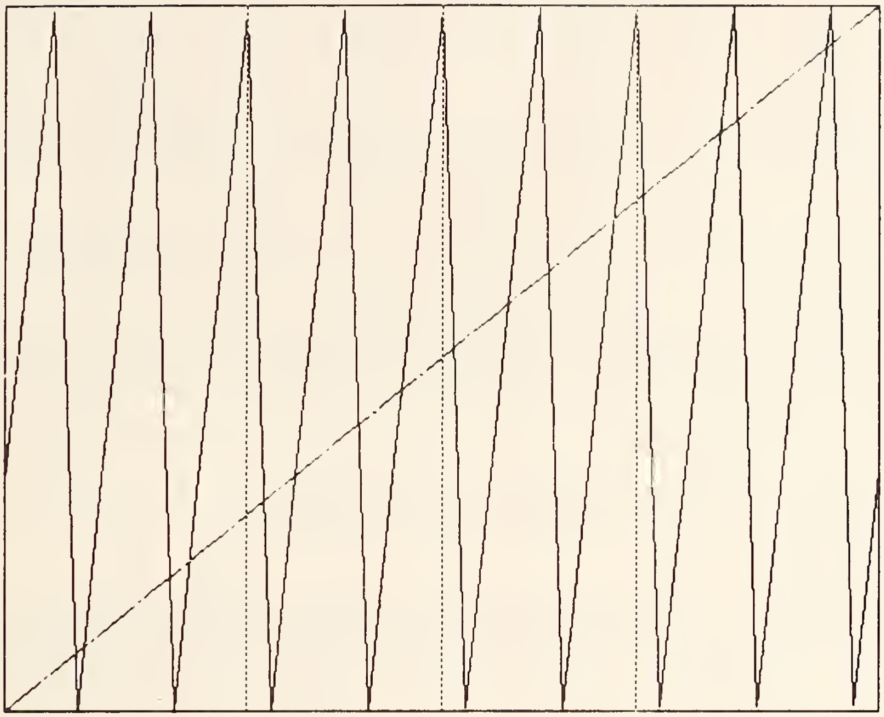


Figure 15-2. Sample diagnostic output of routine "Plot".

```
Data taking began at 82:07:13:16:23:15
Code dtg: 8201011453.  Disk dtg: 8204231351.  Filename: VOR1
Data stored in file DAT027:F8,0, disk 8204231351, at 82:07:13:16:29:41.

Data taking began at 82:07:13:16:29:42
Code dtg: 8201011453.  Disk dtg: 8204231351.  Filename: VOR1
Data stored in file DAT028:F8,0, disk 8204231351, at 82:07:13:16:36:08.

Data taking began at 82:07:13:16:36:09
Code dtg: 8201011453.  Disk dtg: 8204231351.  Filename: VOR1
Data stored in file DAT029:F8,0, disk 8204231351, at 82:07:13:16:42:35.

Data taking began at 82:07:13:16:42:36
Code dtg: 8201011453.  Disk dtg: 8204231351.  Filename: VOR1
Data stored in file DAT030:F8,0, disk 8204231351, at 82:07:13:16:49:02.

Data taking began at 82:07:13:16:49:03
Code dtg: 8201011453.  Disk dtg: 8204231351.  Filename: VOR1
Data stored in file DAT031:F8,0, disk 8204231351, at 82:07:13:16:55:29.
```

Data file	Bearing angle	Sigmasq	Est. std. dev.
DAT027	300.0001	1.671E-02	4.055E-03
DAT028	300.0012	1.679E-02	4.065E-03
DAT029	300.0002	1.667E-02	4.051E-03
DAT030	300.0005	1.653E-02	4.034E-03
DAT031	300.0014	1.647E-02	4.026E-03

```
Code dtg: 8201011453.  Disk dtg: 8204231351.  Filename: VOR1

Mean:......................  300.000 685 degrees
Nominal bearing............  300.00
Variance:..................    3.460E-07
Standard deviation:........    5.882E-04 degrees
Mean minus nominal:........     .000 685 degrees
```

Figure 15-3. Sample output resulting from five measurements at one phase angle.

15.6 Sample Outputs

The printed output produced during a typical measurement run is shown in figure 15-3. The beginning and ending times for each of a series of five measurements is printed as the data are taken. The disk identification, code name and revision date, and data file name are also printed. All of these items are stored on the disk with the raw data. After the last measurement in a series, each data file is retrieved and processed, resulting in the lower part of the printout. Finally, if more than one measurement was made in the set, the mean, standard deviation, etc., are printed. Some of the processed data results are returned to the disk to allow quick abstracting of large numbers of measurements without reprocessing the data. The information in appendix B was obtained in this way.

If, in the initialization, it was specified that old data was to be processed, the program jumps to Retrieve_data. If new data acquisition has just been completed, the program jumps to the same subroutine.

EVALUATION OF THE STANDARDS

16. VOR Measurement Principle

The principal development of digital methods for decoding VOR waveforms derives from the physical model for VOR beacons. To represent an ideal VOR signal mathematically requires two periodic functions described by

$$v(t;\underline{\theta}) = \alpha_1 \cos[2\pi f_1 t + \theta_1 + \theta_2]$$

and

$$s(t;\underline{\theta}) = \alpha_2 \cos\left[2\pi f_2 t + \theta_3 + \beta \sin[2\pi f_1 t + \theta_2]\right],$$

where $\underline{\theta}$ is a vector of unknown phase angles.

The waveform generated by the sum of $v(t;\underline{\theta})$ and $s(t;\underline{\theta})$, with some parameters specified, may be used to represent the ideal audiofrequency signal for the VOR navigation system. The specification for the VOR signal generator demands that

$\alpha_1 = \alpha_2 = 2^{1/2}$ (1 V rms)
$f_1 = 30$ Hz
$f_2 = 9960$ Hz (so $f_2/f_1 = 332$)
$\beta = 16$

In the VOR context, $v(t;\underline{\theta})$ is the 30 Hz variable phase signal, and $s(t;\underline{\theta})$ is the frequency-modulated 9960 Hz subcarrier. The frequency modulating sinusoid in the argument of $s(t;\underline{\theta})$ is the reference phase signal.

The design of VOR beacons is such that, in the mathematical model of the signal, θ_1 provides the necessary bearing information. The description in the following subsection, which outlines the principle for decoding VOR signals, will therefore emphasize the estimation of θ_1, although the nuisance phase angles θ_2 and θ_3 are estimated simultaneously by the phasemeter.

In practice, either transmitted or synthesized waveforms will be accompanied by noise or measurement error. This distortion is modeled by adding random errors or noise to the ideal signal. The resulting noise corrupted voltages, say Y(t), can be represented by

$$Y(t) = v(t;\underline{\theta}) + s(t;\underline{\theta}) + e(t).$$

The random error process is assumed to be white noise when sampled at the rate specified for the digital phasemeter.

16.1 Measurement of VOR Waveforms

The algorithm used to estimate the unknown phase angles θ_1, θ_2, θ_3, relies on a Fourier transform method to process noisy samples from the generated waveform. This technique requires one complete 30 Hz cycle of the VOR waveform, digitized at 1024 evenly spaced points throughout the cycle. The number of sampled points is determined by the requirement that the upper frequency limit of the discrete Fourier transform (DFT) exceed the frequency of the significant FM sidebands of the 332nd harmonic of 30 Hz. Because the FFT algorithm is used, it is efficient to require $2^m (m=10)$ amplitude samples.

The DFT of the noisy time samples was shown in NBS TN1021 [5] to have Fourier sine and cosine coefficients, B_k and A_k (kth harmonic of 30 Hz), characterized by

$$E[B_k] = \begin{cases} 2^{1/2} \sin(\theta_1 + \theta_2) & , k=1 \\ 2^{1/2} J_{k-332}(16)\sin[\theta_3 + (k-332)\theta_2], & k=332-K,\ldots,332,\ldots,332+K \end{cases}$$

and

$$E[A_k] = \begin{cases} 2^{1/2} \cos(\theta_1 + \theta_2) & , k=1 \\ 2^{1/2} J_{k-332}(16)\cos[\theta_3 + (k-332)\theta_2], & k=332-K,\ldots,332,\ldots,332+K \end{cases}$$

$$Var[B_k] = Var[A_k] = \sigma^2/512,$$

where $E[\cdot]$ is used to denote the average, or expected, value of repeated measurements of noise-corrupted sets of 1024 time-samples, $Var[\cdot]$ denotes the expected variability of repeated measurements, $J_n(16)$ is a Bessel function of the first kind, and σ is the RMS level of the measurement errors, e(t). The value of K is chosen to assure that only the most powerful sidebands of the 332nd harmonic are used to estimate θ_1. Figure 16-1 shows an amplitude spectrum obtained from an ideal VOR waveform. Apart from the 30 Hz component (k=1, outside the range of the graph), only about 36 harmonics centered on k=332 have sufficiently high signal/noise ratio to be used in the measurement algorithm.

Inspection of the Fourier coefficients reveals that the essential bearing angle information content of the DFT is likely to be contained in the phase spectrum of amplitude samples, Q_k^* $= \text{Arctan}(B_k/A_k)$ for admissible k. Having transformed the DFT coefficients to this form, it was shown in reference 5 that the expected value and variance of Q_k^* (for admissible k) are

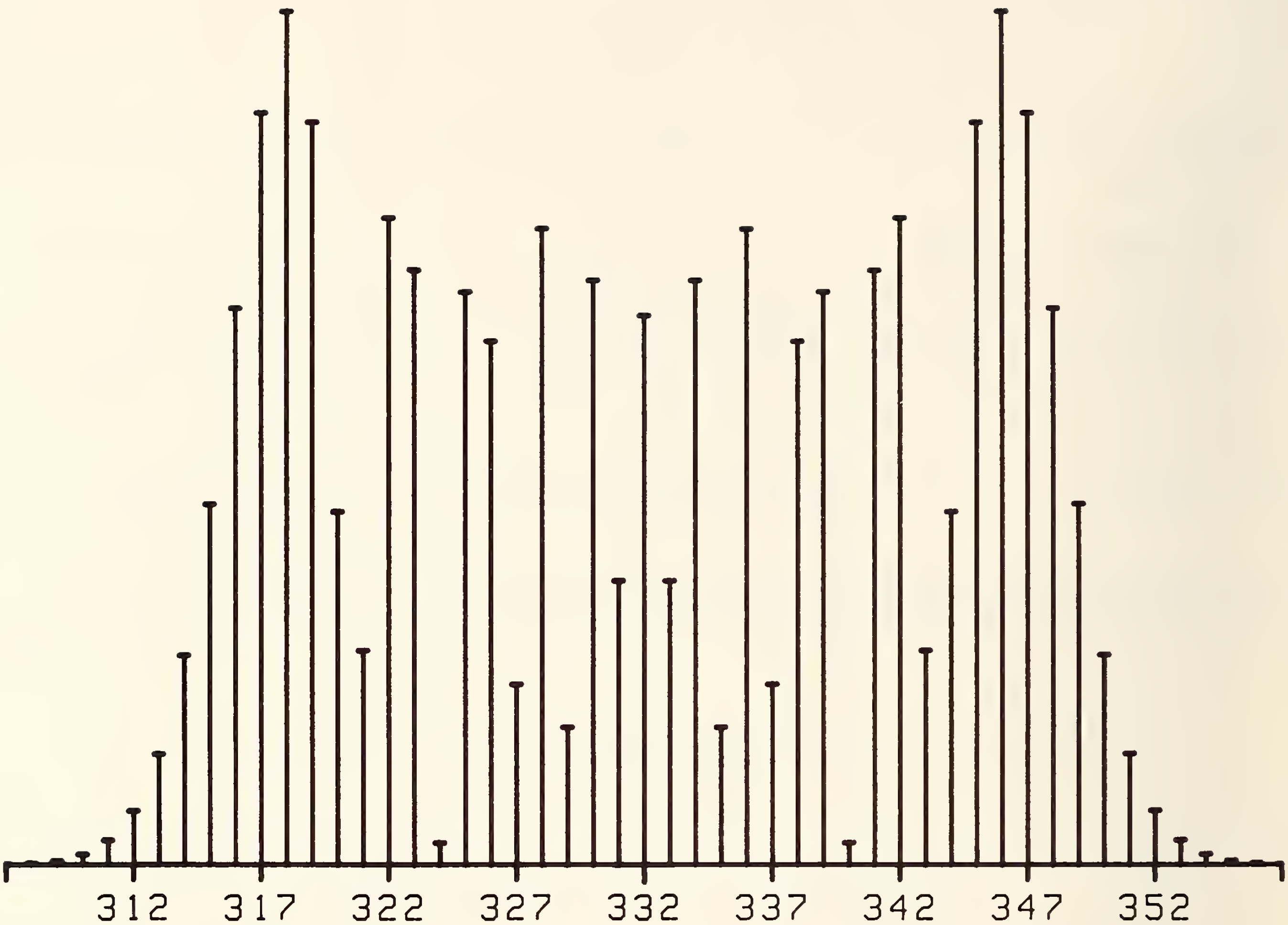


Figure 16-1. 9960 Hz subcarrier spectrum, showing relative sideband amplitudes. The abscissa is the harmonic number relative to 30 Hz.

$$E[Q_k^*] = \begin{cases} (\theta_1 + \theta_2) \bmod 2\pi & , k=1 \\ [\theta_3 + (k-332)\theta_2] \bmod 2\pi, & k\neq 1 \end{cases}$$

and

$$\mathrm{Var}[Q_k^*] = r_k^{-2}\sigma^2/512,$$

where

$$r_k^2 = \begin{cases} 2 & , k=1 \\ 2J^2_{k-332}(16), & |k-332| \leq K. \end{cases}$$

The equations for $E[Q_k*]$ are essentially linear in θ_1, θ_2 and θ_3, except for the restriction to the range $[0, 2\pi)$. However, in reference 5 a procedure was outlined for adjusting the Q_k* by defining

$$Q_k = Q_k* + \gamma_k 2\pi,$$

where the γ_k's are integers which reorder the Q_k* to be consistent with the physical model. The γ_k's are easily obtained for the signal/noise ratios rendered by the NBS signal synthesizer in its current design.

When the Q_k have been determined, all phase angles are estimated by a standard linear least squares technique. The algorithm also provides an estimate of the RMS noise level and obtains estimated standard errors of the measured phase angles from a single sample of the 30 Hz cycle.

The complete model and measurement equations are discussed in reference 5. In this discussion of the measurement technique, only the algebraic expression of the measured VOR bearing angle is reported. The estimator of θ_1 and its estimated variance are

$$\hat{\theta}_1 = Q_1 - C_K \sum_{i=1}^{K} i J_i^2(16)[Q_{332+i} - Q_{332-i}]$$

and

$$S^2(\hat{\theta}_1) = [(1 + C_K)/1024]\hat{\sigma}^2,$$

where

$$C_K = [2 \sum_{i=1}^{K} i^2 J_i^2(16)]^{-1}.$$

Here $\hat{\sigma}$ denotes an estimate of the RMS noise level, but will not be further specified because the characterization of the VOR measurement process and establishment of statistical stability only relies on statistical models for repeated measurements of θ_1. The single sample estimated standard error of θ_1 is, however, a useful diagnostic tool because it is sensitive to the effects of isolated erroneous time-samples and other transient influences.

16.2 Verification of Mathematical Model by Simulation

Empirical verification of the measurement method was achieved by computer simulation on a CDC170/750. To more closely approximate an actual system, the simulated waveforms were corrupted by additive Gaussian white noise. Results of the investigation indicated that measurement of VOR bearing from the phase spectrum was viable for RMS noise levels which are characteristic of the VOR signal generator.

Sample printouts of simulated VOR measurements are shown in tables 16.1 A-L. The parameters listed at the top of each table can be selected to generate VOR waveforms for any configuration within the following specifications:

NUMBER OF OBSERVATIONS	Number of time-samples (≤1024)
STANDARD DEVIATION	Standard deviation, σ, of additive Gaussian white noise ($\sigma \geq 0$);
NUMBER OF RUNS	Number of simulated waveforms desired ($1 \leq n \leq 20$);
NUMBER OF FREQUENCIES	Total number of spectral lines for measurement (= 2 + 2K; K is number of sidebands of 332nd harmonic to be used);
DEGREE MODE	Degrees or radians;
TIME JITTER	If ON will randomly perturb ideal voltage V_t to V_{t+u}, where u is selected from a uniform distribution between -1 ns and 1 ns;
VAR PHASE AMPLIT or SUBCARRIER AMPLIT	Selected value, α_j, can be randomly perturbed to $\alpha_j + u_j$, where u_j is uniformly distributed from -1 to 1 V;
FREQUENCY (VAR PH)	Ideal specification (30 Hz) can be randomly perturbed from 29 to 31 Hz;
FREQUENCY (SUBCAR)	332 (perturbed variable phase frequency);
MODULATION INDEX	Ideal index (16) can be randomly perturbed from 15 to 17; and
THETA1, THETA2, THETA3	Phase angles of noise-free waveform.

For the simulations shown in the tables, these parameters were assigned the values listed. The quantity of interest, namely THETA1, was chosen in 30° increments from 0° to 330°. In each case a sample of 1024 amplitude points was computed with each point perturbed by a random amount to simulate measurement noise. These data were then transformed to the frequency domain using a complex fast-Fourier transform. The transform gives both the amplitude and phase of the spectral lines in the frequency domain. The bearing angle was then estimated from the transformed data by a least-squares fitting technique to give one estimate of THETA1 in the output table. This process was repeated 10 times.

The first column in the table is simply the run number. For each run the sequence of random amplitude errors is completely independent of errors in the other runs.

The second column in the table gives the resulting estimate of the bearing angle, THETA1. As can be seen in the tables, the estimated bearing agrees closely with the selected value, even with a realistic level of measurement noise. The third column is the estimated standard deviation of the bearing angle estimate in column 2, based on the results of the least-squares fitting procedure.

At the bottom of the printout is the sample mean and sample standard deviation of the 10 estimated bearing angles. A measure of the adequacy of the measurement principle is how well the standard deviation of the 10 estimates agrees with the estimated standard deviations from the individual runs. Again, the agreement is very good.

The FORTRAN computer program which produced the tables in this section is available from the authors.

Table 16.1-A. Simulation estimates at 0°.

NUMBER OBSERVATIONS	=	1024	THETA1 =	0.00000	(0.00 DEGREES)
STANDARD DEVIATION	=	.00040	THETA2 =	1.57202	(90.07 DEGREES)
NUMBER OF RUNS	=	10	THETA3 =	1.98479	(113.72 DEGREES)
NUMBER FREQUENCIES	=	38			
DEGREE MODE	=	DEGREE			
TIME JITTER	=	OFF			

VAR PHASE AMPLIT	=	1.00
SUBCARRIER AMPLIT	=	1.00
FREQUENCY (VAR PH)	=	30.00
FREQUENCY (SUBCAR)	=	9960.00
MODULATION INDEX	=	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	359.99954938570590	.00119405563495
2	359.99957171381720	.00108158915795
3	.00014775991736	.00111276992072
4	.00103240123701	.00095987655964
5	359.99995492313246	.00091899987674
6	359.99951056569262	.00082092499755
7	359.99866019857836	.00085147429091
8	359.99967152872341	.00072194591567
9	.00240791006466	.00078422383887
10	359.99998309537114	.00114794596514
MEAN =	.00004894922534	
STD DEV =	.00102160353512	

Table 16.1-B. Simulation estimates at 30°.

NUMBER OBSERVATIONS	=	1024	THETA1 =	.52360	(30.00 DEGREES)
STANDARD DEVIATION	=	.00040	THETA2 =	1.57202	(90.07 DEGREES)
NUMBER OF RUNS	=	10	THETA3 =	1.98479	(113.72 DEGREES)
NUMBER FREQUENCIES	=	38			
DEGREE MODE	=	DEGREE			
TIME JITTER	=	OFF			

VAR PHASE AMPLIT	=	1.00
SUBCARRIER AMPLIT	=	1.00
FREQUENCY (VAR PH)	=	30.00
FREQUENCY (SUBCAR)	=	9960.00
MODULATION INDEX	=	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	29.99993963823840	.00103392079157
2	30.00126027535339	.00098759467158
3	29.99861027460952	.00086885085625
4	30.00059817592546	.00115525779303
5	29.99990380965323	.00103392536103
6	30.00060159382179	.00081133852502
7	29.99883745969794	.00095294092415
8	29.99850603616278	.00078911343657
9	30.00014411366965	.00111572528580
10	29.99922478118856	.00105429131367
MEAN =	29.99976261583197	
STD DEV =	.00093653645245	

Table 16.1-C. Simulation estimates at 60°.

NUMBER OBSERVATIONS =	1024	THETA1 =	1.04720 (60.00 DEGREES)
STANDARD DEVIATION =	.00040	THETA2 =	1.57202 (90.07 DEGREES)
NUMBER OF RUNS =	10	THETA3 =	1.98479 (113.72 DEGREES)
NUMBER FREQUENCIES =	38		
DEGREE MODE =	DEGREE		
TIME JITTER =	OFF		

VAR PHASE AMPLIT =	1.00
SUBCARRIER AMPLIT =	1.00
FREQUENCY (VAR PH) =	30.00
FREQUENCY (SUBCAR) =	9960.00
MODULATION INDEX =	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	60.00073015787370	.00093796514940
2	60.00079587750042	.00099936623493
3	60.00185128541852	.00110351002312
4	60.00149394312098	.00089815327859
5	60.00027527279781	.00096892067312
6	59.99925118575334	.00106782852517
7	59.99947757181963	.00098389805568
8	59.99918095862313	.00114465571664
9	59.99882184537410	.00096290975304
10	59.99909777583844	.00099485735742
MEAN =	60.00009758741135	
STD DEV =	.00108077939295	

Table 16.1-D. Simulation estimates at 90°.

NUMBER OBSERVATIONS =	1024	THETA1 =	1.57080 (90.00 DEGREES)
STANDARD DEVIATION =	.00040	THETA2 =	1.57202 (90.07 DEGREES)
NUMBER OF RUNS =	10	THETA3 =	1.98479 (113.72 DEGREES)
NUMBER FREQUENCIES =	38		
DEGREE MODE =	DEGREE		
TIME JITTER =	OFF		

VAR PHASE AMPLIT =	1.00
SUBCARRIER AMPLIT =	1.00
FREQUENCY (VAR PH) =	30.00
FREQUENCY (SUBCAR) =	9960.00
MODULATION INDEX =	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	89.99946766523772	.00090998066897
2	89.99875735002388	.00125923500240
3	90.00014894665219	.00112885025322
4	90.00018768258451	.00084625622865
5	90.00009667033973	.00103426753230
6	90.00038521687338	.00076236246797
7	90.00022561925334	.00092631936907
8	99.99932038474435	.00094464594400
9	89.99927779618929	.00101840209397
10	89.99815980212998	.00102639012314
MEAN =	89.99960271340160	
STD DEV =	.00073673660291	

Table 16.1-E. Simulation estimates at 120°.

```
NUMBER OBSERVATIONS =      1024          THETA1 =   2.09440 (120.00 DEGREES )
STANDARD DEVIATION  =    .00040          THETA2 =   1.57202 ( 90.07 DEGREES )
NUMBER OF RUNS      =        10          THETA3 =   1.98479 (113.72 DEGREES )
NUMBER FREQUENCIES  =        38
DEGREE MODE         =    DEGREE
TIME JITTER         =       OFF

VAR PHASE AMPLIT    =      1.00
SUBCARRIER AMPLIT   =      1.00
FREQUENCY (VAR PH)  =     30.00
FREQUENCY (SUBCAR)  =   9960.00
MODULATION INDEX    =     16.00
```

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	120.00054718526007	.00118097086621
2	119.99945213320871	.00098260543182
3	119.99891455444640	.00081937912846
4	119.99937085692000	.00104965952930
5	120.00034847214783	.00103307317101
6	120.00005295926394	.00099709829517
7	120.00058927491500	.00088536718816
8	120.00186687731230	.00101293561495
9	119.99931464735620	.00103729955637
10	120.00074916096264	.00109519962580
MEAN =	120.00012061218104	
STD DEV =	.00088791018223	

Table 16.1-F. Simulation estimates at 150°.

```
NUMBER OBSERVATIONS =      1024          THETA1 =   2.61799 (150.00 DEGREES )
STANDARD DEVIATION  =    .00040          THETA2 =   1.57202 ( 90.07 DEGREES )
NUMBER OF RUNS      =        10          THETA3 =   1.98479 (113.72 DEGREES )
NUMBER FREQUENCIES  =        38
DEGREE MODE         =    DEGREE
TIME JITTER         =       OFF

VAR PHASE AMPLIT    =      1.00
SUBCARRIER AMPLIT   =      1.00
FREQUENCY (VAR PH)  =     30.00
FREQUENCY (SUBCAR)  =   9960.00
MODULATION INDEX    =     16.00
```

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	149.99850566463465	.00095428876970
2	150.00099988852071	.00097999567533
3	150.00076115306274	.00115289776610
4	149.99864640391570	.00079427324609
5	150.00020656795914	.00092282309712
6	149.99977508802931	.00105220807877
7	150.00006045401005	.00082965365678
8	150.00087869339040	.00093382162858
9	150.00066679985503	.00093216492993
10	150.00006581906109	.00087328081614
MEAN =	150.00005665324261	
STD DEV =	.00087751304861	

Table 16.1-G. Simulation estimates at 180°.

NUMBER OBSERVATIONS	=	1024	THETA1 =	3.14159 (180.00 DEGREES)
STANDARD DEVIATION	=	.00040	THETA2 =	1.57202 (90.07 DEGREES)
NUMBER OF RUNS	=	10	THETA3 =	1.98479 (113.72 DEGREES)
NUMBER FREQUENCIES	=	38		
DEGREE MODE	=	DEGREE		
TIME JITTER	=	OFF		

VAR PHASE AMPLIT	=	1.00
SUBCARRIER AMPLIT	=	1.00
FREQUENCY (VAR PH)	=	30.00
FREQUENCY (SUBCAR)	=	9960.00
MODULATION INDEX	=	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	180.00027022980521	.00098121728795
2	179.99942448895126	.00106176902454
3	179.99971257608286	.00095223325261
4	179.99826385685083	.00095369457388
5	180.00051959814118	.00104133328262
6	179.99841136136729	.00116657977919
7	180.00087626080131	.00116634640275
8	179.99974042443228	.00102227844207
9	180.00138923771374	.00126098003859
10	180.00041647540093	.00093685659427
MEAN =	179.99990245095978	
STD DEV =	.00100765321683	

Table 16.1-H. Simulation estimates at 210°.

NUMBER OBSERVATIONS	=	1024	THETA1 =	3.66519 (210.00 DEGREES)
STANDARD DEVIATION	=	.00040	THETA2 =	1.57202 (90.07 DEGREES)
NUMBER OF RUNS	=	10	THETA3 =	1.98479 (113.72 DEGREES)
NUMBER FREQUENCIES	=	38		
DEGREE MODE	=	DEGREE		
TIME JITTER	=	OFF		

VAR PHASE AMPLIT	=	1.00
SUBCARRIER AMPLIT	=	1.00
FREQUENCY (VAR PH)	=	30.00
FREQUENCY (SUBCAR)	=	9960.00
MODULATION INDEX	=	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	209.99968610688484	.00117232677505
2	210.00169319902125	.00103879407391
3	210.00138509685712	.00104332572792
4	210.00075030373227	.00085433357835
5	209.99977936434152	.00105397423276
6	210.00070856928414	.00098892448798
7	210.00153538982704	.00081662641280
8	210.00061107483816	.00107337446024
9	209.99768198450333	.00102172874822
10	210.00231368656478	.00107614584471
MEAN =	210.00061447759981	
STD DEV =	.00131989054533	

Table 16.1-I. Simulation estimates at 240°.

NUMBER OBSERVATIONS =	1024	THETA1 =	4.18879 (240.00 DEGREES)
STANDARD DEVIATION =	.00040	THETA2 =	1.57202 (90.07 DEGREES)
NUMBER OF RUNS =	10	THETA3 =	1.98479 (113.72 DEGREES)
NUMBER FREQUENCIES =	38		
DEGREE MODE =	DEGREE		
TIME JITTER =	OFF		

VAR PHASE AMPLIT =	1.00
SUBCARRIER AMPLIT =	1.00
FREQUENCY (VAR PH) =	30.00
FREQUENCY (SUBCAR) =	9960.00
MODULATION INDEX =	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	240.00125033530549	.00126233319957
2	239.99879072895055	.00104321218628
3	239.99910514681505	.00103016997908
4	240.00115432892744	.00088504295284
5	239.99950099138096	.00080585348817
6	240.00046541727534	.00101865975654
7	240.00070129316737	.00088373470628
8	240.00163869015807	.00103492829257
9	240.00069038221500	.00091495556228
10	240.00067465649772	.00126760767647
MEAN =	240.00039719607230	
STD DEV =	.00095194314551	

Table 16.1-J. Simulation estimates at 270°.

NUMBER OBSERVATIONS =	1024	THETA1 =	4.71239 (270.00 DEGREES)
STANDARD DEVIATION =	.00040	THETA2 =	1.57202 (90.07 DEGREES)
NUMBER OF RUNS =	10	THETA3 =	1.98479 (113.72 DEGREES)
NUMBER FREQUENCIES =	38		
DEGREE MODE =	DEGREE		
TIME JITTER =	OFF		

VAR PHASE AMPLIT =	1.00
SUBCARRIER AMPLIT =	1.00
FREQUENCY (VAR PH) =	30.00
FREQUENCY (SUBCAR) =	9960.00
MODULATION INDEX =	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	270.00040220420851	.00085082261064
2	270.00140060647391	.00116341132440
3	270.00021550586098	.00086988014543
4	269.99919308230346	.00093418551952
5	269.99922214188155	.00097760020559
6	269.99942786248721	.00128991362416
7	269.99919627938471	.00110982159669
8	269.99914036323207	.00116160434825
9	270.00051763502597	.00113022454941
10	270.00122291045591	.00105533759784
MEAN =	269.99999385913361	
STD DEV =	.00087568711769	

Table 16.1-K. Simulation estimates at 300°.

NUMBER OBSERVATIONS	=	1024	THETA1 =	5.23599 (300.00 DEGREES)
STANDARD DEVIATION	=	.00040	THETA2 =	1.57202 (90.07 DEGREES)
NUMBER OF RUNS	=	10	THETA3 =	1.98479 (113.72 DEGREES)
NUMBER FREQUENCIES	=	38		
DEGREE MODE	=	DEGREE		
TIME JITTER	=	OFF		

VAR PHASE AMPLIT	=	1.00
SUBCARRIER AMPLIT	=	1.00
FREQUENCY (VAR PH)	=	30.00
FREQUENCY (SUBCAR)	=	9960.00
MODULATION INDEX	=	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	300.00016773029711	.00088957571036
2	299.99967060986455	.00103344149501
3	300.00034197343666	.00105855225361
4	300.00096048743399	.00092941384490
5	300.00159104590039	.00108870233986
6	299.99986858555349	.00111751561541
7	299.99955198512907	.00087143692331
8	299.99997751847695	.00079582161163
9	299.99805894246856	.00106626070899
10	300.00051306488058	.00079623132050
MEAN =	300.00007019430632	
STD DEV =	.00093735437691	

Table 16.1-L. Simulation estimates at 330°.

NUMBER OBSERVATIONS	=	1024	THETA1 =	5.75959 (330.00 DEGREES)
STANDARD DEVIATION	=	.00040	THETA2 =	1.57202 (90.07 DEGREES)
NUMBER OF RUNS	=	10	THETA3 =	1.98479 (113.72 DEGREES)
NUMBER FREQUENCIES	=	38		
DEGREE MODE	=	DEGREE		
TIME JITTER	=	OFF		

VAR PHASE AMPLIT	=	1.00
SUBCARRIER AMPLIT	=	1.00
FREQUENCY (VAR PH)	=	30.00
FREQUENCY (SUBCAR)	=	9960.00
MODULATION INDEX	=	16.00

RUN	BEARING ANGLE EST	ESTIMATED STD DEV
1	330.00047935696784	.00100412476924
2	330.00007763688154	.00090583797783
3	329.99897412378596	.00111489701849
4	330.00089077940538	.00105532956452
5	330.00113187938587	.00112791309952
6	329.99993492922295	.00122478585201
7	329.99978553170513	.00110172756242
8	329.99990903326034	.00107059154876
9	330.00166895042821	.00104388027648
10	329.99988073969971	.00100339566269
MEAN =	330.00027329607656	
STD DEV =	.00077989232886	

17. System Performance and Provisional Uncertainty

The general design goal of the VOR measurement system was to achieve an overall uncertainty of ±0.01°. The objective of tests described in this section is to establish a statistical model which can be used to estimate the measurement process parameters and to demonstrate provisionally that the uncertainty of the measurements is suitably small relative to the allowable error limit. Process parameters are quantities which characterize the behavior with regard to both the long-term average of the process and the inherent variability or imprecision of the process.

The complete system consists of:

(a) a standard VOR audio generator, which is used to calibrate unknown phasemeters;
(b) a standard VOR phasemeter for the calibration of unknown generators;
(c) a desktop computer which controls the system.

At the beginning of the standards development effort, it was decided that it would be necessary to design both the standard generator and standard phasemeter, since otherwise there would be no independent way of checking either one. Thus the two instruments, which work on different principles, are used as independent checks of each other. Because of the complementary nature of the two services, the procedure to assure that both instruments are performing as desired is to demonstrate that they agree without adjustment to either one. Other objective means for evaluating the performance of each instrument independently were described in section 4.

17.1 Systematic Errors

To determine the uncertainty of a measurement process one must quantify both systematic and random errors. Possible systematic errors related to both of the standard instruments were considered in section 8.4. For each potential source of offset, either an experiment or analytic derivation was described to show that the upper limit of systematic error was negligible relative to the overall uncertainty goal. Therefore, in the following sections we focus on techniques that are helpful to establish and monitor random errors, which are the dominant components of the total error budget.

17.2 Statistical Model for Bearing Measurements

The essential characteristic needed to establish control of the VOR measurement process is predictability, i.e., the variability remains at the same level and the process average is not drifting or shifting abruptly from its established values. The evidence of predictability must come from redundant measurement of process parameters over a full range of operating conditions. Requirements for obtaining realistic error bounds and establishing statistical control will be satisfied if the collection of measurements is from a sufficiently broad set of environmental and operating conditions to allow all potential sources of random error to influence the measurement process.

In this section we focus on a statistical model which facilitates estimation of components of the total process variability and allows the implementation of statistical control procedures for the process parameters. The model is sufficiently general to distinguish among three kinds of random variability that may contribute to the total process variability:

(a) short-term variability of sequential measurements on a single day;

(b) long-term variability (days, months, years);

(c) differential levels of long-term variability depending on nominal bearing (switch) settings.

In addition to these components of total process variability, potential offsets between the signal generator and phasemeter, which may depend on bearing angle, can be estimated. These offsets between the two instruments will be used to obtain a heuristic limit on possible systematic errors for the VOR system. In the section 17.3 we describe data which were collected to shed light on the individual contributions to the total uncertainty of the process.

The statistical analysis for quantifying short-term and long-term variability in VOR bearing measurements is based on the assumption that N repeat measurements at the I nominal bearings on each of J occasions can be described by the model:

$$y_{ijk} = \mu + \alpha_i + T_j + D_{ij} + e_{ijk}, \quad i=1,\ldots,I; \; j=1,\ldots,J; \; k=1,\ldots,M$$

where

y_{ijk} is the observed deviation, or offset, of a single measurement from the i_{th} switch setting, i.e., $y = (\hat{\theta}_1$ - nominal bearing);

$\mu+\alpha_i$ is an unknown, but stable, average offset of measurements at the i^{th} switch setting, i.e., $\mu+\alpha_i$ is a parameter to be estimated and is ideally zero for any i;

T_j is a (possible) random shift in all measurements taken on the j^{th} occasion; the T_j's are assumed to follow a Gaussian probability distribution with mean zero and variance σ_T^2;

D_{ij} is a (possible) random shift on the j^{th} occasion which is unique at the i^{th} switch setting; the D_{ij}'s are assumed to have a Gaussian distribution with mean zero and variance σ_D^2;

e_{ijk} is the short-term random error of measurement in the k^{th} repeat measurement at switch setting i on occasion j; the e_{ijk}'s are assumed to have a Gaussian distribution with mean zero and variance σ^2.

The statistical analysis of bearing angle measurements quantifies the individual contributions to the VOR process variability by estimating the various unknown parameters in the model. To be specific, measurements which satisfy the model have the following properties:

$$E[y_{ijk}] = \mu + \alpha_i$$

$$Var[y_{ijk}] = \sigma_T^2 + \sigma_D^2 + \sigma^2$$

$$E[(1/M) \sum_{k=1}^{M} y_{ijk}] = \mu + \alpha_i$$

$$Var[(1/M) \sum_{k=1}^{M} y_{ijk}] = \sigma_T^2 + \sigma_D^2 + \sigma^2/M$$

$$E[(1/JM) \sum_{j=1}^{J} \sum_{k=1}^{M} y_{ijk}] = \mu + \alpha_i$$

$$Var[(1/JM) \sum_{j=1}^{J} \sum_{k=1}^{M} Y_{ijk}] = (\sigma_T^2 + \sigma_D^2)/J + \sigma^2/JM,$$

where E[•] denotes the average value and Var[•] denotes variability. Statistical analysis of the VOR bearing angle measurements provides estimates of the process parameters as follows:

Limiting Offset at Bearing i: $\hat{\mu} + \hat{\sigma}_i = (1/JM) \sum_{j=1}^{J} \sum_{k=1}^{M} y_{ijk}$

Standard Error of $(\hat{\mu} + \hat{\sigma}_i)$: $[(\hat{\sigma}_T^2 + \hat{\sigma}_D^2)/J + \hat{\sigma}^2/M]^{1/2}$

Short-Term Standard Deviation (Single Measurement): $\hat{\partial}$

Short-Term Standard Deviation (Mean of M Measurements at Bearing i): $(\hat{\sigma}^2/M)^{1/2}$

Total Standard Deviation (Single Measurement): $(\hat{\sigma}_T^2 + \hat{\sigma}_D^2 + \hat{\sigma}^2)^{1/2}$

Total Standard Deviation (Mean of M Measurements at Bearing i): $(\hat{\sigma}_T^2 + \hat{\sigma}_D^2 + \hat{\sigma}^2/M)^{1/2}$.

For each measurement y_{ijk}, a residual δ_{ijk} is computed from $\delta_{ijk} = y_{ijk} - (\hat{\mu} + \hat{\alpha}_i)$. These residuals are standardized by computing $t_{ijk} = \delta_{ij}/S(\delta_{ijk})$, where $S(\delta_{ijk})$ is an estimate of the standard deviation of the residual. The residuals from the VOR measurement data are routinely checked to assure the validity of estimated parameters and to assess whether the process is in control. In particular, the residuals are used to identify and, if appropriate, to reject individual outliers in the data set. The outlier rejection criterion could conceivably flag an entire day's measurements that are out-of-control. See reference 5 for a discussion of outlier detection techniques.

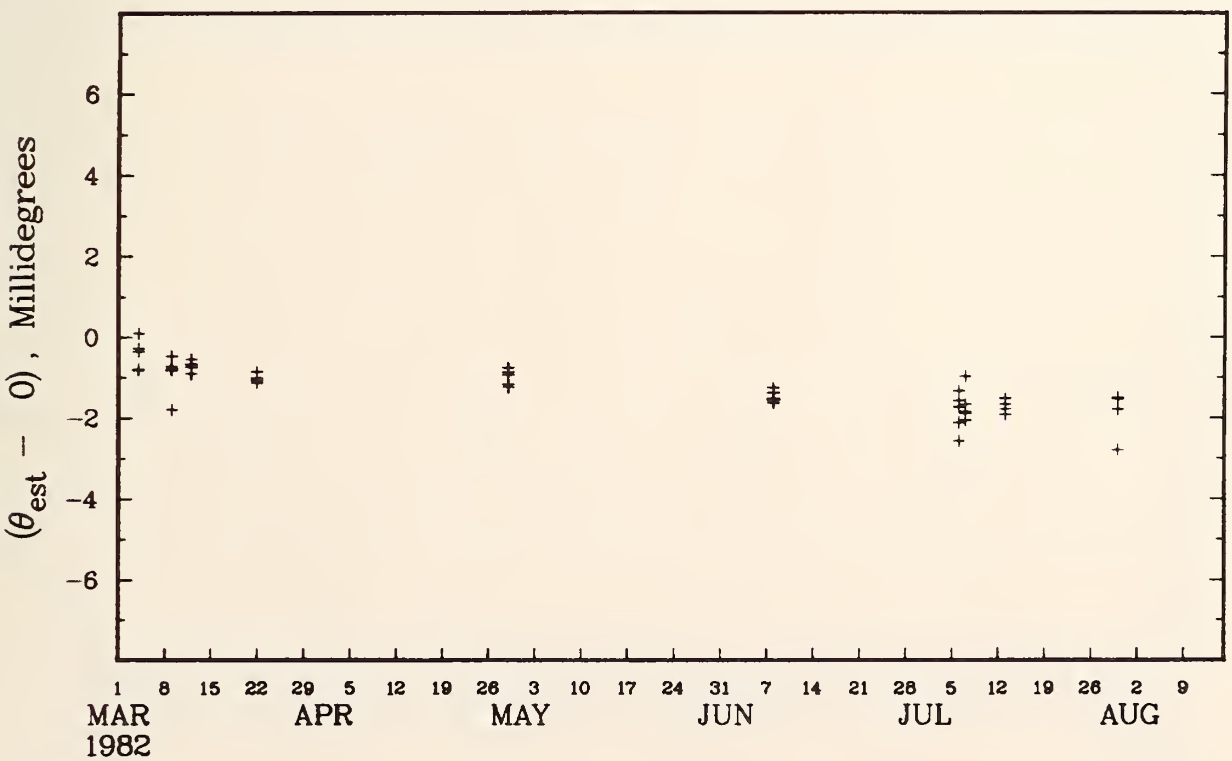


Figure 17-1A. Bearing angle offsets at 0 degrees.

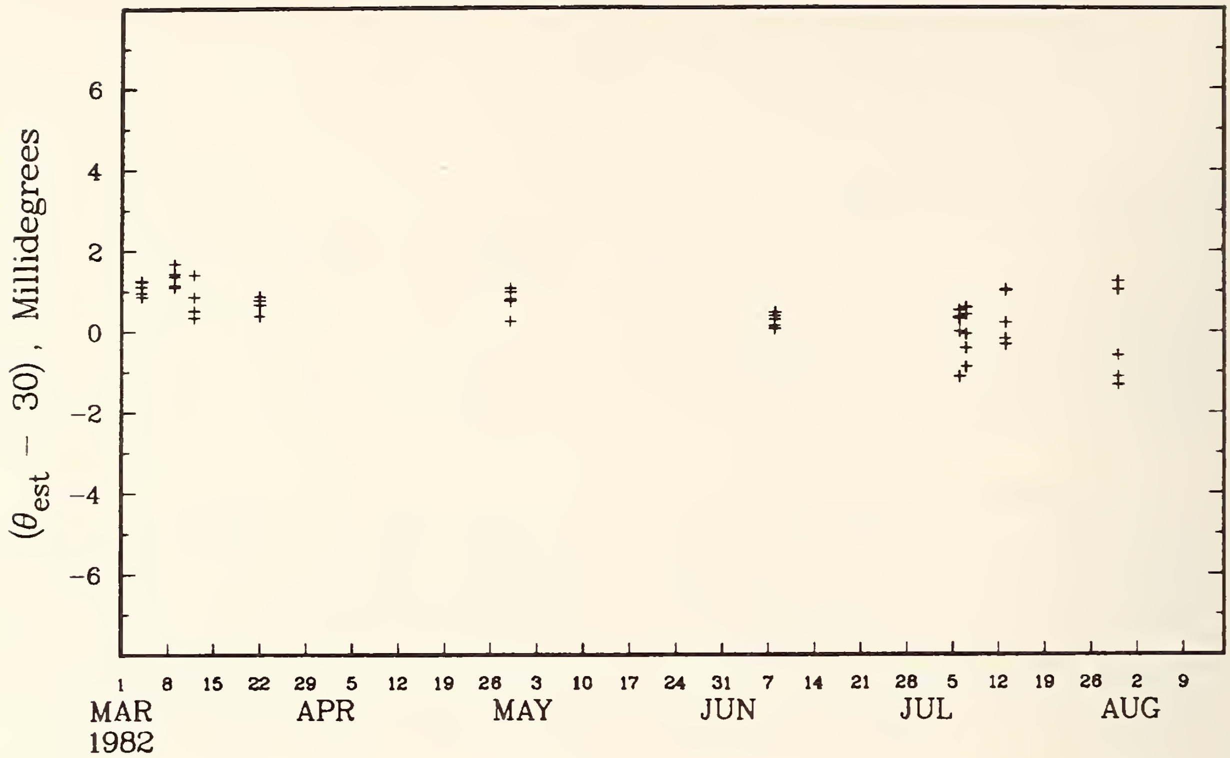


Figure 17-1B. Bearing angle offsets at 30 degrees.

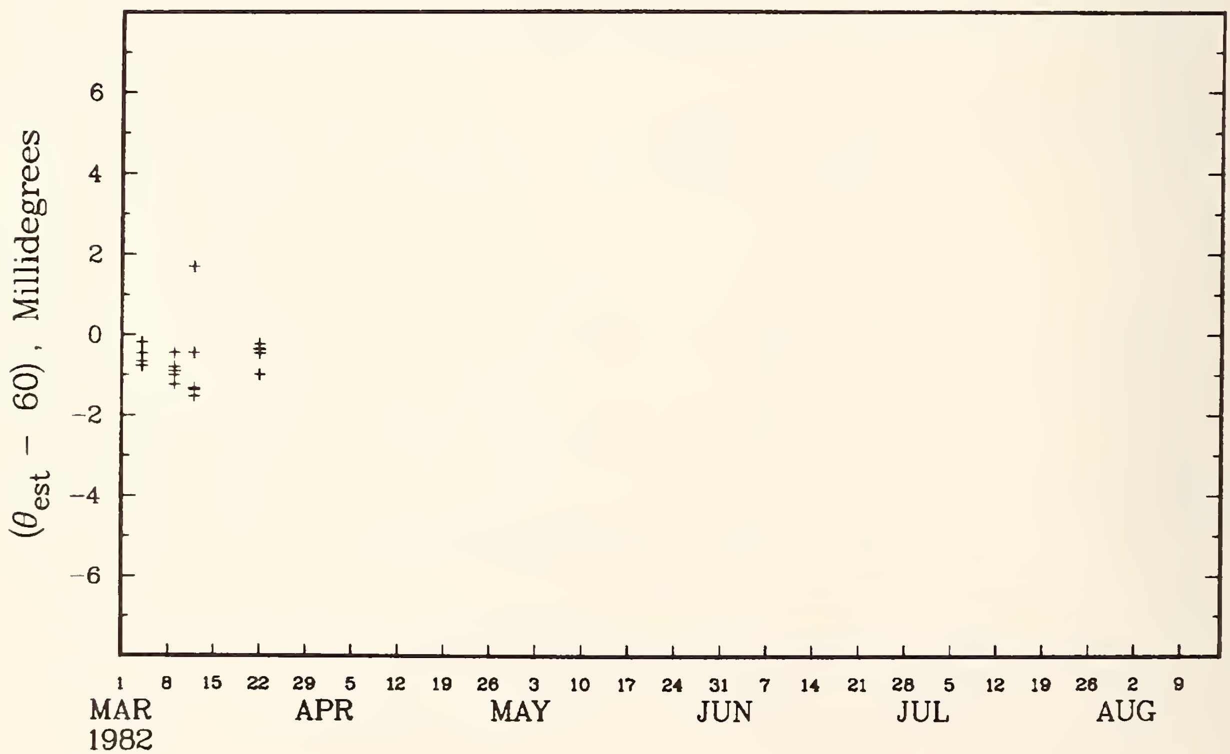


Figure 17-1C. Bearing angle offsets at 60 degrees.

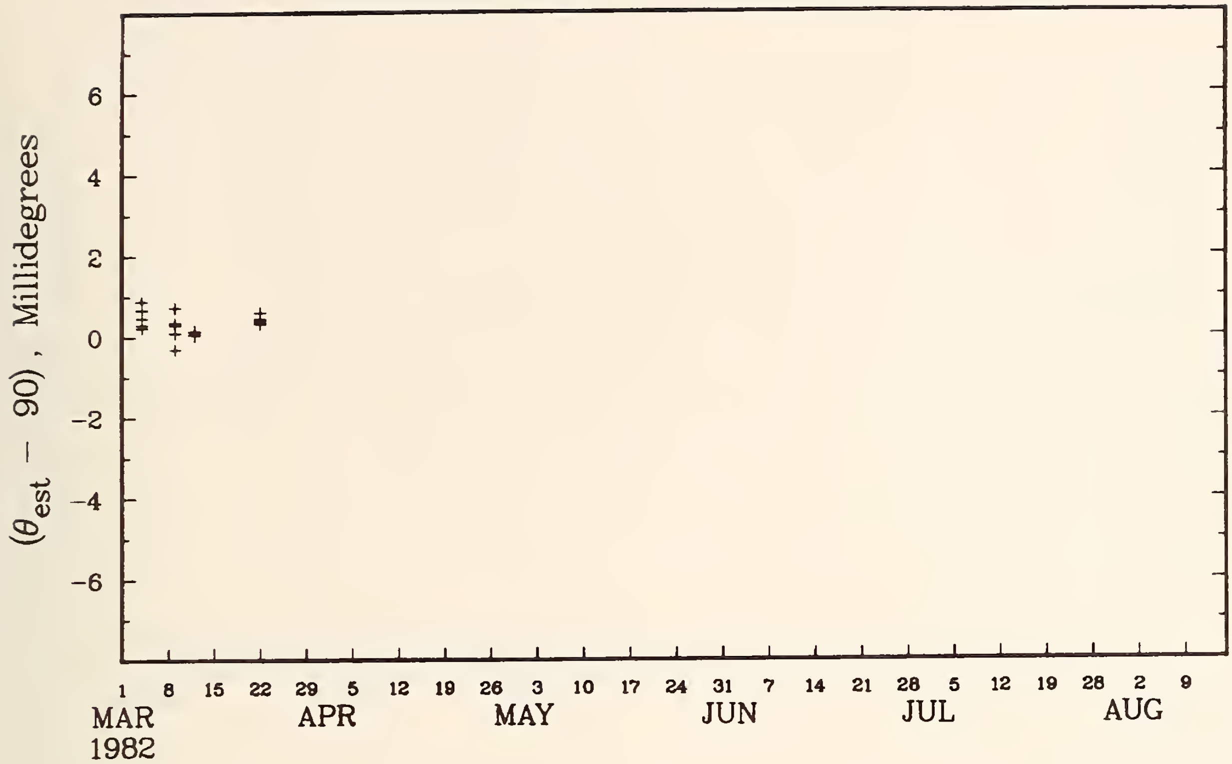


Figure 17-1D. Bearing angle offsets at 90 degrees.

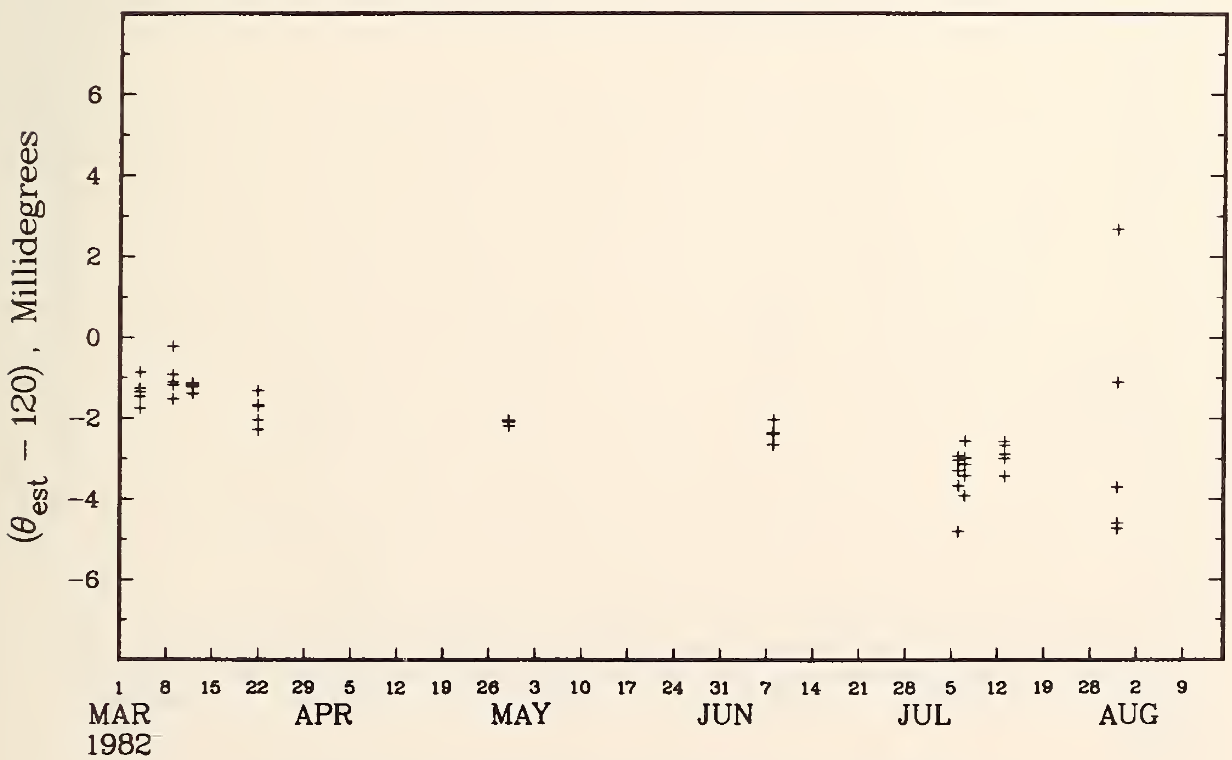


Figure 17-1E. Bearing angle offsets at 120 degrees.

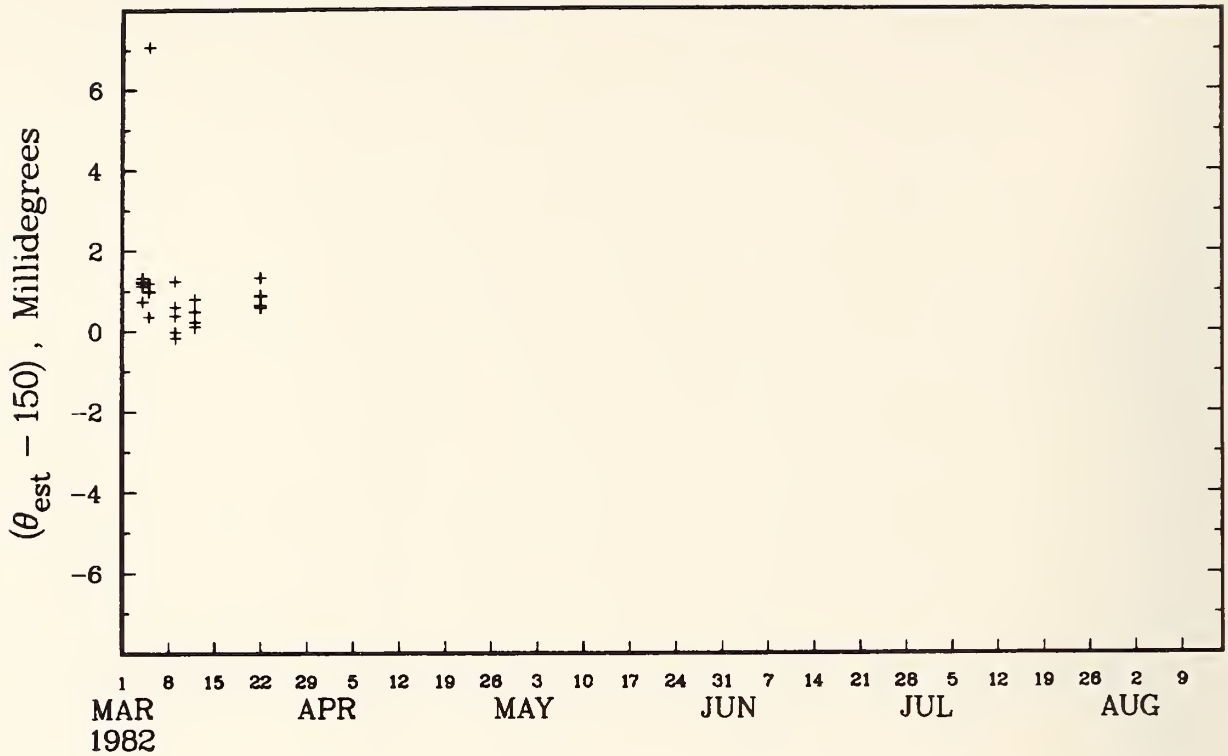


Figure 17-1F. Bearing angle offsets at 150 degrees.

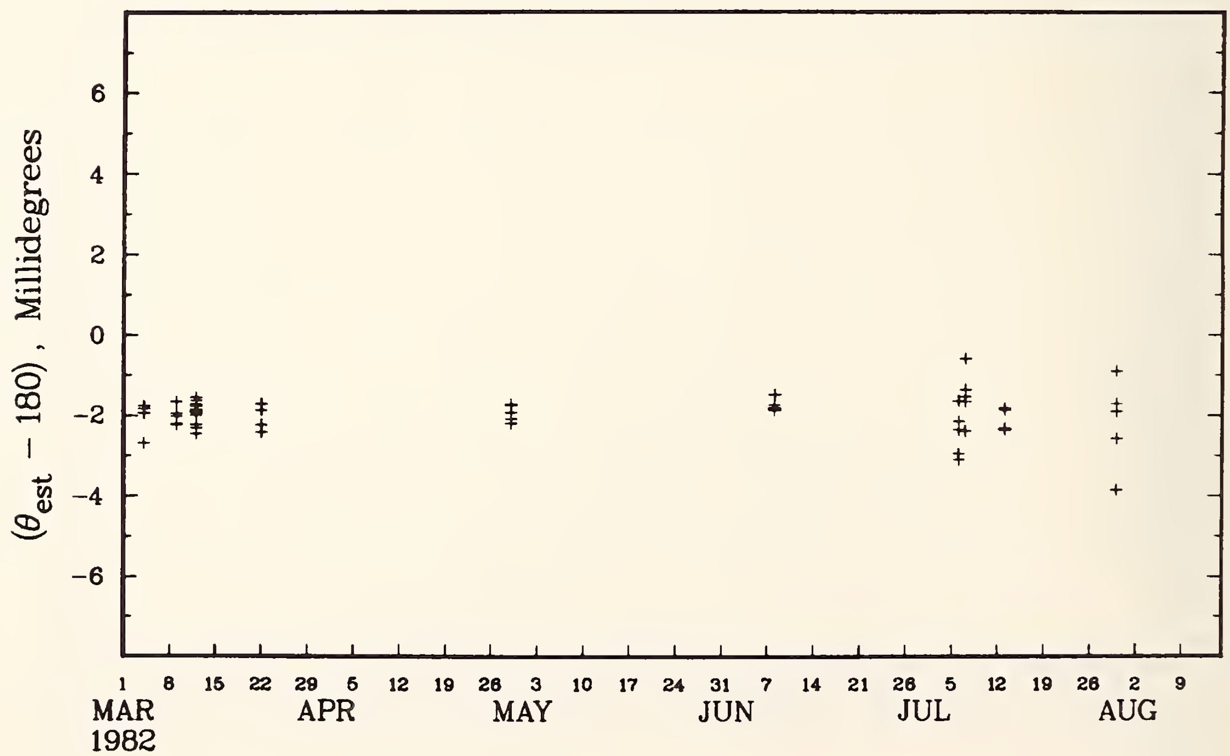


Figure 17-1G. Bearing angle offsets at 180 degrees.

