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Picosecond Time Difference Measurements Utilizing CAMAC-Based ANSI/IEEE-488 Data Acquisition Hardware Operating Manual IE3 Version 1.0

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Picosecond Time Difference Measurements Utilizing CAMAC-Based ANSI/IEEE-488 Data Acquisition Hardware Operating Manual IE3 Version 1.0

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Automated time-difference measurements at the picosecond level have been achieved. The system described combines the best properties of three common methods: the single heterodyne measurement technique, the frequency divider, and the dual-mixer time-difference measurement system. This particular system combines two instrumentation standards, ANSI/IEEE-583 and ANSI/IEEE-488 with new, modular dual-mixer time-difference measurement hardware. The modular, standardized hardware together with the new measurement techniques permit the data acquisition modules to be contained in a standard CAMAC crate. This system, along with an external controller, is capable of measuring eight clocks, at the present time, and is expandable to twenty-four clocks with modified software and additional measurement modules. The system noise performance is described by $\sigma_y(\tau) = 3 \times 10^{-12}\tau^{-1}$ for time difference measurements.

Key words: ANSI/IEEE-488; ANSI/IEEE-583; automated data acquisition system; dual-mixer measurements; picosecond time-difference measurements.

1. Introduction

The measurement system described was developed to make simple, reliable picosecond time-difference measurements on high-performance atomic frequency standards utilized in such applications as atomic scale systems, laboratory or field calibrations, sigma-tau and phase stability measurements. Utilization of adjacent time-difference or phase points provides frequency measurement capability. Software and hardware available yield phase data, sigma-tau data and phase plots (on suitable output devices).

The hardware utilizes two special modules commercially manufactured to NBS specifications. Other special modules, low-noise, isolation amplifiers, were not commercially available in the form required at the time the system was implemented. These items were designed and constructed at the NBS laboratories. All other items, CAMAC crate and interface modules, clock timer, and computing calculator operating over the IEEE-488 bus, are commercially available.

The system has been designed to provide time-difference capability for measurement intervals of 1 second and longer. The speed of the specific implementation described below is limited by software to intervals 5 seconds and longer. Hardware limitations for the present system are due to the tape cartridge which limits data collection to 100 points each for eight clocks under test. System performance is best described by a specification of:

$$\sigma_y(\tau) = 3 \times 10^{-12}/\tau$$

2. Theory

A theoretical description of the system operation is included in Appendix 1.

3. Hardware Description and Configuration

The modular design of the data acquisition hardware used in this system employs a standard CAMAC (IEEE-583) crate, Model 1500-P1K, and power supply as supplied by the manufacturer[1]. The interface modules are designated in the following way:

Model 3981-Z1B Auxiliary rate controller

Model 3953-Z1B Auxiliary controller adapter

Model 3388-G1A IEEE-488 interface

Equivalent hardware manufactured by other vendors is expected to function in precisely the same manner but has not been tested.

The following manuals are provided by the manufacturer of the CAMAC equipment[1]

Model 1500 powered CAMAC crate

Model 3388-G1A IEEE-488 interface

Model 3953-Z1B Auxiliary controller adapter

Model 3981-Z1B Auxiliary crate controller

Model 8021 3981-Based IEEE-488 crate Controller system

Model 6120-B10 Software manual Routines for 488-controlled CAMAC I/O

Block diagrams for the operation and control of the pulse distribution module and the quad clock measurement modules are also included. These circuit diagrams are important to an understanding of the system. They contain sufficient information to permit the design of compatible measurement equipment.

3.1 Crate Configuration

As supplied[1], the crate is Model 1500-P1Z. Power to the crate and modules is derived from a rear mounted, modular power supply. It provides ± 24V dC, ± 12V dC, and ± 6V dC. When mounting the power supply to the crate, follow instructions provided in the crate manual. Install the sheet insulating film provided between the power supply and the crate dataway wirewrap pins. Failure to do so may cause shorts on various pins and destroy the crate and power supply.

3.2 Module Configuration and Installation

Modules are installed in the following way. The crate is constructed so that modules are installed from the front into numbered openings or slots. These slots are numbered from left to right beginning with 1 and continuing through 25. Slot 25 is not a normal slot, but is used for controllers only.

Connect the 40 pin ribbon cable to the connectors on the back and top of the 3953 module and the 3981 module. Note that the 40 pin cable does not connect to the 3388 module.

Install the pulse distribution module[2] in the slots labelled 1 and 2. N=2 for this module.

Install the first quad measurement module[2] in the slots labelled 3 and 4, and the second one in slots 5 and 6. The crate addresses for these modules are N=3 and N=5 respectively. Two of these modules will permit measurement of 8 clocks. Up to four more quad measurement modules may be added to the system allowing measurement of 24 clocks; however software modifications would be required for these additional modules.

3.3 System Synthesizer

The synthesizer, is offset in frequency by 10Hz below the nominal 5.0 MHz value. The synthesizer (user provided) must be referenced to the clock which drives the master channel.

3.4 System Signals, Cables, and Connections

All RF signals are nominally 1V rms at the 50 ohm impedance level. With the present release of system software, (IE3 version 1.0) channel 1 must be the master channel.

3.5 Cables for 5 MHz Signals

Connect cables from clocks to be measured, through suitable isolation amplifiers, to the SMA clock inputs of each quad measurement module. Signals for the NBS isolation amplifiers should be 1V rms at the 50 ohm impedance level.

Attach cables from the synthesizer output, again suitably isolated, to the offset reference SMA connector(s) of the quad measurement module(s).

Install the 3953-Z1B auxiliary controller adapter in the last pair of slots: 24 and 25. The crate address for this module is N=25.

Prior to installation of the 3388-G1A module, set the eight-section switch on the circuit board so that all sections are off. Install the 3388-G1A in the next pair of slots: 22 and 23. The crate address for this module is N=23. However, commands written to this module by the program use the address 700.

Prior to installation of the 3981-Z1B module check to see if the following wire-wrap jumpers have been installed. If not, install them and check to see that no shorts exist between wirewrap pins and adjacent traces of the circuit board. Use only one set of jumpers corresponding to the particular prom supplied. The circuit board jumper pins are numbered from 1 to 14.

	Prom 2708	or	Prom TI2716
Connect Pins:	9 to 13		9 to 3
	11 to 3		11 to 8
	10 to 13		10 to 2
	12 to 2		12 to 8
	7 to 8		7 to 13
	14 to 5		14 to 6
	1 to 4		1 to 5

Consult the 3981-Z1B hardware manual on page 4-2. Note the location and orientation of the prom sockets and install the prom in socket designated prom 1. The four-section switch on the module circuit board should be set so that all sections are off.

Install the 3981-Z1B auxiliary crate controller in slot 21. N=21 for this module.

Connect a cable from the isolated signal driving channel 1 to the synthesizer reference input. The frequency of the reference signal for the synthesizer should be nominally 5.0 MHz within manufacturers specifications. Set the synthesizer frequency to 4.9999900 MHz (10 Hz below nominal 5.0 MHz).

3.6 Other Cable Connections

In subsequent discussions the following conventions apply:

QMM = Quad measurement module

PDM = Pulse distribution module

Attach cables as follows. Use LEMO COAX cables:

From	To
PDM (Slots 1, 2) Master CH 10 Hz in	QMM(1) (Slots 3, 4) Channel 1 10 Hz out
PDM 10 MHz out	QMM(1) 10 MHz in
PDM 10 MHz out	QMM(2) (Slots 5, 6) 10 MHz in
PDM ARM/Start out	QMM1 ARM/Start in
PDM ARM/Start out	QMM2 ARM/Start in
3981 Request	3981 Grant in

Attach IEEE-488 cables as follows:

From	To
9825A, 9872A 59308A (see H and I and J below)	3388 IEEE-488 Conn.

