US/GR PK/

VLB ARRAY MEMO No. 622

A Pulse Calibration Scheme for the VLBA

A. R. Thompson and D. S. Bagri
March 21, 1988

1. INTRODUCTION

The original decision on pulse calibration for the VLBA was that it would not be included as part of the initial installation of electronics on the antennas, but could be added later in the construction, if tests indicated it to be desirable. Some recent tests on the Pie Town antenna have refocussed our attention on this issue. Measurements of the relative phase stability of the IF cables, when the antenna is moved in azimuth, indicate that changes in the electrical lengths of the cables vary from one cable to another by as much as 80 ps. It may be possible to reduce these effects by taking steps to minimize torsional strain on the cables when the antenna is turned, by using thinner cable or different cable mounting. These possibilities are being pursued.

Each of the coaxial cables that carry the IF and LO signals between the B rack in the vertex room and the C rack in the equipment room has 8 connections, which require a total of 16 connectors, each of which may have a VSWR of 1.07 (reflection coefficient = .034). These connectors are necessary in order to use 3/8 inch Heliax cable for most of each run, with flexible sections around the elevation and azimuth axes, and with bulkheads at the walls of the vertex and equipment rooms to maintain effective RFI shielding. The effect of these reflections combined with cable length changes can result in frequency dispersion of the delay. The delay variation could be as large as several ps over the IF band (500-1000 MHz). Thus we must recognize that the present scheme of correcting the variations of the IF cables, by using the LO round trip path measurements at 500 MHz, is not adequate to provide an accuracy of few ps which we hope to achieve with the VLBA.

A further important consideration is the stability of the RF, LO, IF, and baseband electronics. A rough, and perhaps conservative, estimate of the contribution due to the electronics is 40 ps/°C (see Appendix 1), and the temperature stability is, in general, no better than ± 1°C. Barry Clark points out that the use of two separate 2-16 GHz Synthesizer modules for the two ends of the 8.0-8.8 GHz range introduces an additional potential error for this band, since two such units will not have identical phase variations with frequency. Note that for measurements of fringe phase, the IF and baseband components in Appendix 1 have relatively smaller effects because the signals traverse them at reduced frequencies, but for measurements of delay they can have large effects. Analyses of relative errors in phase and delay measurements are given by Larry D'Addario in VLBA Memo No.487, and by Barry Clark in a memo* dated March 16 1988.

A pulse calibration system can, in principle, calibrate the overall receiving system if it is, itself, sufficiently stable. Both phase and

---

* VLBA Test Memo No. 15

delay measurement accuracy should then depend only on the accuracy of the calibrator. Suppose that the calibration system is built with components, i.e., amplifiers, cables etc., with the same temperature coefficients as the receiving system. The overall stability of the calibration system should be better than that of the receiving system because it is simpler; it contains fewer unstable components combined together. Compared with the LO system, for example, the pulse calibration system is much simpler because the frequencies that it generates do not have to be separated from other frequencies to a level of about -60 dB, selectable under computer control, or accurately maintained at relatively high power levels. Thus a pulse calibration system can be expected to improve the performance of the array.

2. DELAY STABILITY REQUIREMENTS OF THE VLBA

Presently the geodesy community achieves a stability of about 10-15 ps with the existing pulse calibration system, and they would like to improve it by an order of magnitude. The VLBA maser provides a stability of 2×10^{-15}. This implies that over a period of 1000 s we may have an instability of 2 ps due to the maser, which may linearly increase with time. Further, for observations at the highest VLBA frequency of 86 GHz, one may wish to integrate signals (assuming that the atmosphere will allow this) using measured values of the instrumental phase variation obtained with a pulse calibration system. Integration of the signals is possible with phase errors of up to 1 radian at the observing frequency. This requires that the pulse calibration system should be stable to < 2 ps. The above considerations imply that we should aim at a stability of about 2 ps over a period of 1000 s, and perhaps < ~10 ps over several hours, but not significantly worse than the inherent stability of the maser (2×10^{-15} for 1,000 to 10,000 s). Note that the overall phase stability of 1° per GHz that has been achieved for the VLA corresponds to 3 ps. For a calibration system alone, we should be able to do even better.

3. THE EXISTING PULSE CALIBRATION SYSTEM

A pulse calibration system consists of two parts: (1) a transmission line to convey a reference frequency from the maser to the vertex room, and (2) a pulse generator to produce harmonics that lie within the observing bands. In this memo we shall not consider the detection of the calibration signal. The transmission line should not degrade the inherent phase stability of the maser signal: its electrical length should be stable or continuously calibrated. The pulse generator should similarly be stable in its electrical delay or its variations should be corrected in some way. For geodetic observations such a calibration system, developed by Alan Rogers at Haystack Observatory, has been in use for some years (see Mark III-VLBI Documentation, and Whitney, et al., 1976, Radio Science, 11, 421-432). In this system a 5 MHz reference signal from the maser is sent on a cable to the front end location where it is used to generate harmonics of

1 MHz using a tunnel diode pulse generator and an RF switch. The length of the cable carrying the 5 MHz signal is calibrated using round trip phase measurement at 5 MHz. The pulse generator has a stability of 6 ps/°C, and the cable measuring system has a short term stability of ± 5 ps, a long term stability of ± 10 ps/hour, and a linearity of 0.05% (MKIII Documentation). The overall stability is estimated to be 10-15 ps.

