NBSIR 73-340 (R)

VOR AIRCRAFT NAVIGATION SYSTEM MEASUREMENTS

Final Report, Task 1

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National Bureau of Standards
Boulder, Colorado 80302

November 1973

Prepared for:
Department of Defense
Calibration Coordination Group
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U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W Roberts, Director

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VOR AIRCRAFT NAVIGATION SYSTEM MEASUREMENTS

Final Report, Task 1

Abstract

This report summarizes the work performed under Task 1 of the VHF Omnidirectional Radio Range (VOR) phase angle measurement standards project. Included are (a) a review of VOR system requirements and performance data, (b) results of a literature search of phase angle measurement techniques, (c) evaluation of phase angle measurement techniques, and (d) recommended approaches for a VOR phase angle measurement standard. The recommended approaches are to develop both a standard source of VOR audiofrequency signal and a precision VOR audiofrequency phase meter. These techniques are described in moderate detail.

Key Words: Aircraft navigation standards; phase angle measurement; phase standard; VHF omnidirectional radio range; VOR standards.

1. INTRODUCTION

This report summarizes the work performed under Task 1 of the VHF omnidirectional radio range (VOR) phase angle measurement standards project, Department of Defense Calibration Coordination Group (DoD/CCG) Project 73-87, National Bureau of Standards (NBS) Project 2724461. The project objective is to develop engineering performance standards necessary to establish a national phase angle standard for VOR application.

The bearing (heading) information provided by the VOR navigation system is contained in the phase angle difference between two 30-Hz audiofrequency signals. The accuracy of the bearing information is assured by calibration of VOR test instruments used to test and maintain VOR system performance. No national standards exist for phase angle for VOR application; present calibrations are accomplished with commercial equipment designed for that purpose. This equipment's accuracy is subject to question, especially as system requirements become more severe because of increasing traffic in the air lanes. An accurate national standard of phase angle for VOR application will decrease the uncertainties inherent in the present VOR test equipment calibration, and will increase the safety and efficiency of aircraft operations.

The objectives of Task 1 are to identify the problem areas for VOR phase angle measurement standards, and recommend approaches for their solution. The objectives of the second task, Task 2, are to develop VOR phase angle standards and measurement techniques for audiofrequency circuitry, and, if practicable, for radiofrequency circuitry.

Task 1 was divided into nine parts, called milestones, to identify the various steps that needed to be taken to complete the task. These milestones are as follows:

(a) Consult with VOR users, equipment manufacturers, and system engineers.

(b) Compile detailed system requirements and performance data.

(c) Publish a letter report on the results of (a) and (b), above.

(d) Conduct a literature search of phase angle measurement techniques.

(e) Evaluate the technical merits of techniques found by (d), above.

(f) Publish a letter report on the results of (d) and (e), above.

(g) Study and suggest an approach or approaches for a VOR phase angle measurement standard.

(h) Publish a final report on the results of (g), above.

(i) Hold a joint meeting with DoD/CCG personnel to discuss results of Task 1.

When the project was originally being set up, it was felt that NBS would procure VOR signal generators and other VOR test equipment in order to evaluate their performance and acquire experimental data for study. This was not done, however, primarily because no measurement standards, suitable for this purpose, are available. Indeed, to develop measurement standards is the primary purpose of this project.

Therefore, the procedure that was followed was to consult with persons who are knowledgeable about the design, operation, and performance characteristics of VOR test equipment, and from these conversations, plus supportive reports and documents, obtain the required information. It soon became apparent that the shortcomings of present VOR test equipment are fairly well known within the avionics community. An alternative procedure would have been to perform error analyses on the various types of VOR test instruments. This did not seem warranted, however, in view of its high cost and the limited benefit to the project's primary objective.

The work that was performed under Task 1 is described below. This information is divided according to the milestones given above.

2. MILESTONE (a): CONSULTATION

2.1 Objective:

Consult with VOR users, equipment manufacturers, and system engineers.

2.2 Results:

The following agencies, organizations, and individuals were consulted to identify the requirements for VOR phase angle measurements and standards, and to gain a clearer understanding of how these requirements relate to those of the VOR navigation system:

a. Federal Aviation Administration (FAA)
Systems Research and Development Service
Short Distance Navigation Branch
Washington, D.C.

Mr. A.W. Randall, Chief

b. Federal Aviation Administration
Avionics Engineering Section
Oklahoma City, Oklahoma

Mr. W.E. Bell, Unit Chief
Mr. Clee M. Hale, Engineer
Mr. Chester Longman (Flight Inspection Office)

c. Federal Aviation Administration
National Aviation Facilities Experimental Center
Atlantic City, New Jersey

Mr. Jack A. Muller, Engineer

d. Federal Aviation Administration
Navigation Measurements Section
Denver, Colorado

Mr. Harry T. Morgensen, Unit Chief
Mr. Tom Annes, Technician-in-Depth

e. U.S. Army
Metrology and Calibration Center
Redstone Arsenal, Alabama

Mr. J.M. Williams, Jr.

f. Radio Technical Commission for Aeronautics (RTCA)
Washington, D.C.

Mr. Robert Fletcher (FAA), Chairman, RTCA Subcommittee SC-121

g. Aeronautical Radio, Incorporated (ARINC)
Washington, D.C.

Mr. William S. Smoot, Secretary

h. Ministry of Transport
Navaids Maintenance Engineering
Ottawa, Canada

Mr. D.R. Vroom, Engineer
Mr. R.J. Gilleland, Engineer

i. Collins Radio Corporation
Cedar Rapids, Iowa

Mr. A.D. Vance, Engineer, Avionics Division
Mr. R.B. Willett, Manager, Metrology Standards Lab.
Mr. Ray Nelson, Metrology Standards Lab.
Mr. A.A. Rogers, Manager, Service Division
Mr. Neil Ennis, Service Division
Mr. Bob Wolter, Service Division

j. The Bendix Corporation
Avionics Division
Fort Lauderdale, Florida

Mr. Joseph Sawicki, Project Engineer

k. Tel-Instrument Electronics Corporation
Carlstadt, New Jersey

Mr. D.L. Shacher, Vice President/Chief Engineer

l. The Singer Company
Palo Alto Operation
Palo Alto, California

Mr. Gunther U. Sorger, Director -- Advanced Programs

m. Instrument Flight Research Corporation
Wichita, Kansas

Mr. Harold Selim, Chief Engineer

n. Rohde & Schwarz
Passaic, New Jersey

Mr. Carroll Barlow, Sales Engineer

o. Hewlett Packard Company
Palo Alto, California

Mr. Ray Shannon, Engineer

This information was reported in Letter Report No. 1, dated June 15, 1973, but is included here to make this present report complete.

3. MILESTONE (b): SYSTEM REQUIREMENTS AND PERFORMANCE

3.1 Objective:

Compile detailed system requirements and performance data.

3.2 Results:

Conversations with the people cited above and a study of the FAA, RTCA, and ICAO (International Civil Aviation Organization) publications on this subject have provided the following information. The conclusions drawn from this information are found in Section 8, below.

Sources of information are identified in the references at the end of this report. Square bracketed [ ] numbers identify these sources. Persons referenced as "private communication" are those listed in Section 2.2, above. For the most part, these private communications were oral, having taken place in person, by telephone, and by correspondence.

This information was reported in Letter Report No. 1 in brief form, but it is included here in more detail.

a. Operational VOR receivers in aircraft are required to provide a bearing information accuracy (airborne component error, E_a) of ± 3° [1]. The operational VOR ground component error spread must not exceed 2°, and the time instability must be no worse than 0.3° per 15-minute period [1]. These requirements can be satisfactorily met only if the instruments used to perform receiver calibrations or VOR station measurements have an accuracy of the order of approximately two or three tenths of a degree or better. New system requirements for future VOR operations through the 1980's will impose smaller error tolerances (e.g., perhaps ± 1.0°) [2], [3]. It appears at the present time that the accuracy of a national standard of VOR phase angle, needed to support present and future system requirements, is approximately one or two hundredths of a degree or better.

b. The bearing indication of operational and test VOR receivers is calibrated with calibrated VOR signal generators and resolver zeroing instruments [4]. Signal generators are calibrated according to RTCA paper 208-53/DO-52 entitled "Calibration Procedures for Signal Generators Used in the Testing of VOR and ILS Receivers." Resolvers are zeroed according to RTCA paper 126-54/SC61-65 entitled "Calibration Procedures for Test Standard Omnibearing Selectors and Omnibearing Selector Test Sets Used in the Testing of VOR Receivers and Omnibearing Selectors." Modern VOR signal generators have a phase angle resolution of ± 0.01° whereas the resolution of older generators is approximately ± 0.05° [5].

c. The bearing adjustment of operational VOR transmitting stations is accomplished with calibrated VOR signal generators and other ancillary instruments as outlined in FAA procedures [6]. The accuracy of this adjustment is limited by the calibration accuracy of the VOR signal generator and the resolution of the VOR phase monitor. The VOR monitor provides an alarm when a 1° change in phase angle difference occurs [7].

d. VOR signal generators used in tests and calibrations are amplitude modulated VHF radiofrequency signal sources. The radiofrequency source may be a separated generator unit from the audiofrequency modulation unit, or it may be incorporated in one instrument with the audiofrequency source [4]. The essential VOR bearing information is contained in the audiofrequency signal [1], [8], [9]. Calibration of the audiofrequency signal at zero phase angle difference between the reference and the variable phase voltages is accomplished by means of a "zero indicator" instrument [4], [10], [11]. No attempt is made to calibrate the bearing information contained in the radiofrequency signal per se [12]. The radiofrequency signal is always demodulated to recover the audiofrequency VOR signal for calibration and testing [13].

e. Two types of zero indicator instruments are generally in use [10]. One uses a null network to indicate when a zero phase condition exists. The claimed accuracy for this type of instrument is ± 0.1°. The other uses a phase detector to measure phase angle difference. The claimed accuracy for this type of instrument is also ± 0.1° when the phase angle difference is within ± 1.0° of zero. However, intercomparisons of VOR zero measurements made with these two different types of instruments have revealed as great as 0.7° difference in the zero indication [9], [10]. Neither type of indicator is a primary standard based on fundamental quantities.

f. The zero indicator instrument, as normally used, is capable of indicating only an in-phase condition of audiofrequency reference and variable phase voltages, although the null network type can be used in conjunction with a phase shifter to check selected non-zero phase differences and the phase detector type can be designed to measure other selected non-zero phase angle differences [4]. Phase angle differences other than zero are presently established by the generating mechanism, either electrical or electro-mechanical, of VOR audiofrequency generators [9], [11]. Modern VOR generators provide a phase angle resolution as small as 0.01° and a claimed accuracy of approximately ± 0.02° to ± 0.03°. Older electromechanical generators provide a resolution as small as 0.05° and a claimed accuracy of approximately ± 0.2° to ± 0.5°. Modern generators, using precision clocks and digital techniques to produce a precise phase angle difference, are known to disagree with the zero indicator type of instrument by as much as approximately 0.4° at zero degrees phase angle difference [14].

g. Because present and future VOR test equipment include both audiofrequency and radiofrequency instruments, means are needed to test both types of equipment [15]. In general, means must be provided to measure the phase angle difference between the reference and variable phase voltages both at the output port of VOR audiofrequency generators and at the output port of VOR radiofrequency generators. In the final analysis, the radiofrequency measurement is the more useful for VOR receiver testing because the test signal applied to the receiver is at radio frequency [16]. The audiofrequency measurement is more useful for testing zero indicator instruments and ground station performance.

h. As can be seen from b, c, and d, above, present VOR test instruments include both active (signal generators) and passive (zero indicators) devices. A national standard for VOR phase angle must support both types of instruments [17]. This means that both a standard VOR phase METER and a standard VOR signal SOURCE may be required. A VOR audiofrequency phase meter should be designed to accept input voltages between approximately 0.1 and 5 volts. A radiofrequency phase meter should accept input voltages between approximately 0.001 and 1 volt. Audiofrequency signal sources should generate a 1-volt minimum output signal at 30 Hz and 9960 Hz. Radiofrequency signal sources should generate a minimum of 50,000 microvolts at VOR frequencies [19].

i. A new generation of test equipment which uses new design concepts is becoming available. However, much of the older test equipment will remain in service. A calibration capability must support both types of equipment [12].

j. Operational VOR receivers vary in design and the VOR signal is not processed in the same way by all the receivers. Measurement techniques or measurement standards must apply to all types of receiving techniques [9].

k. Operational VOR signals are normally not pure sinusoids. Distortion and noise originate from a variety of sources such as (1) mechanical imperfections in the tone wheel generators, (2) instabilities in digital signal synthesizers, (3) nonlinear amplification, modulation, and demodulation in generators, zero indicators, and receivers, and (4) electromagnetic interference [19]. According to an inquiry to ARINC from Deutsche Lufthansa [20], harmonic distortion can shift VOR zero per the following schedule:

Harmonic Distortion	Maximum Phase Shift Error
0.1%	± 0.058°
0.3%	± 0.166°
1.0%	± 0.58°
2.0%	± 1.16°
3.0%	± 1.72°

Residual frequency modulation (FM) can also occur [16]. The long-range objective of this project should include a solution to the additional measurement problems introduced by non-ideal signals. Also, the definition of VOR zero should take distortion into account.