3.7 Configuration of Remaining Switches

3981 module. Set halt-cont switch to center position. This switch is spring loaded and will remain in this position. Set the enable-disable switch to enable position.

3953 module. Set the online-offline switch to online position. C-Z switch should be at center position (spring loaded and will return to center).

3.8 System Controller

The system controller for this application[3] is a 9825A desk top calculator. Required components are:

9872A plotter-gen I/O ROM
98216A extended I/O ROM
98210A string-adv prog ROM

As operated in this system, the 9825A has a total of 23228 bytes of memory. Any other IEEE-488 compatible controller will work with modifications in software. There may be some effect on system speed.

3.9 System Clock

The system "clock"[3] is a 59308A timing generator.

Switch Positions: Front Panel: Function SW: Pacer

Rear Panel: Ext Freq Std: 5 MHz

Ext. Std. Signal: 5.0 MHz derived from

System ref. signal driving channel 1.

Bus Pacer: Off

Trigger and option sections: Not used

Switch A: A1=1; All other sections = zero

3.10 System Plotter

The plotting hardware[3] for the system is a four color pen plotter, Model 9872A.

4. Operation

4.1 Power Up Sequence

When all cables and components are properly installed, the crate may be turned on. Check the multifunction meter monitoring system and the crate manual to be certain that operating voltages and currents are proper. The voltages should be at the monitor set point in all cases.

The other IEEE-488 devices may be powered up. The tape cartridge containing the operating software should be installed in the 9825A. (Rewind the cartridge before it is removed. Failure to do so may destroy program or data stored near the position of the tape head) rewind the cartridge. Press erase a, then reset, for power-up mode only.

4.2 Operation

Data are stored on the tape cartridge on track 1. This track must be formatted before the program can store data. One should use the following commands to format the data tape:

Rewind
TRK 1
Execute
MRK, 800, 64
Execute
Rewind

One may mark more files than 800, but usually only approximately 802 files may be marked before end of tape (EOT) and an error are encountered.

To begin the data acquisition phase of the operation, one must execute the following commands:

TRK 0
Execute
LDF 0
Execute
Run

The controller will now prompt responses from the operator. The questions and responses will be described in a subsequent section. After all entries are made the program will run according to the parameters supplied by the operator. At the end of the first measurement interval (length specified by the operator), the 9825A will print out some data and begin the second measurement interval. Data will be printed or not as the operator specified, and data points will be recorded on the magnetic tape cartridge. This continues until at the end of the run, the 9825A will print out some data on the paper tape and display "Stop. . .operation complete". At this point the operator should rewind the tape then enter the following sequence:

TRK 0
Execute
LDF 1
Execute
Run

Now the system will process the data taken in the previous operation and will again ask the operator questions. After entering all answers to the questions the program will begin processing the data on the tape cartridge. The program has various stop points to permit the operator to set up the paper for plotting and to specify other outputs that may be required. After data from all clocks have been processed, the 9825A will display "Stop...Operation Complete". At this time the operator may choose to stop or to take more data. If more data are to be taken, the program on TRK 0, file 0 must be loaded again. Subsequently, the processing program on TRK 0, file 1 must be loaded to handle the data processing. Note that the tape is rewound by the data acquisition task. Data written on the tape by the acquisition are typically written over the data taken from a previous run. In response to the question "Begin w tape file No.?', one usually types the numeral 1, followed by pressing the continue key. The numeral 1 denotes to the operator the first data file on the tape. The operator may begin a second run at File N + 1, thereby not writing over the first points taken in an earlier run. One must remember, however, where the break points are; otherwise, the data processing task may run together points from more than one set of data, and incorrect results will occur. One may of course use a second data tape if previous data are to be retained. The total number of points recorded may not exceed 800 on any given tape (typically 100 per clock for 8 clocks).

5. Software Description and Discussion

5.1 Introduction

Commands to the data acquisition hardware are typically sent via write statements from the program in the 9825 which employ ASCII strings.

5.2 Command Structure

An ASCII command is composed of three parts:

Function Code:	Choice Of: "F0" through "F31"
Subaddress: Location within the module	Choice Of: "A0" through A15"
Station or Slot No: However only slots 1 through 25 are used in this system.	Choice Of: "N1" through "N31"

A command sent with the above components will address a particular module and location within a module. However, no action will be taken unless an execute command is included and unless the command is written to a specific address (device) on the bus. A typical command might be:

(First set A$ = "F25A0N2E") Notice that the execute command (E) is embedded in the string A$.

```
WRT 700, A$
```

This command writes, with execute, the string A$ to the bus address 700. In this software, 700 is the address of the controller in the crate. The string sent, F25A0N2E, causes the crate controller to initiate a measurement sequence: (This occurs when the above command string is sent to the Pulse Distribution module through the crate controller.)

F25 is the Measurement command

A0 is the Address within the slot

N2 is the Slot no. of the Pulse Distribution module

(701 is the address of the system clock)

(705 is the address of the system plotter)

5.3 General Program Flow for Data Acquisition

As described in Section 5.2, a command has been sent to the 3388 module, which then causes a measurement sequence in the PDM module, in Slot N=2, to be initiated. All measurements are started by the PDM. After the read command (as above) is received by the PDM, the following sequence occurs:

1. The PDM issues an ARM/Start Command wich arms the counters.

2. The next 10 Hz zero-crossing starts the system counters for all quad meas. modules.

3. The following 5 MHz zero-crossings, obtained from each of the individual clock signals, stop the 10 Mhz counters on each individual channel.

At this point the data, in the counters at the time of the measurement, are stored in registers in the 3981 module. Data are read out in the form of three bytes (24 bits are required to contain the data word):

1. High order data byte: Bits 24 through 17

2. Middle order byte: Bits 16 through 9

3. Low order data byte: Bits 8 through 1

These three bytes are transferred out of the registers in the 3981 into variables defined in the 9825A data acquisition task. These variables are combined algebraically to form the raw data. Both the 10 Hz and 10 MHz counter readings are taken this way, for each clock. Some computations are performed to calculate the value of the clock phase using the following equation from appendix 1:

$$\phi_2(t_M) - \phi_1(t_M) = 2\,(N_o - M_o)\pi + 2(N - M)\pi - 2\pi[\bar{\nu}_{B2}(t_M;t_N)]\tau_c P$$

The initial phase reading which was taken during the first interval is subtracted. The difference, called delta time, is recorded along with the channel number, on the magnetic tape cartridge, for each clock measured. During the time of these calculations and recording, the next measurement interval is progressing. After the recording on tape is finished, the 9825A continually checks the counter reading in the system clock, 59308A. When the counter reaches the appropriate value, the software jumps to the initiation of the next measurement sequence. This process continues until the required number of points has been taken. The measurement then ends, and the number of points, the timing interval in seconds, the date and time entered, and the data label, are printed on the paper tape. The operator then decides whether to process the data with another program, or to take more data.

5.4 Detailed Program Flow for Data Acquisition

The program tape is placed in the 9825A and the acquisition program TRK 0, File 0 is loaded. After the run command is issued, the program asks if one wishes to edit the identification file for the clocks:

"Edit Clk Id File?"

The operator may respond with a "n" or any answer except "y", in which case the channels will be identified for the print-out in the following way:

For Channel 1: "Chan 1"

For Channel 2: "Chan 2"

etc

For Channel 8: "Chan 8"

The operator may also respond with a "y", in which case the program will ask: "Channel 1 Clk ID?...6 Char max". To this the operator should respond by typing some suitable name for the clock driving channel 1, then press continue. The program will ask for identification for each clock in turn, and then the following sequence occurs.