4. POSSIBLE IMPROVEMENTS TO THE EXISTING SYSTEM FOR THE VLBA APPLICATION

We believe that there are two ways in which the existing Haystack design of pulse calibrator can be improved. (1) With the present design, any change in the value of the delay of the pulse generator or the switch will introduce a measurement error. However, if one uses a voltage controlled crystal oscillator (VCXO) to drive the pulse generator, and the generator output is used in a phase-lock loop to lock the VCXO to the reference signal, then the effect of the pulse generator variations will be compensated by the loop. A scheme of this kind is shown in Fig. 1. Further, it may be possible to use a step recovery diode instead of a tunnel diode for the pulse generator, since the stability of the generator is no longer critical. The step recovery diode has a higher efficiency in generating harmonics and can generally handle a larger input power. This may facilitate use of the pulse calibration system up to the highest VLBA frequency of 86 GHz. (2) In the Haystack design the round trip phase for the cable is measured at 5 MHz. Therefore, to obtain a 2 ps stability, the phase of the returned 5 MHz signal has to be measured to an accuracy of 4 ps, i.e., 1/50,000 of a cycle. An error of this magnitude can occur as a result of a DC offset of 1/8,000 of the peak amplitude of the signal at the phase detector. Maintaining the required accuracy is not easy. If the reference frequency is increased, the required tolerance is proportionately reduced. Now, to obtain lines at 1 MHz intervals in the calibration signal, the frequency of the pulses must be 1 MHz. In the Haystack system, pulses are generated at the 5 MHz reference frequency using a tunnel diode pulse generator, and then gated at 1 MHz using an RF switch. The use of the RF switch is a good design feature, since the switch is more stable in delay than a digital count-down circuit would be. However, the speed of the switch limits the maximum pulse recurrence frequency that drives the pulse generator, and thus limits the reference frequency unless a frequency divider is used. The latest GaAs diode switches with risetimes of a few ns would perhaps allow frequencies up to about 100 MHz. However, by using a different system design, this restriction on the reference frequency can be avoided. Factors governing the choice of frequency to use for the reference signal transmitted on the cable are discussed in Appendix 2. These have led to a choice of 500 MHz for the VLBA.

A scheme in which a 500 MHz reference is used to produce 1 MHz pulses is shown in Fig. 1. A 1 MHz VCXO is used to drive the pulse generator. The line at 500 MHz in the output of the pulse generator is compared with the 500 MHz reference signal in a phase detector to control the VCXO in a phase-locked loop. No switch or digital counter is needed, and since the pulse generator is within the loop, delay variations in the generator are automatically compensated for. Since the 1 MHz signal phase is determined, in effect, by counting cycles at 500 MHz, there is an ambiguity in the phase. This can be resolved by measuring the 1 MHz phase relative to a signal from the maser, and either slipping cycles of the 500 MHz to obtain a preset phase value, or recording the phase together with the round-trip measurement for phase correction after correlation. For such a measurement a 1 MHz signal could be transmitted between the vertex room and the station building on an unstabilized cable, since the accuracy required is one cycle at 500 MHz, that is, 2 ns.

A development of the 1 MHz VCXO scheme is shown in Fig. 2. The 1 MHz VCXO is replaced by a 500 MHz VCXO and a digital counter which divides the frequency down to 1 MHz. Since the counter is within a phase-locked loop, its delay stability is not important. A 1 MHz signal from the maser controls the counter so that it always resets on the first 500 MHz cycle following the start of each 1 MHz cycle. The 1 MHz signal that drives the pulse generator then retains a fixed phase relationship with the 1 MHz from the maser, but its precise phase is determined by the 500 MHz reference signal.

5. SUGGESTED BLOCK DIAGRAM FOR THE VLBA

Figure 3 shows a scheme in which a pulse calibration system incorporating the ideas discussed above is combined with the VLBA LO system. Factors related to the round-trip phase system are discussed in Appendix 2. A small rearrangement of the present LO scheme is required to offset the 500 MHz signal to the vertex room by a small frequency (2.083 kHz), to facilitate locking of the VCXO in the pulse calibrator. To add flexibility the frequency-dividing counter in the calibrator unit can be programmed to divide down to, say, 5 MHz or 10 MHz to give different line spacings, as desired. Wider spacings result in more power in the lines, and may be useful for the higher frequency bands. The modulated reflector for the round-trip phase measurement can be either in the LO receiver module or in the pulse calibrator. If the pulse calibrator is located in the feed cone, to be as close as possible to the feeds, there will be about 20 feet of cable between it and the LO receiver, and use of a modulator in the pulse generator will maximize the stability of that part of the system. Alternatively, the pulse calibrator could be mounted in the B-Rack, and a length of thermally insulated, Heliax cable (temp. coefficient 10 ppm/°C) used to convey the output to the feeds.

It is possible to generate the 500 MHz signal required for the local oscillator system, as well as the pulse calibration signals, using only one VCXO, as shown in Fig. 4. Switches S1 and S2 are introduced to disable the pulse generator for applications in which it is not desirable to insert the pulses (for example during certain spectral line observations), but a phase-stable 500 MHz signal for the local oscillator system is still provided. Considering (1) that we already have constructed several LO

Receiver modules, (2) that an independent pulse calibration unit would allow more freedom for further development and possible improvements, and (3) that it is desirable to retain the freedom of locating the pulse calibration unit in either the B-rack or in the feed cone near the front-ends, we prefer to build a separate pulse calibration unit, as in Fig 3.