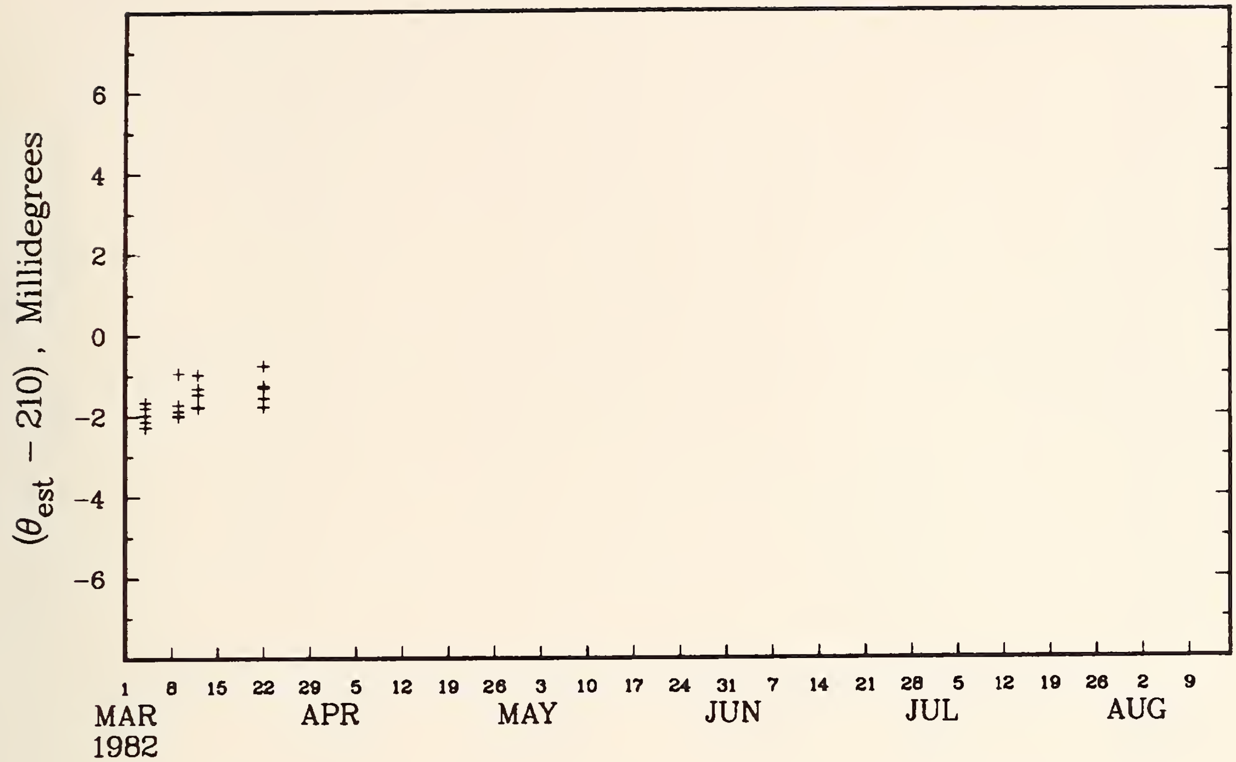


Figure 17-1H. Bearing angle offsets at 210 degrees.

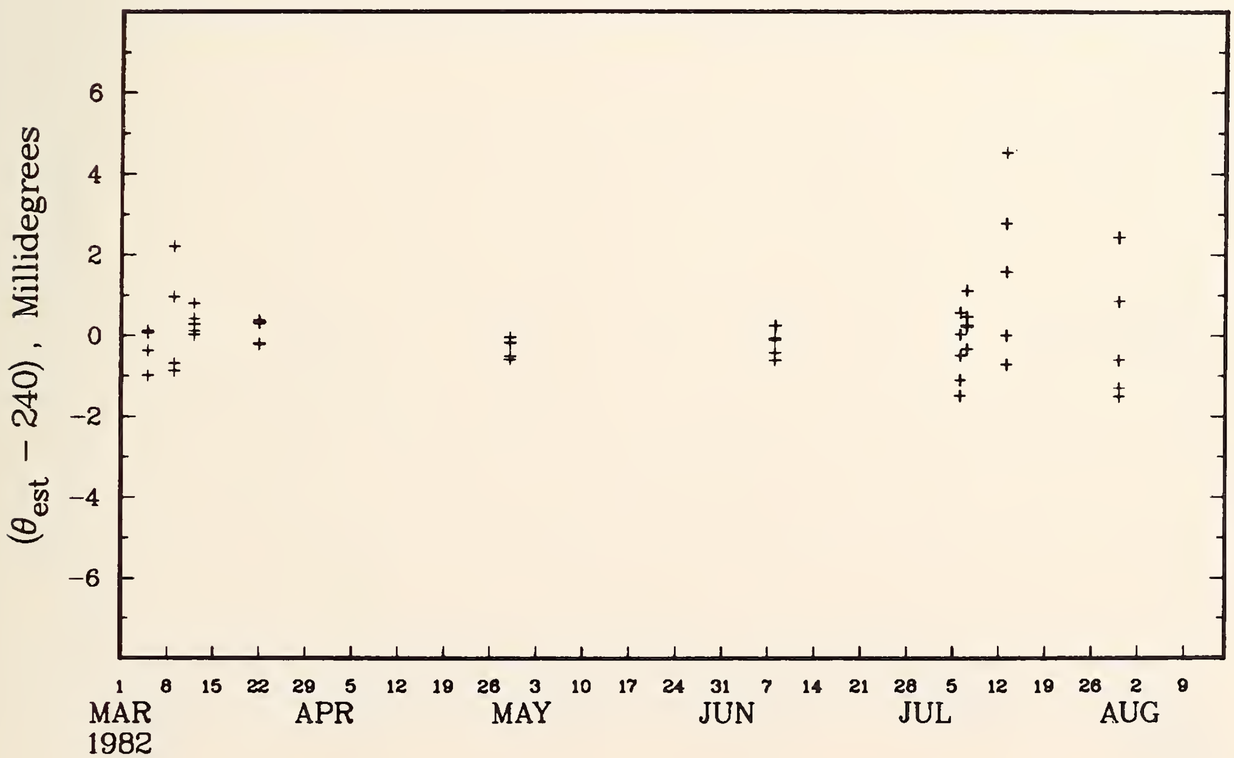


Figure 17-1I. Bearing angle offsets at 240 degrees.

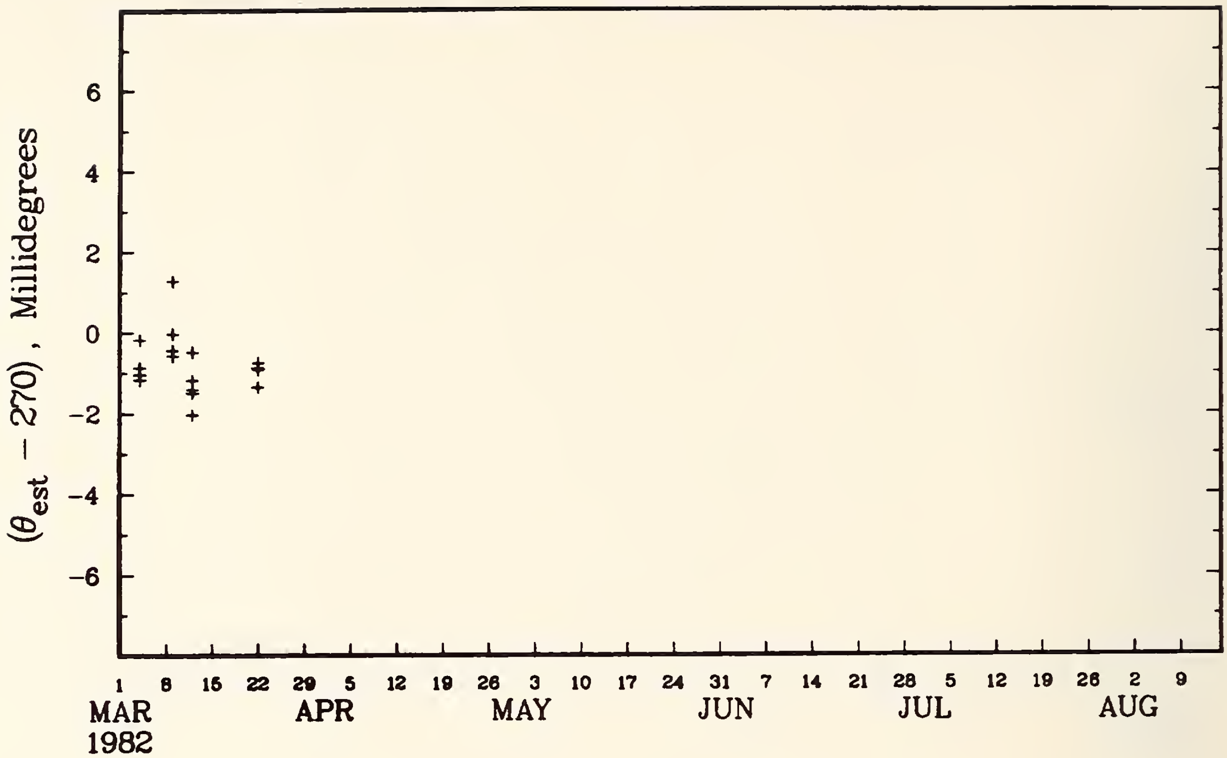


Figure 17-1J. Bearing angle offsets at 270 degrees.

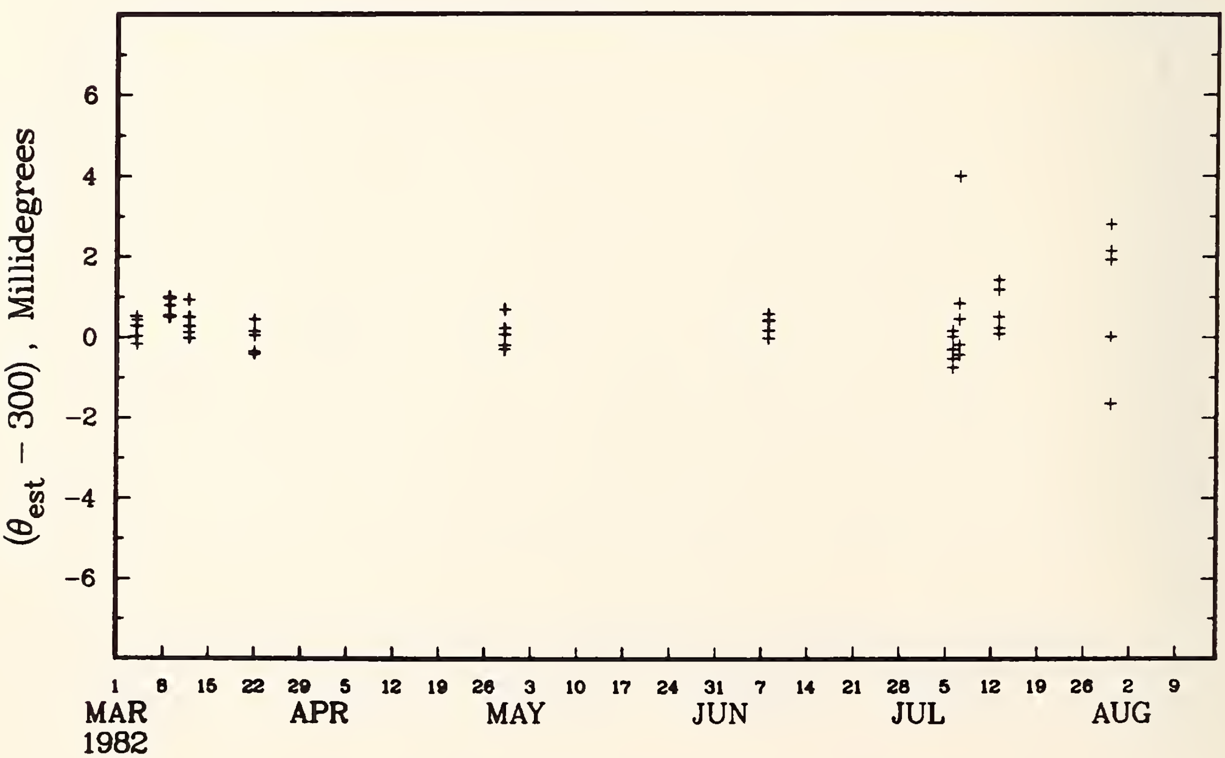


Figure 17-1K. Bearing angle offsets at 300 degrees.

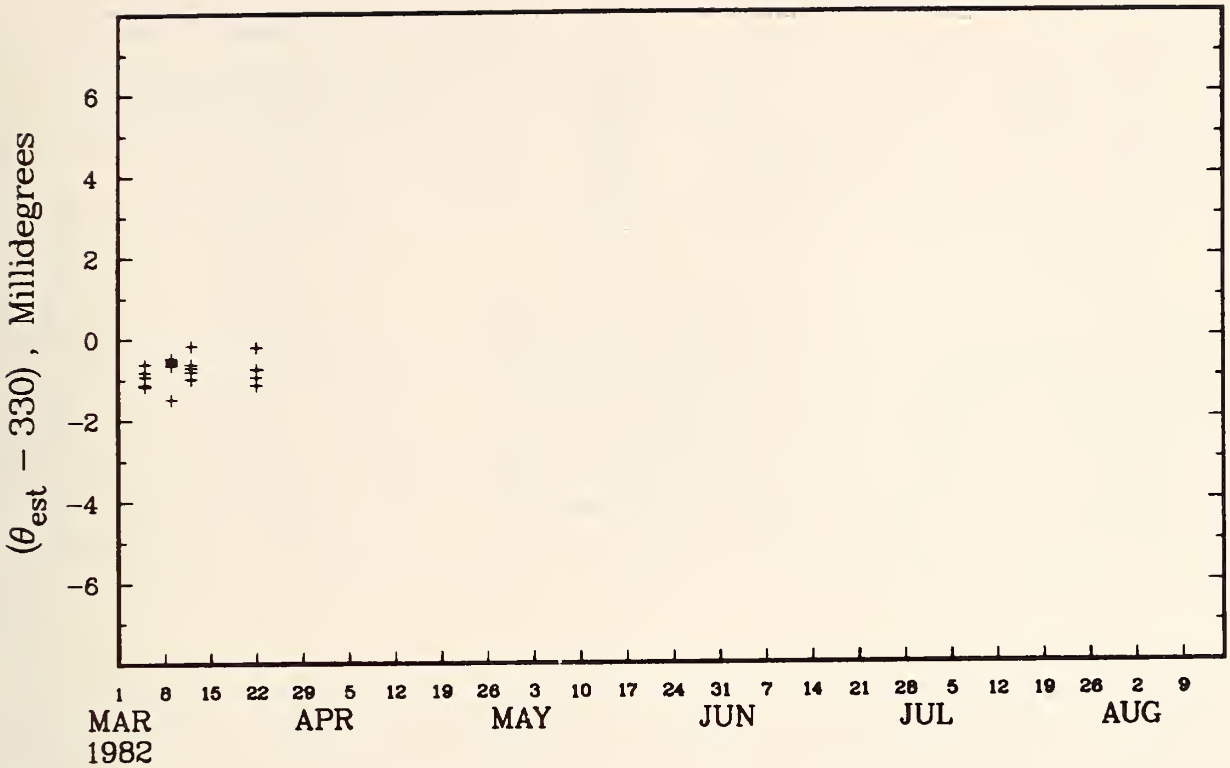


Figure 17-1L. Bearing angle offsets at 330 degrees.

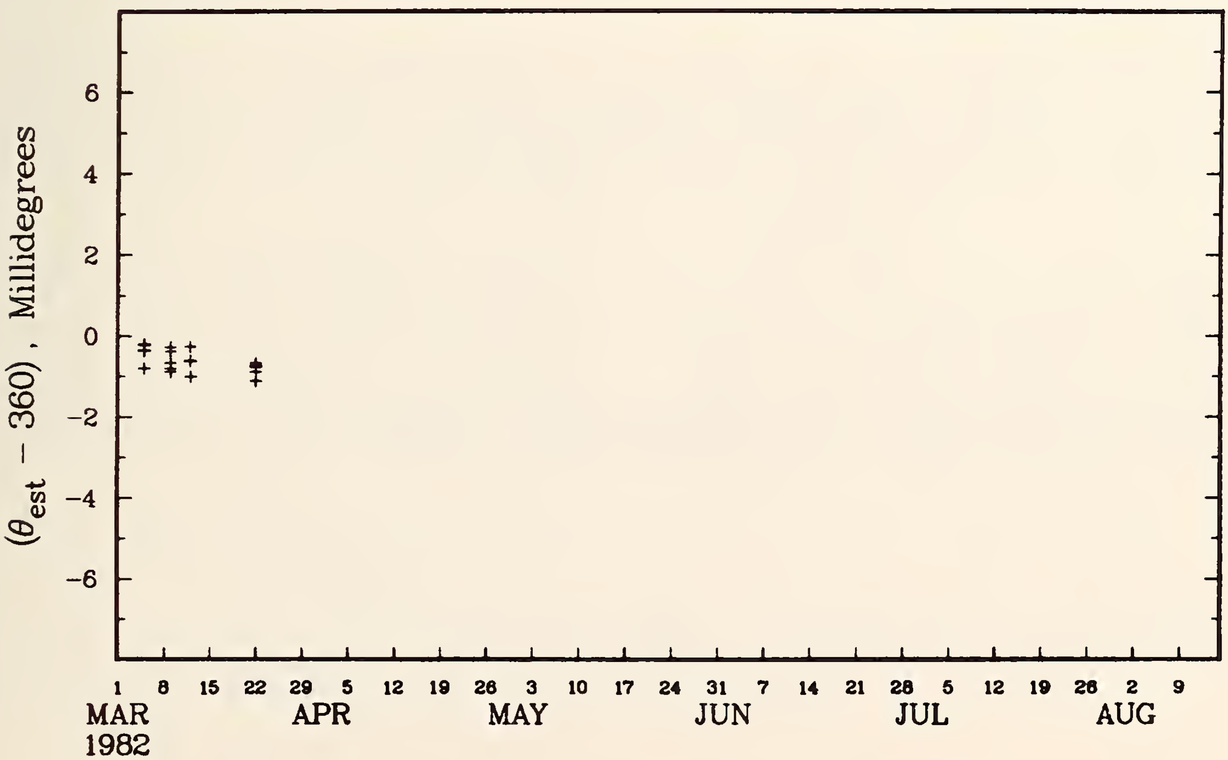


Figure 17-1M. Bearing angle offsets at 360 degrees.

Table 17.1. Measurement occasions.

Date (1982)	Measured bearing angles (degrees)	Total No. of measurements
March 4 & 5	0, 30, 60, ..., 360	70
March 9	0, 30, 60, ..., 360	65
March 12	0, 30, 60, ..., 360	75
March 22	0, 30, 60, ..., 360	65
April 29	0, 30, 120, 180, 240, 300	30
June 8	0, 30, 120, 180, 240, 300	30
July 6	0, 30, 120, 180, 240, 300	30
July 7	0, 30, 120, 180, 240, 300	30
July 13	0, 30, 120, 180, 240, 300	30
July 30	0, 30, 120, 180, 240, 300	30

17.3 Observed Data and Plots

An ac power line conditioner was added to the VOR system in February 1982. It handles the entire system: generator, phasemeter, and computer. During the subsequent period of operation, data were collected on 10 separate measurement occasions to assess the stability of the system, to estimate possible offsets, and to validate the statistical model for the process. Table 17.1 lists the dates of these measurement occasions and notes the bearing angles which were measured in each case. At each bearing at least M=5 measurements were taken in succession, with each measurement requiring about 6.5 minutes to obtain.

To illustrate both the offsets of the process from the nominal bearings and the short- or long-term variability of the measurements, plots of the data are shown in figures 17-1 A through 17-1 M. The value plotted on the vertical axis is an observed measurement minus the nominal bearing angle in degrees. Offsets of each bearing are plotted on a scale from -0.01° to 0.01°.

In figures 17-1 E (120°), 17-1 I (240°), and 17-1 K (300°), repeat measurements on July 13 and/or July 31 exhibited a higher short-term variability than the previous history of the process would suggest. However, these unexpected cases are believed to have been caused by intermittent thunderstorm activity on these days. For this reason, some of the measurements were discarded in the statistical analysis by the outlier detection procedure discussed below. A complete listing of the 455 measurements, and other quantities which are computed by the VOR system, is given in appendix B.

17.4 Statistical Analysis

Because of the complexity of the analysis, the data were transmitted to a CDC 170/750 computer where parameter estimates were computed using the BMDP statistical software package [7]. In this section we discuss a method for detecting isolated outliers, or uncharacteristic measurements, and obtain estimates of the parameters in the statistical model for the VOR system. The statistical model has been found to describe the VOR measurement process adequately during its limited time of operation.

17.4.1 Detection of Outliers

Two types of individual outliers were identified in the set of 455 measurements. The first type is flagged by excessively large values (greater than 0.005) of the single time-sample standard error of a bearing measurement. See section 16.1 for a discussion of this quantity. At present, the computed standard error is not a reliable measure of the actual short-term random error in bearing measurements, but this is thought to be a consequence of deficiencies in the phasemeter ADC, which fails to meet the manufacturer's specifications for linearity by about a factor of 30. Nevertheless, the bearing standard error is a useful indicator of isolated line effects during individual measurement periods.

Outliers of the second type were identified by excessively large values of the standardized residuals when the statistical model was fitted to the data. Standardized residuals were denoted in section 17.3 by

$$t_{ijk} = \delta_{ijk}/S(\delta_{ijk}).$$

The statistical software which was used automatically computes and prints the t_{ijk}'s for the model described in section 17.2.

A measurement y_{ijk} is rejected if $t_{ijk} > 3.0$ or if $t_{ijk} < -3.0$. This rejection criterion is motivated by the observation that t_{ijk}, though its exact distribution is not known, is similar to a Students-t statistic. The critical value 3.0 corresponds to the 0.995 probability level for the Students-t distribution with 35 degrees of freedom. This test is recommended in reference 4 as a good general approach even though probability levels cannot be computed exactly.

The second rejection criterion was applied to the data set three times iteratively to assure that extreme outliers could not mask the effects of less obvious outliers. Together, the two outlier rejection criteria work well for the VOR data in that they reject those measurements which appear to be unrepresentative of the process either because of isolated errors in the amplitude time-samples or because of transient effects during short measurement periods (for example, thunderstorm effects).

In the future, NBS does not plan to conduct calibrations on occasions when the frequent occurrence of uncharacteristic measurements could perturb the results. Aside from such identifiable transient effects, it is also reasonable to reject isolated wild measurements before estimating uncertainties because these effects do not substantially influence the measurement of analog phasemeters which, by design, report average phase over many cycles of the generator.

17.4.2 Parameter Estimates and Tests

Estimates of the unknown parameters were obtained by a statistical maximum likelihood algorithm described in documentation of the analysis of variance program BMDP3V [7]. An example listing of the computer output corresponding to the statistical analysis and parameter estimates discussed below is given in appendix D.

Table 17.2. Sample offsets and standard deviations.

Nominal bearing	After Pass 1 Count	After Pass 1 Average offset	After Pass 1 St. dev.	After Pass 3 (final) Count	After Pass 3 (final) Average offset	After Pass 3 (final) St. dev.
0	49	-0.00125	0.00059	49	0.00125	0.00059
30	48	0.00049	0.00071	47	0.00053	0.00067
60	18	-0.00074	0.00042	18	-0.00074	0.00042
90	20	-0.00032	0.00027	20	0.00032	0.00027
120	48	-0.00227	0.00108	44	-0.00215	0.00086
150	23	0.00074	0.00045	23	0.00074	0.00045
180	56	-0.00195	0.00042	56	-0.00195	0.00042
210	20	-0.00162	0.00041	20	-0.00162	0.00041
240	48	0.00008	0.00106	44	-0.00012	0.00065
270	18	-0.00092	0.00049	18	-0.00092	0.00049
300	50	0.00041	0.00089	46	0.00029	0.00053
330	20	-0.00077	0.00032	20	-0.00077	0.00032
360	20	-0.00061	0.00027	20	-0.00061	0.00027
Total	438			425		

Of the total set of 455 measurements taken at 13 distinct bearing angles, 30 measurements (6.5 percent) were rejected as outliers by the two rejection criteria. Table 17.2 lists the observed average offset at each bearing angle and the corresponding sample standard deviation after first and third (final) iterative application of the second rejection criterion. Recall that a total of three passes were made in the analysis to flag outliers.

The standard deviations listed in table 17.2 were computed using only the data for a particular bearing and, therefore, neither partition the variability into short-term and long-term contributions, nor do they reflect the fact that all bearings are incorporated simultaneously in the statistical model. Table 17.2 has been included to illustrate in a simple fashion the magnitudes of the offsets, their overall variability, and the effects of the outlier detection procedure on descriptive statistics.

The statistical analysis for the model described in section 17.2 was used to estimate the offsets at each bearing, and to partition the total variability into components for both short- and long-term variations (see section 17.2). Because the data are not evenly distributed among bearings or days, the maximum likelihood estimates of offset could differ slightly from the observed (simple) average offsets. Table 17.3 lists the final estimated offsets (through July 30, 1982) of the VOR process and the estimated random uncertainty in these estimates. We have included the corresponding estimates from the analysis after the first pass to reject outliers. Sample counts are given in the previous table.

Table 17.3. Estimated offsets and standard errors.

Nominal Bearing	After Pass 1 Estimated offset	After Pass 1 St. Dev. of estimate	Final Values (7-30-82) Estimated offset	Final Values (7-30-82) St. Dev. of estimate
0	-0.0013	0.0002	-0.0013	0.0001
30	0.0005	0.0002	0.0005	0.0001
60	-0.0009	0.0002	-0.0009	0.0002
90	0.0002	0.0002	0.0001	0.0002
120	-0.0023	0.0002	-0.0022	0.0001
150	0.0005	0.0002	0.0005	0.0002
180	-0.0020	0.0002	-0.0020	0.0001
210	-0.0018	0.0002	-0.0018	0.0002
240	0.0001	0.0002	-0.0001	0.0001
270	-0.0010	0.0002	-0.0011	0.0002
300	0.0004	0.0002	0.0003	0.0001
330	-0.0009	0.0002	-0.0010	0.0002
360	-0.0008	0.0002	-0.0008	0.0002

We remark that slight differences in the standard errors of the final estimated offsets reflect the fact that some bearings were measured more often and therefore have a lower uncertainty. That this difference is not apparent after the first pass for outlier rejection is an indication of the influence of outliers on the estimated components of total variability.

In the analysis which gave rise to the parameter estimates given in table 17.3, we simultaneously obtained estimates of the short-term (σ) and long-term $(\sigma_T^2 + \sigma_D^2)^{1/2}$ standard deviations. Table 17.4 gives estimates of a few functions of these components which are used to establish limits to random errors. The effects of outliers on estimation of variability are more clearly evident in the tabulated comparison between the first and final passes through the data.

The maximum likelihood technique also provides a statistical test based on the Chi-square distribution to determine if the two long-term components of variability (and, so, the corresponding terms in the statistical model) are necessary to characterize the VOR process. Non-negligible contributions to variability are indicated by a small value (< 0.05) of the significance level for the Chi-square test statistic computed by the software. Table 17.5 gives the results of these tests for the final data set, and indicates that both long-term components are non-zero. We also list the estimated standard deviations of the estimated variance; however, the Chi-square test statistic is not computed simply from the quantities listed.

Table 17.4. Components of random error.

Description of random error	Quantity estimated	After Pass 1 estimate	Final (7/30/82) estimate
Short-term st. dev.	σ	0.0006	0.0004
Total st. dev.	$(\sigma^2+\sigma_T^2+\sigma_D^2)^{1/2}$	0.0007	0.0006
Short-term st. dev. (mean of 5 readings at 1 bearing)	$(\sigma^2/5)^{1/2}$	0.0003	0.0002
Total st. dev. (mean of 5 readings at 1 bearing)	$(\sigma^2/5+\sigma_T^2+\sigma_D^2)^{1/2}$	0.0005	0.0004

Table 17.5. Chi-square tests for contributions to random error (7-30-82).

Parameter	Estimate	Standard deviation	Chi-square test statistic	Degrees of freedom	Significance
σ^2	1.775×10^{-7}	0.137×10^{-7}			
σ_T^2	0.518×10^{-7}	0.306×10^{-7}	7.942	1	0.005
σ_D^2	0.916×10^{-7}	0.209×10^{-7}	54.030	1	0.000

17.5 Overall System Performance

In the previous section we obtained estimates of individual offsets between NBS standard generator and standard phasemeter at 13 nominal bearings which are thought to be representative of the system behavior over the full range of 0° to 360°. We also computed reasonable estimates of various components of random variability about these offsets. In this section we characterize the overall system performance by computing the limits to random error in the reported values of the individual offsets. This information about the system performance at 13 distinct bearings has been combined into a single provisional uncertainty statement, which is reported in the following section.

The limit to random error associated with the i-th bearing offset is $3s_i$, where s_i denotes the estimated standard deviation of the reported offset (see table 17.3). Recalling that the estimated offset at bearing i was denoted by $\hat{\mu} + \hat{\alpha}_i$, then statistical bounds on the offsets are given by

$$\hat{\mu} + \hat{\alpha}_i \pm 3s_i .$$

All of the required quantities are documented in table 17.3. The estimated bounds on offsets at the 13 measured bearings are reported below in table 17.6. Note that in each case the maximum limit in magnitude of the offset is less than the allowable uncertainty of ±0.01°.

Table 17.6 Overall system performance.

Nominal bearing	Lower limit	Estimated offset	Upper limit
0	-0.0016	-0.0013	-0.0010
30	0.0002	0.0005	0.0008
60	-0.0015	-0.0009	-0.0003
90	-0.0005	0.0001	0.0007
120	-0.0025	-0.0022	-0.0019
150	-0.0001	0.0005	0.0011
180	-0.0023	-0.0020	-0.0017
210	-0.0024	-0.0018	-0.0012
240	-0.0004	-0.0001	0.0002
270	-0.0017	-0.0011	-0.0005
300	0.0000	0.0003	0.0006
330	-0.0016	-0.0010	-0.0004
360	-0.0012	-0.0006	-0.0000

17.6 Provisional Uncertainty

At the outset of this report it was noted that the primary criterion for judging the performance of the two VOR instruments was to achieve a high degree of confidence that they agree with each other. That is, since they are independent and work on different principles, it is probable that their separate indications are accurate if the nominal setting on the generator agrees with a measurement by the phasemeter.

Because the reported offsets between the generator and phasemeter cannot be attributed wholly or in part to either instrument at this time, it was decided to combine the information in table 17.6 into a single provisional uncertainty statement for either instrument alone. Therefore, until individual error analyses are devised, or until international comparisons are conducted, NBS will use the estimated maximum absolute offset in the group of 13 bearings as the systematic error for either VOR instrument, and will report the nominal bearings as accepted values for the process. The limit to random error is three times the maximum standard deviation of the estimated offsets in table 17.3.

The uncertainty of VOR bearing calibrations is given by:

The assigned values of VOR phase angles are the nominal bearings from 0 to 360° in increments of 0.01°. The overall uncertainty of these values has been estimated from test data at bearings from 0° to 360° at 30° increments. Thus, each of the nominal bearings has been assigned a provisional overall uncertainty of ±0.0028°, based on estimated bounds of ±0.0022° on the systematic error and a computed standard error of 0.0002°.

18. Process Control and Updating Parameters

In sections 17.4 and 17.5, initial accepted values of VOR process parameters were obtained. Once these parameters have been established, overall process control is maintained by checking the observed short-term standard deviation and estimated offsets on each subsequent measurements occasion against their accepted values. As long as the process produces values which are consistent with the accepted parameter values, the system is considered to be performing within the established control pattern. Procedures for detecting out-of-control conditions are discussed briefly below, but procedures for identifying and correcting specific malfunctions from the various statistical tests are evolving as more experience is gained with the VOR system and will not be discussed here.

18.1 Control Charts and Tests

Control charts are used on a continuing basis to monitor the output of the composite VOR measurement system. Given established values for process parameters, the estimated offsets and short-term standard deviations on subsequent calibration dates are plotted against a time scale. The charts for offsets includes control limits so that an out-of-control value is immediately noticable. The chart of the short-term standard deviations provides visual evidence to determine if there has been a change in the within-day process variation.

The short-term variation on a given measurement occasion can be estimated by describing the data using a special case of the statistical model given in section 17.2. If M repeat measurements are made at I nominal bearings the model for the measurements is:

$$y_{ij} = \mu + \alpha_i + e_{ij}, \quad i = 1, \cdot\cdot\cdot, I;$$
$$j = 1, \cdot\cdot\cdot, M;$$

where

y_{ij} is an observed offset [$\hat{\theta}_1$ - nominal bearing];

$\mu + \alpha_i$ is the unknown average offset at bearing i for the current day;

e_{ij} is the short-term error of measurement in the j-th repeat measurement at bearing i.

The errors, e_{ij}, are assumed to have a Gaussian distribution with mean zero and variance σ^2. If the process is in statistical control, the current estimated short-term standard deviation and the estimated offsets should be consistent with the accepted values of these parameters.

The statistical analysis obtains the parameter estimates after outliers have been rejected by the methods discussed in section 17. These estimates are then plotted on the control charts and are also used in statistical tests to determine whether or not the process is in control.

18.1.1 Control Chart for Short-Term Error

Figure 18-1 illustrates the within-day process variation for 17 measurement occasions from March 1, 1982 through May 6, 1983. The first 10 estimated values of σ were obtained from the data used to establish the current accepted values of the process parameters. For reference, the accepted value of σ is also noted in the figure. The inclusion of estimates from data obtained on July 30, 1983 serves to illustrate that the unusually high short-term variation on July 30 was apparently caused by thunderstorm activity on that day. In the next four figures, open circles are used to indicate data used in arriving at the estimate and control limits (if present). Plus signs (+) are used to indicate data taken after the estimates were made.

18.1.2 Control Chart for Individual Measurements

Sufficiently accurate control limits cannot be established during the current stage of initiating the VOR measurement process. However, to illustrate the type of control charts which will be used to monitor the process after a large number of calibration occasions have been inspected, some of the data used to compute process parameters are plotted in figures 18-2 A-F.

During start-up the process is assumed to be in statistical control. The control limits in figures 18-2 A-F will be used until evidence is obtained which is not consistent with the accepted values or until enough data accumulates to effectively revise or update the process parameters.

Although charts on the average offsets are more sensitive than those on individual measurements, the latter was chosen because outlier rejection may result in unequal numbers of repeat measurements from occasion to occasion. Thus, fluctuating control limits would be required for charts on the average offset.

Limits specified in figures 18-2 A-F were set at

$$\hat{\mu} + \hat{\alpha}_i \pm 3(\hat{\sigma}^2 + \hat{\sigma}_T^2 + \hat{\sigma}_D^2)^{1/2},$$

where the estimates of the offset at the ith bearing and the components of error are the initial accepted values. The numeric values were given in tables 17.3 and 17.4.

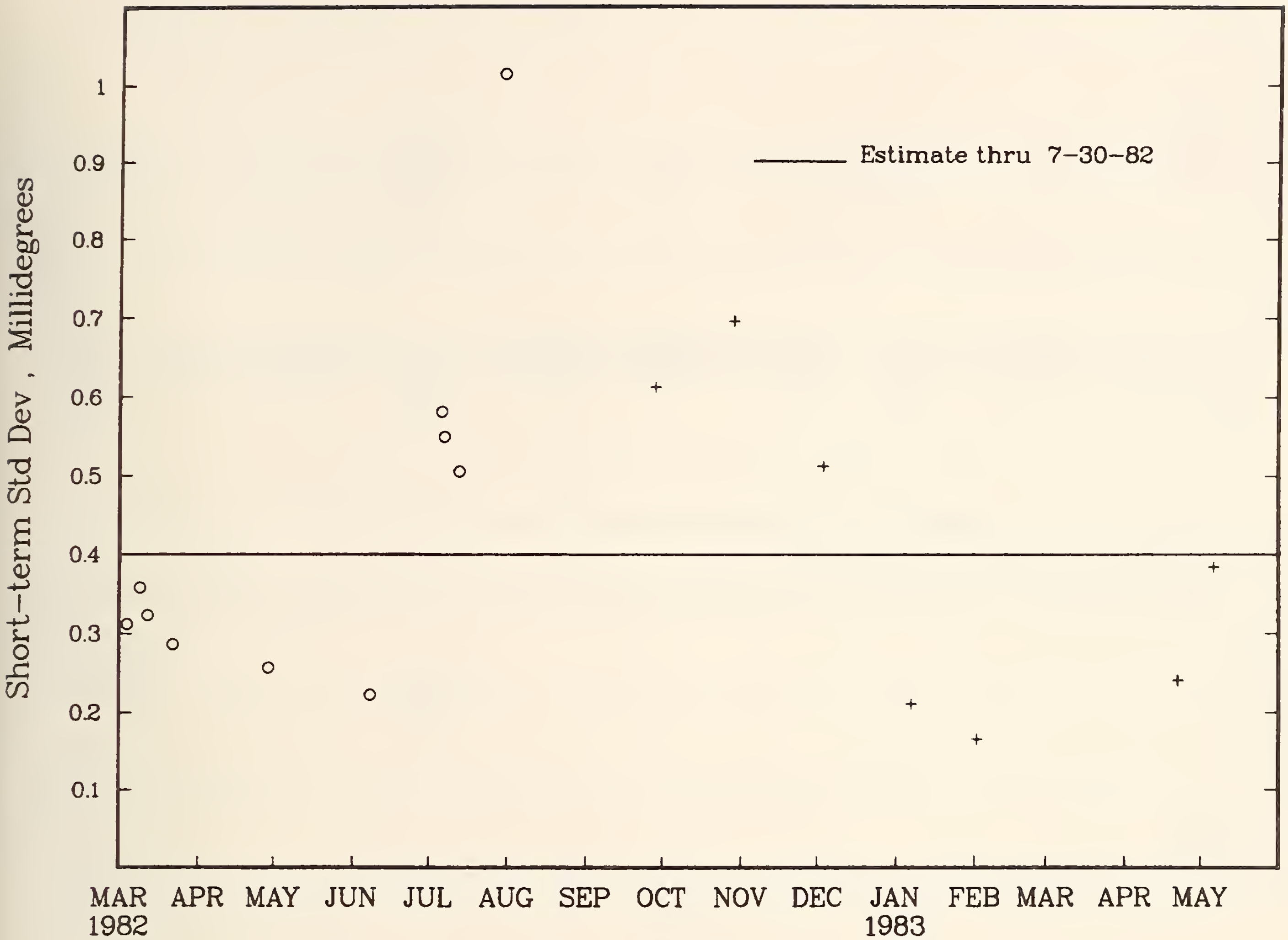


Figure 18-1. Control chart for short-term standard deviation.

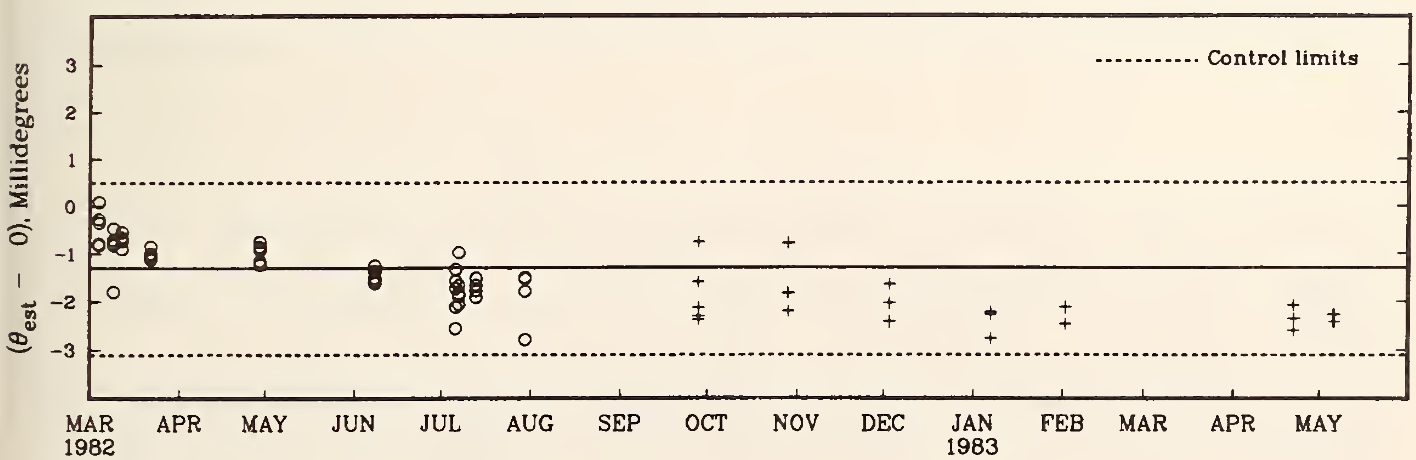


Figure 18-2A. Control chart of offsets at 0 degrees.

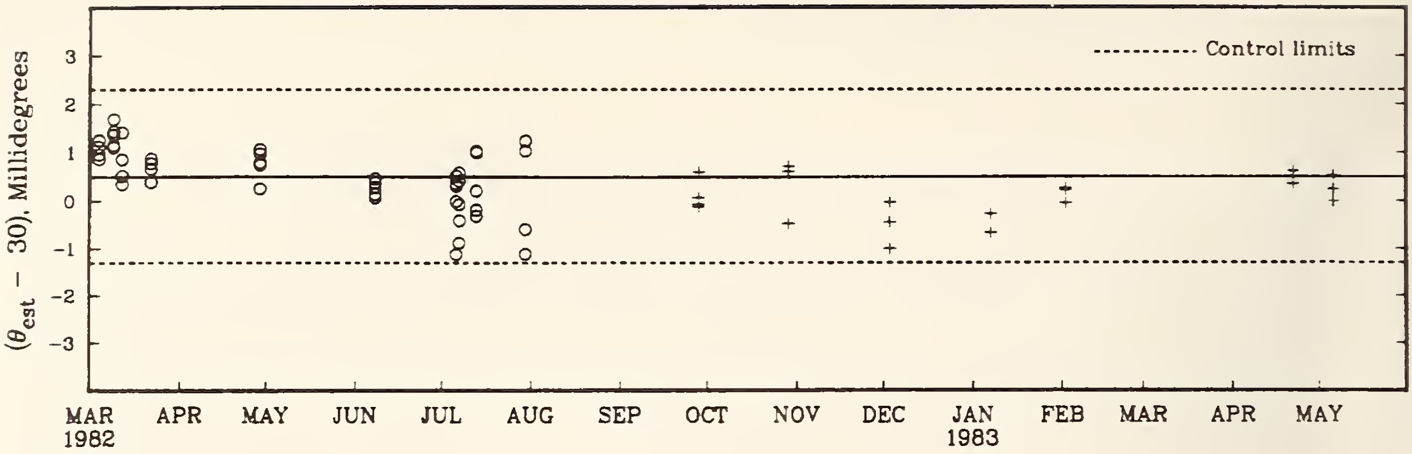


Figure 18-2B. Control chart of offsets at 30 degrees.

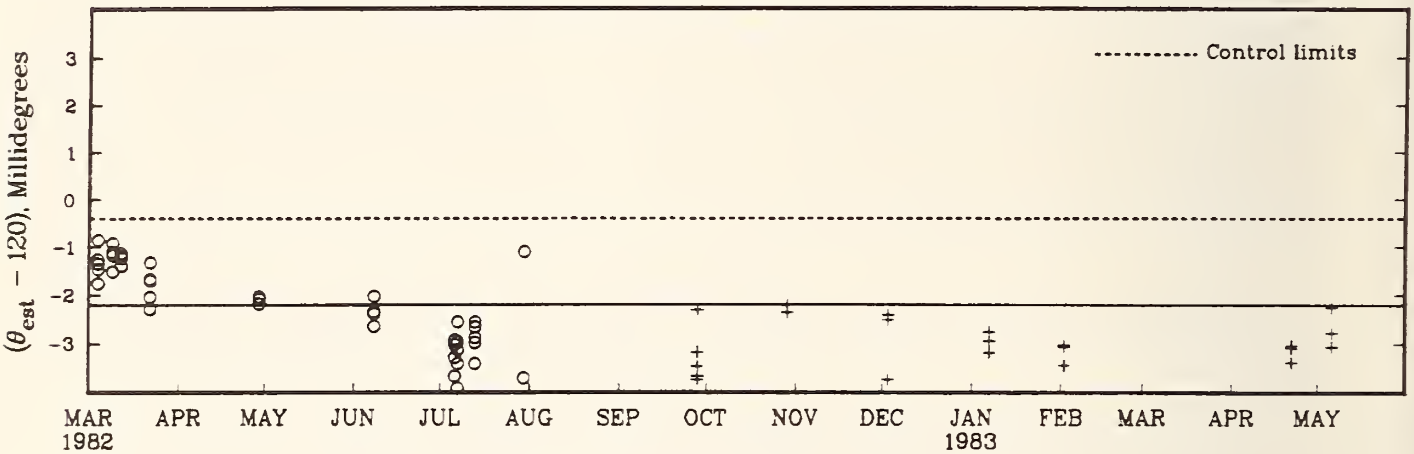


Figure 18-2C. Control chart of offsets at 120 degrees.

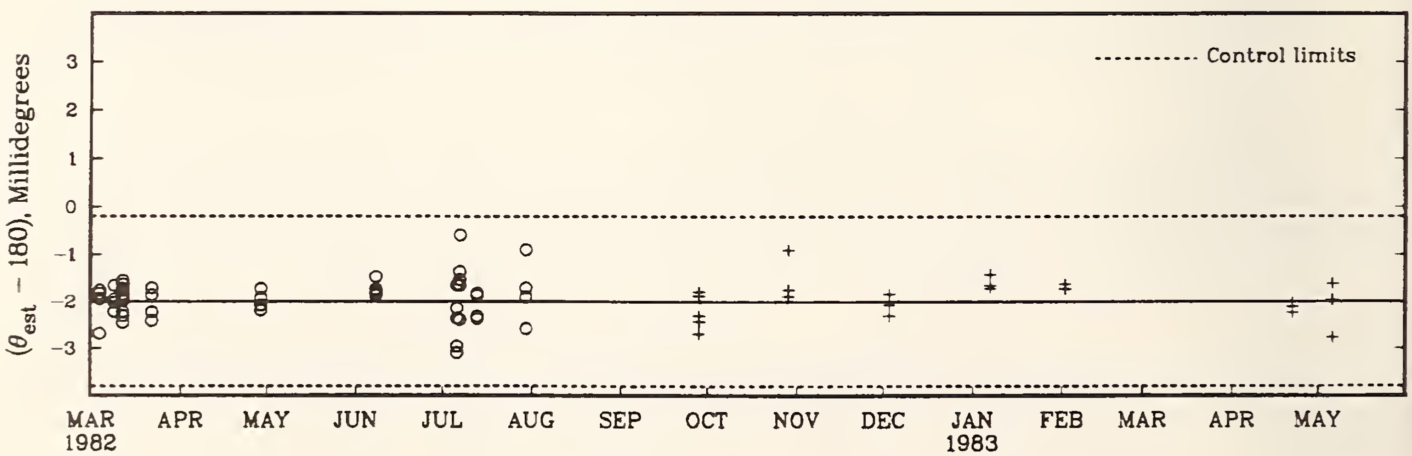


Figure 18-2D. Control chart of offsets at 180 degrees.

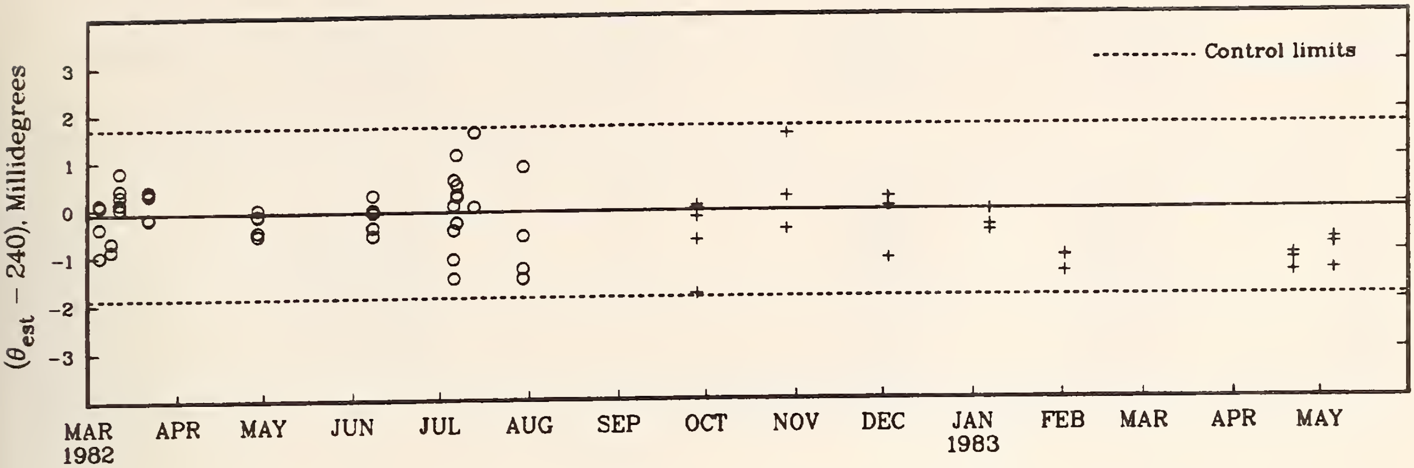


Figure 18-2E. Control chart of offsets at 240 degrees.

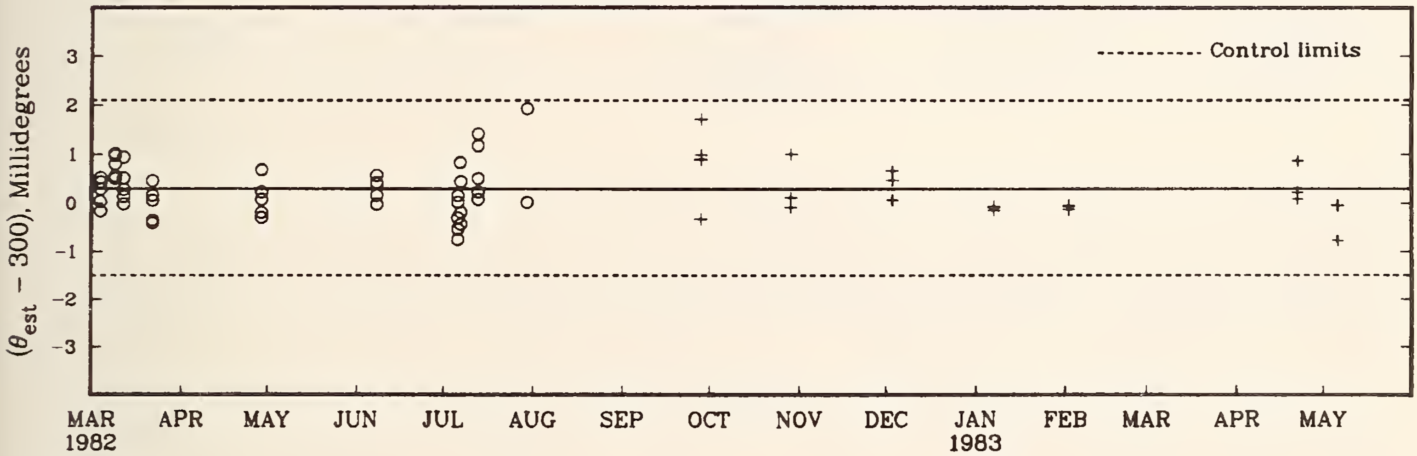


Figure 18-2F. Control chart of offsets at 300 degrees.

18.1.3 Tests for Out-of-Control Conditions

Two types of statistical comparisons are used to determine if process parameters may have changed since previous calibration sessions. These tests monitor, respectively, the process short-term variation and the mutual offsets between generator and phasemeter. Table 18.1 illustrates the procedure and shows the appropriate statistical tests for comparing current offsets to accepted values. Table 18.2 describes the test for an increase in short-term variation.

Tables 18.1 and 18.2 are presented primarily to illustrate the procedures which are used to determine if the process parameters may have changed from the accepted values. However, it is clear from the results, which are based on actual measurements, that values of the components of random error should be recomputed when more process output is available. This is also suggested by visual evidence in the control chart in figure 18-1, which seems to indicate that an abrupt shift in short-term variation may have occurred between June 8 and July 6. If the larger error persists and the process remains within the assigned goal, new values of the parameters will be determined from measurements obtained after June 8, 1982.

Table 18.1. Comparison of new offsets to accepted values.

Nominal bearing	Accepted offset	Estimated offset on 9/28/82	Number observed	Estimated Std. Dev. of offset	t-Test
	γ	$\hat{\gamma}$	n	$s(\hat{\gamma})$	$(\hat{\gamma} - \gamma)/s(\hat{\gamma})$
0	-0.0013	-0.0018	5	2.7342×10^{-4}	-2.19
30	0.0005	0.0001	4	3.0569×10^{-4}	-1.31
120	-0.0022	-0.0033	5	2.7342×10^{-4}	-4.39*
180	-0.0020	-0.0022	5	2.7342×10^{-4}	-0.73
240	-0.0001	-0.0006	5	2.7342×10^{-4}	-1.83
300	0.0003	0.0008	5	2.7342×10^{-4}	1.83

*If $t \geqslant 3$, the new value is not consistent with the accepted offset. In this case a malfunction which affects 120° (or possibly a range of bearings) may be indicated.

Table 18.2. Comparison of new short-term variability with accepted value.

Accepted short-term variance	Estimated variance on 9/28/82	Total number of measurements	Number of bearings	Chi-square (χ^2) test
σ^2	s^2	N	k	$\frac{(N - k)s^2}{\sigma^2}$
1.775×10^{-7}	3.738×10^{-7}	29	6	48.44*

*If $\chi^2 \geqslant \chi^2_{0.01}$ for (N - k) degrees of freedom, the current short-term variability is not consistent with the accepted value. For 23 degrees of freedom, $\chi^2_{0.01} = 9.26$.

Finally, we remark that the t-test and chi-square test were applied assuming that the accepted values of the process parameters were "known," or at least very precisely determined relative to the estimates obtained on the subsequent occasion. These tests will be appropriate when the process has been shown to be in continous statistical control for several measurement occasions, so that highly accurate values of the process parameters can be established from the combined data. During the present stage of initiating the process, or during the start-up of the process after a substantial system modification or other out-of-control process correction, it will be necessary to use tests which incorporate and adjust for uncertainty in the initial accepted values. The appropriate initial comparisons are an F-test for short-term error, and the two-sample t-test for offsets.

18.2 Updating Process Parameters

Initial accepted values for the VOR system were established after 10 calibration runs from March 3, 1982 through July 30, 1982. On subsequent occasions, the process is monitored using the control procedures described above to determine if measurements are adequate relative to the assigned uncertainty goal. Generally, this procedure may be followed as long as the process is confirmed to be performing within the established control pattern.

Periodically, as data accumulate at the control bearings, new accepted values for offsets and components of error will be computed by combining current data with previous measurements and applying the methods described in section 17.4. Initially, the accepted values will be updated after five or six calibration runs and then as convenience dictates (every six months or yearly).

18.3 Procedures for Correcting Out-of-Control Conditions

Actions which can be taken when a statistical test indicates an out-of-control condition are currently being investigated. In the absence of specific assignable causes for out-of-control conditions, the following general questions will be considered.

If the process is found to be out of control by a chi-square or F-test, indicating excessive short-term nonrepeatability:

1. Was there extreme weather activity during the calibration run (thunderstorms, wind, etc.)?
2. Is the accepted value of short-term error realistic?
3. Has the process variation changed? Is the current variation still adequate for the assigned goal?
4. Is there unusual activity in the laboratory or building affecting power supplies?
5. Equipment deterioration or minor malfunction?

If the process is found to be out of control by a t-test, indicating an abrupt shift in bearing:

1. Only at a single bearing? This may indicate an intermittent or transient external disruption.
2. At several control bearings? Look at bearing histories for a steady drift toward out-of-control condition. This could indicate a need for system adjustment. If an abrupt change has occurred, this could indicate a component malfunction in either the generator or in the phasemeter ADC.

The work reported here is the result of vital contributions by several persons over a period of about five years. M. G. Arthur provided the initial project management. He and C. H. Manney, Jr., determined that the use of primarily digital techniques in both the phasemeter and generator was the only approach that could achieve the desired accuracy. G. R. Sugar and C. J. Roubique did most of the detailed logic design in the generator, and E. Niesen constructed and assisted in debugging it. The phasemeter was designed and constructed by N. T. Larsen, and the software was written by Larsen and D. F. Vecchia.

The task of completing the development, verifying the performance, and writing this report fell to the present authors. The credit for the design belongs mainly to those named above; the authors however, take full responsibility for preparing this report.

19. References

[1] Sandretto, Peter C. Electronic avigation engineering. New York: International Telephone and Telegraph Corp.; 1958. 373.

[2] Hurley, H. C.; Anderson, S. R.; Keary, H. F. The Civil Aeronautics Administration VHF ominrange. Proc. IRE 39(12):1506-1520; 1951.

[3] White, R. A.; Clarke, R. N.; Yell, R. W. VOR waveform synthesis and calibration. IEE Proc. 128, Pt. F(7):443-450; 1981 December.

[4] Note: This design decision was made after a demonstration to us of an possibly similar approach by R. H. Huenemann, then with United Air Lines. We used the NBS generator to test his method with good results, but he did not allow us to examine his software. The details of his method are not known. However, the decision was not made until extensive computer simulations had been made and the errors analyzed.

[5] Vecchia, Dominic. Fourier transformation of the nonlinear VOR model to approximate linear form. Nat. Bur. Stand. (U.S.); Tech. Note 1021; 1980.

[6] Barnett, V.; Lewis, T. Outliers in statistical data. New York: John Wiley and Sons, Inc.; 1978.