1. Initialize command is sent to the crate, i.e., "ZE".

2. Enable channel operation command is sent to all even sub-addresses of the two QMM's, i.e., "F26A0N3E".

3. Reset LAM Status command is sent to all odd sub-addresses of the QMM's, i.e., "F10A1N3E".

4. Reset 10 Hz register overflow command is sent to all even sub-addresses of the QMM's, i.e., "F9A0N3E".

5. Reset 10 Hz register command is sent to all even sub-addresses of the QMM's, i.e., "F12A0N3E".

After this sequence is completed, the program asks several questions.

6. "Enter Date...dd-mmm-yy"; the operator types e.g., 27-Apr-82, and then presses continue.

7. "Label?" The operator may enter a label describing the experiment, up to 35 characters, then press continue.

8. "Print Data Output?" A "y" answer here causes flag 2 to be cleared. This in turn causes all data from each point to be printed on the paper tape. The data are always recorded on the magnetic tape cartridge. If, after a few points are printed, the operator wishes to stop the print-out, one simply types "sтg2", followed by "execute", from the live keyboard during a time when the program is in the timing interval between points. This action will suppress all further print-outs until the program ends. Any answer other than "y" to question 8, will inhibit all print out except the value subtracted from

the delta time reading during the first timing interval. Selecting the print option slows the program significantly. With printing, eight clocks require at least 40 seconds. Without printing, this is reduced to approximately 5 seconds.

9. "Enter Seconds in timing interval". This is the number of seconds desired for the elapsed time between points. Type the number (not less than 5 discussed above), then press continue.

10. "Number of clocks?" A number from 1 to 8 should be typed, then press continue. If a number greater than 8 is entered, the program displays "Max Clocks = 8" and returns to question 10 for the proper response.

11. "No. of points?" The operator should enter the number of points per clock desired for that run, then press continue. The program must take one more point in order to compute frequency for the first interval. However, this is accounted for in the program, and the number of points requested will be taken, provided there is room on the magnetic tape.

12. "Begin w/tape file no.?" If the first data file on the tape is to be used, enter 1, and then press continue. If one wants to skip over data already recorded, e.g., to the 16th point, type 16, then continue. This option is included only to permit one to save previously recorded data. One must, however, keep track of these points on the data tape, because the phase points will not be continuous from one run to the next, the processing program will not know that more than one run exists in the data set, and erroneous results will occur.

13. "To start timing, press continue". Here is a pause so that the operator may start the run on a particular second. When continue is pressed, the program begins data acquisition according to the entries made by the operator. The system will run until the specified number of points has been

taken, (or until there is no more space on the data cartridge. 100 points maximum for 8 clocks may be taken).

After the program completes its run, the following items are printed on the data tape:

"No. of Points=" (e.g.) "100"

"Timing Interval="(e.g.)" 60"

"Date"

"Time" time entered at start of run

"Label" entered at the beginning of run

Now the operator must decide to stop, process the data on the magnetic tape, or acquire more date.

5.5 Detailed Program Flow for Data Processing

The program from TRK 0, file 1 is loaded into the 9825A as described above. The system plotter should be set up by entering P1 and P2 from the plotter keys. This matches the plotting window to the size of the paper to be used by the operator. The plotter select code and address are 705. Then press run. The program asks several questions.

1. "Edit clock ID files?" The default clock Id's for all eight channels are: Channel 1, Channel 2,...etc. If the operator wishes to insert other names for clocks he may enter "y" in response to this question. Then the 9825A prompts for the Id's for all clocks. One may assign 6 characters maximum for each clock Id. After each Id entered, press continue.

2. "Enter Date: dd-mm-yy" This is an obvious entry, e.g.: 27-APR-82 then press continue.

3. "Label?" Here the operator may enter a description of the data to be processed. Up to 35 characters may be entered, then press continue.

4. "Process data tape?" If one answers "n" or any answer other than "y", the program branches unconditionally to the end and stops, displaying: "Stop...operation complete". If one answers "y", tape processing begins with question 5.

5. "Read all 8 clocks?" A "y" answer here sets a counter so that data for all 8 clocks will be read from the tape. Branch to question 7. Any other answer causes a branch to question 6.

6. "Enter No. of Clocks to be Read". Here one enters a number from 1 to 8. The clocks will be read beginnning with clock 1 and ending with the clock number entered by the operator. The program continues with question 7.

7. "Number of First data point?" Enter the number of the data point with which the run began. If it is the first point taken, enter 1, and press continue. If one wants to skip to the 10th point, enter 10,...etc., then continue.

8. "Number of last data point?" If 100 points were taken, type 100, then press continue. If one wishes to process only a partial set of the data, type the number of the end point and then press continue. One must specify at least 4 points, otherwise some of the subroutines will not work correctly. Obviously there must be at least 4 points on the tape from the acquisition task.

9, "Measurement Interval, Seconds." Here one should enter the number of seconds in the timing or measurement interval for the data run, e.g., type 100, then press continue.

At this point the tape is read. All points specified for all clocks specified are read. For 8 clocks and 100 points this may take about 6 minutes. Then a branch to question 10, the actual processing, occurs.

10. "Compute sigma(y)?" If one wishes a sigma-tau plot of the data, the answer to this question should be "y". If not the program branches to the point where it asks whether a phase plot is desired. (Question 13).

11. "Subtract linear Lst sqr fit?" Here, if one answers "y", the program will subtract the best linear least square fit from the data points stored in the 9825A registers for that clock. The orginal data, for that clock, as read from the tape is now modified by this procedure, and is lost. If one wishes to reclaim the original data, the tape must be read again for that clock. The least square fit data are retained in the registers for that clock and are used for the sigma-tau plot and for the phase plot that may follow. In the sigma(y) print out following a "y" answer to both 4. and 5., the intercept, Y, the fractional frequency, for the least square line, is also printed out just before the sigma-tau values for the data set for that clock and run.

12. "Plot sigma?" In this case a "y" answer will set up the plotter for a sigma-tau plot. If a point plot is desired, the operator need only press continue in response to the display:

"sig y plot: if line plot cfg6"

If a solid line plot is desired, one should type "cfg6", then press execute, then continue. A pause and prompt to set paper in the plotter follows. Once the paper is set, press continue and the plot will be completed.

13. "Plot Phase?" A "y" answer here will result in a phase plot with either a least square fit subtracted, or not, as requested by the operator in question 13. A prompt and pause to permit replacement of paper in the plotter occurs. When paper is ready, press continue and the plot follows.

This is the last portion of the processing for any clock. After this, the program returns to the point, question 10, at which the data for the next clock are processed. Questions 10 through 13 are again answered by the operator. After data for all clocks specified have been processed, the program ends, and displays:

"Stop...Operation complete".

