

**PHASE AND GROUP DELAY CALIBRATION
OF A VERY LONG BASELINE INTERFEROMETER
BY EAST COAST VLBI GROUP**

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ABSTRACT

Precisely timed pulses injected into the input of each receiver have been used to calibrate the phase and group delay through each interferometer terminal. The short duration (less than 35 picoseconds) pulses are generated at a 1 MHz rate directly from the output of the frequency standard. The pulses are injected into the receiver at a level low enough to produce less than one percent increase in system temperature, yet can be extracted during processing with a high enough signal-to-noise ratio to determine the phase of the calibration "rails" within 1 degree in 1 second of integration. The calibration system also includes precise cable measurement electronics and a pulse echo for clock synchronization.

INTRODUCTION

Very long baseline interferometer (VLBI) systems used for geodetic applications have to be either extremely phase and delay stable or be accurately calibrated. This paper describes a phase and group delay calibration system with millimeter level precision. The calibrator consists of two basic subsystems. The first is a tunnel-diode pulse generator; the second is a cable phase delay measurement subsystem.

THEORY OF OPERATION

The system utilizes the 5 MHz output from the frequency standard to produce short duration (<50 picosecond) calibration pulses at a 1 MHz rate. These pulses are injected into the receiver through an input coupler and are detected by the VLBI processing system. The calibration pulses are generated at a precisely known epoch within the 1 microsecond ambiguity. A component of the 5 MHz signal used to generate the calibration pulses is returned along the same cable and phase compared with the transmitted signal in order to precisely determine the phase delay (with 200 nanosecond ambiguity) in the cable driving the calibration pulse generator. The system block diagram is shown in figure 1. The reflected 5 MHz signal is modulated in order that it may be distinguished from other intermediate reflections. In addition, a component of the calibration pulse itself is returned along the cable and can be viewed on an oscilloscope to resolve the 200 nanosecond ambiguity present in the cable measurement subsystem.

PULSE GENERATOR

General Description

The phase calibrator consists of a tunnel-diode pulse generator driven by a 5 MHz square wave. The pulses (both positive and negative) emerge from the tunnel diode and are gated with a diode attenuator so that only one positive pulse per microsecond appears at the output. The block diagram of the pulse generator is shown in figure 2.

Pulse Duration

The tunnel-diode switching time t (at constant current) is given approximately by the following equation for constant a current drive.

$$t = (VF - VP) * CV / (IP - IV)$$

Where	VF = Forward voltage	575 mV
	VP = Peak point voltage	90 mV
	IP = Peak point current	10 mA (increased to 16 mA in later units)

IV = Valley point current 1 mA
 CV = Valley point terminal capacitance 1 pF. Thus t = approx 50 picoseconds.
 (30 picoseconds in later units)

The condition of constant current is not well maintained as the driving impedance is close to 50 ohms so that the load line intersection point is somewhat below VF. The effect is to reduce the pulse voltage without having much effect on the switching time.

