Phase Cal Basics

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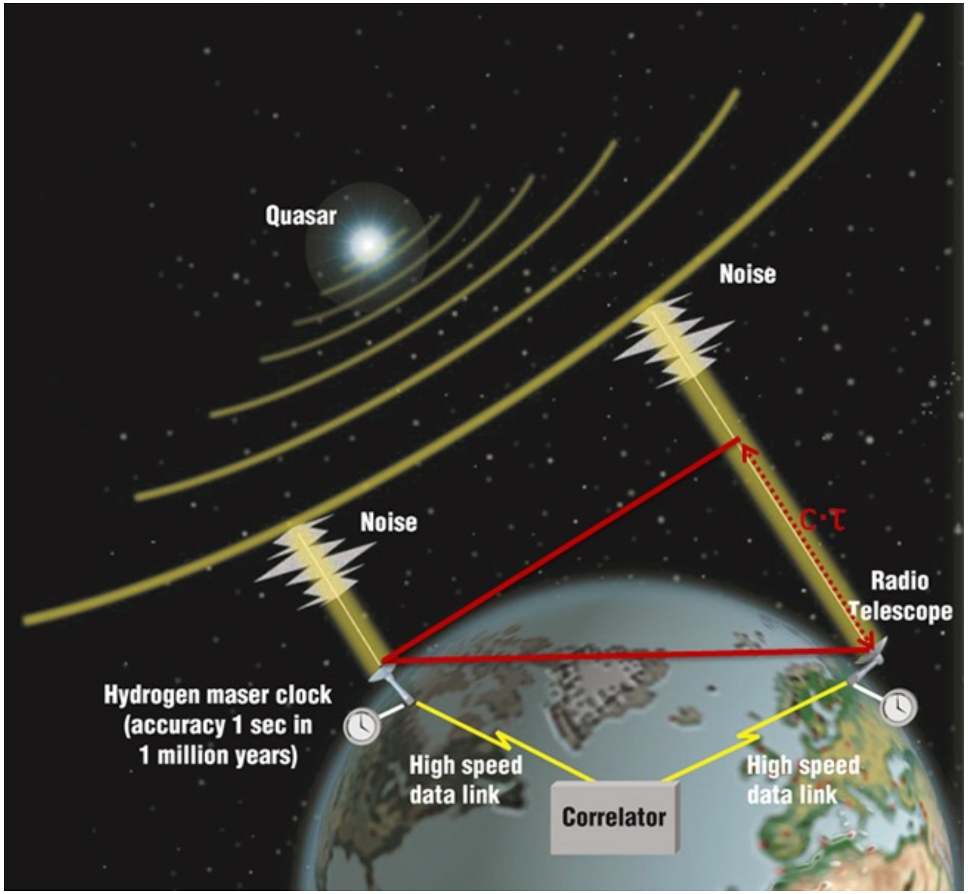
(Acknowledge generous reuse of slides from previous TOW lectures by Brian Corey)

Science Objectives: Geodetic VLBI

- Unique contribution to the Celestial Reference Frame (ICRF) and measurement of Earth's Orientation in Space
- Important input to the Terrestrial Reference Frame (ITRF) – scale
- Needed for precise orbit determination, spacecraft navigation, solar system exploration, astrophysics, sea level change, Earth mass exchanges, nutation