6. Summary of Key Commands and Block Diagrams

A. Key commands used by the quad measurement modules (PDM) and by the pulse distribution modules, (QMM)

1. Quad measurement module

A. Overall function codes
F8A15N3...Test LAM in first QMM.
Response goes to Q
F8A15N5...Test LAM second QMM
Response goes to Q

B. Section Function Codes

1. Section 1, A0 subadresses, use N3 for the first QMM, and N5 for the second QMM
F0A0N3...Read 10Hz register
F9A0N3...Reset 10Hz register o'flow
F12A0N3...Reset 10 Hz register
F24A0N3...Disable channel operation
F27A0N3...Test if channel active,
Response goes to Q

2. Section 1, A1 subaddresses, use N3 for the first QMM, and N5 for the second QMM
F0A1N3...Read 10MHz register
F10A1N3...Reset LAM status
F24A1N3...Disable channel LAM interrupt
F26A1N3...Enable channel LAM interrupt
F27A1N3...Test LAM status, response goes to Q

3. Section 2, use N3 for the first QMM, and N5 for the second QMM
Use same commands as Section 1, but use subaddress:
A2 in place of A0
A3 in place of A1

4. Section 3, use N3 for the first QMM, and N5 for the second QMM
Use same commands as Section 1, but use subaddress:
A4 in place of A0
A5 in place of A1

5. Section 4, use N3 for the first QMM,
and N5 for the second QMM
Use same commands as Section 1, but use subaddress:
A6 in place of A0
A7 in place of A1

2. Pulse distribution module

A. Overall function codes (Subaddress A0)
F0A0N2...Read status
F8A0N2...Test LAM, Response goes to Q
F10A0N2...Reset LAM status and stop measurement cycle
F24A0N2...Disables PDM LAM interrupt
F25A0N2...Start next measurement cycle
F26A0N2...Enable PDM LAM interrupt

B. There are no other subaddresses used by the PDM

B. Diagrams of operational modes

1. Fig. 1. Control logic, Pulse Distribution Module.
2. Fig. 2. Control logic, Quad Measurement Module.
3. Fig. 3. Counting logic, Quad Measurement Module.

Footnotes:

(1) Supplied for this application by Kinetic Systems Corporation, Lockport, Ill.

(2) Based on NBS-supplied conceptual specifications, ERBTEC Engineering Inc., Boulder, CO., designed and manufactured the pulse distribution and quad measurement modules used in this implementation. The original NBS specification and critical ANSI/IEEE-583 interface requirements for these two module types are contained in Section 6. More detailed CAMAC ANSI/IEEE instrumentation standards may be found in (4).

(3) These items were supplied by Hewlett-Packard Co., Denver, Co.

(4) CAMAC Instrumentation and Interface Standards, Institute of Electrical and Electronics Engineering, Inc., 345 E. 47th St., New York, NY 10017.

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CONTROL LOGIC PULSE DISTRIBUTION MODULE

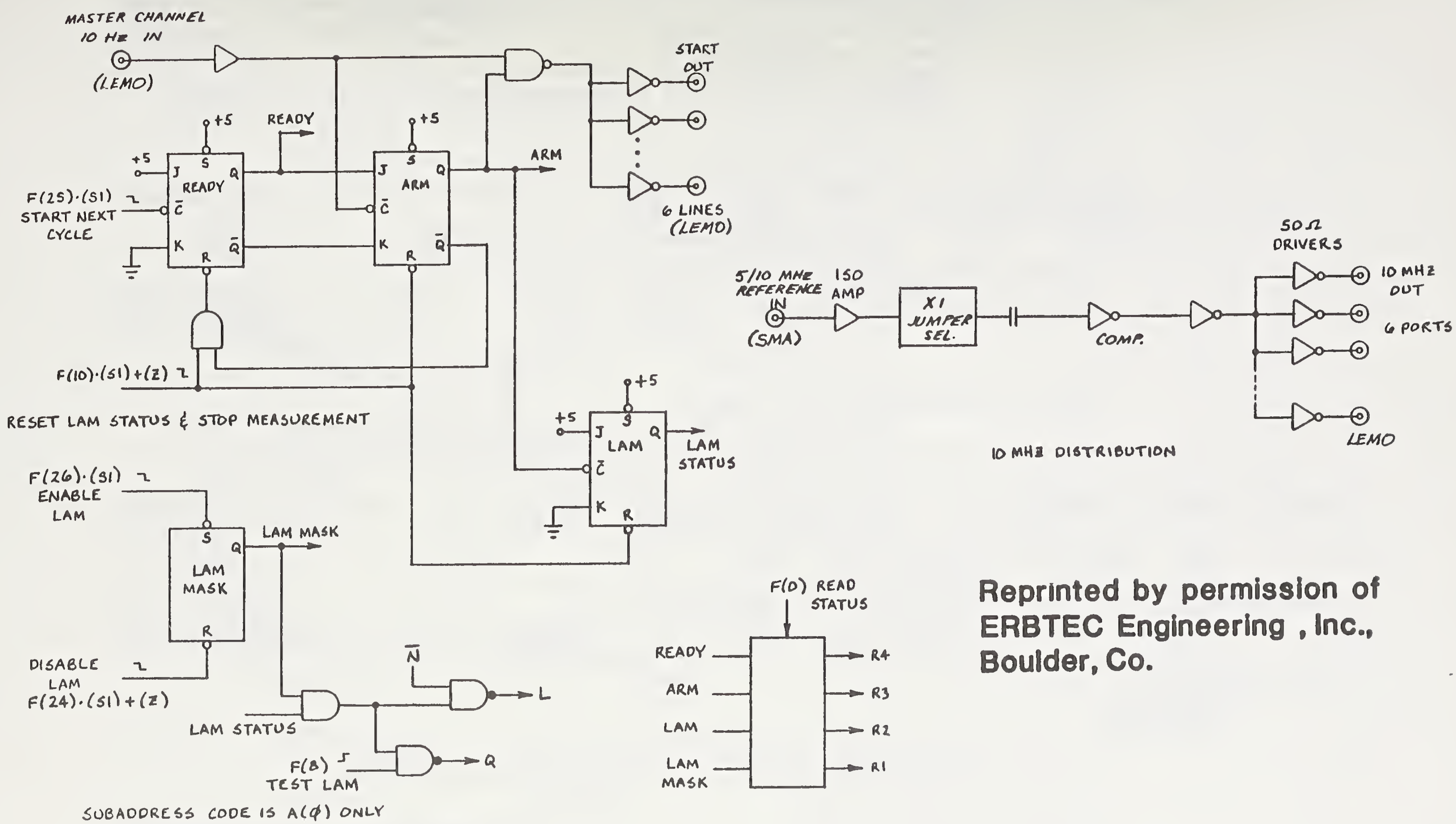

Figure 1. Control logic, Pulse Distribution Module.