[7] Dixon, W. J.; Brown, M. B., eds. BMDP-79: Biomedical computer programs P-series. Berkeley: Univ. of California Press; 1979.

```
100    Rev$="8207140822"              ! This must be a 10-digit number.
120    Disk$=""                       ! A 10-digit no. picked up from the disk.
140    Filename$="VOR1"               ! Filename$ is this program's name.
141    ! 8201011453: Added year to Time$.  Added MATPRINT Theta to Meas_print.
160    ! This program takes 1024 time samples of the VOR composite audio wave-
180    ! form and stores the data on disk.  It drives the analog-to-digital con-
200    ! verter and the time delay generator.  After the data have been stored,
220    ! this program can retrieve and process the file.  The final results of
240    ! the processing are then stored in the original file.  (Intermediate
260    ! results and statistics on sets of measurements are not stored.)
280    !
300    ! A single measurement results in one file, 17 records of 256 bytes each.
320    ! The first 16 records are completely filled by the 1024 integer pre-
340    ! cision data points.  The last record is completely filled by a 32-
360    ! element array used for housekeeping purposes.
380    !
400    ! This program has been tested using simulated, noisy data.  To process
420    ! simulated data, 3 changes should be made:
440    !     1.  Check that the sine transforms are not negated in Fft_driver,
460    !         line Change1.
480    !     2.  Do not MAT READ Housekeeping(*) in Retrieve_data, line Change2.
500    !     3.  Delete the PAUSE in Retrieve_data, line Change3.
520    !
540    !
560    ! Rev$ and Disk$ are stored in Housekeeping(6) & (7), respectively.
580    ! They are the code revision date and the disk identification, and are
600    ! used in documenting printed output.
620    !
640    ! Sine transforms negated, 8005280905.
660    !
680    ! Routine Fft uses code adapted from the Hewlett-Packard 9835 Numerical
700    ! Analysis software package.
720    !
740    ! Arrays used in the Estimation subroutine: Qd(*), Xt(*), Theta(*).
760    !
780    ! Arrays used in the Xt subroutine are dimensioned by label Xt_dim:.
800    ! This line is disabled to conserve 25 kbytes of memory.
820    !
840    ! Integer_data(*)=integer precision time series data, the raw output
860    !     of the A/D converter.  This is the data stored on disk; integer
880    !     precision data takes less disk space.
900    ! Real_data(*)=the full precision array into which the data is loaded
920    !     from disk for FFT processing.  As stored, it is integer data, but
940    !     before it is processed, it is converted to volts by multiplying
960    !     by 5/32768.
980    !     To convert to volts, multiply by 5/32768.
1000   !
1020   ! Housekeeping(*) holds the following elements:
1040   !     1:  Ending date-time group (dtg) of a data run: Time_no.
1060   !     2:  Nominal bearing angle, degrees: Nom_bearing.
1080   !     3:  Number of measurements in the set: No_measmnts.
1100   !     4:  Number of this measurement: Measmnt.
1120   !     5:  Number of data points in the set taken in overload (bad).
1140   !     6:  Revision dtg of the code: VAL(Rev$).
1160   !     7:  Disk dtg: VAL(Disk$).
1180   !     8:  File_no of the measurement, DATnnn.
1200   !     9:  Theta1, the VOR bearing angle (=0 if data not processed).
1220   !    10:  Theta2
1240   !    11:  Theta3
1260   !    12:  Sigmasq, a measure of the precision.
1280   !    13:  Est_std_dev, the estimate of the standard deviation.
1300   !    14:  Processed, a flag that identifies processed data.
1320   !    15
1340   !     ↓
1360   !    32:  Unassigned (=0) for future use.  May be used for customer ID,
1380   !         instrument ID, last recalibration dtg, etc.  See label House-
1400   !         keeping.
```

```
1420   !
1440   ! Delay$=5359A command string.
1460   !
1480   ! I(*) See R(*), below.
1500   !
1520   ! Jn(*) Holds the values of Bessel functions of the first
1540   ! kind, orders -18 through 18 (37 numbers).  Loaded with file "Xt".
1560   !
1580   ! Meas(*) is organized as follows:  The first row contains information
1600   !     about the 30 Hz fundamental frequency, and rows 2 through 38
1620   !     contain the same information for spectral lines 314 through 350
1640   !     (i. e., lower sideband -18 through upper sideband no. 18).  All
1660   !     rows of Meas(*) conform the these column assignments:
1680   !      1.  Real part from R(*)--note that the rows do not correspond.
1700   !          The first row of Meas(*) results from the second row of R(*) &
1720   !          I(*); etc.
1740   !      2.  Imaginary part from I(*)--same rows as above.
1760   !      3.  Magnitude or amplitude of the lines.
1780   !      4.  Phase, in radians, after selection of quadrant.  This col. is
1800   !          placed in Qr(*), for use in the estimation of the std. dev.
1820   !      5.  Phase, in degrees, derived from col. 4.  This col. is placed
1840   !          in Qd(*), which is used in the bearing angle estimation.
1860   !      6.  SGN of Jn(Row-20), the sign of Bessel functions -18 to 18.
1880   !      7.  Pointer(*) value for that row.  The value is one greater than
1900   !          the harmonic number.
1920   !
1940   ! Pointer(*) is set up in the FFT driver to indicate the desired lines in
1960   !     R(*) and I(*); only lines 1 and 314-350 are used.
1980   !
2000   ! Qd(*) is a vector = to col. 5 of Meas(*).  Angles have been ordered.
2020   !     It is used in the estimation of the bearing angle, Theta(1,1).
2040   !
2060   ! Qr(*) is a vector = to col. 4 of Meas(*).  Angles are never ordered.
2080   !     It is used in the estimation of the standard deviation of the bear-
2100   !     ing angle, Est_std_dev.  This estimation helps identify bad data.
2120   !
2140   ! R(*) holds the odd-numbered rows of Data(*); I(*) holds the even-num-
2160   !     bered rows.  R(*) and I(*) are used in the FFT routine.  Conversion
2180   !     from Data(*) to R(*) and I(*) only requires 4 seconds; but if
2200   !     memory is severely limited, the code can be changed to store the
2220   !     data directly in R(*) and I(*).  Otherwise, storing the data in a
2240   !     single array simplifies possible future processing.
2260   !
2280   !     In the FFT, the elements in both R(*) and I(*) are replaced by the
2300   !     real and imaginary parts of the lines.  The first row in R(*) con-
2320   !     tains the DC term and the first row in I(*) contains the maximum
2340   !     frequency.
2360   !
2380   !     Meas(38,7) [q. v.] selects the needed lines from R(*) & I(*) by
2400   !     means of Pointer(*).
2420   !
2440   ! Results(*) holds the bearing angles for all measurements, up to 50 in
2460   !     one set.  This may be reduced to conserve memory, since an estimate
2480   !     of the standard deviation of the bearing angle can be obtained from
2500   !     only one measurement.  (It tends to be overly conservative.)
2520   !
2540   ! Stats(*) replicates Results(*) and is then used to compute mean, s.d.,
2560   !     etc, to preserve Results(*), if needed.  Memory may be saved by
2580   !     allowing Results(*) to be altered in the processing, otherwise.
2600   !
2620   ! Theta(*) contains the estimates of the three (theta) angles in the
2640   !     model of the VOR signal.  Theta(1,1) is the estimated bearing
2660   !     angle.
2680   !
2700 Main_program:  !
2720    OPTION BASE 1
2740    COM REAL Xt(3,38),Jn(37),Pointer(38),Ck,Year$
2760    DIM Real_data(1024,1),Delay$[80],Housekeeping(32),I(512),Meas(39,7)
2780    DIM R(512),Results(50,1),Stats(50,1)
```

```
2800    DIM Qd(38,1),Qr(38,1),Theta(3,1)
2820    DIM X(37),Y(37),Xsq(15),Ysq(15),Xy(15)
2840    INTEGER Integer_data(1024,1)
2860 Xt_dim:! DIM X(38,3),V(38,38),Vi(38,38),A(38,3),B(3,3),C(3,3)
2920    Wait=100                        ! 5359A settling delay
2940    Printer=16
2960    LINPUT "Printer select code? (Default is 16.)",Resp$
2980    IF Resp$="" THEN 3020
3000    Printer=VAL(TRIM$(Resp$))
3020    PRINTER IS Printer
3040    LINPUT "What is the msus where the data and program are stored?",Msus_data$
3060    Msus_data$=TRIM$(UPC$(Msus_data$))
3080    IF Msus_data$[1,1]<>":" THEN Msus_data$=":"&Msus_data$
3081    IF Disk$<>"" THEN 3100
3082    LINK "DTG"&Msus_data$,32000
3083    GOSUB Disk_dtg
3100    No_samples=1024                 ! This is fixed, in this program.
3120    INPUT "Nominal bearing angle (degrees)?",Nom_bearing
3140    Housekeeping(2)=Nom_bearing
3160    INPUT "Process old data (1), or take new data (2)?",Old_data
3180    IF (Old_data<>1) AND (Old_data<>2) AND (Old_data<>0) THEN 3160
3200    IF Old_data=0 THEN End
3220    IF Old_data=1 THEN GOSUB Retrieve_data
3240    IF Old_data=1 THEN End
3241    IF LEN(Year$)=2 THEN 3260
3242    INPUT "Last two digits of the present year?",Year$
3243    IF LEN(Year$)<>2 THEN 3242
3260    INPUT "Number of measurements?",No_measmnts  ! Loop for statistics.
3280    IF (No_measmnts<1) OR (No_measmnts>100) THEN 3260
3300    Storing=0                       ! A flag for Check_files
3320    GOSUB Check_files
3340    FOR Measmnt=1 TO No_measmnts
3360      Measurement=Measmnt
3380      No_overloads=0                ! No_overloads counts bad data points.
3400      GOSUB Setup_5359              ! Resset 5359A for every Measmnt.
3420      GOSUB Take_data
3440      GOSUB Store_data
3460    NEXT Measmnt
3480    PRINTER IS 16
3500    PRINT PAGE
3520    PRINT "Data acquisition is complete.  All data in this set of measurements have been"
3540    PRINT "stored.  Processing is in progress."
3560    File_no=VAL(File$[4,6])-No_measmnts+1  ! If data has just been taken,
3580                                           ! this resets the File_no to the
3600                                           ! first file in the set, for
3620                                           ! processing.
3640    PRINTER IS Printer
3660    GOSUB Retrieve_data             ! Retrieves and processes the data;
3680                                    ! prints out results and stats.
3700 End:!
3720    PRINT LIN(2)
3740    PRINTER IS 16
3760    STOP!

3780 Setup_5359:!
3800    REMOTE 716
3820    Delay$="W200E-9,0A5,000,DSS"
3840    FLOAT 11
3860    Delay$=Delay$&VAL$(1/(30*No_samples))&",TPONSP,D0,"
3880    STANDARD
3900    OUTPUT 716;Delay$
3920    RETURN !

3940 Take_data:!
3960    GOSUB Time
3980    PRINT "Data taking began at ";Time$
4000    PRINT "Code dtg: ";Rev$;".  Disk dtg: ";Disk$;".  Filename: ";Filename$
4020    MAT Integer_data=ZER
4040    OUTPUT 716;Delay$               ! Reset 5359A for each measurement.
```

```
4060    FOR Counter=1 TO No_samples
4080      OUTPUT 716;"SCRA,"            ! Single-Cycle, Re-Arm
4100      WAIT Wait                     ! Wait=settling delay for 5359A.
4120      Sample=READBIN(2)
4140      IF ABS(Sample)<32767 THEN 4240     ! Test for overload.
4160      BEEP
4180      DISP ""
4200      DISP " OVERLOAD! "
4220      No_overloads=No_overloads+1
4240      Integer_data(Counter,1)=Sample
4260      OUTPUT 716;"DSU,"             ! Delay Step Up
4280    NEXT Counter
4300    RETURN !

4320 Statistics:!
4340    PRINT "Code dtg: ";Rev$;".  Disk dtg: ";Disk$;".  Filename: ";Filename$
4360    REDIM Stats(No_measmnts,1)
4380    IF No_measmnts=1 THEN 4860      ! If there has been only one meas-
4400                                    ! urement, statistics are skipped.
4420    MAT Stats=Results
4440    IF Nom_bearing<>0 THEN 4520
4460    FOR Counter=1 TO No_measmnts    ! Allows stats near 0.00 degrees.
4480      IF Stats(Counter,1)>350 THEN Stats(Counter,1)=-(360-Stats(Counter,1))
4500    NEXT Counter
4520    Mean=SUM(Stats)/No_measmnts     ! Stats(*) now contains all the
4540                                    ! measurement results.
4560    MAT Stats=Stats-(Mean)
4580    MAT Stats=Stats.Stats           ! Square each element in Stats(*).
4600    Variance=SUM(Stats)/(No_measmnts-1)
4620    Std_dev=SQR(Variance)
4640    PRINT
4660    IMAGE "Mean:",21("."),M3D.3DX3D," degrees"
4680    PRINT USING 4660;Mean
4700    IMAGE "Nominal bearing",11("."),4D.2D
4720    PRINT USING 4700;Nom_bearing
4740    IMAGE "Variance:",17("."),2X,M1D.3DE
4760    PRINT USING 4740;Variance
4780    IMAGE "Standard deviation:",7("."),2X,M1D.3DE," degrees"
4800    PRINT USING 4780;Std_dev
4820    IMAGE "Mean minus nominal:",7("."),M3D.3DX3D," degrees",/
4840    PRINT USING 4820;Mean-Nom_bearing
4860    RETURN !

4880 Time:   !
4900    OUTPUT 9;"R"
4920    ENTER 9;Time$
4940    Time$=Year$&":"&Time$
4960    Time_no$=Time$[1,2]&Time$[4,5]&Time$[7,8]&Time$[10,11]&Time$[13,14]&Time$[16,17]
4980    Time_no=VAL(Time_no$)           ! Used for Housekeeping(*) info., and
5000    RETURN !                      ! elsewhere.

5020 Store_data:   !
5040    Storing=1
5060    GOSUB Check_files
5080    GOSUB Housekeeping1
5100    IF File_no<10 THEN File$="DAT00"&VAL$(File_no)&Msus_data$
5120    IF File_no>=10 THEN File$="DAT0"&VAL$(File_no)&Msus_data$
5140    IF File_no=100 THEN File$="DAT"&VAL$(File_no)&Msus_data$
5160    CREATE File$,17,256             ! For Integer_data(*) & Housekeeping(*).
5180    ASSIGN #1 TO File$
5200    MAT PRINT #1;Integer_data,Housekeeping
5220    ASSIGN * TO #1
5240    GOSUB Time
5260    PRINT "Data stored in file ";File$;", disk ";Disk$;", at ";Time$;".",LIN(1)
5280    RETURN !

5300 Retrieve_data:                     ! Gets data files, processes them,
5320                                    ! and prints results.
5340                                    !
```

```
5360    IF Old_data<>1 THEN 5420       ! Jumps if processing data just taken.
5380    INPUT "Data files are 'DAT' followed by a number.  What's the no. of the first file?",File_no
5400    INPUT "How many measurements were in the set?",No_measmnts
5420    REDIM Results(No_measmnts,1)
5440    Result_no=0
5460    IF Xt(1,1)=1 THEN 5540         ! IF...THEN Xt(*) is in COMmon memory.
5480    ASSIGN #1 TO "Xt____"&Msus_data$
5500    READ #1;Xt(*),Jn(*),Pointer(*),Ck
5520    ASSIGN * TO #1
5540    FOR File=File_no TO File_no+No_measmnts-1
5560      Processed=0                  ! (Set to 1 when the file is processed.)
5580      Result_no=Result_no+1
5600      IF File<10 THEN File$="DAT00"
5620      IF File>=10 THEN File$="DAT0"
5640      IF File=100 THEN File$="DAT"
5660      File$=File$&VAL$(File)&Msus_data$
5680      PRINTER IS 16
5700      PRINT File$                  ! Shows the progress in the processing.
5720      ASSIGN #1 TO File$
5740 Change2:                          ! To process simulated data, READ only
5760                                   ! Real_data.
5780      MAT READ #1;Real_data,Housekeeping
5800      ASSIGN * TO #1
5820      Processed=Housekeeping(14)
5840      IF NOT Processed THEN 6180   ! Data has not been processed before.
5860      BEEP
5880      PRINT "File "&File$&" has already been processed.";
5900      IF Housekeeping(15) THEN PRINT "  It is a bad file.";
5901      INPUT "Do you wish to reprocess it? (1 or 0)",Reprocess
5920      PRINT
5940      PRINTER IS Printer
5960      Results(Result_no,1)=Housekeeping(9)
5980      Sigmasq=Housekeeping(12)
6000      Est_std_dev=Housekeeping(13)
6020      IF File<>File_no THEN 6100
6040      IMAGE "Data file",5X,"Bearing angle",5X,"Sigmasq",5X,"Est. std. dev."
6060      PRINT USING 6040
6080      IMAGE #,2X,6A,8X,4D.4D,6X,D.3DE,6X,D.3DE
6100      IF Est_std_dev>=1E-2 THEN PRINT CHR$(132);
6120      PRINT USING 6080;File$,Housekeeping(9),Sigmasq,Est_std_dev
6140      IF Est_std_dev>=1E-2 THEN PRINT CHR$(248);"POSSIBLE BAD DATA"
6160      PRINT CHR$(128)
6180      IF Housekeeping(3)=No_measmnts THEN 6260           ! Test No_measmnts.
6200      BEEP
6220      IMAGE "The data file just loaded shows that there were ",K," measurements in the
set,",/,"not ",K,".",/
6240      PRINT USING 6220;Housekeeping(3),No_measmnts
6260      IF Housekeeping(8)=File THEN 6400  ! Test file identification for con-
6280      BEEP                               ! sistency, to avoid false results.
6300      IMAGE "Data in the last file loaded show that the file number is ",K," rather than ",K,".",/
6320      PRINT USING 6300;Housekeeping(8),File
6340 Change3:                          ! To process simulated data, delete the
6360                                   ! following line:
6380      PAUSE                        ! There is a file error.
6400      PRINTER IS Printer
6420      IF Processed AND NOT Reprocess THEN GOTO Next_file
6440      MAT Real_data=(5/32768)*Real_data  ! Convert to volts.
6460      GOSUB Fft_driver
6480      GOSUB Estimation
6500      Processed=1                  ! Data now processed.
6520      GOSUB Housekeeping2          ! Update the array.
6540      ASSIGN #1 TO File$
6560      MAT PRINT #1,17;Housekeeping ! Update the Housekeeping(*) file.
6580      ASSIGN * TO #1
6600      Results(Result_no,1)=Theta(1,1)
6620      Signflag=0                   ! Used for diagnostics.
6640 Next_file:     !
6660    NEXT File
6680    IF No_measmnts=1 THEN 6720     ! Don't do stats if only 1 measmnt.
```

```
6700    GOSUB Statistics

6720    RETURN !
6740 Check_files:! (Data acquisition)  ! Are there enough files left, and
6760                                   ! when Storing, what's the next no?
6780    DIM Cat$(100)[41]
6800    Skip=Return=0
6820    CAT TO Cat$(*),Skip,Return;"DAT"&Msus_data$,1
6840    IF Cat$(1)<>"" THEN 6900
6860    File_no=1
6880    GOTO 7300
6900    FOR File_no=1 TO 100
6920      IF POS(Cat$(File_no),"DAT")=0 THEN 6980
6940      IF VAL(Cat$(File_no)[4,6])=100 THEN 7140
6960    NEXT File_no
6980    IF Storing THEN 7300           ! File adequacy has been checked, by now.
7000    IF File_no-1+No_measmnts<=100 THEN 7300
7020    BEEP
7040    IF 100-File_no+1=0 THEN 7140
7060    PRINT "There are ";100-File_no+1;"files remaining on this disk.  Either re-RUN and reduce"
7080    PRINT "the number of measurements, or use a new disk and CONTinue.  All of the"
7100    PRINT "measurements in a set should be on the same disk, however."
7120    GOTO 7280
7140    PRINT "The highest-numbered data file on this disk is DAT_100.  To store any new data,"
7160    PRINT "some of these data files must be purged, using the program PURDAT.  It will"
7180    PRINT "purge all data files at and beyond a specified file number.",LIN(2),"New files cannot
be written with numbers lower than files already on the"
7200    PRINT "disk.  Attempting to do so will result in a STOP.",LIN(1)
7220    PRINT "If files are deleted, they should be deleted in complete sets, if possible, to "
7240    PRINT "avoid the chance of processing only part of a set at a later date."
7260    STOP
7280    PAUSE
7300    RETURN !

7320 Fft_driver: ! (Data processing)   ! Prepare R(*) & I(*) for Fft:.
7340                                   ! (Fft: is from the hp 9835A Numerical
7360                                   ! Analysis package.  This driver creates
7380                                   ! Meas(*) & Q(*) for use by Estimation
7400                                   ! and Diagnostic.)
7420    MAT Meas=ZER
7440    Counter=0
7460    FOR I=1 TO No_samples/2        ! This loop needs only 4 sec. and retains
7480                                   ! the original data in one array.  It's
7500                                   ! worth the memory.
7520      Counter=Counter+1
7540      R(I)=Real_data(Counter,1)    ! Odd rows of Data(*) go in R(*).
7560      Counter=Counter+1
7580      I(I)=Real_data(Counter,1)    ! Even rows of Data(*) go in I(*).
7600    NEXT I
7620    GOSUB Fft                      ! Do the transform.
7640 Marker1:   !
7660    FOR Counter=1 TO 38
7680      Meas(Counter,1)=R(Pointer(Counter))
7700 Change1:                          ! To process simulated data, remove the
7720                                   ! minus sign (if any) in the next line.
7740      Meas(Counter,2)=-I(Pointer(Counter))
7760      Meas(Counter,7)=Pointer(Counter)-1
7780    NEXT Counter
7800    Meas(39,1)=R(1)                ! DC term
7820    Meas(39,2)=I(1)                ! Max. frequency term
7840    REDIM Jn(-18:18)
7860    FOR Row=2 TO 38                ! Correct the signs of real & imag.
7880                                   ! components of the spectral lines.
7900                                   ! Pointer(Row)-1=harmonic #.
7920                                   ! Jn(Row-20)=Bessel function for
7940                                   ! the kth sideband away from 9960
7960                                   ! Hz (k runs from -18 to 18).
7980      Meas(Row,6)=SGN(Jn(Row-20))
8000      Meas(Row,1)=Meas(Row,1)*Meas(Row,6)
```

```
8020      Meas(Row,2)=Meas(Row,2)*Meas(Row,6)
8040    NEXT Row
8060    DEFAULT ON
8080    FOR Row=1 TO 38
8100                                  ! Magnitude
8120      Meas(Row,3)=SQR(Meas(Row,1)^2+Meas(Row,2)^2)
8140                                  ! Phase
8160      A=Meas(Row,1)
8180      B=Meas(Row,2)
8200      IF A>0 THEN Phase=ATN(B/A)
8220      IF (A<0) AND (B<0) THEN Phase=ATN(B/A)-PI
8240      IF (A<0) AND (B>=0) THEN Phase=ATN(B/A)+PI
8260      IF (A=0) AND (B<0) THEN Phase=-PI/2
8280      IF (A=0) AND (B>0) THEN Phase=PI/2
8300      Meas(Row,4)=Qr(Row,1)=Phase    ! This is in radians, unordered.
8320      Meas(Row,5)=Meas(Row,4)*180/PI ! This is in degrees, unordered here.
8340      IF Meas(Row,5)<0 THEN Meas(Row,5)=Meas(Row,5)+360  ! Place phase
8360                                                         ! angles in 0 to
8380                                                         ! 360 degrees.
8400    NEXT Row
8420    Ordered=0
8440    Check=(ABS(Meas(21,5)-Meas(20,5))+ABS(Meas(20,5)-Meas(19,5)))*.5
8460    ! Don't order the phase angles of the lines if not necessary:
8480    IF (Meas(20,5)+18*Check<180) AND (Meas(20,5)-18*Check>-180) THEN 10180
8500 Order_lines:                     ! Put phase angles for sidebands -7
8520    Ordered=1                     ! through 7 in sequence:
8540    ! Sidebands -7 through 7 have a large signal-to-noise ratio.
8560    ! This routine fits a straight line to the ordered phase angles for side-
8580    ! bands -7 through 7.  It extrapolates phase angles to sidebands -18
8600    ! through 18, to be used for ordering lines outside the original inter-
8620    ! val.  Then, if an angle must be changed, it is incremented (up, if
8640    ! the sideband no. is +, down if -) by 360 degrees.  This continues
8660    ! until the phase angle and its last value have bracketed the value
8680    ! extrapolated.  A comparison is then made of between (the original and
8700    ! extrapolated values), and (the incremented and the extrapolated
8720    ! values).  The closer is the correct phase angle.
8740    !
8760    ! Note that only the measured data is used in the estimation of the
8780    ! bearing angle.  The fitting and extrapolation process is used only
8800    ! to determine the correct number of multiples of 360 degrees to be
8820    ! added to or subtracted from the phase angles of the sidebands.  The
8840    ! fitted values are not used in any other way; they help prevent order-
8860    ! ing errors when a line's signal-to-noise ratio is low, as for lines
8880    ! +8 and -8.
8900    FOR Row=21 TO 27              ! Order lines 1 through 7.
8920      IF Meas(Row,5)>Meas(Row-1,5) THEN 8980
8940      Meas(Row,5)=Meas(Row,5)+360
8960      GOTO 8920
8980    NEXT Row
9000    FOR Row=19 TO 13 STEP -1      ! Order lines -1 through -7.
9020      IF Meas(Row,5)<Meas(Row+1,5) THEN 9080
9040      Meas(Row,5)=Meas(Row,5)-360
9060      GOTO 9020
9080    NEXT Row
9100    REDIM X(-7:7),Y(-7:7)
9120    PLOTTER IS 13,"GRAPHICS"
9140    FOR Row=-7 TO 7
9160      X(Row)=Row                  ! Set up X and Y arrays to do a linear
9180      Y(Row)=Meas(Row+20,5)       ! regression on the 15 lines.
9200    NEXT Row
9220 !  GOSUB Plot_data               ! For diagnostic use.
9240    MAT Xsq=X.X                   ! Squares of the sideband numbers
9260    MAT Ysq=Y.Y                   ! Squares of the phase angles
9280    MAT Xy=X.Y                    ! Products of (sideband times phase)
9300    Mean_y=SUM(Y)/15              ! Mean phase
9320    Slope=SUM(Xy)/280             ! Slope of best-fit straight line
9340    Totalss=SUM(Ysq)-SUM(Y)*SUM(Y)/15  ! Total sum of squares
9360    Regss=SUM(Xy)*SUM(Xy)/280     ! Regression sum of squares
9380    Resss=Regms=Totalss-Regss     ! Residual sum of squares
```

```
9400    Resms=Resss/13                  ! Residual mean square
9420    REDIM Y(-18:18)                 ! Expand Y(*) to accept extrapolation.
9440    FOR Row=-18 TO 18               ! Compute Y(*) using fitted line.  None
9460      Y(Row)=Mean_y+Slope*Row       ! of these values are substituted into
9480    NEXT Row                        ! Meas(*); they are used for ordering.
9500 !  GOSUB Plot_curve                ! For diagnostic use.
9520    FOR Row=28 TO 38                ! Order lines 8 through 18; Row=row in
9540                                    ! Meas(*).
9560      IF Meas(Row,5)>=Y(Row-20) THEN 9840  ! Row-20=sideband number.
9580      Value=Meas(Row,5)             ! Save Meas(Row,5) for comparison.
9600      Meas(Row,5)=Meas(Row,5)+360   ! Add the first 360 degrees and test.
9620      IF Meas(Row,5)>Y(Row-20) THEN 9740   ! Y(sideband) has been bracketed.
9640      Value=Meas(Row,5)             ! Reset Value.
9660      Meas(Row,5)=Meas(Row,5)+360
9680      GOTO 9620                     ! Add another 360 degrees until Y(side-
9700                                    ! band) has been bracketed.  Then pick
9720                                    ! the closer value.
9740      Distance1=ABS(Value-Y(Row-20))        ! Test the previous value.
9760      Distance2=ABS(Meas(Row,5)-Y(Row-20))  ! Test the current value.
9780      Test=MIN(Distance1,Distance2)         ! Select the closer of the two.
9800      IF Test=Distance1 THEN Meas(Row,5)=Value
9820      IF Test=Distance2 THEN Meas(Row,5)=Meas(Row,5)
9840    NEXT Row
9860    FOR Row=12 TO 2 STEP -1         ! Order lines -8 through -18:
9880      IF Meas(Row,5)<=Y(Row-20) THEN 10160
9900      Value=Meas(Row,5)
9920      Meas(Row,5)=Meas(Row,5)-360   ! Subtract the first 360 degrees.
9940      IF Meas(Row,5)<Y(Row-20) THEN 10060
9960      Value=Meas(Row,5)
9980      Meas(Row,5)=Meas(Row,5)-360
10000     GOTO 9940                     ! Repeat subtracting 360 degrees until
10020                                   ! Y(Row-20) has been bracketed, then pick
10040                                   ! the closer value.
10060     Distance1=ABS(Value-Y(Row-20))
10080     Distance2=ABS(Meas(Row,5)-Y(Row-20))
10100     Test=MIN(Distance1,Distance2)
10120     IF Test=Distance1 THEN Meas(Row,5)=Value
10140     IF Test=Distance2 THEN Meas(Row,5)=Meas(Row,5)
10160   NEXT Row
10180   DEFAULT OFF
10200   FOR Row=1 TO 38
10220     Qd(Row,1)=Meas(Row,5)         ! Q(*) in degrees (since ordered).
10240                                   ! Eventually, order Meas(*,4),
10260                                   ! and convert Theta(*) to deg.
10280   NEXT Row
10300   RETURN !

10320 Fft:
10340   K=0
10360   FOR J=1 TO No_samples/2-1
10380     I=2
10400     IF K<No_samples/(2*I) THEN 10480
10420     K=K-No_samples/(2*I)
10440     I=I+I
10460     GOTO 10400
10480     K=K+No_samples/(2*I)
10500     IF K<=J THEN 10640
10520     A=R(J+1)
10540     R(J+1)=R(K+1)
10560     R(K+1)=A
10580     A=I(J+1)
10600     I(J+1)=I(K+1)
10620     I(K+1)=A
10640   NEXT J
10660   G=.5
10680   P=1
10700   FOR I=1 TO 10-1                 ! The "10" is the power of 2 equal to
10720                                   ! No_samples.  See hp original.
10740     G=G+G
```

```
10760     C=1
10780     E=0
10800     Q=SQR((1-P)/2)
10820     P=(1-2*(I=1))*SQR((1+P)/2)
10840     FOR R=1 TO G
10860       FOR J=R TO No_samples/2 STEP G+G
10880         K=J+G
10900         A=C*R(K)+E*I(K)
10920         B=E*R(K)-C*I(K)
10940         R(K)=R(J)-A
10960         I(K)=I(J)+B
10980         R(J)=R(J)+A
11000         I(J)=I(J)-B
11020       NEXT J
11040       A=E*P+C*Q
11060       C=C*P-E*Q
11080       E=A
11100     NEXT R
11120   NEXT I
11140   A=2*PI/No_samples
11160   P=COS(A)
11180   Q=SIN(A)
11200   A=R(1)
11220   R(1)=A+I(1)
11240   I(1)=A-I(1)
11260   R(1)=R(1)/2
11280   I(1)=I(1)/2
11300   C=1
11320   E=0
11340   FOR J=2 TO No_samples/4
11360     A=E*P+C*Q
11380     C=C*P-E*Q
11400     E=A
11420     K=No_samples/2-J+2
11440     A=R(J)+R(K)
11460     B=(I(J)+I(K))*C-(R(J)-R(K))*E
11480     U=I(J)-I(K)
11500     V=(I(J)+I(K))*E+(R(J)-R(K))*C
11520     R(J)=(A+B)/2
11540     I(J)=(U-V)/2
11560     R(K)=(A-B)/2
11580     I(K)=-(U+V)/2
11600   NEXT J
11620   I(No_samples/4+1)=-I(No_samples/4+1)
11640   MAT R=R/(No_samples/2)
11660   MAT I=I/(No_samples/2)
11680   RETURN !

11700 Estimation:!
11720   Bad_file=0
11740   MAT Theta=Xt*Qd
11760   MAT Qr=(180/PI)*Qr              ! Convert to degrees.
11780   IF Theta(1,1)<0 THEN Theta(1,1)=Theta(1,1)+360
11800   Theta1_2=Theta(1,1)+Theta(2,1)
11820   IF Theta1_2>180 THEN Theta1_2=Theta1_2-360
11840   IF Theta1_2>180 THEN 11820      ! Iterate if needed.
11860   IF Theta1_2<=-180 THEN Theta1_2=Theta1_2+360
11880   IF Theta1_2<=-180 THEN 11860    ! Iterate if needed.
11900   REDIM Jn(-18:18)
11920   Sum=(Qr(1,1)-Theta1_2)^2
11940   FOR I=314 TO 350
11960     J=I-332                       ! J=sideband number.
11980     K=I-312                       ! K=harmonic number.
12000     Theta2_3=Theta(3,1)+J*Theta(2,1)
12020     IF Theta2_3>180 THEN Theta2_3=Theta2_3-360
12040     IF Theta2_3>180 THEN 12020
12060     IF Theta2_3<=-180 THEN Theta2_3=Theta2_3+360
12080     IF Theta2_3<=-180 THEN 12060
12100     Sum=Sum+Jn(ABS(J))^2*(Qr(K,1)-Theta2_3) 2
```

```
12120   NEXT I
12140   Sigmasq=No_samples*Sum/35        ! No_samples is fixed at 1024, in this
12160                                    ! program.  The 35 results from using
12180                                    ! 38 lines in this estimate and 3 degrees
12200                                    ! of freedom when estimating Theta(*).
12220   Var=(1+Ck)*Sigmasq/No_samples    ! Ck came from file "Xt____".
12240   Est_std_dev=SQR(Var)
12260   IF File<>File_no THEN 12320
12280   IMAGE "Data file",5X,"Bearing angle",5X,"Sigmasq",5X,"Est. std. dev."
12300   PRINT USING 12280
12320   IMAGE #,2X,6A,8X,4D.4D,6X,D.3DE,6X,D.3DE
12340   IF Est_std_dev>=1E-2 THEN PRINT CHR$(132);
12360   PRINT USING 12320;File$,Theta(1,1),Sigmasq,Est_std_dev
12380   IF Est_std_dev>=1E-2 THEN PRINT CHR$(248);"POSSIBLE BAD DATA"
12400   PRINT CHR$(128)
12420   IF Est_std_dev>=1E-2 THEN Bad_file=1
12440   RETURN !

12460 Xt:                                ! The routine below is used to compute
12480                                    ! and store Xt(*) in file "Xt____".  To
12500                                    ! use this code, lable Xt_dim: must be
12520                                    ! enabled.  In most cases, it is simpler
12540                                    ! to COPY file "Xt____" from an existing
12560                                    ! copy.
12580   Pointer(1)=2                     ! Set up Pointer(*).
12600   FOR Counter=2 TO 38
12620     Pointer(Counter)=313+Counter
12640   NEXT Counter
12660   REDIM Jn(-18:18)
12680   Jn(0)=-.174899073984             ! Jn(0) & Jn(1) are used in the following
12700   Jn(1)=.0903971756613             ! recursion to generate Jn(-18) through
12720   FOR Counter=1 TO 18              ! Jn(18), where n=16.
12740     IF Counter=18 THEN 12780
12760     Jn(Counter+1)=Counter/8*Jn(Counter)-Jn(Counter-1)
12780     Jn(-Counter)=(-1)^Counter*Jn(Counter)
12800   NEXT Counter
12820   Ck=0                             ! Compute the constant Ck.
12840   FOR J=1 TO 18
12860     Ck=Ck+J^2*Jn(J)^2
12880   NEXT J
12900   Ck=1/(2*Ck)
12920   REDIM Jn(1:37)
12940   MAT X=ZER                        ! Compute Xt(*).
12960   MAT V=ZER
12980   X(1,1)=X(1,2)=1
13000   V(1,1)=1
13020   FOR Row=2 TO 38
13040     X(Row,2)=Row-20
13060     X(Row,3)=1
13080     V(Row,Row)=1/(Jn(Row-1)*Jn(Row-1))
13100   NEXT Row
13120   MAT V=V*(2/No_samples)
13140   MAT Xt=TRN(X)
13160   MAT Vi=INV(V)
13180   MAT A=Vi*X
13200   MAT B=Xt*A
13220   MAT C=INV(B)
13240   REDIM A(3,38)                    ! Re-use MAT A.
13260   MAT A=Xt*Vi
13280   MAT Xt=C*A                       ! Re-use MAT Xt.
13300   ON ERROR GOSUB 13440
13320   CREATE "Xt____",1,3*38*8+37*8+38*8+8
13340   ASSIGN #1 TO "Xt____"
13360   PRINT #1,1;Xt(*),Jn(*),Pointer(*),Ck
13380   ASSIGN * TO #1
13400   OFF ERROR
13420   END
13440   IF ERRN=54 THEN RETURN
13460   BEEP
```

```
13480   PRINT ERRM$
13500   STOP!

13520 Meas_print:                       ! Prints Meas(*) for diagnostics.
13540   PRINT CHR$(27)&"&10T";          ! Supress margins on perf. paper.
13560   PRINT "Code dtg: ";Rev$;".  Disk dtg: ";Disk$;".  Filename: ";Filename$
13580   PRINT File$&" Nominal bearing angle=";Housekeeping(2),LIN(1)
13600   IMAGE "Corr",2X,"Real",1X,"Corr",3X,"Imag",X,"Bess",3X,"Line",6X,"Rad-",7X,"Deg-
",3X,"Line",X,"Row",2X,"Row"
13620   PRINT USING 13600
13640   IMAGE "sign",2X,"part",1X,"sign",3X,"part",X,"sign",3X,"ampl",6X,"ians",7X,"rees",3X,"
no.",X," no.",X,"-20"
13660   PRINT USING 13640
13680   PRINT
13700   IMAGE 3D,2D.4D,1X,3D, X,2D.4D,X,3D,X2D.4D,X5D.4D,X7D.2D,2X,4D,X,3D,2X,3D
13720   FOR Row=1 TO 39
13740     IF (Row<>39) AND (Row<>1) THEN 13800
13760     S1=S2=J3=0
13780     GOTO 13880
13800     S1=SGN(Jn(Row-20))*SGN(Meas(Row,1))
13820     S2=SGN(Jn(Row-20))*SGN(Meas(Row,2))
13840     J3=SGN(Jn(Row-20))
13860     IF Signflag THEN S1=S2=0
13880     PRINT USING
13700;S1,Meas(Row,1),S2,Meas(Row,2),J3,Meas(Row,3),Meas(Row,4),Meas(Row,5),Meas(Row,7),Row,Row-20
13900     IF (Row=1) OR (Row=4) OR (Row=9) OR (Row=14) OR (Row=19) OR (Row=20) OR (Row=25) OR (Row=30)
OR (Row=35) THEN PRINT
13920   NEXT Row
13940   Signflag=1                      ! Prints CSGN's only first pass.
13960                                   ! They are meaningless after that.
13961   PRINT "Theta(*):"
13962   MAT PRINT Theta
13980   PRINT "&136T";                 ! Restore margins.
14000   RETURN !

14020 Plot:                             ! Used for diagnostics.
14040   PRINT "&10T";                  ! Supress auto feed at perforations.
14060   INPUT "Do you want a GRAPHICS dump? (Y or N)",Dump$
14080   Dump$=UPC$(Dump$)
14100   GCLEAR                          ! Kill this line for overlaid plots.
14120   LINE TYPE 1
14140   FRAME
14160   GRAPHICS
14180   Rmax=Dmax=-1E99
14200   Rmin=Dmin=1E99
14220   FOR Row=2 TO 38
14240     Rmax=MAX(Rmax,Meas(Row,4))
14260     Rmin=MIN(Rmin,Meas(Row,4))
14280     Dmax=MAX(Dmax,Meas(Row,5))
14300     Dmin=MIN(Dmin,Meas(Row,5))
14320   NEXT Row
14340   SCALE 2,38,Rmin,Rmax
14360   FOR Row=2 TO 38
14380     PLOT Row,Meas(Row,4)
14400   NEXT Row
14420   SCALE 2,38,Dmin,Dmax
14440   MOVE 2,Meas(2,5)
14460   LINE TYPE 6
14480   FOR Row=2 TO 38
14500     PLOT Row,Meas(Row,5)
14520   NEXT Row
14540   LINE TYPE 3
14560   MOVE 12,Dmin
14580   DRAW 12,Dmax
14600   MOVE 20,Dmax
14620   DRAW 20,Dmin
14640   MOVE 28,Dmin
14660   DRAW 28,Dmax
14680   IF POS(Dump$,"Y") THEN Graph_printer=0
```

```
14700   IF NOT POS(Dump$,"Y") THEN Graph_printer=16
14720   PRINTER IS Graph_printer
14740   PRINT File$,"Code revision dtg:";Rev$,
14760   IF Ordered THEN PRINT "Ordered angles."
14780   IF NOT Ordered THEN PRINT "Angles not ordered."
14800   PRINT "Rmin=",Rmin,"Rmax=",Rmax,LIN(1);"Dmin=",Dmin,"Dmax=",Dmax
14820   IF Sigmasq THEN 14880          ! False values for the variance and
14840   GOSUB Estimation               ! est. s. d. will result if Estimation
14860                                  ! has already be done once.
14880   IF POS(Dump$,"Y") THEN DUMP GRAPHICS
14900   PRINTER IS Printer             ! Restore printer designation.
14920   PRINT "&l36T";                ! Restore margins at perforations.
14921   EXIT GRAPHICS
14940   STOP!LFLF
14960 Plot_curve:!
14980   GRAPHICS
15000   FRAME
15020   SCALE -20,20,Meas(2,5),Meas(38,5)
15040   AXES 1,10,0,0
15060   MOVE -18,Y(-18)
15080   FOR X=-18 TO 18
15100     DRAW X,Y(X)
15120   NEXT X
15140   PENUP
15160   LORG 1
15180   CSIZE 3.3
15200   MOVE .5,-15
15220   IMAGE 22A,D.DDE
15240   LABEL USING 15220
15260   LABEL USING "5A,14X,4D.4D";"Mean=",Mean_y
15280   LABEL USING "6A,13X,4D.4D";"Slope=",Slope
15300   LABEL USING 15220;"Total sum of sq.=",Totalss
15320   LABEL USING 15220;"Regression sum of sq.=",Regss
15340   LABEL USING 15220;"Residual sum of sq.=",Resss
15360   LABEL USING 15220;"Residual mean sq.=",Resms
15380   RETURN !

15400 Plot_data:!
15420   GRAPHICS
15440   LORG 5
15460   CSIZE 1.7
15480   FOR Row=-7 TO 7
15500     MOVE Row,Y(Row)
15520     LABEL USING "2D";Row
15540   NEXT Row
15560   PENUP
15580   RETURN !
15600 File_list:                       ! Checks DAT files for bearing angle.
15620   PRINT "Code dtg: ";Rev$;".  Disk dtg: ";Disk$;".  Filename: ";Filename$
15640   ON ERROR GOTO 15860
15660   FOR N=1 TO 100
15680     IF N<10 THEN File$="DAT00"&VAL$(N)
15700     IF N>=10 THEN File$="DAT0"&VAL$(N)
15720     IF N=100 THEN File$="DAT"&VAL$(N)
15740     ASSIGN #1 TO File$
15760     MAT READ #1;Integer_data,Housekeeping
15780     PRINT File$;": Nominal bearing angle=";Housekeeping(2)
15800     ASSIGN * TO #1
15820   NEXT N
15840   END
15860   IF ERRN=56 THEN 15940
15880   PRINT ERRM$
15900   OFF ERROR
15920   END
15940   PRINT File$;" not yet assigned."
15960   OFF ERROR
15980   STOP!LFLF

16000 Re_store:                        ! Called by key 20.  Assures that program
```

```
16020   RE-STORE "VOR1"                 ! is RE_STORE'd in the file identified by
16040   STOP!LFLF                       ! Re_store:.

16240 Housekeeping1:                    ! Used when data is first stored.
16260   MAT Housekeeping=ZER
16280   Housekeeping(1)=Time_no         ! Date-time-group data were stored.
16300   Housekeeping(2)=Nom_bearing     ! Nominal bearing angle, deg.
16320   Housekeeping(3)=No_measmnts     ! Number of measurements in the set.
16340   Housekeeping(4)=Measurement     ! Number of this measurement in the set.
16360   Housekeeping(5)=No_overloads    ! Number of ADC overloads.
16380   Housekeeping(6)=VAL(Rev$)       ! Program revision date-time-group.
16400   Housekeeping(7)=VAL(Disk$)      ! Disk serial number.
16420   Housekeeping(8)=File_no         ! Data file number (1-100).
16440   RETURN !

16460 Housekeeping2:                    ! Used after data is processed.
16480   Housekeeping(9)=Theta(1,1)      ! Computed bearing angle.
16500   Housekeeping(10)=Theta(2,1)     ! See analysis.
16520   Housekeeping(11)=Theta(3,1)     ! See analysis.
16540   Housekeeping(12)=Sigmasq        ! See analysis.
16560   Housekeeping(13)=Est_std_dev    ! Estimated s. d. for a large set.
16580   Housekeeping(14)=Processed      ! If =1, data has been processed.
16600   Housekeeping(15)=Bad_file       ! Flags files with excessive est. s. d.
16620   RETURN !

32000 Disk_dtg:!
32010 Disk$="8204231411"
32020 RETURN
```

Appendix B. Test-Data Listings

These data lists are abstracted from the "housekeeping" files of the permanent magnetic records maintained on every measurement. The result from the processing of the raw data taken by the phasemeter ADC. Each row represents a single measurement of 1024 time samples at a given bearing angle. Each block of five rows represents (usually) a set of five measurements at a given angle, taken over a period of about 32.5 min.

The columns present the following information for each measurement:

1.	RUN DTG:	This is a 10-digit numerical representation of the date and time in the form YYMMDDHHMM, where the first pair of digits is the the last two digits of the calendar year, the next two give the month, then the day, hour, and minute. This results in a unique number that identifies every measurement. It comes from a real-time clock in the measurement computer.
2.	BEARING:	The nominal bearing angle set on the front panel switches of the standard generator. The number is not used in the estimation of the bearing angle, only in the calculation of the deviation between the setting and Thetal, the measured angle.
3.	SET:	The number of measurements in the set.
4.	NO.:	The number of the measurement in the set.
5.	DISK DTG:	This is another date-time group having the same interpretation as the RUN DTG. Is is recorded on the disk when it is first initialized, and becomes a unique serial number identification for that disk. It is recorded in every data file on that disk and allows tracing processed results back to the original raw data, for further study.
6.	FILE:	The file number of a measurement. It ranges from 001 to 100, and the corresponding data file names are DAT001 to DAT100. The file names (and numbers) are computed automatically by the software and allow tracing processed data back to the original file.
7.	THETA1:	The estimated VOR bearing angle. It is stored as a full-precision result, without rounding.
8.	THETA2:	The second angle measured by the phasemeter. See the equation for the model for interpretation. It is a result that is not directly involved in the final answer, but is useful for detecting certain system instabilities. Note that it does not change appreciably from measurement to measurement or from month to month.
9.	THETA3:	Similar to THETA2; see above.
10.	SIGMA SQUARED:	An estimate of the mean square error in the voltage measurements in a single bearing angle measurement.
11.	ST.DEV. THETA1	An estimate of the standard deviation of THETA1, again based on a single measurement. It is not the standard deviation for the set of measurements. Usually, the standard deviation for the set is one-third to one-tenth this estimate, which is therefore conservative.

RUN DTG	BEARING	SET	NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820304083015	000.00	005	001	8112141105	001	3.59999182928E+02	9.00715106425E+01	1.13729996347E+02	7.24508222509E-04	8.44457278895E-04
820304083640	000.00	005	002	8112141105	002	3.59999728996E+02	9.00715036362E+01	1.13729666121E+02	7.36721339683E-04	8.51545089721E-04
820304084305	000.00	005	003	8112141105	003	3.59999654954E+02	9.00715166111E+01	1.13729615161E+02	7.94788776240E-04	8.84467515567E-04
820304084930	000.00	005	004	8112141105	004	9.70970200000E-05	9.00714975626E+01	1.13729492303E+02	7.11504235457E-04	8.36844505496E-04
820304085555	000.00	005	005	8112141105	005	3.59999212454E+02	9.00715148129E+01	1.13729816361E+02	7.66918616703E-04	8.68821709628E-04
820304091116	090.00	005	001	8112141105	006	9.00008812189E+01	9.00715919969E+01	1.13727455174E+02	2.29364804387E-03	1.50251706293E-03
820304091741	090.00	005	002	8112141105	007	9.00006759562E+01	9.00715877268E+01	1.13727921958E+02	2.23306054760E-03	1.48253950078E-03
820304092407	090.00	005	003	8112141105	008	9.00004678404E+01	9.00715997094E+01	1.13727909860E+02	2.25061481523E-03	1.48835527445E-03
820304093033	090.00	005	004	8112141105	009	9.00003018754E+01	9.00716011692E+01	1.13728183930E+02	2.24608767623E-03	1.48685759856E-03
820304093659	090.00	005	005	8112141105	005	9.00002299786E+01	9.00715740880E+01	1.13728218093E+02	2.27596381767E-03	1.49671358622E-03
820304095323	180.00	005	001	8112141105	011	1.79998174215E+02	9.00717522171E+01	1.13731830024E+02	8.52209885526E-04	9.15860456093E-04
820304095948	180.00	005	002	8112141105	012	1.79997315802E+02	9.00717859512E+01	1.13732136586E+02	7.81732049957E-04	8.77172450099E-04
820304100614	180.00	005	003	8112141105	013	1.79998065186E+02	9.00717600986E+01	1.13732457109E+02	8.72095263023E-04	9.26484137154E-04
820304101241	180.00	005	004	8112141105	014	1.79998239415E+02	9.00717583638E+01	1.13732974343E+02	8.23710079180E-04	9.00416022036E-04
820304101907	180.00	005	005	8112141105	015	1.79998055062E+02	9.00717755940E+01	1.13733030671E+02	8.44642699220E-04	9.11785204036E-04
820304103423	270.00	005	001	8112141105	016	2.69998961453E+02	9.00714893883E+01	1.13734103412E+02	2.30767911595E-03	1.50710577525E-03
820304104049	270.00	005	002	8112141105	017	2.69999136847E+02	9.00715040628E+01	1.13734766431E+02	2.48599735312E-03	1.56425068962E-03
820304104715	270.00	005	003	8112141105	018	2.69998968207E+02	9.00715117778E+01	1.13734897103E+02	2.18400764518E-03	1.46616585548E-03
820304105341	270.00	005	004	8112141105	019	2.69998838830E+02	9.00715486075E+01	1.13734834732E+02	2.39031293189E-03	1.53385181546E-03
820304110007	270.00	005	005	8112141105	020	2.69999825633E+02	9.00715194598E+01	1.13734830513E+02	2.45414012679E-03	1.55419569765E-03
820304112115	030.00	005	001	8112141105	021	3.00011142708E+01	9.00714817679E+01	1.13732308275E+02	3.11249825854E-03	1.75029230198E-03
820304112741	030.00	005	002	8112141105	022	3.00012533277E+01	9.00714822468E+01	1.13732418407E+02	3.18884960097E-03	1.77163006793E-03
820304113407	030.00	005	003	8112141105	023	3.00009545337E+01	9.00715026798E+01	1.13732275815E+02	3.19673232989E-03	1.77381842137E-03
820304114033	030.00	005	004	8112141105	024	3.00012389070E+01	9.00715106966E+01	1.13732585795E+02	3.25782979506E-03	1.79068922189E-03
820304114659	030.00	005	005	8112141105	025	3.00008640623E+01	9.00714999808E+01	1.13732620356E+02	3.25082409911E-03	1.78876282049E-03
820304120532	120.00	005	001	8112141105	026	1.19998746707E+02	9.00716333272E+01	1.13733265757E+02	2.14778787905E-03	1.45395751904E-03
820304121158	120.00	005	002	8112141105	027	1.19998536764E+02	9.00716080283E+01	1.13733583667E+02	2.08683658100E-03	1.43317836887E-03
820304121824	120.00	005	003	8112141105	028	1.19998657236E+02	9.00715925187E+01	1.13733790482E+02	2.16110268565E-03	1.45845732381E-03
820304122451	120.00	005	004	8112141105	029	1.19999146167E+02	9.00716125962E+01	1.13733341891E+02	2.04783978564E-03	1.41972428858E-03
820304123117	120.00	005	005	8112141105	030	1.19998244875E+02	9.00716058523E+01	1.13733441942E+02	2.13607917607E-03	1.44998896561E-03
820304130755	210.00	005	001	8112141105	031	2.09998201362E+02	9.00716459419E+01	1.13733671739E+02	2.30650383891E-03	1.50672194966E-03
820304131422	210.00	005	002	8112141105	032	2.09998023103E+02	9.00716362294E+01	1.13733788593E+02	2.20895289981E-03	1.47451519395E-03
820304132048	210.00	005	003	8112141105	033	2.09997720841E+02	9.00716188874E+01	1.13734196510E+02	2.32232234286E-03	1.51187983437E-03
820304132715	210.00	005	004	8112141105	034	2.09998337193E+02	9.00716373577E+01	1.13734614430E+02	2.25959123026E-03	1.49132041969E-03
820304133342	210.00	005	005	8112141105	035	2.09997863702E+02	9.00716453172E+01	1.13734736319E+02	2.19716791315E-03	1.47057659004E-03
820304134917	300.00	005	001	8112141105	036	3.00000036996E+02	9.00714919290E+01	1.13735091146E+02	2.71039928499E-03	1.63332519438E-03
820304135543	300.00	005	002	8112141105	037	3.00000286153E+02	9.00714799277E+01	1.13735235778E+02	2.61121169007E-03	1.60316072525E-03
820304140210	300.00	005	003	8112141105	038	3.00000520786E+02	9.00715072249E+01	1.13735574840E+02	2.63695160353E-03	1.61104289433E-03
820304140837	300.00	005	004	8112141105	039	2.99999835903E+02	9.00714857640E+01	1.13735684587E+02	2.65532777223E-03	1.61664659941E-03
820304141504	300.00	005	005	8112141105	040	3.00000431476E+02	9.00714967313E+01	1.13735952403E+02	2.72416447342E-03	1.63746749097E-03
820304144955	060.00	005	001	8112141105	041	5.99998191414E+01	9.00716786668E+01	1.13736901973E+02	2.07773448418E-03	1.43004942620E-03
820304145621	060.00	005	002	8112141105	042	5.99993445008E+01	9.00717181353E+01	1.13737085398E+02	1.98628962547E-03	1.39822579950E-03
820304150248	060.00	005	003	8112141105	043	5.99777142766E+01	9.00742351935E+01	1.13714535205E+02	1.44142173327E+00	3.76661782332E-02
820304150915	060.00	005	004	8112141105	044	5.99995431089E+01	9.00716814507E+01	1.13737368760E+02	2.02755533419E-03	1.41267539788E-03
820304151542	060.00	005	005	8112141105	045	5.99992361946E+01	9.00717131640E+01	1.13737845503E+02	1.95847550762E-03	1.38840157130E-03

RUN DTG	BEARING	SET	NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820304153050	150.00	005	001	8112141105	046	1.50001124469E+02	9.00715579724E+01	1.13734668096E+02	1.95805826028E-03	1.38825366601E-03
820304153717	150.00	005	002	8112141105	047	1.50001320953E+02	9.00715458637E+01	1.13734432672E+02	2.07671589742E-03	1.42969885017E-03
820304154345	150.00	005	003	8112141105	048	1.50001194706E+02	9.00715443963E+01	1.13734601801E+02	2.07094184807E-03	1.42770991710E-03
820304155013	150.00	005	004	8112141105	049	1.50000735042E+02	9.00715455856E+01	1.13734659466E+02	1.94812350418E-03	1.38472734081E-03
820304155640	150.00	005	005	8112141105	050	1.50001234809E+02	9.00715719320E+01	1.13734287570E+02	2.00263889292E-03	1.40396844629E-03
820305070010	150.00	005	001	8112141105	999	1.50007076500E+02	9.00665998615E+01	1.13493027584E+02	2.08900413187E-02	4.53446102797E-03
820305070635	150.00	005	002	8112141105	052	1.50000355096E+02	9.00715916814E+01	1.13725634316E+02	2.24386141808E-03	1.48612055042E-03
820305071301	150.00	005	003	8112141105	053	1.50001190330E+02	9.00716169087E+01	1.13725048309E+02	2.06148363609E-03	1.42444593446E-03
820305071926	150.00	005	004	8112141105	054	1.50000984591E+02	9.00716127286E+01	1.13724348964E+02	2.08663270531E-03	1.43310835919E-03
820305072551	150.00	005	005	8112141105	055	1.50000996280E+02	9.00716097887E+01	1.13724115144E+02	2.09370246090E-03	1.43553407559E-03
820305074100	240.00	005	001	8112141105	056	2.40000124044E+02	9.00716910650E+01	1.13725551921E+02	2.11287526494E-03	1.44209195358E-03
820305074726	240.00	005	002	8112141105	057	2.39999629792E+02	9.00716745871E+01	1.13725700820E+02	2.12410896798E-03	1.44592051766E-03
820305075353	240.00	005	003	8112141105	058	2.39999018802E+02	9.00716605521E+01	1.13725112053E+02	2.22363965060E-03	1.47940890635E-03
820305080020	240.00	005	004	8112141105	059	2.39999628439E+02	9.00717009964E+01	1.13724975334E+02	2.17097625669E-03	1.46178520173E-03
820305080647	240.00	005	005	8112141105	060	2.40000077606E+02	9.00716773284E+01	1.13724840634E+02	2.06200046594E-03	1.42462448308E-03
820305082157	330.00	005	001	8112141105	061	3.29999078532E+02	9.00715192057E+01	1.13723359677E+02	4.89666355417E-03	2.19581036348E-03
820305082825	330.00	005	002	8112141105	062	3.29998836395E+02	9.00715195344E+01	1.13723484539E+02	5.12273257060E-03	2.24546797928E-03
820305083452	330.00	005	003	8112141105	063	3.29999187918E+02	9.00715347950E+01	1.13723318160E+02	5.02265642509E-03	2.22342640926E-03
820305084120	330.00	005	004	8112141105	064	3.29999381373E+02	9.00714934865E+01	1.13723210323E+02	4.79818726683E-03	2.17317460366E-03
820305084748	330.00	005	005	8112141105	065	3.29998876926E+02	9.00715227141E+01	1.13723396831E+02	4.90279707869E-03	2.19673658775E-03
820305091523	360.00	005	001	8112141105	066	3.59999638196E+02	9.00715330164E+01	1.13723302029E+02	7.62628564674E-04	8.66388258807E-04
820305092150	360.00	005	002	8112141105	067	3.59999184998E+02	9.00715326419E+01	1.13723496324E+02	7.06301234386E-04	8.33779104114E-04
820305092818	360.00	005	003	8112141105	068	3.59999653552E+02	9.00715240242E+01	1.13723425374E+02	7.29278680726E-04	8.47232843440E-04
820305093445	360.00	005	004	8112141105	069	3.59999774913E+02	9.00715350989E+01	1.13723880449E+02	8.01021050280E-04	8.87928485515E-04
820305094112	360.00	005	005	8112141105	070	3.59999797012E+02	9.00715516379E+01	1.13723846807E+02	7.31421623709E-04	8.48476702573E-04