6. MAJOR SOURCES OF INSTABILITIES AND EXPECTED PERFORMANCE

The following are the major sources of instability in the system in Fig. 3. (1) The phase stability of the 500 MHz reference delivered from the maser to the power divider in the LO transmitter, which is determined by the cable from the maser to the C-rack and 100 to 500 MHz multiplier. (2) The phase stability of the low frequency amplifiers in the various phase lock loops. (3) The modulated reflector phase stability. (4) The delay stability of various cables, especially the cable carrying the pulse calibration signal from the generator output to each front end. The cables are particularly important if the pulse generator is located in the B rack and not at the feed-cone level close to the front ends. It is possible to minimize the various instabilities by careful design and layout. Some obvious precautions are: (1) to use low temperature-coefficient cable (such as 3/8 inch Heliax) wherever possible (e.g., from the maser to the C rack) and to keep the lengths short, (2) to use equal length cables for signals on the two inputs of a phase detector, and (3) to avoid using any unnecessary amplifier in the round trip phase measurement. With careful design it should be possible to keep the variations of the 100 to 500 MHz multiplier, the modulated reflector, and the low frequency amplifiers used in various phase lock loops, to < ~0.1°/°C of phase. Also we should be able to minimize the effects of cable length variations to a minimum as outlined above. Thus, we should be able to come close to the requirements discussed above for the VLBA.

7. CONCLUSION

At the present time there is no specific allocation for a pulse calibration system in the VLBA electronics budget, but the extra components needed are only those within the pulse calibration module in Fig. 3, and should cost only $1000-2000 per antenna. Later in 1988 the Pie Town antenna will be equipped with a pulse calibration system of the Haystack design and used in some crustal dynamics observations in the last quarter of the year. These observations should provide an evaluation of the stability of the Pie Town system, both with and without the pulse calibration. Measurements with a pulse calibrator can also provide checks of some of the estimates given in Appendix 1. In the meantime we should assume that a calibration system is a very likely requirement for the VLBA, and consider the optimum design for such a system. We, therefore, propose to develop one system based on the scheme of Fig. 3, which should be ready for test on the Pie Town antenna sometime in 1989. Since this part of the electronics can determine the instrumental phase stability of the entire array, it will be necessary to take time for careful design and adequate testing.

APPENDIX 1. Phase/Delay Errors in the VLBA

An accurate estimate of all the delay errors in the VLBA electronics seems pretty hard, but an attempt to get some feeling for the numbers is shown below. The following estimates are based on actual measurements on VLBA hardware for some of the items, and on prior experience plus some guess work for the others.

1)	Front-ends:	< ~1 ps
2)	2-16 GHz Synthesizers: 1°/°C/GHz	= ~3 ps/°C
3)	IF Converters: (Guess) 0.5°/°C/GHz	= ~2 ps/°C
4)	IF Cables- VR to Equip. Room:	
	a) Differential with temp.(10°C change)	= ~10 ps
	b) Differential with Ant. Rotation	= ~10 to 80 ps *
	-----------Total Items 1) to 4a)-----	= ~12 ps
5)	IF Distributer: (Guess) 0.6°/°C	= ~2 ps/°C
6)	BBC IF-Video path:	
	a) IF	= ~2 ps/°C
	b) Mixer	= ~5-10 ps/°C
	c) Video filter	= ~200 ps/°C *
	--------Total Items 5) to 6b)------	= ~12 ps
7)	BBC-LO:	
	a) With Temp.	= ~3 ps/°C
	b) With 5V Power Supply	= ~2 ps/mV
8)	100 MHz From Maser to 500 MHz to 2-16 GHz Synthesizers excluding 500 MHz round trip correction	= ~6 ps/°C
	----------Total Items 7) to 8)--------	= ~10 ps
9)	5 MHz Maser to BBC-LO:2 of 5 MHz Distr.	= ~10 ps/°C
10)	5 MHz to 32 MHz Synthesizer	= ~20 ps/°C *
11)	Samplers	= ~10-20 ps/°C *
12)	Change of ALC phase	= ~5-10 ps
13)	Various cables Front-end to Samplers: Assuming 20 m length & 100 ppm/°C	= ~10 ps/°C

It is difficult to estimate how these errors will combine (the result may even depend on the analysis procedure, e.g., phase-delay/group delay), but it is unlikely that they would be simply additive or independent. Assuming a temperature variation of 1°C for both the vertex and equipment rooms, a rough estimate may give a total of about 30-40 ps (excluding a few major items marked with * in the above list, for which we assume we would have some other way to take care of). The above estimate does not include things like power supply varions, physical movements and VSWR changes, and is probably optimistic. Variations for some of the items in the above list could well be worse by a factor of 2.

APPENDIX 2. Design Considerations for the Round-Trip Phase System

The round trip phase measurement to monitor the electrical length of the transmission line from the maser location to the antenna vertex room must be performed at the frequency of the reference signal being transmitted, since the electrical length depends upon reflections within the line and is therefore slightly dependent upon the frequency. The choice of the reference frequency is governed by the following considerations. (1) The higher the frequency, the greater the sensitivity of the round-trip phase to changes in line length. (2) The wavelength of the reference signal should be greater than the variation in the round-trip path length, to avoid ambiguity in the measurement. (3) The reference frequency should be low enough that the transmission line remains well matched. (4) The frequency should also be low enough that harmonics of it provide sufficiently fine tuning steps for the local oscillator at the antenna. Frequency division, and the resulting phase ambiguity problem, are thereby avoided. For the VLBA LO system, harmonics of 500 MHz are required. (5) It is convenient if the reference frequency lies within the range for which voltage-controlled crystal oscillators are available. In designing the local oscillator system, 500 MHz was chosen as a frequency that satisfactorily takes account of the above considerations. (The following part of this appendix is concerned with technical details of the system design that are not essential to a basic explanation of the pulse calibration).