3.3 Summary of Requirements:

a. Operational bearing accuracy:
Receivers: ± 3° accuracy,
Ground Station: 2° error spread;
0.3°/15 minutes stability.

b. Operational test equipment accuracy: ± 0.1° to ± 0.2°.

c. National standards accuracy: ± 0.01° to ± 0.02°.

d. Types of operational test equipment needing support:
    - Audiofrequency signal generators
    - Radiofrequency signal generators
    - Zero indicators.

e. Requirements b and c, above, apply over the complete range of 0° to 360° azimuth.

f. Requirement d, above, applies for both older and newer types of test equipment.

g. Requirement d, above, applies to both older and newer types of receiving techniques.

h. National standards and measurement techniques must apply to non-ideal (distorted and noisy) VOR signal sources as well as to ideal waveforms.

4. MILESTONE (c): REPORT RESULTS OF MILESTONES (a), (b)

4.1 Objective:

Publish a letter report on the results of milestones (a) and (b), above.

4.2 Results:

The subject information was contained in Letter Report No. 1, dated June 15, 1973. It has been somewhat expanded in the present report.

5. MILESTONE (d): LITERATURE SEARCH

5.1 Objective:

Conduct a literature search of phase angle measurement techniques.

5.2 Results:

5.2.1 Extent of Search:

An extensive, but by no means exhaustive, literature search was conducted for phase angle measurement techniques. The search was confined to those methods that pertain to VOR phase angle metrology. In general, two approaches apply to this problem, viz., (a) determination of phase angle difference by comparison with a standard VOR signal source of known characteristics, and (b) direct measurement of phase angle difference by means of an accurate, calibrated phase meter.

The more useful papers found by this search are appended at the end of this report under Bibliography. This bibliography is restricted to documents that describe methods, techniques, equipment, and analyses for either one or both of the two approaches cited above. Other papers could be included in this list, but for the most part, they would be redundant to the papers listed. In addition to these papers, we have acquired and studied other related papers, e.g., on VOR system design, but they have been excluded from the present bibliography on phase angle measurement.

The resources used in this literature search are as follows:

a. We searched the card catalog of the Technical Library of the U.S. Department of Commerce in Boulder, Colorado. The following subjects were included in the search: Angle, Electronic instruments, Electronic measurements, Measurement, Navigation, Phase, VOR.

b. We searched, for 1971 and 1972, the KWOC Index for technical reports. This is a computer printout of key words maintained by the Technical Library of the U.S. Department of Commerce in Boulder, Colorado. The following key words were included in the search: Angle, Measurement, Navigation, Phase, Standard, VOR.

c. We scanned the listings under "Phase, Phase Shift and Time Delay" of the Electromagnetic Metrology Current Awareness Service (EMMCAS). We scanned each issue from August 1969 through May 1973, inclusive. EMMCAS is prepared monthly by the Electromagnetics Division of the National Bureau of Standards, Boulder, Colorado, 80302.

d. We searched, for 1971, the Permuterm Subject Index (PSI) of the Institute for Scientific Information. This is a broad, powerful method of search. The following generic terms were used: Angle, Phase, Standard, and VOR. NOTE: Three items attributed to the generic term "phase" were found under the complete terms "Phase-Meter" and "Phase-Shifter." This illustrates the complications which arise in the PSI. However, we feel the effort is worthwhile, for this method of search leads to additional references which are relevant but which likely would not be found in other practical methods of search.

e. We used the Science Citation Index (SCI) through 1972 to discover related and useful papers.

f. We searched the entire index for Electronics magazine for each of the years 1966 through 1971, inclusive. We also scanned each individual issue for January 1973 through April 1973. The index for 1972 is not yet available.

g. An extensive bibliography on phase shift measurements appears as Section 11 in an unpublished report (Beatty et al., 1967) of the Electromagnetics Division of the National Bureau of Standards. Most of that bibliography is directed toward phase metrology for UHF and microwave signals. Only four of the 156 items in the bibliography were chosen as relevant and useful for our present study of VOR phase angle measurement standards.

Of the eleven sections in this report, Section 2 was the one specifically directed toward low frequency measurements of phase (Turgel, 1967). Of the nineteen references in Section 2, we chose eleven as relevant and useful for our present study.

Incidentally, Section 2 is the most complete and useful survey of basic methods of phase angle metrology which we found in our literature search.

h. We searched each of the documents listed in the Bibliography for references to additional papers which would be relevant and useful. Several important items were found this way. There was considerable duplication, triplication, ..., as might be expected.

i. We scanned several books on electronic navigation systems, searching for references to literature on methods of phase angle metrology. We similarly scanned several articles on VOR. The effort was unrewarding in that it revealed very few useful references, and all of those few had already been found in earlier procedures. The books scanned included:

Radio Navigation Systems for Aviation and Maritime Use, edited by W. Bauss. Pergamon Press: New York, 1963.

Navigation Systems, A Survey of Modern Electronic Aids, edited by G.E. Beck. Van Nostrand Reinhold: London, 1971.

Avionics Navigation Systems, by M. Kayton and W.R. Fried. John Wiley & Sons: New York 1969.

Electronic Avigation Engineering, by P.C. Sandretto. International Telephone and Telegraph Corporation: New York, 1958.

5.2.2 Results of Search:

The literature search did not yield any methods, per se, for directly determining the phase angle difference of the two 30-Hz signals contained in the composite VOR audiofrequency signal (i.e., the 30-Hz variable phase voltage plus the 9960-Hz subcarrier, frequency modulated by the 30-Hz reference phase voltage). Neither did we find any methods for phase difference of these 30-Hz signals as they exist in the VOR radiofrequency signal (i.e., the radiofrequency carrier amplitude modulated by the composite VOR audiofrequency signal). If such methods have been described in the open literature, we have yet to find them. All of the methods found pertained to a pair of sinusoids of the same frequency. This would be a natural consequence of the common definition of phase angle difference, which pertains only to this condition.

Methods that use mechanical or electro-mechanical devices as critical measurement elements were arbitrarily excluded from our considerations, for the present time at least, because our belief that the maximum accuracy obtainable with such devices is poorer than with all-electric techniques, and that precision automation methods are more difficult to apply to mechanical devices.

Although none of the methods found dealt with the composite VOR signal, it is instructive to review the variety of methods that were found. There are basically four different metrology methods using the Standard Source approach and six different methods using the Direct Measurement approach that are applicable to the VOR problem. These ten methods are briefly described below. This information was reported in Letter Report No. 1, but is included here for completeness.

5.2.2.1 Standard Source Methods:

In each of the standard source methods, two 30-Hz signals are generated by some suitable means, and their phase angle relationship is established by a specific technique as follows:

a. Digital divider method. See figure 1. The 30-Hz signals are generated by digitally dividing a high frequency signal (e.g., 1.08 MHz) by a suitable factor (e.g., 36,000). These 30-Hz signals can be shifted in relative phase by altering the delay in a digital phase shifter. Precise incremental shifts (e.g., 0.01 degree and multiples thereof) can be readily produced. See Dreifus, 1971; Drogin, 1967; Krikorian, 1973; Leuenberger, 1971; and Turgel, 1967.

b. RLC method. See figure 2. A 30-Hz signal drives a network of resistors, inductors, or capacitors of known values. The phase shift of the output signal, relative to the driving signal, is computed from the network equations. Switchable sections are employed to obtain the values of phase shift desired. See Haynie and Rosenfeld, 1963; Heydeman, 1963; Kritz, 1950; Khomyak, 1971; Park and Cones, 1960; Shkol'nik, 1971; Smirnov, 1970; Turgel, 1967; and Wintle, 1951.

c. Vector addition method. See figure 3. By some means, for example by methods a or b above, two 30-Hz signals are generated with a phase angle difference of 90 degrees. Using calibrated resistive or inductive voltage dividers, phase inverters, and an adding network, a vector sum of exact portions of the two in-quadrature signals is generated. The phase angle difference between one of the original signals and the sum signal is computed from the voltage ratios employed. See Kritz, 1950; Turgel, 1967; and Wintle, 1951.

d. Phase meter method. See figure 4. Two stable 30-Hz signals are generated by some suitable means, and a variable network is provided to shift their relative phase. The phase difference is measured with an accurate phase meter. See Scott, 1966.

5.2.2.2 Direct Measurement Methods:

e. Zero-crossing detector/time-interval counter method. See figure 5. A zero-crossing of one signal starts a time-interval counter. A zero-crossing of the other signal stops the counter. The elapsed time is a measure of the phase angle difference. See Anon., Electronics, May 1970; Drogin, 1967; Drogin, 1971; Elliot, 1962; Epstein, 1964; Fritz, 1972; Maxwell, 1966; McKinney, 1967; Rinkel, 1956; and Turgel, 1967.

f. Zero-crossing detector/pulse-area method. See figure 6. A zero-crossing of one signal starts a train of pulses or initiates a step change in a d.c. voltage. A zero-crossing of the other signal stops the pulse train or restores the d.c. voltage to its original value. An analog integrator measures the area under the string of pulses or under the single d.c. pulse. The integrator output is a measure of the phase angle difference. See Ehret, Wood, and Thompson, 1969; Frater, 1966; Gruner, 1969; Herbst, 1971; Heydeman, 1963; Paull, 1971; Rinkel, 1956; Turgel, 1967; and Yu, 1958.

g. Three-voltmeter method. See figure 7. The two 30-Hz signal sources are connected with one common terminal. Three voltages are measured: (a) the voltage of one of the signals; (b) the voltage of the other signal; and (c) the voltage difference between the two signals. The phase angle difference between the two signals is calculated from these three voltages by use of the cosine law of vector addition. See Pirkle, 1973, and Scott, 1966.

h. Lissajous pattern method. See figure 8. The two 30-Hz signals are connected to the vertical and horizontal inputs, respectively, of an oscilloscope or oscillograph. The loops of the pattern configuration are an indication of the phase angle difference. See Heydemann, 1963; Rinkel, 1956; Stickel, 1971; and Turgel, 1967.

i. Power factor method. See figure 9. The two 30-Hz signals are connected to the two inputs of a true power meter. Also, the individual signal voltages, v_1 and v_2, are measured. The "effective phase angle difference," θ, is computed by use of the equation

$$\theta = \cos^{-1} \frac{<v_1 v_2>}{[<v_1^2> <v_2^2>]^{\frac{1}{2}}}$$

where the angular brackets indicate an average over the time of one period. The numerator of the equation is the reading of the true power meter, and the denominator is the product of the rms values of v_1 and v_2. θ is the phase angle difference between fundamental components of the 30-Hz signals if the signals are distortion-free, or if they have identical waveforms. See Khomyak, 1971, and Turgel, 1967.

j. Null detector method. See figure 10. One of the two 30-Hz signals is connected directly to the phase sensitive null detector, and the other 30-Hz signal is connected through a calibrated phase shifter. The setting of the phase shifter to produce a null gives the desired phase angle difference between the two signals. See Heydeman, 1963; Kritz, 1950; Rinkel, 1956; and Turgel, 1967.

k. Supplemental Procedures for Attaining and Checking Measurement Accuracy. Often, measurement procedures can be extended to monitor or verify the accuracy and internal consistency of the above methods. One such procedure is to check closure around the circle from 0° to 360° phase difference. Another is to interchange the two signals, which should give the same result as a change in the sign of the phase angle. Still another is to use one signal to represent both signals at 0° phase angle difference. There are potentially a large number of symmetry and logic operations of this sort that can provide supplemental checks on the accuracy of a standard source or of a phase angle meter. See Dreifus, 1971; Drogin, 1967; Epstein, 1964; Heydeman, 1963; McKinney, 1967; Paull, 1971; Pirkle, 1973; and Turgel, 1967.