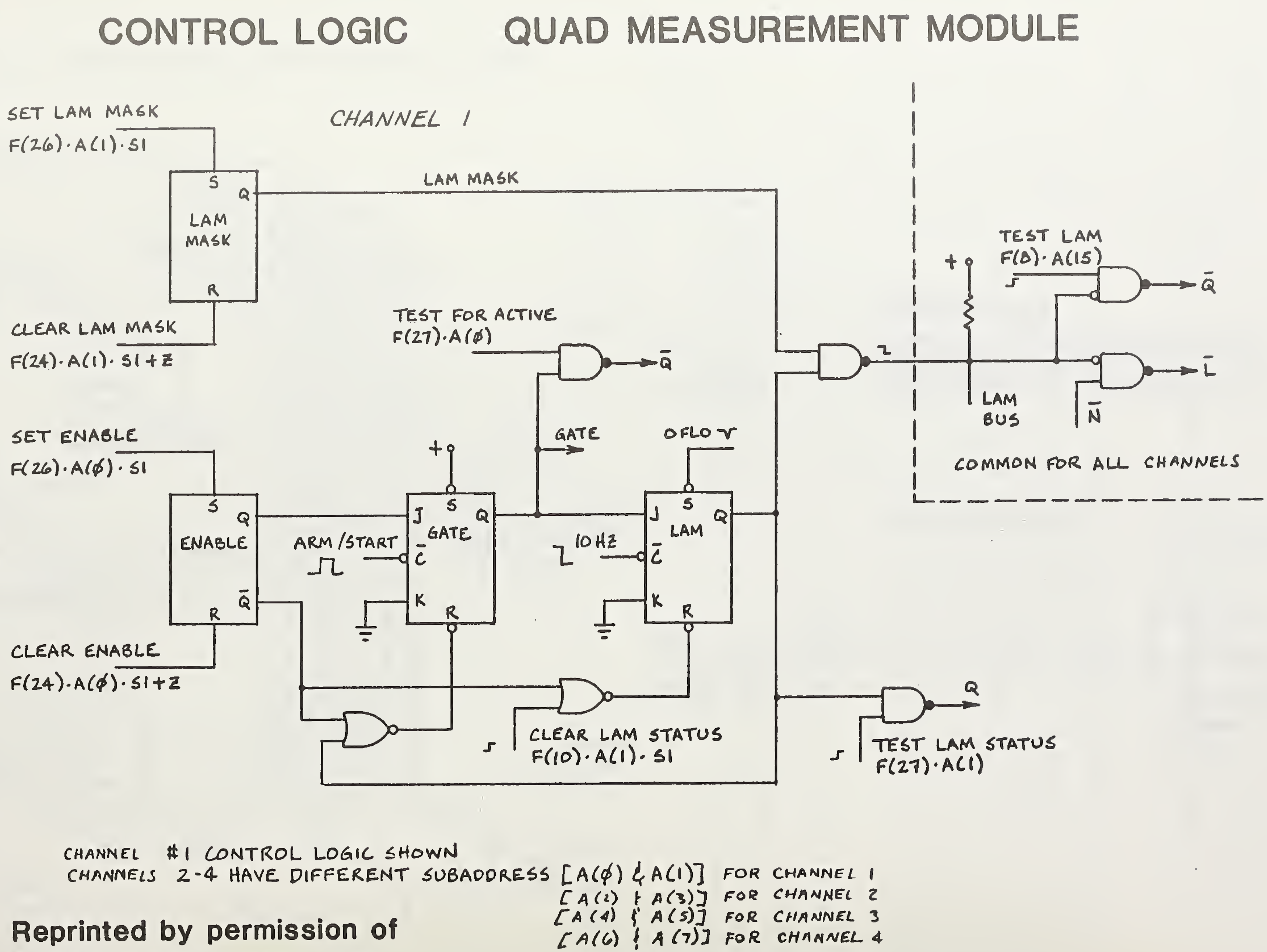

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Figure 2. Control logic, Quad Measurement Module.

COUNTING LOGIC QUAD MEASUREMENT MODULE

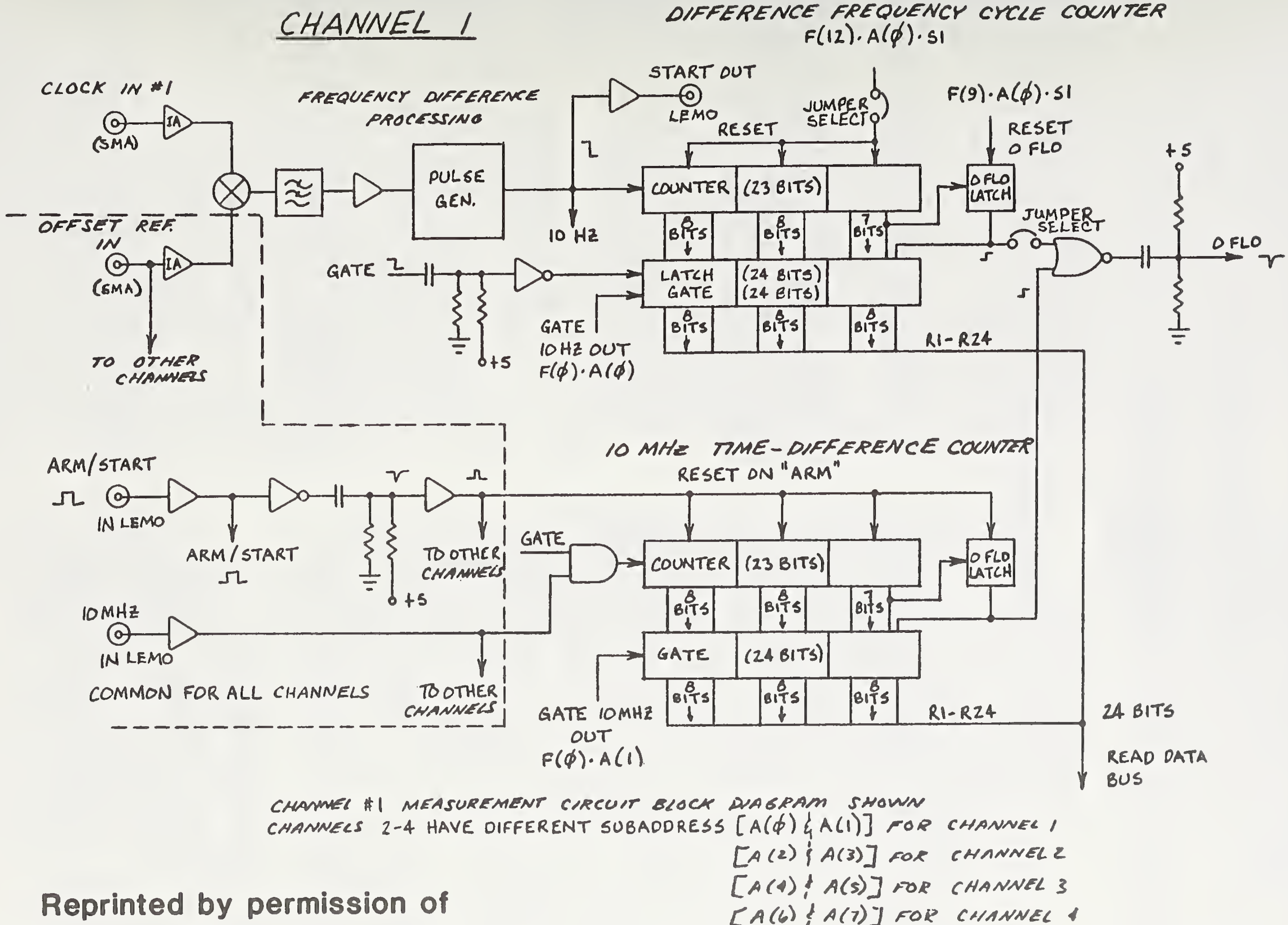

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Figure 3. Counting logic, Quad Measurement Module.

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PERFORMANCE OF AN AUTOMATED HIGH ACCURACY PHASE MEASUREMENT SYSTEM

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Summary

A fully automated measurement system has been developed that combines many properties previously realized with separate techniques. This system is an extension of the dual mixer time difference technique, and maintains its important features: zero dead time, absolute phase difference measurement, very high precision, the ability to measure oscillators of equal frequency and the ability to make measurements at the time of the operator's choice.[1] For one set of design parameters, the theoretical resolution is 0.2 ps, the measurement noise is 2 ps rms and measurements may be made within 0.1 s of any selected time. The dual mixer technique has been extended by adding scalers which remove the cycle ambiguity experienced in previous realizations. In this respect, the system functions like a divider plus clock, storing the epoch of each device under test in hardware.

The automation is based on the ANSI/IEEE-583 (CAMAC) interface standard.[2] Each measurement channel consists of a mixer, zero-crossing detector, scaler and time interval counter. Four channels fit in a double width CAMAC module which in turn is installed in a standard CAMAC crate. Controllers are available to interface with a wide variety of computers as well as any IEEE-488 compatible device. Two systems have been in operation for several months. One operates 24 hours a day, taking data from 15 clocks for the NBS time scale, and the other is used for short duration laboratory experiments.

Review of the Dual Mixer Time Difference Technique

It is advantageous to measure time directly rather than time fluctuations, frequency or frequency fluctuationns. These measurements constitute a hierarchy in which the subsequently listed quantities may always be calculated from the previous ones. However, the reverse is not true when there are gaps in the measurements. In the past, frequency was usually not derived from time measurements for short sample times because time interval measurements could not be performed with adequate precision. The dual mixer technique, illustrated in Figure 1, made it possible to realize the precision of the beat frequency technique in time interval measurements.