For the pulse calibration system, the minimum requirement for accuracy of the round-trip measurement is about 2 ps in the signal delivered at the antenna, which corresponds to 0.6 mm in the one-way path length of the transmission line. The corresponding accuracy of the measurement of the 500 MHz reference signal is 0.36°. For the highest frequency band contemplated on the VLBA, 86 GHz, the corresponding phase error in the local oscillator is about one radian. However, in calculations involving the round-trip phase measurement given below, a tolerance corresponding to 1/5 of a radian at 86 GHz has been used. The corresponding error in the 500 MHz reference phase is 0.066°. This allows for possible improvements in methods of handling atmospheric effects, which provide the ultimate limit.

To enable the signals in the two directions in the transmission line to be separated, there is usually a small difference in their frequencies. Because of reflections in the line, the effective length at the two frequencies will be slightly different. This can result in an error in the round-trip phase measurement. The required accuracy of the measurement thus places a limit on the frequency difference, which can be calculated by using a result derived in VLA Electronics Memorandum No. 202, and also given in Thompson, Moran and Swenson (1986), pp. 186-191. In this calculation we use the following parameters. The length of the transmission line is 72 m and its attenuation at 500 MHz is 6 dB. The maximum fractional change in the line length is 1.3×10^{-3}, which corresponds to a temperature change of 50°C. The velocity factor of the line is 0.7. We consider the effects of pairs of reflecting points with coefficient 0.2, one pair separated by the total length of the line and two others by half the length. (In practice there may be more but smaller reflections, but this model gives a representative estimate of the effect, and allows for some deterioration in the cable matching at a few points.) For a tolerable error of 0.066° at 500 MHz the resulting upper limit on the frequency offset in the signals in the two directions in the line is about 20 kHz.

The offset of approximately 2 kHz in the system in Fig. 3 is chosen for convenience rather than to comply with the above requirement.

Figure A1 shows a simple scheme for transmitting a reference frequency $f + \Delta f$ to lock an oscillator at a required frequency f, with a round-trip phase measurement included. In the VLBA the scheme is slightly different from that in Fig. 1A, but the corresponding frequencies are $f = 500$ MHz and $\Delta f = 2$ kHz. The difference frequency Δf can be transmitted on a separate cable of relatively low quality. Frequency f is returned along the line to the master station and converted in mixer 1 to produce a component Δf, the phase of which is compared with that of a signal from a source of frequency Δf, to provide the required round-trip phase. A source of error in this scheme results from reflections within the line which cause a fraction of the outgoing power at $f + \Delta f$ to be returned and appear on port 2 of mixer 1. If the power transmitted into the line at frequency $f + \Delta f$ at the master station is 10 dBm, then the reflected power from, say, three reflections with coefficient 0.2 is about -1 dBm. If the level of $f + \Delta f$ on port 1 of mixer 1 is 7 dBm from the generator, the reflected component that leaks through from port 2 is about -31 dBm, i.e., 38 dB below the wanted component. The unwanted component will cause a phase error, which varies with temperature and antenna position as the reflecting properties of the cable vary. The tolerable error in the (two-way) round-trip phase is $0.13° = 2.3 \times 10^{-3}$ radians, which can result from an unwanted signal at a relative level of -53 dB.

The required reduction of the reflected component of the outgoing reference signal at mixer 1 by 53-38 = 15 dB can be obtained in part by reduction of the outgoing reference level and improvement of the return loss of the transmission line. Note that the same situation occurs with mixer 2 in Fig. A1, at which a component at frequency f transmitted from the remote location to the master station is reflected in the line and appears at port 2. However, it is preferable that the accuracy of the system should not depend on the matching of the cable which may vary with time.

The problem of the reflected component would not occur if the frequencies of the two wanted components being combined in the mixer were both different from that of the unwanted reflected component. This situation can be brought about by using two offset frequencies Δf_1 and Δf_2, as in Fig. A2. Here the frequency $f + \Delta f_1$ is transmitted out to the remote station to lock an oscillator at frequency f. However, the component returned for the round-trip phase measurement is at frequency $f + \Delta f_1 - \Delta f_2$, and is produced by the modulated reflector driven at frequency Δf_2. The round-trip phase is obtained by comparing phases of signals at frequency $\Delta f_1 - \Delta f_2$. In the scheme for the VLBA shown in Fig. 3, the three frequencies Δf_1, Δf_2, and $\Delta f_1 - \Delta f_2$ are obtained by frequency division of a 5 MHz signal from the maser as follows:

$$\Delta f_1 = 5 \times 10^6/2^5 \times 3 \times 5^2 = 2{,}083.3 \text{ Hz}$$
$$\Delta f_2 = 5 \times 10^6/2^9 \times 5 = 1{,}953.1 \text{ Hz}$$
$$\Delta f_1 - \Delta f_2 = 5 \times 10^6/2^9 \times 3 \times 5^2 = 130.2 \text{ Hz}$$

Various combinations of Δf_1 and Δf_2 can appear at the output port of mixer 1 in Fig. A2, but, with the values for Δf_1 and Δf_2 given above, the only one that is lower in frequency than 200 Hz is $\Delta f_1 - \Delta f_2$. Thus by low-pass filtering this required component can be extracted. The phase of $\Delta f_1 - \Delta f_2$ from the mixer is compared with that of the same frequency obtained by frequency division from the maser. This measurement takes place in a phase comparator circuit that counts 5 MHz cycles. One cycle at 5 MHz provides a resolution of 10^{-2} degrees at 130 Hz, so it is quite adequate for the required accuracy of 0.13° in the (two way) round-trip phase.