6. MILESTONE (e): TECHNIQUE EVALUATION

6.1 Objective:

Evaluate the technical merits of techniques found in milestone (d), above.

6.2 Results:

The evaluations presented below are first-pass evaluations only, and are based upon the published material found in the literature. They are not based upon analyses or experimental testing conducted at NBS for the purposes of this project. The principal purpose of these evaluations is to help determine what application, if any, these techniques might have to the VOR problem. Since none of these techniques dealt with the composite VOR signal per se, they would need to be augmented or modified in some manner to be useful to the problem. Thus an in-depth evaluation of each technique, based upon a thorough technical analysis, is not considered to be the best use of project funds at this time. A more thorough analysis of the techniques recommended for Task 2 is given in Section 8.2.3.

6.2.1 Standard Source Methods:

a. Digital divider method. This method is readily capable of 0.01° accuracy and resolution, and appears capable in principle of exceeding this figure. It can provide complete coverage of 0° to 360° with uniform accuracy. The principle of this method has been applied in several instances (e.g., Turgel, 1967, and Dreifus, 1971), including application to VOR systems (Drogin, 1967, and Neuvo, 1973). Several commercial generators exploit this method.

This method has the desirable feature of being easily programmable and automatable, which makes it useful in automatic testing applications. The digital circuits which it uses can be interchanged one channel with the other, and in other ways can be readily checked for proper performance and verification of phase angle accuracy. The cost of implementing this method is not expected to be excessive.

b. RLC method. This method has the single strong point of conceptual simplicity, but has several weaknesses as follows: (1) Although the attainable accuracy is 0.01°, precision components and careful adjustments are required to realize this accuracy. (2) The method can be used at only a single frequency with little tolerance for off-frequency operation, unless a heterodyne scheme is used (Turgel, 1967). For example, to obtain a 0.01° accuracy, the 30-Hz signals must each have a fractional frequency stability of 111 ppm or better. (3) Although it is conceptually possible, it would be very expensive and awkward to cover the range of 0° to 360° in 0.01° steps by switching RLC network sections.

c. Vector addition method. This method is potentially capable of excellent accuracy (e.g., 0.0005°) when precision inductive or resistive voltage dividers are used. It has the disadvantage that the basic range is 0° to 90°, and inverter networks are required to cover 90° to 360°. The relationship between phase angle difference and divider ratio is not linear, which causes the absolute accuracy to vary with phase angle according to the slope of an arctangent function. The method is not highly sensitive to frequency variations if the quadrature generator is designed properly. In terms of practicality, speed of operation, and automatability, this method does not appear as attractive as the digital divider method.

d. Phase meter method. This method is an indirect way of obtaining a known phase angle difference, and its accuracy depends directly upon the accuracy of the phase meter. In general, this method will be slower to use, less efficient, less capable of self-checking using supplemental procedures, and less automatable than the digital divider method.

6.2.2 Direct Measurement Methods:

e. Zero-crossing detector/time-interval counter method. This method utilizes the basic concept of phase angle difference by measuring the time interval between equivalent points on the two signal waveforms. The method has been available for some time, and is used in several commercial meters. It appears capable of readily providing 0.01° or better resolution or accuracy over the complete range of 0° to 360°. It is readily automatable, and convenient to use. Its accuracy is degraded by distortion and noise unless means are included to reduce these effects. The method uses standard circuits of high performance, and is not expected to be costly to implement.

f. Zero-crossing detector/pulse-area method. This method has similar characteristics to the time-interval counter method except that the measurement accuracy is somewhat less (e.g., 0.1°) because of the lower attainable accuracy of electronic integrators. Improved accuracy can be attained with increased averaging time together with highest quality analog integration techniques. Time and cost considerations indicate a preference for the time-interval counter method, above.

g. Three-voltmeter method. Although the accuracy of this method can be as small as approximately 0.01° to 0.05° for phase angle differences between -170° and +170°, the accuracy rapidly degrades seriously for angles near 180°. The cause of this is the severe loss of sensitivity near 180°. For best results between ± 170°, the measurements must be performed carefully with accurate (e.g., ± 0.003%) voltmeters or an inductive voltage divider. The method is not particularly sensitive to frequency variation, but is susceptible to distortion and noise. It does not lend itself to rapid or automatable phase measurement. An ambiguity of 180° is present.

h. Lissajous pattern method. This is the classic phase angle measurement method. It, and variations of it (Rinkel, 1956), have been used for many years, and its limitations are well known. It relies upon a human observer to be the detector, with the resulting error caused by subjective judgment. With a precision cathode ray oscilloscope tube and carefully adjusted amplifiers, the accuracy can be very good except near 90° and 270°, but it is difficult to verify and could remain open to question. Accuracy varies with the value of phase angle difference, and there is the ambiguity of 180° to resolve. For certain types of harmonic distortion, special techniques can minimize the measurement error that would otherwise occur.

i. Power factor method. The principal shortcoming of this method lies in the difficulty of accurately measuring the time average of the product of the two 30-Hz signals. In addition, the method will require accurate square-law devices to measure the power in each signal. An analysis of this method shows that the calculated value of phase angle is relatively little affected by harmonic distortion on the signals (Turgel, 1967). The method appears to be rarely used.

j. Null meter method. The accuracy of this method depends upon the accuracy of the calibrated phase meter and the sensitivity of the null detector. Distortion and noise will greatly reduce its accuracy. In general, this method will be slower and less convenient than the direct reading methods.

7. MILESTONE (f): REPORT RESULTS OF MILESTONES (d), (e)

7.1 Objective:

Publish a letter report on the results of milestones (d) and (e), above.

7.2 Results:

The subject information was contained in Letter Report No. 1, dated June 15, 1973. It has been somewhat expanded in the present report.

8. MILESTONE (g): STUDY AND RECOMMENDATIONS

8.1 Objective:

Study and suggest an approach or approaches for a VOR phase angle measurement standard.

8.2 Results:

8.2.1 Metrological Considerations:

The problem of VOR phase angle metrology can be divided into four parts; viz., (a) definition of VOR zero and VOR phase angle; (b) national reference standards of phase angle; (c) accurate and precise phase angle measurement techniques; and (d) practical and satisfactory calibration methods for VOR test equipment and VOR receivers. In this section we discuss the present state of affairs, from a metrology standpoint, with regard to these four items, in order to identify the particulars of the problem to be solved.

8.2.1.1 Definitions:

The present legal definition of VOR zero in the USA is given [1] as follows: "The reference and variable phase modulations are in phase when the maximum value of the sum of the radio frequency carrier and the sideband energy due to the amplitude modulation signal occurs at the same time as the highest instantaneous frequency of the frequency modulation signal." The ICAO wording [8] is essentially the same. This definition is precise, unambiguous, and clearly understood, but it is difficult to utilize because of the following measurement problems:

(1) The definition deals with the radiofrequency VOR signal which is difficult to generate or measure with precision at the present state-of-the-art.

(2) The highest instantaneous frequency of the FM signal occurs at the maximum voltage value of the 30-Hz reference phase signal, which is a point of zero slope of the 30-Hz sinusoid, thus making a precise determination of this point very difficult.

(3) None of the present or known future VOR receivers detect the highest instantaneous radio frequency as a means of decoding the bearing information on the VOR radiofrequency signal; they all detect the average instantaneous frequency [9]. Thus a standard VOR signal, based on this definition, would not bear a direct relationship to the receiver process by which it is decoded, and equivalency criteria would have to be established.

(4) Distortion and noise present on the received VOR signal may seriously displace the VOR zero from the undistorted position, depending upon the nature of the distortion [20].

(5) On the widely used tone wheel type audiofrequency generator, measurements show that the instantaneous frequency of the 9960-Hz frequency modulated subcarrier may exhibit more than one

peak in the vicinity of the highest instantaneous frequency because of manufacturing imperfections [9]. Which peak is the true highest instantaneous frequency may be difficult to ascertain.

The definition of VOR phase angle difference is implied in Section 3.4 of reference [1]. It is quoted in part as follows: "The VOR shall radiate a radiofrequency carrier with which are associated two separate 30-Hz modulations. One of these modulations shall be such that its phase is independent of the azimuth of the point of observation (reference phase). The other modulation (variable phase) shall be such that ITS PHASE AT THE POINT OF OBSERVATION DIFFERS FROM THAT OF THE REFERENCE PHASE BY AN ANGLE EQUAL TO THE MAGNETIC BEARING OF THE POINT OF OBSERVATION WITH RESPECT TO THE VOR. ..." (Emphasis added.) This definition, per se, would not appear to raise any measurement problems for this project. However, it does not take into consideration the effects of unspecified (arbitrary) distortions of the modulation waveforms.

8.2.1.2 Reference Standards:

8.2.1.2.1 National Standards:

No national standards of VOR zero or VOR phase angle difference exist. The only electromagnetic standards or calibration services which the National Bureau of Standards maintains that are related to this specific measurement requirement are for Voltage, Impedance (resistance, inductance, and capacitance), and Attenuation [21]. Measurement techniques are not presently available at NBS for VOR phase angle per se, either for audiofrequency signals or radiofrequency signals.

8.2.1.2.2 Audiofrequency Standards:

The virtual standard of VOR zero within the FAA and within most of the aircraft community at the present time is a small group of audiofrequency null network type zero indicator instruments [9] which are maintained by their commercial manufacturer, and which are used to check the performance, by a comparison process, of other instruments of like kind [22]. They are quite stable, and a history of their relative performance characteristics, as a group, has been maintained over a period of approximately twenty years. These qualifications, along with the claimed accuracy of ± 0.1°, have led to general acceptance of these instruments as the best available reference standard.

Many (≃ 800 to 900) of the null network type of zero indicator instrument are in use within the FAA and the avionics community, and serve as the local reference standard for individual test shops [12]. Their calibrations "trace" back to the small group cited above. The phase meter type of zero indicator is also in use throughout the avionics community, but does not appear to enjoy the favor which the former type has [9].

8.2.1.2.3 Radiofrequency Standards:

Although the essential VOR bearing information is contained within the VOR audiofrequency signal, it is carried to an aircraft via a radiofrequency signal which is then demodulated by the VOR receiver. Both the modulation and demodulation processes may introduce bearing errors in the audiofrequency signal used on the aircraft [12]. This facet of the VOR metrology problem is essentially one of accurate measurement and calibration techniques, and should not be one which requires a reference standard in the sense discussed above for the VOR audiofrequency signal. However, the definition of VOR zero is expressed in terms of the radiofrequency signal. To provide a reference standard that is based on this definition would require (1) the generation of a precision VOR radiofrequency signal of known characteristics, and (2) a precision technique for comparing this signal with those of VOR test generators used in the field.

No such radiofrequency standard exists [17]. None of the presently available VOR test equipment is designed to function on a principle that ties directly to the stated definition. The approach that generally is followed is to make provision to minimize the parasitic phase shifts in the modulation circuits of the radiofrequency generator, and to provide a monitor circuit that demodulates the radiofrequency signal and delivers a close facsimile of the original audiofrequency signal. The claimed accuracy of modulator/demodulator circuits in the most modern test equipment, under best conditions, is approximately ± 0.01° [10]. However, these circuits are known to be susceptible to drift under varying operating conditions, and the typical accuracy may be as poor as ± 0.1° [23].

8.2.1.3 Measurement Techniques:

Many techniques are available for measuring the phase angle difference between two sinusoidal audiofrequency voltages of the same frequency, and several of these techniques appear capable of extremely high accuracy and precision. However, none of these techniques is entirely satisfactory for the particular waveforms of VOR signals for the following reasons:

a. The basic VOR audiofrequency signal components are not of the same frequency. The variable phase component is at 30 Hz whereas the reference phase component exists as frequency modulation sidebands of the 9960-Hz subcarrier. Thus FM demodulation is required before same-frequency measurement techniques can be applied.

b. The "working" VOR signal is a VHF radiofrequency carrier, amplitude modulated by the basic VOR audiofrequency signal. Thus amplitude demodulation is required before audiofrequency techniques can be applied.

c. The audiofrequency signals from VOR sources often are non-ideal, i.e., they contain distortion and noise of a variety of types, depending upon the particular device. Examples are harmonic distortion, phase distortion, additive hum, and additive noise. All known measurement techniques are adversely affected by noise and distortion to a greater or lesser degree. Also, the definition of phase angle difference becomes suspect when applied to complex waveforms.

