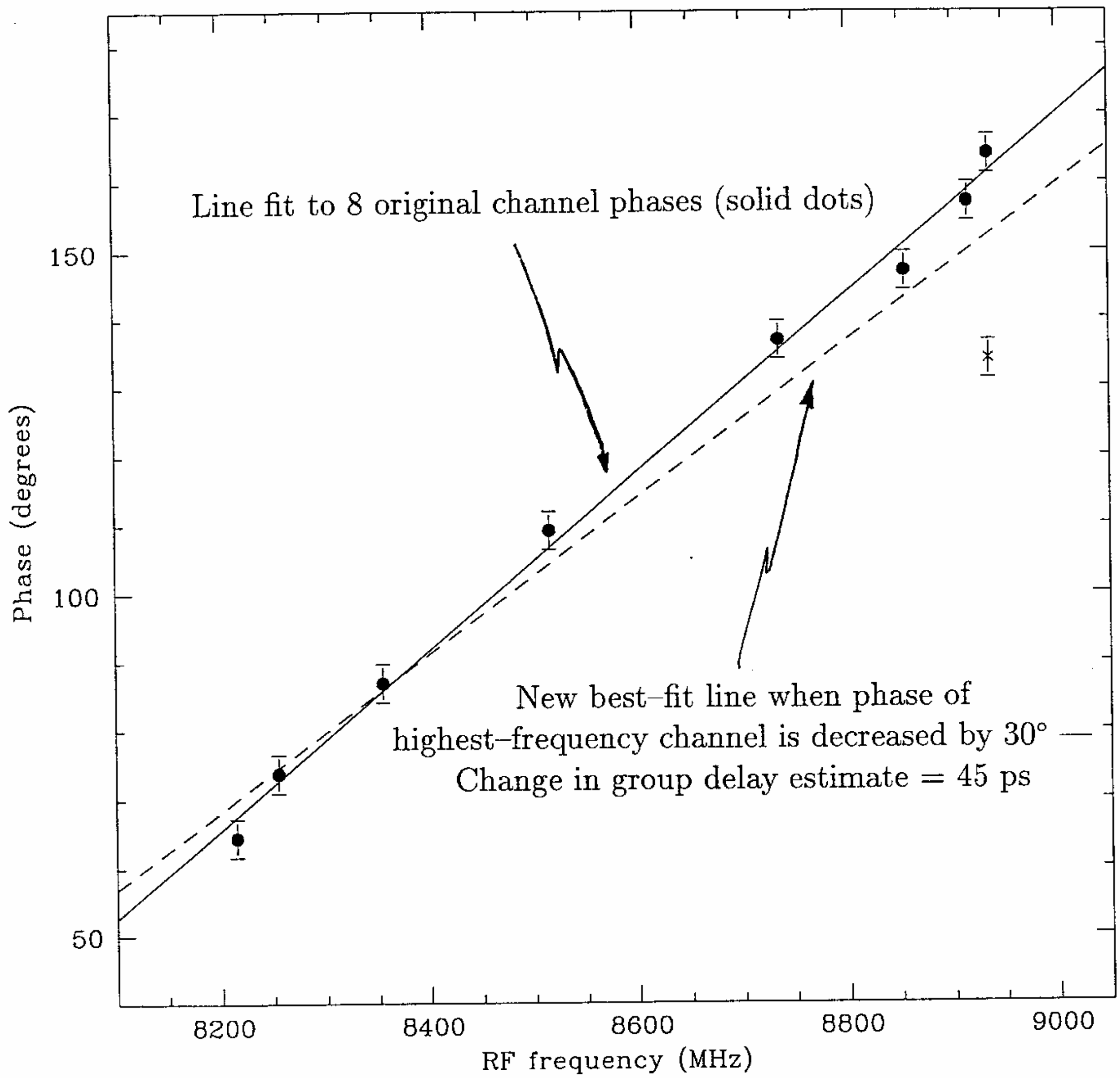
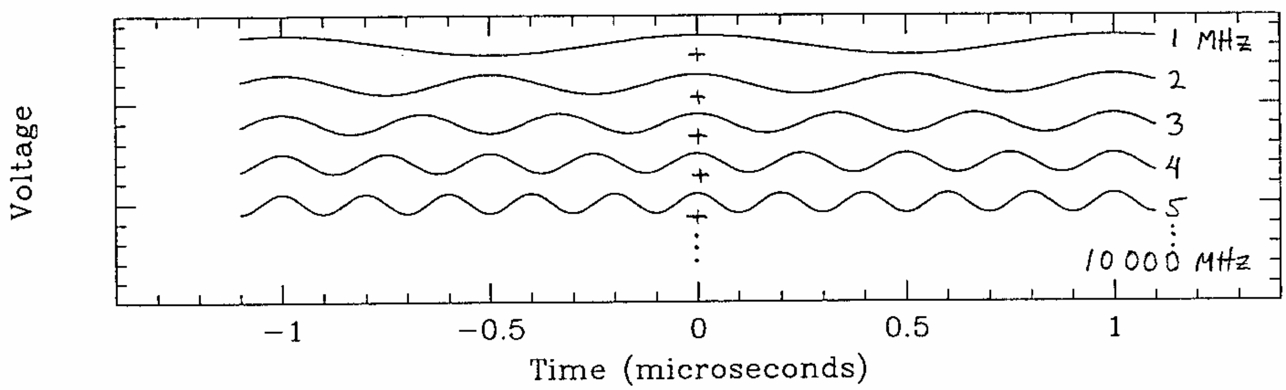
Effect on Group Delay Estimate of Changing Channel Phase



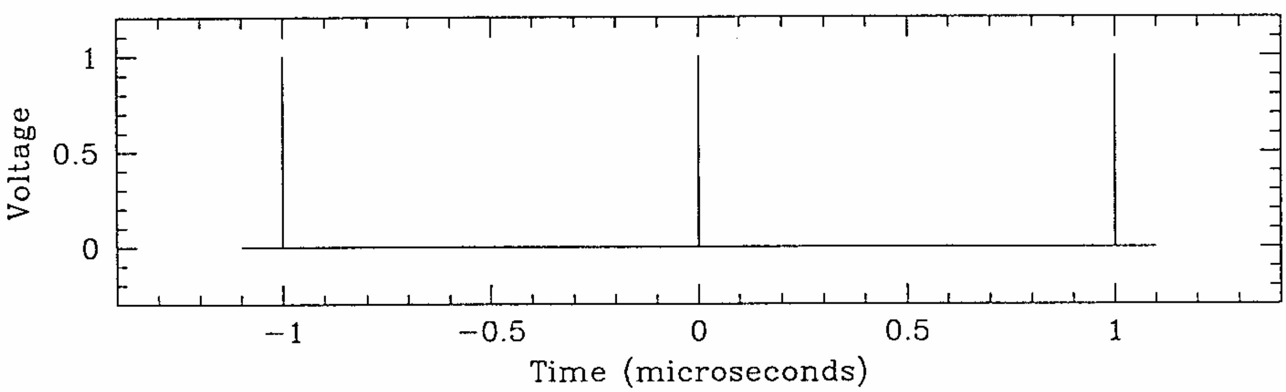
Group delay estimate = slope of best–fit line

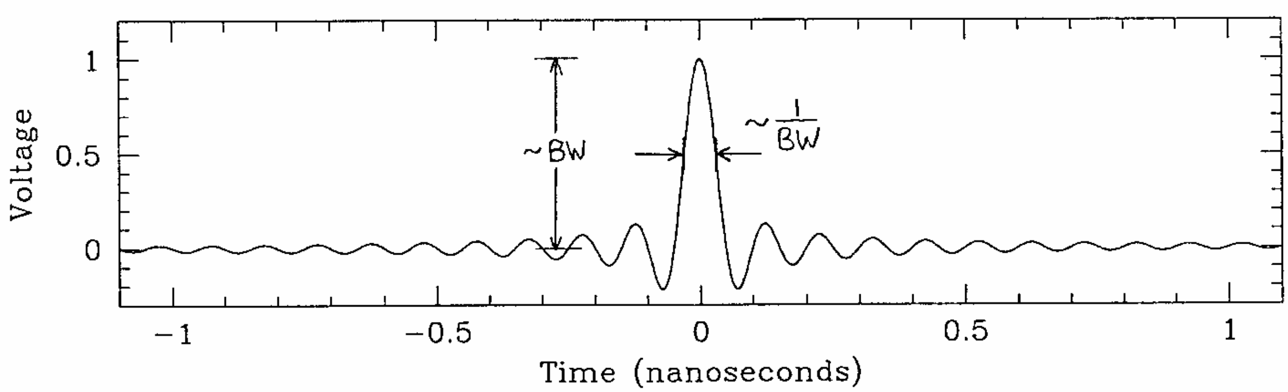
$$= \frac{\Delta\text{Phase (cycles)}}{\Delta\text{Frequency (Hz)}}$$