By making Δf_1 and Δf_2 a little more than one order of magnitude less than Δf_1 and Δf_2, it is possible to separate the wanted component from the others without using a very sharp filter which would be a possible source of phase instability. The value of 130.2 Hz for $\Delta f_1 - \Delta f_2$ is just over 2 Hz away from the second harmonic of a computer frequency of 64 Hz. This should not cause problems, but if it should be necessary to change the frequencies a possible set would be:

$$\Delta f_1 = 5 \times 10^6/8 \times 15 \times 2^4 = 2604.2 \text{ Hz}$$
$$\Delta f_2 = 5 \times 10^6/9 \times 15 \times 2^4 = 2314.8 \text{ Hz}$$
$$\Delta f_1 - \Delta f_2 = 5 \times 10^6/72 \times 15 \times 2^4 = 289.4 \text{ Hz}$$

The frequency dividers in Fig. 3 that produce the waveforms at Δf_1, Δf_2 and $\Delta f_1 - \Delta f_2$ from 5 MHz are periodically reset to eliminate errors in the relative phases which can be introduced by transients.

Three different frequencies occur on port 2 of mixer 1 in Fig. A2. These are $f + \Delta f_1$ which results from reflection in the line, and $f + \Delta f_1 \pm \Delta f_2$. An unwanted component at the output frequency $\Delta f_1 - \Delta f_2$ can be formed from the third order product $2(f + \Delta f_1) - (f + \Delta f_1 + \Delta f_2)$ at port 2. By making port 2 the signal (low power) port and port 1 the LO port, this unwanted response is kept at a level of -55 to -65 dB, which should be satisfactory. Use of a high level mixer can further reduce the unwanted response to about -77 dB. Note that the largest errors from this effect are likely to result from variation of the reflection within the cable when the antenna is turned, which may cause large phase changes in the unwanted reflected component at $f + \Delta f_1$.

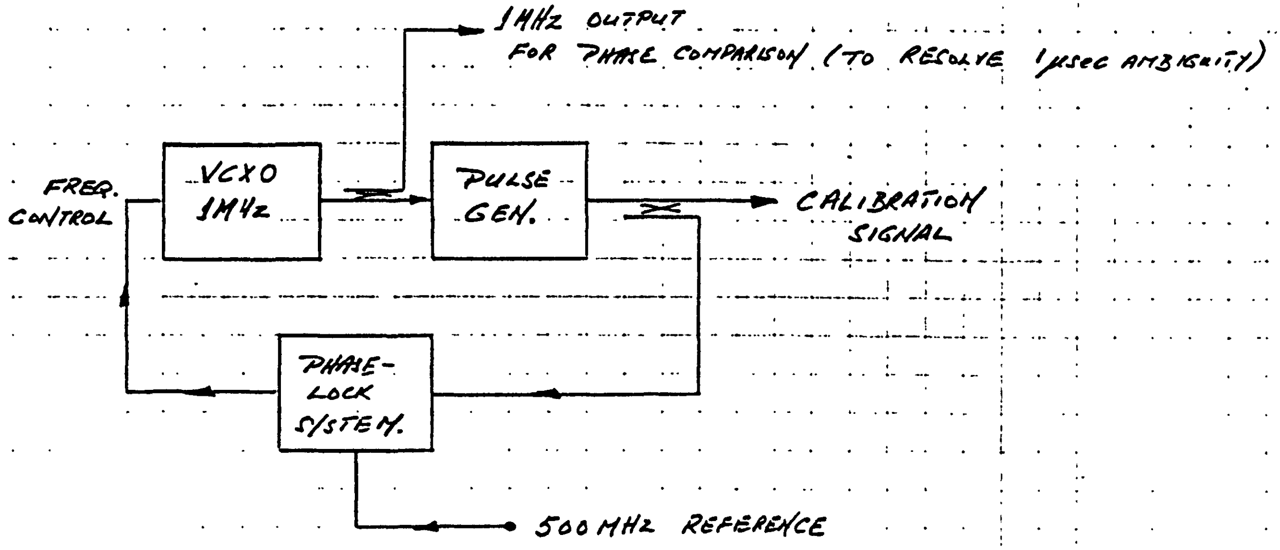

Fig. 1 System for producing 1MHz pulses using a 500 MHz phase reference.