8.2.1.3.1 VOR Audiofrequency Phase Meters:

The measurement approach that is used by all current VOR audiofrequency phase meters is to demodulate the 9960-Hz subcarrier to recover the 30-Hz reference phase signal, and then by some means determine the phase angle difference between this 30-Hz signal and the 30-Hz variable phase signal [19]. This technique suffers from the following problems:

a. The predetection filter network that separates the 9960-Hz FM subcarrier signal from the 30-Hz variable phase signal will introduce a relative phase shift unless its time delay is the same at both 30 Hz and 9480 through 10440 Hz [19].

b. Because of the large frequency deviation ratio of 16, the major FM sidebands extend relatively far each side of the 9960-Hz subcarrier frequency. The spectral bandwidth is approximately twice the frequency deviation, i.e., 960 Hz. If the pre-detection filter networks have a non-linear phase shift throughout this bandwidth, phase distortion can occur which will introduce a phase shift in the 30-Hz reference signal at the output of the demodulator.

c. The FM demodulator network itself may introduce phase distortion of the 9960-Hz FM signal [13].

d. Because the frequency ratio of the 9960-Hz subcarrier to the 30-Hz reference phase modulation is small (332:1), the post-detector filter network, needed to remove the 9960-Hz component from the detector output, can introduce a significant phase shift in the recovered 30-Hz reference phase signal [10].

e. Although the phase shifts of the pre-detection and post-detection networks can be evaluated and a correction applied, the phase shift caused by the detector network cannot be evaluated by standard means [13].

Either (1) some means must be devised to overcome these problems, or (2) a new technique must be found to circumvent the need to demodulate the 9960-Hz subcarrier (see Section 8.2.3.2, below).

8.2.1.3.2 VOR Radiofrequency Phase Meters:

The measurement approach that is used in all current VOR radiofrequency signal generators to determine VOR phase is to demodulate the rf signal and apply the recovered composite audiofrequency signal to a VOR audiofrequency phase meter [19]. This technique is believed to be adequate [13] because (1) the AM demodulator circuit can be optimized for very linear demodulation of the radiofrequency signal, and (2) the phase shifts in the post-detector filter network can be made quite linear with frequency over the VOR audiofrequency range. However, the degree to which these two objectives are actually met in practice should be carefully tested if this approach is to be continued.

8.2.1.4 Calibration Methods:

We have not made a study of the calibration procedures used for VOR test equipment. VOR signal generators are presumably calibrated according to procedures given in RTCA paper 208-53/DO-52 [23]. VOR zero indicators are normally not calibrated by the user since they are considered to be a primary reference standard, but presumably their manufacturers have procedures for verifying their performance at the factory [22].

A study of VOR instrument accuracy by National Aviation Facilities Experimental Center (NAFEC) personnel [4] shows that VOR signal generators used in repair stations to calibrate airborne receivers provide average bearing indications within ± 1.58° at the 95% (2-sigma) probability level. Omnibearing selectors provide average bearing indications within ± 1.36° with 95% probability. Although available calibration procedures were apparently considered to be adequate for the needs of that day, the study revealed that they were not being followed by all shops. A program is needed to improve the calibration activity by (1) increased surveillance of testing practices, (2) establishment of a single standard of zero reference, (3) traceability of test equipment calibration back to the manufacturer's standard, (4) development of a low-cost bearing checker to check the calibration accuracy of shop test equipment, and (5) development of a program of regular periodic testing of signal generators and portable standards.

8.2.2 Characteristics of VOR Test Instruments:

In this section, we discuss briefly the characteristics of VOR test instruments (audiofrequency signal generators, radiofrequency signal generators, and zero indicators) that impact the establishment of a VOR phase angle measurement standard.

VOR test equipment is generally of high quality. A great amount of development and engineering effort has gone into design and production, resulting in instruments having very good resolution and stability. However, absolute accuracy is often suspect because measurement differences between two instruments, much greater than those expected from claimed accuracies, routinely occur without adequate explanation or resolution.

The principal source of signal imperfection in VOR audiofrequency signal generators is the FM modulation process by which the frequency-modulated subcarrier signal is produced [19]. Phase shifts in the modulator are difficult to evaluate accurately. Other potential signal imperfections include (1) harmonic distortion on all three VOR audio frequencies, (2) residual AM on the 9960-Hz subcarrier, (3) frequency modulation of the 9960-Hz subcarrier by the 30-Hz variable phase signal, (4) drift in the phase of either the 30-Hz variable phase or 30-Hz reference phase signals, and (5) variations in the frequency modulation index from the design value of 16.

The principal problem in VOR radiofrequency signal generators is the phase shifts in the amplitude modulation process [19]. The site of this phase shift is in the modulator network itself, and the resulting bearing error cannot be accurately measured by present techniques. Other problems are (1) drift in the phase shift of the amplitude modulation circuits, (2) bearing errors caused by amplitude clipping or phase distortion in the generator's RF stages, and (3) residual FM on the VHF radiofrequency carrier.

The principal source of error in zero indicator instruments is the FM demodulator. Phase shifts in this circuit cannot be accurately determined. Other sources of measurement error are uncorrected phase shifts in the pre-demodulation and post-demodulation filter circuits. The claimed accuracy of ± 0.1° is suspect, but the stability of zero indication is quite good, e.g., better than 0.1° over many years. The two types of zero indicators (see Section 3.2, e, above) in general use have consistently shown a 0.7° difference in VOR zero [9], [10].

8.2.3 Recommended Action:

In view of the findings to date, as presented in the preceding sections, above, we recommend the following steps be taken:

a. Standard VOR Source

The National Bureau of Standards should develop a precision audiofrequency signal source for VOR application based upon the digital divider method. A description of this method is given in Section 8.2.3.1, below. This source would be maintained at NBS, and would serve as the national standard of VOR phase angle.

The purposes of this standard source will be, first, to bring into uniform performance the present and future measurement instrumentation for VOR phase angle, and second, to provide measurement support for improved test instrumentation and improved operational equipment (VOR receivers and ground stations) that will be required for the safe and efficient use of the airways.

The application of this standard source will be to calibrate the zero indicators and other VOR phase meters that serve as primary standards in calibration facilities of the DoD, FAA, and other avionics users and suppliers.

The design of this standard source will be such as to deliver a stable, well-characterized, nearly-ideal VOR audiofrequency signal that will merit the support of all parties by virtue of its superior characteristics and thorough evaluation. It will not be the function of this source to simulate non-ideal signals having distortion and noise such as may be found in the real-world VOR environment. The rationale of this statement is discussed in d, below.

b. Precision Phase Meter

The National Bureau of Standards should develop a precision audiofrequency phase meter for VOR application based upon the time interval counter method. A description of this method is given in Section 8.2.3.2, below. This phase meter would be maintained at NBS, and would serve as a co-standard of VOR phase angle with the Standard VOR Source. These two approaches complement each other, and serve as a check on each other. Because they are entirely different approaches, when taken together they provide the very desirable metrological virtue of having two completely independent techniques for establishing a national standard of VOR phase angle.

The purposes of this phase meter are the same as for the Standard Source. The applications of this phase meter will be, first, to serve as an independent check on the accuracy of the Standard Source, and, second, to calibrate the VOR audiofrequency generators that may serve as primary or transfer standards in calibration facilities of the DoD, FAA, and other avionics users or suppliers.

This phase meter will be designed primarily to measure undistorted VOR signals. Its accuracy with distorted signals has not been investigated at this time.

c. VOR Radiofrequency Standards

Measurement standards should be developed to provide measurement support for VOR radiofrequency test equipment. To develop rf standards will require the audiofrequency standards described above. Therefore, development of rf standards should be planned to begin toward the end of the audiofrequency standards development.

d. Distortion Effects

Techniques should be developed for measuring the effects of distortion and noise on the accuracy of VOR test equipment and operational systems. To do this will first require the capability of accurately measuring VOR phase angle for nearly-ideal VOR signals. The standards discussed in a and b, above, are for this purpose. Once these are available, they will provide a foundation upon which work on distorted and noisy VOR signals can proceed.

e. Definitions

The question of the usefulness of the present definition of VOR zero should be settled. In at least one person's opinion [24], one of the "first things" to be done in this VOR project is to develop a better definition. Although we at NBS do not yet claim to be sufficiently expert in VOR navigational matters to recommend a definition change at this time, we do see serious shortcomings from a metrology point of view in the present definition. We also know how difficult it is to change a definition and how far-ranging the impact can be, especially when it could have international implications. However, we believe we can contribute to the formulation of a better definition, and we are willing to work with other cognizant parties in doing so.

f. Measurement Verification System

A measurement verification system should be established to transmit the accuracy of the national VOR standard to other test instruments with a minimum of degradation. This system would include (1) accurate calibration techniques, (2) standardized calibration procedures, and (3) suitable calibration schedules.

8.2.3.1 Standard VOR Source:

The digital divider method appears to be the most promising method for generating a standard source of VOR audiofrequency voltages. The basic principles behind this method have been described in the literature (Drogen, 1967, and Neuvo, 1973), and have been exploited commercially. The method appears to be capable of the desired accuracy of 0.01° or better, and is capable of covering the entire range of 360° with uniform accuracy. It has the desirable feature of being easily programmable and automatable, which makes it useful in automatic testing applications. The digital circuits which it uses are such that they can be readily checked for proper performance and verification of phase angle accuracy. The method can generate all of the required VOR audio-frequency phase signals, viz., the 30-Hz variable phase, the 30-Hz reference phase, the 9960-Hz subcarrier, and the 9960-Hz subcarrier frequency modulated with a 30-Hz signal.

A block diagram of the VOR audiofrequency source is shown in figure 11. The 30-Hz variable phase signal is produced by a digital sinewave generator. The 30-Hz reference phase signal is produced as a frequency modulation on the 9960-Hz subcarrier by another digital waveform generator consisting of a subcarrier argument calculator and a sinewave amplitude generator. The desired adjustable phase angle difference between the reference phase and variable phase signals is obtained by pre-setting a down-counter to the desired phase difference, and starting the reference phase generator and the down-counter simultaneously. The variable phase generator is started when the down-counter has reached its zero state.

The down-counter counts zero crossings from the internal precision clock. A basic clock frequency of 1.08 MHz is selected so that one cycle of this clock signal corresponds to 0.01° phase angle for a 30-Hz signal. By delaying the start of the variable waveform generator by the down-counter, any phase angle difference from 0° to 359.99° can be obtained in 0.01° steps.

The 30-Hz variable phase generator uses a read-only memory (ROM) in which sinusoid amplitudes are stored. An up/down counter selects the positive sine value from the ROM, and also controls the complementing of these sine values to produce the negative half cycle. Thus the generated waveform is a synthesized approximation of an ideal sinusoid using discrete amplitude segments. Each segment is represented by an equation of the form

$$v(i) = \cos 2\pi f_a(t_o+iT) \qquad (1)$$

where i = segment index $(0, 1, 2, \cdots)$
f_a = frequency, 30 Hz
t_o = time when $v(i)$ is maximum positive
T = segment time interval.

Signal distortion caused by this approximation is reduced to an acceptable level by choice of sampling rate, $1/T$, from the ROM and subsequent filtering.

The frequency modulated waveform generator also uses a ROM plus other circuits. The waveform to be generated is of the form

$$v_c(t) = \cos (2\pi f_c t + b \sin 2\pi f_a t) \qquad (2)$$

where f_c = subcarrier frequency, 9960 Hz
b = modulation index, 16
t = running time variable.

Discrete amplitude segments that approximate $v_c(t)$ are of the form

$$v(n) = \cos(2\pi f_c nT' + b \sin 2\pi f_a nT') \qquad (3)$$

where n = segment index (0, 1, 2, •••)
T' = segment time interval.

The segment interval, T', is made very small (e.g., a few microseconds) to hold the distortion of $v_c(t)$ to an acceptable level.