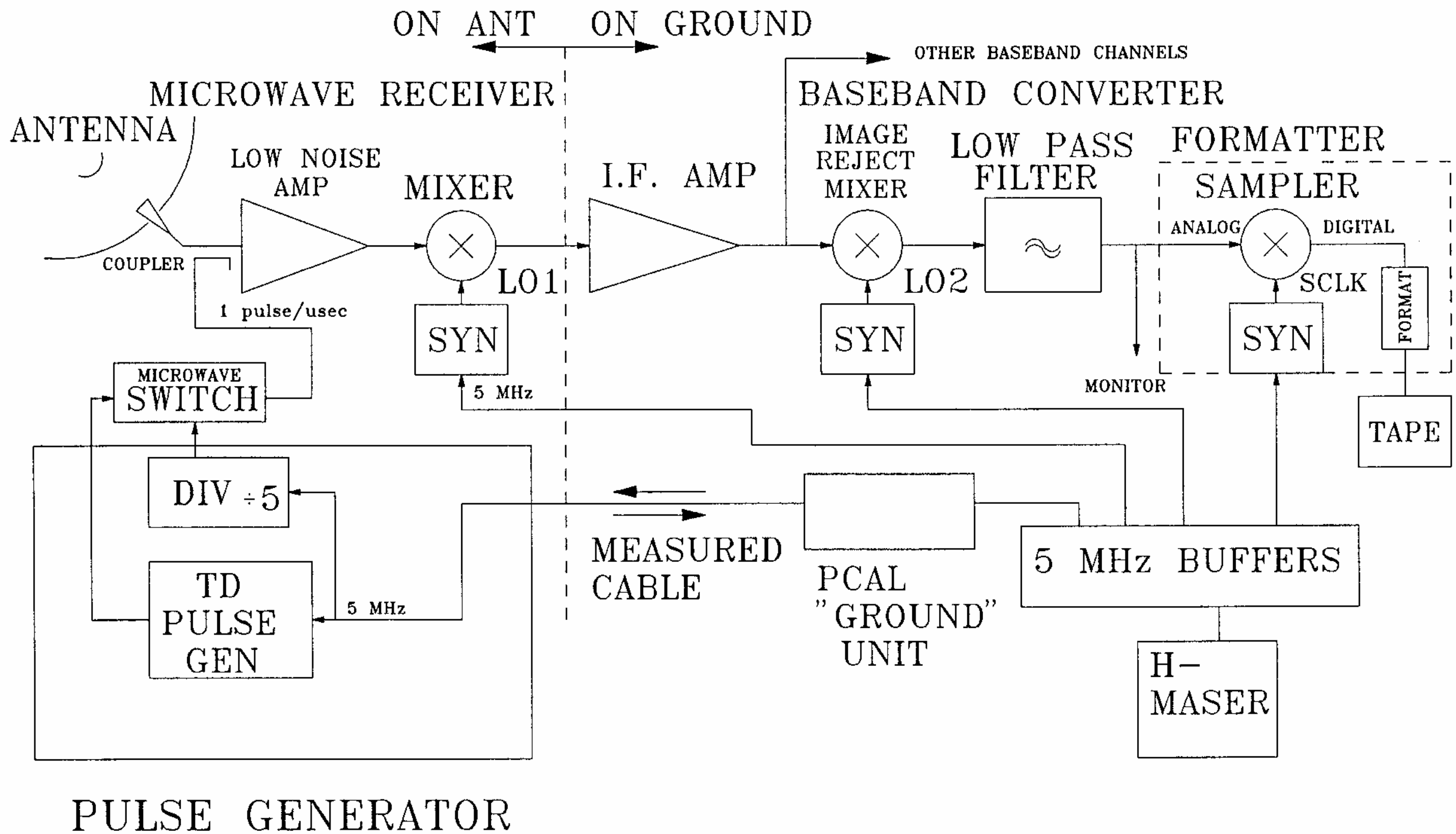
Phase Cal Signal in Time Domain



equals



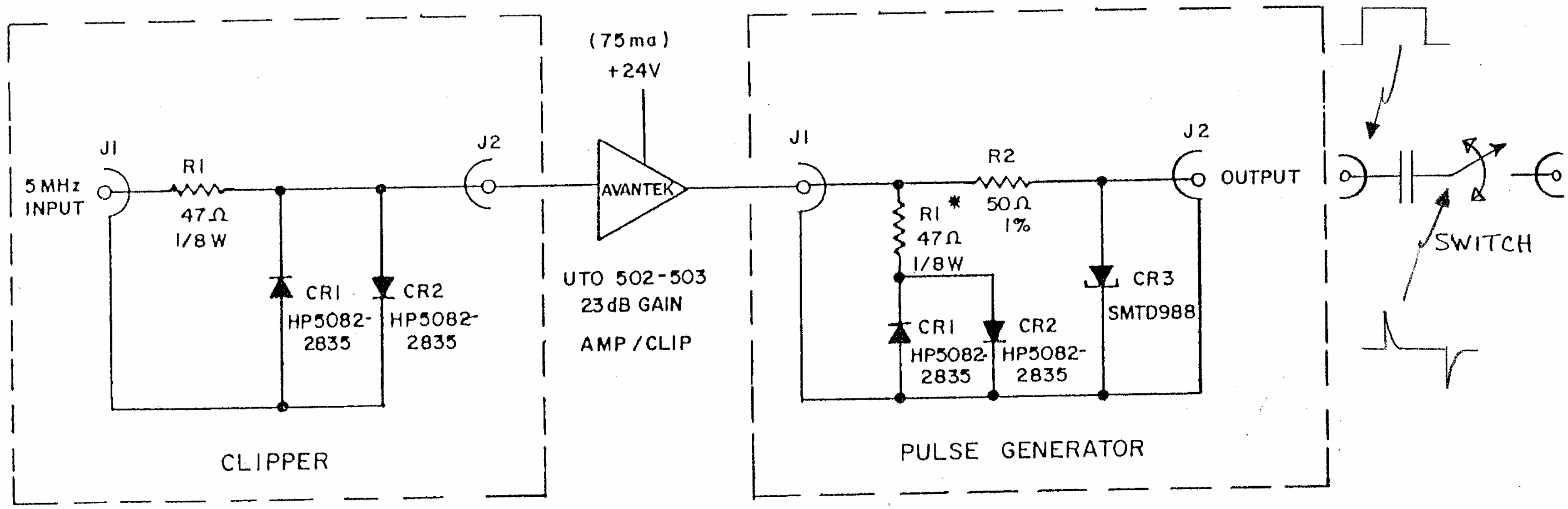




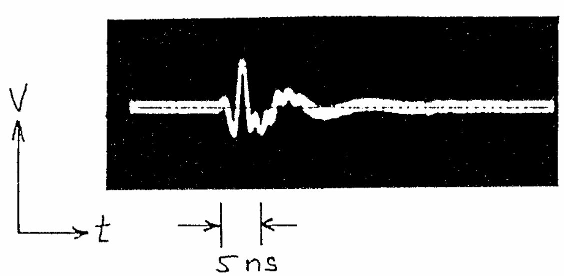
GROUP AND PHASE DELAY CALIBRATION FOR VLBI

CHANGE LETTER	D'WN BY	CHK'D BY	APP'D BY	DATE	D.C.N. & DESCRIPTION

B- 6025



Pulse at IF



NOTES

* R1 CHANGED TO 100Ω IN UNITS WITH TD PEAK CURRENT > 15 ma

MATERIAL	USED ON	
FINISH AND/OR HEAT TREATMENT	NEXT ASSEMBLY	
	WEIGHT	
	SCALE	
	CLASSIFICATION	

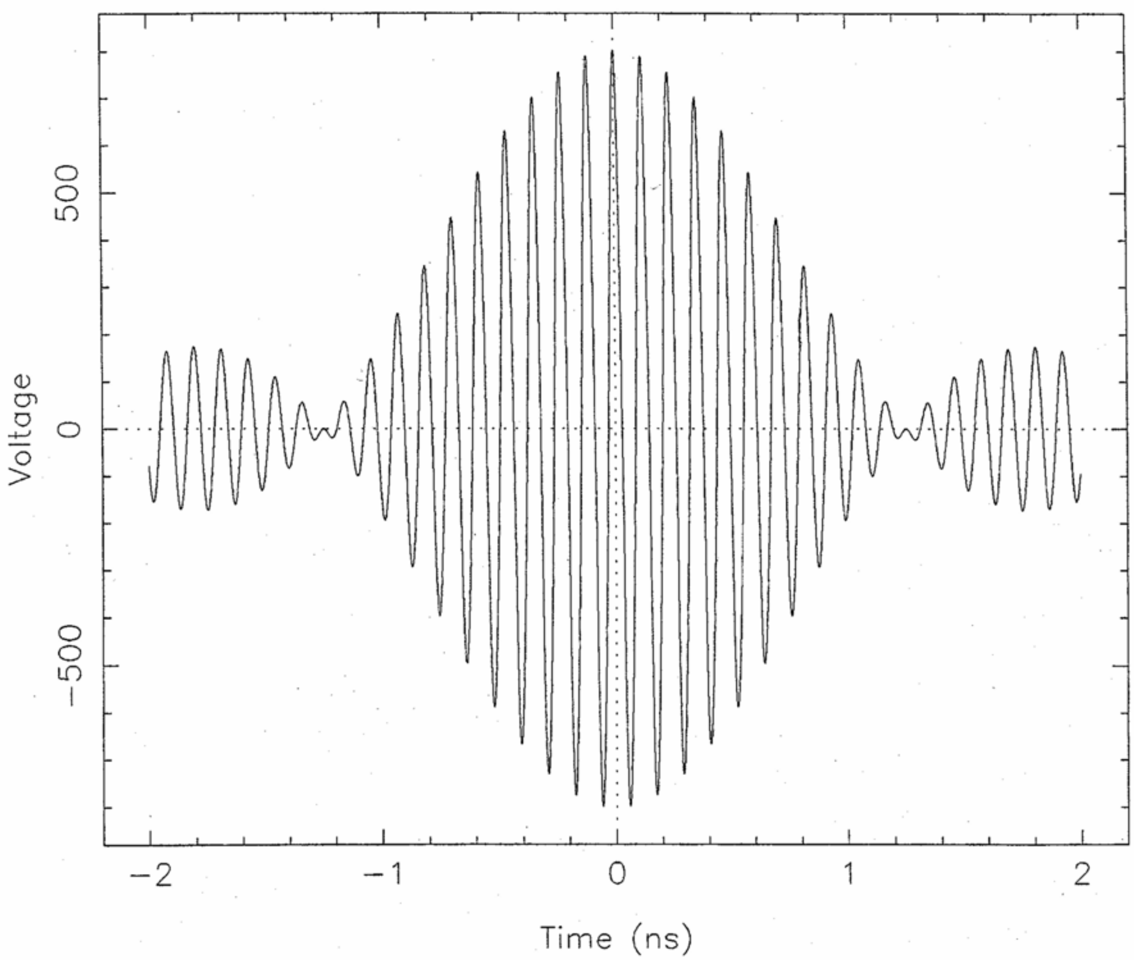
		DATE
DRAWN FOR	A. Rogers	4/29/78
DRAWN BY	J. Lacasse	4/29/78
CHECKED BY	AEEK	13 Nov 78
APPROVALS: PROJECT	AEEK	
ENGINEER		
MATL. & PROCESS		
STRUCTURES		
THERMAL		
MECH. ANALYSIS		

NORTHEAST RADIO OBSERVATORY CORPORATION
HAYSTACK OBSERVATORY
WESTFORD, MASSACHUSETTS

PULSE GENERATOR
(SUBMODULE FOR DELAY CALIBRATOR.
- ANTENNA UNIT)

	DWG. SIZE	DWG. NO.	REV.
3HA2DAS	B	6025	

Simulated X–band RF phase cal pulse waveform for an 8180–8980 MHz rectangular passband



What Is Phase Cal Phase Sensitive To?

Phase cal **phase**, as measured in analog baseband or in digital bit stream, depends on:

- Phase of 5 MHz output from delay cal ground unit
- Electrical length of cable from ground unit to antenna unit
  (Measured by cable cal system)
- Phase delay through antenna unit
- Phase delay from antenna unit to cal injection point
- Phase of the first LO in receiver
- Phase delay of receiver, from cal injection point to IF output
- Electrical length of IF cable from receiver to control room
- Phase delay through IF up/downconverter, IF distributor and VC/BBC
- Phase of LO in IF up/downconverter and VC/BBC

Phase cal phase is affected by all the instrumental delays that affect fringe phase, except for delay through antenna structure and delay from feed to cal injection point.

What Is Phase Cal Amplitude Sensitive To?

Phase cal **amplitude**, as measured in **analog** baseband, depends on:

- Phase cal voltage at antenna unit output
- Loss between antenna unit and cal injection coupler
- Coupling strength of cal injection coupler
- Gain/loss through receiver, IF cables, IF distributor, and VC/BBC
- Coherence loss due to unstable LO in receiver or VC/BBC
- Reflections in RF or IF path from antenna unit to VC/BBC
- Level of USB/LSB image rejection in VC/BBC
- Interference from spurious signals

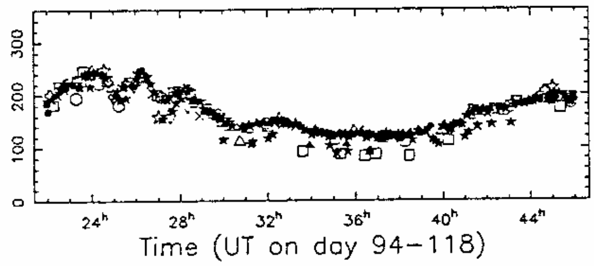
Phase cal **amplitude**, as measured in **digital** bit stream (1 bit/sample or 2 bits with AGC), is the ratio between analog phase cal amplitude and average noise voltage magnitude, *i.e.*, $|V_{pcal}|/\sqrt{T_{sys}}$. Digital phase cal amplitude depends on:

- Phase cal voltage at antenna unit output
- Loss between antenna unit and cal injection coupler
- Coupling strength of cal injection coupler
- System temperature of receiver (including increase due to RFI)
- Coherence loss due to unstable LO in receiver or VC/BBC
- Reflections in RF path from antenna unit to cal coupler
- Level of USB/LSB image rejection in VC/BBC
- Interference from spurious signals

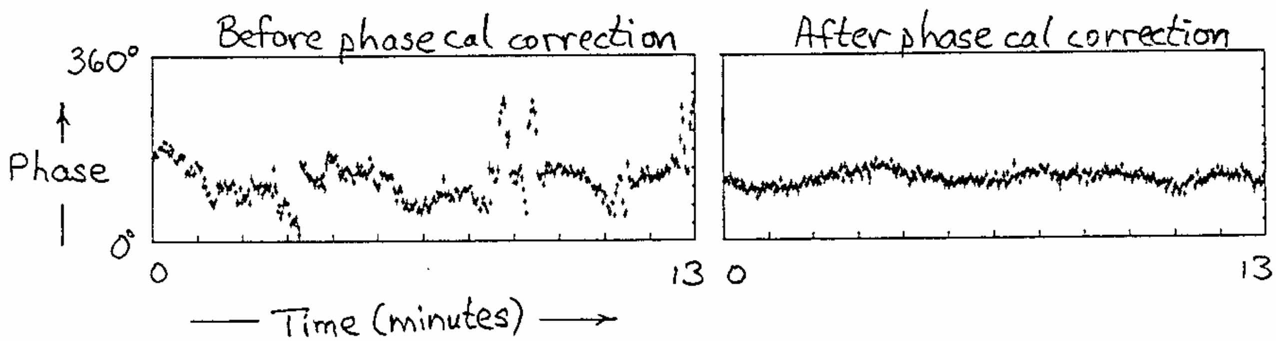
Phase Cal Applications

- Measure changes in instrumental phase and delay during scans and between scans.
  - Example: Measurement of change in electrical length of X-band IF cable at particular antenna orientations

Difference in phase cal phase between two X-band channels



- Improve fringe phase coherence within a scan by correcting for LO phase variations.
  - Example: Phase cal correction of LO phase jumps due to an intermittent cable connection

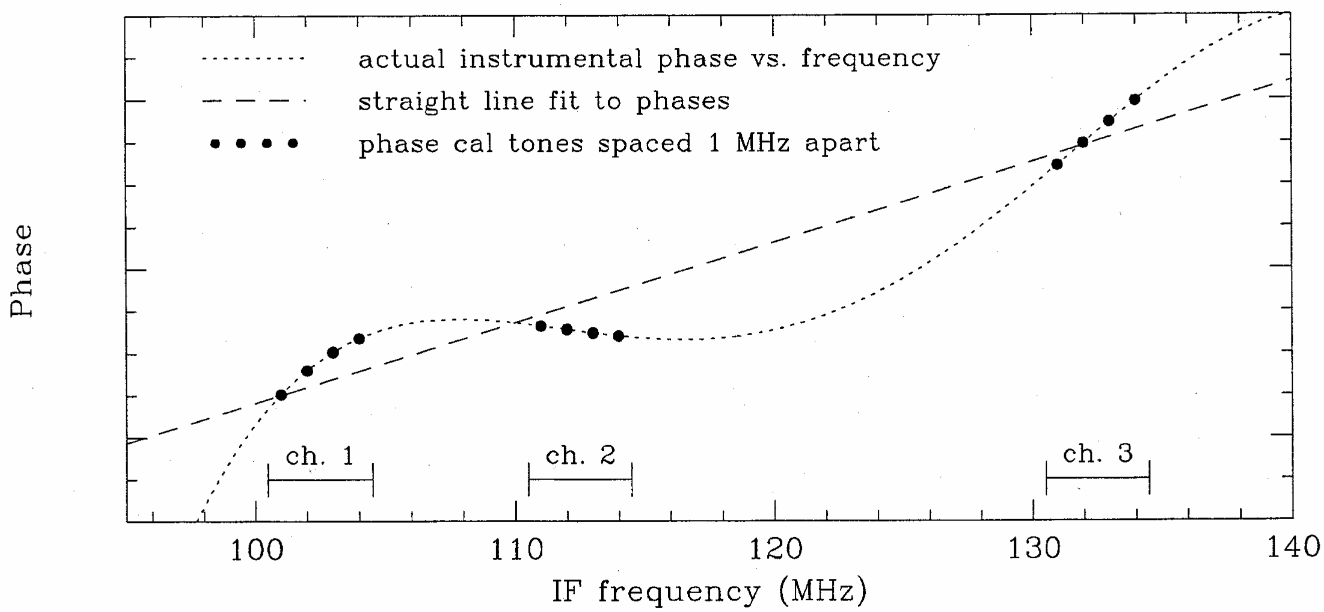


- Check for modulation sidebands on LO that can degrade phase coherence and VLBI sensitivity.