RUN DTG	BEARING	SET NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820309065930	360.00	005 001	8203080829	001	3.59999338770E+02	9.00716115427E+01	1.13724048802E+02	8.69719569011E-04	9.25221348596E-04
820309070555	360.00	005 002	8203080829	002	3.59999727416E+02	9.00716348117E+01	1.13723101444E+02	8.57999773166E-04	9.18966353505E-04
820309071219	360.00	005 003	8203080829	003	3.59999115750E+02	9.00716488039E+01	1.13722367647E+02	9.19943172066E-04	9.51560759631E-04
820309071844	360.00	005 004	8203080829	004	3.59999620376E+02	9.00716231903E+01	1.13721428061E+02	9.21465606020E-04	9.52347813431E-04
820309072508	360.00	005 005	8203080829	005	3.59999193385E+02	9.00716165741E+01	1.13721305540E+02	7.85657172829E-04	8.79371860097E-04
820309074012	330.00	005 001	8203080829	006	3.29999475487E+02	9.00715507920E+01	1.13720733493E+02	5.46119412717E-03	2.31846119544E-03
820309074638	330.00	005 002	8203080829	007	3.29998499034E+02	9.00715750093E+01	1.13720891298E+02	5.71747657371E-03	2.37223779600E-03
820309075304	330.00	005 003	8203080829	008	3.29999523704E+02	9.00715783290E+01	1.13720485056E+02	5.51462763314E-03	2.32977575002E-03
820309075930	330.00	005 004	8203080829	009	3.29999356007E+02	9.00715827580E+01	1.13719642531E+02	5.55953452183E-03	2.33924246815E-03
820309080555	330.00	005 005	8203080829	010	3.29999421163E+02	9.00715629608E+01	1.13718865656E+02	5.64971995666E-03	2.35813945579E-03
820309082051	240.00	005 001	8203080829	999	2.40000961212E+02	9.00716491887E+01	1.13719718365E+02	2.77738114163E-03	1.65338413219E-03
820309082717	240.00	005 002	8203080829	012	2.39999315866E+02	9.00715816002E+01	1.13720044550E+02	2.44267284501E-03	1.55056035754E-03
820309083343	240.00	005 003	8203080829	013	2.39999320263E+02	9.00716065753E+01	1.13719722949E+02	2.47997391687E-03	1.56235449319E-03
820309084009	240.00	005 004	8203080829	014	2.39999137910E+02	9.00715965544E+01	1.13720072454E+02	2.48268673837E-03	1.56320878247E-03
820309084636	240.00	005 005	8203080829	999	2.40002209179E+02	9.00716475696E+01	1.13719535869E+02	2.55193427322E-03	1.58485949648E-03
820309090133	150.00	005 001	8203080829	016	1.49999824316E+02	9.00714787909E+01	1.13720026310E+02	2.26912997985E-03	1.49446487138E-03
820309090759	150.00	005 002	8203080829	017	1.50000384304E+02	9.00714726052E+01	1.13719235639E+02	2.35913756170E-03	1.52381644747E-03
820309091425	150.00	005 003	8203080829	018	1.49999960063E+02	9.00714688886E+01	1.13718524040E+02	2.23744200776E-03	1.48399322417E-03
820309092051	150.00	005 004	8203080829	019	1.50001237374E+02	9.00714503852E+01	1.13718082246E+02	2.20121979866E-03	1.47193194007E-03
820309092717	150.00	005 005	8203080829	020	1.50000596409E+02	9.00714843737E+01	1.13717084219E+02	2.18039611327E-03	1.46495310887E-03
820309094217	060.00	005 001	8203080829	021	5.99995565887E+01	9.00716901332E+01	1.13718122414E+02	2.53380043961E-03	1.57921851736E-03
820309094843	060.00	005 002	8203080829	022	5.99990001540E+01	9.00716940820E+01	1.13717397205E+02	2.37321633655E-03	1.52835657194E-03
820309095509	060.00	005 003	8203080829	023	5.99987719920E+01	9.00716568160E+01	1.13716909225E+02	2.32893920068E-03	1.51403215798E-03
820309100136	060.00	005 004	8203080829	024	5.99990989365E+01	9.00716629211E+01	1.13716570776E+02	2.41900024405E-03	1.54302861587E-03
820309100802	060.00	005 005	8203080829	025	5.99992051131E+01	9.00716492189E+01	1.13716449247E+02	2.31799129722E-03	1.51046937638E-03
820309102318	300.00	005 001	8203080829	026	3.00000973501E+02	9.00714687742E+01	1.13715971636E+02	3.24261822203E-03	1.78650375599E-03
820309102945	300.00	005 002	8203080829	027	3.00001009933E+02	9.00714968591E+01	1.13715535740E+02	3.15435877491E-03	1.76202298061E-03
820309103612	300.00	005 003	8203080829	028	3.00000505607E+02	9.00714585585E+01	1.13715119042E+02	3.29203891011E-03	1.80006631111E-03
820309104239	300.00	005 004	8203080829	029	3.00000551691E+02	9.00714616566E+01	1.13715230361E+02	3.25449147291E-03	1.78977152050E-03
820309104906	300.00	005 005	8203080829	030	3.00000799783E+02	9.00714573504E+01	1.13715734333E+02	3.26939786863E-03	1.79386564140E-03
820309110416	210.00	005 001	8203080829	031	2.09998119479E+02	9.00715039834E+01	1.13717484465E+02	2.54514249023E-03	1.58274909862E-03
820309111042	210.00	005 002	8203080829	032	2.09999058114E+02	9.00715071725E+01	1.13717593960E+02	2.49540281944E-03	1.56720697146E-03
820309111709	210.00	005 003	8203080829	033	2.09998016818E+02	9.00715542170E+01	1.13717164056E+02	2.69513172771E-03	1.62871847419E-03
820309112336	210.00	005 004	8203080829	034	2.09997996979E+02	9.00715614345E+01	1.13716543075E+02	2.60490232100E-03	1.60122272648E-03
820309113003	210.00	005 005	8203080829	035	2.09998279848E+02	9.00715514140E+01	1.13716676922E+02	2.55895154377E-03	1.58703701198E-03
820309114503	120.00	005 001	8203080829	036	1.19999777974E+02	9.00715212877E+01	1.13716637030E+02	2.65232400307E-03	1.61573194633E-03
820309115129	120.00	005 002	8203080829	037	1.19990079429E+02	9.00715260766E+01	1.13716029035E+02	2.63566690467E-03	1.61065040378E-03
820309115757	120.00	005 003	8203080829	038	1.19998831057E+02	9.00715165554E+01	1.13716431249E+02	2.84079811129E-03	1.67215375883E-03
820309120424	120.00	005 004	8203080829	039	1.19998488988E+02	9.00715059250E+01	1.13716707329E+02	2.76174996580E-03	1.64872492223E-03
820309121051	120.00	005 005	8203080829	040	1.19998896873E+02	9.00715188491E+01	1.13717330355E+02	2.72876593875E-03	1.63884985444E-03
820309122549	030.00	005 001	8203080829	041	3.00014283536E+01	9.00714527139E+01	1.13715726177E+02	3.81531994494E-03	1.93785601621E-03
820309123216	030.00	005 002	8203080829	042	3.00011004494E+01	9.00714456737E+01	1.13715275050E+02	4.16539111963E-03	2.02480832411E-03
820309123843	030.00	005 003	8203080829	043	3.00013599421E+01	9.00714905308E+01	1.13715739584E+02	4.09810842549E-03	2.00838859471E-03
820309124511	030.00	005 004	8203080829	044	3.00011440268E+01	9.00714657725E+01	1.13715326183E+02	3.99166007389E-03	1.98213303266E-03
820309125139	030.00	005 005	8203080829	045	3.00016808256E+01	9.00714487603E+01	1.13716328412E+02	4.08659543389E-03	2.00556548449E-03

RUN DTG	BEARING	SET NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820309130639	270.00	005 001	8203080829	999	2.70001277167E+02	9.00715101680E+01	1.13716552089E+02	2.90078602854E-03	1.68971660367E-03
820309131306	270.00	005 002	8203080829	999	2.70010682567E+02	9.00715469265E+01	1.13714411760E+02	3.58164999051E-03	1.87757630433E-03
820309131934	270.00	005 003	8203080829	048	2.69999970098E+02	9.00714814430E+01	1.13713588876E+02	2.59808391158E-03	1.59912572926E-03
820309132602	270.00	005 004	8203080829	049	2.69999557951E+02	9.00714880545E+01	1.13713326606E+02	2.56178190263E-03	1.58791445002E-03
820309133229	270.00	005 005	8203080829	050	2.69999425630E+02	9.00715228143E+01	1.13713413221E+02	2.46272048686E-03	1.55691027833E-03
820309134742	180.00	005 001	8203080829	051	1.79997779210E+02	9.00716581988E+01	1.13721676471E+02	8.55576957086E-04	9.17667949627E-04
820309135409	180.00	005 002	8203080829	052	1.79998049065E+02	9.00716367402E+01	1.13722302190E+02	8.15970453951E-04	8.96175859083E-04
820309140037	180.00	005 003	8203080829	053	1.79997980897E+02	9.00716658289E+01	1.13721533675E+02	8.03469171449E-04	8.89284316406E-04
820309140705	180.00	005 004	8203080829	054	1.79998342036E+02	9.00716386570E+01	1.13721288538E+02	8.18181953529E-04	8.97389476239E-04
820309141333	180.00	005 005	8203080829	055	1.79997791568E+02	9.00716120956E+01	1.13721800723E+02	8.06070514251E-04	8.90722743682E-04
820309143020	090.00	005 001	8203080829	056	9.00007268662E+01	9.00715325393E+01	1.13719151030E+02	2.40547423692E-03	1.53870859287E-03
820309143647	090.00	005 002	8203080829	057	9.00003553386E+01	9.00715633504E+01	1.13719301667E+02	2.60274956299E-03	1.60056094398E-03
820309144315	090.00	005 003	8203080829	058	9.00003020097E+01	9.00715597922E+01	1.13719261810E+02	2.74196259960E-03	1.64280791841E-03
820309144943	090.00	005 004	8203080829	059	8.99996947623E+01	9.00715583982E+01	1.13718950705E+02	2.78709778075E-03	1.65627378068E-03
820309145612	090.00	005 005	8203080829	060	9.00001027493E+01	9.00715320560E+01	1.13718294591E+02	2.54275941557E-03	1.58200794315E-03
820309151120	000.00	005 001	8203080829	061	3.59999285970E+02	9.00716163842E+01	1.13720838224E+02	7.90326651194E-04	8.81981220050E-04
820309151748	000.00	005 002	8203080829	062	3.59999184748E+02	9.00716169029E+01	1.13721049858E+02	8.23750135506E-04	9.00437915005E-04
820309152417	000.00	005 003	8203080829	063	3.59999224073E+02	9.00716161094E+01	1.13720962852E+02	7.58333753669E-04	8.63945242932E-04
820309153046	000.00	005 004	8203080829	064	3.59998210094E+02	9.00716204968E+01	1.13720793146E+02	7.71758947971E-04	8.71559138467E-04
820309153714	000.00	005 005	8203080829	065	3.59999535769E+02	9.00715790130E+01	1.13720576326E+02	8.16656468437E-04	8.96552502903E-04

RUN DTG	BEARING	SET NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820312080100	360.00	005 001	8203120745	001	3.59999391293E+02	9.00716376903E+01	1.13731541875E+02	7.18933362486E-04	8.41202089987E-04
820312080726	360.00	005 002	8203120745	002	3.59999739277E+02	9.00716550273E+01	1.13732204040E+02	6.64928248406E-04	8.08990489329E-04
820312081351	360.00	005 003	8203120745	003	3.59999385402E+02	9.00716734655E+01	1.13732656805E+02	7.81144963026E-04	8.76843006521E-04
820312082017	360.00	005 004	8203120745	004	3.59999378797E+02	9.00716587677E+01	1.13733143464E+02	7.72127472757E-04	8.71767203958E-04
820312082643	360.00	005 005	8203120745	005	3.59998996674E+02	9.00716877192E+01	1.13733222913E+02	7.74533844254E-04	8.73124598882E-04
820312084148	330.00	005 001	8203120745	006	3.29999374060E+02	9.00716548137E+01	1.13732989440E+02	6.03021054806E-03	2.43625230023E-03
820312084814	330.00	005 002	8203120745	007	3.29999020193E+02	9.00716511011E+01	1.13732277235E+02	5.91469807303E-03	2.41280550036E-03
820312085440	330.00	005 003	8203120745	008	3.29999191167E+02	9.00716303577E+01	1.13732089825E+02	6.08912057517E-03	2.44812343418E-03
820312090106	330.00	005 004	8203120745	009	3.29999829794E+02	9.00716352266E+01	1.13732617464E+02	5.93528530863E-03	2.41700096776E-03
820312090732	330.00	005 005	8203120745	010	3.29999286027E+02	9.00716343866E+01	1.13732942777E+02	6.07269679617E-03	2.44481962483E-03
820312092222	240.00	005 001	8203120745	011	2.40000029624E+02	9.00716745935E+01	1.13734668639E+02	2.74763247123E-03	1.64450555280E-03
820312092848	240.00	005 002	8203120745	012	2.40000127144E+02	9.00716753193E+01	1.13735360600E+02	2.74366610098E-03	1.64331815355E-03
820312093515	240.00	005 003	8203120745	013	2.40000294924E+02	9.00716918747E+01	1.13735262542E+02	2.58974421015E-03	1.59655711504E-03
820312094141	240.00	005 004	8203120745	014	2.40000425636E+02	9.00716797432E+01	1.13734877123E+02	2.60333274811E-03	1.60074024882E-03
820312094807	240.00	005 005	8203120745	015	2.40000806941E+02	9.00716616455E+01	1.13735312107E+02	2.86728688123E-03	1.67993159467E-03
820312101014	150.00	005 001	8203120745	016	1.50000105030E+02	9.00715443942E+01	1.13732923629E+02	2.82190198283E-03	1.66658314974E-03
820312101640	150.00	005 002	8203120745	017	1.50000224772E+02	9.00715387449E+01	1.13732830359E+02	2.75992339810E-03	1.64817961472E-03
820312102306	150.00	005 003	8203120745	018	1.50000478954E+02	9.00715071995E+01	1.13732417508E+02	2.70145634202E-03	1.63062839568E-03
820312102932	150.00	005 004	8203120745	019	1.50000790007E+02	9.00715328816E+01	1.13731061858E+02	3.22271487563E-03	1.78101249366E-03
820312103558	150.00	005 005	8203120745	020	1.49953182276E+02	9.00716139706E+01	1.13753552333E+02	1.51484783516E+00	3.86136209892E-02
820312105242	060.00	005 001	8203120745	999	6.00016979777E+01	9.00717466479E+01	1.13733424691E+02	3.09976247874E-03	1.74670769163E-03
820312105908	060.00	005 002	8203120745	022	5.99995646227E+01	9.00717464369E+01	1.13732900178E+02	2.88369380526E-03	1.68473111326E-03
820312110534	060.00	005 003	8203120745	023	5.99986441119E+01	9.00717529185E+01	1.13733262576E+02	2.78103292579E-03	1.65447073470E-03
820312111201	060.00	005 004	8203120745	024	5.99984826828E+01	9.00717292530E+01	1.13732966487E+02	2.92696657194E-03	1.69732459900E-03
820312111827	060.00	005 005	8203120745	025	5.99986849466E+01	9.00717578778E+01	1.13733322457E+02	2.89419530991E-03	1.68779595555E-03
820312113347	300.00	005 001	8203120745	026	3.00000935733E+02	9.00715517135E+01	1.13733767056E+02	3.75442403720E-03	1.92232885537E-03
820312114013	300.00	005 002	8203120745	027	3.00000511064E+02	9.00715386292E+01	1.13733742782E+02	3.92339526917E-03	1.96511086206E-03
820312114640	300.00	005 003	8203120745	028	3.00000279569E+02	9.00715561188E+01	1.13733341841E+02	3.82030278851E-03	1.93912103237E-03
820312115307	300.00	005 004	8203120745	029	2.99999983216E+02	9.00715643467E+01	1.13733105899E+02	3.78401754714E-03	1.92989017423E-03
820312115934	300.00	005 005	8203120745	030	3.00000135451E+02	9.00715402421E+01	1.13732927748E+02	3.96781201734E-03	1.97620306431E-03
820312123705	210.00	005 001	8203120745	031	2.09998227037E+02	9.00715689745E+01	1.13733742646E+02	3.11804911317E-03	1.75185234948E-03
820312124332	210.00	005 002	8203120745	032	2.09999025900E+02	9.00715663528E+01	1.13733567987E+02	2.90538553706E-03	1.69105568707E-03
820312124958	210.00	005 003	8203120745	033	2.09998216730E+02	9.00715530083E+01	1.13733854270E+02	2.95512172789E-03	1.70546853661E-03
820312125625	210.00	005 004	8203120745	034	2.09998677350E+02	9.00715599801E+01	1.13733805851E+02	2.86541500494E-03	1.67938314282E-03
820312130252	210.00	005 005	8203120745	035	2.09998539345E+02	9.00715900866E+01	1.13733416770E+02	2.79363030987E-03	1.65821367030E-03
820312131844	120.00	005 001	8203120745	036	1.19998866693E+02	9.00715617757E+01	1.13732843899E+02	3.29110424917E-03	1.79981075960E-03
820312132510	120.00	005 002	8203120745	037	1.19998773879E+02	9.00715738096E+01	1.13732523139E+02	3.31115595317E-03	1.80528528521E-03
820312133137	120.00	005 003	8203120745	038	1.19998837248E+02	9.00715604737E+01	1.13733075613E+02	3.13779723606E-03	1.75739126007E-03
820312133804	120.00	005 004	8203120745	039	1.19998609959E+02	9.00715534714E+01	1.13733912042E+02	3.11985773234E-03	1.75236035534E-03
820312134431	120.00	005 005	8203120745	040	1.19998823204E+02	9.00715743588E+01	1.13734336196E+02	3.23713513140E-03	1.78499267673E-03
820312140005	030.00	005 001	8203120745	041	3.00005125792E+01	9.00715639312E+01	1.13735521698E+02	4.52845816871E-03	2.11120888203E-03
820312140631	030.00	005 002	8203120745	042	3.00014058840E+01	9.00715558732E+01	1.13735801811E+02	4.46362142257E-03	2.09604064908E-03
820312141258	030.00	005 003	8203120745	043	3.00008535338E+01	9.00716042461E+01	1.13735839509E+02	4.36288886989E-03	2.07225453919E-03
820312141926	030.00	005 004	8203120745	044	3.00003415280E+01	9.00715905738E+01	1.13735570727E+02	4.45088729006E-03	2.09304864769E-03
820312142553	030.00	005 005	8203120745	045	3.00684283200E+01	9.01002702799E+01	1.13499102371E+02	3.06224952691E+01	1.73610629686E-01

RUN DTG	BEARING	SET	NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820312152638	270.00	005	001	8203120745	046	2.69998506598E+02	9.00715137526E+01	1.13741902321E+02	3.03463151669E-03	1.72825971219E-03
820312153304	270.00	005	002	8203120745	047	2.69997965200E+02	9.00715510668E+01	1.13743574402E+02	2.91278297963E-03	1.69320712867E-03
820312153930	270.00	005	003	8203120745	048	2.69998590121E+02	9.00715583792E+01	1.13744608771E+C2	3.06783418591E-03	1.73768865404E-03
820312154556	270.00	005	004	8203120745	049	2.69998818825E+02	9.00715580504E+01	1.13745435458E+02	3.08601511131E-03	1.74283008557E-03
820312155222	270.00	005	005	8203120745	050	2.69999513198E+02	9.00715377418E+01	1.13746206824E+02	2.99582190894E-03	1.71717287819E-03
820312164407	180.00	005	001	8203120745	051	1.79831283876E+02	9.01009003895E+01	1.13471754205E+02	2.94525758780E+01	1.70261974656E-01
820312165034	180.00	005	002	8203120745	052	1.79998108494E+02	9.00717163951E+01	1.13750416842E+02	9.23407185103E-04	9.53350610275E-04
820312165702	180.00	005	003	8203120745	053	1.79997694578E+02	9.00717054485E+01	1.13750267554E+02	9.14080850849E-04	9.48524012134E-04
820312170329	180.00	005	004	8203120745	054	1.79998074110E+02	9.00716921224E+01	1.13749859300E+02	8.71005960569E-04	9.25905337550E-04
820312170957	180.00	005	005	8203120745	055	1.80121591229E+02	9.00372365043E+01	1.13473174504E+02	4.78742615663E+01	2.17073629761E-01
820312183735	180.00	005	001	8203120745	056	1.79997547653E+02	9.00717221597E+01	1.13748267445E+02	8.48481364691E-04	9.13854760026E-04
820312184403	180.00	005	002	8203120745	057	1.79860868241E+02	9.00700382321E+01	1.13711486243E+02	1.44657058771E+01	1.19323460392E-01
820312185031	180.00	005	003	8203120745	058	1.79998369060E+02	9.00716826003E+01	1.13748036940E+02	8.95494363786E-04	9.38831067148E-04
820312185659	180.00	005	004	8203120745	059	1.79998087532E+02	9.00716976897E+01	1.13747815710E+02	8.91431050649E-04	9.36698668559E-04
820312190326	180.00	005	005	8203120745	060	1.79998230334E+02	9.00716905385E+01	1.13747624636E+02	7.74661903960E-04	8.73196776140E-04
820312192008	180.00	005	001	8203120745	061	1.79998015569E+02	9.00717282025E+01	1.13747147019E+02	8.36899469649E-04	9.07596203351E-04
820312192635	180.00	C05	002	8203120745	062	1.79998442784E+02	9.00717754587E+01	1.13747732926E+02	1.01976741212E-03	1.00185896532E-03
820312193304	180.00	005	003	8203120745	063	1.79998153450E+02	9.00717191582E+01	1.13746895567E+02	8.55938315314E-04	9.17861720540E-04
820312193932	180.00	005	004	8203120745	064	1.79997782199E+02	9.00717510962E+01	1.13746844215E+02	7.91072133063E-04	8.82397089887E-04
820312194600	180.00	005	005	8203120745	065	1.79998271543E+02	9.00717227671E+01	1.13746508443E+02	7.74504293714E-04	8.73107942703E-04
820312200505	090.00	005	001	8203120745	066	9.00000628668E+01	9.00716557282E+01	1.13743269356E+02	2.89119324423E-03	1.68692037731E-03
820312201133	090.00	005	002	8203120745	067	9.00001317517E+01	9.00716438536E+01	1.13743670688E+02	2.79145267429E-03	1.65756725534E-03
820312201802	090.00	C05	003	8203120745	068	9.00000461694E+01	9.00716339763E+01	1.13744377731E+02	2.91786695683E-03	1.69468414803E-03
820312202431	090.00	005	004	8203120745	069	9.00001354220E+01	9.00716406365E+01	1.13744050336E+02	2.86192556637E-03	1.67836027360E-03
820312203100	090.00	005	005	8203120745	070	9.00001472912E+01	9.00716285112E+01	1.13743738763E+02	2.87212070337E-03	1.68134705661E-03
820312204609	000.00	005	001	8203120745	071	3.59999099763E+02	9.00717287959E+01	1.13746030262E+02	8.10513708240E-04	8.93174275553E-04
820312205237	000.00	005	002	8203120745	072	3.59999265431E+02	9.00717105528E+01	1.13745510616E+02	7.14913458066E-04	8.38847009245E-04
820312205905	000.00	005	003	8203120745	073	3.59999460662E+02	9.00717144168E+01	1.13745194594E+02	8.36582604757E-04	9.07424371124E-04
820312210534	000.00	005	004	8203120745	074	3.59999323724E+02	9.00717187258E+01	1.13744885120E+02	7.63295496297E-04	8.66767011638E-04
820312211203	000.00	005	005	8203120745	075	3.59999342557E+02	9.00717057230E+01	1.13744758333E+02	7.08189966106E-04	8.34893171016E-04

RUN DTG	BEARING	SET	NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820322065847	030.00	005	001	8203190827	001	3.00008678814E+01	9.00716729566E+01	1.13729593129E+02	6.16049596371E-03	2.46242982576E-03
820322070511	030.00	005	002	8203190827	002	3.00007723889E+01	9.00716394492E+01	1.13727233391E+02	5.97688423431E-03	2.42545625509E-03
820322071137	030.00	005	003	8203190827	999	2.97206964539E+01	9.00637400993E+01	1.13973325926E+02	4.87728557077E+01	2.19101381816E-01
820322071802	030.00	005	004	8203190827	004	3.00006534683E+01	9.00715818723E+01	1.13727166087E+02	5.99136354494E-03	2.42839237447E-03
820322072427	030.00	005	005	8203190827	005	3.00003821478E+01	9.00716076795E+01	1.13727190751E+02	5.88059903806E-03	2.40584037196E-03
820322073927	210.00	005	001	8203190827	006	2.09999247336E+02	9.00715728546E+01	1.13728355390E+02	3.82797695549E-03	1.94106769387E-03
820322074553	210.00	005	002	8203190827	007	2.09998226940E+02	9.00715622465E+01	1.13728005902E+02	3.65565494251E-03	1.89687460413E-03
820322075219	210.00	005	003	8203190827	008	2.09998746947E+02	9.00715772261E+01	1.13727725396E+02	3.72529047611E-03	1.91485589097E-03
820322075845	210.00	005	004	8203190827	009	2.09998447576E+02	9.00715594988E+01	1.13727498645E+02	3.64333158646E-03	1.89367468573E-03
820322080511	210.00	005	005	8203190827	010	2.09998692953E+02	9.00715597707E+01	1.13727325517E+02	3.73832871049E-03	1.91820388937E-03
820322082006	360.00	005	001	8203190827	011	3.59998896923E+02	9.00717366340E+01	1.13726827918E+02	7.77300524514E-04	8.74682634879E-04
820322082632	360.00	005	002	8203190827	012	3.59999275615E+02	9.00717245432E+01	1.13726960770E+02	7.28809486003E-04	8.46960258249E-04
820322083258	360.00	005	003	8203190827	013	3.59999122207E+02	9.00717215805E+01	1.13727659083E+02	6.89423229514E-04	8.23756738821E-04
820322083924	360.00	005	004	8203190827	014	3.59999231879E+02	9.00717238240E+01	1.13728107809E+02	7.76702252080E-04	8.74345957349E-04
820322084550	360.00	005	005	8203190827	015	3.59999338009E+02	9.00717342305E+01	1.13728205462E+02	7.53750903686E-04	8.61330740123E-04
820322090204	060.00	005	001	8203190827	016	5.99996419572E+01	9.00717394710E+01	1.13729915997E+02	3.57248201517E-03	1.87517174178E-03
820322090829	060.00	005	002	8203190827	017	5.99995531332E+01	9.00717439427E+01	1.13730000404E+02	3.67083530614E-03	1.90080897635E-03
820322091455	060.00	005	003	8203190827	018	5.99996619143E+01	9.00717352225E+01	1.13730707069E+02	3.67530167837E-03	1.90196499925E-03
820322092120	060.00	005	004	8203190827	019	5.99997786372E+01	9.00717037938E+01	1.13730793358E+02	3.61082158503E-03	1.88520698025E-03
820322092746	060.00	005	005	8203190827	020	5.99990186039E+01	9.00717310503E+01	1.13731548574E+02	3.72404913471E-03	1.91453683020E-03
820322094238	090.00	005	001	8203190827	021	9.00004410978E+01	9.00715900316E+01	1.13728174981E+02	3.38750899366E-03	1.82598099321E-03
820322094904	090.00	005	002	8203190827	022	9.00004194609E+01	9.00716035620E+01	1.13728093000E+02	3.37314967420E-03	1.82210680581E-03
820322095530	090.00	005	003	8203190827	023	9.00005967014E+01	9.00715869966E+01	1.13728301255E+02	3.28369816654E-03	1.79778453169E-03
820322100156	090.00	005	004	8203190827	024	9.00003547622E+01	9.00715955255E+01	1.13728333825E+02	3.30595540743E-03	1.80386702553E-03
820322100822	090.00	005	005	8203190827	025	9.00003274726E+01	9.00715981224E+01	1.13728208211E+02	3.23145951251E-03	1.78342719021E-03
820322102313	150.00	005	001	8203190827	026	1.50001325724E+02	9.00714607806E+01	1.13729362519E+02	3.42637493557E-03	1.83642614183E-03
820322102939	150.00	005	002	8203190827	027	1.50000855434E+02	9.00714697471E+01	1.13729783417E+02	3.35738377031E-03	1.81784360828E-03
820322103606	150.00	005	003	8203190827	028	1.50000633200E+02	9.00715009474E+01	1.13729912697E+02	3.48168550111E-03	1.85118913917E-03
820322104233	150.00	005	004	8203190827	029	1.50000882126E+02	9.00715185269E+01	1.13730124014E+02	3.67181980846E-03	1.90106385368E-03
820322104859	150.00	005	005	8203190827	030	1.50000579854E+02	9.00715131518E+01	1.13730024982E+02	3.49381440129E-03	1.85441076388E-03
820322110417	180.00	005	001	8203190827	031	1.79997775675E+02	9.00716902025E+01	1.13732987090E+02	8.28033367643E-04	9.02775871587E-04
820322111044	180.00	005	002	8203190827	032	1.79998138056E+02	9.00716920573E+01	1.13733039185E+02	8.86118033246E-04	9.33903088404E-04
820322111711	180.00	005	003	8203190827	033	1.79997589926E+02	9.00716896916E+01	1.13733011072E+02	8.02861781297E-04	8.88948121394E-04
820322112337	180.00	005	004	8203190827	034	1.79998287206E+02	9.00716756391E+01	1.13732741144E+02	8.63295105883E-04	9.21797792146E-04
820322113004	180.00	005	005	8203190827	035	1.79998293222E+02	9.00716719535E+01	1.13733032710E+02	8.29806008631E-04	9.03741679256E-04
820322114454	000.00	005	001	8203190827	036	3.59998880083E+02	9.00717276913E+01	1.13732572414E+02	6.67145019877E-04	8.10337893986E-04
820322115121	000.00	005	002	8203190827	037	3.59999153788E+02	9.00717465706E+01	1.13732847235E+02	7.32527341280E-04	8.49117797440E-04
820322115748	000.00	005	003	8203190827	038	3.59998934900E+02	9.00717190904E+01	1.13733077981E+02	8.54755802963E-04	9.17227470422E-04
820322120414	000.00	005	004	8203190827	039	3.59998970035E+02	9.00717291026E+01	1.13733190662E+02	7.99447331397E-04	8.87055826287E-04
820322121041	000.00	005	005	8203190827	040	3.59999000740E+02	9.00717731636E+01	1.13733315231E+02	7.77819326771E-04	8.74974485725E-04
820322122540	120.00	005	001	8203190827	041	1.19998679608E+02	9.00715830279E+01	1.13733676804E+02	4.36578325077E-03	2.07294180164E-03
820322123207	120.00	005	002	8203190827	042	1.19997719470E+02	9.00715788213E+01	1.13733504610E+02	4.60148918051E-03	2.12816465843E-03
820322123834	120.00	005	003	8203190827	043	1.19998304952E+02	9.00715828378E+01	1.13733257782E+02	4.50457934143E-03	2.10563526024E-03
820322124501	120.00	005	004	8203190827	044	1.19997961957E+02	9.00715921524E+01	1.13733819934E+02	4.31598043774E-03	2.06108431331E-03
820322125129	120.00	005	005	8203190827	045	1.19998331486E+02	9.00715789260E+01	1.13733430717E+02	4.49568153777E-03	2.10355462310E-03

RUN DTG	BEARING	SET NO.		DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820322130631	270.00	005	001	8203190827	046	2.69999082600E+02	9.00716161896E+01	1.13737110780E+02	3.83528211766E-03	1.94291894010E-03
820322131259	270.00	005	002	8203190827	047	2.69999248117E+02	9.00715946219E+01	1.13736897682E+02	3.79828873969E-03	1.93352598125E-03
820322131926	270.00	005	003	8203190827	048	2.69999244478E+02	9.00716124750E+01	1.13737386041E+02	3.80690737471E-03	1.93622681290E-03
820322132554	270.00	005	004	8203190827	049	2.69999124575E+02	9.00716233136E+01	1.13737553414E+02	3.90829676329E-03	1.96132602312E-03
820322133221	270.00	005	005	8203190827	050	2.69998647586E+02	9.00716009490E+01	1.13738290585E+02	3.75413674383E-03	1.92225530437E-03
820322134721	300.00	005	001	8203190827	051	2.99999646811E+02	9.00715919468E+01	1.13738707592E+02	5.14648248026E-03	2.25066715691E-03
820322135348	300.00	005	002	8203190827	052	3.00000159537E+02	9.00716501129E+01	1.13739109239E+02	4.97450055326E-03	2.21274193194E-03
820322140016	300.00	005	003	8203190827	053	3.00000054554E+02	9.00716204081E+01	1.13739029912E+02	5.15449835343E-03	2.25241923158E-03
820322140644	300.00	005	004	8203190827	054	2.99999590473E+02	9.00716212220E+01	1.13739226859E+02	4.91049709357E-03	2.19846093692E-03
820322141311	300.00	005	005	8203190827	055	3.00000457254E+02	9.00716081528E+01	1.13739233802E+02	5.09239604649E-03	2.23880934132E-03
820322142828	240.00	005	001	8203190827	056	2.40000344517E+02	9.00716997828E+01	1.13740444739E+02	3.90392340243E-03	1.96022835991E-03
820322143455	240.00	005	002	8203190827	057	2.39999792868E+02	9.00717397172E+01	1.13740817230E+02	3.91151157734E-03	1.96213251285E-03
820322144123	240.00	005	003	8203190827	058	2.39999815719E+02	9.00717461722E+01	1.13741280473E+02	3.90642509754E-03	1.96085633181E-03
820322144751	240.00	005	004	8203190827	059	2.40000394392E+02	9.00717300729E+01	1.13741375366E+02	3.73162270120E-03	1.91648262992E-03
820322145419	240.00	005	005	8203190827	060	2.40000306824E+02	9.00717255554E+01	1.13741603162E+02	3.82691772386E-03	1.94079912087E-03
820322151007	330.00	005	001	8203190827	061	3.29999054816E+02	9.00717417322E+01	1.13740478031E+02	7.22650155043E-03	2.66698193672E-03
820322151635	330.00	005	002	8203190827	062	3.29999245818E+02	9.00717473869E+01	1.13741081338E+02	7.74014731380E-03	2.76013699033E-03
820322152303	330.00	005	003	8203190827	063	3.29999785748E+02	9.00717569778E+01	1.13741046549E+02	7.28421516783E-03	2.67761052903E-03
820322152931	330.00	005	004	8203190827	064	3.29999253240E+02	9.00717533204E+01	1.13740975923E+02	7.91650524049E-03	2.79140451074E-03
820322153600	330.00	005	005	8203190827	065	3.29998863291E+02	9.00717433405E+01	1.13741260099E+02	7.78830876174E-03	2.76871086486E-03

RUN DTG	BEARING	SET NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820429062519	240.00	005 001	8204231340	001	2.39999501992E+02	9.00717012157E+01	1.13741107462E+02	4.56453306826E-03	2.11960142597E-03
820429063143	240.00	005 002	8204231340	002	2.39999830139E+02	9.00716797841E+01	1.13740859678E+02	4.42840714191E-03	2.08775626407E-03
820429063806	240.00	005 003	8204231340	003	2.39999425167E+02	9.00716820639E+01	1.13740612575E+02	4.42549840949E-03	2.08707049583E-03
820429064430	240.00	005 004	8204231340	004	2.39999845947E+02	9.00716732462E+01	1.13741011769E+02	4.50907096589E-03	2.10668478847E-03
820429065053	240.00	005 005	8204231340	005	2.39999974036E+02	9.00716653354E+01	1.13740876146E+02	4.50908282503E-03	2.10668755884E-03
820429080746	000.00	005 001	8204231340	006	3.59999080283E+02	9.00717416759E+01	1.13739403713E+02	7.42507489060E-04	8.54882532413E-04
820429081411	000.00	005 002	8204231340	007	3.59999252951E+02	9.00717494002E+01	1.13739639847E+02	7.97795249951E-04	8.86138788780E-04
820429082036	000.00	005 003	8204231340	008	3.59999143749E+02	9.00717189117E+01	1.13739632216E+02	7.39368346517E-04	8.53073499791E-04
820429082701	000.00	005 004	8204231340	009	3.59998841572E+02	9.00717160134E+01	1.13739943198E+02	7.09825924929E-04	8.35856939940E-04
820429083326	000.00	005 005	8204231340	010	3.59998774878E+02	9.00717259688E+01	1.13740431798E+02	6.91662162820E-04	8.25093248351E-04
820429084949	030.00	005 001	8204231340	011	3.00010608777E+01	9.00715102300E+01	1.13740215082E+02	6.72464680323E-03	2.57270957960E-03
820429085614	030.00	005 002	8204231340	012	3.00007442254E+01	9.00715242570E+01	1.13740439504E+02	6.72594826714E-03	2.57295852403E-03
820429090239	030.00	005 003	8204231340	013	3.00007892229E+01	9.00715232702E+01	1.13740768451E+02	6.80322446406E-03	2.58769701151E-03
820429090904	030.00	005 004	8204231340	014	3.00009718410E+01	9.00715284670E+01	1.13740946182E+02	6.87605824300E-03	2.60151178429E-03
820429091530	030.00	005 005	8204231340	015	3.00002470631E+01	9.00714970597E+01	1.13741377804E+02	6.71051622229E-03	2.57000512536E-03
820429095437	120.00	005 001	8204231340	016	1.19997966288E+02	9.00715576889E+01	1.13743197178E+02	5.16943286737E-03	2.25567992286E-03
820429100102	120.00	005 002	8204231340	017	1.19997932688E+02	9.00715296345E+01	1.13743712891E+02	5.16393358943E-03	2.25447979973E-03
820429100727	120.00	005 003	8204231340	018	1.19997957449E+02	9.00715192496E+01	1.13744091216E+02	5.15063844986E-03	2.25157572086E-03
820429101352	120.00	005 004	8204231340	019	1.19997923329E+02	9.00715220004E+01	1.13744105416E+02	5.07457391380E-03	2.23488826678E-03
820429102017	120.00	005 005	8204231340	020	1.19997820560E+02	9.00715445884E+01	1.13744387175E+02	5.09723222777E-03	2.23987217287E-03
820429103847	300.00	005 001	8204231340	021	3.00000228658E+02	9.00715906148E+01	1.13746112537E+02	6.16964548000E-03	2.46425773725E-03
820429104512	300.00	005 002	8204231340	022	2.99999704950E+02	9.00715887981E+01	1.13745674426E+02	6.09823550766E-03	2.44995507269E-03
820429105137	300.00	005 003	8204231340	023	3.00000692838E+02	9.00716041441E+01	1.13746136282E+02	5.92347110291E-03	2.41459424520E-03
820429105802	300.00	005 004	8204231340	024	3.00000077060E+02	9.00715815500E+01	1.13746677842E+02	6.08777403971E-03	2.44785273278E-03
820429110428	300.00	005 005	8204231340	025	2.99999811003E+02	9.00716116934E+01	1.13746815450E+02	6.02513548706E-03	2.43522690224E-03
820429112855	180.00	005 001	8204231340	026	1.79998270689E+02	9.00716267344E+01	1.13746339782E+02	7.94803105843E-04	8.84475488761E-04
820429113521	180.00	005 002	8204231340	027	1.79998078282E+02	9.00716156756E+01	1.13746546247E+02	8.48627603289E-04	9.13933509594E-04
820429114146	180.00	005 003	8204231340	028	1.79997816761E+02	9.00716330329E+01	1.13746943811E+02	7.85242779046E-04	8.79139917777E-04
820429114812	180.00	005 004	8204231340	029	1.79998280293E+02	9.00716218425E+01	1.13747263787E+02	8.23482209280E-04	9.00291468564E-04
820429115437	180.00	005 005	8204231340	030	1.79997919880E+02	9.00716290077E+01	1.13747179039E+02	7.64489655957E-04	8.67444765986E-04

RUN DTG	BEARING	SET	NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820608070958	240.00	005	001	8204231340	031	2.40000255835E+02	9.00716699192E+01	1.13730990024E+02	1.05772232785E-02	3.22657571115E-03
820608071623	240.00	005	002	8204231340	032	2.39999404990E+02	9.00715832521E+01	1.13728995304E+02	1.06887198267E-02	3.24353710806E-03
820608072247	240.00	005	003	8204231340	033	2.39999896315E+02	9.00715593039E+01	1.13728487614E+02	1.06070917219E-02	3.23112817508E-03
820608072912	240.00	005	004	8204231340	034	2.39999584827E+02	9.00715572120E+01	1.13728061775E+02	1.02708361036E-02	3.17950069083E-03
820608073537	240.00	005	005	8204231340	035	2.39999951281E+02	9.00715793447E+01	1.13727878546E+02	1.05279216310E-02	3.21904720888E-03
820608075155	000.00	005	001	8204231340	036	3.59998484393E+02	9.00718046411E+01	1.13726713088E+02	9.15493504274E-04	9.49256670736E-04
820608075821	000.00	005	002	8204231340	037	3.59998380885E+02	9.00717635943E+01	1.13727243151E+02	9.78283370266E-04	9.81269634340E-04
820608080447	000.00	005	003	8204231340	038	3.59998444670E+02	9.00717668288E+01	1.13727348904E+02	1.04251214185E-03	1.01297000350E-03
820608081113	000.00	005	004	8204231340	039	3.59998630944E+02	9.00717876086E+01	1.13727394881E+02	1.01171847409E-03	9.97897338514E-04
820608081740	000.00	005	005	8204231340	040	3.59998750666E+02	9.00717852852E+01	1.13727659082E+02	1.05599789503E-03	1.01950075183E-03
820608083434	030.00	005	001	8204231340	041	3.00004565794E+01	9.00714989620E+01	1.13724331668E+02	1.46264801348E-02	3.79424994919E-03
820608084058	030.00	005	002	8204231340	042	3.00003721965E+01	9.00715031292E+01	1.13724578873E+02	1.45045652435E-02	3.77840391099E-03
820608084723	030.00	005	003	8204231340	043	3.00000621736E+01	9.00715334978E+01	1.13724953042E+02	1.48520309771E-02	3.82339305850E-03
820608085348	030.00	005	004	8204231340	044	3.00001322207E+01	9.00715374282E+01	1.13725161313E+02	1.44712352921E-02	3.77406022866E-03
820608090013	030.00	005	005	8204231340	045	3.00002793729E+01	9.00715399252E+01	1.13725232033E+02	1.43252422051E-02	3.75497466327E-03
820608091849	120.00	005	001	8204231340	046	1.19997971189E+02	9.00713240562E+01	1.13725578722E+02	1.25973067713E-02	3.52123392114E-03
820608092516	120.00	005	002	8204231340	047	1.19997617003E+02	9.00712864415E+01	1.13725291003E+02	1.31455720433E-02	3.59704415502E-03
820608093142	120.00	005	003	8204231340	048	1.20021234760E+02	9.00706155538E+01	1.13696953291E+02	2.44500818433E+00	4.90564574255E-02
820608093808	120.00	005	004	8204231340	049	1.19997652153E+02	9.00713302724E+01	1.13725821495E+02	1.26058801232E-02	3.52243194083E-03
820608094435	120.00	005	005	8204231340	050	1.19997360198E+02	9.00713193325E+01	1.13725638432E+02	1.27289851775E-02	3.53958963381E-03
820608095940	300.00	005	001	8204231340	051	3.00000407151E+02	9.00715522846E+01	1.13728983250E+02	1.35668268402E-02	3.65422399584E-03
820608100606	300.00	005	002	8204231340	052	3.00000167243E+02	9.00715468801E+01	1.13728674599E+02	1.36548123003E-02	3.66605428519E-03
820608101233	300.00	005	003	8204231340	053	3.00000424007E+02	9.00715611764E+01	1.13729073295E+02	1.36340064736E-02	3.66326023844E-03
820608101900	300.00	005	004	8204231340	054	3.00000572284E+02	9.00715955189E+01	1.13729307757E+02	1.38657880373E-02	3.69426718830E-03
820608102527	300.00	005	005	8204231340	055	2.99999978723E+02	9.00715507808E+01	1.13728886259E+02	1.39410360863E-02	3.70427780826E-03
820608105058	180.00	005	001	8204231340	056	1.79998522485E+02	9.00713746108E+01	1.13727948367E+02	1.17000089152E-03	1.07312205456E-03
820608105725	180.00	005	002	8204231340	057	1.79998192909E+02	9.00713828164E+01	1.13728249600E+02	1.16791531621E-03	1.07216518559E-03
820608110352	180.00	005	003	8204231340	058	1.79998134000E+02	9.00713855874E+01	1.13728235357E+02	1.12628178169E-03	1.05288164282E-03
820608111019	180.00	005	004	8204231340	059	1.79998262495E+02	9.00713974580E+01	1.13728024866E+02	1.19134786553E-03	1.08286750057E-03
820608111646	180.00	005	005	8204231340	060	1.79998190914E+02	9.00713874415E+01	1.13728181695E+02	1.14640525347E-03	1.06224600870E-03

RUN DTG	BEARING	SET NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820706093349	240.00	005 001	8204231340	001	2.39998514311E+02	9.00715999345E+01	1.13721297247E+02	1.30772327683E-02	3.58768207841E-03
820706094014	240.00	005 002	8204231340	002	2.39998911242E+02	9.00716330904E+01	1.13721438661E+02	1.30408229932E-02	3.58268416523E-03
820706094639	240.00	005 003	8204231340	003	2.40000038798E+02	9.00716212285E+01	1.13720778220E+02	1.30675580563E-02	3.58635472523E-03
820706095303	240.00	005 004	8204231340	004	2.39999515003E+02	9.00716362539E+01	1.13721063608E+02	1.31102594513E-02	3.59220958525E-03
820706095928	240.00	005 005	8204231340	005	2.40000577480E+02	9.00716042751E+01	1.13720922154E+02	1.32970649844E-02	3.61771141123E-03
820706101833	000.00	005 001	8204231340	006	3.59998268352E+02	9.00716308680E+01	1.13719635996E+02	1.46907650600E-03	1.20248102188E-03
820706102458	000.00	005 002	8204231340	007	3.59998427188E+02	9.00716191657E+01	1.13719527668E+02	1.41979934623E-03	1.18214162586E-03
820706103124	000.00	005 003	8204231340	008	3.59998667584E+02	9.00716225164E+01	1.13719183365E+02	1.52579973090E-03	1.22547594582E-03
820706103749	000.00	005 004	8204231340	009	3.59997442516E+02	9.00716436078E+01	1.13718971200E+02	1.79102705926E-03	1.32772183600E-03
820706104414	000.00	005 005	8204231340	010	3.59997886235E+02	9.00716320345E+01	1.13718344654E+02	1.49891692434E-03	1.21463224384E-03
820706110041	030.00	005 001	8204231340	011	3.00005122629E+01	9.00713286272E+01	1.13714118924E+02	1.76693927937E-02	4.17029557084E-03
820706110706	030.00	005 002	8204231340	012	2.99999873041E+01	9.00712994722E+01	1.13714381127E+02	1.75754225856E-02	4.15919145507E-03
820706111332	030.00	005 003	8204231340	013	3.00003504623E+01	9.00713132027E+01	1.13713994209E+02	1.77967861399E-02	4.18530213506E-03
820706111957	030.00	005 004	8204231340	014	3.00003058888E+01	9.00712883260E+01	1.13713849211E+02	1.77633894503E-02	4.18137331131E-03
820706112622	030.00	005 005	8204231340	015	2.99988745745E+01	9.00712919699E+01	1.13714215049E+02	1.77971231797E-02	4.18534176599E-03
820706114350	120.00	005 001	8204231340	016	1.19996716447E+02	9.00713182439E+01	1.13715253711E+02	1.55756890739E-02	3.91543175483E-03
820706115015	120.00	005 002	8204231340	017	1.19996977285E+02	9.00713317586E+01	1.13714186387E+02	1.57751434753E-02	3.94042152767E-03
820706115641	120.00	005 003	8204231340	018	1.19997069814E+02	9.00713256619E+01	1.13713774580E+02	1.58642549208E-02	3.95153528317E-03
820706120306	120.00	005 004	8204231340	019	1.19995211065E+02	9.00713089956E+01	1.13712956929E+02	1.58484418457E-02	3.94956539854E-03
820706120932	120.00	005 005	8204231340	020	1.19996335976E+02	9.00712906594E+01	1.13713300053E+02	1.57247301487E-02	3.93412019925E-03
820706134916	300.00	005 001	8204231340	021	2.99999469536E+02	9.00714627320E+01	1.13711930514E+02	1.71790135537E-02	4.11201921427E-03
820706135542	300.00	C05 002	8204231340	022	2.99999249241E+02	9.00714478442E+01	1.13712326831E+02	1.67695148117E-02	4.06271420769E-03
820706140207	300.00	005 003	8204231340	023	2.99999698720E+02	9.00714839606E+01	1.13712729859E+02	1.67998309197E-02	4.06638485854E-03
820706140833	300.00	005 004	8204231340	024	3.00000159260E+02	9.00714731889E+01	1.13713283875E+02	1.69486516645E-02	4.08435611454E-03
820706141458	300.00	005 005	8204231340	025	3.00000020021E+02	9.00714374145E+01	1.13713166170E+02	1.67742148335E-02	4.06328349990E-03
820706143040	180.00	005 001	8204231340	026	1.79997044965E+02	9.00714512412E+01	1.13712982483E+02	1.03727485058E-03	1.01042235990E-03
820706143706	180.00	005 002	8204231340	027	1.79998353733E+02	9.00714456540E+01	1.13712811858E+02	1.07796614480E-03	1.03005066030E-03
820706144332	180.00	005 003	8204231340	028	1.79996904542E+02	9.00714404484E+01	1.13712990808E+02	1.05759599297E-03	1.02027189268E-03
820706144958	180.00	005 004	8204231340	029	1.79997857425E+02	9.00714369150E+01	1.13712819620E+02	1.18295415528E-03	1.07904605480E-03
820706145624	180.00	005 005	8204231340	030	1.79997644723E+02	9.00714472098E+01	1.13713417819E+02	1.01544971939E-03	9.99735781305E-04

RUN DTG	BEARING	SET NO.		OISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUAREO	ST.OEV. THETA1
820707085930	240.00	005	001	8204231340	031	2.40001116841E+02	9.00717462930E+01	1.13714519403E+02	1.37852240997E-02	3.68351921314E-03
820707090555	240.00	005	002	8204231340	032	2.40000223030E+02	9.00716723480E+01	1.13711073148E+02	1.36263531765E-02	3.66223192905E-03
820707091220	240.00	005	003	8204231340	033	2.40000475524E+02	9.00716145693E+01	1.13710466895E+02	1.37335145184E-02	3.67660412089E-03
820707091845	240.00	005	004	8204231340	034	2.40000262857E+02	9.00716173016E+01	1.13710857356E+02	1.35756874277E-02	3.65541710044E-03
820707092509	240.00	005	005	8204231340	035	2.39999671874E+02	9.00716304212E+01	1.13710962556E+02	1.36160565368E-02	3.66084800009E-03
820707094244	000.00	005	001	8204231340	036	3.59998155955E+02	9.00716321221E+01	1.13708985296E+02	1.45336970409E-03	1.19603551469E-03
820707094911	000.00	005	002	8204231340	037	3.59998333830E+02	9.00716265986E+01	1.13709274308E+02	1.39079870606E-03	1.17000619998E-03
820707095538	000.00	005	003	8204231340	038	3.59998116213E+02	9.00716501191E+01	1.13708985325E+02	1.40515150851E-03	1.17602783529E-03
820707100204	000.00	005	004	8204231340	039	3.59999023474E+02	9.00716406463E+01	1.13708842472E+02	1.37338063828E-03	1.16265666187E-03
820707100831	000.00	005	005	8204231340	040	3.59997943521E+02	9.00716142525E+01	1.13709045638E+02	1.38305211429E-03	1.16674324887E-03
820707102445	030.00	005	001	8204231340	041	3.00004085864E+01	9.00712763257E+01	1.13705572599E+02	1.84969780648E-02	4.26684056142E-03
820707103111	030.00	005	002	8204231340	042	3.00005792217E+01	9.00712885733E+01	1.13705789008E+02	1.81411876648E-02	4.22560484825E-03
820707103738	030.00	005	003	8204231340	043	2.99991148800E+01	9.00712912531E+01	1.13705982128E+02	1.81711965298E-02	4.22909836839E-03
820707104405	030.00	005	004	8204231340	044	2.99995797369E+01	9.00712735035E+01	1.13705915329E+02	1.80559782301E-02	4.21566930251E-03
820707105032	030.00	005	005	8204231340	045	2.99999223650E+01	9.00713099961E+01	1.13706022293E+02	1.80006919642E-02	4.20921029778E-03
820707110631	120.00	005	001	8204231340	046	1.19997446424E+02	9.00712570323E+01	1.13706457399E+02	1.57250361669E-02	3.93415847995E-03
820707111258	120.00	005	002	8204231340	047	1.19996873887E+02	9.00713919376E+01	1.13705661362E+02	1.64229222246E-02	4.02051088492E-03
820707111925	120.00	005	003	8204231340	048	1.19996594041E+02	9.00713035885E+01	1.13707596281E+02	1.56959078928E-02	3.93051307136E-03
820707112552	120.00	005	004	8204231340	049	1.19997034789E+02	9.00713054012E+01	1.13706763516E+02	1.57003628595E-02	3.93107083021E-03
820707113219	120.00	005	005	8204231340	050	1.19996092704E+02	9.00714611671E+01	1.13702954243E+02	1.60606009835E-02	3.97591343645E-03
820707115245	300.00	005	001	8204231340	051	3.00003966308E+02	9.00713556374E+01	1.13711549261E+02	1.75986267444E-02	4.16193616020E-03
820707115912	300.00	005	002	8204231340	052	2.99999813098E+02	9.00712459271E+01	1.13720752847E+02	1.72384574879E-02	4.11912740798E-03
820707120539	300.00	005	003	8204231340	053	3.00000444843E+02	9.00714006395E+01	1.13730495009E+02	1.64513462475E-02	4.02398863653E-03
820707121206	300.00	005	004	8204231340	054	3.00000842585E+02	9.00714184627E+01	1.13738255289E+02	1.62629737085E-02	4.00088440815E-03
820707121833	300.00	005	005	8204231340	055	2.99999567096E+02	9.00714528252E+01	1.13744293915E+02	1.60141797725E-02	3.97016333170E-03
820707134056	180.00	005	001	8204231340	056	1.79999405397E+02	9.00718244772E+01	1.13755469544E+02	1.29306257070E-03	1.12814726405E-03
820707134723	180.00	005	002	8204231340	057	1.79997612965E+02	9.00718059082E+01	1.13742452055E+02	1.26976859338E-03	1.11793953441E-03
820707135350	180.00	005	003	8204231340	058	1.79998632903E+02	9.00716912933E+01	1.13732072975E+02	1.13407795379E-03	1.05651940502E-03
820707140017	180.00	005	004	8204231340	059	1.79998344948E+02	9.00716138939E+01	1.13724804655E+02	1.31025451895E-03	1.13562215661E-03
820707140644	180.00	005	005	8204231340	060	1.79998463859E+02	9.00715109236E+01	1.13720652916E+02	1.10264542718E-03	1.04177507985E-03

RUN DTG	BEARING	SET	NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820713131759	240.00	005	001	8204231351	007	2.40004526006E+02	9.00715801998E+01	1.13707239714E+02	1.49469480099E-02	3.83559095764E-03
820713132425	240.00	005	002	8204231351	008	2.40001581876E+02	9.00716776222E+01	1.13708270943E+02	1.53612674779E-02	3.88838760303E-03
820713133052	240.00	005	003	8204231351	009	2.39999289309E+02	9.00716905574E+01	1.13707871427E+02	1.54365830392E-02	3.89790823691E-03
820713133718	240.00	005	004	8204231351	010	2.40000006673E+02	9.00716728341E+01	1.13707129240E+02	1.55967135786E-02	3.91807344379E-03
820713134345	240.00	005	005	8204231351	011	2.40002773210E+02	9.00715578242E+01	1.13709864491E+02	1.54140134253E-02	3.89505765582E-03
820713140153	000.00	005	001	8204231351	012	3.59998221485E+02	9.00716451715E+01	1.13729292250E+02	1.51648828410E-03	1.22173088787E-03
820713140818	000.00	005	002	8204231351	013	3.59816402077E+02	9.00710310089E+01	1.13761156071E+02	2.58783566295E+01	1.59596870420E-01
820713141444	000.00	005	003	8204231351	014	3.59998085908E+02	9.00717223286E+01	1.13738448470E+02	1.48613462721E-03	1.20944215231E-03
820713142109	000.00	005	004	8204231351	015	3.59998338895E+02	9.00717812746E+01	1.13741246563E+02	1.44792125062E-03	1.19379153548E-03
820713142735	000.00	005	005	8204231351	016	3.59998486078E+02	9.00717504140E+01	1.13744004300E+02	1.36245229863E-03	1.15802164530E-03
820713144317	030.00	005	001	8204231351	017	3.00010261627E+01	9.00713274022E+01	1.13744416538E+02	1.69558798115E-02	4.08522695606E-03
820713144942	030.00	005	002	8204231351	018	3.00002058921E+01	9.00713555506E+01	1.13745881983E+02	1.72373479072E-02	4.11899483876E-03
820713145607	030.00	005	003	8204231351	019	2.99996782507E+01	9.00713212747E+01	1.13747082244E+02	1.70291283275E-02	4.09404143044E-03
820713150232	030.00	005	004	8204231351	020	2.99998074284E+01	9.00713513931E+01	1.13748421423E+02	1.69518303783E-02	4.08473910638E-03
820713150857	030.00	005	005	8204231351	021	3.00009990029E+01	9.00713634049E+01	1.13749780531E+02	1.72212890379E-02	4.11707569745E-03
820713152442	120.00	005	001	8204231351	022	1.19997339579E+02	9.00714537905E+01	1.13753454093E+02	1.40922804818E-02	3.72431720558E-03
820713153109	120.00	005	002	8204231351	023	1.19996586908E+02	9.00714641721E+01	1.13753373327E+02	1.38871536486E-02	3.69711231671E-03
820713153735	120.00	005	003	8204231351	024	1.19997443590E+02	9.00714430803E+01	1.13754131343E+02	1.42623326970E-02	3.74672057855E-03
820713154401	120.00	005	004	8204231351	025	1.19997125443E+02	9.00714542068E+01	1.13754310240E+02	1.40303987637E-02	3.71613113840E-03
820713155028	120.00	005	005	8204231351	026	1.19997021763E+02	9.00714539165E+01	1.13755117068E+02	1.38984313494E-02	3.69861321697E-03
820713162315	300.00	005	001	8204231351	027	3.00000079135E+02	9.00716559148E+01	1.13759060751E+02	1.67097869124E-02	4.05547267920E-03
820713162942	300.00	005	002	8204231351	028	3.00001177650E+02	9.00716304551E+01	1.13759485008E+02	1.67881107382E-02	4.06496618108E-03
820713163609	300.00	005	003	8204231351	029	3.00000234611E+02	9.00716352815E+01	1.13759721328E+02	1.66717121140E-02	4.05084965899E-03
820713164236	300.00	005	004	8204231351	030	3.00000510789E+02	9.00716337765E+01	1.13759969711E+02	1.65341955777E-02	4.03410835801E-03
820713164903	300.00	005	005	8204231351	031	3.00001420477E+02	9.00716288739E+01	1.13760507630E+02	1.64662069882E-02	4.02580569007E-03
820713171051	180.00	005	001	8204231351	032	1.79997637666E+02	9.00716211601E+01	1.13761504851E+02	1.35916714168E-03	1.15662468675E-03
820713171718	180.00	005	002	8204231351	033	1.79997683342E+02	9.00716200563E+01	1.13762097281E+02	1.19030015556E-03	1.08239124137E-03
820713172345	180.00	005	003	8204231351	034	1.79997663470E+02	9.00716272347E+01	1.13762026867E+02	1.23353763831E-03	1.10187473925E-03
820713173012	180.00	005	004	8204231351	035	1.79998175315E+02	9.00716045193E+01	1.13762304021E+02	1.19620103740E-03	1.08507088754E-03
820713173639	180.00	005	005	8204231351	036	1.79998135753E+02	9.00716227887E+01	1.13763114974E+02	1.20903646080E-03	1.09087684419E-03