The signals from two oscillators (clocks) are applied to two ports of a pair of double balanced mixers. Another signal synthesized from one of the oscillators is applied to the remaining two ports of the mixer pair. The input signals may be represented in the usual fashion

$$V_1(t) = V_{10} \sin [2\pi\nu_{10}t + \phi_1(t)],$$

$$V_2(t) = V_{20} \sin [2\pi\nu_{20}t + \phi_2(t)] \text{ and}$$

$$V_s(t) = V_{so} \cos [2\pi\nu_{so}t + \phi_s(t)]$$

where $\nu_{so} = \nu_{10}(1-1/R)$ and R is a constant usually called the heterodyne factor.

The low passed outputs of the two mixers are

$$V_{B1} = V_{B10} \sin [\Phi_1(t) - \Phi_s(t)] \text{ and}$$

$$V_{B2} = V_{B20} \sin [\Phi_2(t) - \Phi_s(t)] \text{ where}$$

$$\Phi(t) = 2\pi\nu_o t + \phi(t).$$

The time interval counter starts at time t_M when V_{B1} crosses zero in the positive direction and stops at time t_N, the time of the very next positive zero crossing of V_{B2}. Thus

$$\Phi_1(t_M) - \Phi_s(t_M) = 2M\pi \text{ and}$$

$$\Phi_2(t_N) - \Phi_s(t_N) = 2N\pi \text{ where}$$

N and M are integers.
Subtracting the two equations in order to compare the phases of oscillators 1 and 2, one obtains

$$\Phi_2(t_N) - \Phi_1(t_M) = \Phi_s(t_N) - \Phi_s(t_M) + 2(N-M)\pi.$$

The phase of an oscillator at time t_N may be written in terms of its phase at t_M and its average frequency over the interval $t_M < t_N$.

$$\Phi(t_N) = \Phi(t_M) + 2\pi[\bar{\nu}(t_M;t_N)](t_N - t_M) \text{ and}$$

when we apply this equation to both Φ_2 and Φ_S we find

$$\Phi_2(t_M) - \Phi_1(t_M) = 2(N-M)\pi$$
$$-2\pi[\bar{\nu}_{B2}(t_M;t_N)](t_N - t_M)$$

where $\nu_{B2} = \nu_2 - \nu_s$.

Since M and N are not measureable with the equipment in Figure 1, the dual mixer technique has heretofore only been used to measure the phase difference between two oscillators modulo 2π. We denote the period of the time interval counter time base by τ_c and the number of counts recorded in a measurement by P. Then the phase difference between the two oscillators is given by

$$[\Phi_2(t_M) - \Phi_1(t_M)] \bmod 2\pi = -2\pi[\bar{\nu}_{B2}(t_M;t_N)]\tau_c P$$

Figure 2 illustrates the output of the measurement system over a period of time. If a measurement begins and ends without the time interval counter making a transition between zero and its maximum value, e.g., $t_a < t_M < t_N < t_b$, then the phase difference can be calculated from the data. If $t_a < t_M < t_b < t_N < t_c$, then the data must be corrected by 2π to calculate the phase difference. Experience has shown that there are many measurement situations for which the number of transitions of the time interval counter which occur between t_M and t_N cannot be known. For this reason, a modification has been developed which removes the ambiguïty by measuring M and N.

Extended Dual Mixer Time Difference Measurement Technique

In order to configure the system to acquire complete phase information, two scalers are added to count the zero crossings of each mixer. Figure 3 is the block diagram of a two channel system. It is constructed from identical circuit modules and therefore contains an unused time interval counter. However, this design permits very straightforward and inexpensive extension to the comparison of an arbitrarily large number of oscillators with no need for switching any signals.

The counter outputs are combined to form the phase difference between oscillators.

$$\Phi_2(t_M) - \Phi_1(t_M) = 2(N_o - M_o)\pi + 2(N-M)\pi$$
$$-2\pi[\bar{\nu}_{B2}(t_M;t_N)]\tau_c P$$

The first term is a constant which represents the choice of the time origin and can be ignored. The last two terms and their sum are plotted in Figure 4.

The average beat frequency $\bar{\nu}_{B2}(t_M;t_N)$ cannot be known exactly. However, it may be estimated with sufficient precision from the previous pair of measurements designated ' and ". The average frequency is approximately

$$\bar{\nu}_{B2}(t_M;t_N) \cong (N'' - N')/[R(M'' - M')/\nu_{10} + \tau_c(P'' - P')]$$

provided that it changes sufficiently slowly compared to the interval $t_M < t_N$. A typical value for this error will be given in the following section.

Hardware Implementation

All measurement channels consist of a mixer, zero-crossing detector, scaler and time interval counter. Four such circuits can be built in a double width CAMAC module. The system is easily expanded to compare many oscillators and a complete system for making phase comparisons among four clocks is shown in Figure 5. We have chosen parameters which are reasonable for comparing state-of-the-art atomic standards. Thus, the synthesizer is offset 10Hz below oscillator # 1 and R = 5 x 10^5. The outputs from both mixers are approximately 10Hz. The noise bandwidth is 100 Hz. The time interval counter is twice the frequency of oscillator #1 or approximately 10 MHz. The quantization error is 1/2R = 10^{-6} cycle or 0.2ps which is a factor of ten smaller than the measurement noise. As stated earlier, an error will result from frequency changes which violate the constancy assumption used to estimate ν_{B2}. A change in ν_2 by 10^{-10} during the interval between two measurements will result in a time deviation error of 10ps. Thus, one must make more closely spaced measurements for oscillators which have large dynamic frequency changes than for more stable devices. Two other sources of inaccuracy are the sensitivities to the amplitude and phase of the common oscillator. Figure 6 shows the measured value of $x = \phi/2\pi\nu_o$ as a function of the amplitude of the input signal and the phase of the synthesizer.

The new measurement system has many desirable features and properties:

(1) It has very high resolution, limited by the internal counters to 0.2 ps and by noise to approximately 2 ps.

(2) It has much lower noise than divider based measurement systems. However compromises made to achieve low cost, low power, small size and automatic operation degrade the performance compared to state-of-the-art systems for comparing 2 oscillators.

(3) The operation is fully automatic.

(4) NBS has developed a detailed operating manual for the equipment and software.[3]

(5) All oscillators in the range of 5 MHz ± 5 Hz may be compared. Other carrier frequencies such as 1 MHz, 5.115 MHz, 10 MHz and 10.23 MHz are also usable. However, different carrier frequencies may not be mixed on the same system. The system has been successfully tested with an oscillator offset 4.6 Hz from nominal 5MHz. Measurements were made at intervals of 2 hours between which the system had to accumulate approximately $2 \times 10^6 \pi$. The system has also been tested with an oscillator offset 4×10^{-5}, and no errors were detected during a period of 40 days.

(6) All sampling times in the range of 1 second to 16 days with a resolution of 0.1 second are possible. Measurements may be made on command or in a preprogrammed sequence.

(7) Measurements are synchronized precisely, i.e. at the picosecond level, with the reference clock. They may therefore be synchronized with important user system events, such as the switching times of a FSK or PSK system.

(8) All oscillators are compared synchronously and all measurements are performed within a maximum interval of 0.1 second. As a result, the phase of any oscillator needs to be interpolated to the chosen measurement time for an interval of 0.1 second maximum. This capability, which is not present in either single heterodyne measurement systems or switched measurement systems eliminates a source of "measurement" error which is generally much larger than the noise induced errors. For example, interpolation of the phase of a high performance Cs clock ($\sigma_y \sim 10^{-11}/\tau^{\frac{1}{2}}$) over a period of 3 hours would produce approximately 1.5 ns phase uncertainty. To maintain 4 ps accuracy requires measurements simultaneous to 0.1s.