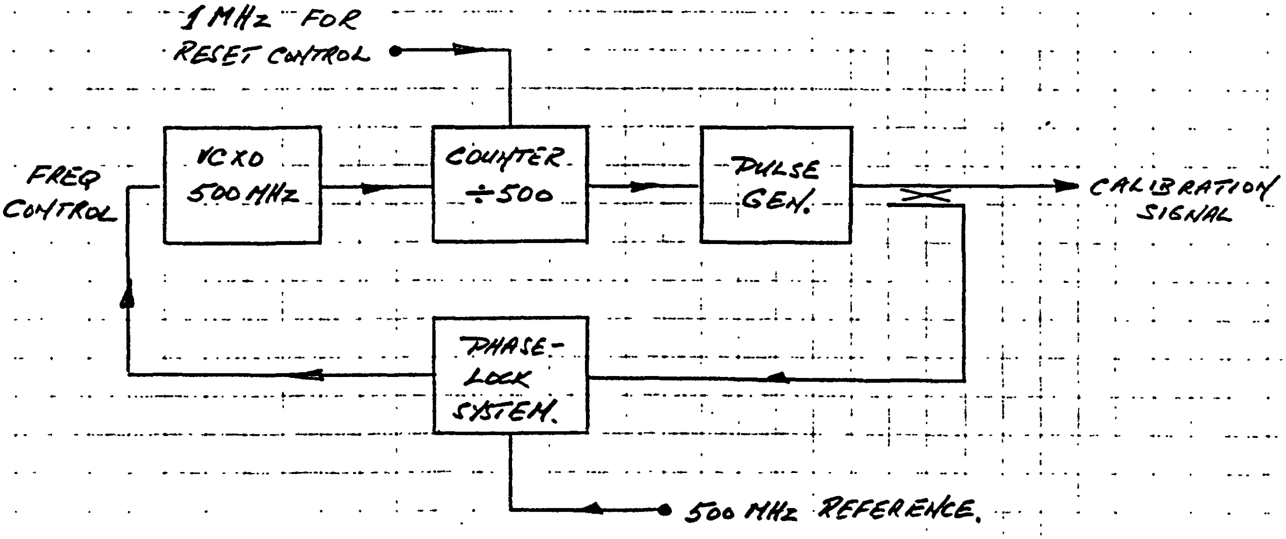

Fig. 2 System for producing 1MHz pulses with 500 MHz reference but avoiding 1μsec ambiguity.

ARI / DS3 2/19/88

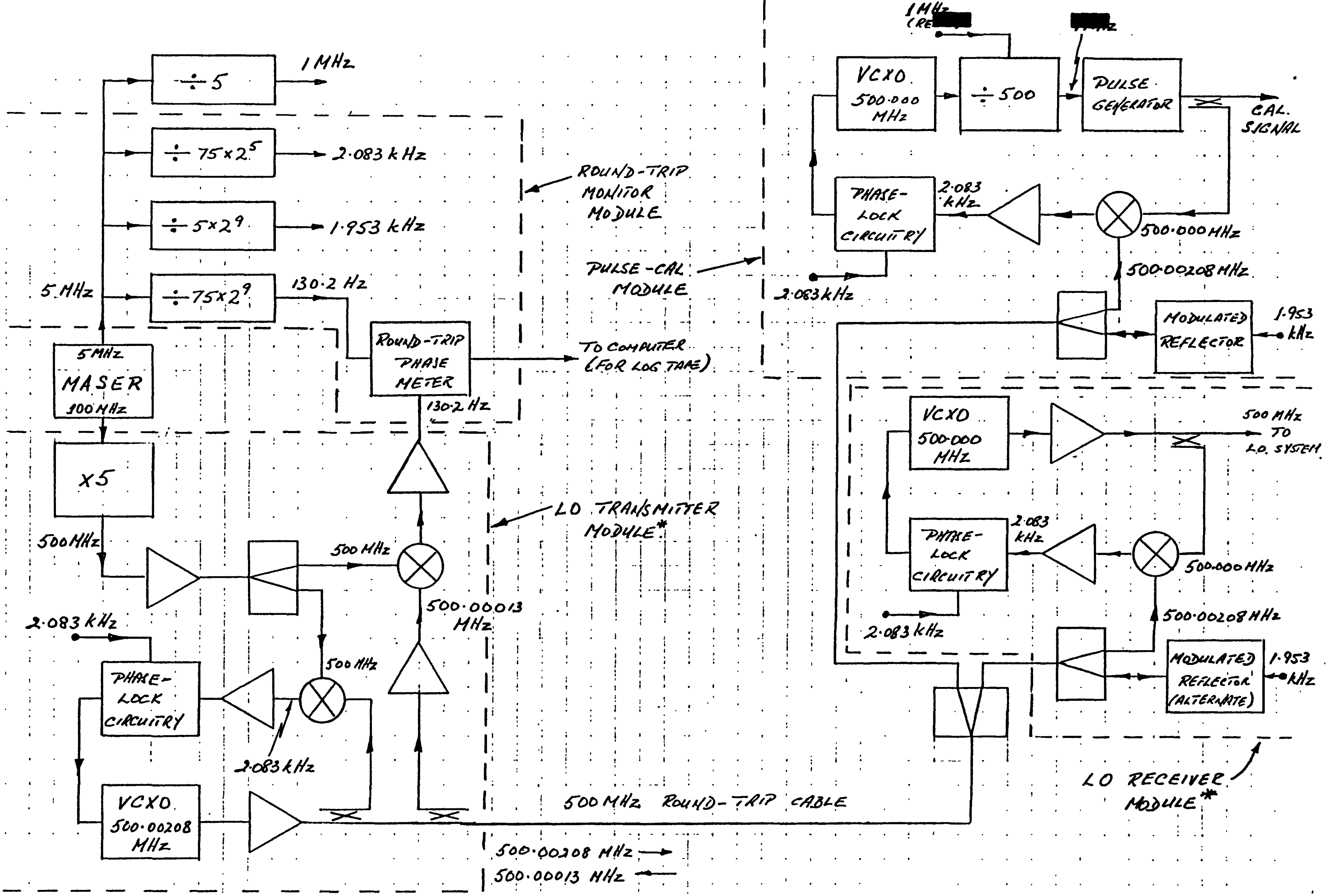

Fig 3. SCHEMATIC DIAGRAM FOR COMBINED 500 MHz L.O. REFERENCE DISTRIBUTION AND PULSE CALIBRATION SYSTEMS.