RUN DTG	BEARING	SET NO.	DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820730121951	240.00	005	001	8204231351	037	2.39998495363E+02	9.00716626449E+01	1.13720233890E+02	1.35821205334E-02	3.65628309338E-03
820730122617	240.00	005	002	8204231351	038	2.40000853312E+02	9.00716242567E+01	1.13721200376E+02	1.35356654141E-02	3.65002491914E-03
820730123244	240.00	005	003	8204231351	039	2.40002432698E+02	9.00716290462E+01	1.13722096360E+02	1.37962975050E-02	3.68499836621E-03
820730123910	240.00	005	004	8204231351	040	2.39998702470E+02	9.00716464204E+01	1.13721778010E+02	1.36095431030E-02	3.65997228609E-03
820730124537	240.00	005	005	8204231351	041	2.39999393423E+02	9.00716304966E+01	1.13721896206E+02	1.37047397903E-02	3.67275045484E-03
820730133106	000.00	005	001	8204231351	042	3.59998473519E+02	9.00716375528E+01	1.13719967775E+02	1.57522640261E-03	1.24516675084E-03
820730133732	000.00	005	002	8204231351	043	3.59998210831E+02	9.00716378368E+01	1.13721088221E+02	1.43284756877E-03	1.18756125425E-03
820730134359	000.00	005	003	8204231351	044	3.59998489623E+02	9.00716839176E+01	1.13721563551E+02	1.36934852688E-03	1.16094868413E-03
820730135026	000.00	005	004	8204231351	045	3.59997208302E+02	9.00716642754E+01	1.13721287408E+02	1.43023794870E-03	1.18647931916E-03
820730135653	000.00	005	005	8204231351	046	3.59998499066E+02	9.00716644849E+01	1.13720404905E+02	1.45881170003E-03	1.19827263951E-03
820730141458	030.00	005	001	8204231351	047	2.99988821115E+01	9.00713723508E+01	1.13718202990E+02	1.83261104053E-02	4.24708715679E-03
820730142125	030.00	005	002	8204231351	048	3.00012393347E+01	9.00713898358E+01	1.13717967823E+02	1.84163369199E-02	4.25752934446E-03
820730142752	030.00	005	003	8204231351	049	3.00010345274E+01	9.00713460064E+01	1.13717857761E+02	1.84053644179E-02	4.25626083190E-03
820730143419	030.00	005	004	8204231351	050	2.99994024066E+01	9.00713836778E+01	1.13718588146E+02	1.86783502895E-02	4.28770879514E-03
820730144046	030.00	005	005	8204231351	051	2.99986812342E+01	9.00713962567E+01	1.13718180653E+02	1.84865945824E-02	4.26564277433E-03
820730150621	120.00	005	001	8204231351	052	1.20002673987E+02	9.00712211557E+01	1.13719343274E+02	7.38327610551E-01	2.69575599051E-02
820730151248	120.00	005	002	8204231351	053	1.19996298762E+02	9.00713012226E+01	1.13719723905E+02	1.40194187747E-02	3.71467675829E-03
820730151915	120.00	005	003	8204231351	054	1.19995408464E+02	9.00713438528E+01	1.13719924692E+02	1.59984260362E-02	3.96821005353E-03
820730152542	120.00	005	004	8204231351	055	1.19995279543E+02	9.00713384513E+01	1.13719713961E+02	1.63536241879E-02	4.01201945939E-03
820730153208	120.00	005	005	8204231351	056	1.19998899788E+02	9.00713456562E+01	1.13719519177E+02	1.67806953351E-02	4.06406832267E-03
820730154845	300.00	005	001	8204231351	057	3.00001931903E+02	9.00715131611E+01	1.13722929529E+02	2.14107915639E-02	4.59063100908E-03
820730155512	300.00	005	002	8204231351	058	2.99998342087E+02	9.00715153173E+01	1.13722121360E+02	1.76369815761E-02	4.16646899911E-03
820730160140	300.00	005	003	8204231351	059	3.00002802934E+02	9.00715241145E+01	1.13722918458E+02	1.73587974081E-02	4.13348000800E-03
820730160807	300.00	005	004	8204231351	060	3.00002140874E+02	9.00715213806E+01	1.13722960324E+02	1.78759917840E-02	4.19460526226E-03
820730161435	300.00	005	005	8204231351	061	3.00000017915E+02	9.00715247137E+01	1.13722050927E+02	1.71465828976E-02	4.10813603209E-03
820730163332	180.00	005	001	8204231351	062	1.79996163165E+02	9.00714285990E+01	1.13720466602E+02	9.58552630191E-02	9.71323745266E-03
820730163959	180.00	005	002	8204231351	063	1.79999098705E+02	9.00714805122E+01	1.13720470620E+02	1.10920566778E-03	1.04486952879E-03
820730164627	180.00	005	003	8204231351	064	1.79997420623E+02	9.00714347555E+01	1.13720495902E+02	1.03850321711E-03	1.01102046645E-03
820730165255	180.00	005	004	8204231351	065	1.79998094582E+02	9.00714688235E+01	1.13721098703E+02	1.10130267258E-03	1.04114057196E-03
820730165923	180.00	005	005	8204231351	066	1.79998290033E+02	9.00715042624E+01	1.13720770661E+02	9.88050793591E-04	9.86156087206E-04

RUN DTG	BEARING	SET NO.		DISK DTG	FILE	THETA1	THETA2	THETA3	SIGMA SQUARED	ST.DEV. THETA1
820928080347	240.00	005	001	8204231411	001	2.39999763904E+02	9.00718940133E+01	1.13772124252E+02	1.56350301771E-02	3.92288327618E-03
820928081012	240.00	005	002	8204231411	002	2.39999944161E+02	9.00718900589E+01	1.13772852094E+02	1.53519620610E-02	3.88720968757E-03
820928081637	240.00	005	003	8204231411	003	2.39999279389E+02	9.00718579357E+01	1.13774421637E+02	1.55868245770E-02	3.91683113151E-03
820928082302	240.00	005	004	8204231411	004	2.40000009225E+02	9.00719126796E+01	1.13774718990E+02	1.50956953687E-02	3.85462901143E-03
820928082928	240.00	005	005	8204231411	005	2.39998158247E+02	9.00718971626E+01	1.13774728139E+02	1.52645152304E-02	3.87612284366E-03
820928084509	000.00	005	001	8204231411	006	3.59999246039E+02	9.00718526110E+01	1.13776033497E+02	1.41374222786E-03	1.17961731675E-03
820928085135	000.00	005	002	8204231411	007	3.59998407361E+02	9.00718517250E+01	1.13777880393E+02	1.42537016250E-03	1.18445851898E-03
820928085801	000.00	005	003	8204231411	008	3.59997867355E+02	9.00718745170E+01	1.13779228723E+02	1.49059685951E-03	1.21125651246E-03
820928090427	000.00	005	004	8204231411	009	3.59997629302E+02	9.00718567461E+01	1.13780710032E+02	1.51658416874E-03	1.22176951107E-03
820928091053	000.00	005	005	8204231411	010	3.59997699036E+02	9.00718599996E+01	1.13780690897E+02	1.46214504247E-03	1.19964086750E-03
820928092815	030.00	005	001	8204231411	011	2.99088793826E+01	9.00731001857E+01	1.13752107521E+02	4.70702481451E+00	6.80658493347E-02
820928093441	030.00	005	002	8204231411	012	2.99998818011E+01	9.00715705181E+01	1.13777116929E+02	2.03830913543E-02	4.47910300174E-03
820928094107	030.00	005	003	8204231411	013	2.99999318377E+01	9.00715744368E+01	1.13777399244E+02	2.01310210479E-02	4.45132112036E-03
820928094733	030.00	005	004	8204231411	014	3.00005975696E+01	9.00715786431E+01	1.13777744310E+02	2.00947527283E-02	4.44730953258E-03
820928095359	030.00	005	005	8204231411	015	3.00000695273E+01	9.00715855280E+01	1.13777858189E+02	2.01886535454E-02	4.45768834348E-03
820928101213	120.00	005	001	8204231411	016	1.19996533346E+02	9.00715596688E+01	1.13777341421E+02	1.74214749412E-02	4.14093567680E-03
820928101839	120.00	005	002	8204231411	017	1.19996269078E+02	9.00715732782E+01	1.13776707712E+02	1.73620391853E-02	4.13386595626E-03
820928102506	120.00	005	003	8204231411	018	1.19996828827E+02	9.00715631618E+01	1.13776784553E+02	1.78143933765E-02	4.18737198595E-03
820928103132	120.00	005	004	8204231411	019	1.19996336327E+02	9.00715782565E+01	1.13776558712E+02	1.76340166850E-02	4.16611877915E-03
820928103758	120.00	005	005	8204231411	020	1.19997693507E+02	9.00715527995E+01	1.13776333995E+02	1.75940242734E-02	4.16139190060E-03
820928105335	300.00	005	001	8204231411	021	3.00001715655E+02	9.00717567593E+01	1.13780538091E+02	1.97703806610E-02	4.41126897853E-03
820928110001	300.00	005	002	8204231411	022	3.00000911533E+02	9.00717675820E+01	1.13780886874E+02	1.93107986947E-02	4.35969535066E-03
820928110627	300.00	005	003	8204231411	023	3.00000989655E+02	9.00717610820E+01	1.13781065102E+02	1.89647822676E-02	4.32045966154E-03
820928111253	300.00	005	004	8204231411	024	2.99999658775E+02	9.00717649762E+01	1.13781240271E+02	1.91860698318E-02	4.34559285881E-03
820928111920	300.00	005	005	8204231411	025	3.00000892873E+02	9.00717558000E+01	1.13781469589E+02	1.95920898205E-02	4.39133334701E-03
820928113518	180.00	005	001	8204231411	026	1.79997696296E+02	9.00716832945E+01	1.13781566194E+02	9.84859495866E-04	9.84562210139E-04
820928114144	180.00	005	002	8204231411	027	1.79997315063E+02	9.00717019699E+01	1.13781666653E+02	1.04718037957E-03	1.01523544618E-03
820928114810	180.00	005	003	8204231411	028	1.79997577540E+02	9.00717041574E+01	1.13781370433E+02	1.07418984057E-03	1.02824485342E-03
820928115437	180.00	005	004	8204231411	029	1.79998210438E+02	9.00716688581E+01	1.13782086620E+02	1.09273221791E-03	1.03708152620E-03
820928120104	180.00	005	005	8204231411	030	1.79998122213E+02	9.00716646490E+01	1.13782806466E+02	1.01760262522E-03	1.00079501517E-03

Appendix C. Graphical Illustrations*

The purpose of this attachment is to illustrate graphically some of the characteristics of the VOR measurement process which have been explored. The data were collected to help answer some questions which are often at the core of an examination of a new measurement process, for example,

1. Are there warm-up effects which affect the process?
2. What is the systematic error in an estimated value?
3. Are there within-day or day-to-day differences which will affect the results?
4. Is the bearing measurement system linear?
5. What is the best procedure for monitor the process?

The answers to these (and other) questions are the components of the final documentation of the statistical properties of the VOR measurement process. Quality control, or measurement assurance, procedures follow naturally from the analysis.

Data which are shown in the exhibits were collected by sound statistical practices to answer one or more of the questions listed above. Whenever data were collected at several bearing angles, switch settings on the signal generator were selected at random. Various quantities which are plotted are identified by:

1. "Bias": Nominal bearing minus estimated bearing;
2. Theta(1): Estimated bearing;
3. Bear Std: Estimated standard deviation of Theta(1); used to flag individual outliers (see ref. 3);
4. Theta(2): Auxiliary phase angle (see ref. 3); used to monitor the system;
5. Theta(3): Auxiliary phase angle; also used to monitor the system.

There are four sets of graphs:

Exhibit C.1: Start-up effects

Exhibit C.2: Within-day effects

Exhibit C.3: Systematic offset from nominal bearing

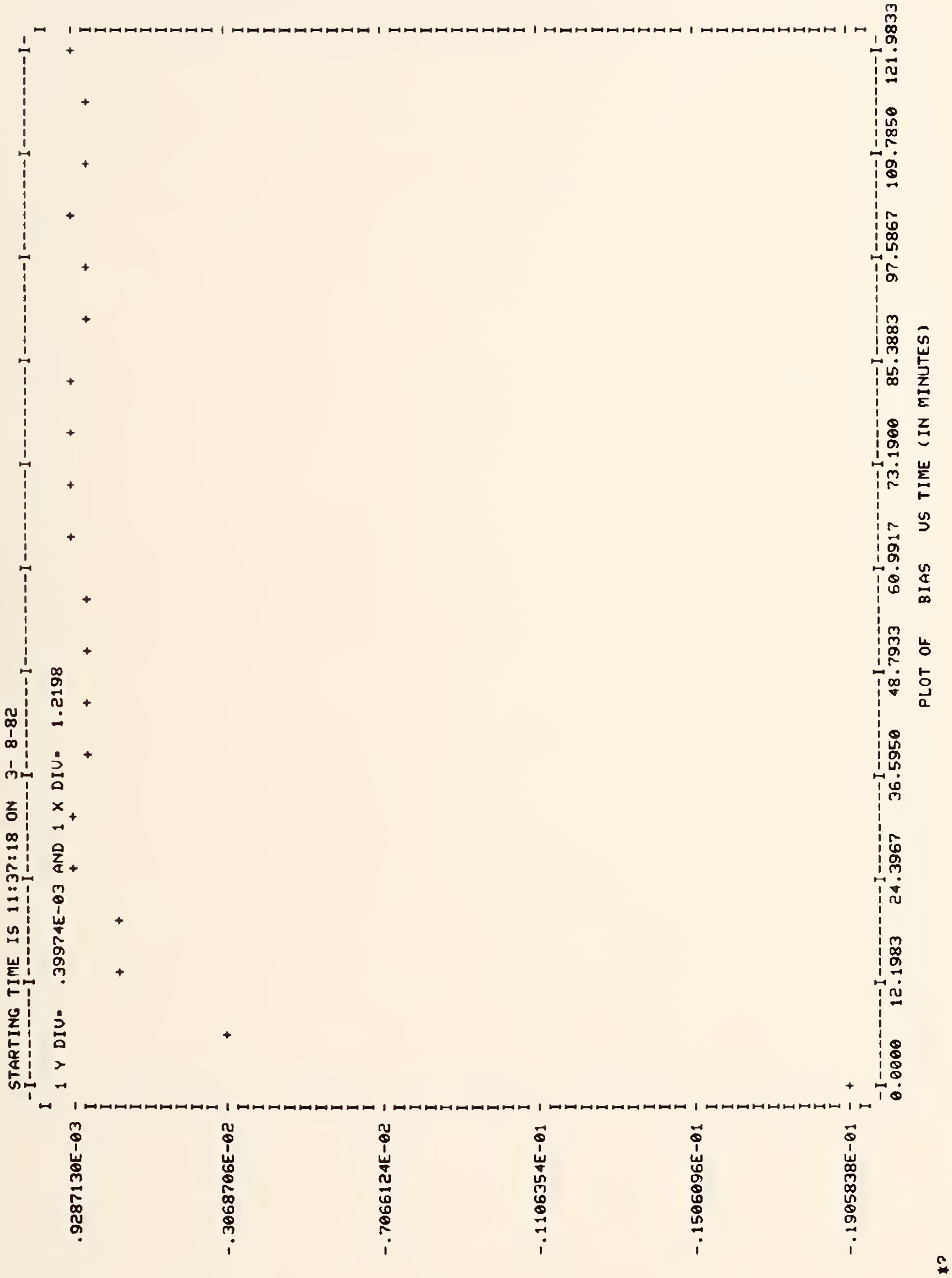
Exhibit C.4: Systematic offset, 5° interval

*The NBS statistical software package STATLIB was used to obtain plots in this appendix.

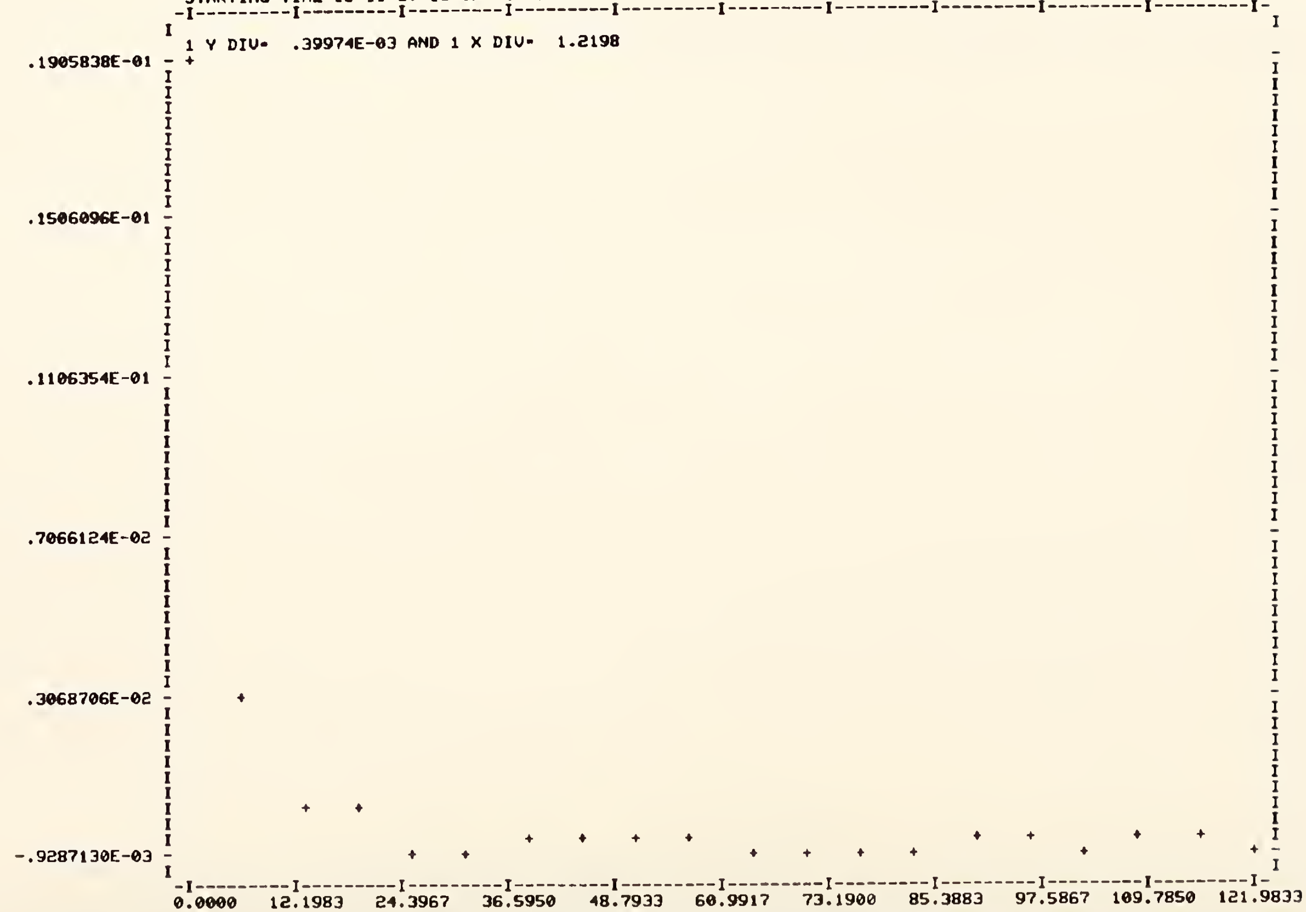
Exhibit C.1

Start-up effects: 20 successive measurements at a fixed nominal bearing were collected on both March 8 and March 10 (1982). Each run began from a cold-start of all system components and continued for approximately two hours.

Remarks: Approximately 45 to 60 min should be allowed for warm-up of the system before performing calibrations. Theta(3), and its associated DAC, requires the most time to stabilize.

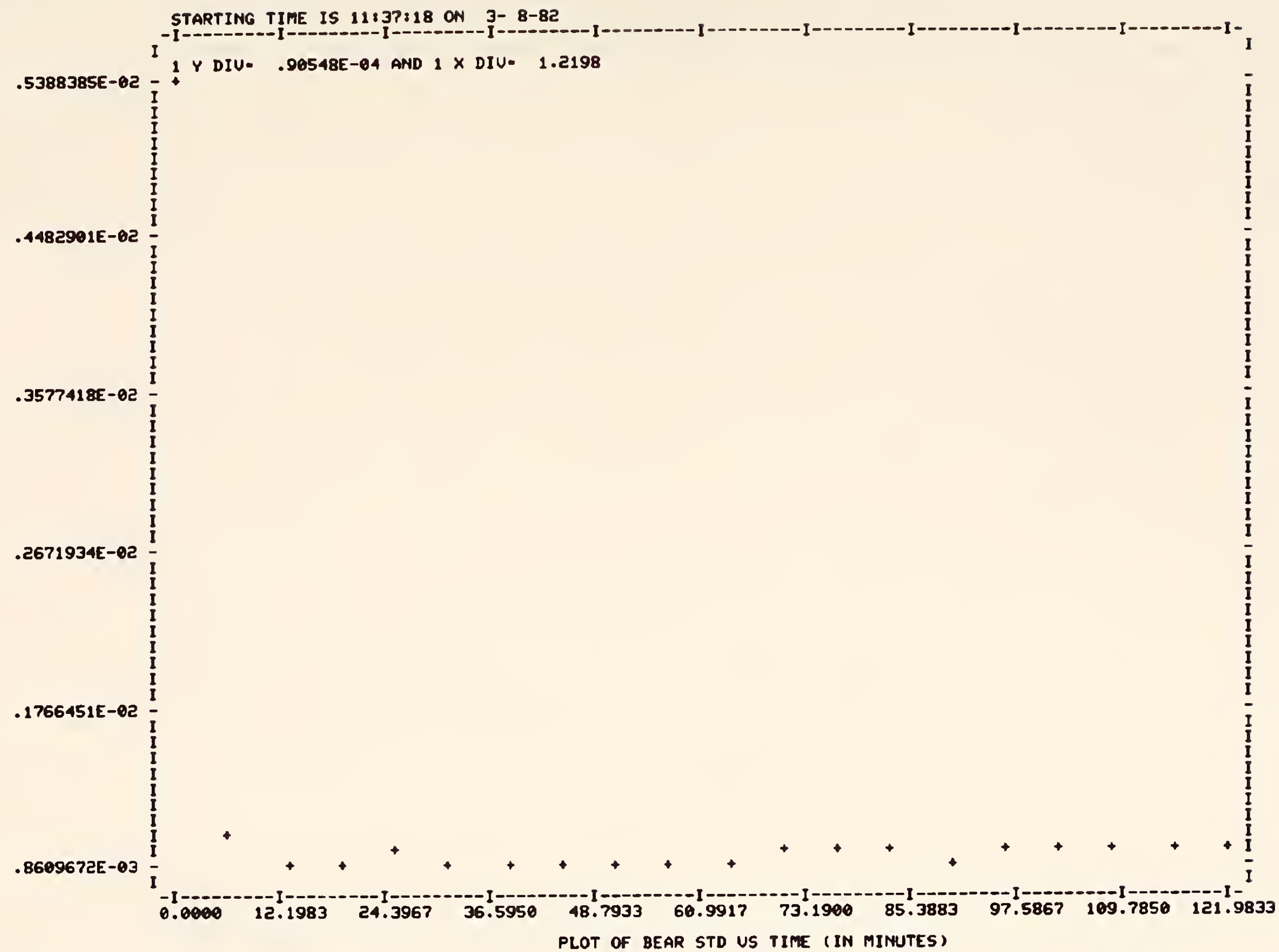

STARTING TIME IS 11:37:18 ON 3- 8-82
1 Y DIV= .39974E-03 AND 1 X DIV= 1.2198
.9287130E-03
-.3068706E-02
-.7066124E-02
-.1106354E-01
-.1506096E-01
-.1905838E-01
0.0000 12.1983 24.3967 36.5950 48.7933 60.9917 73.1900 85.3883 97.5867 109.7850 121.9833
PLOT OF BIAS VS TIME (IN MINUTES)

STARTING TIME IS 11:37:18 ON 3- 8-82



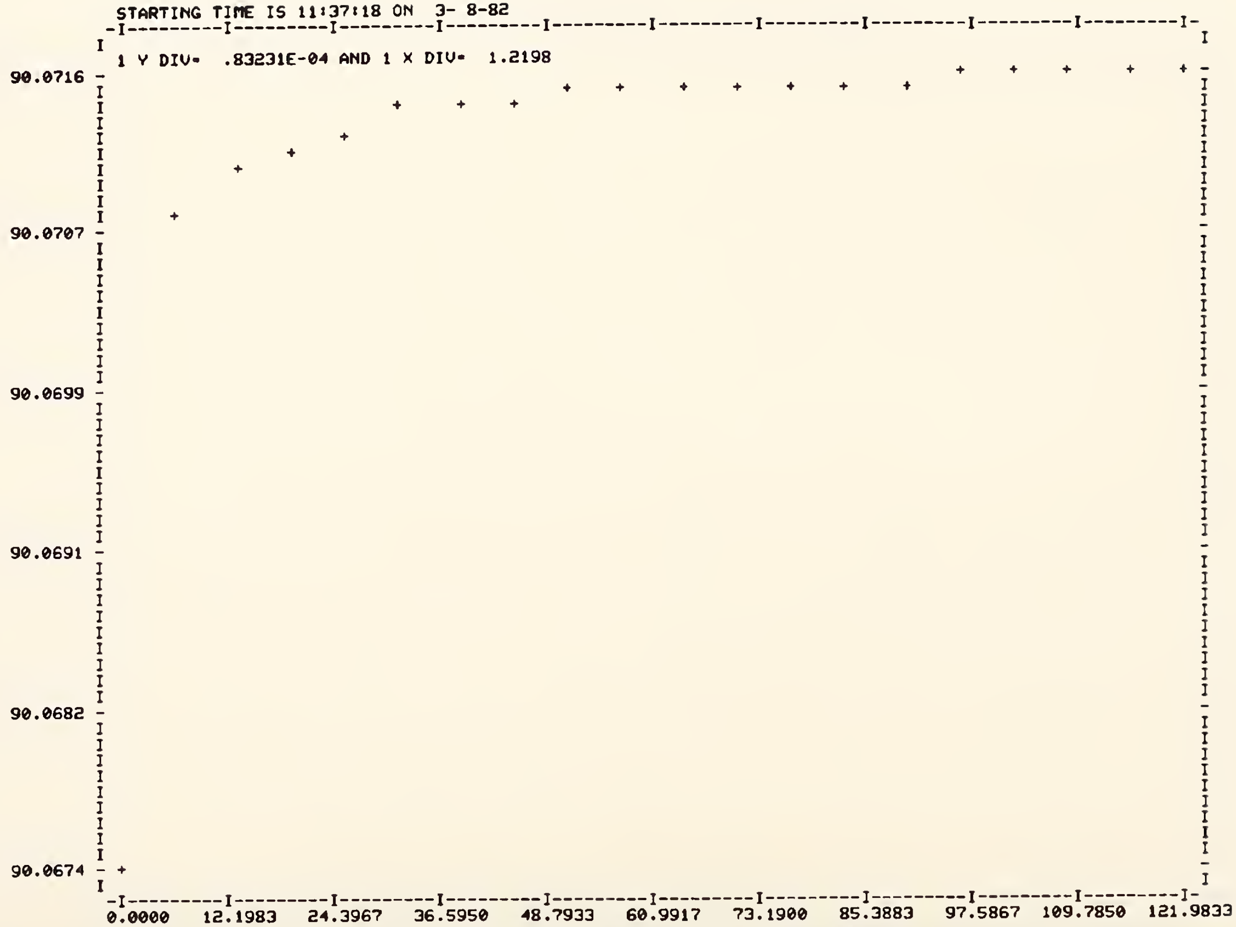
PLOT OF THETA(1) VS TIME (IN MINUTES)

*?


STARTING TIME IS 11:37:18 ON 3- 8-82
1 Y DIV= .90548E-04 AND 1 X DIV= 1.2198
.5388385E-02
.4482901E-02
.3577418E-02
.2671934E-02
.1766451E-02
.8609672E-03
0.0000
12.1983
24.3967
36.5950
48.7933
60.9917
73.1900
85.3883
97.5867
109.7850
121.9833
PLOT OF BEAR STD VS TIME (IN MINUTES)

x?

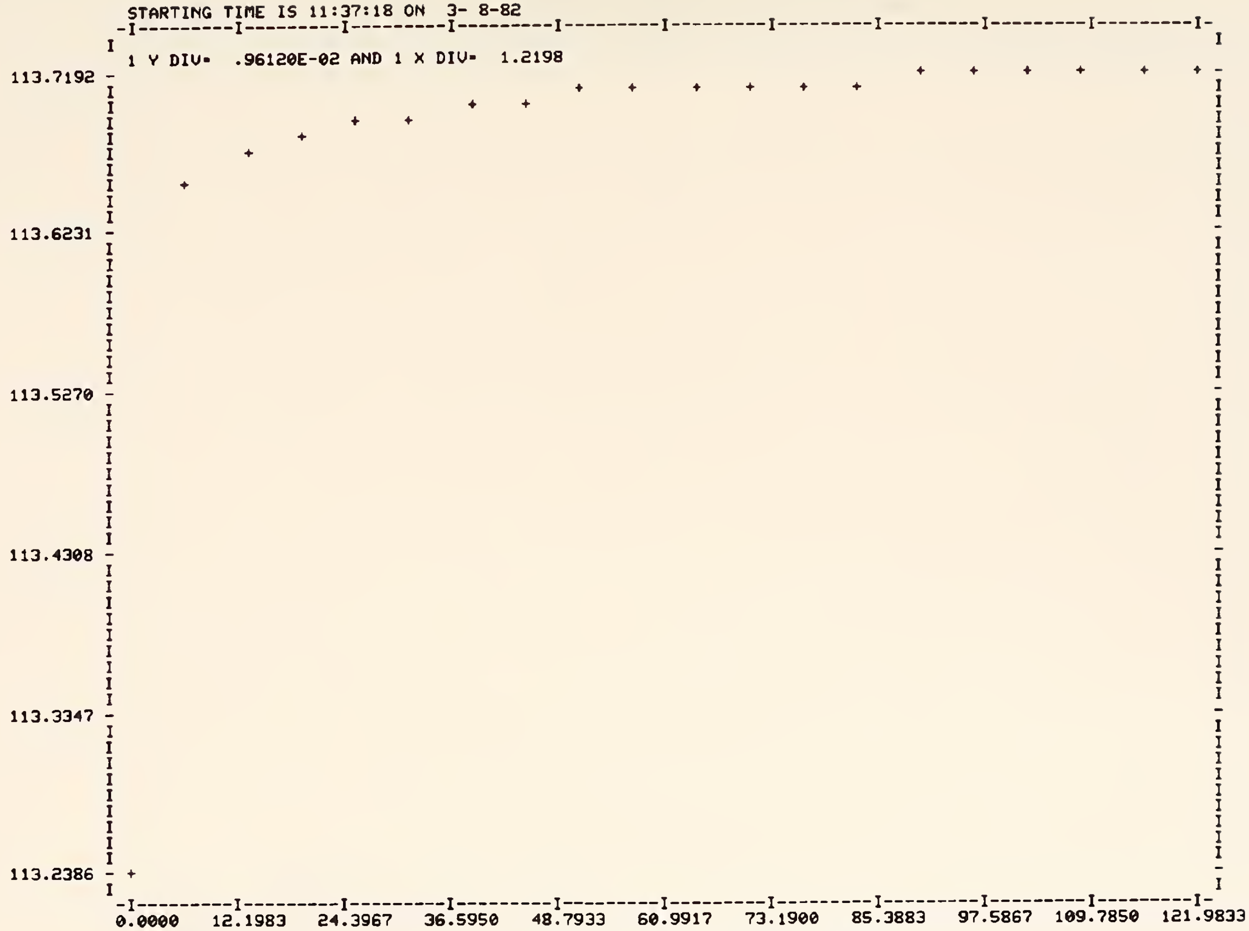
STARTING TIME IS 11:37:18 ON 3- 8-82



PLOT OF THETA(2) VS TIME (IN MINUTES)

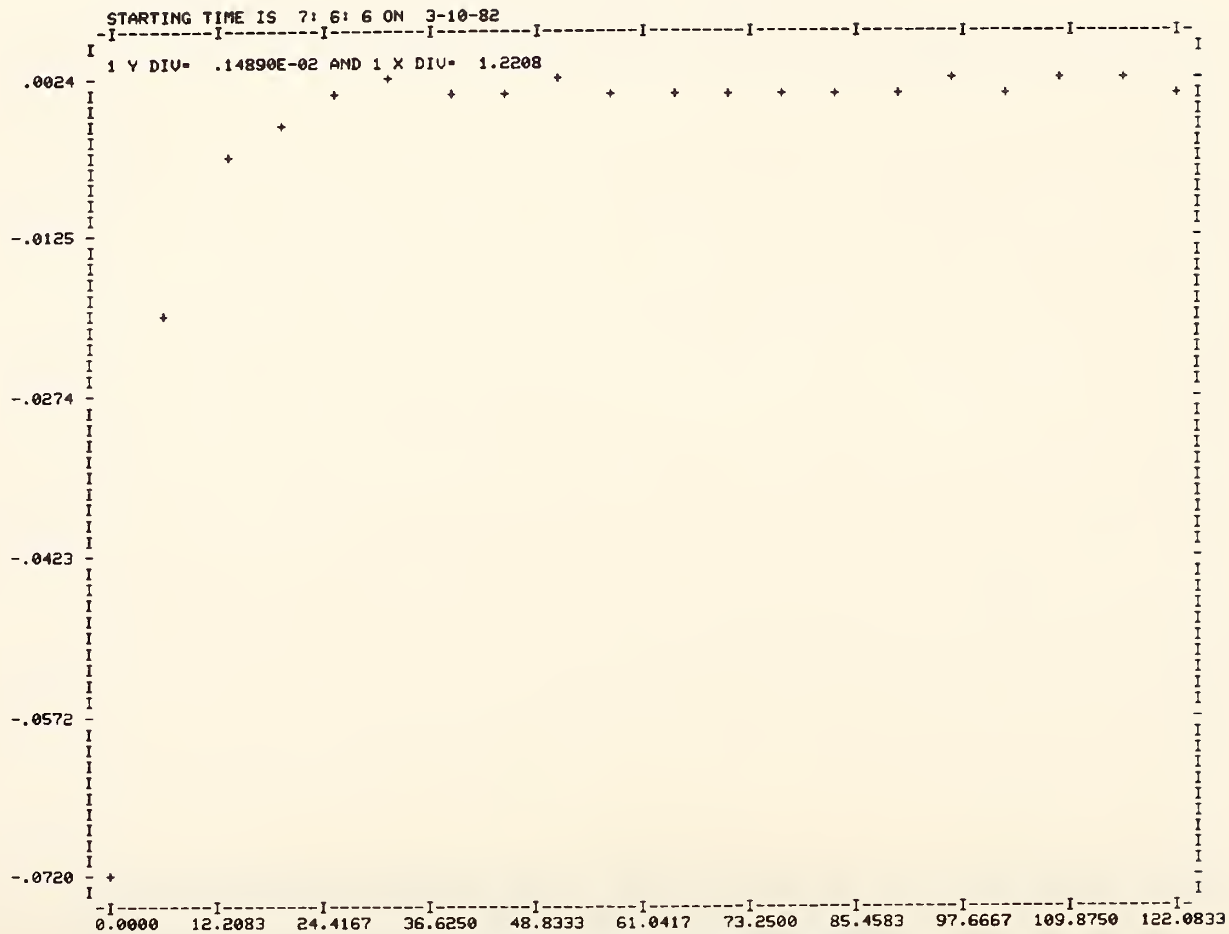
*?

STARTING TIME IS 11:37:18 ON 3- 8-82



PLOT OF THETA(3) VS TIME (IN MINUTES)

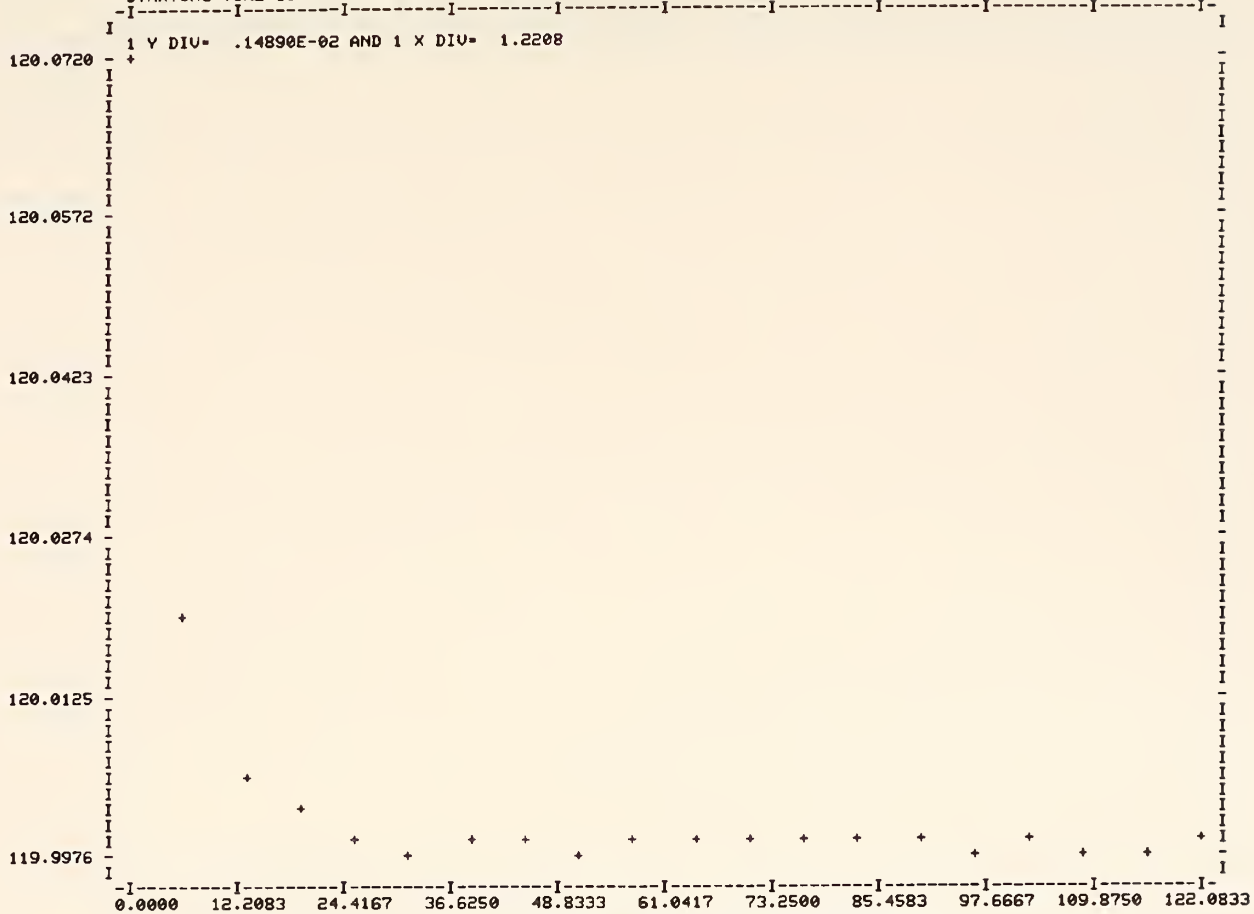
*?



PLOT OF BIAS VS TIME (IN MINUTES)

*?

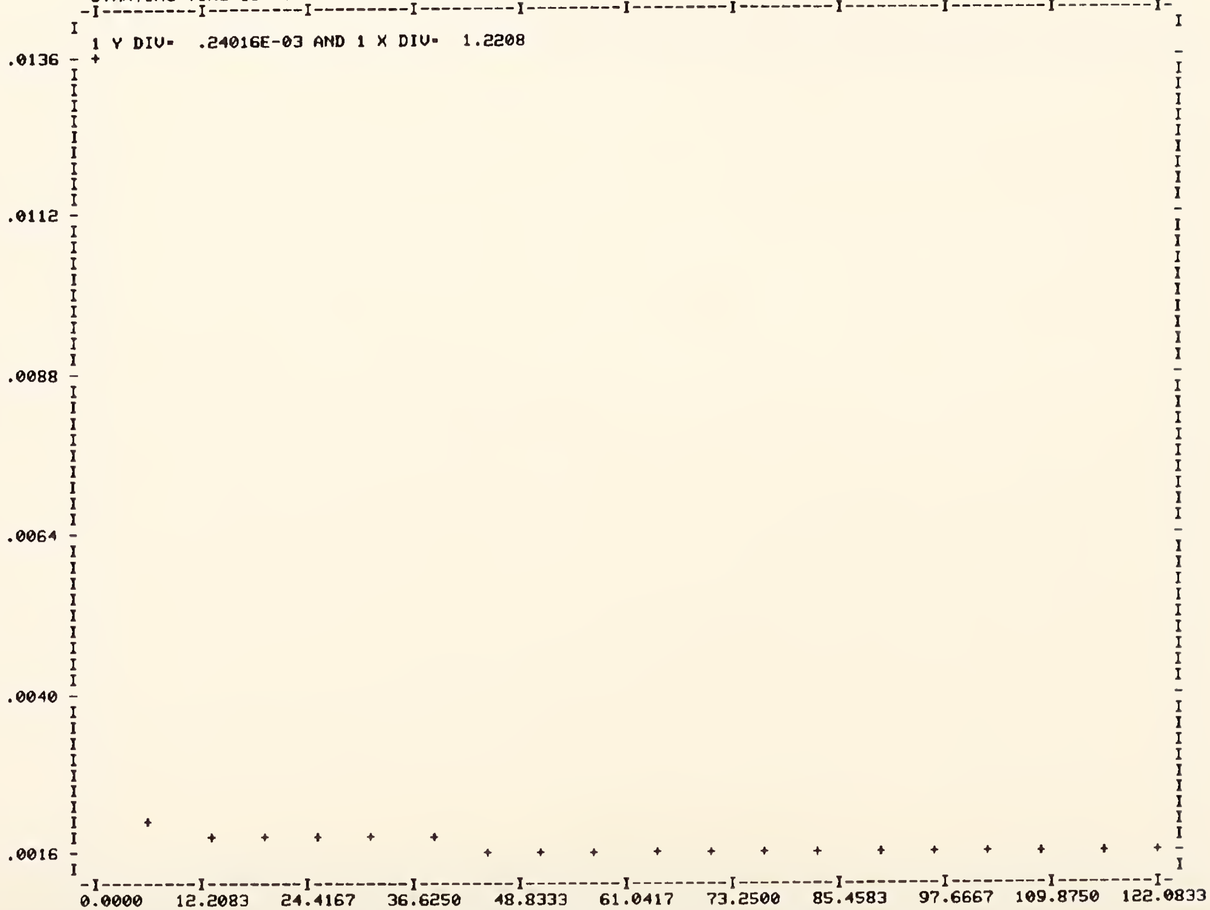
STARTING TIME IS 7: 6: 6 ON 3-10-82



PLOT OF THETA(1) VS TIME (IN MINUTES)

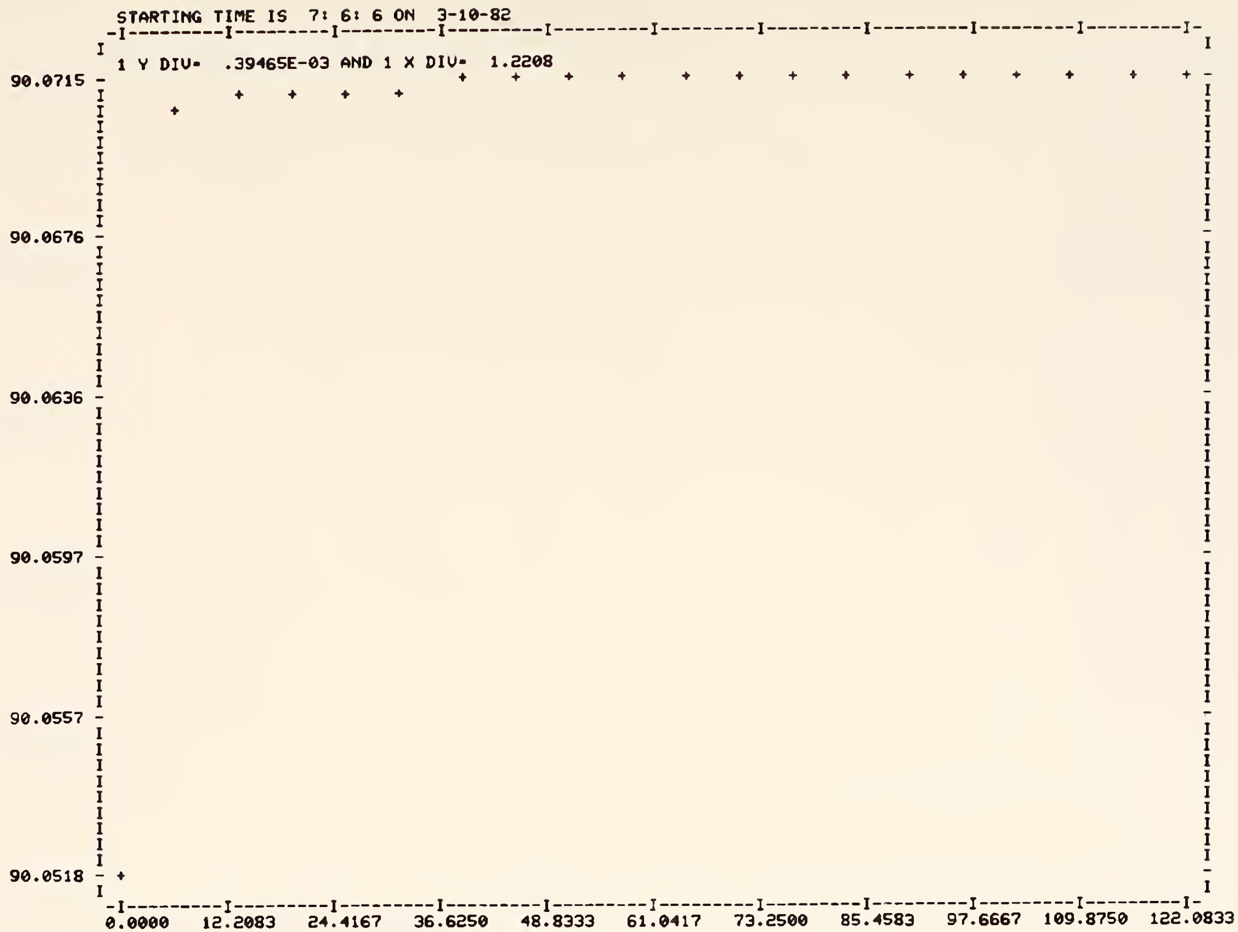
*?

STARTING TIME IS 7: 6: 6 ON 3-10-82



PLOT OF BEAR STD VS TIME (IN MINUTES)

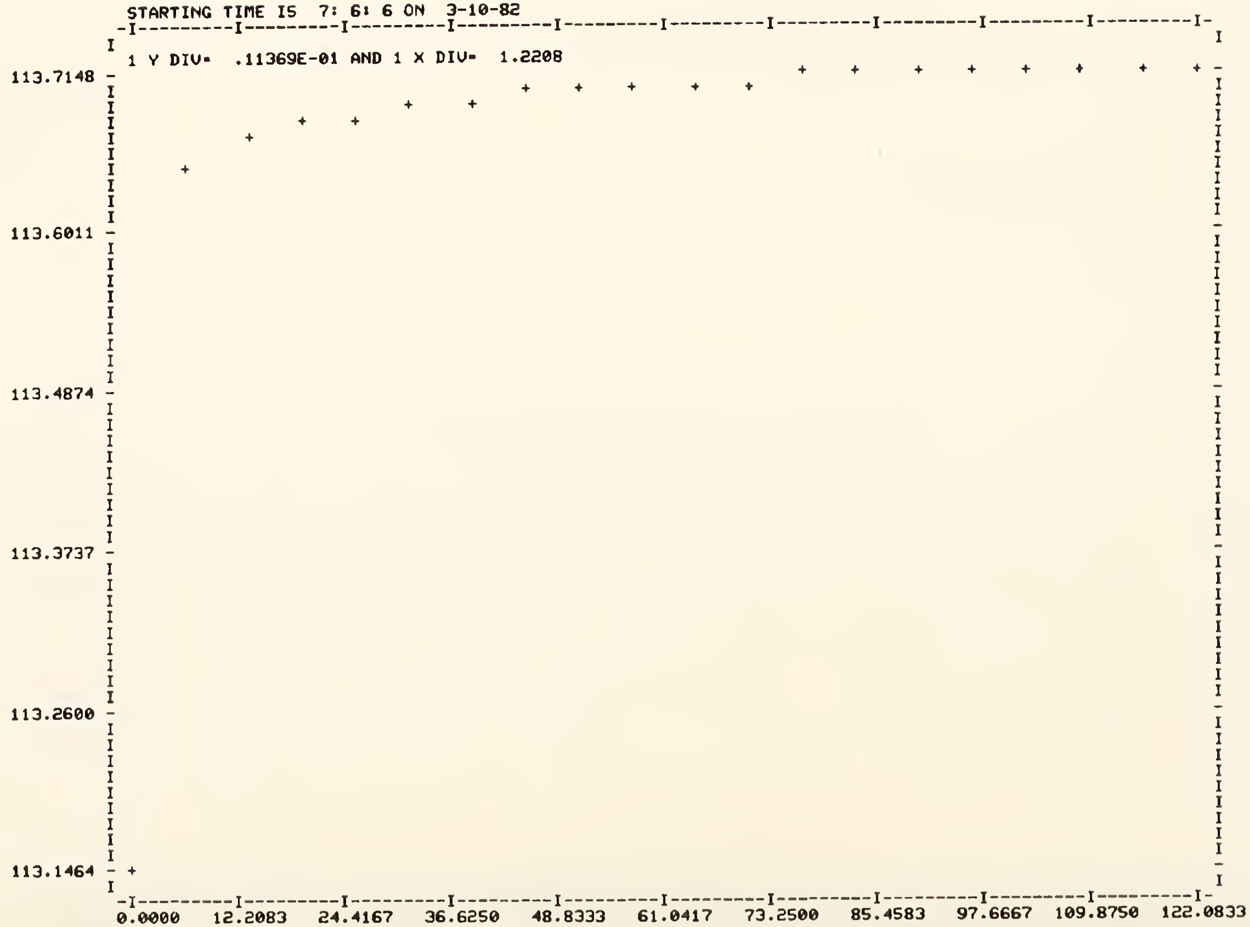
*?



PLOT OF THETA(2) VS TIME (IN MINUTES)

*?

STARTING TIME IS 7: 6: 6 ON 3-10-82



PLOT OF THETA(3) VS TIME (IN MINUTES)

*?

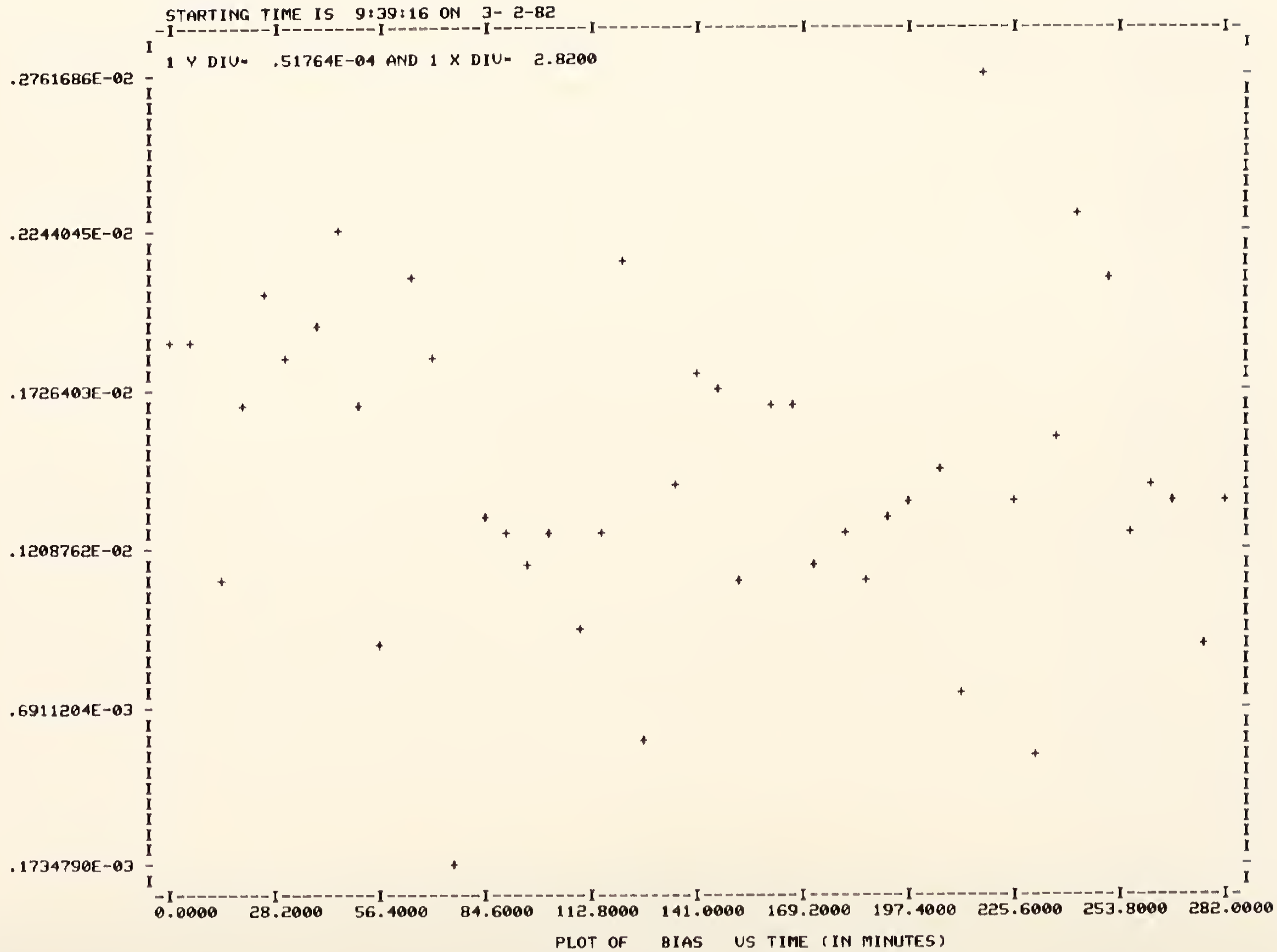
Exhibit C.2

Within-day effects: 45 successive measurements at nominal bearing 120° were collected on March 2, March 26, and March 31 (1982). Each run began from a warm-up start and lasted approximately 4 h, 40 min.

Remarks: 1. Theta(1) has no apparent trend.

2. Theta(2) exhibited a trend on 3-26 and 3-31, but not on 3-2.

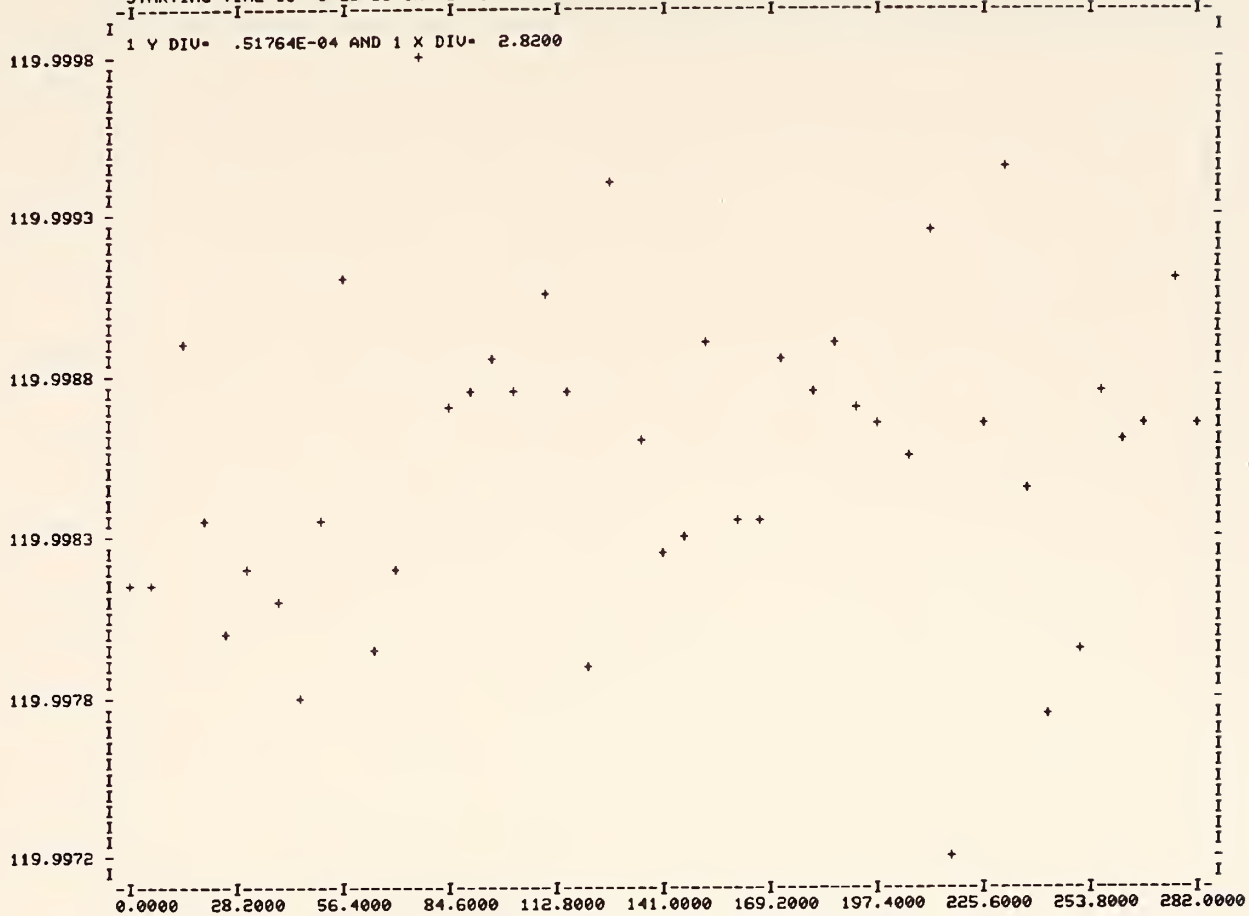
3. Theta(3) plots depict a thermal drift in the associated DAC on all three days. Note, however, that the range of Theta(3) is only 0.0074 on 3-2, 0.0128 on 3-26, and 0.0115 on 3-31. The effect on the drift will be negligible if Theta(3) remains relatively stable during a single determination of Theta(1), i.e., for approximately 6 min.