(9) There are no phase errors due to the switching of rf signals since there is no switching anywhere in the analog measurement system.

(10) No appreciable phase errors are introduced when it is necessary to change the reference clock since, as shown in Figure 6, the peak error due to changes in synthesizer phase is 20 ps.

(11) The measurement system is capable of measuring its own phase noise when the same signal is applied to two input ports. Figure 7 shows the phase deviations between two such channels over a period of 75,000 seconds and Figure 8 is the corresponding Allan variance plot. Figure 9 shows the phase deviations between 2 input channels over a period of 40 days.

(12) Since the IEEE-583 (CAMAC) interface standard has been followed for all the custom hardware, the system may be easily interfaced to almost any instrument controller. NBS has already tested the system using a large minicomputer, a small minicomputer and a desk top calculator. Interfaces between IEEE-583 and IEEE-488 controllers are available and have been used successfully.

(13) The system is capable of camparing a very large number of oscillators at a reasonable cost per device.

There are also disadvantages to this measurement system. The most important are:

(1) The complexity of the hardware is greater than for some systems. It is possible that this will reduce reliability.

(2) A high level of redundancy is difficult to achieve. The system design stresses size, power, convenience and cost, resulting in an increase in the number of possible single point failure mechanisms compared to some other techniques. For example, a CAMAC power supply failure will result in a loss of data for all devices being measured.

(3) A substantial committment is required in both specialized hardware and software.

(4) If an oscillator under test experiences a phase jump which exceeds 1 cycle, the measurement system records a jump with incorrect absolute magnitude. As a result, it may not be applicable to signals which are frequency modulated with discontinuous phase steps larger than 2π.

Conclusions

We have demonstrated a new phase measurement system with very desirable properties: All oscillators in the range of 5MHz ± 5Hz may be measured directly. The sampling times are only restricted by the requirement that they exceed one second. The noise floor is $\sigma_y(2,\tau) = 3 \times 10^{-12}/\tau$ in short term and the time deviations are less than 100 ps. All circuitry is designed as modules which allows expansion at modest cost. Compatibility with a variety of computers is insured through the use of the IEEE-583 interface and adapters are available to permit use with an IEEE-488 controller. The system makes it feasible to make completely automated phase measurements at predetermined times on large numbers of atomic clocks. It's own noise is one-hundred times less than the state-of-the-art in clock performance. It will be used in the near future to make all measurement needed to compute NBS atomic time, but it will also be very valuable for any laboratory which uses three or more atomic clocks.

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and frequency stability of precision oscillators," NBS Tech. Note 669 (1975).
2. "CAMAC instrumentation and interface standards," Institute of Electrical and Electronic Engineers, Inc., 345 E. 47th St. New York, NY 10017.
3. D. J. Glaze and S. R. Stein, "Picosecond time difference measurements utilizing CAMAC based ANSI/IEEE -488 data acquisition hardware", NBS Tech Note 1056 (in preparation).