- Test for adequate USB/LSB image rejection in VC's/BBC's.

- Provide second–by–second estimates of system temperature in each frequency channel.

Correcting for instrumental channel delays using multiple phase cal tones in each channel



If measured phases are available from multiple phase cal tones within each frequency channel...

- SNR can be increased by correcting for the differences in the instrumental delays between channels.
- Effects of time–varying instrumental channel delays (due to sampler problems, for instance) can be removed from the data.

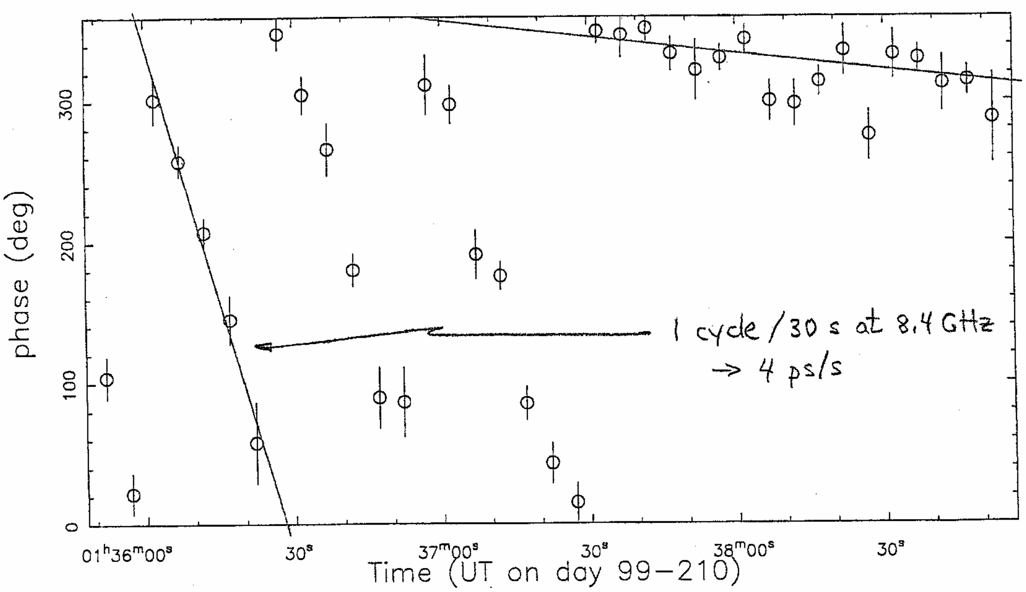
Causes for variations in timing of phase cal pulses

Accurate measurement of instrumental contributions to group and phase delays requires that the phase cal “time ticks” be generated as stably as possible with respect to the maser “time ticks”. The epochs at which the phase cal pulses are generated may vary due to:

- Variations in delay of 5 MHz signal from maser through ground unit
  - High-stability 5 MHz buffer amplifiers should be used, and the temperature of the electronics should be well controlled.
- Changes in electrical length of cable carrying 5 MHz to phase cal antenna unit
  - These changes are measured with the cable calibration system and can be corrected for in the analysis stage.
- Variations in 5 MHz signal delay through antenna unit, due primarily to temperature variations
  - Temperature sensitivity of delay through standard (Haystack-designed) antenna unit is low: ~2 ps/°C.
  - Antenna units are operated in temperature-controlled enclosures.
- If 5 MHz to antenna unit is temporarily interrupted, epoch of pulses will shift by 0-4 cycles of 5 MHz = (0-4) x 200 ns.
  - The phase cal-corrected multiband delay will shift by the same amount as the change in pulse epoch, unless the frequency channels are spaced in multiples of 5 MHz, in which case there is no change in multiband delay.
    - Example: An old S-band IVS-R1/R&D sequence had spacings in multiples of 8 MHz. Interrupting the 5 MHz would usually cause a jump in the multiband delays.
  - As a general rule, 5 MHz between ground and antenna units should not be interrupted during a geodetic or astrometric observing session. Testing of cable measurement system should be done before or after a session.

A Cautionary Tale

X-band fringe phase vs. time during a 3-minute scan



- Geodetic solutions for this experiment indicated an instrumental problem affecting the delays and delay rates at one station.
- Phase cal phase during the scan shown above varied by only 90° at the station.
- Cause of fringe phase wandering was traced to a temperature–sensitive (80 ps/°C) 5 MHz distributor next to an air conditioning outlet.
- Because the 5 MHz distributor fed the phase cal system as well as the receiver and VLBI backend, baseband phase cal phases were insensitive to LO phase drift.

Moral: The quality of the phase calibration signal can be no better than the quality of the 5 MHz input to the phase calibration system.

Spurious Phase Cal Signals

Definition:

- A spurious phase cal signal is any narrowband signal that is
  - at the same frequency as the true phase cal
  - coherent with the true phase cal
  - **not** the phase cal signal you want!

Origins:

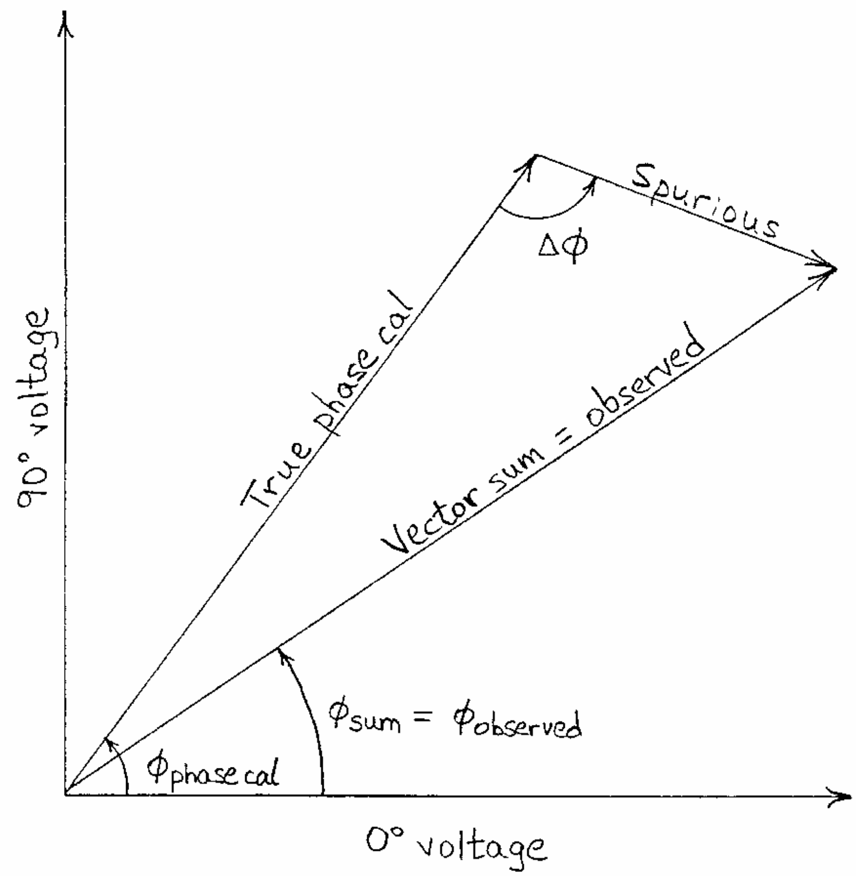
- In MkIV/VLBA rack (esp. formatter) & other control room electronics (*e.g.*, MkIV VC03 & VC09 narrowband phase cal freqs = $N \times 4.5$ MHz)
- Generated by receiver LO module (every $N \times 5$ MHz at S–band)
- Phase cal images in receiver and IF up/downconverters
- Phase cal intermodulation/saturation
- Multiple injection paths in receiver
- Crosstalk between phase cal signals in two different IF's
- Faulty "true" phase cal signals
  - Defective antenna unit
  - Reflections in cal injection path

Diagnostic tests:

- Turn off phase cal with ground unit switch
- Disconnect cable from ground unit to antenna unit
- Unlock receiver LO
- Offset receiver LO frequency
- Disconnect output signal from phase cal antenna unit in receiver
- Repeat first test at RF phase cal frequencies = $N \times 5$ MHz

Goal: Spurious signals > 40 dB below phase cal.

Spurious Phase Cal Signals



Error caused by −20 dB spurious signal, as $\Delta\phi$ varies through 360°:

Observed phase cal amplitude:	±10%
Observed phase cal phase:	±6°
Phase cal–corrected delay (360 MHz BW):	±44 ps

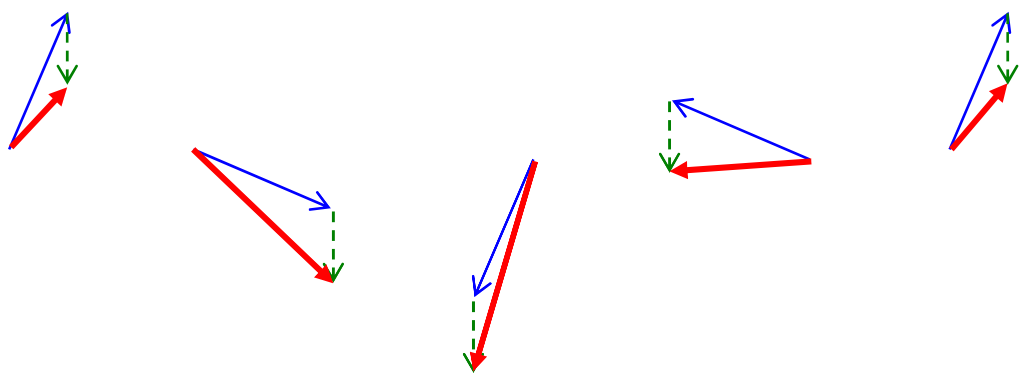
Vector sum of true phase cal and spurious signal
as phase of true phase cal rotates through 360°