STARTING TIME IS 9:39:16 ON 3- 2-82
1 Y DIV= .51764E-04 AND 1 X DIV= 2.8200
.2761686E-02
.2244045E-02
.1726403E-02
.1208762E-02
.6911204E-03
.1734790E-03
0.0000
28.2000
56.4000
84.6000
112.8000
141.0000
169.2000
197.4000
225.6000
253.8000
282.0000
PLOT OF BIAS VS TIME (IN MINUTES)

*?

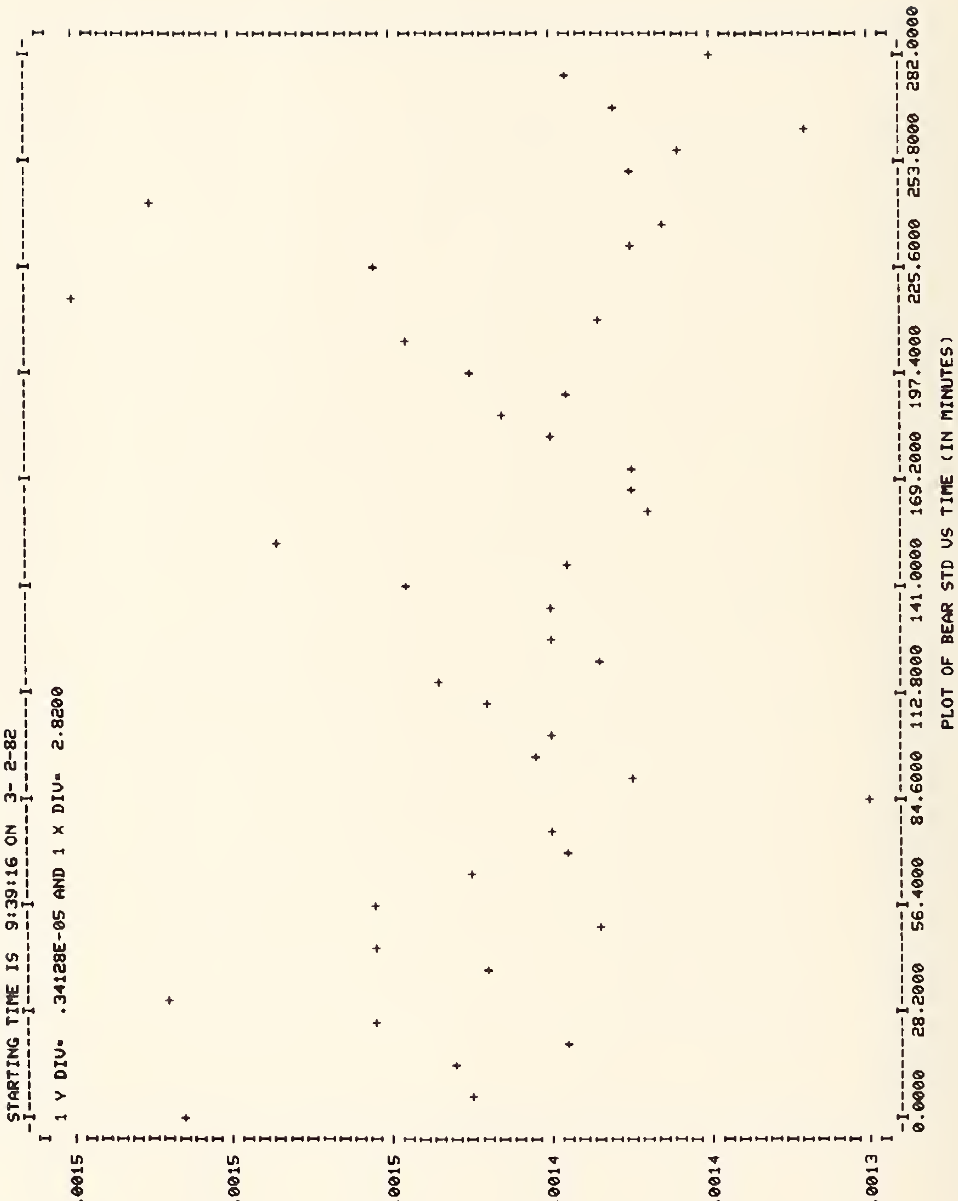
STARTING TIME IS 9:39:16 ON 3- 2-82

1 Y DIV= .51764E-04 AND 1 X DIV= 2.8200

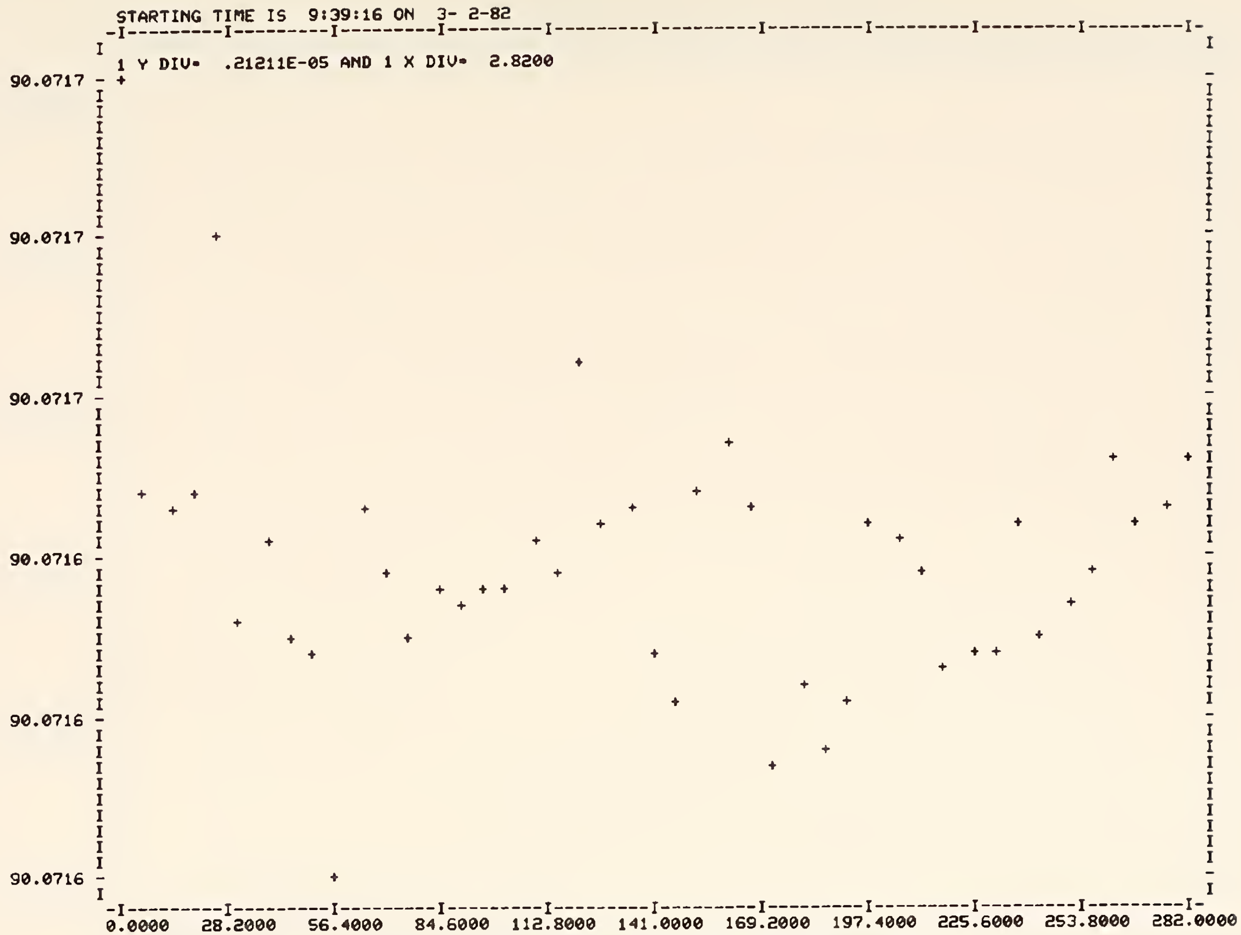


PLOT OF THETA(1) VS TIME (IN MINUTES)

*?


STARTING TIME IS 9:39:16 ON 3- 2-82
1 Y DIV= .34128E-05 AND 1 X DIV= 2.8200
.0015
.0015
.0015
.0014
.0014
.0013
0.0000
28.2000
56.4000
84.6000
112.8000
141.0000
169.2000
197.4000
225.6000
253.8000
282.0000
PLOT OF BEAR STD VS TIME (IN MINUTES)

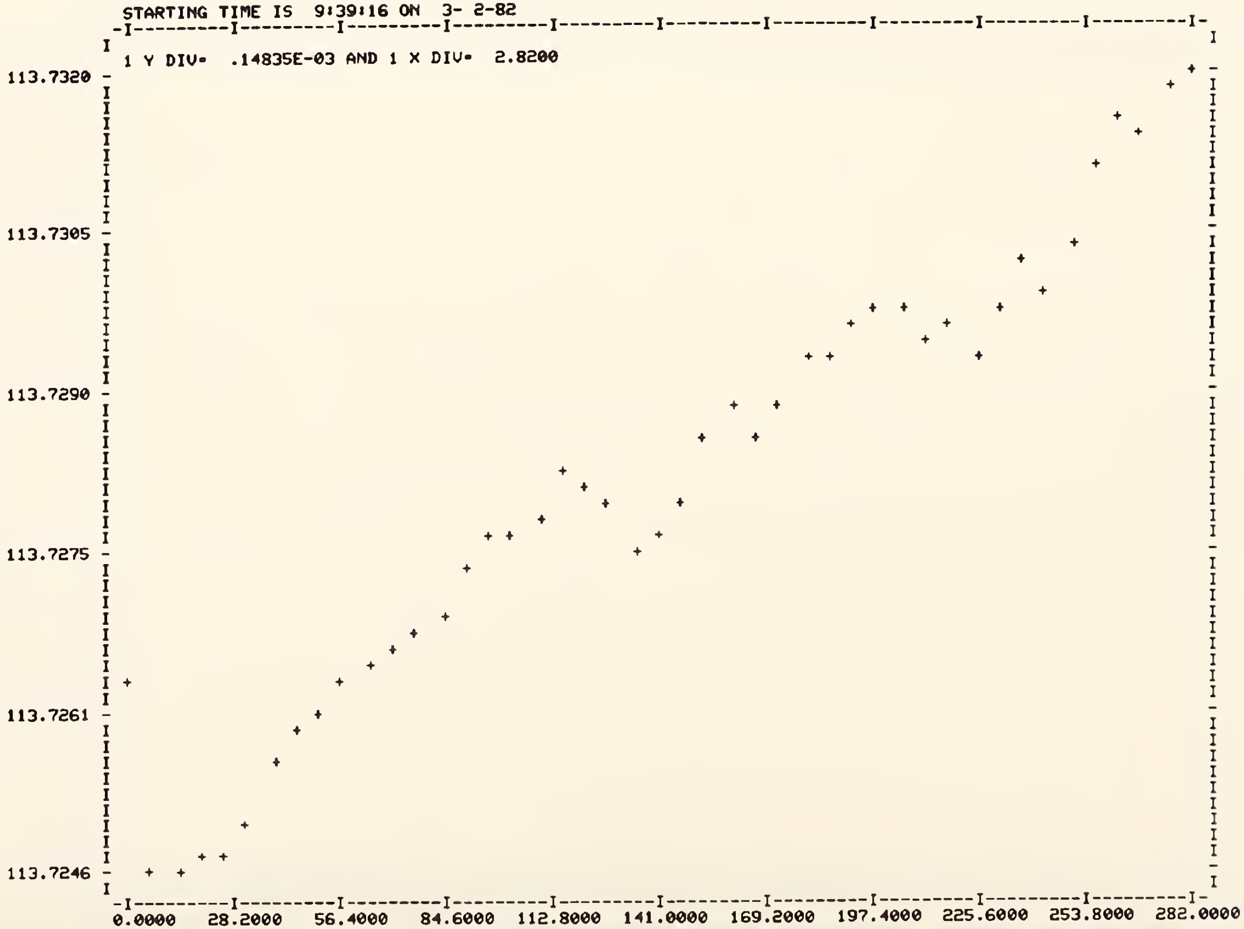
*?



PLOT OF THETA(2) VS TIME (IN MINUTES)

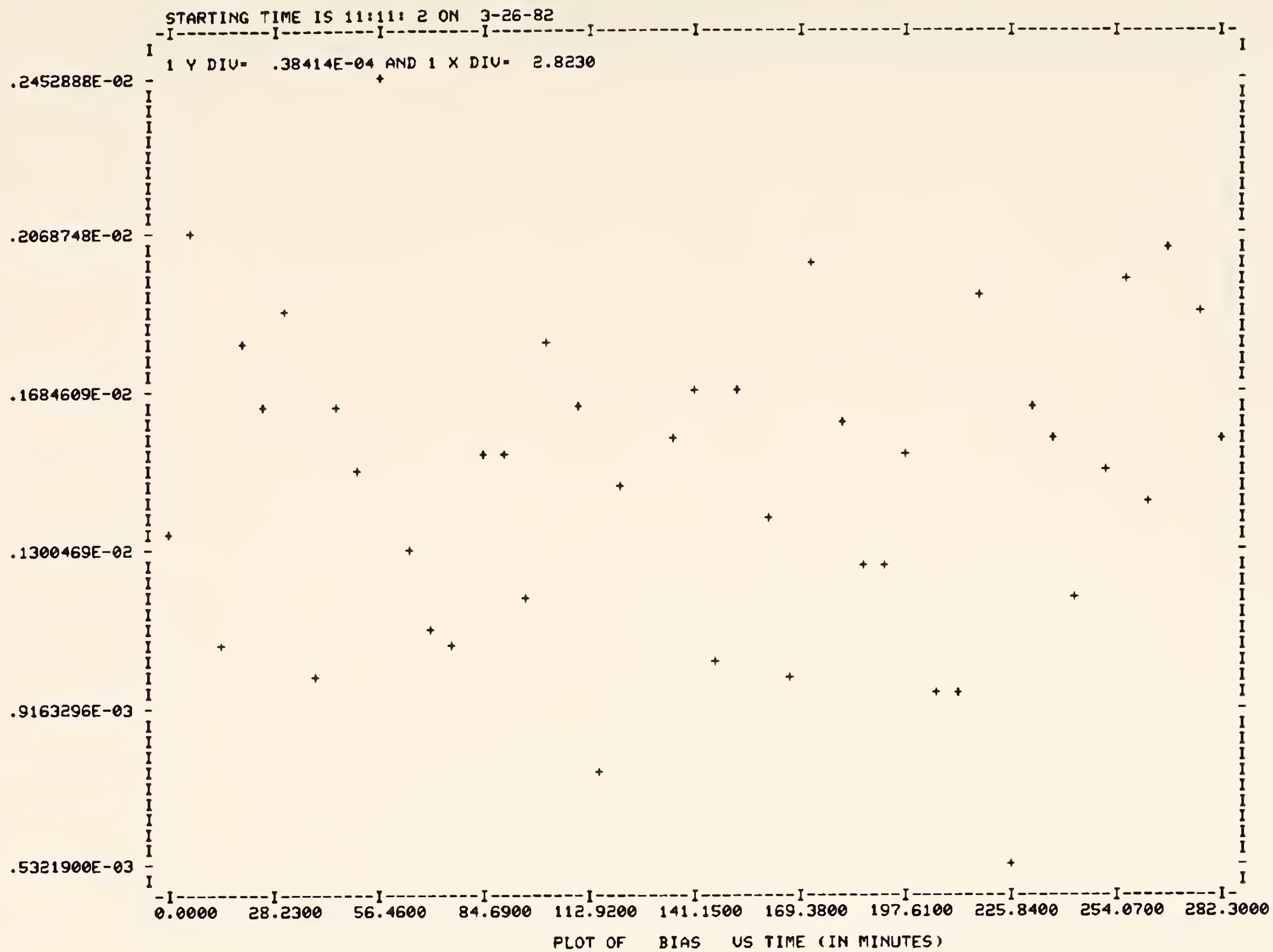
*?

STARTING TIME IS 9:39:16 ON 3- 2-82



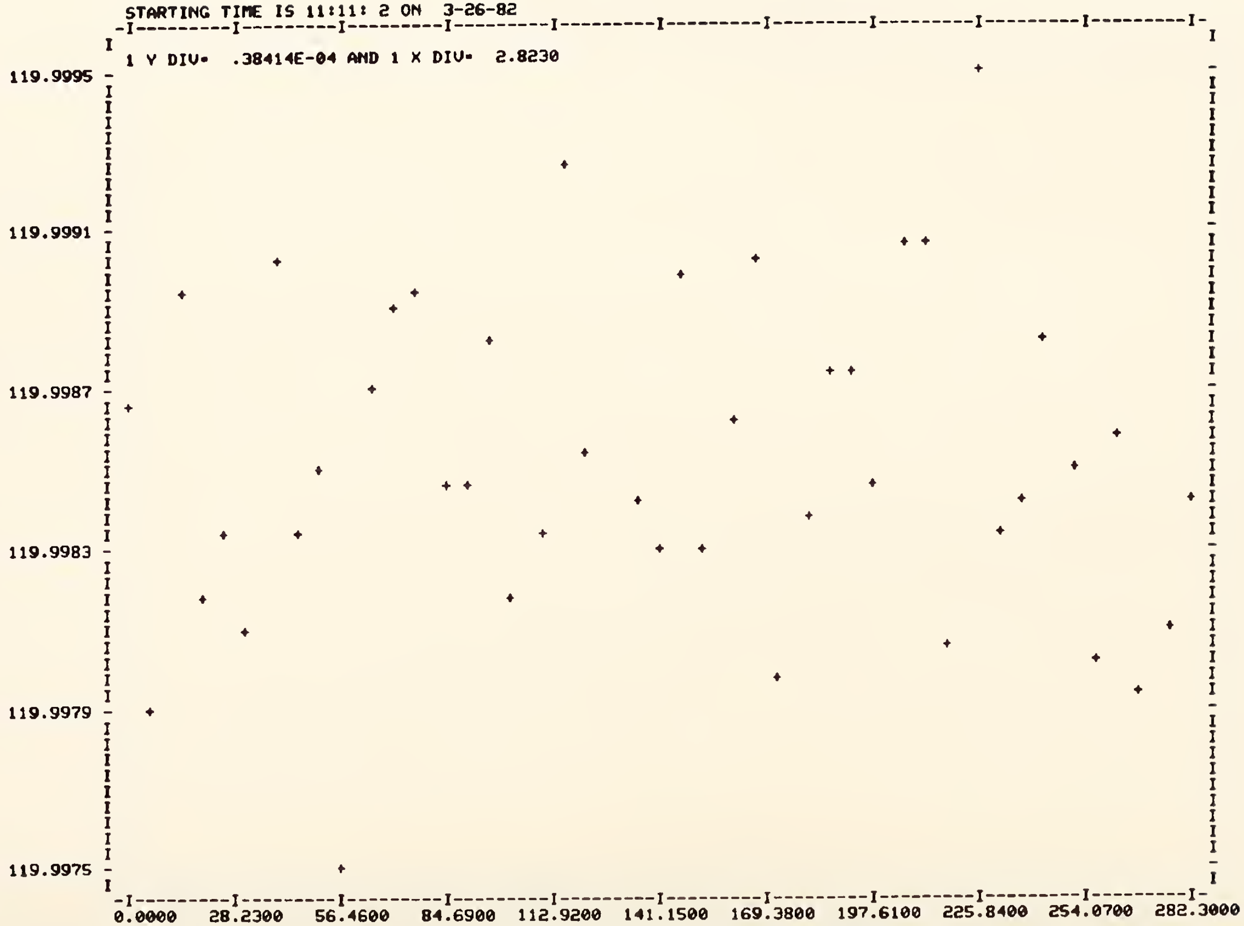
PLOT OF THETA(3) VS TIME (IN MINUTES)

*?


STARTING TIME IS 11:11: 2 ON 3-26-82
1 Y DIV= .38414E-04 AND 1 X DIV= 2.8230
.2452888E-02
.2068748E-02
.1684609E-02
.1300469E-02
.9163296E-03
.5321900E-03
0.0000
28.2300
56.4600
84.6900
112.9200
141.1500
169.3800
197.6100
225.8400
254.0700
282.3000
PLOT OF BIAS VS TIME (IN MINUTES)

*?

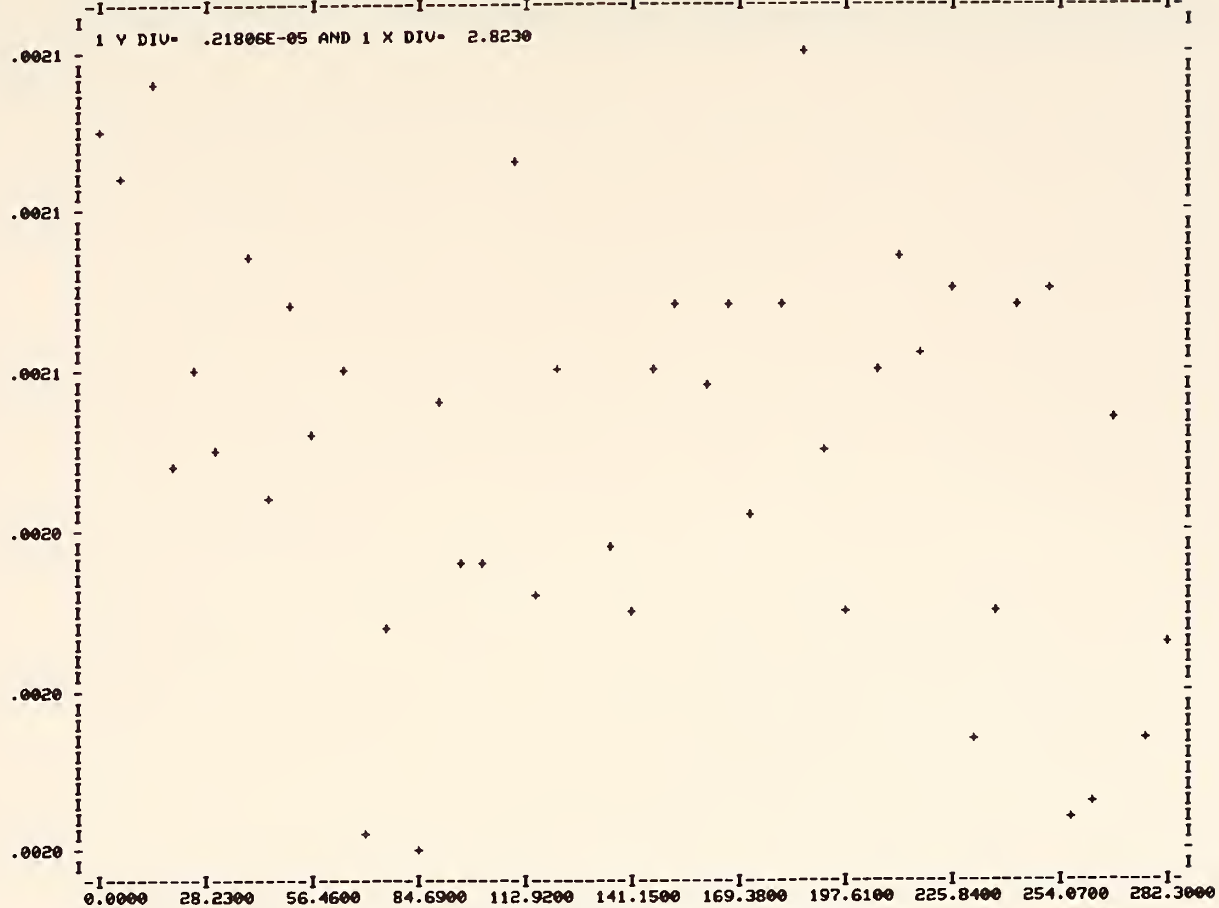
STARTING TIME IS 11:11: 2 ON 3-26-82



PLOT OF THETA(1) VS TIME (IN MINUTES)

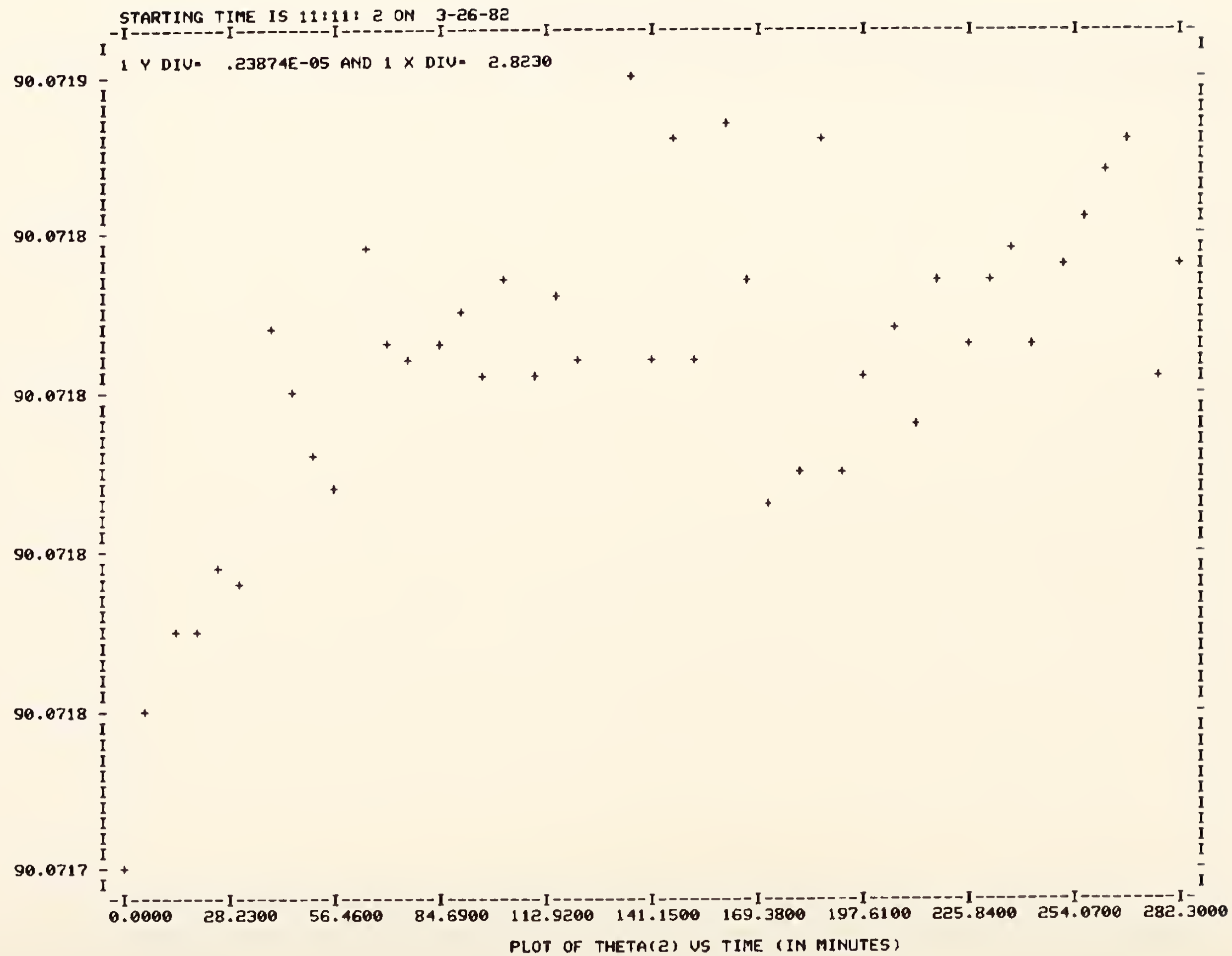
*?

STARTING TIME IS 11:11: 2 ON 3-26-82



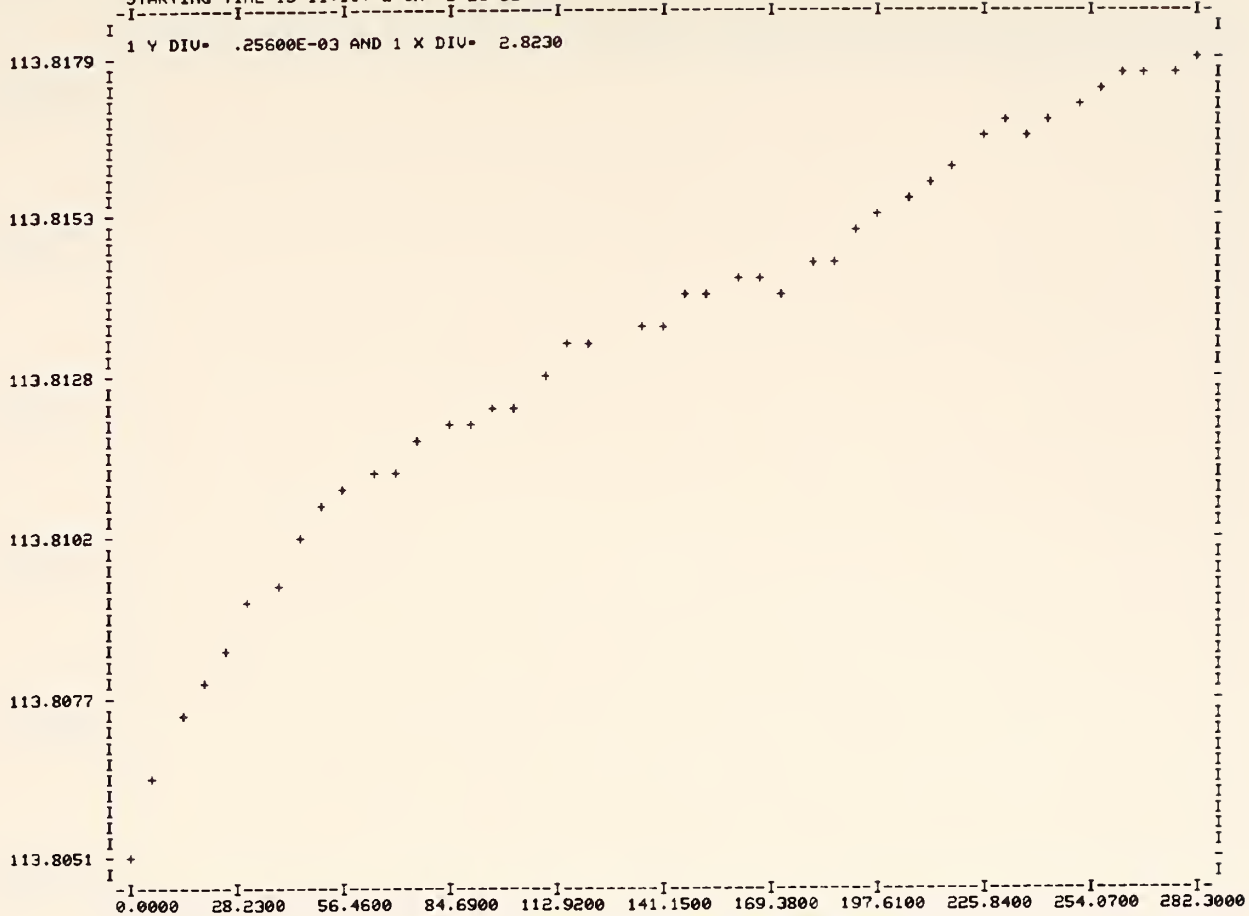
PLOT OF BEAR STD VS TIME (IN MINUTES)

*?


STARTING TIME IS 11:11: 2 ON 3-26-82
1 Y DIV= .23874E-05 AND 1 X DIV= 2.8230
90.0719
90.0718
90.0718
90.0718
90.0718
90.0717
0.0000
28.2300
56.4600
84.6900
112.9200
141.1500
169.3800
197.6100
225.8400
254.0700
282.3000
PLOT OF THETA(2) VS TIME (IN MINUTES)

*?

STARTING TIME IS 11:11: 2 ON 3-26-82

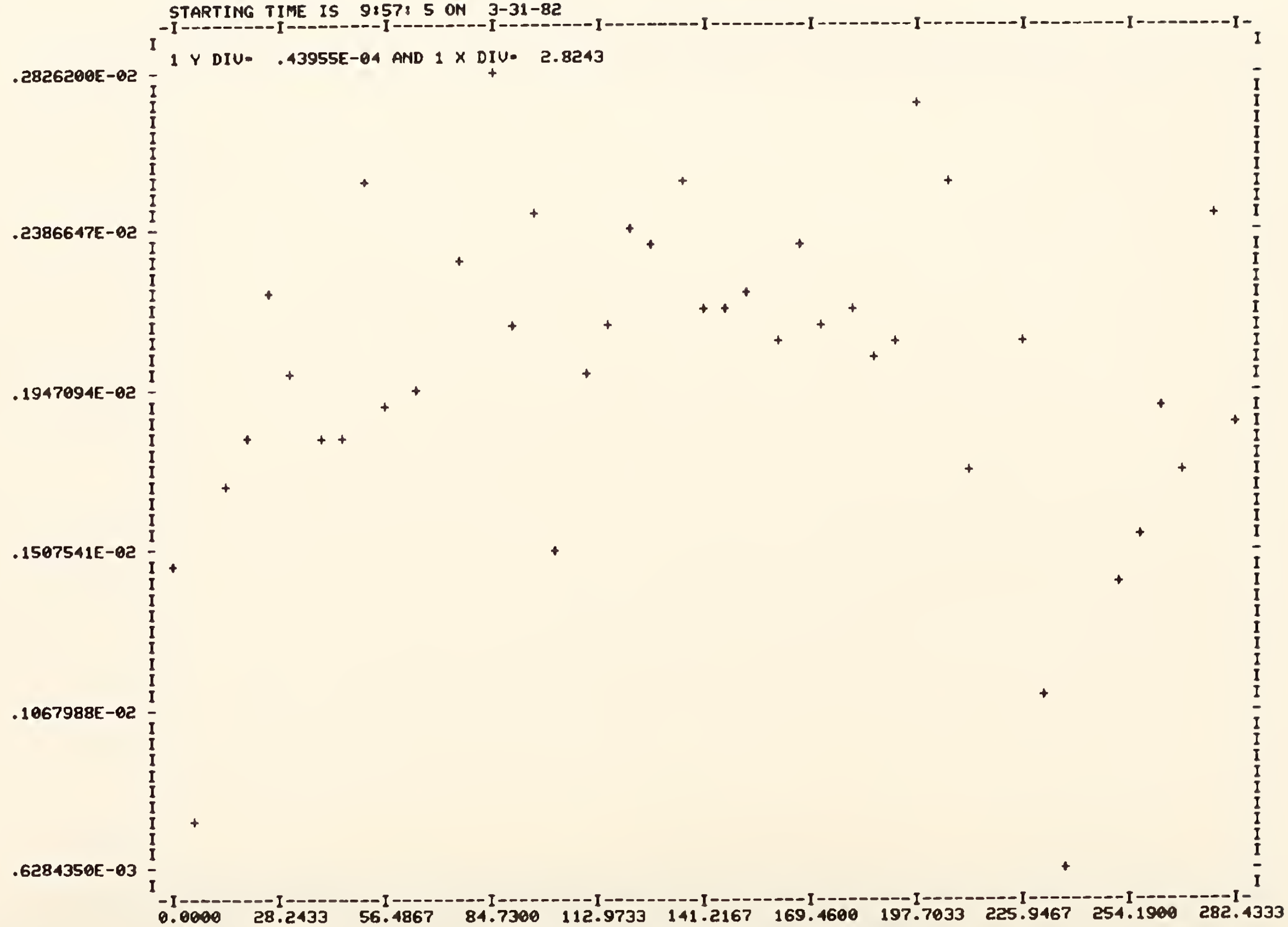


PLOT OF THETA(3) VS TIME (IN MINUTES)

*?

STARTING TIME IS 9:57: 5 ON 3-31-82

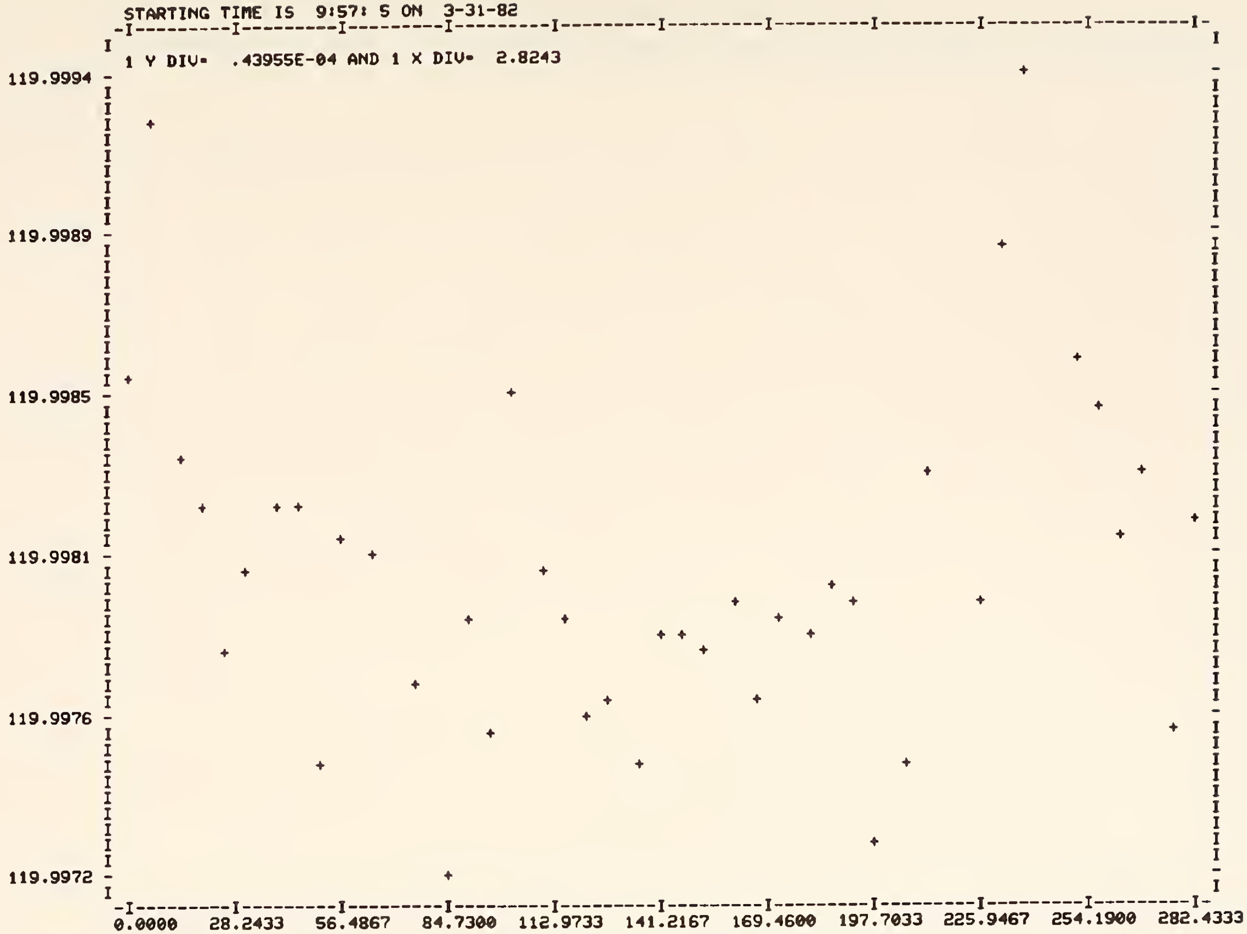
1 Y DIV= .43955E-04 AND 1 X DIV= 2.8243



PLOT OF BIAS BY TIME (IN MINUTES)

*?

STARTING TIME IS 9:57: 5 ON 3-31-82

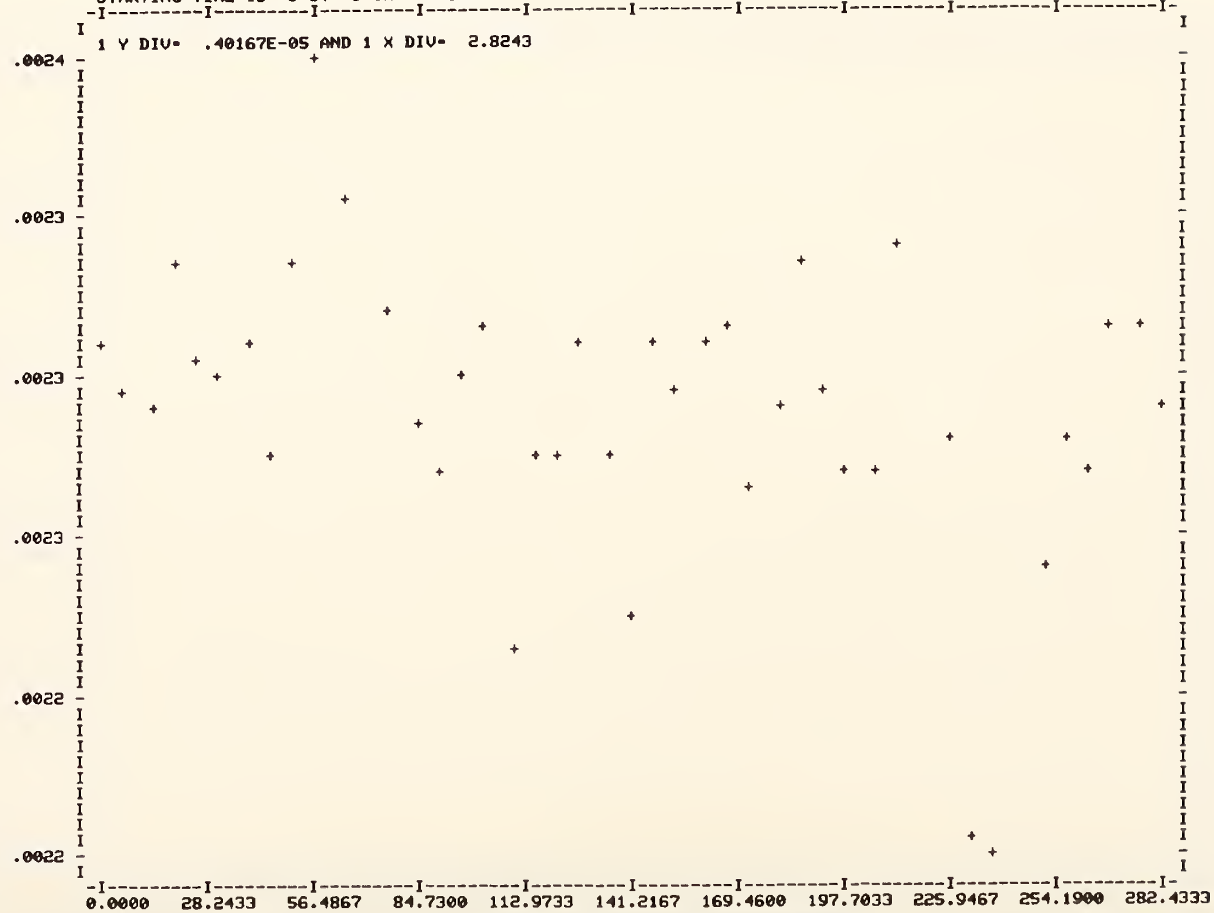


PLOT OF THETA 1 BY TIME (IN MINUTES)

*?

STARTING TIME IS 9:57: 5 ON 3-31-82

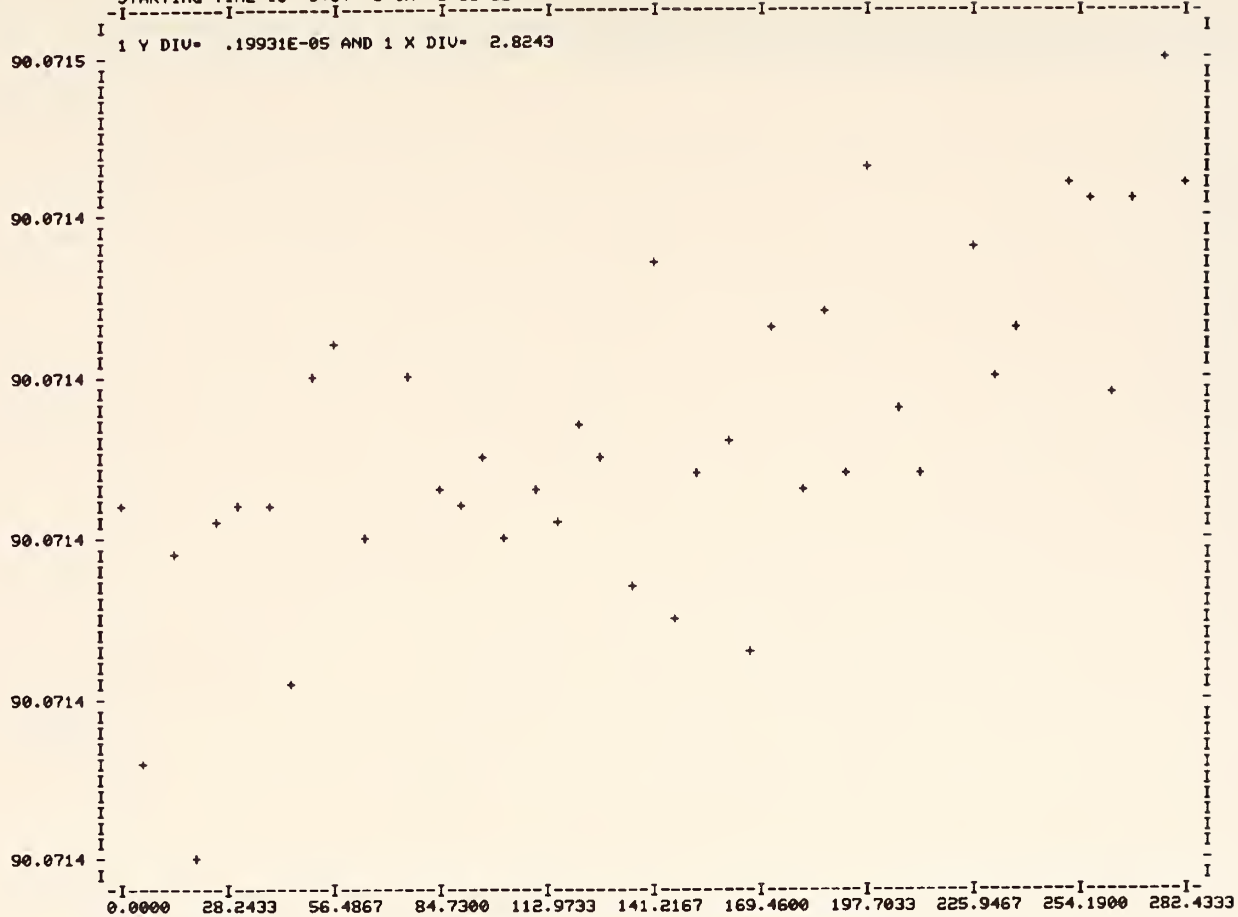
1 Y DIV= .40167E-05 AND 1 X DIV= 2.8243



PLOT OF BEARSTD BY TIME (IN MINUTES)

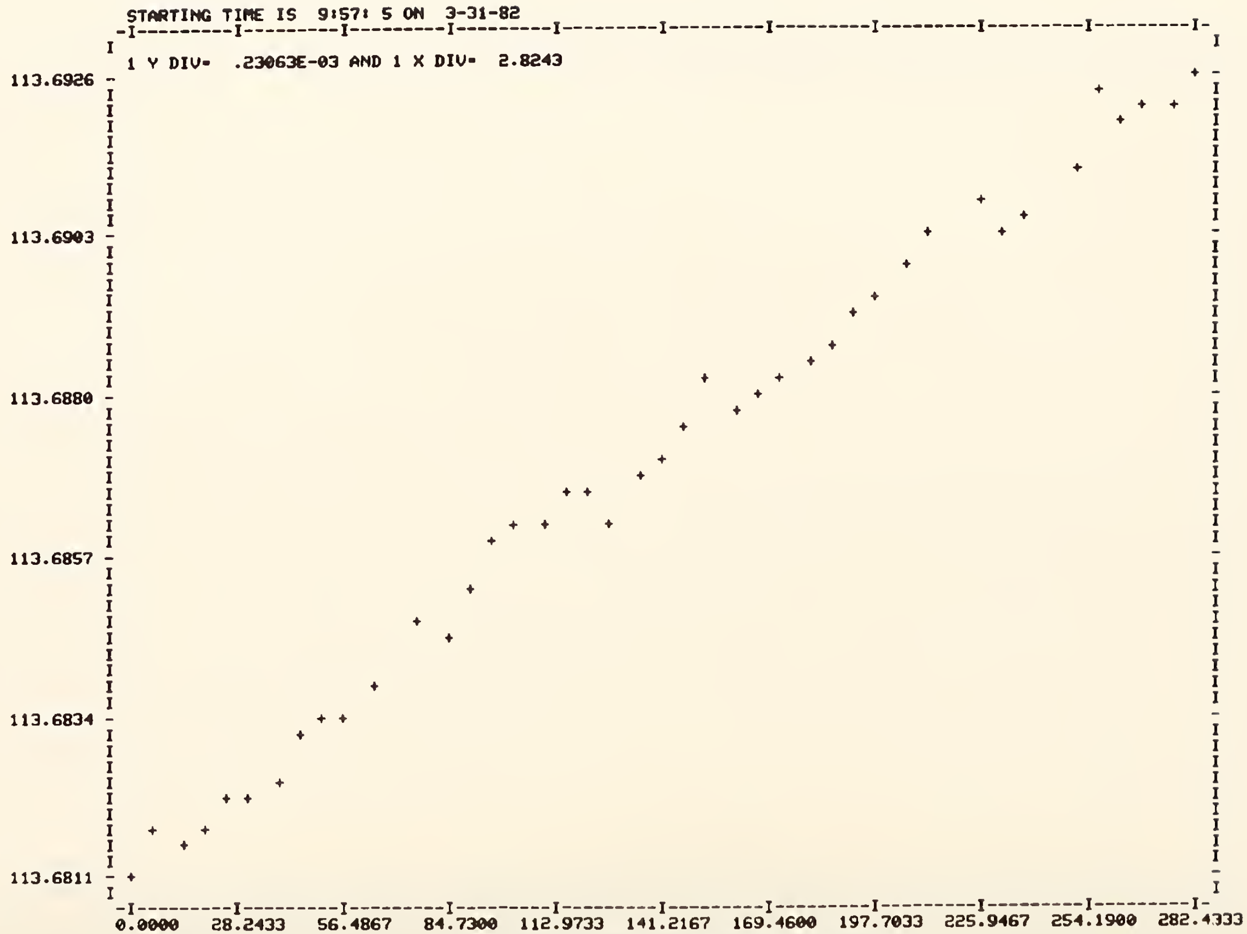
*?

STARTING TIME IS 9:57: 5 ON 3-31-82



PLOT OF THETA 2 BY TIME (IN MINUTES)

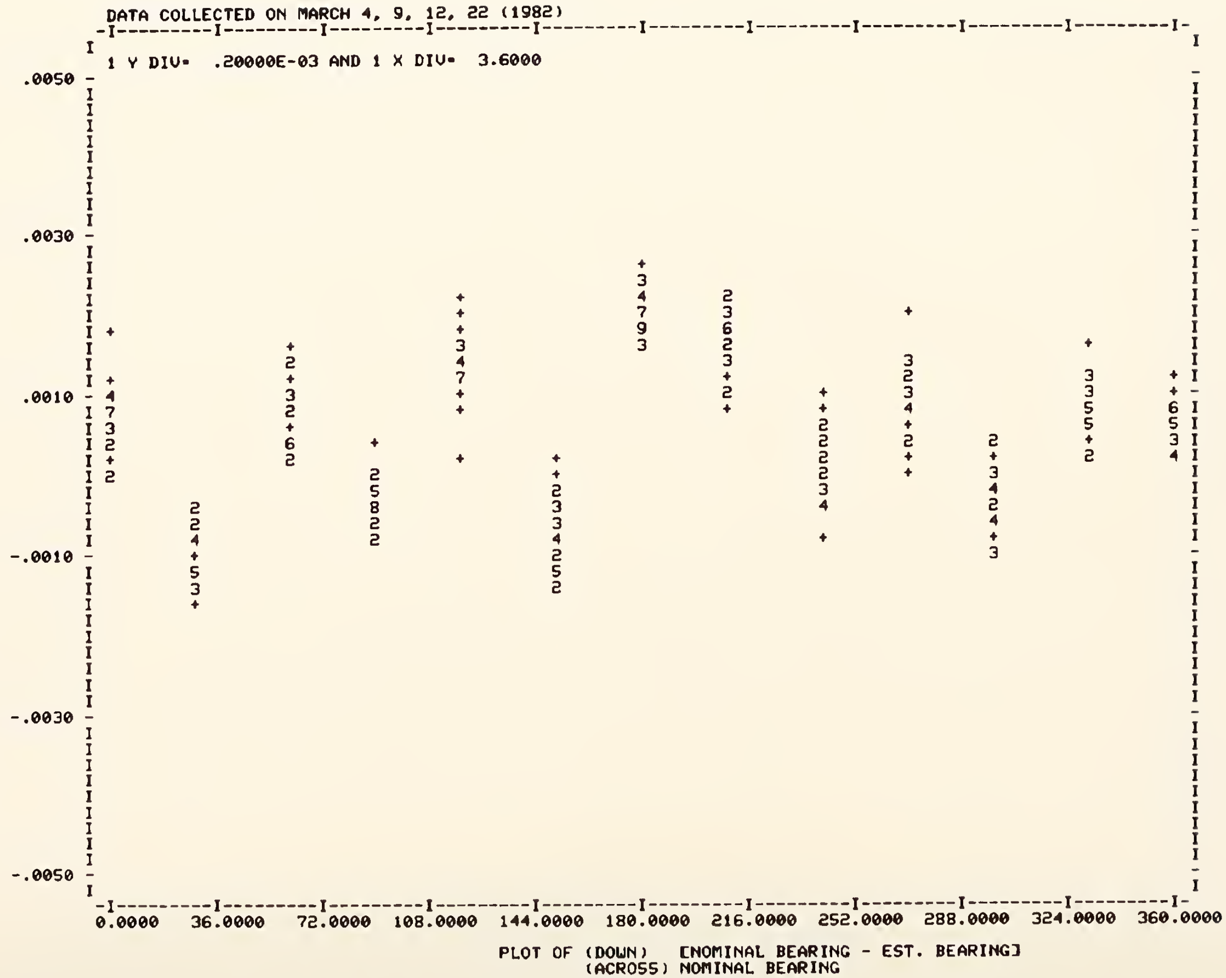
*?



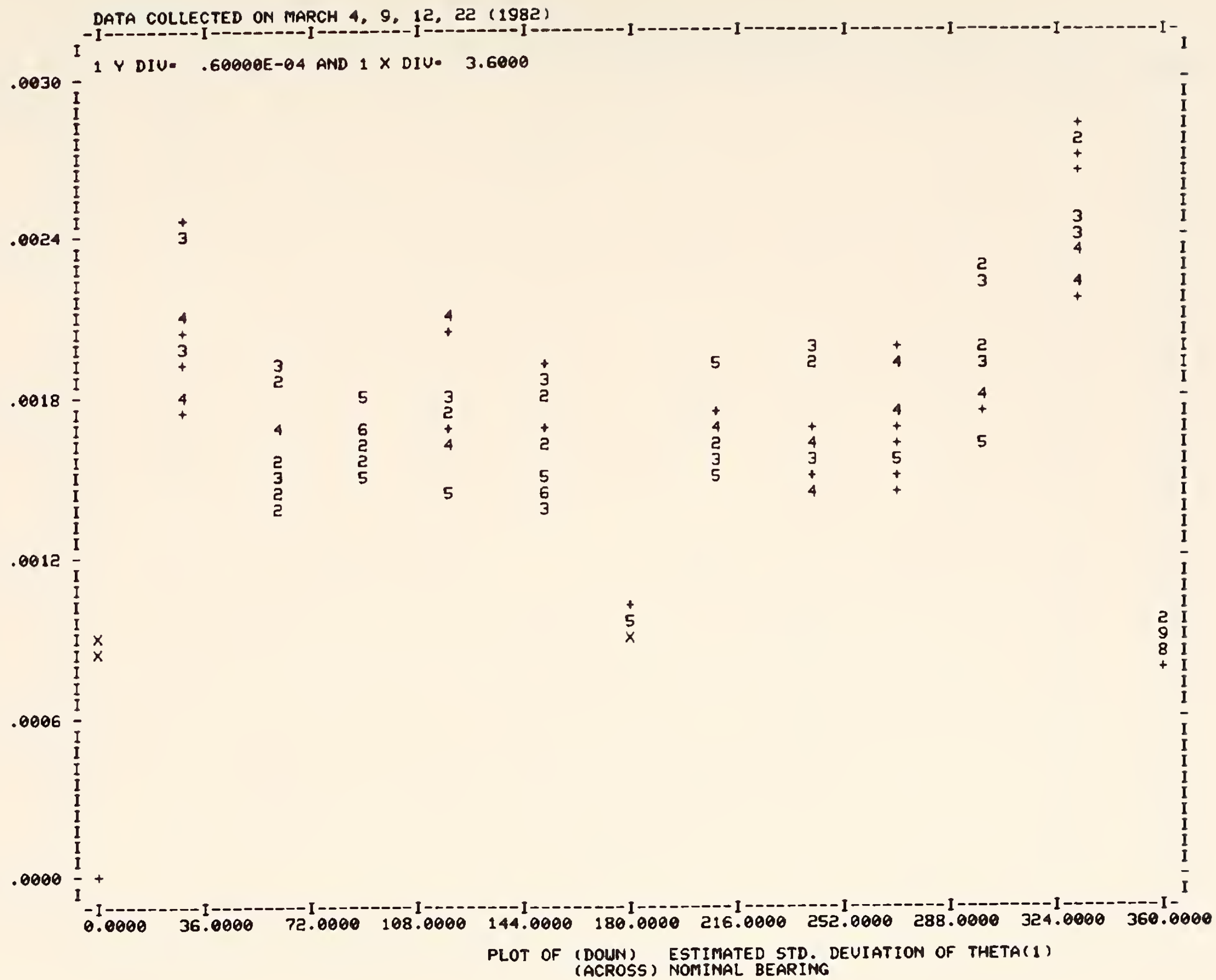
PLOT OF THETA 3 BY TIME (IN MINUTES)

*?