VGOS accuracy goal is 1 mm for site position and 0.1 mm/yr site velocity

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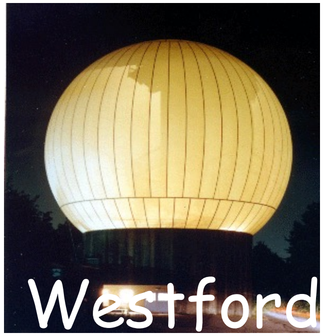
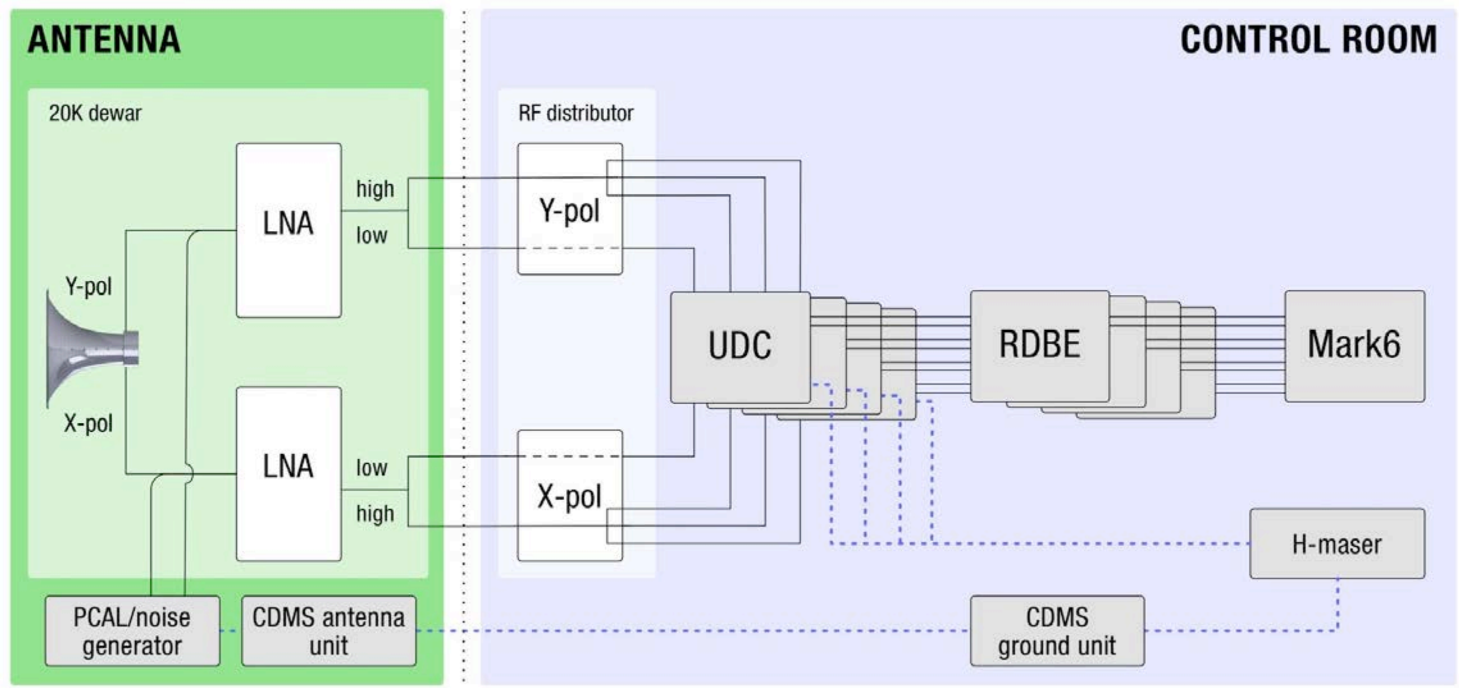
VGOS Signal Chain in the NASA network in the USA