The outputs from the 30-Hz variable phase generator and the frequency modulated waveform generator are added to obtain the composite VOR audiofrequency signal having the form

$$v_o(t) = \cos(2\pi f_a+\phi) + \cos(2\pi f_c t+b \sin 2\pi f_a t), \qquad (4)$$

where ϕ is the phase angle difference between the variable phase signal (first term) and the reference phase signal (contained in the argument of the second term).

We have not yet made a complete error analysis of this method. However, preliminary study indicates that circuit components and techniques are available to implement this method with the desired accuracy (≃ 0.01°).

8.2.3.2 Precision VOR Phase Meter:

The zero-crossing detector time-interval counter method appears to be the best method for measuring the phase angle difference between the VOR reference phase and variable phase voltages. The method we propose is a novel application of well-established principles involving measuring the time intervals between zero crossings of the given voltages. In our method, the 30-Hz reference phase signal is not demodulated from the 9960-Hz subcarrier, but rather the zero crossings of the 9960-Hz frequency-modulated voltage are measured and compared with those of the 30-Hz variable phase signal voltage. Also, the method can be used to measure the phase difference between the two 30-Hz voltages themselves (i.e., apart from the 9960-Hz subcarrier). Internal phase shifts can be measured by using the method itself in a self-checking mode. The method appears to be capable of the desired accuracy over the entire range of 360 degrees. It is programmable and automatable, thus lending itself to ATE applications.

A block diagram of the precision VOR phase meter is shown in figure 12. The 9960-Hz frequency-modulated subcarrier, containing the 30-Hz reference phase signal, is fed to zero-crossing detector No. 1. The 30-Hz variable phase signal is fed to zero-crossing detector No. 2. The output of zero-crossing detector No. 2 activates the initiate flip-flop which (1) enables the pre-set count-down counter and (2) starts the time interval counter.

The sequence of operations is as follows: The normally open momentary operate switch zeros the count-down counter and the time interval counter, and resets the Initiate flip-flop. The first positive going zero crossing of the 30-Hz variable phase signal operates the Initiate flip-flop at time t_o; this allows pulses from zero-crossing detector No. 1, occuring AFTER time t_o, to be counted in the count-down counter. Simultaneously, the time interval counter begins counting pulses from the clock, starting at time t_o. When the pre-set number of pulses (zero crossings), k, from zero-crossing detector No. 1 have been counted, a pulse from the count-down counter turns the time interval counter OFF. This time count is stored or read out, and is a measure of the time between time t_o and the kth zero crossing of the subcarrier waveform AFTER time t_o. The pulse from the count-down counter also deactivates the zero-crossing detectors so that the measurement cycle is not repeated until the operate switch is again momentarily closed.

Mathematically, the operation of this method is described as follows: Given the variable phase signal, $v_a(t)$,

$$v_a(t) = V_a \cos \omega_a t, \tag{5}$$

and the frequency modulated subcarrier signal, $v_c(t)$,

$$v_c(t) = V_c \cos[\omega_c t + b \sin(\omega_a t+\phi_r)+\phi_c], \tag{6}$$

where V_a = amplitude of variable phase signal
ω_a = angular frequency of $v_a(t)$, 2π x 30 Hz
V_c = amplitude of subcarrier signal
ω_c = angular frequency of subcarrier, 2π x 9960 Hz
b = modulation index, 16
ϕ_r = phase angle of reference phase signal relative to variable phase signal
ϕ_c = phase angle of unmodulated subcarrier at time zero.

Positive going zero crossings of $v_a(t)$ occur at times t_p, where

$$\omega_a t_p = 2p\pi + 3\pi/2, \tag{7}$$

and p is an integer (e.g., 0,1,2,3,···). Positive going zero crossings of $v_c(t)$ occur at times t_n, where

$$\omega_c t_n + b \sin(\omega_a t_n+\phi_r) + \phi_c = 2\pi k_n + 3\pi/2, \tag{8}$$

and k is the integral number of positive going zero crossings of $v_c(t)$ AFTER time $t_p = t_o$. In the time of one period of $v_a(t)$, k can range from 1 up through 332. In (8), n is an index that relates a given k to a particular point in time; n therefore also ranges from 1 through 332.

For three selected positive zero crossings, k_1, k_2, and k_3 (i.e., n = 1, 2, and 3), we have

$$\omega_c t_1 + b \sin(\omega_a t_1 + \phi_r) + \phi_c = 2\pi k_1 + 3\pi/2, \tag{9}$$

$$\omega_c t_2 + b \sin(\omega_a t_2 + \phi_r) + \phi_c = 2\pi k_2 + 3\pi/2, \tag{10}$$

$$\omega_c t_3 + b \sin(\omega_a t_3 + \phi_r) + \phi_c = 2\pi k_3 + 3\pi/2. \tag{11}$$

That is, in this method, there are k_1 positive zero crossings of the subcarrier signal between time t_o and time t_1; k_2 crossings between t_o and t_2; k_3 crossings between t_o and t_3.

Algebraically eliminating ϕ_c and $3\pi/2$ from (9), (10), and (11) gives

$$\omega_c(t_2-t_1) + b[\sin(\omega_a t_2+\phi_r)-\sin(\omega_a t_1+\phi_r)] = 2\pi(k_2-k_1) \tag{12}$$

$$\omega_c(t_3-t_1) + b[\sin(\omega_a t_3+\phi_r)-\sin(\omega_a t_1+\phi_r)] = 2\pi(k_3-k_1). \tag{13}$$

Eliminating b from (12) and (13), and solving for ϕ_r gives

$$\phi_r = -\omega_a t_1 + \arctan \frac{X_2(X_7-X_5) - X_1(X_8-X_6)}{[X_4(X_7-X_5) - X_3(X_8-X_6)]} \tag{14}$$

where $X_1 = \frac{1}{2} \sin \omega_a(t_2-t_1)$ (15)
$X_2 = \frac{1}{2} \sin \omega_a(t_3-t_1)$ (16)
$X_3 = \sin^2 \frac{1}{2} \omega_a(t_2-t_1)$ (17)
$X_4 = \sin^2 \frac{1}{2} \omega_a(t_3-t_1)$ (18)
$X_5 = \frac{1}{2} \omega_c(t_2-t_1)$ (19)
$X_6 = \frac{1}{2} \omega_c(t_3-t_1)$ (20)
$X_7 = (k_2-k_1)\pi$ (21)
$X_8 = (k_3-k_1)\pi.$ (22)

All of the quantities ω_a, ω_c, t_1, t_2, and t_3 are measurable. The quantities k_1, k_2, and k_3 are set in the pre-set count-down counter. A small computer can be programmed to calculate ϕ_r from the data.

Having calculated ϕ_r, the modulation index, b, can be computed from (14) by the relationship

$$b = \frac{2\pi(k_2-k_1) - \omega_c(t_2-t_1)}{\sin(\omega_a t_2+\phi_r) - \sin(\omega_a t_1+\phi_r)}. \tag{23}$$

Further, having calculated b, the phase angle, ϕ_c, of the unmodulated subcarrier signal, at time t_o, can be computed from (8) by the relationship

$$\phi_c = 2\pi k_1 + 3\pi/2 - \omega_c t_1 - b \sin(\omega_a t_1+\phi_r). \tag{24}$$

Thus, this method can provide the complete phase information contained within the composite VOR audiofrequency signal.

We have not yet made a complete error analysis of this method. However, preliminary study indicates that circuit components and techniques are available to implement this method with the desired accuracy (≃ 0.01°). For example, time interval measurements can be made with an uncertainty of less than 0.1 microseconds. For a 30 Hz signal, this corresponds to a phase angle uncertainty of 0.00108°.

In order to utilize this accuracy, the zero-crossing detectors and the pre-set count-down counter must each have comparable accuracy. The design task is to select or develop circuits and operating procedures that will satisfy the error budget in which the sum of all error contributions does not exceed the desired accuracy.

This method is not immune to the effects of distortions of the VOR audiofrequency signals. However, it may be capable of correcting for these effects, or even measuring the phase angles of distortion products. Further analysis is required to determine if this is true.

9. MILESTONE (h): REPORT RESULTS OF MILESTONE (g)

9.1 Objective:

Publish a final report on the results of (g), above.

9.2 Results:

A brief final report, Letter Report No. 2, was submitted on September 10, 1973. The material of that report is greatly expanded in the present report.

10. MILESTONE (i): JOINT MEETING

10.1 Objective:

Hold a joint meeting with DoD/CCG personnel to discuss results of Task 1.

10.2 Results:

The subject meeting was held September 18, 1973 at the Aeronautical Center, Federal Aviation Administration, Oklahoma City, Oklahoma. The minutes of that meeting are being prepared by Mr. J.W. Williams, J of Redstone Arsenal.

11. ACKNOWLEDGMENTS

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12. REFERENCES

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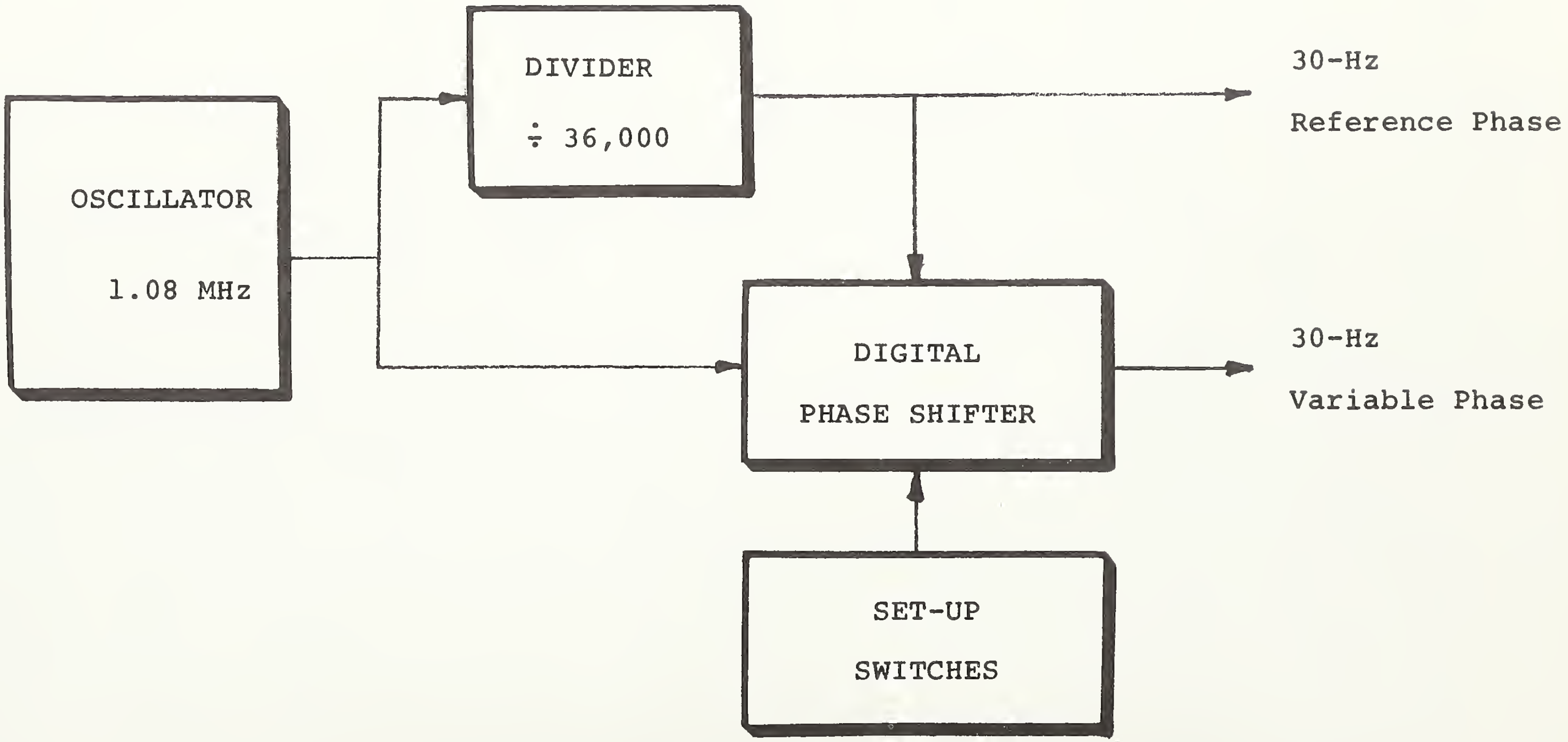