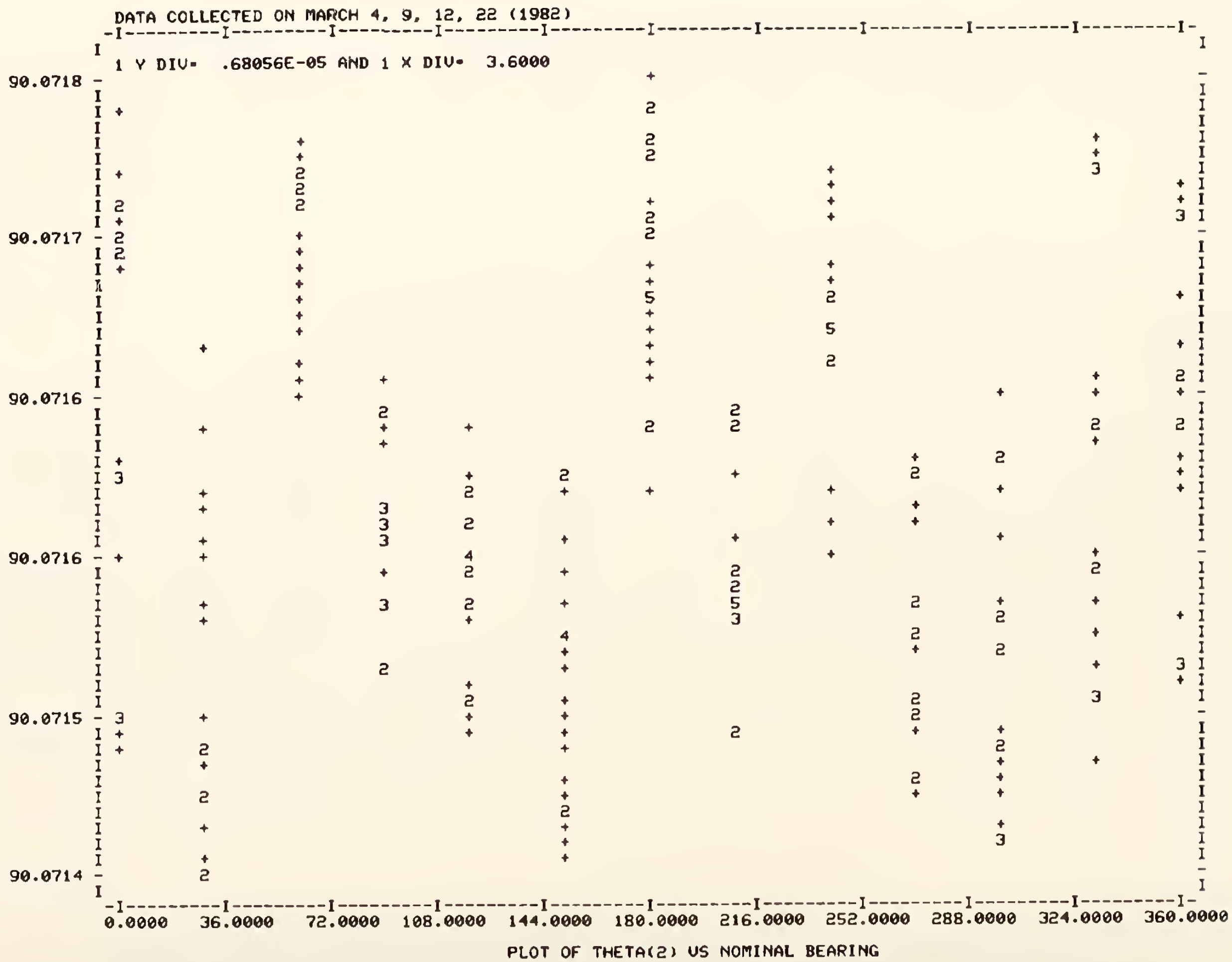
Systematic offset from nominal bearing: The 275 measurements from the first 4 occasions used to obtain the provisional uncertainty statement for the VOR calibration service are useful to illustrate the slight offset of the standard phasemeter measurements from the nominal bearing of the standard signal generator. The various quantities obtained from the set of measurements, excluding outliers, is plotted versus nominal bearing. There are five groups of plots, each with four separate graphs. The first group shows the combined data from the four measurement occasions. The other four sets of plots show each occasion separately, as labeled.


DATA COLLECTED ON MARCH 4, 9, 12, 22 (1982)
1 Y DIV= .20000E-03 AND 1 X DIV= 3.6000
.0050
.0030
.0010
-.0010
-.0030
-.0050
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF (DOWN) [NOMINAL BEARING - EST. BEARING]
(ACROSS) NOMINAL BEARING

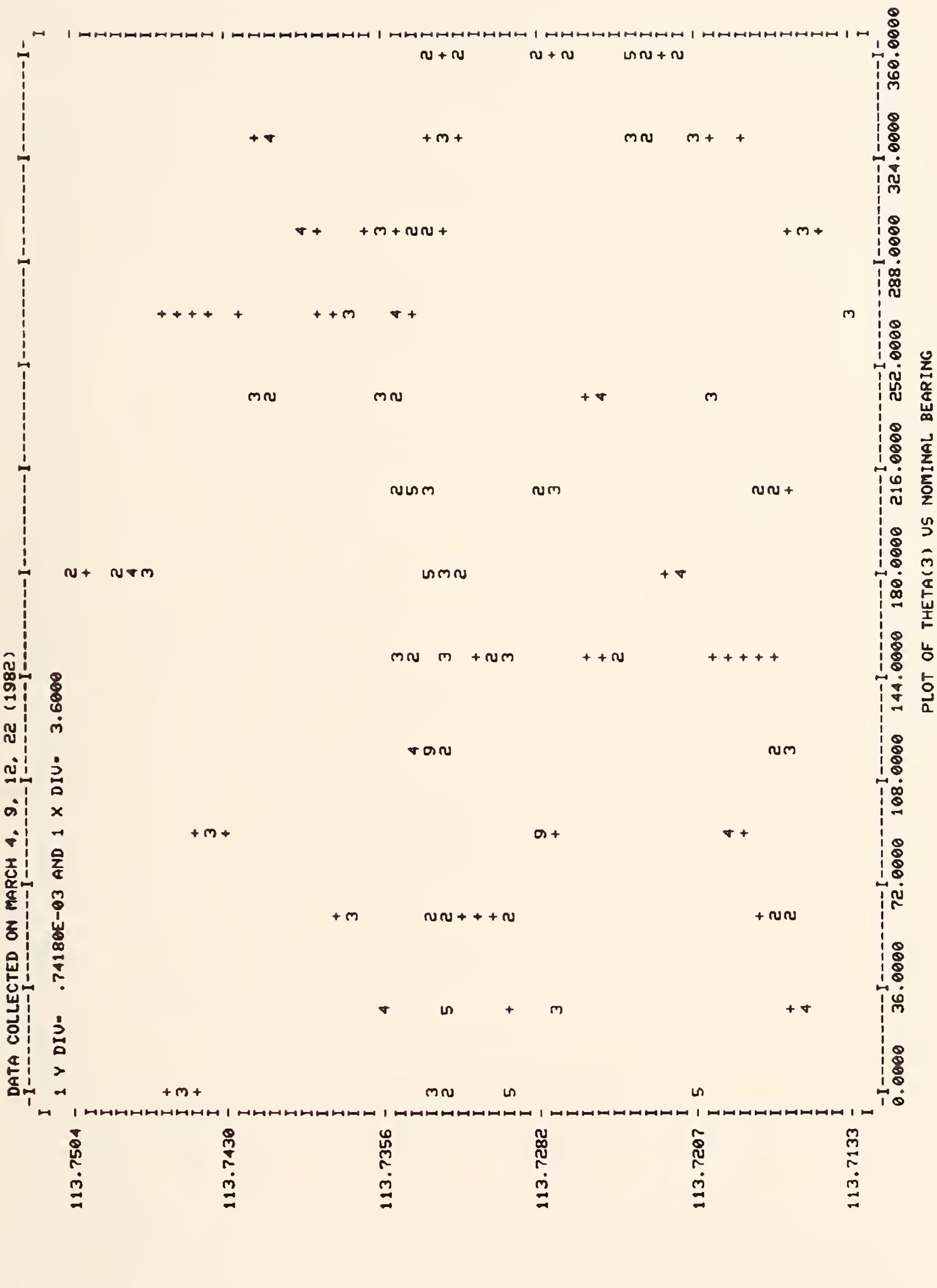
*?


DATA COLLECTED ON MARCH 4, 9, 12, 22 (1982)
1 Y DIV= .60000E-04 AND 1 X DIV= 3.6000
.0030
.0024
.0018
.0012
.0006
.0000
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF (DOWN) ESTIMATED STD. DEVIATION OF THETA(1)
(ACROSS) NOMINAL BEARING

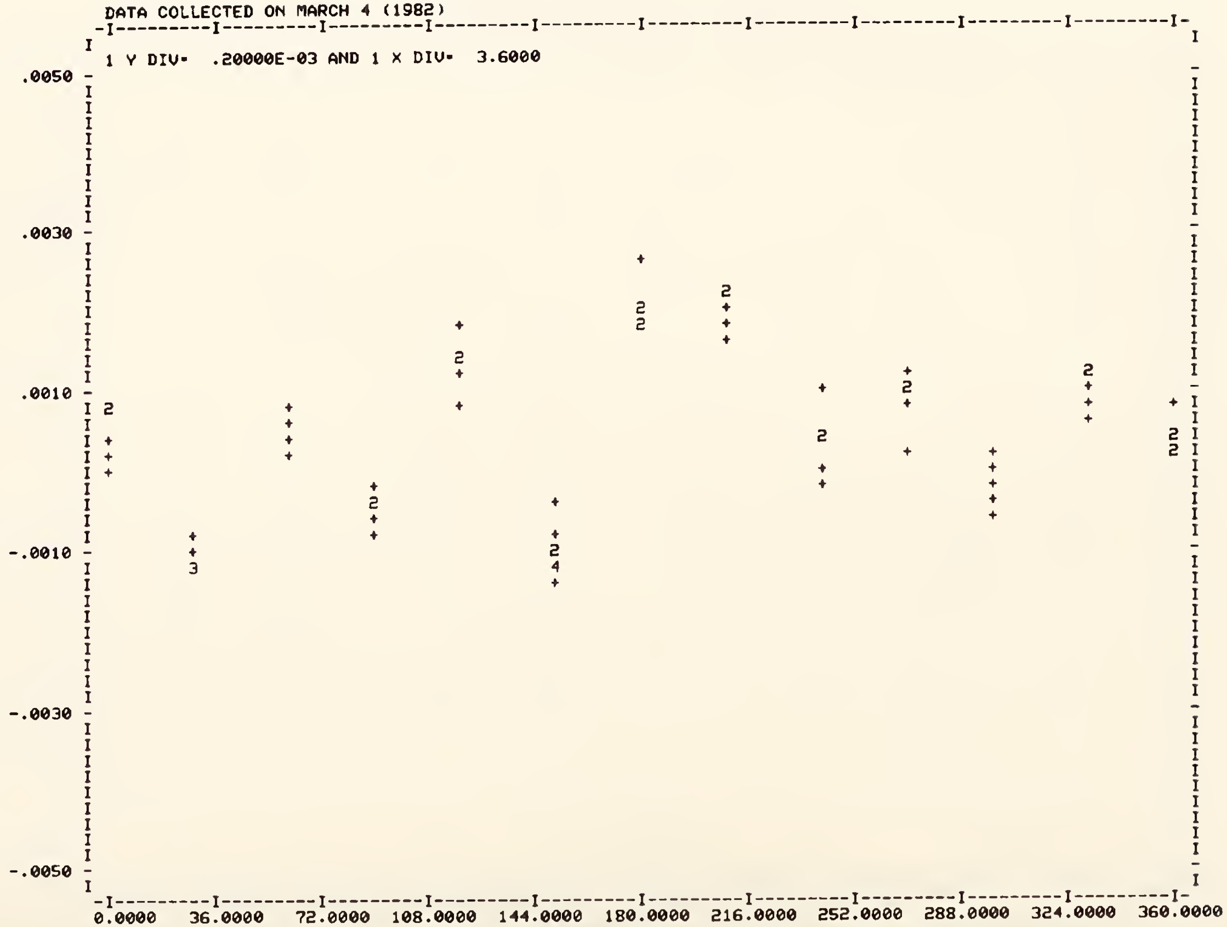
*?


DATA COLLECTED ON MARCH 4, 9, 12, 22 (1982)
1 Y DIV= .68056E-05 AND 1 X DIV= 3.6000
90.0718
90.0717
90.0716
90.0716
90.0715
90.0714
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF THETA(2) VS NOMINAL BEARING

*?

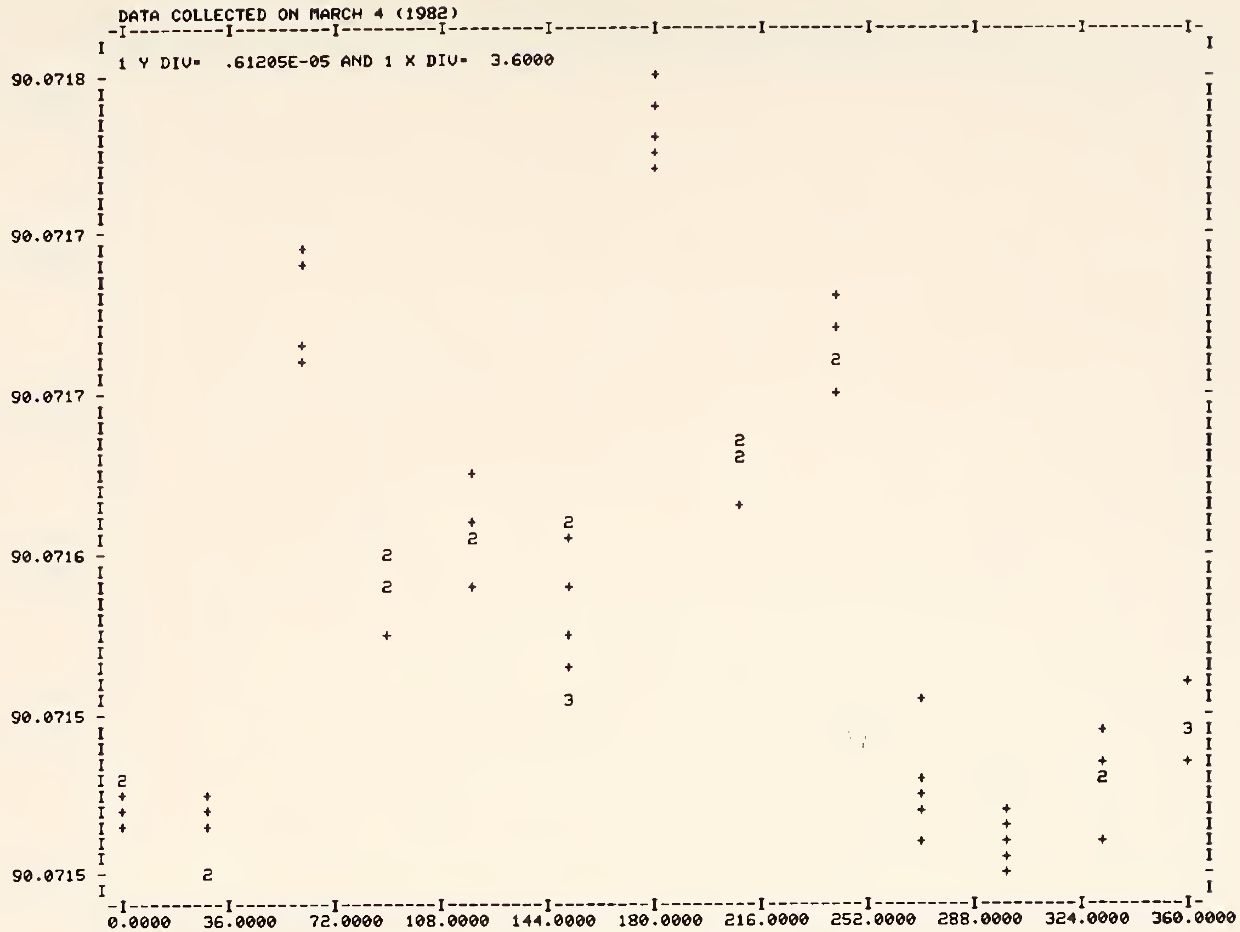

DATA COLLECTED ON MARCH 4, 9, 12, 22 (1982)
1 Y DIV= .74180E-03 AND 1 X DIV= 3.6000
113.7504
113.7430
113.7356
113.7282
113.7207
113.7133
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF THETA(3) VS NOMINAL BEARING

DATA COLLECTED ON MARCH 4 (1982)



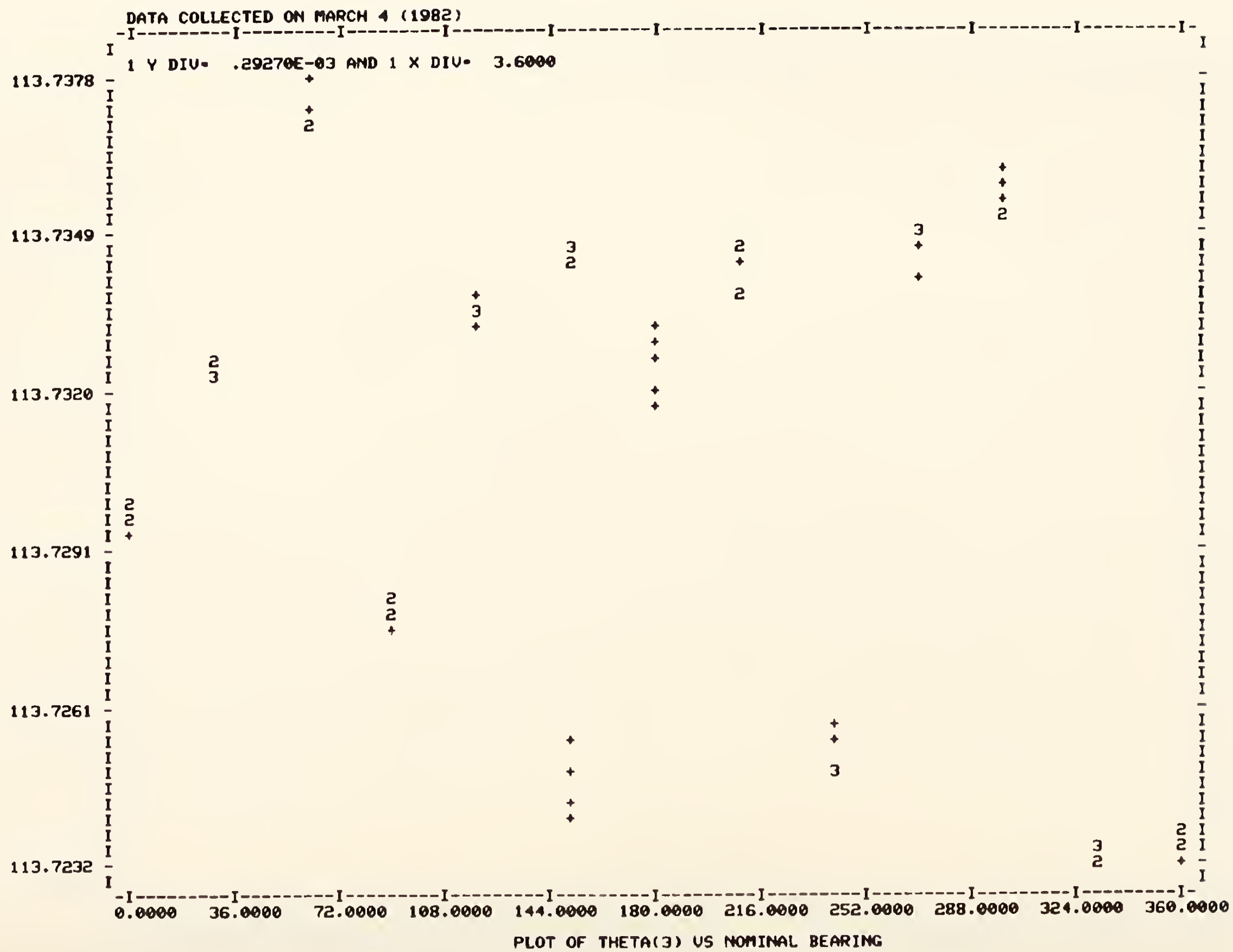
PLOT OF [BEARING - THETA(1)] VS NOMINAL BEARING

*?



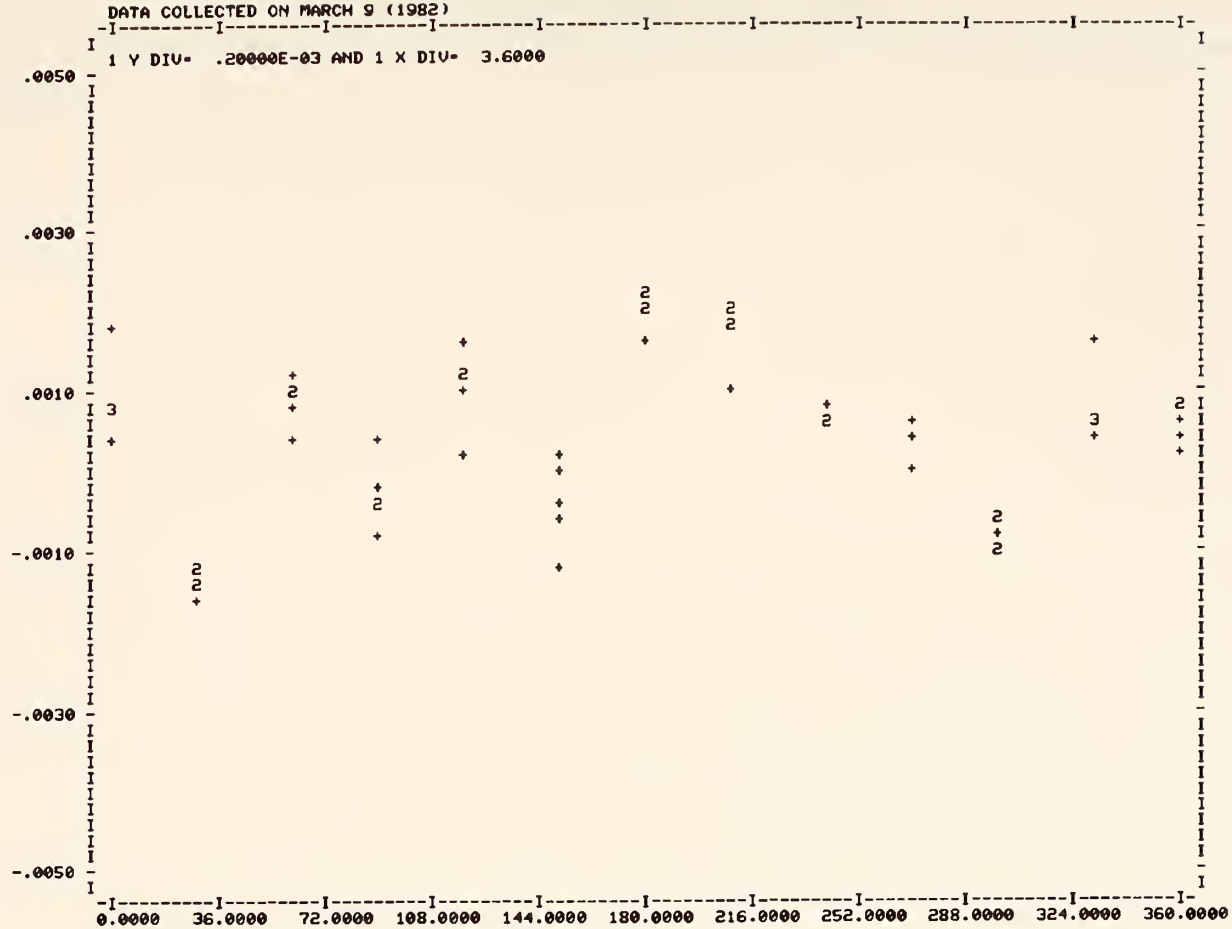
PLOT OF THETA(2) VS NOMINAL BEARING

*?


DATA COLLECTED ON MARCH 4 (1982)
1 Y DIV= .29270E-03 AND 1 X DIV= 3.6000
113.7378
113.7349
113.7320
113.7291
113.7261
113.7232
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF THETA(3) VS NOMINAL BEARING

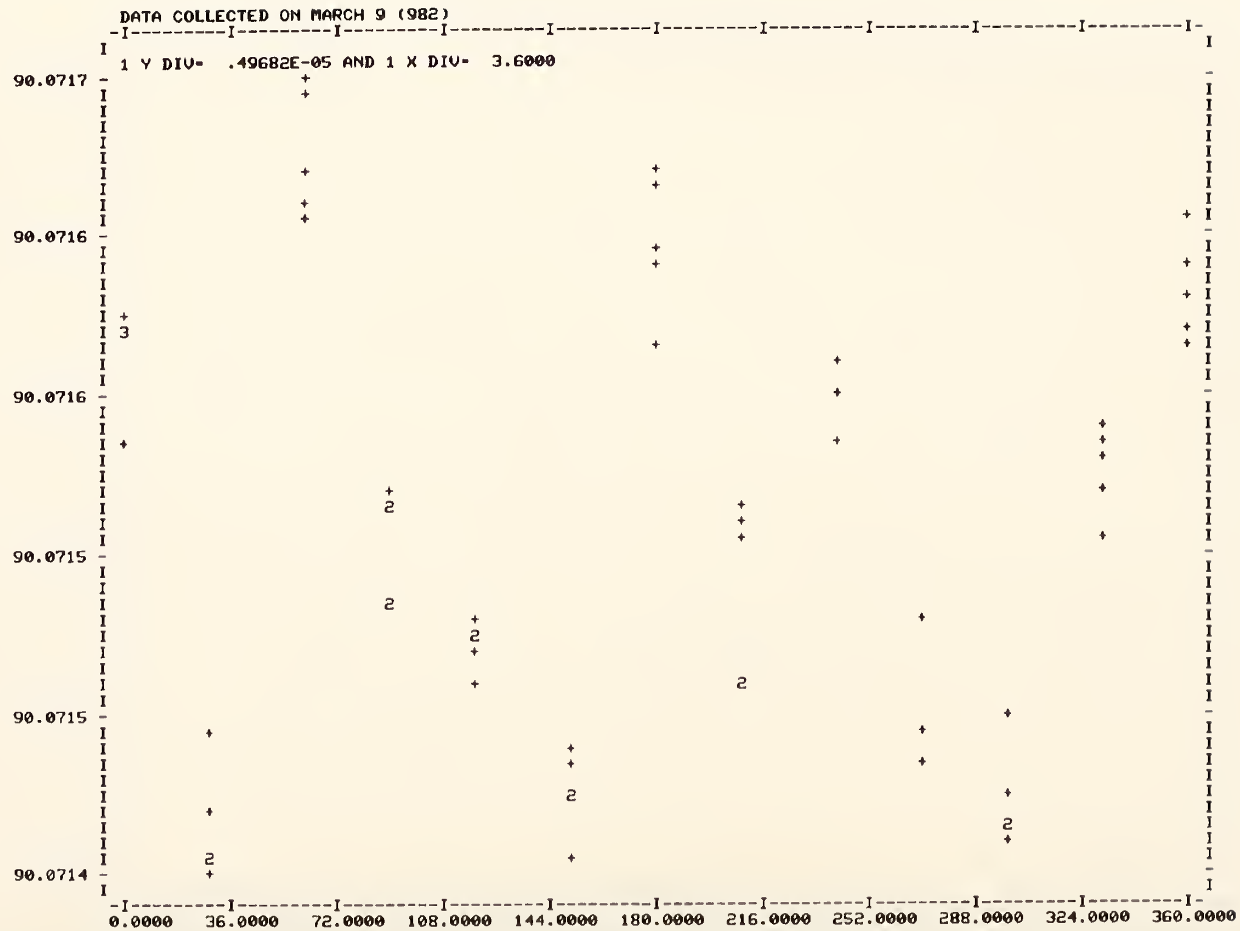
*?

DATA COLLECTED ON MARCH 9 (1982)



PLOT OF [BEARING - THETA(1)] VS NOMINAL BEARING

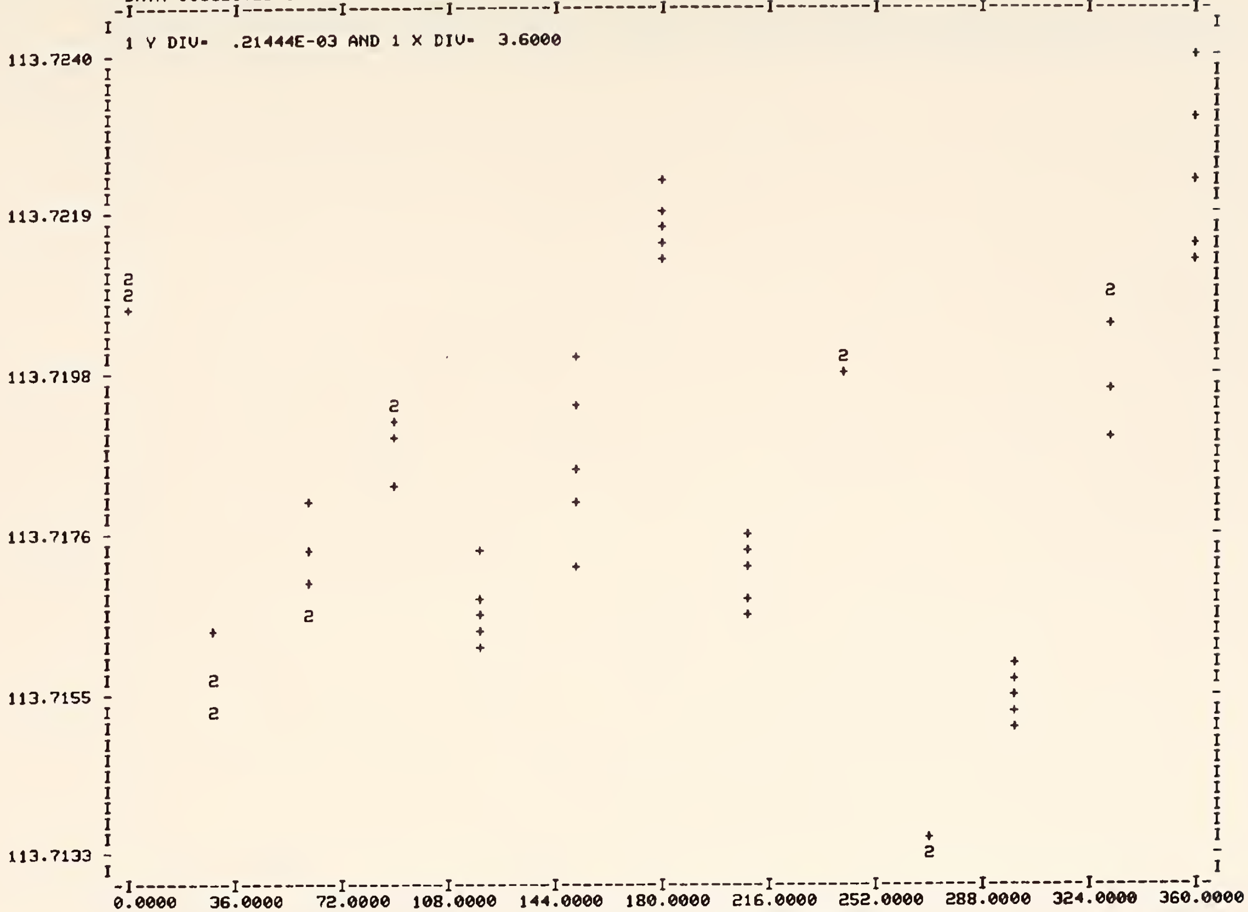
*?



PLOT OF THETA(2) VS NOMINAL BEARING

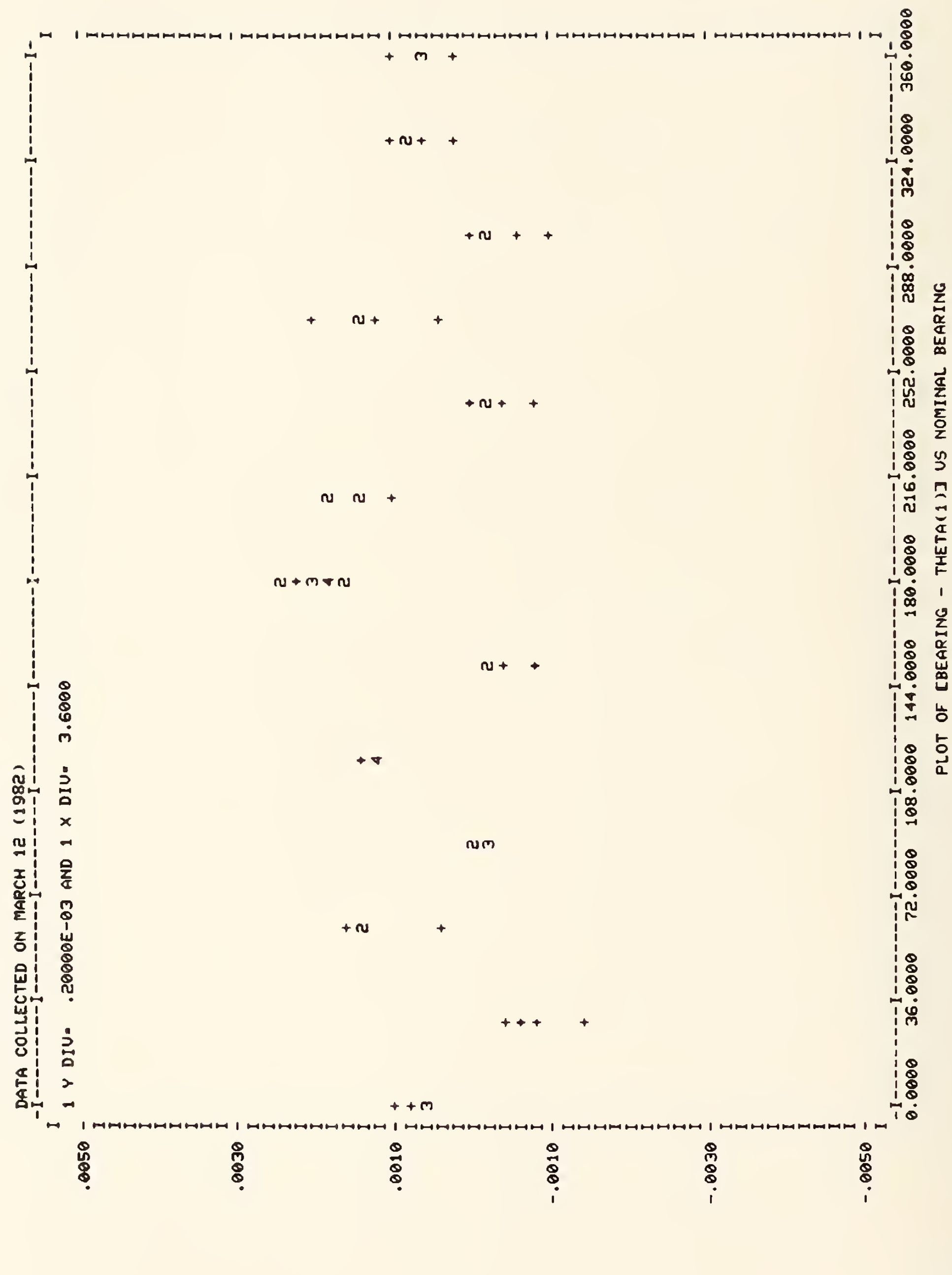
*?

DATA COLLECTED ON MARCH 9 (1982)

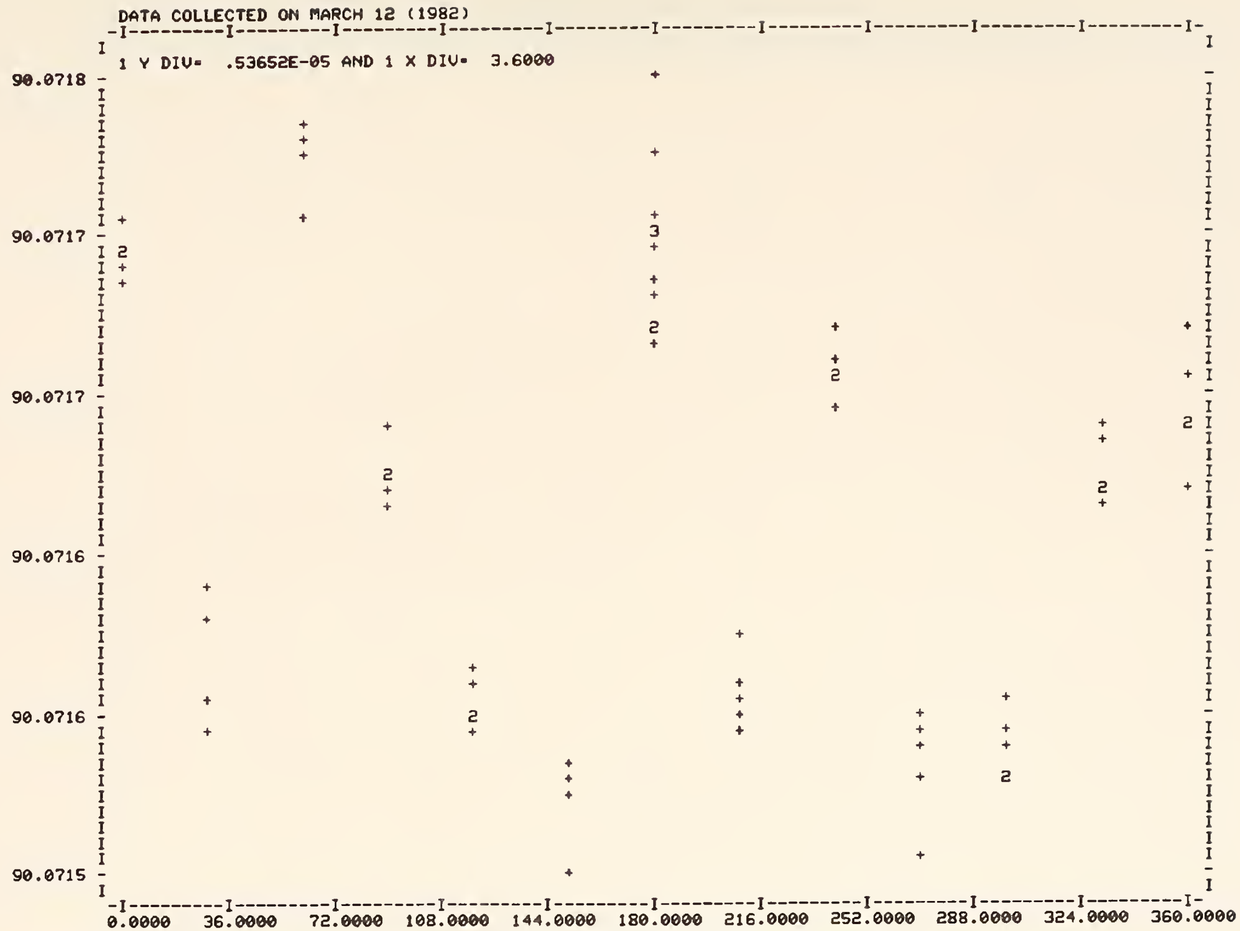


PLOT OF THETA(3) VS NOMINAL BEARING

*?

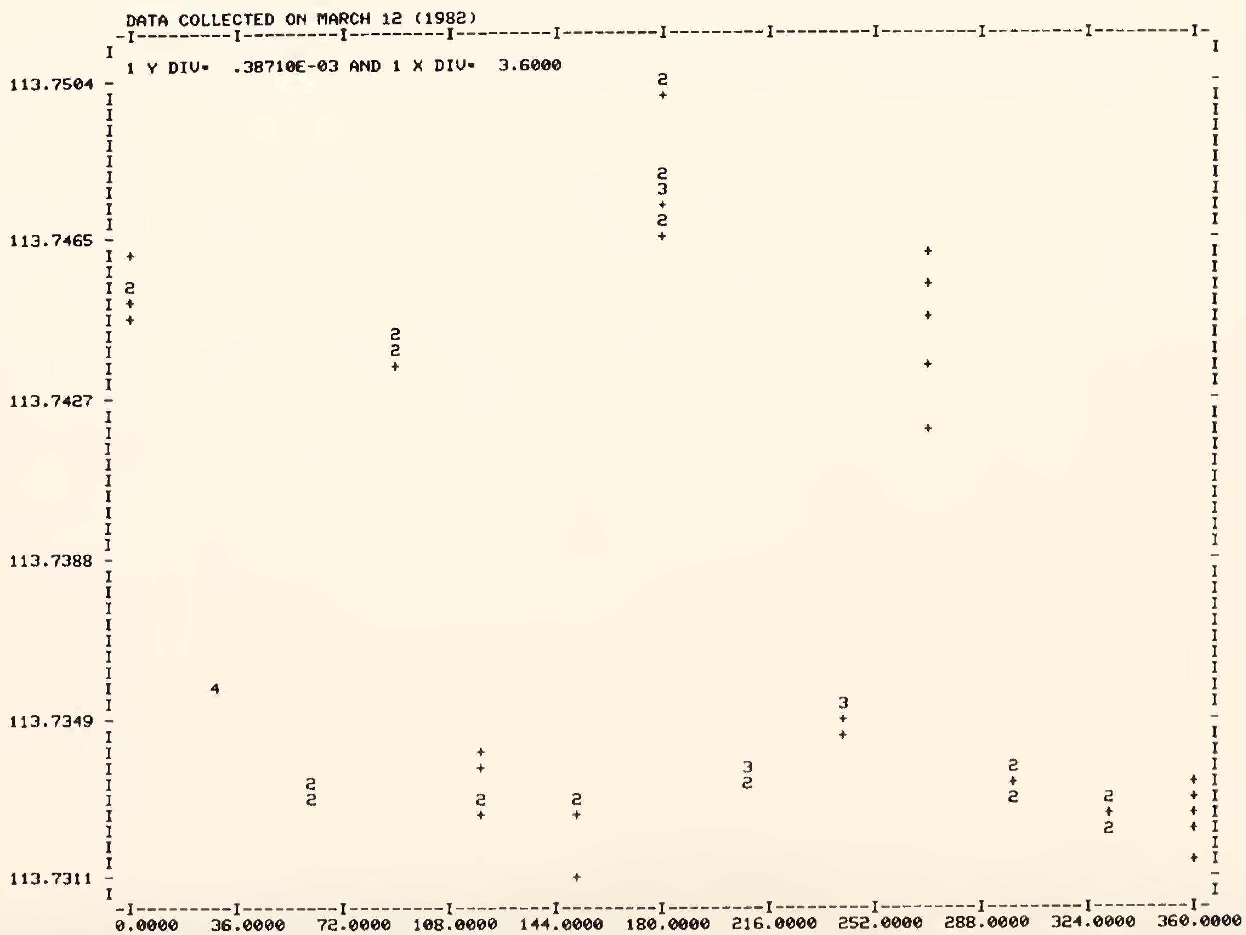

DATA COLLECTED ON MARCH 12 (1982)
1 Y DIV= .20000E-03 AND 1 X DIV= 3.6000
.0050
.0030
.0010
-.0010
-.0030
-.0050
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF [BEARING - THETA(1)] VS NOMINAL BEARING

*?



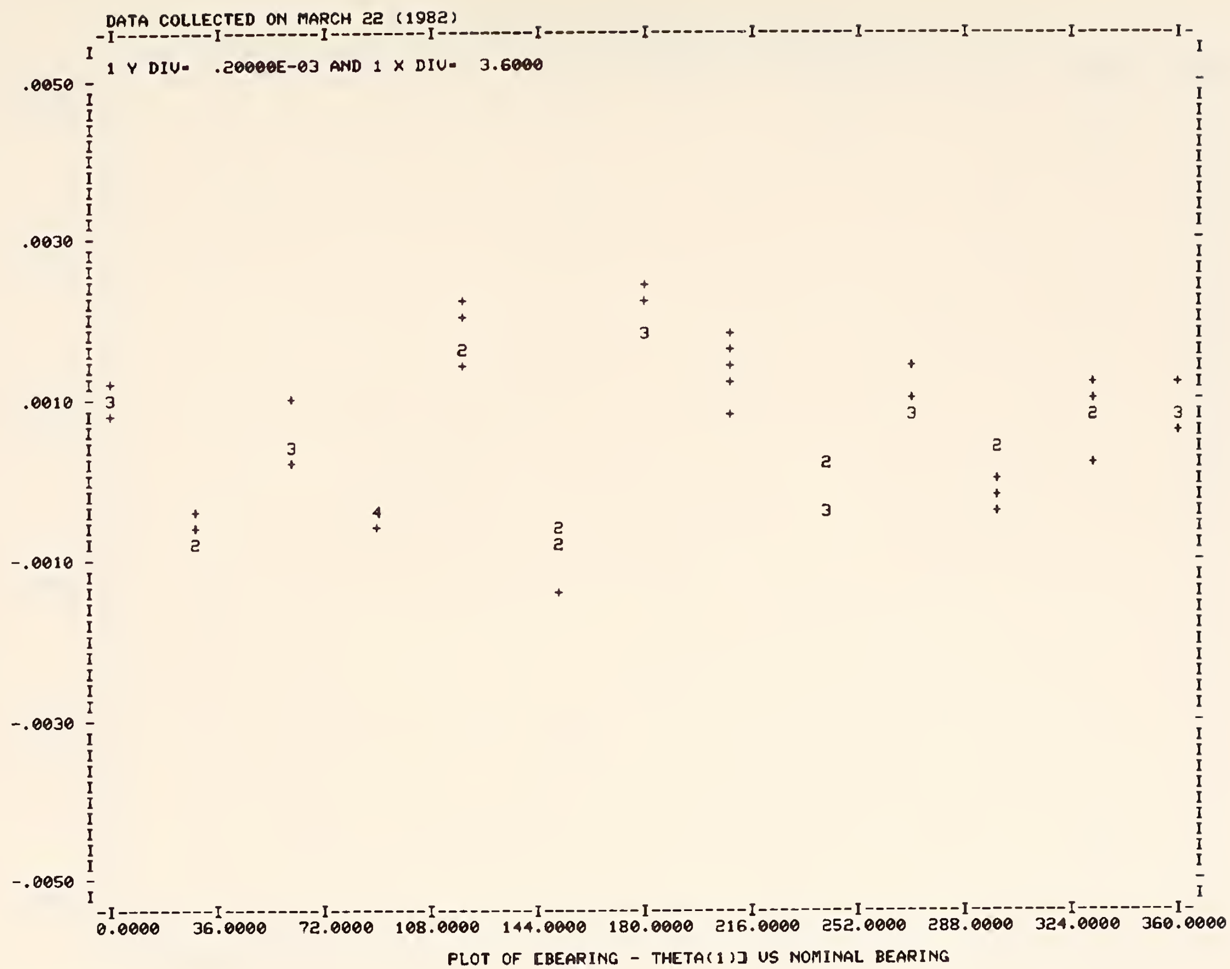
PLOT OF THETA(2) VS NOMINAL BEARING

*?



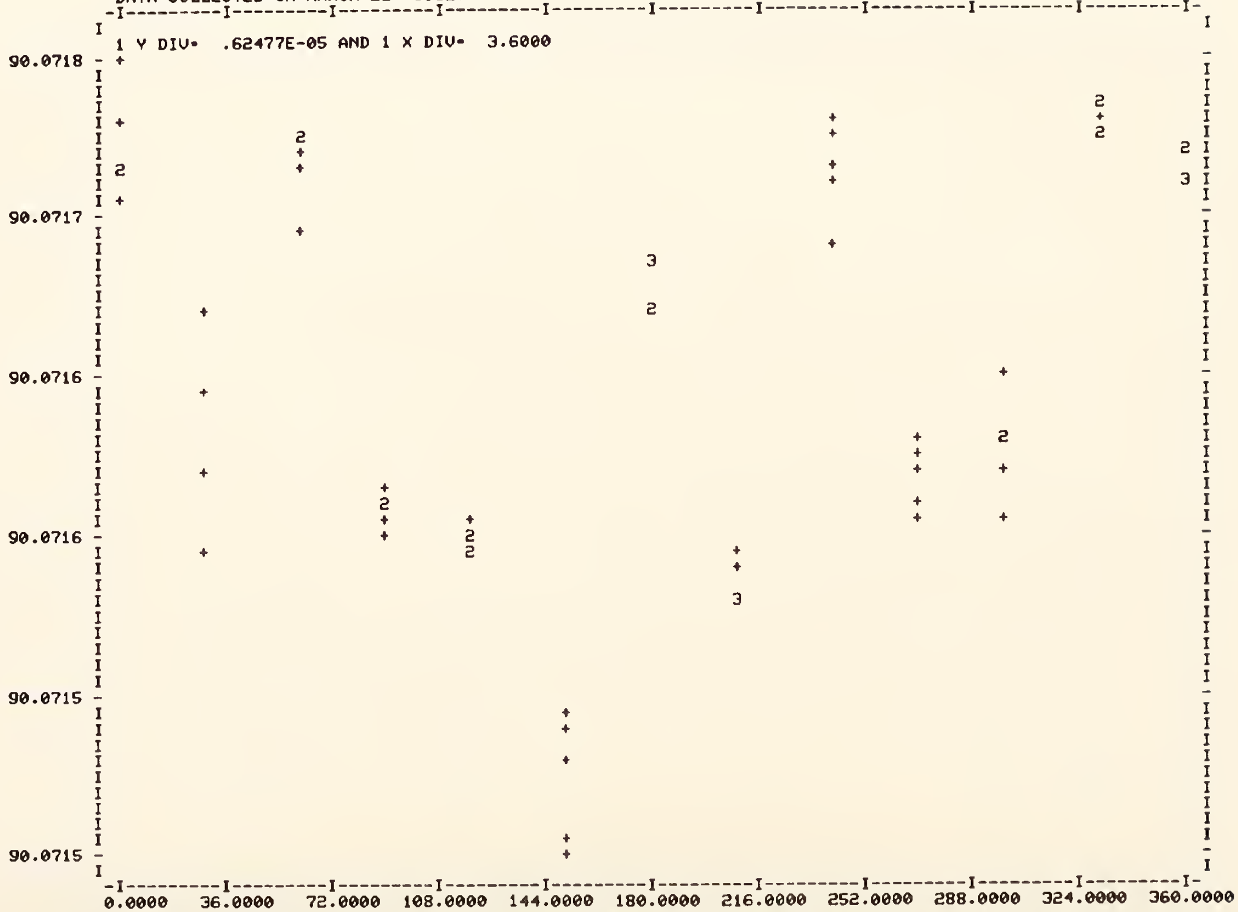
PLOT OF THETA(3) VS NOMINAL BEARING

*?


DATA COLLECTED ON MARCH 22 (1982)
1 Y DIV= .20000E-03 AND 1 X DIV= 3.6000
.0050
.0030
.0010
-.0010
-.0030
-.0050
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF [BEARING - THETA(1)] VS NOMINAL BEARING

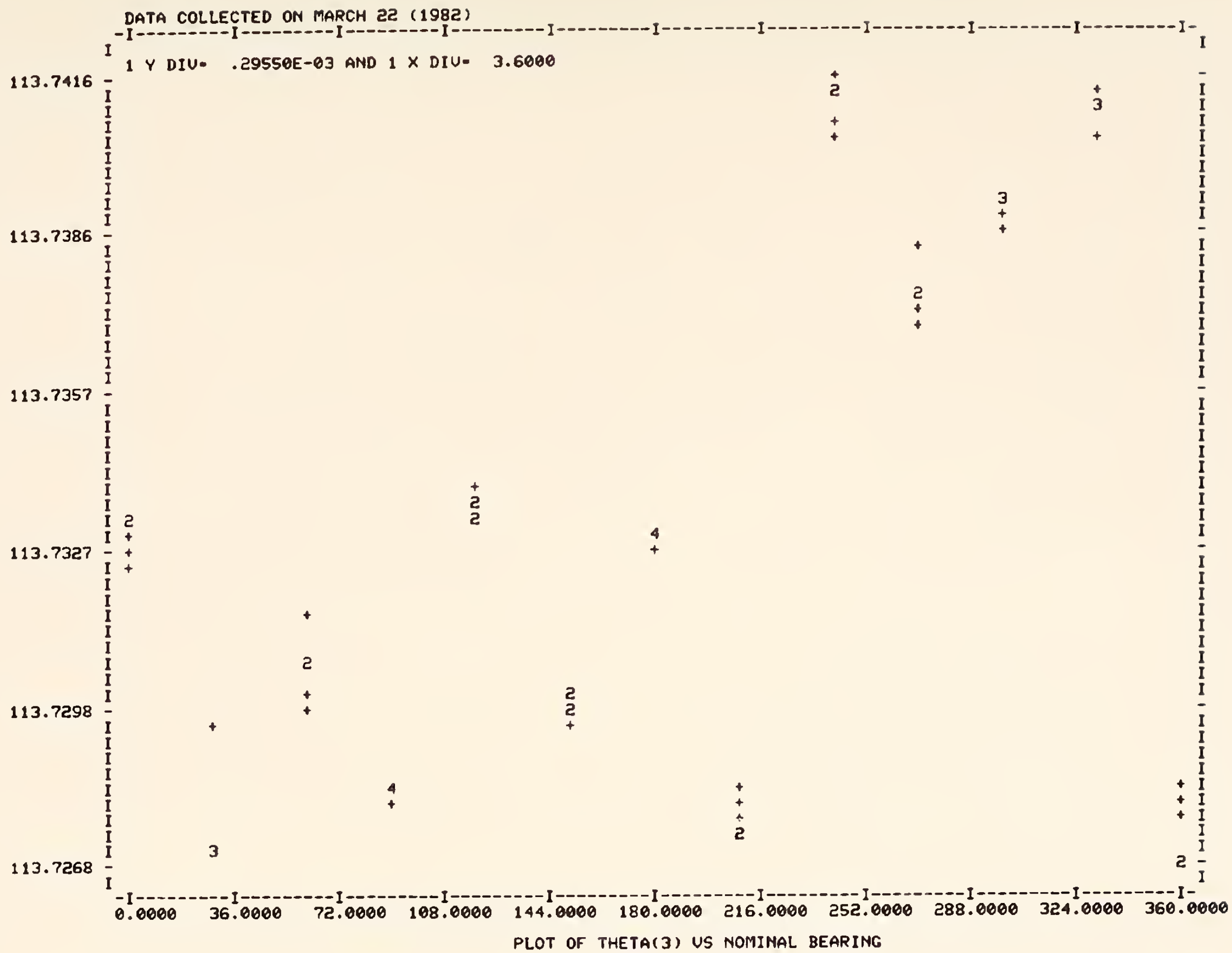
*?

DATA COLLECTED ON MARCH 22 (1982)



PLOT OF THETA(2) VS NOMINAL BEARING

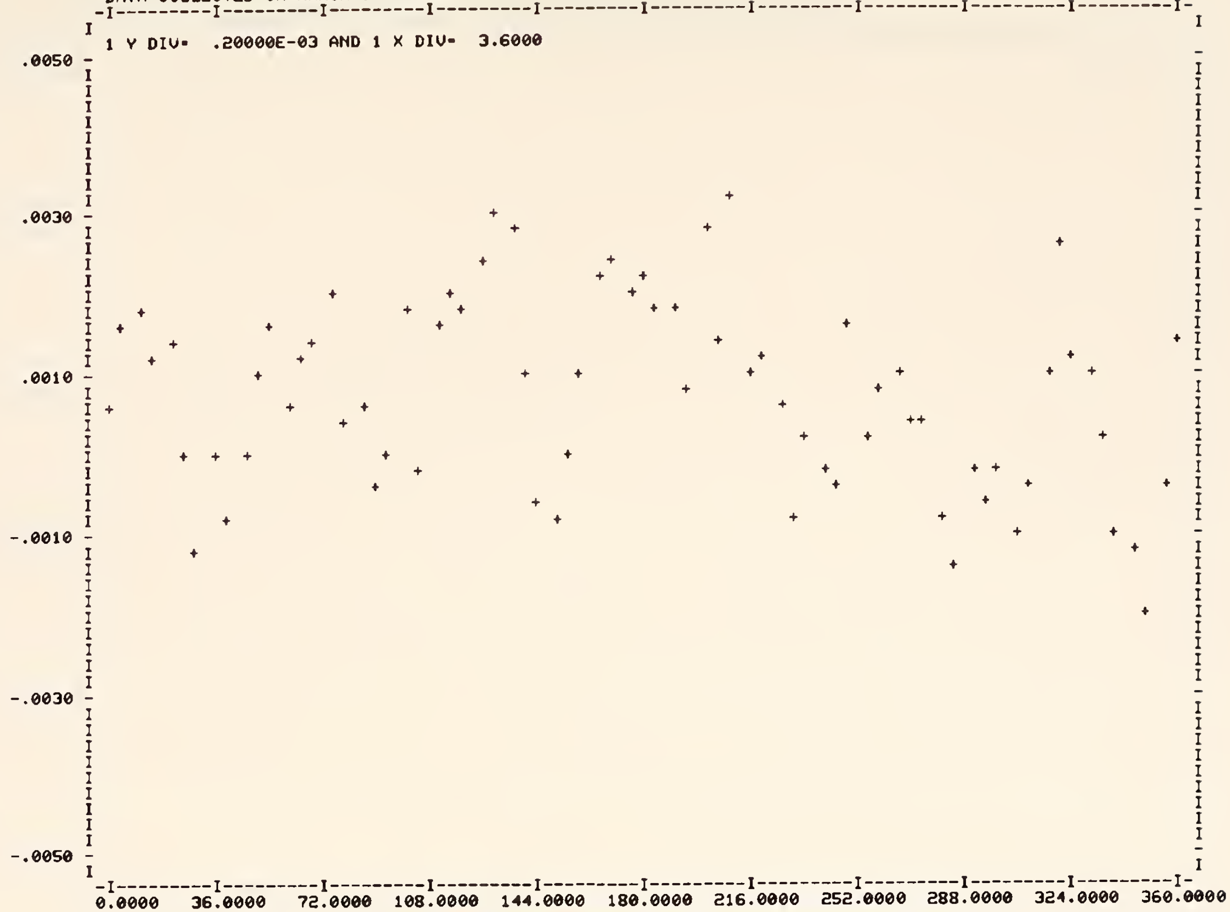
*?


DATA COLLECTED ON MARCH 22 (1982)
1 Y DIV= .29550E-03 AND 1 X DIV= 3.6000
113.7416
113.7386
113.7357
113.7327
113.7298
113.7268
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF THETA(3) VS NOMINAL BEARING

*?