True phase cal, rotated in steps of 90°

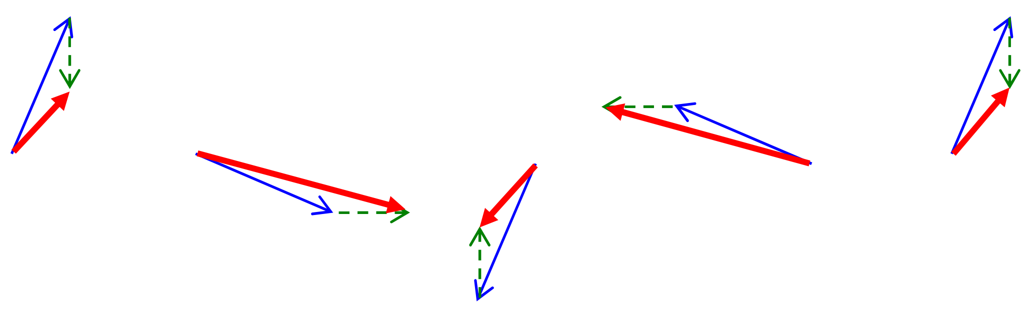
Spurious signal

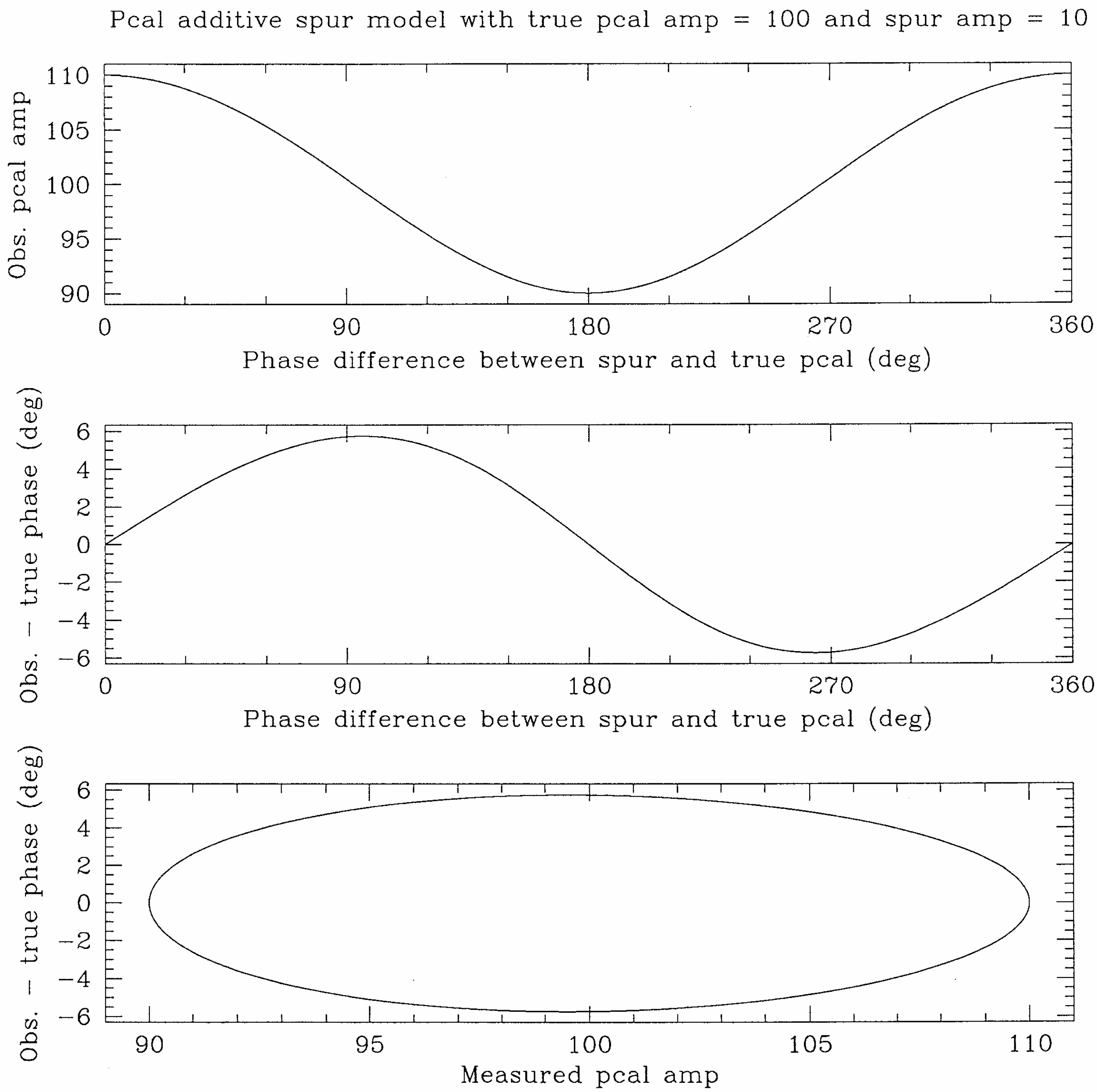
Vector sum of true phase cal & spurious signal

1) Spurious signal of constant amplitude and phase –
Amplitude of vector sum varies through one cycles:
short-long-short



2) Spurious signal = phase cal at image frequency –
Amplitude of vector sum varies through two cycles:
short-long-short-long-short

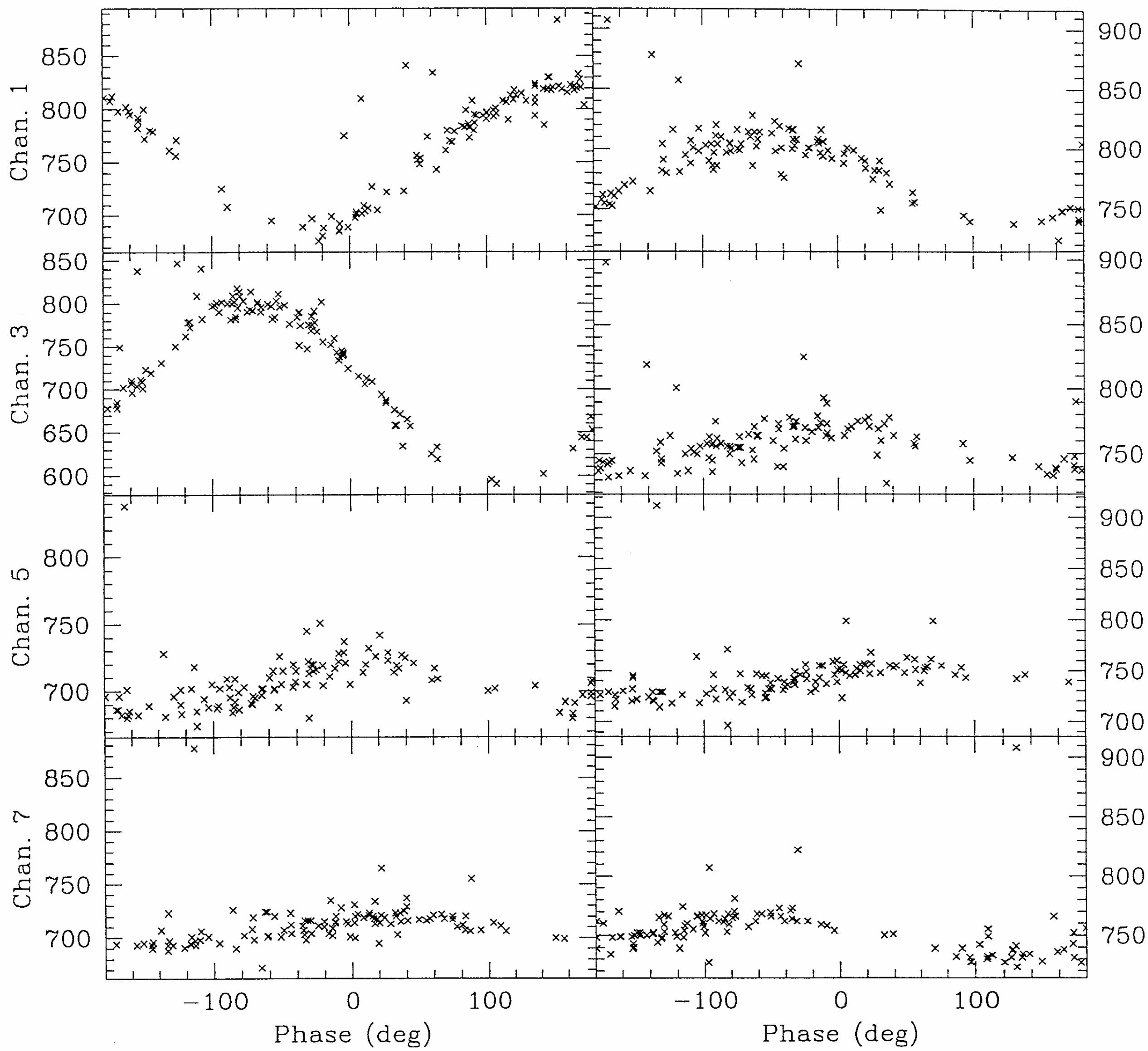



Pcal additive spur model with true pcal amp = 100 and spur amp = 10
Obs. pcal amp
110
105
100
95
90
0
90
180
270
360
Phase difference between spur and true pcal (deg)
Obs. − true phase (deg)
6
4
2
0
−2
−4
−6
0
90
180
270
360
Phase difference between spur and true pcal (deg)
Obs. − true phase (deg)
6
4
2
0
−2
−4
−6
90
95
100
105
110
Measured pcal amp