Figure 1. Standard Source; Digital Divider Method

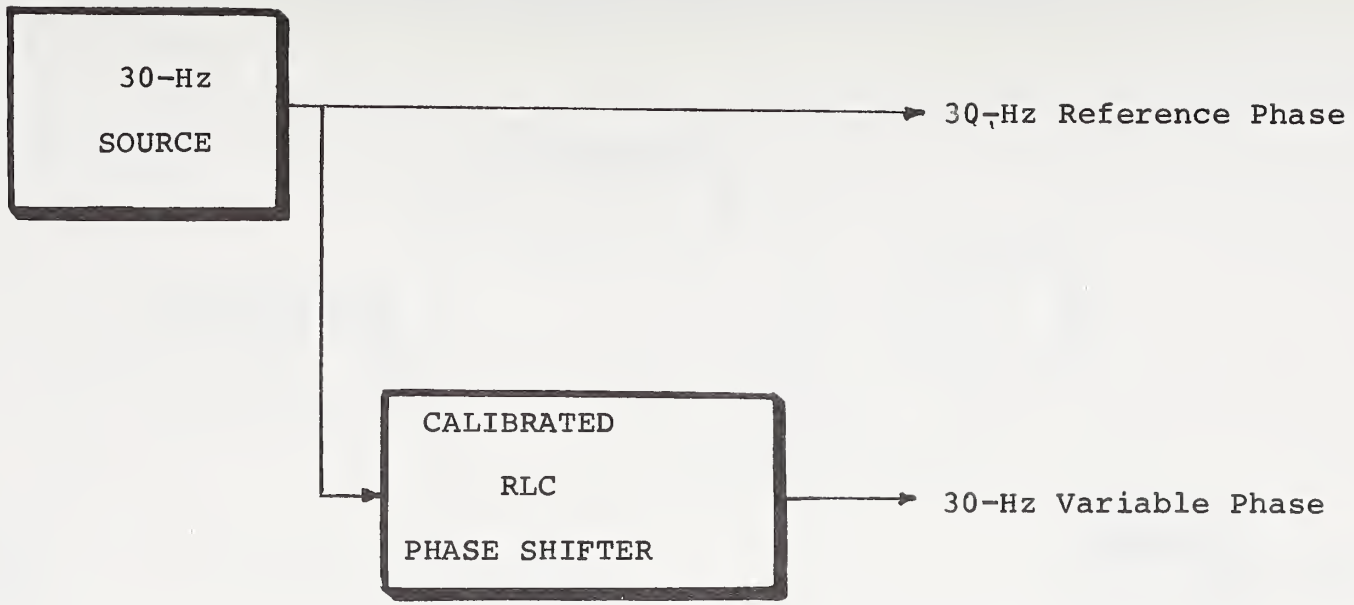

Figure 2. Standard Source; RLC Method

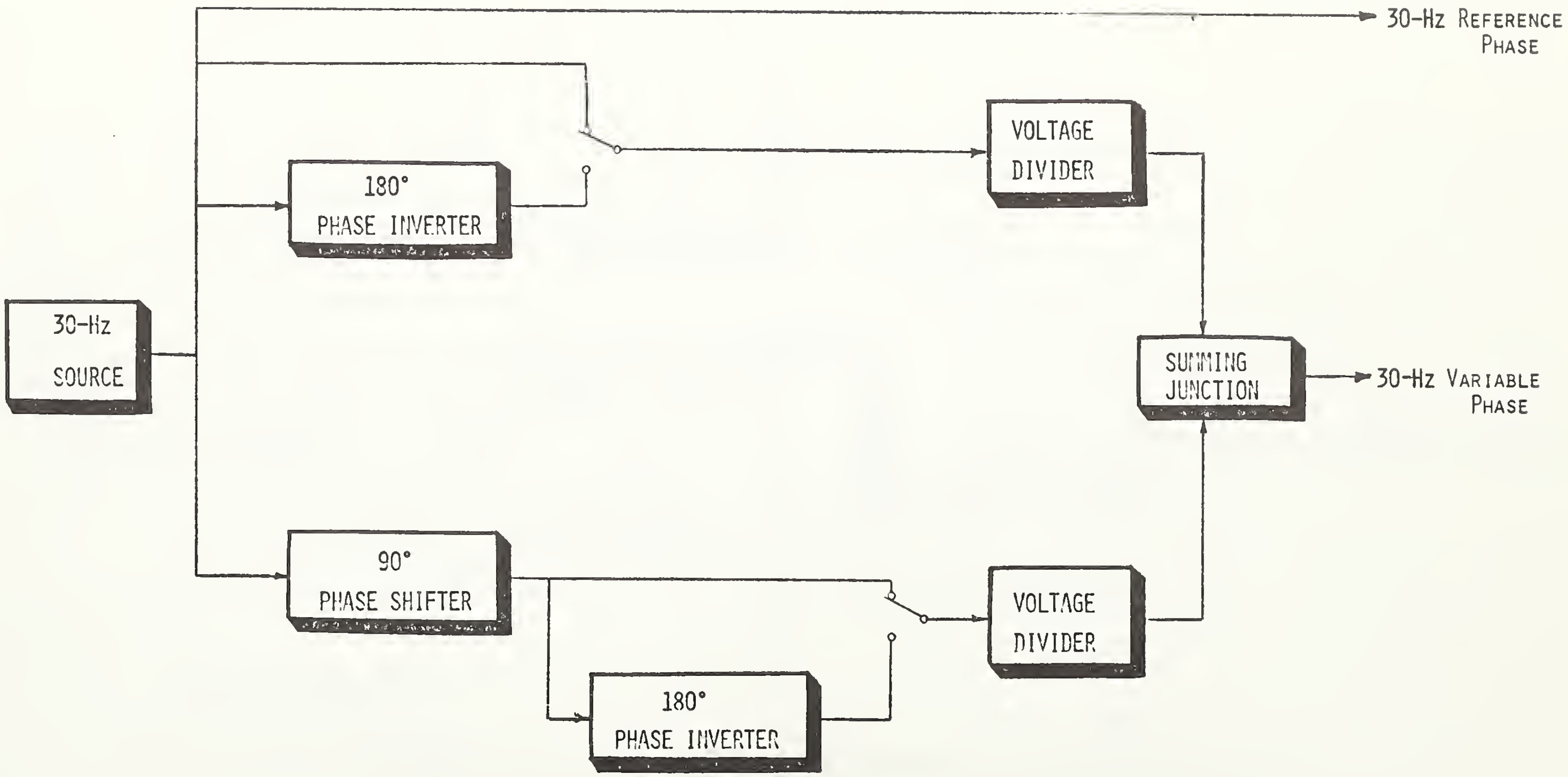

Figure 3. Standard Source; Vector Addition Method

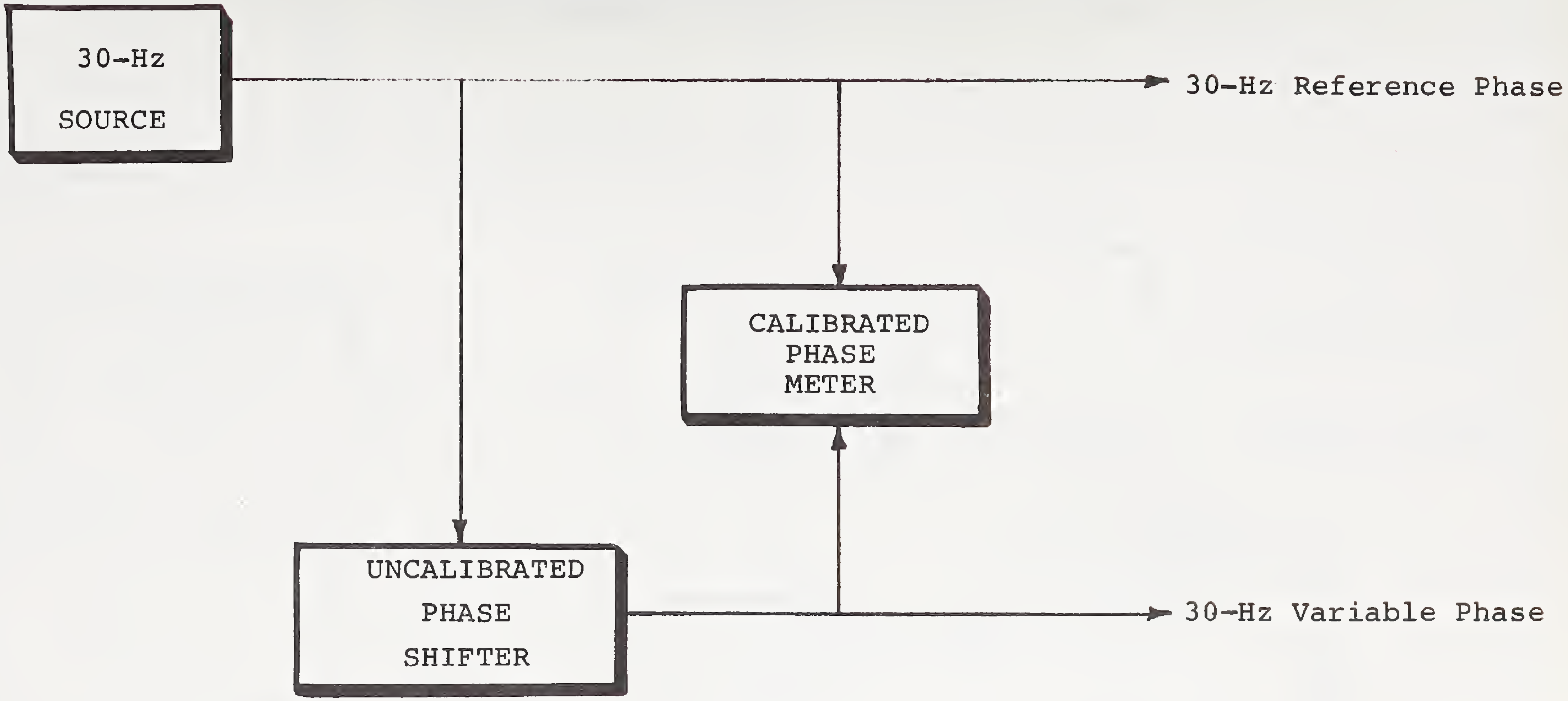

Figure 4. Standard Source; Phase Meter Method