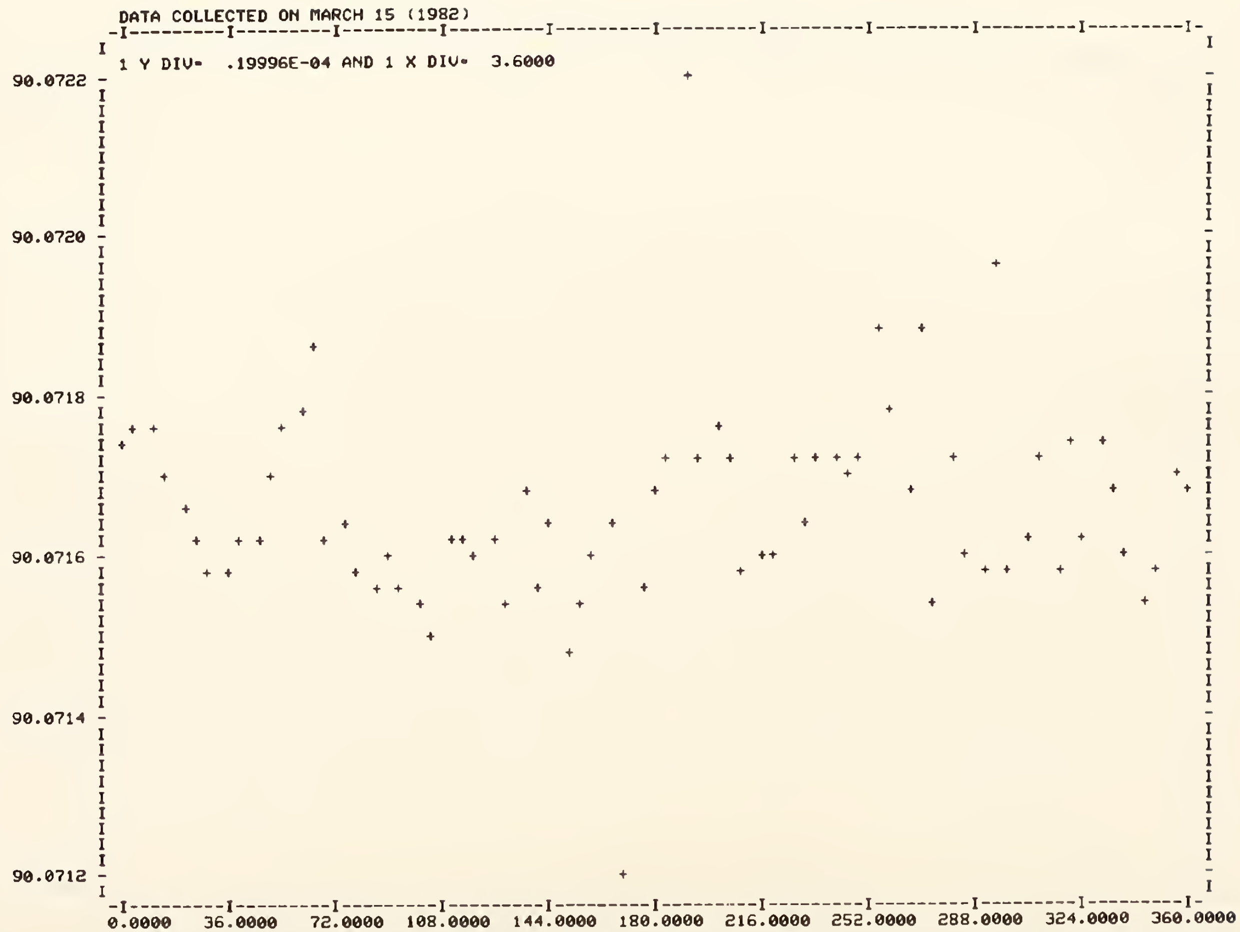
Systematic offset, 5° interval: 73 measurements were obtained at 5° bearing intervals on March 15, 1982. Data collection began at 8:15 a.m. and ended at 2:30 p.m. Measurements at the 73 bearings were obtained in random order. Following are plots of the "Bias," Theta(2) and Theta(3) versus the nominal bearing.

DATA COLLECTED ON MARCH 15 (1982)



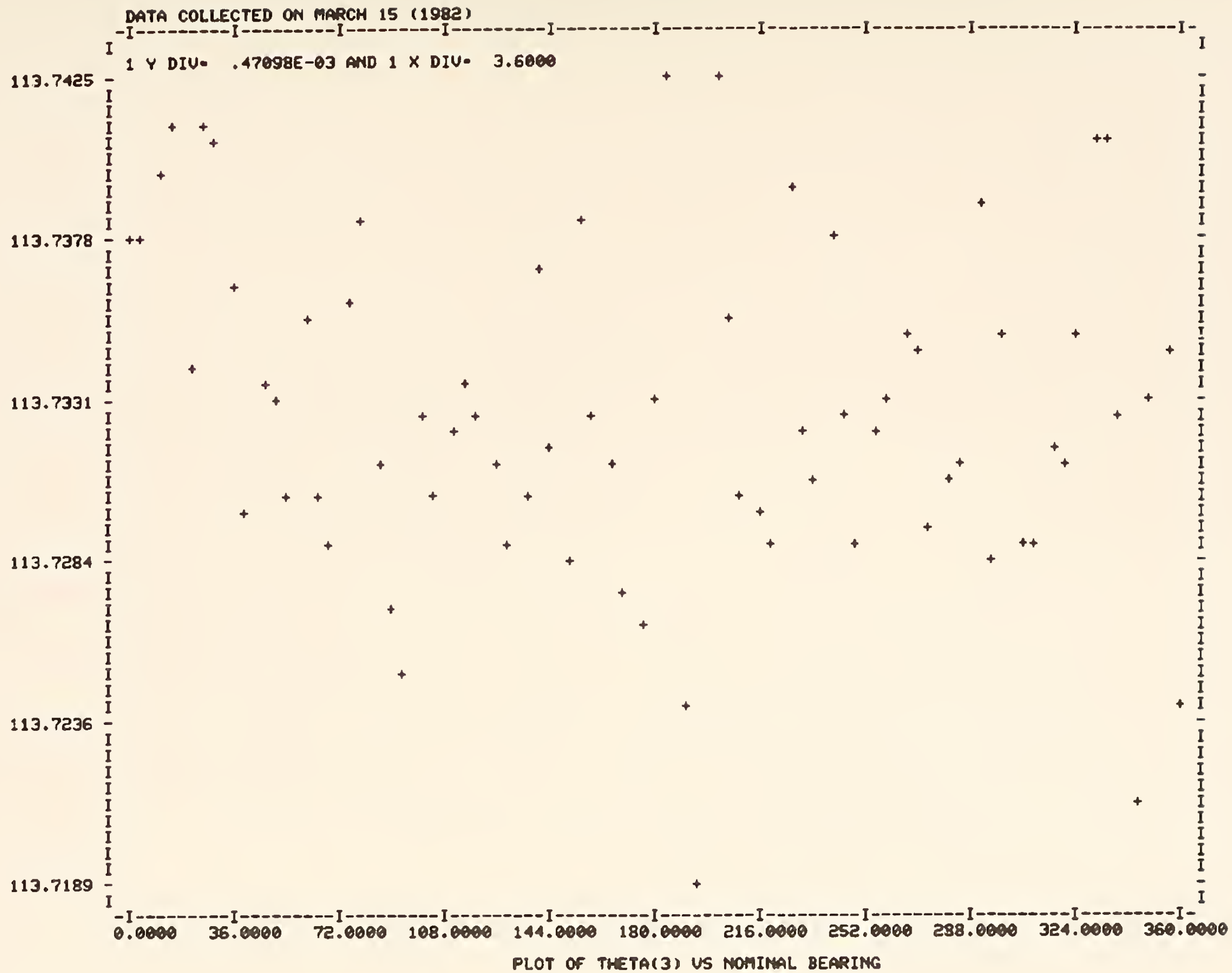
PLOT OF [BEARING - THETA(1)] VS NOMINAL BEARING

x?



PLOT OF THETA(2) VS NOMINAL BEARING

*?


DATA COLLECTED ON MARCH 15 (1982)
1 Y DIV= .47098E-03 AND 1 X DIV= 3.6000
113.7425
113.7378
113.7331
113.7284
113.7236
113.7189
0.0000
36.0000
72.0000
108.0000
144.0000
180.0000
216.0000
252.0000
288.0000
324.0000
360.0000
PLOT OF THETA(3) VS NOMINAL BEARING

Appendix D. BMDP3V Program Listing

```
*** CONTROL LANGUAGE TRANSFORMATIONS ARE PERFCRMEO ***

 VARIABLFS TO BF USED
             1  DAY           2  BEARING       3  SET           4  FILE          5  THETA1
             6  THFTA2        7  THETA3        8  SIGMASQ       9  BEARSO

                  BEFORE TRANSFORMATION                                   INTERVAL RANGE
VARIABLE        MINIMUM    MAXIMUM    MISSING    CATEGORY  CATEGORY    GREATER     LESS THAN
NO. NAME        LIMIT      LIMIT      COOE       COOE      NAME        THAN        OR EQUAL TO

 1   DAY                                           1.00000  * 1.0000
                                                   2.00000  * 2.0000
                                                   3.00000  * 3.0000
                                                   4.00000  * 4.0000
                                                   5.00000  * 5.0000
                                                   6.00000  * 6.0000
                                                   7.00000  * 7.0000
                                                   8.00000  * 8.0000
                                                   9.00000  * 9.0000
                                                  10.00000  * 10.000

 2   BFARING                                        0.0000  * 0.0000
                                                  30.00000  * 30.000
                                                  60.00000  * 60.000
                                                  90.00000  * 90.000
                                                 120.00000  * 120.00
                                                 150.00000  * 150.00
                                                 180.00000  * 180.00
                                                 210.00000  * 210.00
                                                 240.00000  * 240.00
                                                 270.00000  * 270.00
                                                 300.00000  * 300.00
                                                 330.00000  * 330.00
                                                 360.00000  * 360.00

NOTE--CATEGORY NAMES BEGINNING WITH * WERE GENERATED BY THE PROGRAM.

 NUMBER OF CASES READ. . . . . . . . . . . . . . .       455
    CASES WITH USE SET TO ZERO . . . . . . . . . .        30
       REMAINING NUMBER OF CASES . . . . . . . . .       425
```

```
BMDP3V - GENERAL MIXED MODEL ANALYSIS OF VARIANCE                         NOVEMBER, 1978
HEALTH SCIENCES COMPUTING FACILITY                                        MANUAL OATE  --  1977
UNIVERSITY OF CALIFORNIA, LOS ANGELES
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** IN THIS VERSION OF BMDP3V -

-- A COMPLETE SET OF PARAMETER LANGUAGE MUST BE GIVEN
   FOR EACH PROBLEM.  VALUES ARE NOT ASSUMED EROM
   PREVIOUS PROBLEM.

-- IF REML (RESTRICTED MAXIMUM LIKELIHOOO) IS USED
   THE HYPOTHESIS OPTION IS NOT AVAILABLE.  MULTIPLE
   RUNS ARE REOUIRED TO TEST HYPOTHESES IN THIS CASE.


 PROGRAM CONTROL INFORMATION

        /PROBLEM   TITLE IS 'VOR DATA ANALYSIS'.
        /INPUT     VARIABLES ARE 9.
                   FORMAT IS '(F2.0,10X,F7.2,F4.0,15X,E4.0,5E18.11)'.
                   UNIT IS B.
        /VARIABLES NAMES ARE DAY, BEARING, SET, FILE, THETA1, THETA2,
                             THETA3, SIGMASQ, BEARSO.
        /TRANSFORM  USE = OAY LE 10.
            IF (FILE EO 999) THEN USE = 0.
            IF (BEARSD GT .005) THEN USE = 0.


            IF (BEARING EO 000 AND THETA1 GT 300) THEN ( THETA1 = THETA1 - 360).
            IF (BEARING EQ 360 AND THETA1 LT 300) THEN ( THETA1 = THETA1 + 360).
            THETA1 = THETA1 - BEARING.
        /GROUP     LEVEL(2) = 13.
        /DESIGN    DEPEND IS THETA1.
                   FIXEO IS BEARING.
                   FNAME IS BEARING.
                   RANDOM IS OAY.
                   RANOOM IS BEARING, OAY.
                   RNAME IS OAY, 'BEAR*DAY'.
                   PARAMETERS = .0000003, -.0007, -.0005, .0013, -.0002, .0008,
                               -.0010, .0014, -.0013, -.0010, .0004, -.0003,
                                .0008, -.0003, .00000004, .0000001.
        /HYPOTH    EIXEO IS 1.
        /HYPOTH    RANOOM IS 1.
        /HYPOTH    RANDOM IS 2.
        /ENO

 PROBLEM TITLE . . . . . . .VOR OATA ANALYSIS

 NUMBER OF VARIABLES TO REAO IN. . . . . . . . .        9
 NUMBER OF VARIABLES ADDED BY TRANSFORMATIONS. .        0
 TOTAL NUMBER OF VARIABLES . . . . . . . . . . .        9
 NUMBER OF CASES TO REAO IN. . . . . . . . . . . 1000000
 CASE LABELING VARIABLES . . . . . . . . . . . .
 LIMITS AND MISSING VALUE CHECKEO BEFORE TRANSFORMATIONS
 BLANKS ARE. . . . . . . . . . . . . . . . . . .    ZEROS
 INPUT UNIT NUMBER . . . . . . . . . . . . . . .        B
 REWINO INPUT UNIT PRIOR TO READING. . DATA. . .      YES

 INPUT FORMAT
```

CELL INFORMATION FOR VARIABLE THETA1

CELL	MEAN	ST.DEV.	COEF. OF VARIATION	COUNT	GROUPING VARIABLES BEARING
1	-.00125	.00059	-.47133	49.00000	* 0.0000
2	.00053	.00067	1.25466	47.00000	* 30.000
3	-.00074	.00042	-.55987	18.00000	* 60.000
4	.00032	.00027	.85411	20.00000	* 90.000
5	-.00215	.00086	-.40083	44.00000	* 120.00
6	.00074	.00045	.60509	23.00000	* 150.00
7	-.00195	.00042	-.21645	56.00000	* 180.00
8	-.00162	.00041	-.25669	20.00000	* 210.00
9	-.00012	.00065	-5.28794	44.00000	* 240.00
10	-.00092	.00049	-.53307	18.00000	* 270.00
11	.00029	.00053	1.80877	46.00000	* 300.00
12	-.00077	.00032	-.41597	20.00000	* 330.00
13	-.00061	.00027	-.44546	20.00000	* 360.00

DEPENDENT VARIABLE THETA1

PARAMETER	ESTIMATE	STANDARD DEVIATION	EST/ST.DEV.	TWO-TAIL PROBABILITY (ASYMPTOTIC THEORY)
ERR.VAR.	.0000001775	.0000000137		
CONSTANT	-.0007445361	.0000874514	-8.5137110464	0.000
BEARING	-.0005109644	.0001152619	-4.4330724268	.000
BEARING	.0012768254	.0001160237	11.0048688278	0.000
BEARING	-.0002052279	.0001733964	-1.1835764962	.237
BEARING	.0008650401	.0001707507	5.0660999120	.000
BEARING	-.0014193839	.0001171721	-12.1136694969	0.000
BEARING	.0012268822	.0001692969	7.2469282683	.000
BEARING	-.0012091573	.0001141595	-10.5918276247	0.000
BEARING	-.0010717618	.0001707507	-6.2767634690	.000
BEARING	.0006288064	.0001174742	5.3527205399	.000
BEARING	-.0003390427	.0001739569	-1.9490042697	.051
BEARING	.0010510057	.0001164968	9.0217560088	0.000
BEARING	-.0002280048	.0001707507	-1.3353080575	.182
DAY	.0000000518	.0000000306		
BEAR*DAY	.0000000916	.0000000209		

-2*LOG(MAXIMUM LIKELIHOOD)   -5276.67666101

VARIANCE-COVARIANCE MATRIX OF THE PARAMETERS

	ERR.VAR.	CONSTANT	BEARING	BEARING	BEARING	BEARING	BEARING	BEARING
ERR.VAR.	.0000							
CONSTANT	0.0000	.0000						
BEARING	0.0000	-.0000	.0000					
BEARING	0.0000	-.0000	.0000	.0000				
BEARING	0.0000	.0000	-.0000	-.0000	.0000			
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	.0000		
BEARING	0.0000	-.0000	.0000	.0000	-.0000	-.0000	.0000	
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	.0000
BEARING	0.0000	-.0000	.0000	.0000	-.0000	-.0000	.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	-.0000	.0000	.0000	-.0000	-.0000	.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	-.0000	.0000	.0000	-.0000	-.0000	.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
DAY	-.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEAR*OAY	-.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

	BEARING	BEARING	BEARING	BEARING	BEARING	BEARING	OAY	BEAR*OAY
BEARING	.0000							
BEARING	-.0000	.0000						
BEARING	.0000	-.0000	.0000					
BEARING	-.0000	-.0000	-.0000	.0000				
BEARING	.0000	-.0000	.0000	-.0000	.0000			
BEARING	-.0000	-.0000	-.0000	-.0000	-.0000	.0000		
OAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0000	
BEAR*OAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-.0000	.0000

CELL	GROUPING VARIABLES BEARING	OUMMY VARIABLES												
1	* 0.0000	1.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	* 30.000	1.	0.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3	* 60.000	1.	0.	0.	1.	0.	0.	0.	0.	0.	0.	0.	0.	C.
4	* 90.000	1.	0.	0.	0.	1.	0.	0.	0.	0.	0.	0.	0.	0.
5	* 120.00	1.	0.	0.	0.	0.	1.	0.	0.	0.	0.	0.	0.	0.
6	* 150.00	1.	0.	0.	0.	0.	0.	1.	0.	0.	0.	0.	0.	0.
7	* 180.00	1.	0.	0.	0.	0.	0.	0.	1.	0.	0.	0.	0.	C.
8	* 210.00	1.	0.	0.	0.	0.	0.	0.	0.	1.	0.	0.	0.	0.
9	* 240.00	1.	0.	0.	0.	0.	0.	0.	0.	0.	1.	0.	0.	0.
10	* 270.00	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	0.	0.
11	* 300.00	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	0.
12	* 330.00	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.
13	* 360.00	1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.	-1.

CELL	OBSERVED MEAN	PREDICTED MEAN	SD.DEV. PRED.
1	-.0012	-.0013	.0001
2	.0005	.0005	.0001
3	-.0007	-.0009	.0002
4	.0003	.0001	.0002
5	-.0021	-.0022	.0001
6	.0007	.0005	.0002
7	-.0020	-.0020	.0001
8	-.0016	-.0018	.0002
9	-.0001	-.0001	.0001
10	-.0009	-.0011	.0002
11	.0003	.0003	.0001
12	-.0008	-.0010	.0002
13	-.0006	-.0008	.0002

VARIANCE-COVARIANCE MATRIX OF PREDICTED CELL MEANS

	1	2	3	4	5	6	7	8
1	.0000							
2	.0000	.0000						
3	.0000	.0000	.0000					
4	.0000	.0000	.0000	.0000				
5	.0000	.0000	.0000	.0000	.0000			
6	.0000	.0000	.0000	.0000	.0000	.0000		
7	.0000	.0000	.0000	.0000	.0000	.0000	.0000	
8	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
9	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
10	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
11	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
12	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
13	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000

	9	10	11	12	13
9	.0000				
10	.0000	.0000			
11	.0000	.0000	.0000		
12	.0000	.0000	.0000	.0000	
13	.0000	.0000	.0000	.0000	.0000

PAIRWISE TESTS FOR PREDICTED CELL MEANS

	1	2	3	4	5	6	7	8
1	0.0000							
2	11.1382	0.0000						
3	1.3967	-6.7542	0.0000					
4	6.3576	-1.8979	4.2098	0.0000				
5	-5.6145	-16.6114	-5.5181	-10.4995	0.0000			
6	8.0800	-.2316	5.6586	1.4419	12.2384	0.0000		
7	-4.3852	-15.5613	-4.6019	-9.6175	1.3056	-11.3660	0.0000	
8	-2.5911	-10.8248	-3.4084	-7.6824	1.5977	-9.1598	.6371	0.0000
9	7.0401	-3.9892	3.7863	-1.0845	12.5111	-2.7629	11.4050	7.8073
10	.7835	-7.3462	-.5211	-4.7276	4.8985	-6.1764	3.9791	2.8769
11	9.6873	-1.3961	5.7206	.8564	15.1590	-.8150	14.0857	9.7762
12	1.3074	-6.9358	-.0896	-4.3356	5.4757	-5.7976	4.5493	3.3468
13	2.0604	-6.1846	.5515	-3.6891	6.2249	-5.1481	5.3051	3.9933

	9	10	11	12	13
9	0.0000				
10	-4.3838	0.0000			
11	2.5877	6.3149	0.0000		
12	-3.9336	.4360	-5.8904	0.0000	
13	-3.1853	1.0759	-5.1397	.6465	0.0000

RESIDUAL ANALYSIS

CELL	OBSERVED THETA1	PREDICTED THETA1	ST.DEV. PRED.	OBSERVED-PREDICTED	ST.DEV. O-P	(O-P)/ ST.DEV.
1	-.0008	-.0013	.0001	.0004	.0006	.797
1	-.0003	-.0013	.0001	.0010	.0006	1.789
1	-.0003	-.0013	.0001	.0009	.0006	1.654
1	.0001	-.0013	.0001	.0014	.0006	2.458
1	-.0008	-.0013	.0001	.0005	.0006	.850
2	.0011	.0005	.0001	.0006	.0006	1.058
2	.0013	.0005	.0001	.0007	.0006	1.310
2	.0010	.0005	.0001	.0004	.0006	.767
2	.0012	.0005	.0001	.0007	.0006	1.284
2	.0009	.0005	.0001	.0003	.0006	.603
3	-.0002	-.0009	.0002	.0008	.0005	1.452
3	-.0007	-.0009	.0002	.0003	.0005	.556
3	-.0005	-.0009	.0002	.0005	.0005	.931
3	-.0008	-.0009	.0002	.0002	.0005	.351
4	.0009	.0001	.0002	.0008	.0005	1.433
4	.0007	.0001	.0002	.0006	.0005	1.047
4	.0005	.0001	.0002	.0003	.0005	.654
4	.0003	.0001	.0002	.0002	.0005	.342
4	.0002	.0001	.0002	.0001	.0005	.206
5	-.0013	-.0022	.0001	.0009	.0005	1.656
5	-.0015	-.0022	.0001	.0007	.0005	1.274
5	-.0013	-.0022	.0001	.0008	.0005	1.493
5	-.0009	-.0022	.0001	.0013	.0005	2.383
5	-.0018	-.0022	.0001	.0004	.0005	.743

6	.0011	.0005	.0002	.0006	.0005	1.209
6	.0013	.0005	.0002	.0008	.0005	1.579
6	.0012	.0005	.0002	.0007	.0005	1.341
6	.0007	.0005	.0002	.0003	.0005	.476
6	.0012	.0005	.0002	.0008	.0005	1.416
6	.0004	.0005	.0002	-.0001	.0005	-.240
6	.0012	.0005	.0002	.0007	.0005	1.333
6	.0010	.0005	.0002	.0005	.0005	.945
6	.0010	.0005	.0002	.0005	.0005	.967
7	-.0018	-.0020	.0001	.0001	.0006	.232
7	-.0027	-.0020	.0001	-.0007	.0006	-1.327
7	-.0019	-.0020	.0001	.0000	.0006	.034
7	-.0018	-.0020	.0001	.0002	.0006	.351
7	-.0019	-.0020	.0001	.0000	.0006	.016
8	-.0018	-.0018	.0002	.0000	.0005	.033
8	-.0020	-.0018	.0002	-.0002	.0005	-.303
8	-.0023	-.0018	.0002	-.0005	.0005	-.872
8	-.0017	-.0018	.0002	.0002	.0005	.289
8	-.0021	-.0018	.0002	-.0003	.0005	-.603
9	.0001	-.0001	.0001	.0002	.0005	.436
9	-.0004	-.0001	.0001	-.0003	.0005	-.463
9	-.0010	-.0001	.0001	-.0009	.0005	-1.574
9	-.0004	-.0001	.0001	-.0003	.0005	-.465
9	.0001	-.0001	.0001	.0002	.0005	.352
10	-.0010	-.0011	.0002	.0000	.0005	.085
10	-.0009	-.0011	.0002	.0002	.0005	.416
10	-.0010	-.0011	.0002	.0001	.0005	.098
10	-.0012	-.0011	.0002	-.0001	.0005	-.147
10	-.0002	-.0011	.0002	.0009	.0005	1.717
11	.0000	.0003	.0001	-.0003	.0006	-.490
11	.0003	.0003	.0001	-.0000	.0006	-.037
11	.0005	.0003	.0001	.0002	.0006	.390
11	-.0002	.0003	.0001	-.0005	.0006	-.856
11	.0004	.0003	.0001	.0001	.0006	.227
12	-.0009	-.0010	.0002	.0001	.0005	.096
12	-.0012	-.0010	.0002	-.0002	.0005	-.360
12	-.0008	-.0010	.0002	.0002	.0005	.302
12	-.0006	-.0010	.0002	.0004	.0005	.667
12	-.0011	-.0010	.0002	-.0002	.0005	-.284
13	-.0004	-.0008	.0002	.0004	.0005	.844
13	-.0008	-.0008	.0002	-.0000	.0005	-.010
13	-.0003	-.0008	.0002	.0005	.0005	.873
13	-.0002	-.0008	.0002	.0006	.0005	1.101
13	-.0002	-.0008	.0002	.0006	.0005	1.143
13	-.0007	-.0008	.0002	.0001	.0005	.279
13	-.0003	-.0008	.0002	.0005	.0005	1.012
13	-.0009	-.0008	.0002	-.0001	.0005	-.141
13	-.0004	-.0008	.0002	.0004	.0005	.810
13	-.0008	-.0008	.0002	.0000	.0005	.006
12	-.0005	-.0010	.0002	.0004	.0005	.844
12	-.0015	-.0010	.0002	-.0005	.0005	-.996
12	-.0005	-.0010	.0002	.0005	.0005	.935
12	-.0006	-.0010	.0002	.0003	.0005	.619
12	-.0006	-.0010	.0002	.0004	.0005	.742
9	-.0007	-.0001	.0001	-.0006	.0005	-1.034

9	-.0007	-.0001	.0001	-.0006	.0005	-1.026
9	-.0009	-.0001	.0001	-.0007	.0005	-1.357
6	-.0002	.0005	.0002	-.0007	.0005	-1.239
6	.0004	.0005	.0002	-.0001	.0005	-.185
6	-.0000	.0005	.0002	-.0005	.0005	-.983
6	.0012	.0005	.0002	.0008	.0005	1.421
6	.0006	.0005	.0002	.0001	.0005	.215
3	-.0004	-.0009	.0002	.0005	.0005	.956
3	-.0010	-.0009	.0002	-.0001	.0005	-.095
3	-.0012	-.0009	.0002	-.0003	.0005	-.525
3	-.0009	-.0009	.0002	.0000	.0005	.092
3	-.0008	-.0009	.0002	.0002	.0005	.292
11	.0010	.0003	.0001	.0007	.0006	1.213
11	.0010	.0003	.0001	.0007	.0006	1.279
11	.0005	.0003	.0001	.0002	.0006	.362
11	.0006	.0003	.0001	.0002	.0006	.446
11	.0008	.0003	.0001	.0005	.0006	.897
8	-.0019	-.0018	.0002	-.0001	.0005	-.121
8	-.0009	-.0018	.0002	.0009	.0005	1.648
8	-.0020	-.0018	.0002	-.0002	.0005	-.314
8	-.0020	-.0018	.0002	-.0002	.0005	-.352
8	-.0017	-.0018	.0002	.0001	.0005	.181
5	-.0009	-.0022	.0001	.0012	.0005	2.261
5	-.0012	-.0022	.0001	.0010	.0005	1.810
5	-.0015	-.0022	.0001	.0007	.0005	1.187
5	-.0011	-.0022	.0001	.0011	.0005	1.929
2	.0014	.0005	.0001	.0009	.0006	1.629
2	.0011	.0005	.0001	.0006	.0006	1.033
2	.0014	.0005	.0001	.0008	.0006	1.504
2	.0011	.0005	.0001	.0006	.0006	1.112
2	.0017	.0005	.0001	.0011	.0006	2.087
10	-.0000	-.0011	.0002	.0011	.0005	1.990
10	-.0004	-.0011	.0002	.0006	.0005	1.212
10	-.0006	-.0011	.0002	.0005	.0005	.962
7	-.0022	-.0020	.0001	-.0003	.0006	-.485
7	-.0020	-.0020	.0001	.0000	.0006	.005
7	-.0020	-.0020	.0001	-.0001	.0006	-.119
7	-.0017	-.0020	.0001	.0003	.0006	.537
7	-.0022	-.0020	.0001	-.0003	.0006	-.463
4	.0007	.0001	.0002	.0006	.0005	1.143
4	.0004	.0001	.0002	.0002	.0005	.443
4	.0003	.0001	.0002	.0002	.0005	.342
4	-.0003	.0001	.0002	-.0004	.0005	-.802
4	.0001	.0001	.0002	-.0000	.0005	-.033
1	-.0007	-.0013	.0001	.0005	.0006	.984
1	-.0008	-.0013	.0001	.0004	.0006	.800
1	-.0008	-.0013	.0001	.0005	.0006	.871
1	-.0018	-.0013	.0001	-.0005	.0006	-.971
1	-.0005	-.0013	.0001	.0008	.0006	1.438
13	-.0006	-.0008	.0002	.0002	.0005	.378
13	-.0003	-.0008	.0002	.0005	.0005	1.034
13	-.0006	-.0008	.0002	.0002	.0005	.367
13	-.0006	-.0008	.0002	.0002	.0005	.355
13	-.0010	-.0008	.0002	-.0002	.0005	-.365
12	-.0006	-.0010	.0002	.0003	.0005	.653

8

12	-.0010	-.0010	.0002	-.0000	.0005	-.014
12	-.0008	-.0010	.0002	.0002	.0005	.308
12	-.0002	-.0010	.0002	.0008	.0005	1.512
12	-.0007	-.0010	.0002	.0003	.0005	.487
9	.0000	-.0001	.0001	.0001	.0005	.264
9	.0001	-.0001	.0001	.0002	.0005	.442
9	.0003	-.0001	.0001	.0004	.0005	.747
9	.0004	-.0001	.0001	.0005	.0005	.985
9	.0008	-.0001	.0001	.0009	.0005	1.678
6	.0001	.0005	.0002	-.0004	.0005	-.710
6	.0002	.0005	.0002	-.0003	.0005	-.485
6	.0005	.0005	.0002	-.0000	.0005	-.006
6	.0008	.0005	.0002	.0003	.0005	.579
3	-.0004	-.0009	.0002	.0005	.0005	.971
3	-.0014	-.0009	.0002	-.0004	.0005	-.767
3	-.0015	-.0009	.0002	-.0006	.0005	-1.071
3	-.0013	-.0009	.0002	-.0004	.0005	-.690
11	.0009	.0003	.0001	.0006	.0006	1.144
11	.0005	.0003	.0001	.0002	.0006	.372
11	.0003	.0003	.0001	-.0000	.0006	-.049
11	-.0000	.0003	.0001	-.0003	.0006	-.588
11	.0001	.0003	.0001	-.0002	.0006	-.311
8	-.0018	-.0018	.0002	.0000	.0005	.082
8	-.0010	-.0018	.0002	.0008	.0005	1.587
8	-.0018	-.0018	.0002	.0000	.0005	.062
8	-.0013	-.0018	.0002	.0005	.0005	.930
8	-.0015	-.0018	.0002	.0004	.0005	.670
5	-.0011	-.0022	.0001	.0010	.0005	1.874
5	-.0012	-.0022	.0001	.0009	.0005	1.706
5	-.0012	-.0022	.0001	.0010	.0005	1.821
5	-.0014	-.0022	.0001	.0008	.0005	1.407
5	-.0012	-.0022	.0001	.0010	.0005	1.795
2	.0005	.0005	.0001	-.0000	.0006	-.036
2	.0014	.0005	.0001	.0009	.0006	1.588
2	.0009	.0005	.0001	.0003	.0006	.584
2	.0003	.0005	.0001	-.0002	.0006	-.347
10	-.0015	-.0011	.0002	-.0004	.0005	-.774
10	-.0020	-.0011	.0002	-.0010	.0005	-1.797
10	-.0014	-.0011	.0002	-.0003	.0005	-.616
10	-.0012	-.0011	.0002	-.0001	.0005	-.184
10	-.0005	-.0011	.0002	.0006	.0005	1.127
7	-.0019	-.0020	.0001	.0001	.0006	.113
7	-.0023	-.0020	.0001	-.0004	.0006	-.639
7	-.0019	-.0020	.0001	.0000	.0006	.050
7	-.0025	-.0020	.0001	-.0005	.0006	-.906
7	-.0016	-.0020	.0001	.0003	.0006	.586
7	-.0019	-.0020	.0001	.0000	.0006	.075
7	-.0018	-.0020	.0001	.0002	.0006	.334
7	-.0020	-.0020	.0001	-.0000	.0006	-.056
7	-.0016	-.0020	.0001	.0004	.0006	.720
7	-.0018	-.0020	.0001	.0001	.0006	.195
7	-.0022	-.0020	.0001	-.0003	.0006	-.480
7	-.0017	-.0020	.0001	.0002	.0006	.409
4	.0001	.0001	.0002	-.0001	.0005	-.109
4	.0001	.0001	.0002	.0000	.0005	.021

4	.0000	.0001	.0002	-.0001	.0005	-.140
4	.0001	.0001	.0002	.0000	.0005	.028
4	.0001	.0001	.0002	.0000	.0005	.050
1	-.0009	-.0013	.0001	.0004	.0006	.645
1	-.0007	-.0013	.0001	.0005	.0006	.947
1	-.0005	-.0013	.0001	.0007	.0006	1.301
1	-.0007	-.0013	.0001	.0006	.0006	1.052
1	-.0007	-.0013	.0001	.0006	.0006	1.087
2	.0009	.0005	.0001	.0003	.0006	.610
2	.0008	.0005	.0001	.0002	.0006	.436
2	.0007	.0005	.0001	.0001	.0006	.220
2	.0004	.0005	.0001	-.0002	.0006	-.273
8	-.0008	-.0018	.0002	.0011	.0005	2.004
8	-.0018	-.0018	.0002	.0000	.0005	.081
8	-.0013	-.0018	.0002	.0006	.0005	1.061
8	-.0016	-.0018	.0002	.0003	.0005	.497
8	-.0013	-.0018	.0002	.0005	.0005	.960
13	-.0011	-.0008	.0002	-.0003	.0005	-.553
13	-.0007	-.0008	.0002	.0001	.0005	.160
13	-.0009	-.0008	.0002	-.0001	.0005	-.129
13	-.0008	-.0008	.0002	.0000	.0005	.078
13	-.0007	-.0008	.0002	.0001	.0005	.278
3	-.0004	-.0009	.0002	.0006	.0005	1.117
3	-.0004	-.0009	.0002	.0005	.0005	.949
3	-.0003	-.0009	.0002	.0006	.0005	1.155
3	-.0002	-.0009	.0002	.0007	.0005	1.375
3	-.0010	-.0009	.0002	-.0000	.0005	-.060
4	.0004	.0001	.0002	.0003	.0005	.604
4	.0004	.0001	.0002	.0003	.0005	.563
4	.0006	.0001	.0002	.0005	.0005	.897
4	.0004	.0001	.0002	.0002	.0005	.441
4	.0003	.0001	.0002	.0002	.0005	.390
6	.0013	.0005	.0002	.0008	.0005	1.588
6	.0009	.0005	.0002	.0004	.0005	.702
6	.0006	.0005	.0002	.0002	.0005	.284
6	.0009	.0005	.0002	.0004	.0005	.753
6	.0006	.0005	.0002	.0001	.0005	.184
7	-.0022	-.0020	.0001	-.0003	.0006	-.492
7	-.0019	-.0020	.0001	.0001	.0006	.167
7	-.0024	-.0020	.0001	-.0005	.0006	-.829
7	-.0017	-.0020	.0001	.0002	.0006	.438
7	-.0017	-.0020	.0001	.0002	.0006	.448
1	-.0011	-.0013	.0001	.0001	.0006	.246
1	-.0008	-.0013	.0001	.0004	.0006	.744
1	-.0011	-.0013	.0001	.0002	.0006	.346
1	-.0010	-.0013	.0001	.0002	.0006	.410
1	-.0010	-.0013	.0001	.0003	.0006	.466
5	-.0013	-.0022	.0001	.0008	.0005	1.534
5	-.0023	-.0022	.0001	-.0001	.0005	-.212
5	-.0017	-.0022	.0001	.0005	.0005	.853
5	-.0020	-.0022	.0001	.0001	.0005	.229
5	-.0017	-.0022	.0001	.0005	.0005	.901
10	-.0009	-.0011	.0002	.0002	.0005	.314
10	-.0008	-.0011	.0002	.0003	.0005	.626
10	-.0008	-.0011	.0002	.0003	.0005	.620

10	-.0009	-.0011	.0002	.0002	.0005	.393
10	-.0014	-.0011	.0002	-.0003	.0005	-.508
11	-.0004	.0003	.0001	-.0007	.0006	-1.199
11	.0002	.0003	.0001	-.0001	.0006	-.267
11	.0001	.0003	.0001	-.0003	.0006	-.458
11	-.0004	.0003	.0001	-.0007	.0006	-1.302
11	.0005	.0003	.0001	.0002	.0006	.274
9	.0003	-.0001	.0001	.0005	.0005	.837
9	-.0002	-.0001	.0001	-.0001	.0005	-.166
9	-.0002	-.0001	.0001	-.0001	.0005	-.125
9	.0004	-.0001	.0001	.0005	.0005	.928
9	.0003	-.0001	.0001	.0004	.0005	.769
12	-.0009	-.0010	.0002	.0000	.0005	.052
12	-.0008	-.0010	.0002	.0002	.0005	.411
12	-.0002	-.0010	.0002	.0008	.0005	1.429
12	-.0007	-.0010	.0002	.0002	.0005	.425
12	-.0011	-.0010	.0002	-.0002	.0005	-.309
9	-.0005	-.0001	.0001	-.0004	.0005	-.695
9	-.0002	-.0001	.0001	-.0001	.0005	-.098
9	-.0006	-.0001	.0001	-.0005	.0005	-.835
9	-.0002	-.0001	.0001	-.0000	.0005	-.070
9	-.0000	-.0001	.0001	.0001	.0005	.163
1	-.0009	-.0013	.0001	.0003	.0006	.610
1	-.0007	-.0013	.0001	.0005	.0006	.924
1	-.0009	-.0013	.0001	.0004	.0006	.725
1	-.0012	-.0013	.0001	.0001	.0006	.176
1	-.0012	-.0013	.0001	.0000	.0006	.055
2	.0011	.0005	.0001	.0005	.0006	.961
2	.0007	.0005	.0001	.0002	.0006	.385
2	.0008	.0005	.0001	.0003	.0006	.467
2	.0010	.0005	.0001	.0004	.0006	.799
2	.0002	.0005	.0001	-.0003	.0006	-.518
5	-.0020	-.0022	.0001	.0001	.0005	.237
5	-.0021	-.0022	.0001	.0001	.0005	.176
5	-.0020	-.0022	.0001	.0001	.0005	.221
5	-.0021	-.0022	.0001	.0001	.0005	.159
5	-.0022	-.0022	.0001	-.0000	.0005	-.028
11	.0002	.0003	.0001	-.0001	.0006	-.141
11	-.0003	.0003	.0001	-.0006	.0006	-1.094
11	.0007	.0003	.0001	.0004	.0006	.702
11	.0001	.0003	.0001	-.0002	.0006	-.417
11	-.0002	.0003	.0001	-.0005	.0006	-.901
7	-.0017	-.0020	.0001	.0002	.0006	.408
7	-.0019	-.0020	.0001	.0000	.0006	.058
7	-.0022	-.0020	.0001	-.0002	.0006	-.417
7	-.0017	-.0020	.0001	.0002	.0006	.425
7	-.0021	-.0020	.0001	-.0001	.0006	-.230
9	.0003	-.0001	.0001	.0004	.0005	.676
9	-.0006	-.0001	.0001	-.0005	.0005	-.872
9	-.0001	-.0001	.0001	.0000	.0005	.022
9	-.0004	-.0001	.0001	-.0003	.0005	-.545
9	-.0000	-.0001	.0001	.0001	.0005	.122
1	-.0015	-.0013	.0001	-.0003	.0006	-.473
1	-.0016	-.0013	.0001	-.0004	.0006	-.661
1	-.0016	-.0013	.0001	-.0003	.0006	-.545

1	-.0014	-.0013	.0001	-.0001	.0006	-.206
1	-.0012	-.0013	.0001	.0000	.0006	.011
2	.0005	.0005	.0001	-.0001	.0006	-.138
2	.0004	.0005	.0001	-.0002	.0006	-.291
2	.0001	.0005	.0001	-.0005	.0006	-.854
2	.0001	.0005	.0001	-.0004	.0006	-.727
2	.0003	.0005	.0001	-.0003	.0006	-.460
5	-.0020	-.0022	.0001	.0001	.0005	.246
5	-.0024	-.0022	.0001	-.0002	.0005	-.398
5	-.0023	-.0022	.0001	-.0002	.0005	-.335
5	-.0026	-.0022	.0001	-.0005	.0005	-.865
11	.0004	.0003	.0001	.0001	.0006	.183
11	.0002	.0003	.0001	-.0001	.0006	-.253
11	.0004	.0003	.0001	.0001	.0006	.214
11	.0006	.0003	.0001	.0003	.0006	.483
11	-.0000	.0003	.0001	-.0003	.0006	-.596
7	-.0015	-.0020	.0001	.0005	.0006	.865
7	-.0018	-.0020	.0001	.0001	.0006	.266
7	-.0019	-.0020	.0001	.0001	.0006	.159
7	-.0017	-.0020	.0001	.0002	.0006	.393
7	-.0018	-.0020	.0001	.0001	.0006	.263
9	-.0015	-.0001	.0001	-.0014	.0005	-2.492
9	-.0011	-.0001	.0001	-.0010	.0005	-1.770
9	.0000	-.0001	.0001	.0002	.0005	.281
9	-.0005	-.0001	.0001	-.0004	.0005	-.672
9	.0006	-.0001	.0001	.0007	.0005	1.261
1	-.0017	-.0013	.0001	-.0005	.0006	-.865
1	-.0016	-.0013	.0001	-.0003	.0006	-.577
1	-.0013	-.0013	.0001	-.0001	.0006	-.140
1	-.0026	-.0013	.0001	-.0013	.0006	-2.366
1	-.0021	-.0013	.0001	-.0009	.0006	-1.559
2	.0005	.0005	.0001	-.0000	.0006	-.036
2	-.0000	.0005	.0001	-.0005	.0006	-.990
2	.0004	.0005	.0001	-.0002	.0006	-.330
2	.0003	.0005	.0001	-.0002	.0006	-.411
2	-.0011	.0005	.0001	-.0017	.0006	-3.013
5	-.0033	-.0022	.0001	-.0011	.0005	-2.036
5	-.0030	-.0022	.0001	-.0009	.0005	-1.562
5	-.0029	-.0022	.0001	-.0008	.0005	-1.394
5	-.0037	-.0022	.0001	-.0015	.0005	-2.728
11	-.0005	.0003	.0001	-.0008	.0006	-1.522
11	-.0008	.0003	.0001	-.0011	.0006	-1.922
11	-.0003	.0003	.0001	-.0006	.0006	-1.105
11	.0002	.0003	.0001	-.0001	.0006	-.268
11	.0000	.0003	.0001	-.0003	.0006	-.521
7	-.0030	-.0020	.0001	-.0010	.0006	-1.819
7	-.0016	-.0020	.0001	.0003	.0006	.558
7	-.0031	-.0020	.0001	-.0011	.0006	-2.074
7	-.0021	-.0020	.0001	-.0002	.0006	-.343
7	-.0024	-.0020	.0001	-.0004	.0006	-.729
9	.0011	-.0001	.0001	.0012	.0005	2.242
9	.0002	-.0001	.0001	.0003	.0005	.616
9	.0005	-.0001	.0001	.0006	.0005	1.075
9	.0003	-.0001	.0001	.0004	.0005	.689
9	-.0003	-.0001	.0001	-.0002	.0005	-.386

1	-.0018	-.0013	.0001	-.0006	.0006	-1.069
1	-.0017	-.0013	.0001	-.0004	.0006	-.746
1	-.0019	-.0013	.0001	-.0006	.0006	-1.142
1	-.0010	-.0013	.0001	.0003	.0006	.507
1	-.0021	-.0013	.0001	-.0008	.0006	-1.455
2	.0004	.0005	.0001	-.0001	.0006	-.225
2	.0006	.0005	.0001	.0000	.0006	.085
2	-.0009	.0005	.0001	-.0014	.0006	-2.576
2	-.0004	.0005	.0001	-.0010	.0006	-1.731
2	-.0001	.0005	.0001	-.0006	.0006	-1.109
5	-.0026	-.0022	.0001	-.0004	.0005	-.709
5	-.0031	-.0022	.0001	-.0010	.0005	-1.750
5	-.0034	-.0022	.0001	-.0012	.0005	-2.259
5	-.0030	-.0022	.0001	-.0008	.0005	-1.457
5	-.0039	-.0022	.0001	-.0017	.0005	-3.171
11	-.0002	.0003	.0001	-.0005	.0006	-.897
11	.0004	.0003	.0001	.0001	.0006	.252
11	.0008	.0003	.0001	.0005	.0006	.975
11	-.0004	.0003	.0001	-.0007	.0006	-1.344
7	-.0006	-.0020	.0001	.0014	.0006	2.468
7	-.0024	-.0020	.0001	-.0004	.0006	-.787
7	-.0014	-.0020	.0001	.0006	.0006	1.065
7	-.0017	-.0020	.0001	.0003	.0006	.542
7	-.0015	-.0020	.0001	.0004	.0006	.758
9	.0016	-.0001	.0001	.0017	.0005	3.088
9	.0000	-.0001	.0001	.0001	.0005	.223
1	-.0018	-.0013	.0001	-.0005	.0006	-.950
1	-.0019	-.0013	.0001	-.0007	.0006	-1.197
1	-.0017	-.0013	.0001	-.0004	.0006	-.737
1	-.0015	-.0013	.0001	-.0003	.0006	-.470
2	.0010	.0005	.0001	.0005	.0006	.898
2	.0002	.0005	.0001	-.0003	.0006	-.593
2	-.0003	.0005	.0001	-.0009	.0006	-1.552
2	-.0002	.0005	.0001	-.0007	.0006	-1.317
2	.0010	.0005	.0001	.0005	.0006	.848
5	-.0027	-.0022	.0001	-.0005	.0005	-.903
5	-.0034	-.0022	.0001	-.0012	.0005	-2.272
5	-.0026	-.0022	.0001	-.0004	.0005	-.714
5	-.0029	-.0022	.0001	-.0007	.0005	-1.292
5	-.0030	-.0022	.0001	-.0008	.0005	-1.481
11	.0001	.0003	.0001	-.0002	.0006	-.413
11	.0012	.0003	.0001	.0009	.0006	1.584
11	.0002	.0003	.0001	-.0001	.0006	-.131
11	.0005	.0003	.0001	.0002	.0006	.371
11	.0014	.0003	.0001	.0011	.0006	2.025
7	-.0024	-.0020	.0001	-.0004	.0006	-.742
7	-.0023	-.0020	.0001	-.0004	.0006	-.659
7	-.0023	-.0020	.0001	-.0004	.0006	-.695
7	-.0018	-.0020	.0001	.0001	.0006	.234
7	-.0019	-.0020	.0001	.0001	.0006	.162
9	-.0015	-.0001	.0001	-.0014	.0005	-2.526
9	.0009	-.0001	.0001	.0010	.0005	1.763
9	-.0013	-.0001	.0001	-.0012	.0005	-2.149
9	-.0006	-.0001	.0001	-.0005	.0005	-.893
1	-.0015	-.0013	.0001	-.0003	.0006	-.492

1	-.0018	-.0013	.0001	-.0005	.0006	-.970
1	-.0015	-.0013	.0001	-.0003	.0006	-.463
1	-.0028	-.0013	.0001	-.0015	.0006	-2.791
1	-.0015	-.0013	.0001	-.0002	.0006	-.446
2	-.0011	.0005	.0001	-.0017	.0006	-2.999
2	.0012	.0005	.0001	.0007	.0006	1.285
2	.0010	.0005	.0001	.0005	.0006	.913
2	-.0006	.0005	.0001	-.0011	.0006	-2.054
5	-.0037	-.0022	.0001	-.0015	.0005	-2.796
5	-.0011	-.0022	.0001	.0011	.0005	1.935
11	.0019	.0003	.0001	.0016	.0006	2.955
11	.0000	.0003	.0001	-.0003	.0006	-.525
7	-.0009	-.0020	.0001	.0011	.0006	1.911
7	-.0026	-.0020	.0001	-.0006	.0006	-1.136
7	-.0019	-.0020	.0001	.0000	.0006	.088
7	-.0017	-.0020	.0001	.0002	.0006	.443

CONSTRAINED MODEL - HYPOTHESIS NUMBER 1

PARAMETER	ESTIMATE	STANDARD DEVIATION	EST/ST.DEV.	TWO-TAIL PROBABILITY (ASYMPTOTIC THEORY)
ERR.VAR.	.0000001761	.0000000136		
CONSTANT	-.0006901514	.0001136168	-6.0743786447	.000
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
BEARING	0.0000000000	0.0000000000		
DAY	0.0000000000	0.0000000000		
BEAR*DAY	.0000010976	.0000001713		

-2*LOG(MAXIMUM LIKELIHOOD) -5103.13270458

VARIANCE-COVARIANCE MATRIX OF THE PARAMETERS

	ERR.VAR.	CONSTANT	BEARING	BEARING	BEARING	BEARING	BEARING	BEARING
ERR.VAR.	.0000							
CONSTANT	0.0000	.0000						
BEARING	0.0000	0.0000	0.0000					
BEARING	0.0000	0.0000	0.0000	0.0000				
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000			
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEAR*DAY	-.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

	BEARING	BEARING	BEARING	BEARING	BEARING	BEARING	DAY	BEAR*DAY
BEARING	0.0000							
BEARING	0.0000	0.0000						
BEARING	0.0000	0.0000	0.0000					
BEARING	0.0000	0.0000	0.0000	0.0000				
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000			
BEARING	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
BEAR*DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0000

```
LIKELIHOOD RATIO TEST
CHI-SQUARE =       173.544
DEGREES OF FREEDOM     12
PROBABILITY          0.000
```

CONSTRAINED MODEL - HYPOTHESIS NUMBER 2

PARAMETER	ESTIMATE	STANDARD DEVIATION	EST/ST.DEV.	TWO-TAIL PROBABILITY (ASYMPTOTIC THEORY)
ERR.VAR.	.0000001767	.0000000136		
CONSTANT	-.0006357397	.0000485353	-13.0984917499	0.000
BEARING	-.0006200440	.0001289158	-4.8096835078	.000
BEARING	.0011665924	.0001294767	9.0100558597	0.000
BEARING	-.0001153500	.0001968422	-.5860027146	.558
BEARING	.0009558193	.0001945153	4.9138513096	.000
BEARING	-.0015242934	.0001308600	-11.6482759847	0.000
BEARING	.0013155558	.0001933125	6.8053325784	.000
BEARING	-.0013137374	.0001281450	-10.2519586160	0.000
BEARING	-.0009809826	.0001945153	-5.0432154809	.000
BEARING	.0005215163	.0001309958	3.9811666973	.000
BEARING	-.0002441979	.0001973919	-1.2371218851	.216
BEARING	.0009505852	.0001302770	7.2966463864	.000
BEARING	-.0001372256	.0001945153	-.7054746547	.481
DAY	0.0000000000	0.0000000000		
BEAR*DAY	.0000001324	.0000000258		

-2*LOG(MAXIMUM LIKELIHOOD) -5268.73487829

VARIANCE-COVARIANCE MATRIX OF THE PARAMETERS

	ERR.VAR.	CONSTANT	BEARING	BEARING	BEARING	BEARING	BEARING	BEARING
ERR.VAR.	.0000							
CONSTANT	0.0000	.0000						
BEARING	0.0000	-.0000	.0000					
BEARING	0.0000	-.0000	-.0000	.0000				
BEARING	0.0000	.0000	-.0000	-.0000	.0000			
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	.0000		
BEARING	0.0000	-.0000	-.0000	-.0000	-.0000	-.0000	.0000	
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	.0000
BEARING	0.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEAR*DAY	-.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

	BEARING	BEARING	BEARING	BEARING	BEARING	BEARING	DAY	BEAR*DAY
BEARING	.0000							
BEARING	-.0000	.0000						
BEARING	-.0000	-.0000	.0000					
BEARING	-.0000	-.0000	-.0000	.0000				
BEARING	-.0000	-.0000	-.0000	-.0000	.0000			
BEARING	-.0000	-.0000	-.0000	-.0000	-.0000	.0000		
DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
BEAR*DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0000

```
LIKELIHOOD RATIO TEST

CHI-SQUARE =          7.942

DEGREES OF FREEDOM      1

PROBABILITY          .005
```

CONSTRAINED MODEL - HYPOTHESIS NUMBER 3

PARAMETER	ESTIMATE	STANDARD DEVIATION	EST/ST.DEV.	TWO-TAIL PROBABILITY (ASYMPTOTIC THEORY)
ERR.VAR.	.0000002545	.0000000177		
CONSTANT	-.0007786462	.0000895574	-8.6943779329	0.000
BEARING	-.0004724218	.0000739855	-6.3853296908	.000
BEARING	.0013148106	.0000755624	17.4003295579	0.000
BEARING	-.0002216187	.0001137475	-1.9483380451	.051
BEARING	.0008416696	.0001082670	7.7740170993	.000
BEARING	-.0013870471	.0000770294	-18.0067134784	0.000
BEARING	.0012489654	.0001020221	12.2421057041	0.000
BEARING	-.0012016388	.0000694758	-17.2957940297	0.000
BEARING	-.0010951323	.0001082670	-10.1151056068	0.000
BEARING	.0006561600	.0000774099	8.4764354487	0.000
BEARING	-.0003974420	.0001137454	-3.4941351369	.000
BEARING	.0010534580	.0000755841	13.9375648296	0.000
BEARING	-.0002513753	.0001082670	-2.3218086912	.020
DAY	.0000000693	.0000000341		
BEAR*DAY	0.0000000000	0.0000000000		

-2*LOG(MAXIMUM LIKELIHOOD) -5222.64679308

VARIANCE-COVARIANCE MATRIX OF THE PARAMETERS

	ERR.VAR.	CONSTANT	BEARING	BEARING	BEARING	BEARING	BEARING	BEARING
ERR.VAR.	.0000							
CONSTANT	0.0000	.0000						
BEARING	0.0000	-.0000	.0000					
BEARING	0.0000	-.0000	.0000	.0000				
BEARING	0.0000	.0000	-.0000	-.0000	.0000			
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	.0000		
BEARING	0.0000	-.0000	.0000	.0000	-.0000	-.0000	.0000	
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	.0000
BEARING	0.0000	-.0000	.0000	.0000	-.0000	-.0000	.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	-.0000	.0000	.0000	-.0000	-.0000	.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
BEARING	0.0000	-.0000	.0000	.0000	-.0000	-.0000	.0000	-.0000
BEARING	0.0000	.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
DAY	-.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BEAR*DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

	BEARING	BEARING	BEARING	BEARING	BEARING	BEARING	DAY	BEAR*DAY
BEARING	.0000							
BEARING	-.0000	.0000						
BEARING	.0000	-.0000	.0000					
BEARING	-.0000	-.0000	-.0000	.0000				
BEARING	.0000	-.0000	.0000	-.0000	.0000			
BEARING	-.0000	-.0000	-.0000	-.0000	-.0000	.0000		
DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0000	
BEAR*DAY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

LIKELIHOOD RATIO TEST

CHI-SQUARE = 54.030

DEGREES OF FREEDOM 1

PROBABILITY 0.000

Appendix E. Sample Report of Calibration

The results of a calibration are reported to the customer using a form letter similar to that in this appendix. There are a number of different phasemeter designs on the market, so there is some variation in the way the test is conducted and the results reported. If the phasemeter is designed to permit the forcing of a self-calibration or autozero, this is done before every observation. Some instruments have provision for internal digital adjustment by means of switches. Since these switches affect the calibration, their settings are recorded on the data sheet. If settings have been changed since the last calibration, results cannot be compared.

The data sheet carries information to identify the customer, the instrument (by make, model, and serial number), and other useful information. It shows a tabulation of the raw data, the standard deviation for each bearing angle, and difference between the mean and nominal for each angle. The customer can then correct the instrument readings using the table.

The data are taken using a computer program named "CALDAT". This program allows the operator to specify the number of bearing angles, the number of readings at each, and all of the housekeeping information needed to document the measurement. It then prompts the operator as to the setting to be made on the NBS generator. When the phasemeter under test achieves a stable reading, the operator enters it into the computer. In order to minimize drift effects, the generator settings are randomized, both by bearing angle and by the reading number for each angle. The observed readings and the housekeeping data are stored on disc, along with data that allows unscrambling the order of reading in a case a future time-trend analysis is desired. The program then prints out the data sheet for the Report of Calibration.

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
325 Broadway
Boulder, Colorado 80303

Reply to the attention of:

March 29, 1985

Airframe Manufacturing Inc.
1234 S. Broadway
Needles, CA 99999
ATTN: Standards Laboratory Manager

Dear Sir:

Enclosed is a copy of the data from an informal calibration of your VOR Radial Standard, (manufacturer and model), Serial No. _____, NBS Test No. _____.

The instrument was warmed for a minimum of 24 hours before calibration. If an autozero function was provided by the instrument, it was forced before every observation. If present, the hexadecimal number displayed during the autozero period was recorded on the data sheet.

Four observations were made at each of 12 bearing angles. The raw data and the standard deviations for each bearing angle are tabulated on the attached data sheet. The bearing angles for the set of 48 observations were randomized to reduce the effects of any time trends and interactions.

Measurements made on several instruments of this type suggest that repeatability at any bearing angle is about ±0.01 degrees immediately after autozero.

The NBS standard VOR generator and phasemeter are believed to have a combined systematic and random uncertainty of less than ±0.0023 degrees (95 percent confidence level).

Sincerely,

Neil T. Larsen
Microwave Metrology Group
Electromagnetic Technology Division

Test No. 123456 Data file: DEMDAT Disk No. 8210050830

Customer: Airframe Mfg. Inst. mfr: X Avionics Ser. No 123

Test date: 8411281438 Zero set: -FFF3-

NOMINAL BEARING	RDG NO. 1	RDG NO. 2	RDG NO. 3	RDG NO. 4	STANDARD DEV.
0.00	.078	-.057	-.089	-.088	7.95E-02
30.00	30.071	29.910	30.073	29.943	8.55E-02
60.00	59.944	60.024	60.073	60.065	5.92E-02
90.00	89.906	89.993	89.916	90.027	5.88E-02
120.00	119.933	119.955	120.099	119.917	8.33E-02
150.00	150.005	149.913	149.972	150.095	7.59E-02
180.00	179.977	179.951	179.946	180.077	6.09E-02
210.00	210.031	209.902	209.916	209.903	6.26E-02
240.00	239.992	239.927	240.007	239.959	3.59E-02
270.00	269.981	270.096	270.055	270.086	5.22E-02
300.00	299.990	300.016	299.982	299.934	3.42E-02
330.00	329.989	330.045	330.075	330.019	3.65E-02

NOMINAL BEARING	MSMNT MEAN	MEAN-NOMINAL
0.00	-.039	-.039
30.00	29.999	-.001
60.00	60.026	.026
90.00	89.961	-.039
120.00	119.976	-.024
150.00	149.996	-.004
180.00	179.988	-.012
210.00	209.938	-.062
240.00	239.971	-.029
270.00	270.055	.055
300.00	299.980	-.020
330.00	330.032	.032

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS TN-1069	2. Performing Organ. Report No.	3. Publication Date April 1985

4. TITLE AND SUBTITLE

VOR Calibration Services

5. AUTHOR(S)

Neil T. Larsen, Dominic F. Vecchia, George R. Sugar

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

U.S. Department of Defense

10. SUPPLEMENTARY NOTES

Document is intended to support the new VOR calibrations service with explanatory material, software, and statistical control charts. It is not intended to supply information required to duplicate the service.

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The National Bureau of Standards has designed, constructed, and evaluated a standard for the support of very-high-frequency omnidirectional range (VOR) air navigation aids. The standard consists of two instruments: (1) a digital waveform signal generator for the composite VOR audio waveform, and (2) a standard phasemeter based on time series analysis of this waveform. Experimental results, a statistical analysis of them, and the principal software listings are included.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

air; calibration standard; navigation; omnidirectional; range; very-high frequency; VOR

13. AVAILABILITY

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