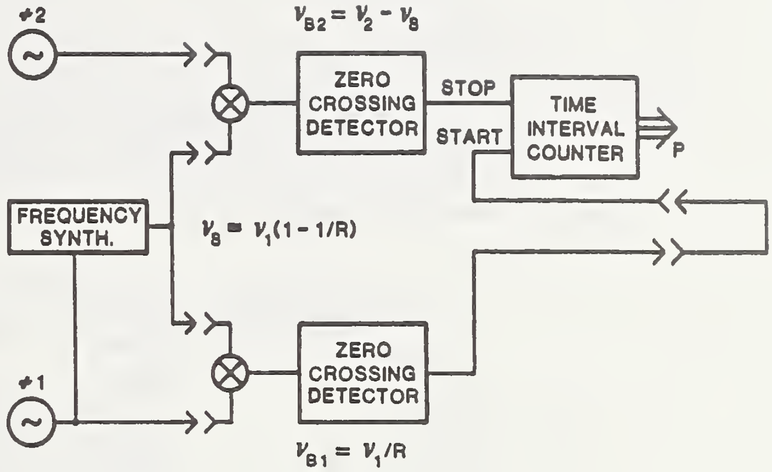

Figure 1. Dual Mixer Time Difference Measurement System

$$[\Phi_2(t_M)-\Phi_1(t_M)]\bmod 2\pi = -2\pi[\bar{\nu}_{B2}(t_M;t_N)]\tau_c P$$

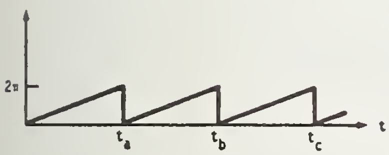

Figure 2. Dual Mixer Data

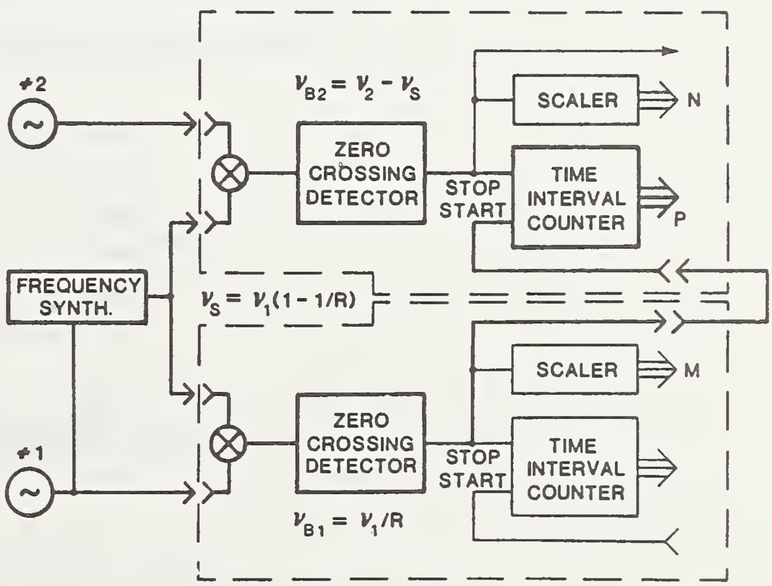

Figure 3. Extended Dual Mixer Time Difference Measurement System

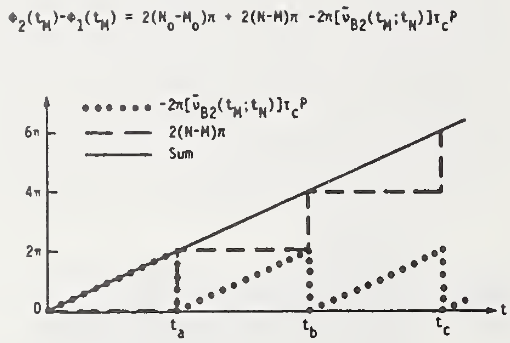

Figure 4. Extended Dual Mixer Data

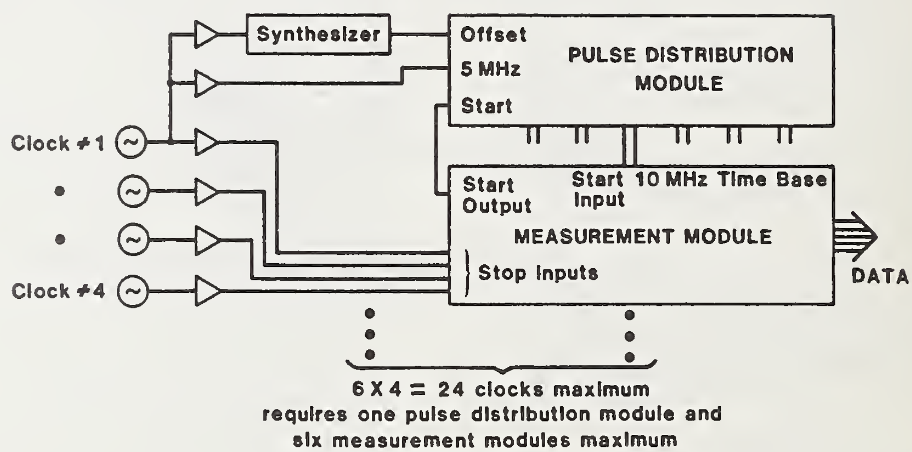

Figure 5. System Block Diagram

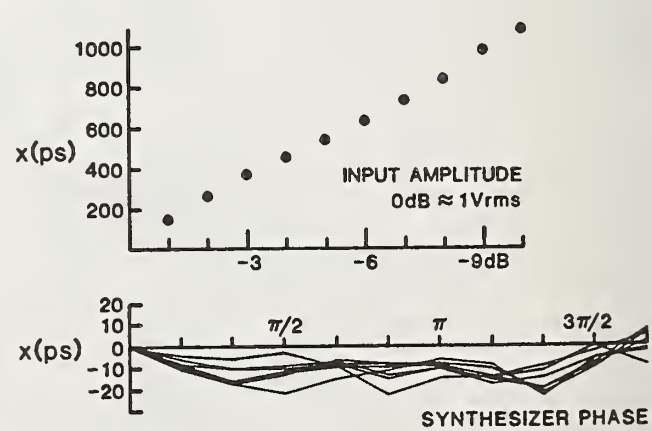

Figure 6. Measured Time Difference vs. Input Amplitude and Synthesizer Phase

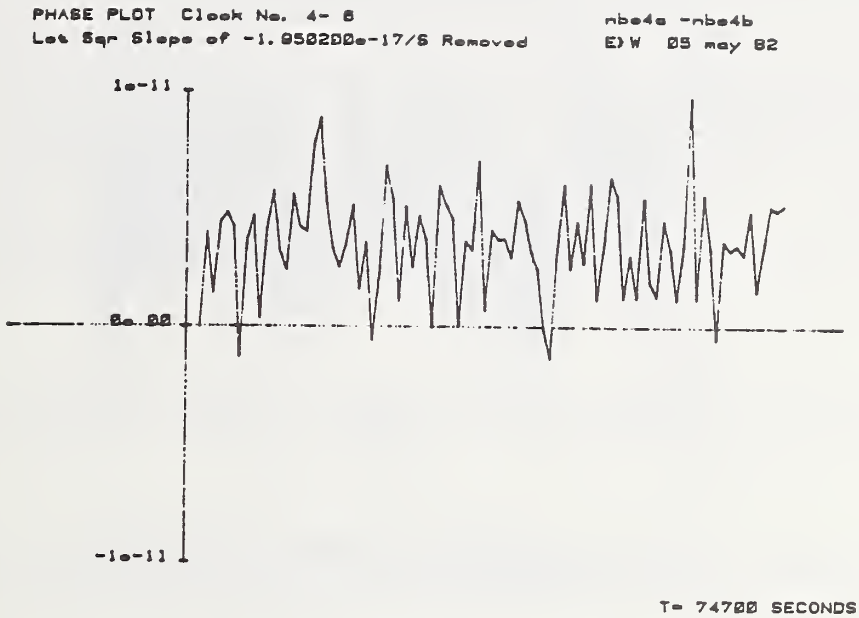

Figure 7. Raw Phase Data for Two Channels Driven from the Same Source

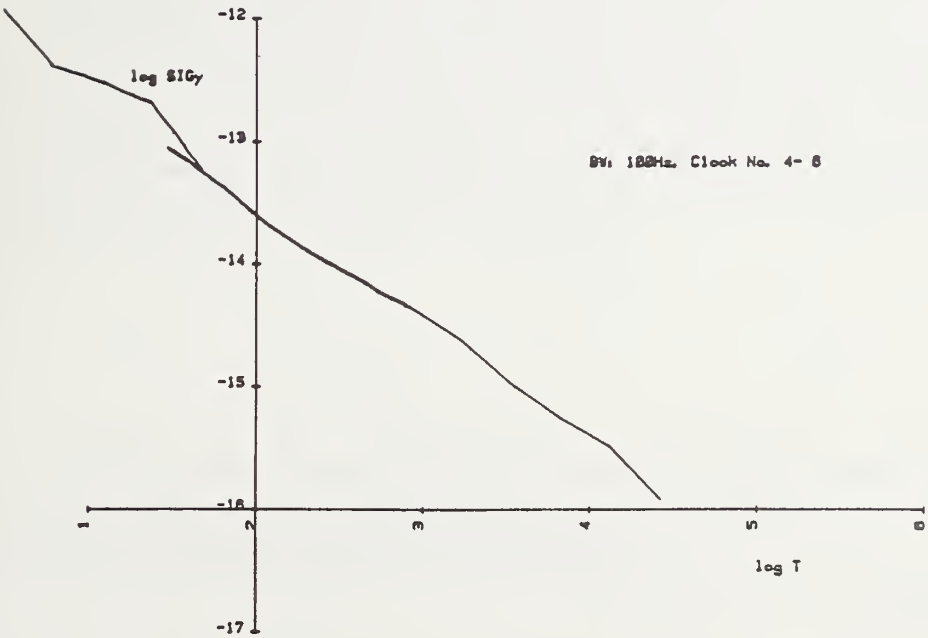

Figure 8. Noise Floor of Measurement System

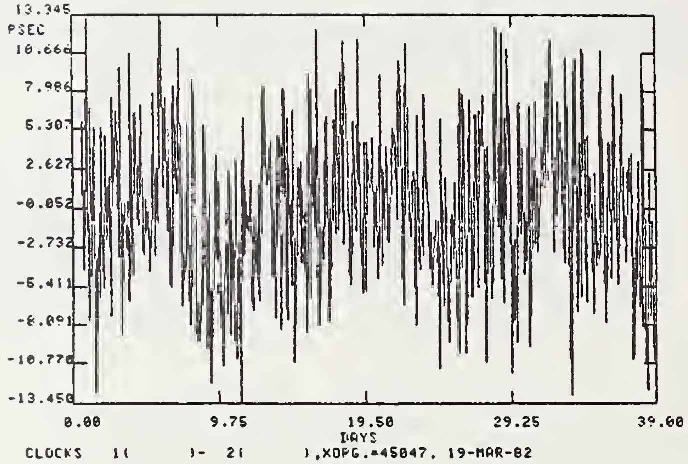

Figure 9. Raw Phase Data for Two Channels Driven from the Same Source

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DATA ACQUISITION HARDWARE
OPERATION MANUAL IE3 Version 1.0

5. AUTHOR(S)

D. J. Glaze and S. R. Stein

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

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Automated time-difference measurements at the picosecond level have been achieved. The system described combines the best properties of three common methods: the single heterodyne measurement technique, the frequency divider, and the dual-mixer time-difference measurement system. This particular system combines two instrumentation standards, ANSI/IEEE-583 and ANSI/IEEE-488 with new, modular dual-mixer time-difference measurement hardware. The modular, standardized hardware together with the new measurement techniques permit the data acquisition modules to be contained in a standard CAMAC crate. This system, along with an external controller, is capable of measuring eight clocks, at the present time, and is expandable to twenty-four clocks with modified software and additional measurement modules. The system noise performance is described by $\sigma_y(\tau) = 3 \times 10^{-12}\tau^{-1}$ for time difference measurements.

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

ANSI/IEEE-488; ANSI/IEEE-583; automated data acquisition system; dual-mixer measurements; picosecond time-difference measurements.

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