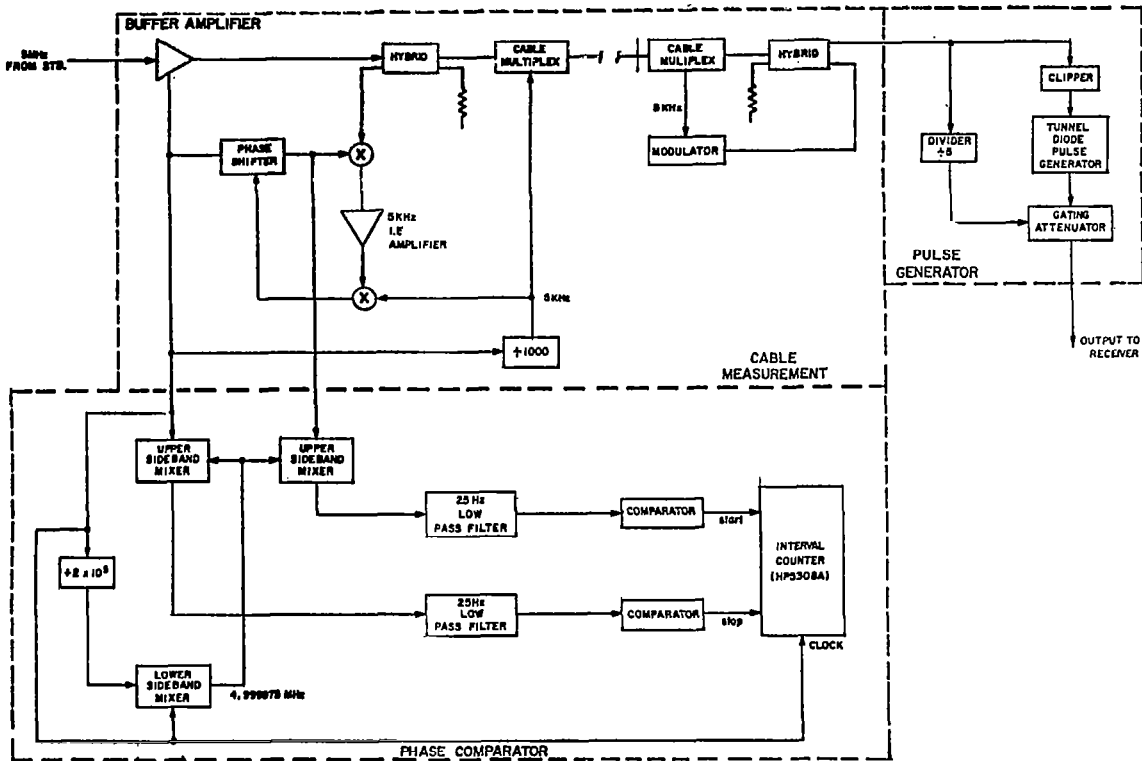


Figure 1. Delay calibration system block diagram.

Output Power

The output temperature (averaged over several MHz) is approximately:

$$2(V_L - V_P)^2 / (R_L * (\omega^2 t^2 / 12 + 1) * T * K \omega^2) \text{ approx } 5 \times 10^4 \text{ deg K (at 10 GHz)}$$

- where $\omega / 2\pi$ = Center Frequency (Hz)
- T = Pulse Repetition Period
- R_L = Load Resistance Seen by Diode
- K = Boltzmann Constant
- V_L = Load line intersection voltage

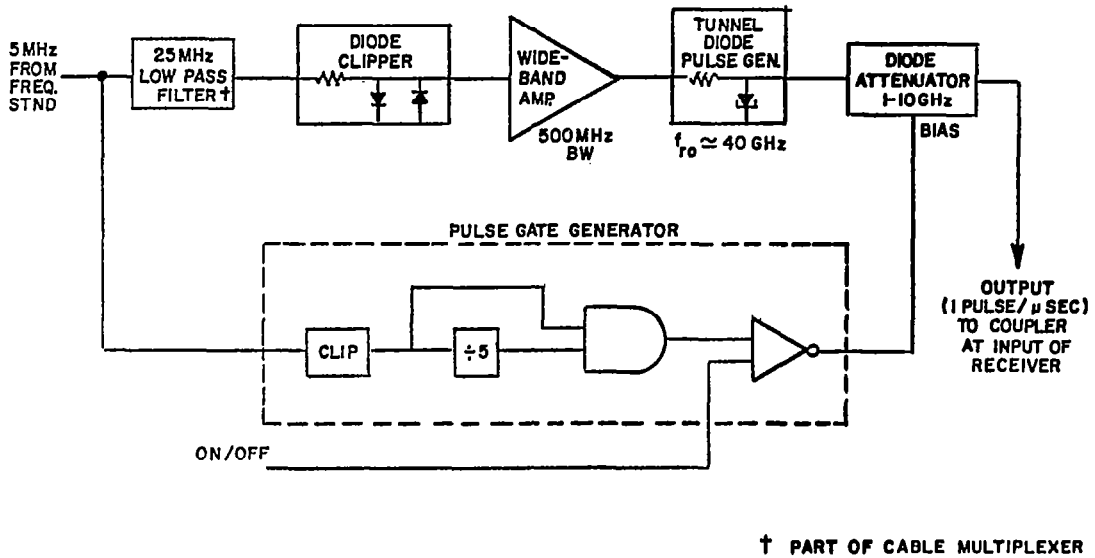


Figure 2. Delay calibrator pulse generator.

CABLE MEASUREMENT SYSTEM

General Description

The delay through a cable changes with temperature (approx 1×10^{-4} per deg C) and flexure. Pressurized cables also change their electrical length with pressure. The phase delay through a cable also varies in almost the same way as the group delay but with small differences owing to dispersion and multiple-reflection effects.

Theory

The transmitted signal $V_T(t)$ is reflected after modulation by $m(t)$ so that the signal received back at the transmitting end is

$$V_R(t) = m(t)\text{Re}(\exp(j\omega t)\exp(-2j\phi)) \quad \text{Re} = \text{real part of.}$$

This signal is mixed with a version of the transmitted signal phase shifted by P and low-pass filtered to form

$$V_D(t) = m(t)\text{Re}(\exp(-2j\phi)\exp(jP))$$

which is mixed with the modulation and low pass filtered again so that

$$V_o(t) = \langle m^2(t) \rangle \cos(2\phi - P).$$

$V_o(t)$ is integrated and the loop closed on the phase shifter so that

$$P = 2p + 2\pi(N \pm 1/4) \text{ where } N \text{ is an integer constant}$$

allowing the cable phase-delay p to be measured from the measurement of P . A high-resolution phase comparator has been developed for the measurement of P with picosecond precision.

PICOSECOND PHASE COMPARATOR

The signal whose phase is to be measured is mixed down from 5 MHz to 25 Hz using a local oscillator signal of 5 MHz - 25 Hz which is derived from the reference signal. The mixing operation results in a time expansion of 2×10^5 which is sufficiently large that a digital time interval counter (such as HP5308A counter with D/A converter 5311B) operating at a 5 MHz clock rate can now be used to determine the phase of the 25 Hz signal with respect to the reference 25 Hz signal with quantization of only 1.8×10^{-3} degrees. One count corresponds to 1 picosecond two-way phase delay or 0.5 picosecond one-way delay. Cycle averaging can be used to provide even higher resolution.