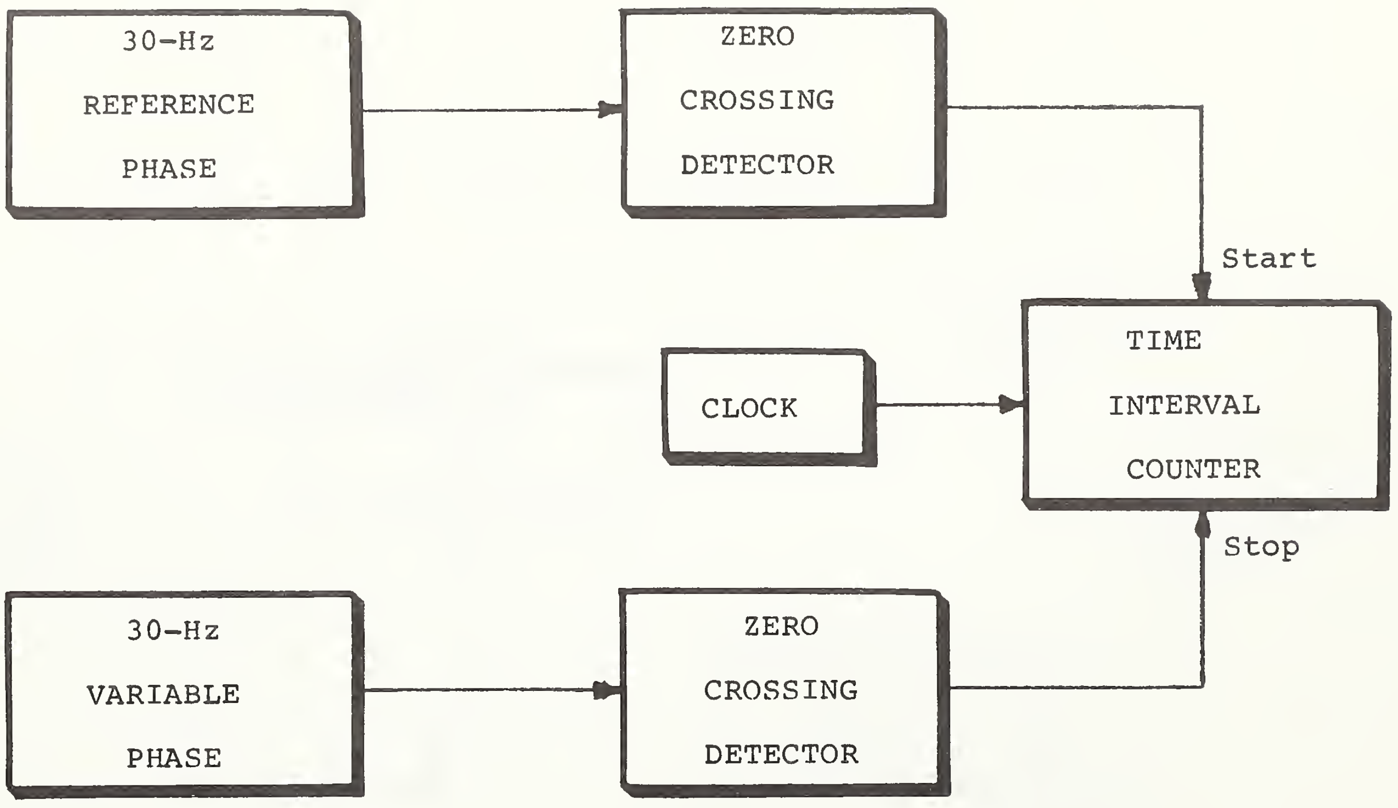

Figure 5. Direct Measurement; Time Interval Counter Method

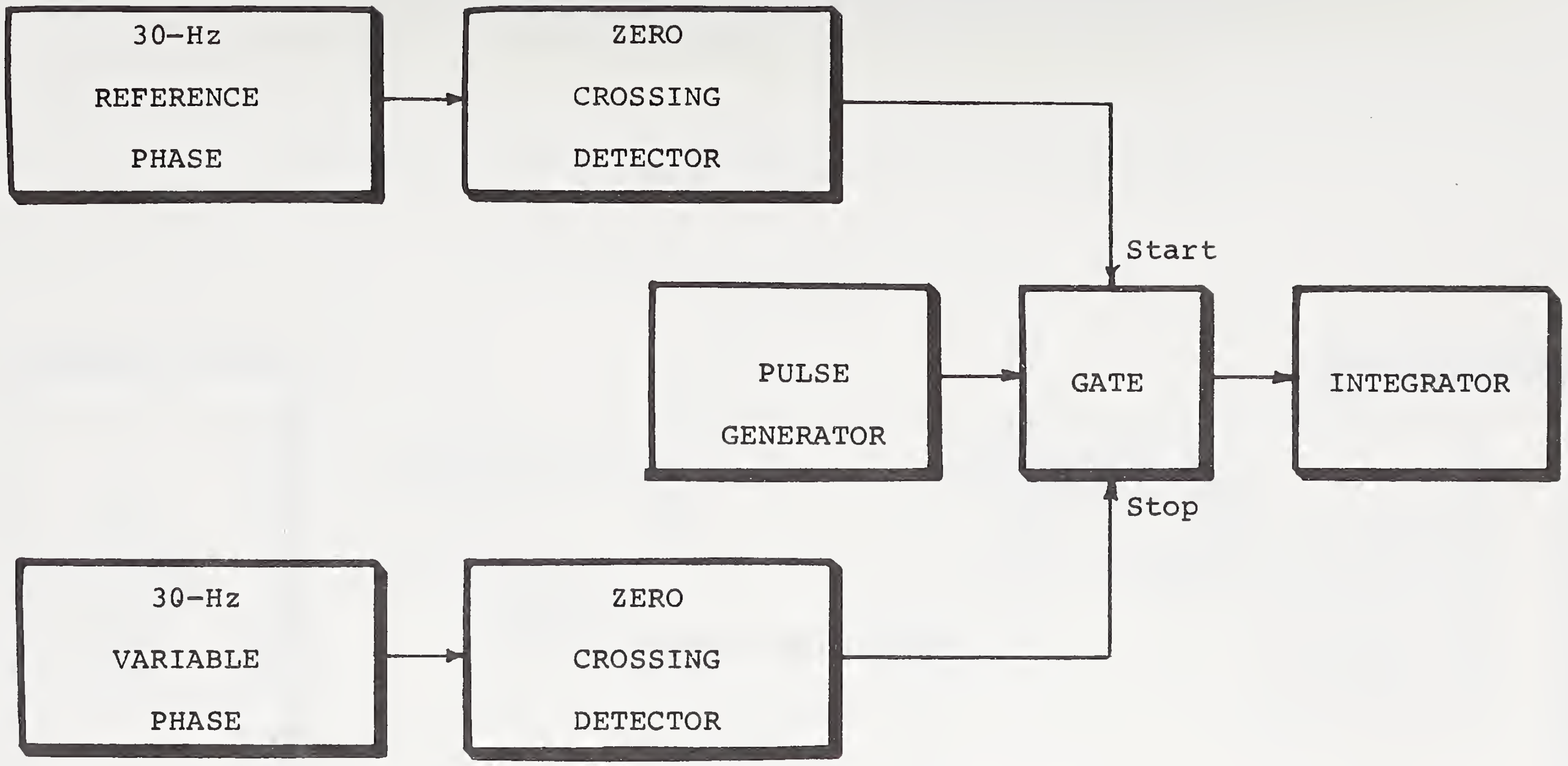

Figure 6. Direct Measurement; Pulse Area Method

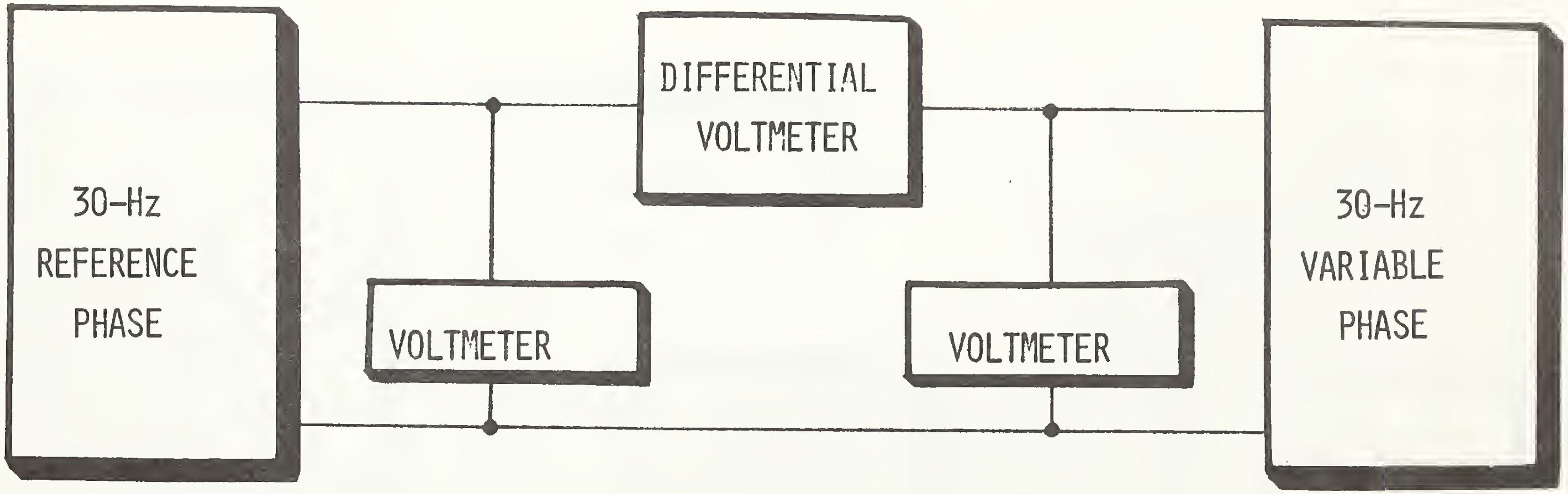

Figure 7. Direct Measurement; Three-Voltmeter Method.