MGO


KPGO


GGAO


Westford

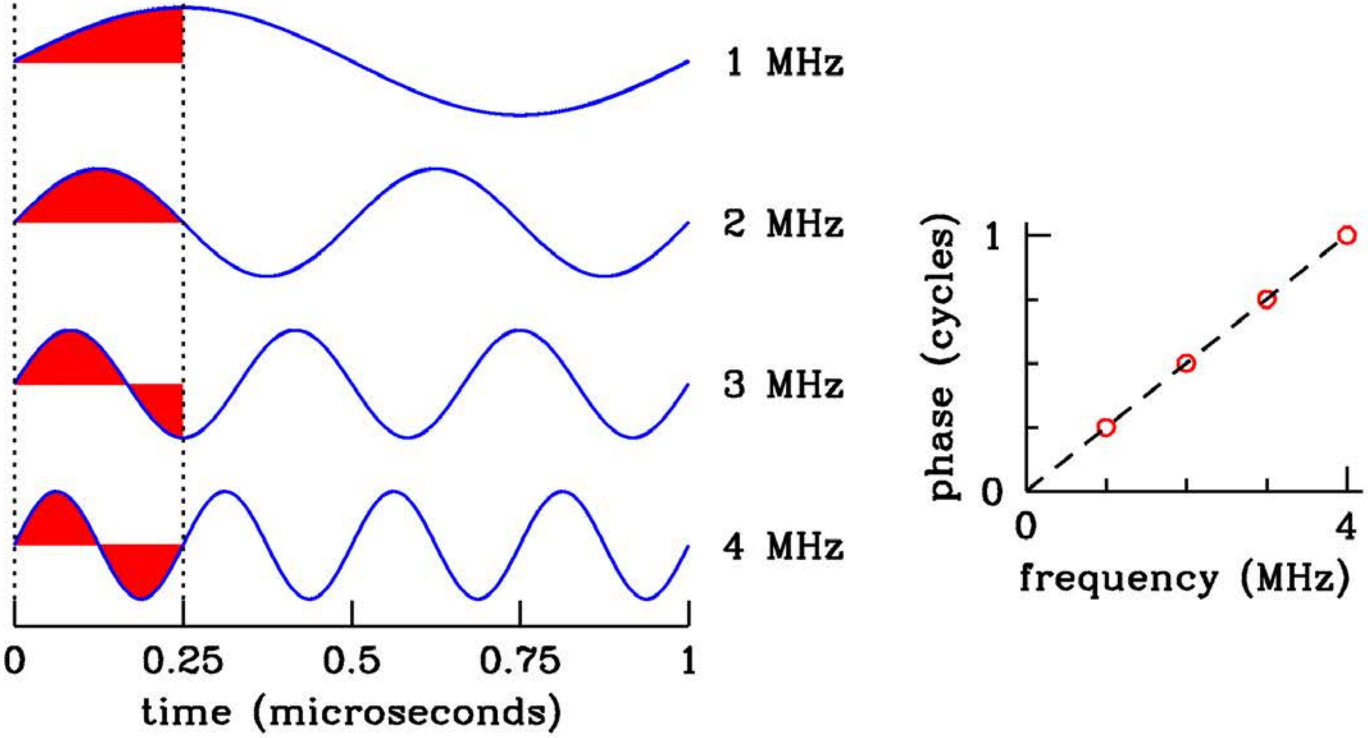


- VGOS observations use four 0.5 GHz or 1 GHz bands in the 2.2-14 GHz range
- Frequency Agile Up-Down Converter (UDC) enables tuning to different frequencies within the 2.2 to 14 GHz frequency range