Strong additive spurious signals in channels 1 and 3

[redacted] GTRF9 X-band Tsys-normalized pcal amp vs. pcal phase

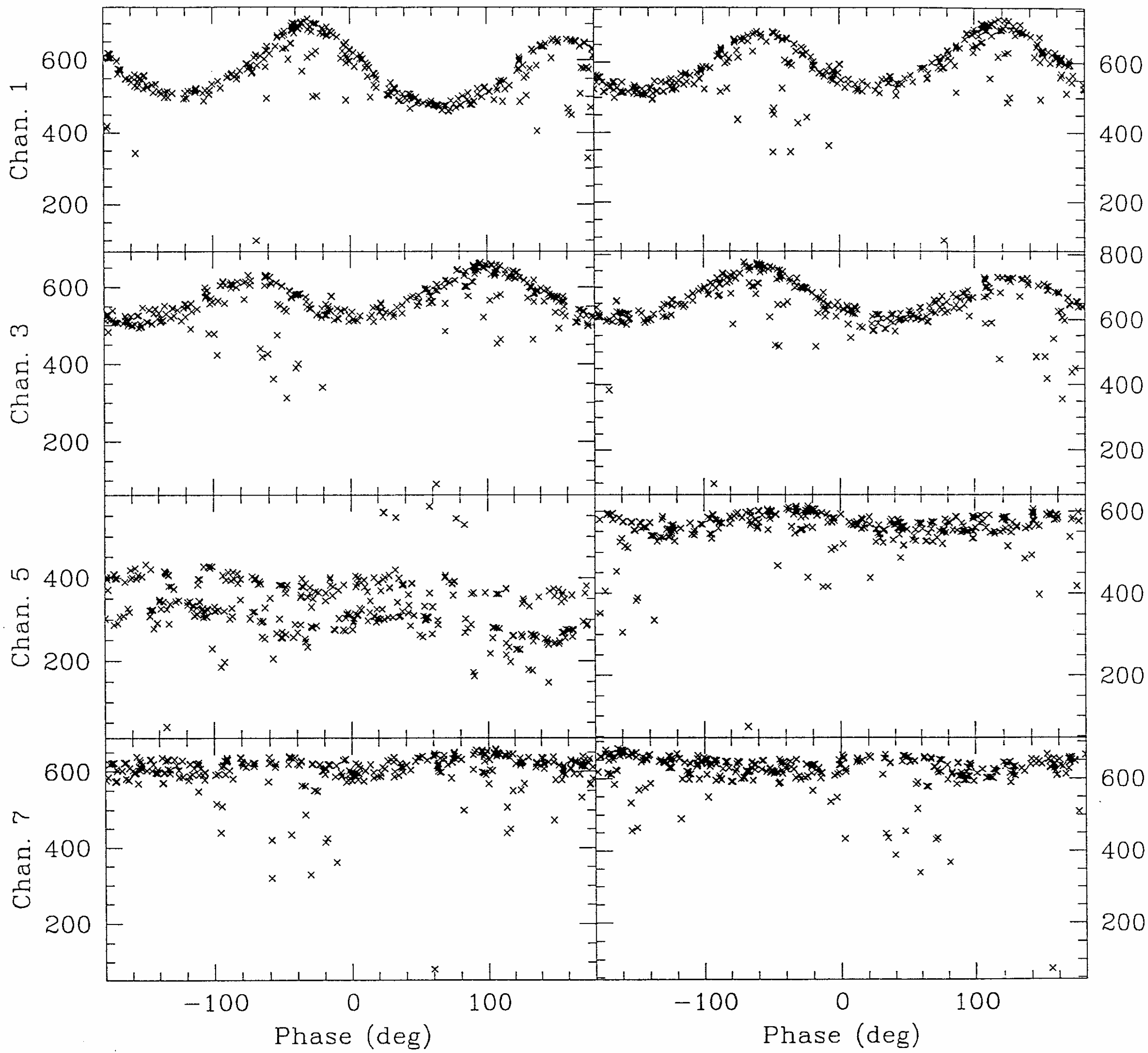
Station X

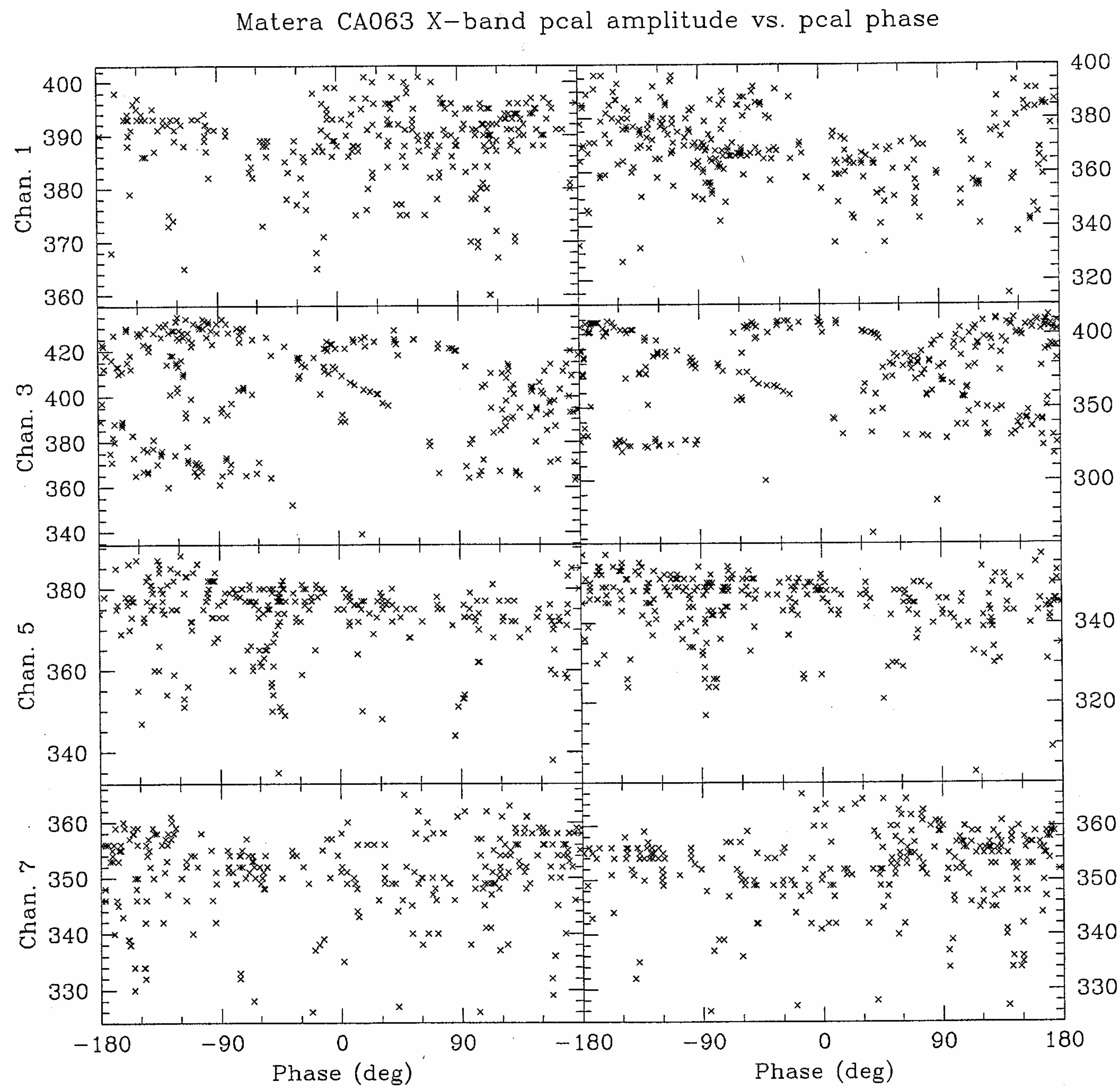


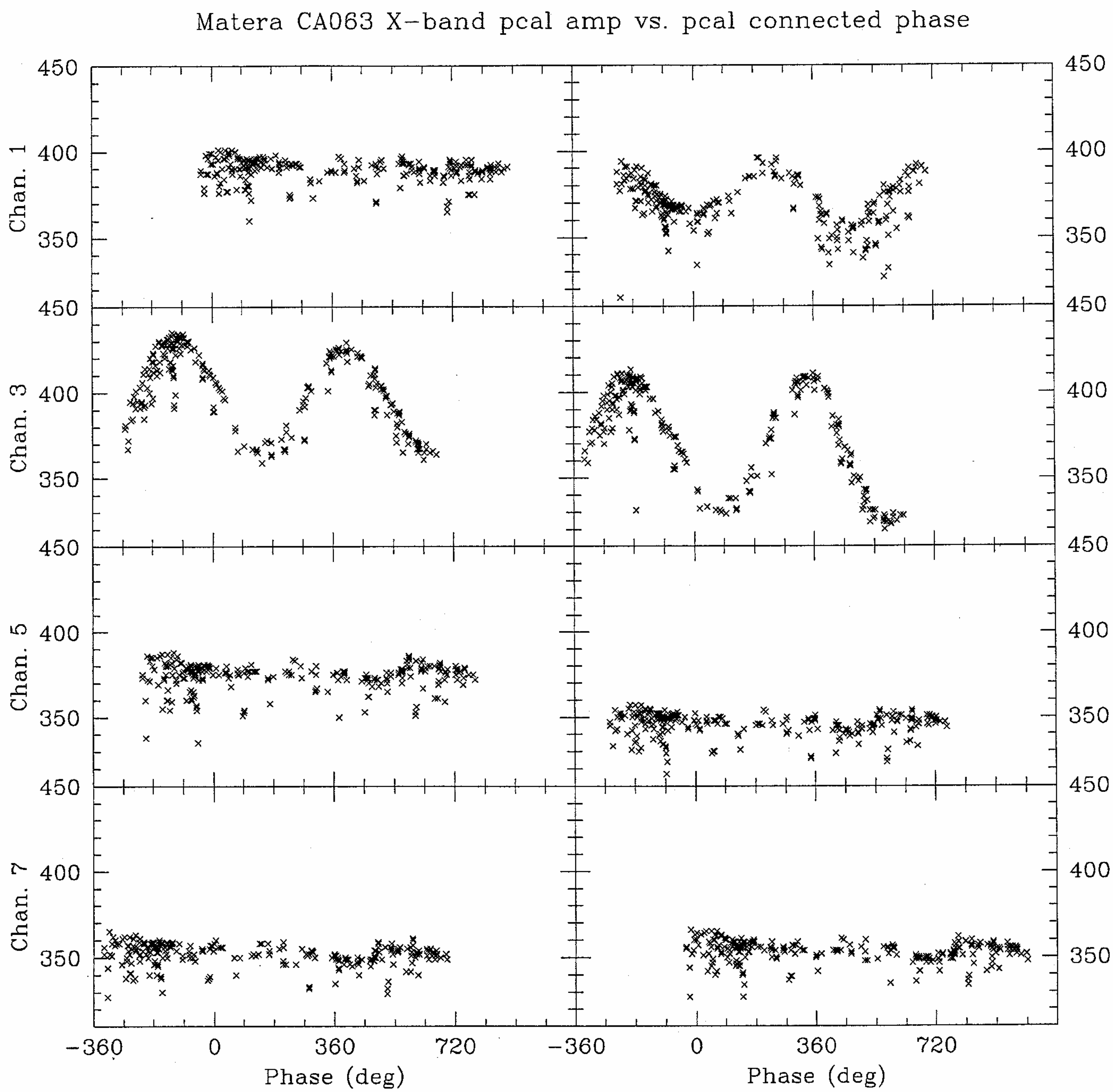
Channels 1-4 contaminated by pcal signals at image frequencies

[redacted] GTRF9 X-band unnormalized pcal amp vs. pcal phase

Station Z




Matera CA063 X-band pcal amplitude vs. pcal phase
Chan. 1
Chan. 3
Chan. 5
Chan. 7
Phase (deg)
Phase (deg)


Matera CA063 X-band pcal amp vs. pcal connected phase
Chan. 1
Chan. 3
Chan. 5
Chan. 7
450
400
350
-360
0
360
720
Phase (deg)

Cable Calibration

Purpose:

- Measure electrical length of cable between ground unit and phase cal antenna unit, so that epochs of phase cal pulses can be tied more closely to maser.

Method:

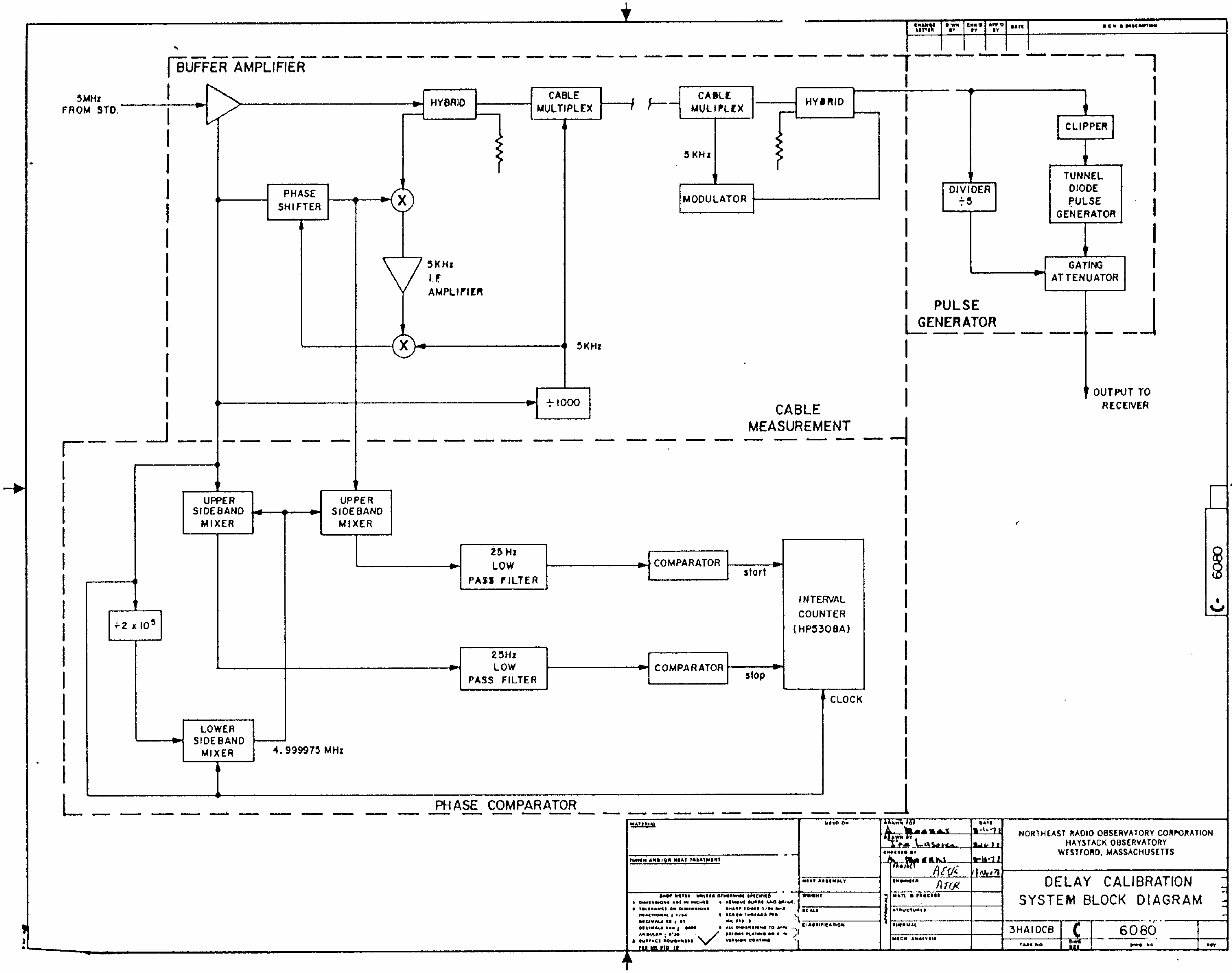
- Simple method: With vector voltmeter in control room, measure phase difference between
  - reference signal transmitted from control room to antenna unit, and
  - signal reflected back from antenna unit to control room.

  Potential disadvantage: Reflections in cable between control room and receiver (*e.g.*, at bad connections) cause measurement errors.

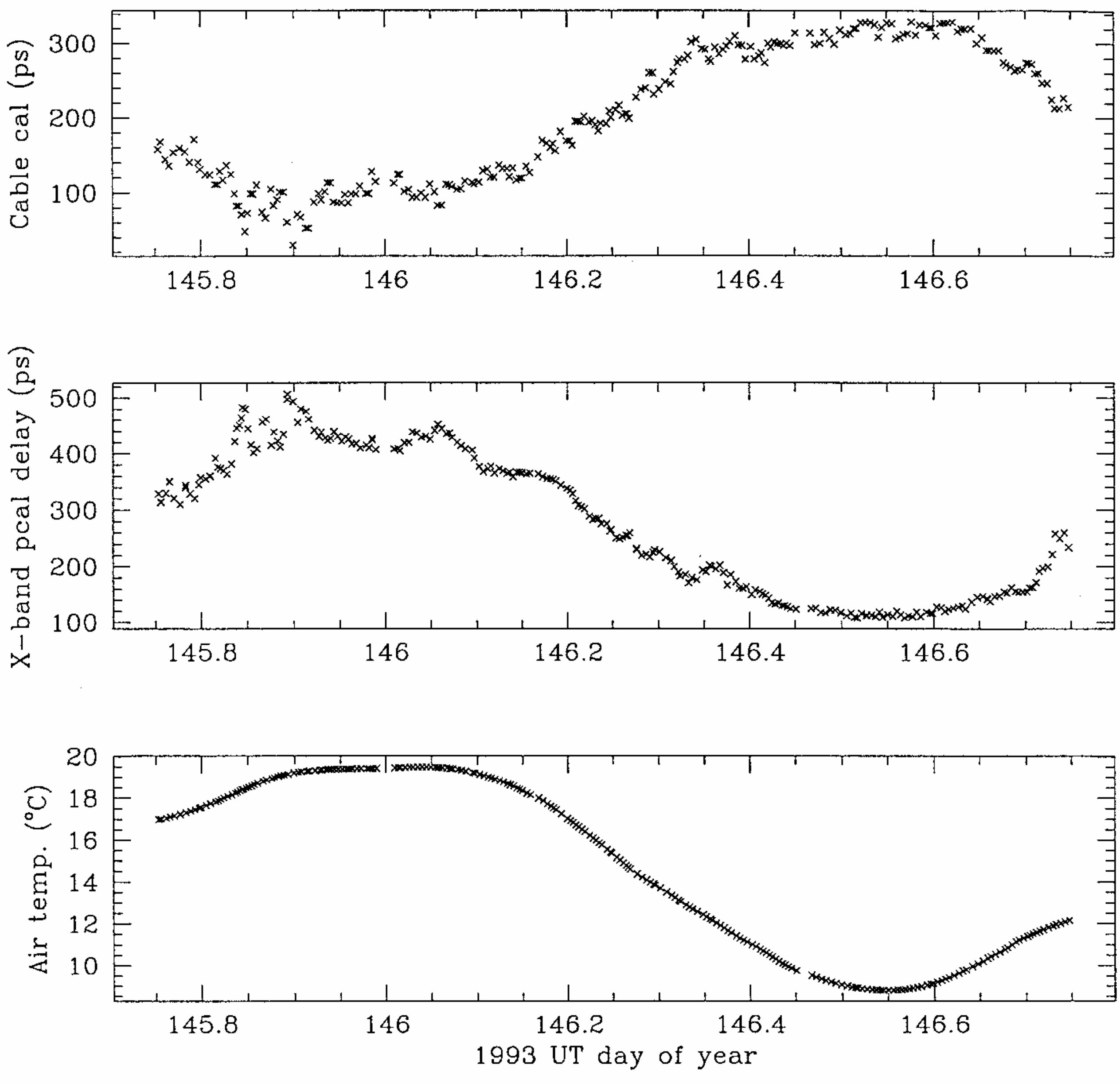
- MkIV method: Ground unit measures phase difference between
  - 5 MHz sent from ground unit to antenna unit, and
  - 5 MHz *modulated by 5 kHz in the antenna unit* and returned to the ground unit.