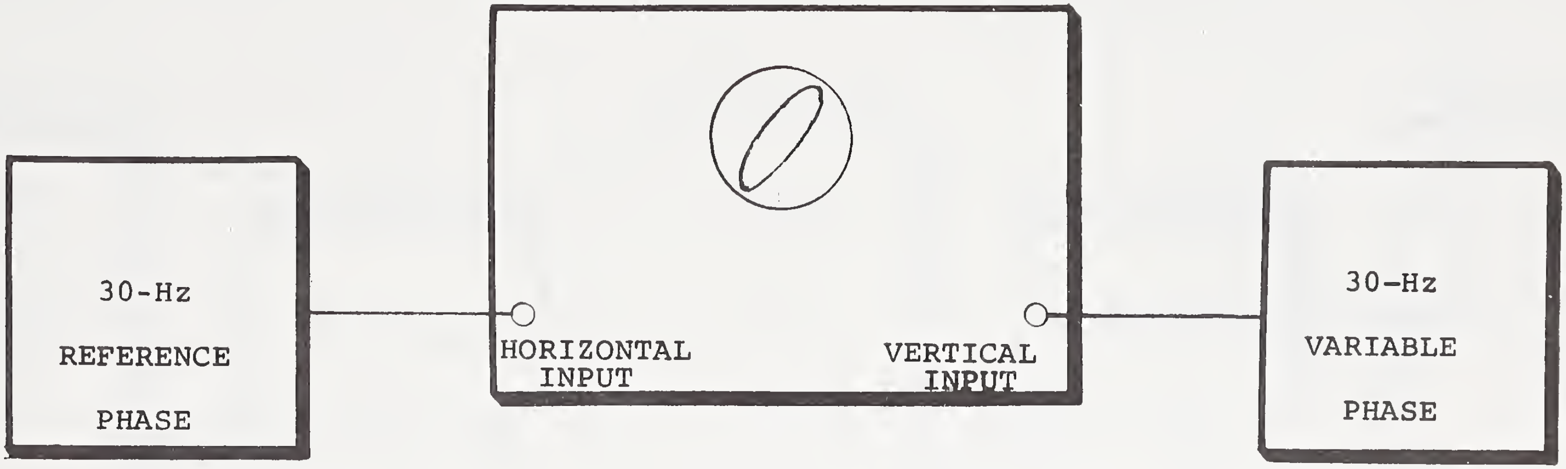

Figure 8. Direct Measurement; Lissajous Pattern Method

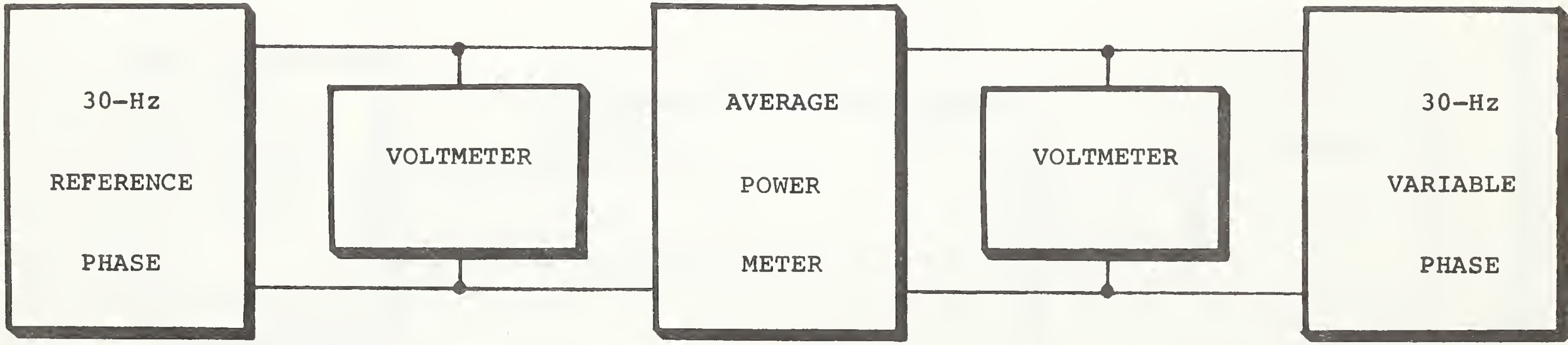

Figure 9. Direct Measurement; Power Factor Method

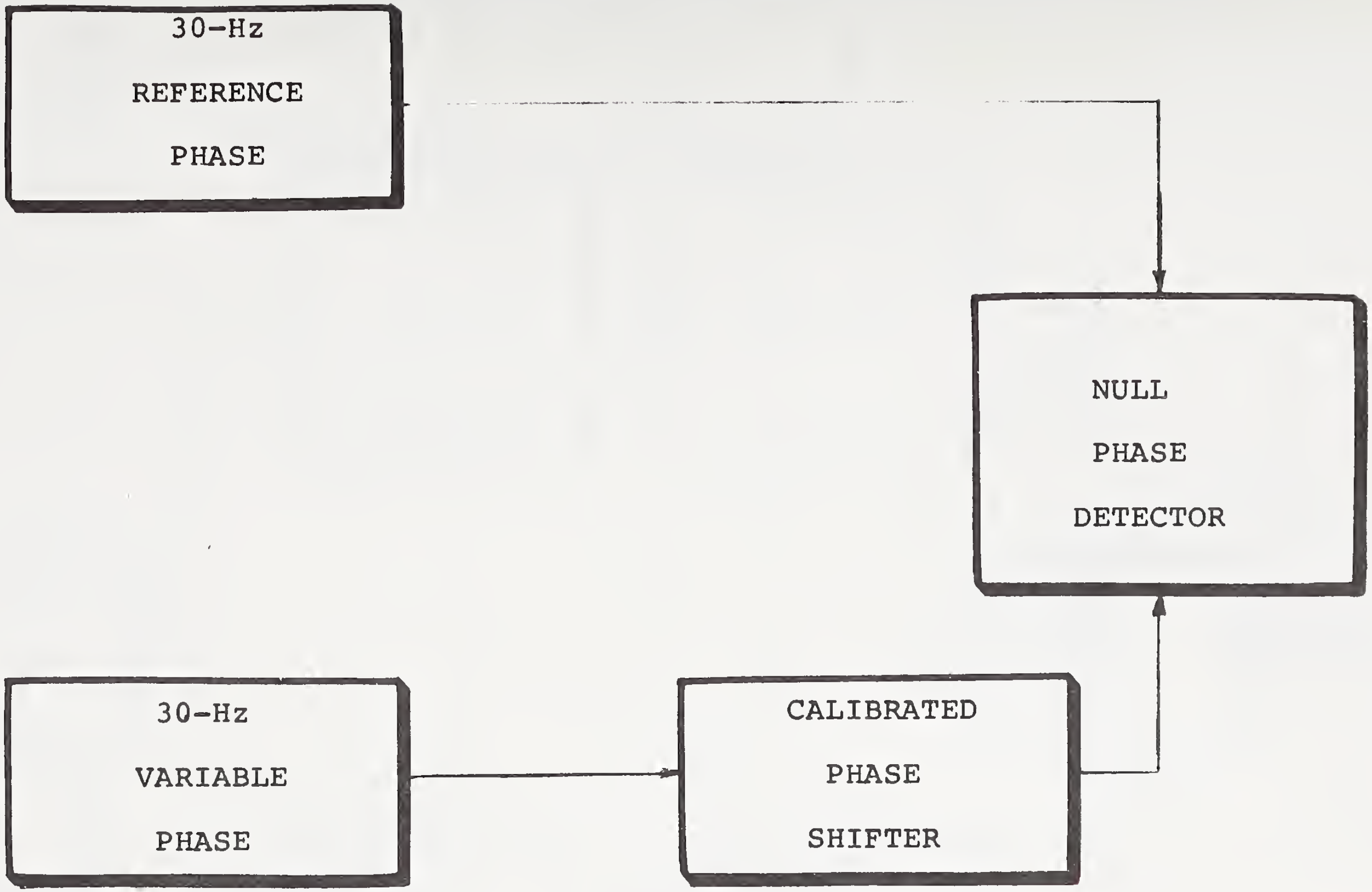

Figure 10. Direct Measurement; Null Detector Method

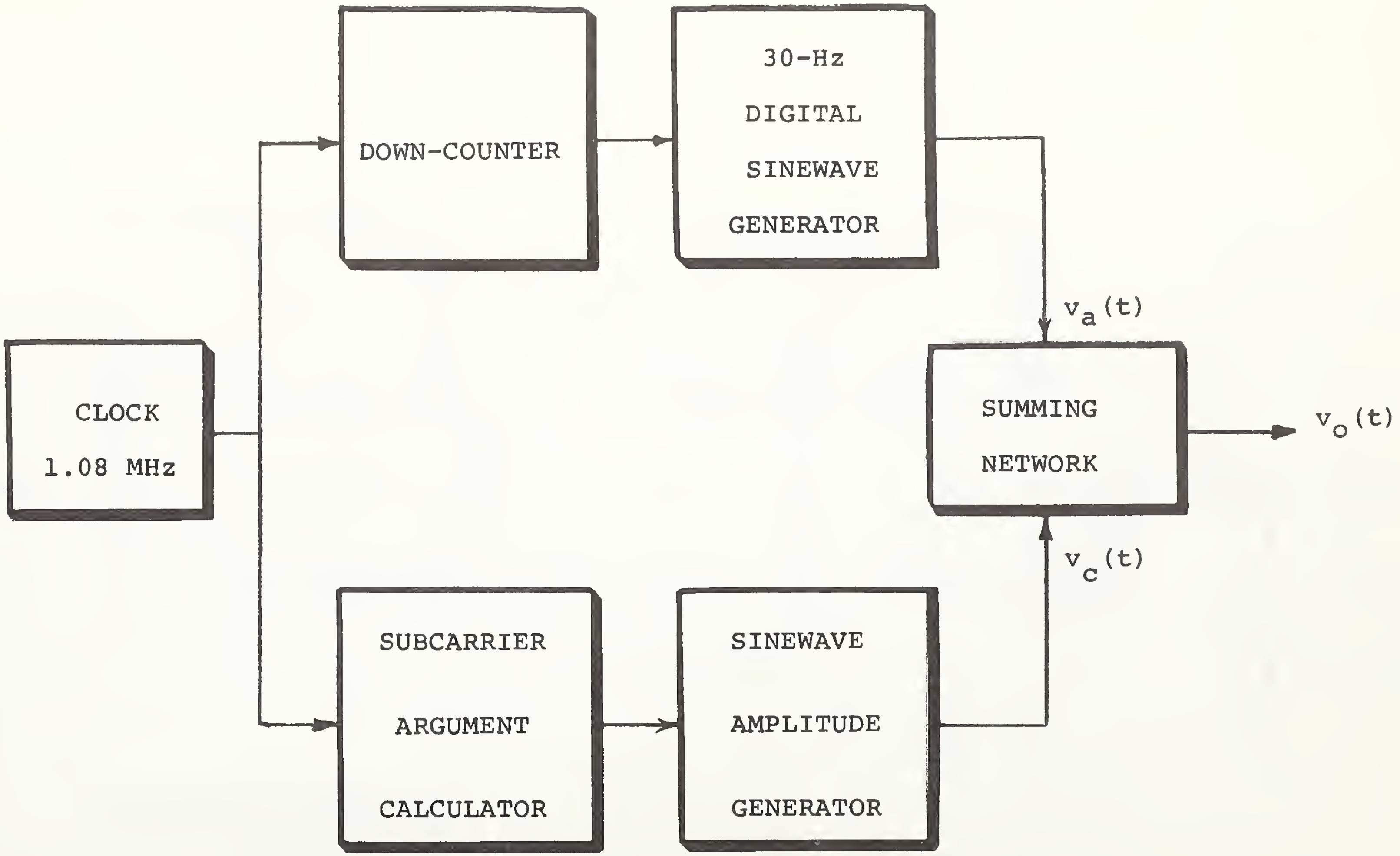

Figure 11. Standard VOR Audiofrequency Signal Source

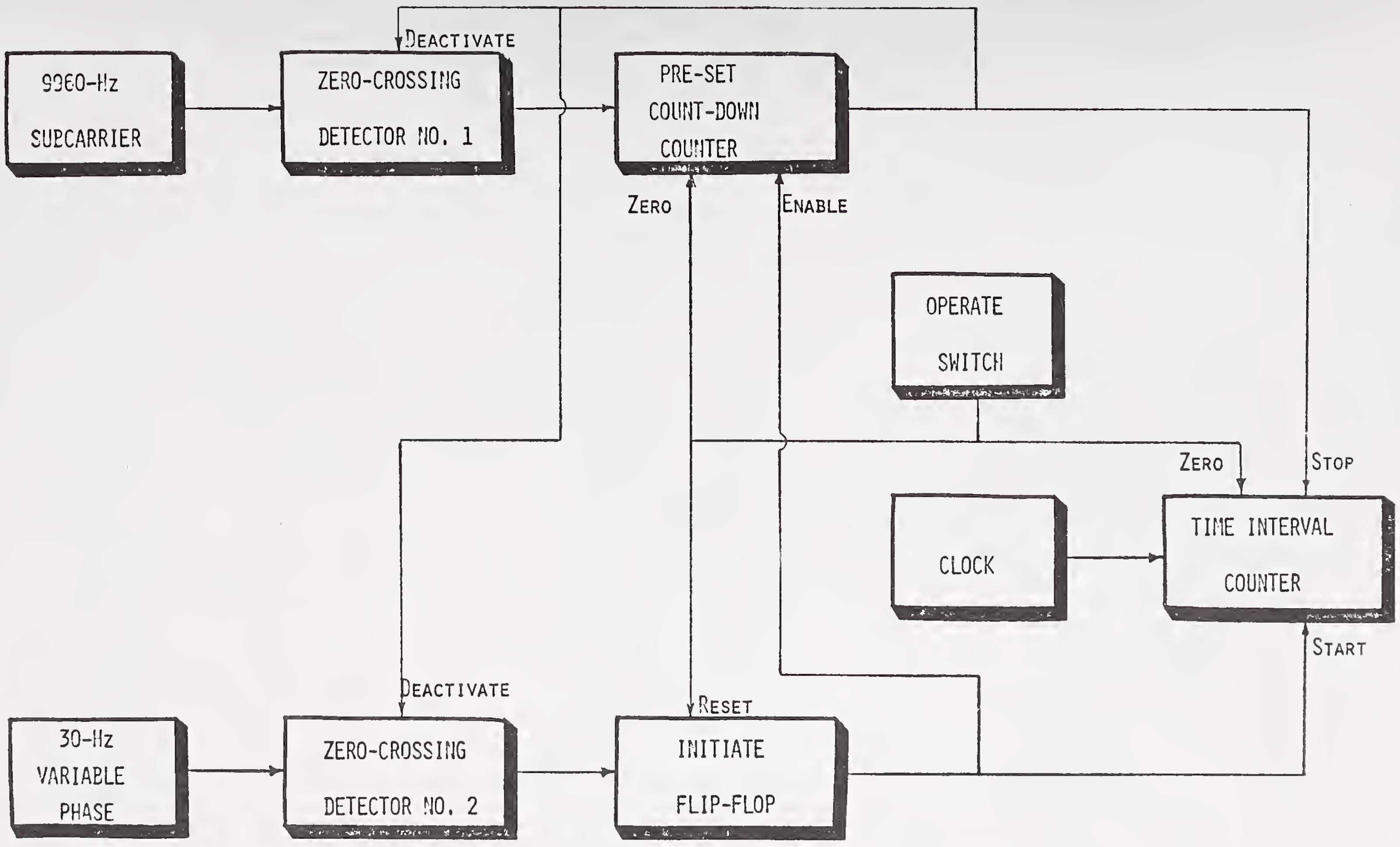

Figure 12. Precision VOR Phase Meter

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15. SUPPLEMENTARY NOTES

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

This report summarizes the work performed under Task 1 of the VHF Omnidirectional Radio Range (VOR) phase angle measurement standards project. Included are (a) a review of VOR system requirements and performance data, (b) results of a literature search of phase angle measurement techniques, and (d) recommended approaches for a VOR phase angle measurement standard. The recommended approaches are to develop both a standard source of VOR audiofrequency signal and a precision VOR audiofrequency phase meter. These techniques are described in moderate detail.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Aircraft navigation standards; phase angle measurement; phase standard; VHF omnidirectional radio range; VOR standards

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