Phase/delay calibration systems in VLBI

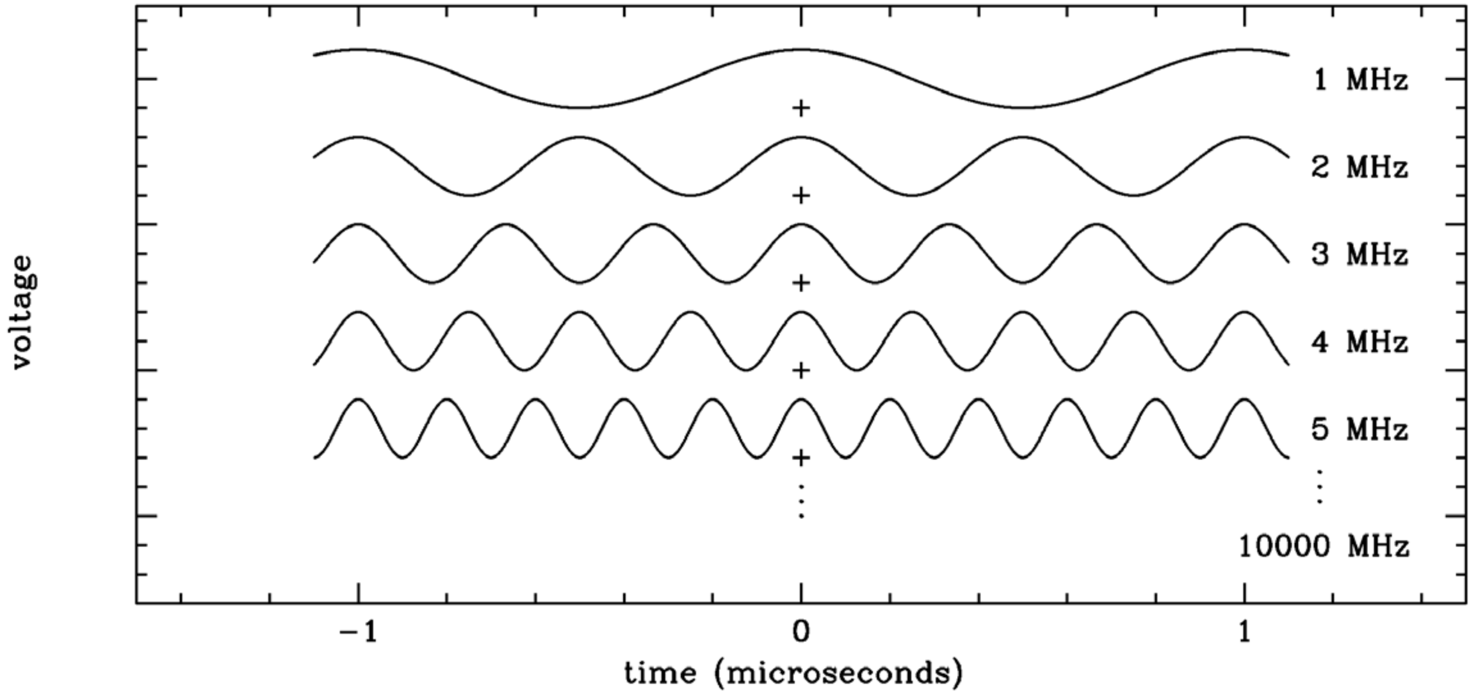
- Astrometric and geodetic VLBI rely on accurate measurement of phase and delay, devoid of errors caused by instrumentation.
- In absence of perfectly stable systems, calibration signals can be used to measure, and hence correct for, instrumental time and frequency variations of phase and delay.

group delay = slope of phase vs. frequency



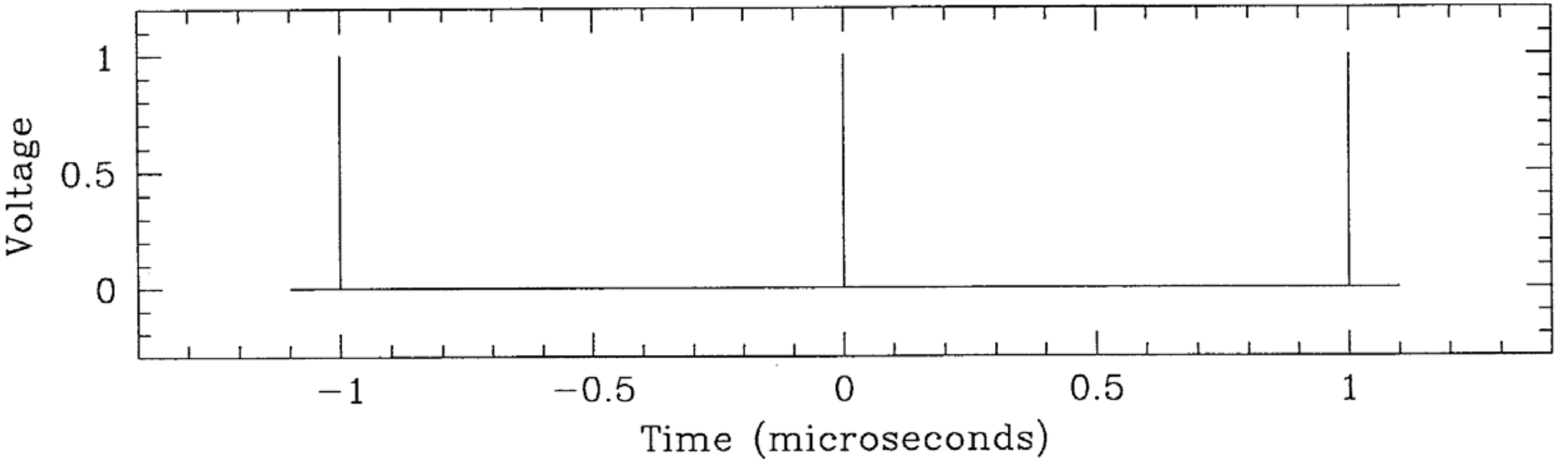
Phase cal signal in time domain, as sum of sinusoids