  Time interval as read on counter is "time–expanded" by ground unit by $\times 200\ 000$.

  $$\begin{aligned} \Rightarrow\ 1\ \mu\text{sec on counter} &= 2.5 \text{ psec one–way cable delay} \\ &= 0.5 \text{ mm path length in dielectric–filled cable} \end{aligned}$$


BUFFER AMPLIFIER
5MHz
FROM STD.
HYBRID
CABLE
MULTIPLEX
CABLE
MULIPLEX
HYBRID
CLIPPER
5 KHz
MODULATOR
DIVIDER
÷5
TUNNEL
DIODE
PULSE
GENERATOR
PHASE
SHIFTER
5KHz
I.F.
AMPLIFIER
GATING
ATTENUATOR
PULSE
GENERATOR
5KHz
OUTPUT TO
RECEIVER
÷1000
CABLE
MEASUREMENT
UPPER
SIDEBAND
MIXER
UPPER
SIDEBAND
MIXER
25 Hz
LOW
PASS FILTER
COMPARATOR
start
INTERVAL
COUNTER
(HP5308A)
÷2 x 10^5
25Hz
LOW
PASS FILTER
COMPARATOR
stop
CLOCK
LOWER
SIDEBAND
MIXER
4.999975 MHz
PHASE COMPARATOR
NORTHEAST RADIO OBSERVATORY CORPORATION
HAYSTACK OBSERVATORY
WESTFORD, MASSACHUSETTS
DELAY CALIBRATION
SYSTEM BLOCK DIAGRAM
3HAIDCB
C
6080
C- 6080

Example of Cable Cal and Phase Cal Delay: Gilmore Creek in NEOS-A004



Phase calibrator hardware

Most phase calibrators used in geodetic VLBI systems since the 1970s have employed tunnel diodes to generate the pulse train. See, e.g., the memo dated 11 May 1988 by Alan Rogers (included in TOW notes). It describes the ‘delay calibrator “antenna unit”’ that was installed in many S/X receivers built in the 1980s and 1990s.

Tunnel diodes have become increasingly scarce in the commercial market, and alternatives have been sought. Fortunately, the maximum speed of digital logic has continued to increase, to the point that now a pulse generator can be built around commercially available digital devices.

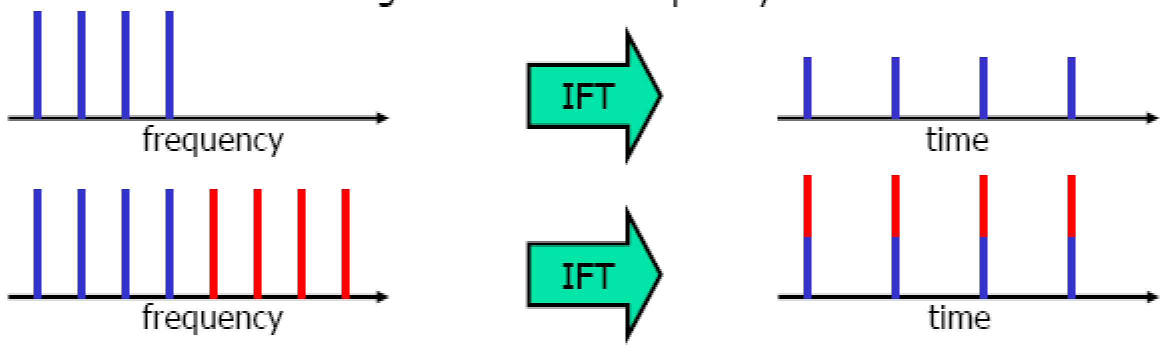
A new “digital” phase calibrator was designed by Alan Rogers for the VLBI2010 broadband development project. Its design is described in http://www.haystack.mit.edu/geo/vlbi_td/BBDev/023.pdf, a copy of which is included in the TOW notes. Some differences from the 1988 design are:

- The input frequency can be 5 or 10 MHz.
- The output has a pulse repetition frequency that is the same as the input frequency, i.e., 5 or 10 MHz.
- There is no circuitry to support cable calibration.

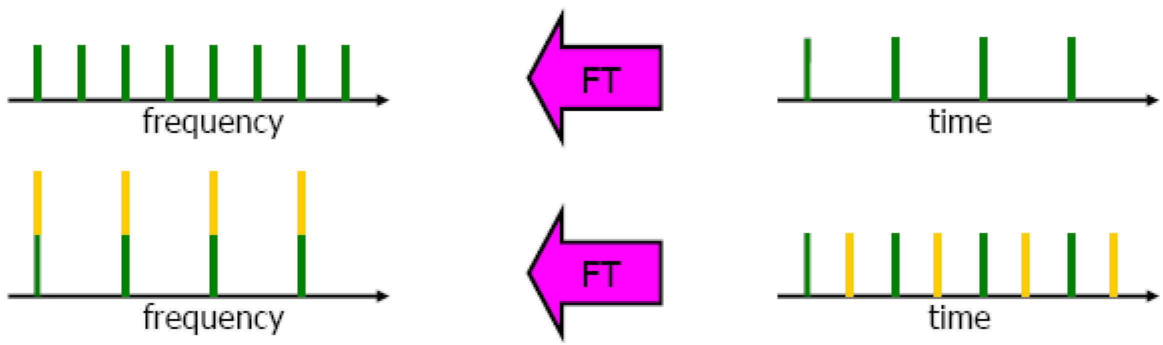
The higher pulse rate of the digital design, compared with the traditional rate of 1 MHz in older designs, and the lack of cable calibration support mean that it cannot serve as a drop-in replacement for old calibrators in most cases. Its primary application at present is in VLBI2010-style receivers, where the RF bandwidths (of order 10 GHz) and channel bandwidths (typically 32 MHz) are much wider than in current systems. The higher pulse rate has the advantage that the peak pulse power (which can be a problem in wideband systems) can be reduced while maintaining the same power level in each phase cal tone.

Effects on phase cal of changing bandwidth or pulse rate

Pulse voltage scales with frequency bandwidth –



Amplitude and spacing of frequency tones scales with pulse rate –



Phase calibration in VLBI2010

With analog VLBI electronics being increasingly replaced by digital equivalents, it might be thought that phase calibration would become unnecessary. This is not the case.

Much of the analog electronics in Mark4, VLBA4, and similar acquisition systems will be replaced by digital systems in VLBI2010, notably including baseband converters. One of the most critical functions of the phase cal system traditionally has been to monitor the LO phases of the baseband converters. In a digital backend, the relative phases between channels spread over the 512-1024 MHz bandwidth of the DBE are set by digital logic and should never drift. Phase cal is therefore not needed to align the channel phases introduced by the FPGA firmware.

But there are still many components of a VLBI2010 system that are analog and hence are subject to drift and/or may introduce nonlinear phase-vs.-frequency distortions. These components, which will need to be monitored with phase cal, include:

- amplifiers and filters in the front end and in updown converters,
- cable (coax or optical fiber) from front end to back end,
- LO phases in updown converters, and
- Nyquist zone filters.

The phase cal injection point is ideally between the feed and LNA. Depending on which feed is adopted for VLBI2010, however, it may not be feasible to inject at that location. Other options include injecting after the LNA or radiating the phase cal signal into the feed.

In current VLBI systems, tones at harmonics of 5 MHz are prone to serious contamination from spurious signals and are generally ignored in the post-correlation processing. In the “digital” phase calibrator, however, *only* tones at 5 MHz harmonics are generated. Reducing the level of spurious signals at these frequencies will therefore be important for VLBI2010.

Whether a cable cal system will be needed in VLBI2010 has not yet been determined. The mechanical and temperature stability of some coax and fiber cable types is low enough that it *may* be possible to omit cable cal.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

HAYSTACK OBSERVATORY

WESTFORD, MASSACHUSETTS 01886

11 May 1988
(Figures Updated 14 September 1988)
(Figures Updated 5 May 1989)

To: VLBI Group

From: Alan E.E. Rogers AEER

Subject: The New Delay Calibrator "Antenna Unit"

1] Description

The new "antenna" unit uses a circuit that is very similar to the original version documented in the MKIII manual. The input is demultiplexed into 5 MHz (using a 100 KHz high pass and 25 MHz low pass), 5 KHz (using a bandpass filter) and D.C. control. The 5 MHz is used to drive a diode reflection modulator which produces 180 degree phase modulation at a 5 KHz rate on the signal returned back down the cable while being isolated from the pulse generator by a hybrid power splitter. The tunnel diode produces a positive pulse going into the high state and a negative pulse upon return to the low state. These pulses are gated so that only one positive pulse per microsecond emerges from the microwave switch. A high D.C. level on the input turns off all pulses.

2] Measured Performance

Pulse duration	25 ps (Tektronix tunnel diode spec.)
Pulse rate	1 MHz (1 pulse/microsecond)
Pulse Spectrum (power in each rail)	-80 dBm at 2.2 GHz -94 dBm at 8.3 GHz -95 dBm at 12 GHz -106 dBm at 22 GHz
Spectral Flatness	0.1 dB peak to peak over 10 MHz 0.6 dB peak to peak from 8 to 9 GHz

Level of Pulse reflections -29 dB (VSWR = 1.07:1) at 8.3 GHz
Calculated from Spectrum

Pulse Delay Variation	with Voltage	- 5 ps/volt
	with Level	-10 ps/dB
	with Warmup	30 ps
	with Temperature	1.5 ps/oC

Strength of Reflected Signal for Cable Measurement	- 65 dBc
Level of 5KHz Sidebands	- 30 dBc at 8 GHz
Nominal 5 MHz Input	+ 13 dBm
Nominal 5 KHz Input	0.4 Volt P-P
Power Requirement	12 volts* at 225 ma (2.70W) or 15 volts at 250 ma (3.75W)

Note: *Recommended operating voltage (can be derived from +15V switching power supply via I.C. voltage regulator LAMBDA LAS1612)

3] Circuit Revision

The original circuit (shown in memo of 12 April 1988) fails to operate for 5 MHz levels below +6 dBm because the risetime of the waveform driving the tunnel diode is too slow to provide the 50 ma needed to snap the diode into the high state. In order to correct this problem I breadboarded several new circuits for the conversion of a 5 MHz sine wave to a 5 MHz square wave. The circuits included several variations of the original circuit using linear amplifiers and clipper diode, a very fast comparator (AD96858D) and various ECL line receivers. The following results were obtained:

Circuit	Approx. Temp. Co.	Noise Figure
Original	5 ps/^{o}C	6 dB
AD9685	6 ps/^{o}C	
MC10115	3 ps/C	
MC10H115	1 ps/^{o}C	10 dB