* Minor modifications required in current design of these modules.

A.R.T. 2/18/88

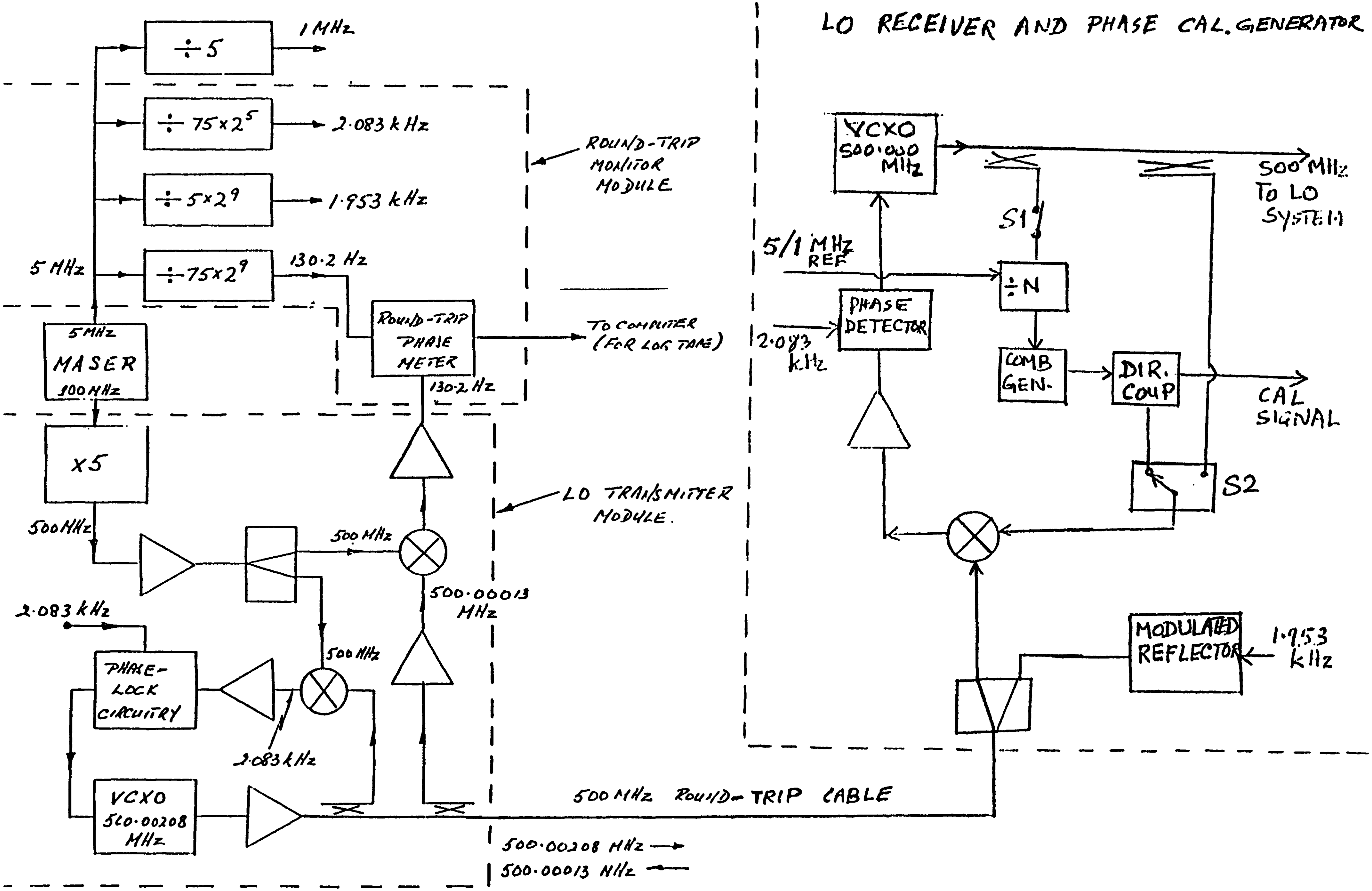

FiG. 4

SCHEMATIC DIAGRAM FOR COMBINED 500 MHz L.O. REFERENCE DISTRIBUTION AND PULSE CALIBRATION SYSTEMS USING ONLY ONE VCXO IN THE VERTEX ROOM.