Figure 1 shows a block diagram of the comparator. The outputs of the comparator are two 25 Hz square waves with relative phases equal to the relative phases of the 5 MHz input signals. Single sideband mixing and filters are required to minimize the presence of spurious image signals and harmonics.

MEASUREMENTS OF CALIBRATOR PERFORMANCE

Output power can be measured by comparing output with that of a noise diode. A typical output power level is 60 Kelvin at 7850 MHz when coupled into the receiver through a 30 dB coupler. The VLBI processor requires only a relatively weak calibration signal since the processor extracts the signal by correlating the signals from each station with a sine and cosine at the frequency of the calibrator rail. With this method, a calibrator signal strength of 1 percent is sufficient for the phase to be determined within 1-degree rms with 1 second coherent integration.

The stability of the calibrator was measured by observing the phase of the frequency rails from the calibrator in the receiver video output. The overall sensitivity of the phase calibrator to temperature changes was measured by cycling the temperature of the calibrator from 30 degrees C to 40 degrees C. In addition, an attempt was made to thermally isolate the individual components within the calibrator and so measure the individual coefficients. The results of these measurements are shown in table 1. The sensitivity of the calibrator to input ac voltage changes was undetectable being less than 1 ps per percentage voltage change.

Table 1
Temperature Sensitivity of Phase Calibrator

25 MHz low pass filter	+1.0+/-5 ps/deg. C
Diode clipper	+10+/-2 ps/deg. C
Wideband amplifier	-3 +/-1 ps/deg. C*
Tunnel Diode	-2 +/-1 ps/deg. C*
Overall sensitivity (measured separately)	6 +/-2 ps/deg. C

*A negative coefficient indicates that an increase in temperature decreases the phase delay through the device.

TESTS OF THE VLBI RECEIVER AND CALIBRATOR

In order to acquire high quality VLBI data, it is useful to test the performance of each interferometer terminal. An adjustable line in the calibrator cable allows testing of the cable measurement system and can be used to change the phase of the calibrator. Since the frequency of the calibration rail being observed is known, a complete test of the system can be made by comparing the change in cable length from the cable measurement system with that computed from the change in fringe count observed when the adjustable line is changed. The coherence of the calibrator and receiver local oscillator can be measured from the ratio of power in the calibrator rail to the total power contribution of the calibrator. The fractional coherence is given by

$$(T_s/T_{cal})^{1/2} A_{cal}$$

where

T_s = system temperature

T_{cal} = effective temperature of the calibrator from total power

A_{cal} = measured correlation coefficient of calibrator.

Complete tests of the calibrator performance can be made by injecting a common noise source into two terminals to form a "zero baseline." In this configuration, receiver local oscillator phases and IF cable lengths can be changed. If the calibration system is working correctly, these changes should produce no changes in the calibrated delay measurements. In addition, the calibrator cable length can be changed, and the observed delay changes compared with the corresponding changes in the cable measurement readout. Figure 3 gives a summary of the calibration technique.

REASON FOR USE:

TO CALIBRATE DRIFTS IN GROUP AND PHASE DELAY THROUGH:

- 1) LOW NOISE AMPLIFIERS - WITH TEMPERATURE AND MAGNETIC FIELD
- 2) LOCAL OSCILLATORS - WITH TEMPERATURE
- 3) CABLES - WITH TEMPERATURE AND FLEXURE

METHOD:

INJECTION OF SHORT DURATION PULSES (≈ 35 ps (1 cm)) INTO RECEIVER AT A RATE OF 1 PULSE/MICROSECOND

DETECTION METHOD:

EXTRACTION OF THE PHASE OF EACH CALIBRATION "RAIL" IN THE DATA STREAM FROM EACH STATION

SENSITIVITY:

WITH A SIGNAL OF ONLY 1% (OF TOTAL POWER) PHASE CAN BE MEASURED TO WITHIN 1 DEGREE R.M.S. IN 1 SECOND

PERFORMANCE:

- 1) PRECISION 1 ps (0,3 mm)
- 2) TEMPERATURE COEFF. 6 ps / °C

EXPERIMENTS THAT DEMONSTRATE PERFORMANCE:

- 1) CALIBRATION SEEN TO IMPROVE RESULTS IN EARLY EXPTS 72-74
- 2) HAYSTACK-WESTFORD BASELINE REPEATABILITY 5 MM 74-76
- 3) "ZERO BASELINE TESTS" - SHOW AGREEMENT BETWEEN MEASURED DELAYS, CABLE LENGTH ELECTRONIC READOUT AND LINE STRETCHER MECHANICAL READOUT TO BETTER THAN 3 MM 76
- 4) RESIDUALS OF LONG BASELINE EXPTS EXAMINED WITH AND WITHOUT CALIBRATION CLEARLY SHOW THE EFFECTIVENESS OF THE CALIBRATION SYSTEM 78

Figure 3. Phase and group delay calibration.