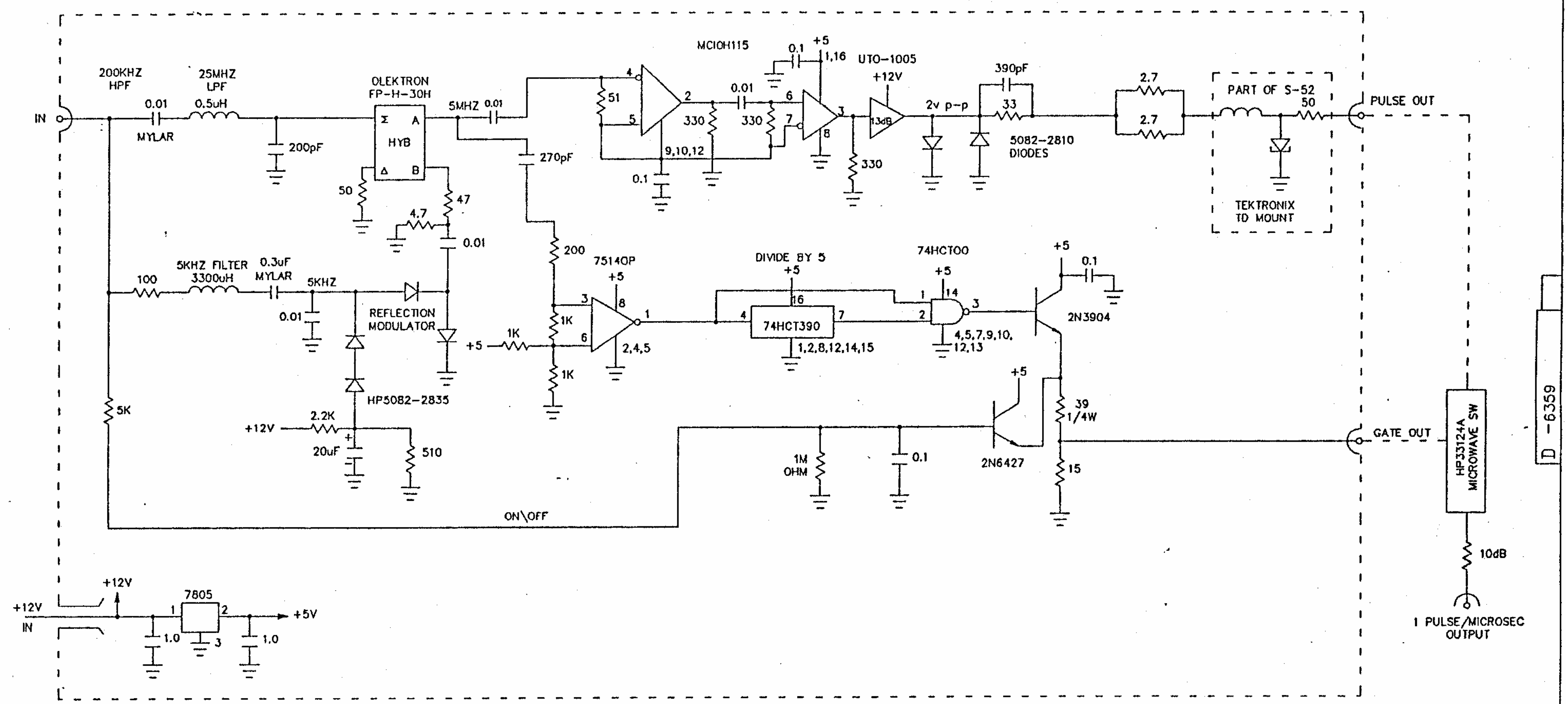
Two states of MC10H115 followed by a UTO-1005 has the best performance as the sensitivities to voltage and temperature are low and with two stages will continue to drive the tunnel diode to a 5 MHz input of -20 dBm. The 10 dB noise figure produces only about 2 ps additional phase noise with +10 dBm 5 MHz input. The data sheets attached explain the excellent performance of the MECL 10KH circuit.

4] Orientation Sensitivity

With this revised circuit there are now virtually no highly temperature sensitive components and tests using the Kwaj receiver (in fixed orientation) and the new calibrator injected via a waveguide transition and flexible cable showed no measurable orientation sensitivity at a limit of less than 1 ps (without any insulating beads in the calibrator box).

xc:: David Shaffer
Thomas Clark

CHANGE LETTER	DWN BY:	CHK'D BY:	APP'D BY:	DATE:	D.C.N. & DESCRIPTION



TEMPERATURE CONTROLLED
SUB - MODULE

NOTES:

DWG. LAST CHANGED 04/05/89

ELECTRONICS NOTES: UNLESS OTHERWISE NOTED:	USED ON	DRAWN FOR: A.E.ROGERS	DATE: 4/88	NORTHEAST RADIO OBSERVATORY CORPORATION HAYSTACK OBSERVATORY WESTFORD,MASSACHUSETTS
RESISTORS:		DRAWN BY: A.P.HEBERT	4/88	
INDUCTORS:		APPROVALS CHECKED BY:		DELAY CALIBRATOR ANTENNA UNIT NEW DESIGN FOR NASA CDP
CAPACITORS:	SCALE: NONE	ENGINEER:		
	CLASSIFICATION:	PROJECT:		AER\NASA\NASACDP D 6359

Massachusetts Institute of Technology
Haystack Observatory
WESTFORD, MASSACHUSETTS 01886
25 February 2009
Updated: 5 March 2010

To: Broadband Development Group

From: A.E.E. Rogers

Subject: Tests of new "digital" phase calibrator.

1] Circuit

Figure 1 shows the circuit of the phase calibrator. The ADCMP572 ultrafast comparator provides sufficient gain to help ensure low sensitivity to the 5/10 MHz level. The HMC672LC3C ultrafast logic output is a square wave with very fast transitions (See MK5 memo #71). The output capacitor differentiates the waveform to generate positive and negative pulses. Pulses of one sign are passed by the HMC019 switch.

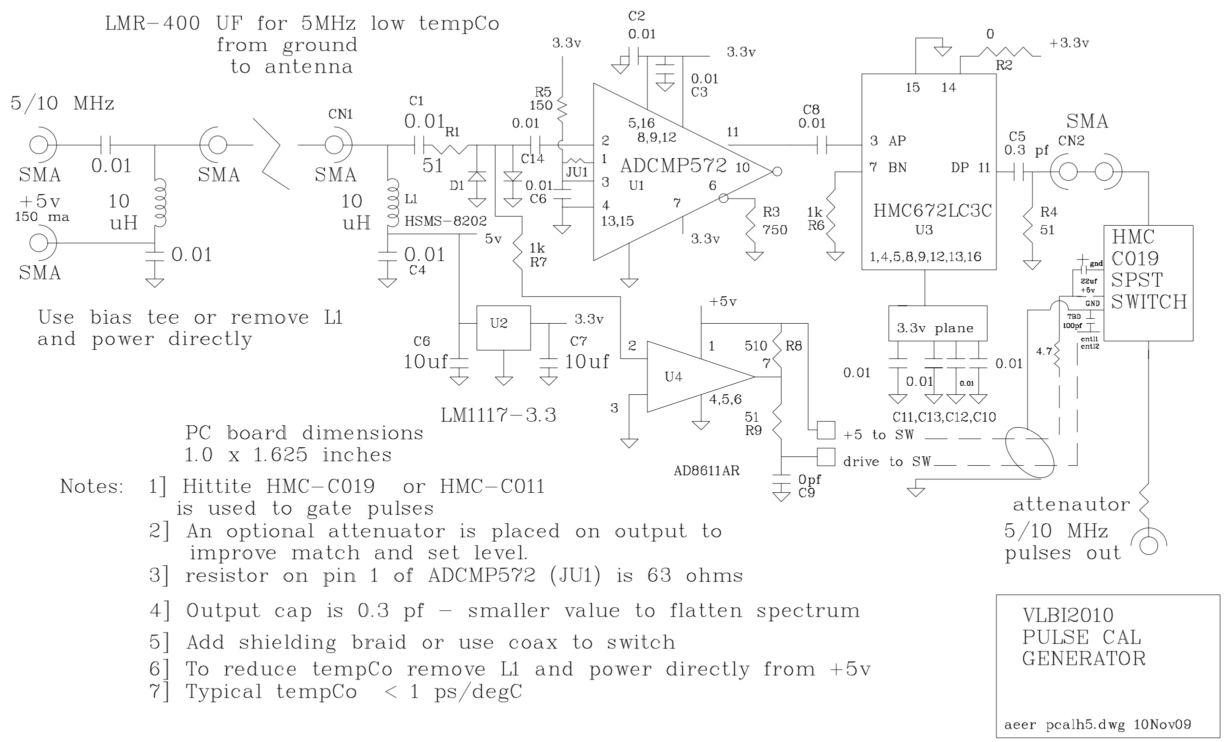


Figure 1. Circuit updated 9 November 2009

2]   Output spectrum

The output spectrum is a series of "rails" or "tones" with 5 or 10 MHz spacing depending on the input frequency. The following table shows the rail strength and level of the undesired switch control waveform "feed thru" vs frequency. The feed through is given relative to the rail strength.

	5 MHz		10 MHz	
Freq. (GHz)	Rail strength (dBm)	Feedthru (dBc)	Rail (dBm)	Feed thru (dBc)
1	-60	-15	-54	-20
1.5	-60	-25	-55	-30
2.0	-60	-35	-53	-40
3.0	-65	<-40	-56	<-40
5.0	-74	<-40	-64	<-40
8.0	-78	<-40	-69	<-40
10.0	-81	<-40	-74	<-40
15.0	-86	<-40	-80	<-40

For comparison the output of the current tunnel diode pcal running at a 5 MHz pulse rate is about -80 dBm per rail at 8 GHz.

3]   Temperature coefficient

Figure 2 shows the set-up for measuring the temperature coefficient. The temperature of the pcal was cycled from 23 to 45 deg C. The following results were obtained from measurements of the phase rail at 9.07 GHz. For measurements at a 5 MHz rate the pcal was driven from a 5 MHz buffer instead of the 10 MHz output of the UDC.

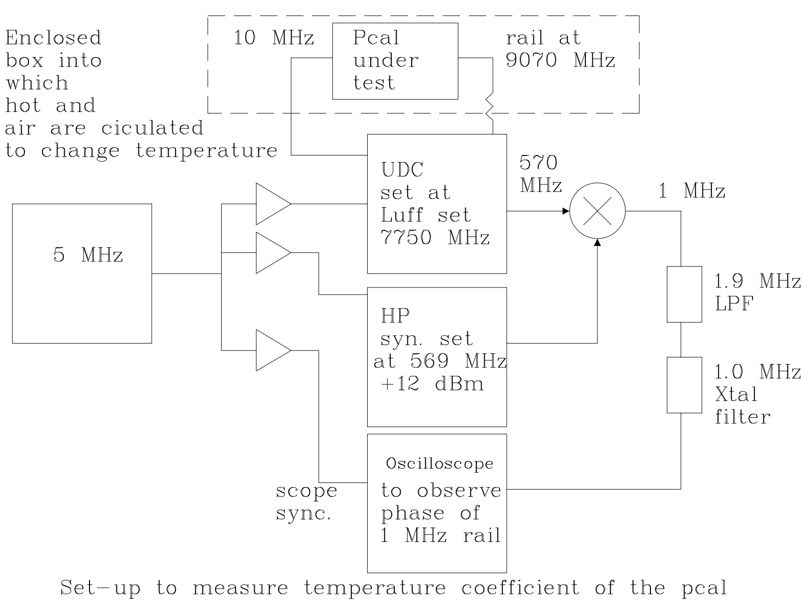


Figure 2.

Pulse rate MHz	Temp Co ps/degC	
5	0.0 ± 0.5	Note 2
10*	+2 ± 0.3	Note 1

Note 1 Measured in Feb. 09 before eliminating the power injection via bias tee.
Note 2 TempCo reduced from 5±1 ps/s after using +5v directly to the regulator and removing L1.

4] Comments

a. Output slope
The output slope can be controlled by the value of the HMC672 output capacitor C5. For radiated injection of the pcal the 1 pf might be a good choice. For injection via a broadband coupler C5 has been changed to 0.3 pf to reduce the signal level at the low frequency end.
b. Temperature coefficient
The temperature coefficient at 5 MHz is limited by the input offset drifts in the ADCMP572. The input voltage tempCo is $10\mu V/\deg C$ which is equivalent to about 0.3 ps/degC at 5 MHz for a 1 volt signal. The resistor value on JU1 was originally 0 ohms 0402 resistor of 63 ohms may improve performance and this new value is recommended. If the bias tee method of power injection is to be used L1 should be a low tempCo inductor. The current part (Panasonic ELJ-PB100KF) has a ferrite cone with large temperature coefficient.
c. Output reflections.
Originally I thought that the differentiating capacitor should be after the microwave switch to reduce the relative level of the feed through the switch control waveform but since the differentiator provides a poor match it was found to be better to have the mismatch at only one place.

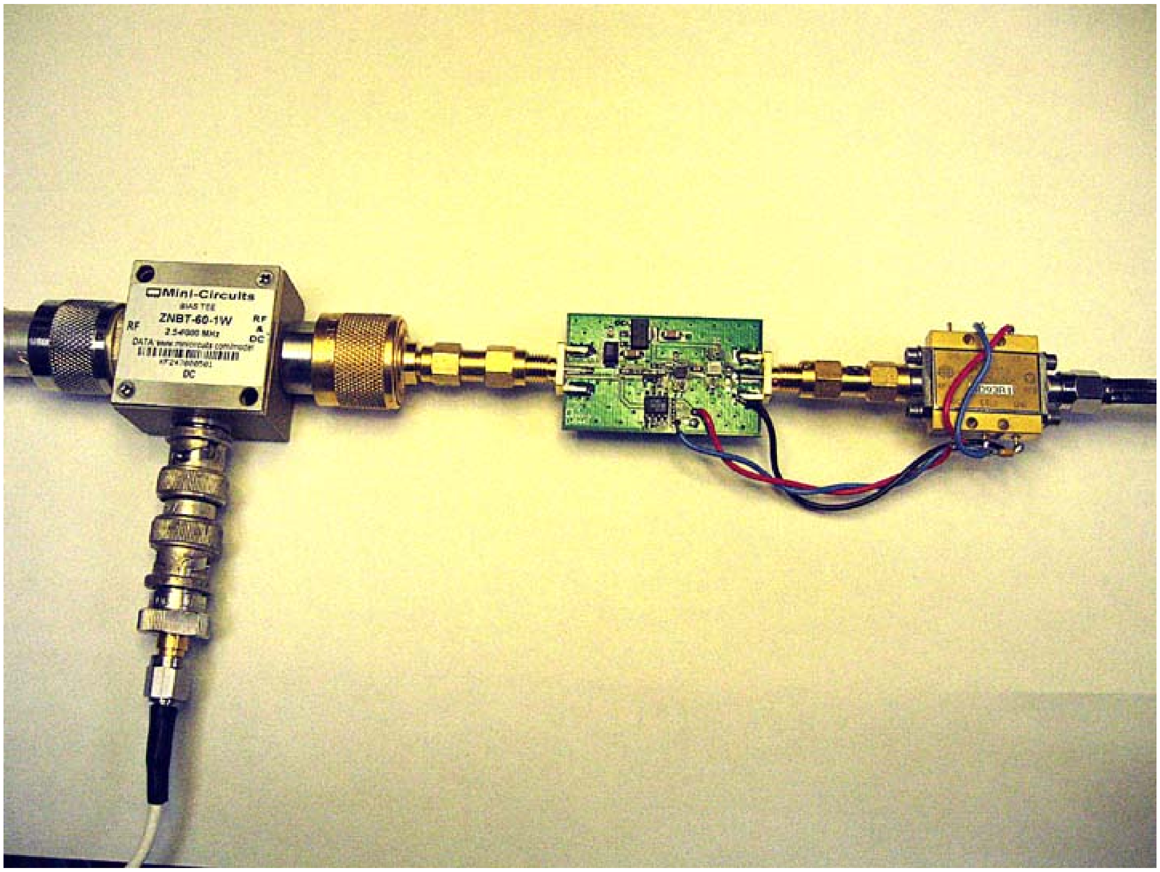


Figure 3. Pcal shown with bias tee power injection. Later versions use direct power injection for reduced temperature coefficient.