A.R.T. 2/18/88
DSB 3/11/88

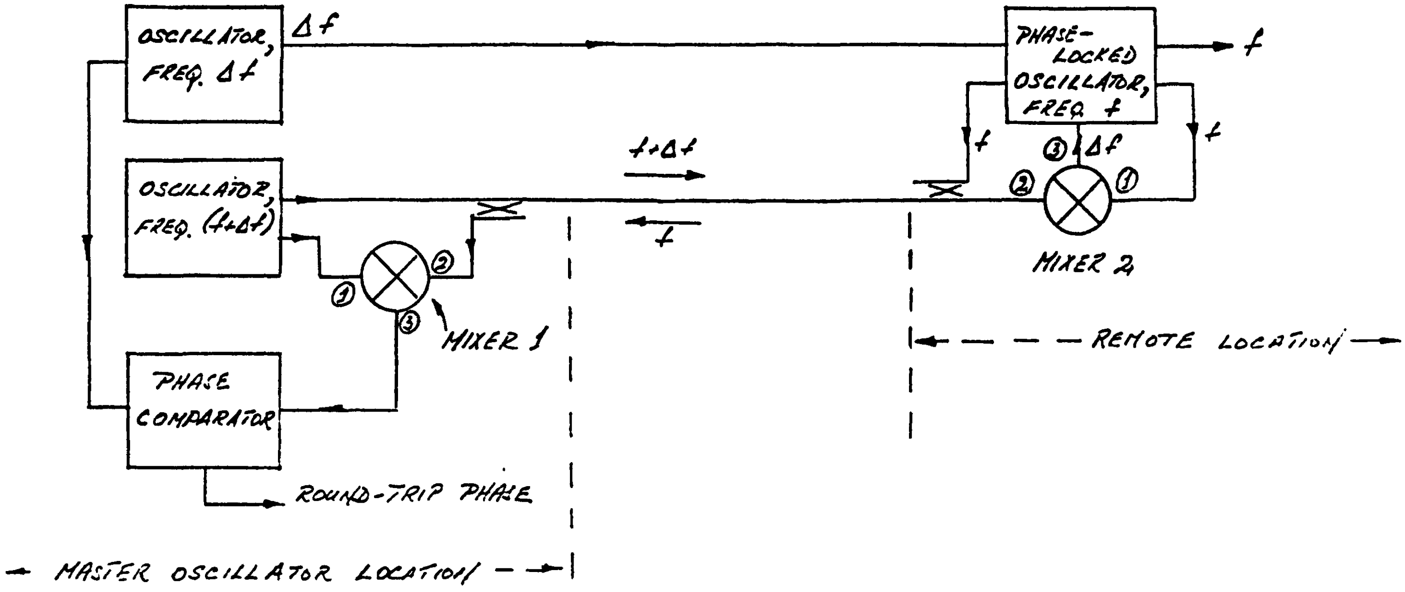

Figure A1. Simplified block diagram of system for locking an oscillator at a remote location (e.g. vertex room) to a signal from a master oscillator, with round-trip phase monitoring of the transmission line.

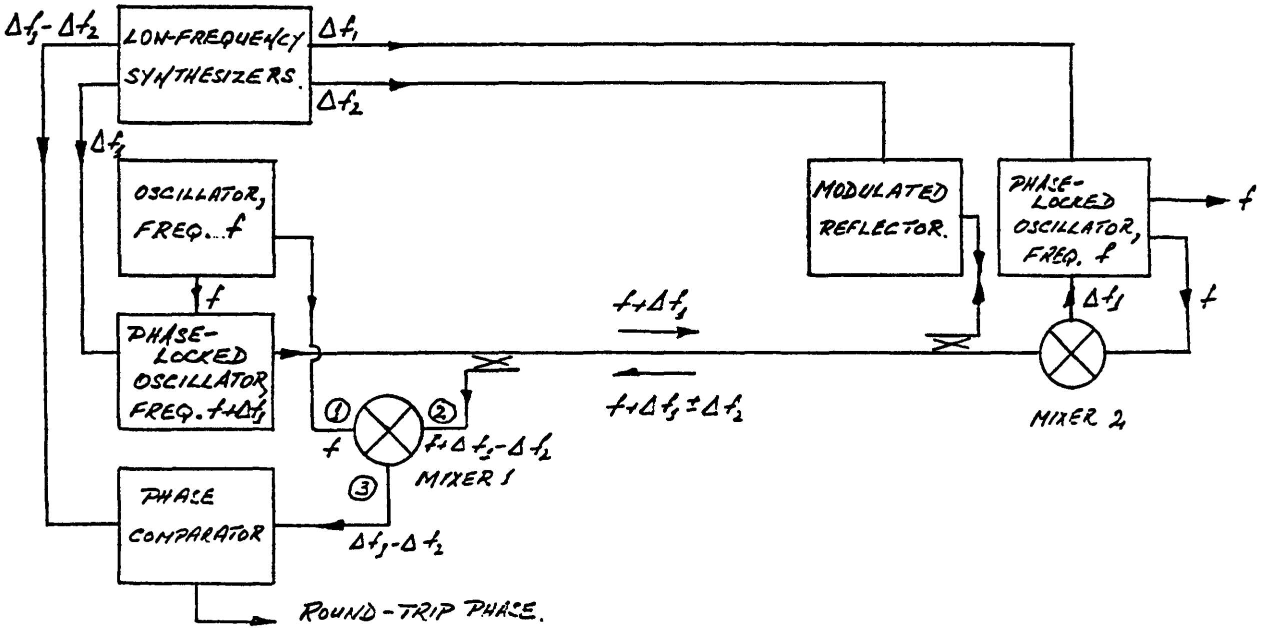

Figure A2. System as in Fig. A1, but with a separate low frequency reference for the round-trip phase measurement. With this scheme, signal components resulting from reflections within the cable cannot introduce errors in the round-trip phase.

A.R.T. 3/6/88