Spurious Phase Calibration Signals:
How To Find Them and How To Cure Them

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12 November 1994
Last revised 30 July 1999

This memo describes some of the causes of spurious phase calibration signals in geodetic VLBI systems, tests that can be performed at the stations to detect the signals, and measures that can be taken to reduce their levels. The discussion assumes a Mark III/IV calibration system with a "ground unit" in the control room driving an "antenna unit" in the receiver; the antenna unit generates narrow pulses spaced 1 μsec apart, which are injected into the RF signal path via a directional coupler. Most of the discussion is also applicable to other systems, with some minor modifications.

What are spurious signals?

As used in this memo, the term "spurious phase calibration signal" (or, in interests of brevity, "spur") means a signal that interferes with the true phase cal generated by the means described above, and which thereby can cause a systematic error in the measurement of the phase of a baseband phase cal signal. More specifically, it is a narrowband signal that is coherent with, and has the same frequency as, the true phase cal. Note that this definition excludes noise-like signals (e.g., RFI) that can degrade the measurement precision but will not bias the measurement systematically.

How weak should they be?

Ideally, spurious signals should be at least 50 dB below the true phase cal, i.e., < -50 dBc. Under such conditions, the effect of a spur on the measured phase is <0.2 degree. A level under –40 dBc is acceptable. A –30 dBc spur is serious cause for concern, and a –20 dBc spur may well render the phase cal unusable in the geodetic analysis of the VLBI data.

What causes them? What cures them?

1. **Externally generated spurs in the control room:** Often the strongest spurious signals originate in control room electronics that are not a part of the calibration system, but that use a frequency reference signal from the maser as an input and so are able to generate signals coherent with the phase cal system. The formatter in particular is a potent source of spurs, as it generates harmonics of the sample clock (usually $N \times 4$ MHz) and the sample+parity clock (usually $N \times 4.5$ MHz), as well as harmonics of 5 MHz. For example, when observing with the standard narrowband S/X frequency sequence and with receiver LO frequencies of 2020/8080 MHz, it is common to observe strong spurious signals in X channel 3 and S channel 1, because the two IF phase cal frequencies (171 and 198 MHz, respectively) are both harmonics of 4.5 MHz.

   These externally generated spurs usually enter the signal path at IF frequencies, although on occasion a spur is picked up at RF frequencies by being radiated into the receiver feed. For instance, a spur has been observed at 2268 MHz (the phase cal frequency for S channel 4 in the narrowband sequence), which was due to the 12th harmonic of the 189 MHz clock on the tape transport control board being radiated out of the control room and into the feed.

When a spur originates at IF frequencies, it is usually picked up at the point in the control room where the IF signal level from the receiver is lowest, i.e., at the input to the IF distributor. One test for helping to locate where the spur is being picked up is to change the attenuation in the IF distributor: if the amplitude of the spur does not change relative to the broadband IF or baseband noise level, it is being picked up before the IF attenuator.

Cures:

a. Raise the IF level from the receiver by adding amplifier stages in the receiver or at the point where the signal enters the control room.

b. Put filter capacitors on the IFD power supply lines. In a Mark III/IV IFD, be sure the capacitors called for in NASA/CDP VLBI CCR #031 are present on the power lines and on the bias lines to the normal/alternate switches.

c. Check for cables with broken outer shields or bad connectors, where spurs may leak in.

d. Use double-shielded cables for running IF signals, including on the IFD patch panel.

e. Put a ferrite bead on the 1 pps line going into the IFD.

f. Run the offending spur generator off a frequency reference source other than the maser. (This was the solution for the 2268 MHz spur.)

g. Turn off the spur generator, if possible!

h. If all else fails, change the frequency sequence to avoid spur frequencies, in collaboration with the experiment scheduler and other stations.

2. **Receiver LO electronics spurs:** Receiver LO electronics can be a source of spurs at harmonics of the LO reference frequency. For example, the CTI 2020/8080-MHz oscillator used in many NASA receivers radiates harmonics of 5 MHz well up into the S-band frequency range, and they may be picked up at RF.

   Cures:

   a. Avoid observing at RF frequencies for which the phase cal frequency is a harmonic of the LO reference frequency (an action to be taken by the experiment scheduler, not just by an individual station!).

   b. Lower the level of radiated spurs by using copper tape on the seams of the oscillator, putting the LO in a Faraday cage, etc.

   c. Ensure the integrity of all connectors and cables.

3. **Phase cal images:** If the LO frequency in a downconverter is an integer number of MHz, two RF phase cal tones will contribute to each tone in the IF: (1) the desired RF tone at frequency f_{RF} and (2) the image tone in the opposite sideband at frequency $f_{RF,image} = 2f_{LO} - f_{RF}$. The image tone is a spurious signal. An image rejection filter is generally placed ahead of the mixer to attenuate the image tones.

   Cures:

   a. Ensure the image rejection filter attenuates image frequencies by >50 dB.

b. Offset the LO from an integer number of MHz. If $f_{LO} = (N + x)$ MHz, where N is an integer and $0 < x < 1$ ($x \neq 0.5$), the desired and image phase cal tones will be at different frequencies in the IF. For instance, the LO frequency of the IF3 downconverter is set to 500.1 MHz; the 0.1 MHz offset is there to separate the desired and image tones in the IF3 output.

4. **Amplifier saturation spurs:** When the phase cal pulse is on, the total system power level at RF or IF is momentarily higher (typically 10-20 times higher at X-band) than when the pulse is off. The pulse may drive an amplifier close to saturation, in which case the amplifier will distort the pulse waveform. This distortion is a source of spurs, the phases of which generally differ from those of the undistorted phase cal. For a pulse repetition rate of 1 MHz, the spur frequencies are harmonics of 1 MHz.

   Often the strongest spurs arise in the final IF amplifier in a receiver, where the IF power level is highest. The isolation amplifier in a Mark III/IV video converter typically generates spurs at the –40 to –45 dBc level.

   Cures:

   a. Use amplifiers capable of higher output levels.

   b. Lower the RF/IF system gain. (But this may conflict with cure 1a.)

   c. Attenuate the RF phase cal level. There is no need for the phase cal level to be higher than 1–2% of the T_{sys} noise power.

   d. Offset by a fractional MHz the LO frequency of a mixer preceding an offending amplifier.

5. **Mixer feedthrough:** If the RF and IF frequency ranges of a mixer overlap each other (not good practice, generally speaking!), imperfect balance in the mixer diodes will allow some direct feedthrough of RF phase cal signals into the IF, without any frequency up- or down-conversion.

   Cures:

   a. Offset the LO frequency from integer MHz.

   b. Redesign the circuit!

6. **Multiple RF injection paths:** The RF phase cal signal from the antenna unit may inadvertently be injected into the main RF signal path via routes other than through the calibration coupler. For instance, the antenna unit radiates well into the X-band frequency range (even when the ground unit switch is turned off!), and radiated tones may be picked up by the feed.

   Cures: Highly dependent on specific case.

7. **Antenna unit spurs:** The antenna unit itself may generate additional signals that interfere with the desired phase cal signal. The tunnel diode pulse generator in a Mark III/IV antenna unit actually puts out a positive-voltage pulse every 200 ns, and a negative-voltage pulse approximately midway between each pair of positive pulses. A microwave switch following the generator allows only one of every 5 positive pulses, and no negative pulses, to pass, thereby creating the usual 1 MHz pulse train. If the switch is not functioning properly, however, and does not attenuate the negative pulses sufficiently, the negative pulse train may be a significant source of spurs.

   Cure: Fix the antenna unit!

8. **Reflection in phase cal injection path:** If there are multiple impedance mismatches in the signal path between the antenna unit and the cal injection point, reflections in the path will cause multiple, time-delayed replicas of the pulse to be transmitted to the coupler, and the phase cal phase will be corrupted.

   Cure: Eliminate reflections by ensuring cables and connections are good. Attenuators may also be of use.

9. **Phase cal pick-up at IF frequencies:** The antenna unit generates phase cal tones at frequencies from 1 MHz to above 10 GHz, including tones in the IF frequency range. These IF tones may leak out of the antenna unit and may then be picked up in the receiver IF, without passing through the RF electronics. In one case, for instance, tones were observed to be injected into the S-band IF via the LO detector port on the MITEQ mixer/preamp used in many NASA receivers.

   Cures:

   a. Improve the filtering on the power supply, monitor/control, and other DC lines to the antenna unit and to the IF electronics.

   b. Offset the LO frequency from integer MHz.

10. **Crosstalk between IF signals:** There may be insufficient isolation between two IF signals (e.g., S- and X-band, or two polarizations in the same band), with the result that the phase cal in one IF may contaminate the phase cal in the other IF and act like a spur. Such crosstalk between S- and X-band has been observed to originate in a receiver on an antenna and in a dual-IF upconverter in a VLBI backend.

    Cure: Improve the isolation. Details depend on the specific case.

How can spurious signals be detected?

Most station tests for the presence of spurs involve using a spectrum analyzer (or, if an analyzer is not available, an oscilloscope with a narrowband filter) to measure the power level at the baseband phase cal frequency, which is typically 10 kHz. The general idea behind most tests is to change something in the system that should make the phase cal disappear (e.g., disconnect the reference signal to the antenna unit), and then see if it did disappear. If a signal at the phase cal frequency is still present above the analyzer noise level after the change, then a spur is present.

Some of the tests that can be performed at the stations to detect spurious signals are:

A. Turn off the phase cal with the ground unit switch. If a spur persists, it is type 1 or 2 or, less likely, 6 or 7.

B. Disconnect the cable from the ground unit to the antenna unit. If a spur persists, it is type 1 or 2.

C. Turn off the phase cal as in test A or B, and disconnect the IF cable either at the output from the receiver or at the point where the IF enters the control room. If a spur persists, it is type 1.

D. Unlock the receiver LO by disconnecting its reference signal. Any spur still present is type 1 or 4.

E. Disconnect the cable from the antenna unit to the calibration coupler. Any spur still present is type 1, 2, 6, 9, or 10. While this test may be difficult to carry out, as it requires access to the receiver, it is probably the most reliable means for detecting spurs of types 6, 9, and 10.

F. Set the LO frequency on a video converter to observe a phase cal tone whose RF frequency is an integer multiple of 5 MHz. Repeat test A. If the power level drops less than 20 dB, and if no spur is present at that level when test B is done at the same frequency, then the microwave switch in the antenna unit is probably defective (type 7 spur).

G. Offset the receiver LO from integer MHz by, e.g., using a high-quality crystal oscillator to supply the LO reference, instead of the maser. If the baseband phase cal tones are observed to shift by x MHz in frequency, the image tones will shift by $-x$, and type 1 and 4 spurs will remain unshifted. A type-2 spur will shift, but by an amount different from x.

H. Use an adjustable line in the receiver LO reference line to vary the receiver LO phase. For selected baseband phases over the 360° range, measure the phase cal amplitude and phase (using, e.g., an FFT analyzer or the Field System commands `pcal` or `dqa`). Plot the amplitudes versus phases. The amplitude should be independent of phase, in the absence of spurs. An externally generated spur of type 1, with stable amplitude and phase, will cause a single-cyle sinusoidal variation in amplitude over 360° of phase, as will spurs of types 4, 5, and 9. A spur from a phase cal image causes a two-cycle sinusoid over 360°. A type-10 spur in IF band 1 (e.g., S or X) caused by crosstalk from IF band 2 will have a period of $360°/|f_{LO2}/f_{LO1} - 1|$, provided the same LO reference signal serves the two LO's.

I. Wiggle connections in the receiver and look for phase or amplitude variations.

J. The phase cal amplitude should have no strong frequency dependence within a band (S or X). If the amplitude varies from channel to channel, and particularly if it does so with a quasi-sinusoidal dependence on frequency, then there may be multiple reflections in the cal injection path (type 8 spurs).