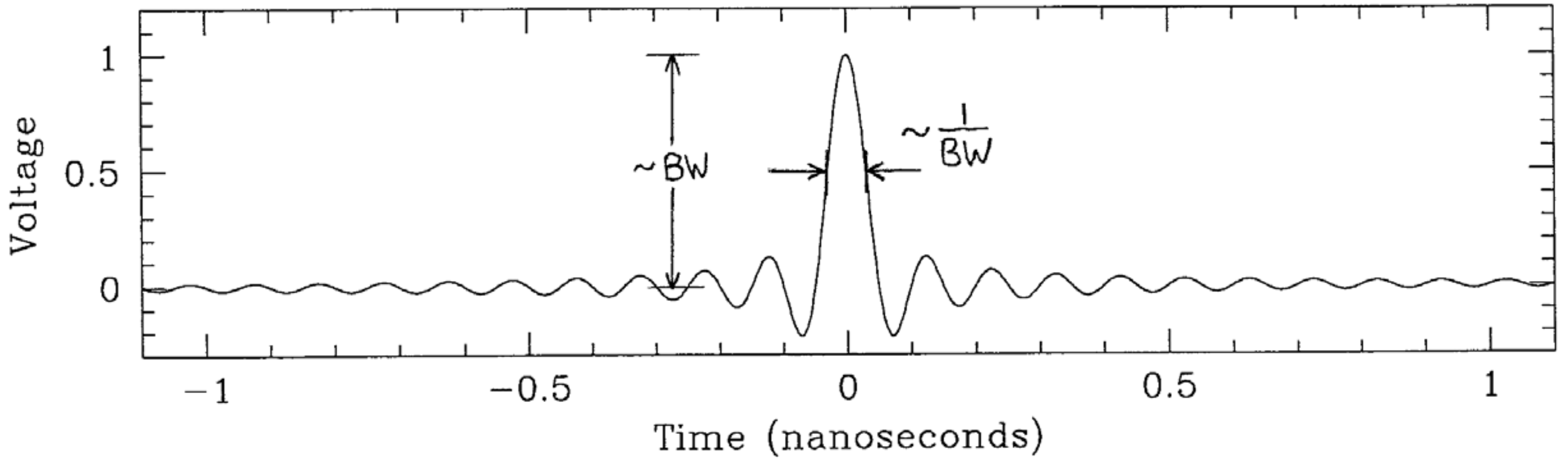
Say we want a calibration signal every 1 MHz, up to 10 GHz:



Add up all 10 000 tones and you get…

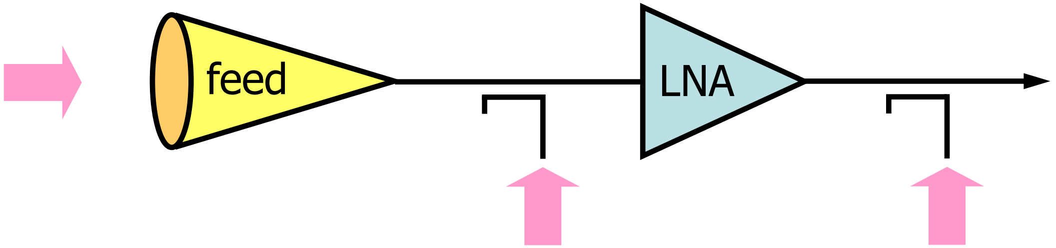
Phase cal in time domain, as pulses





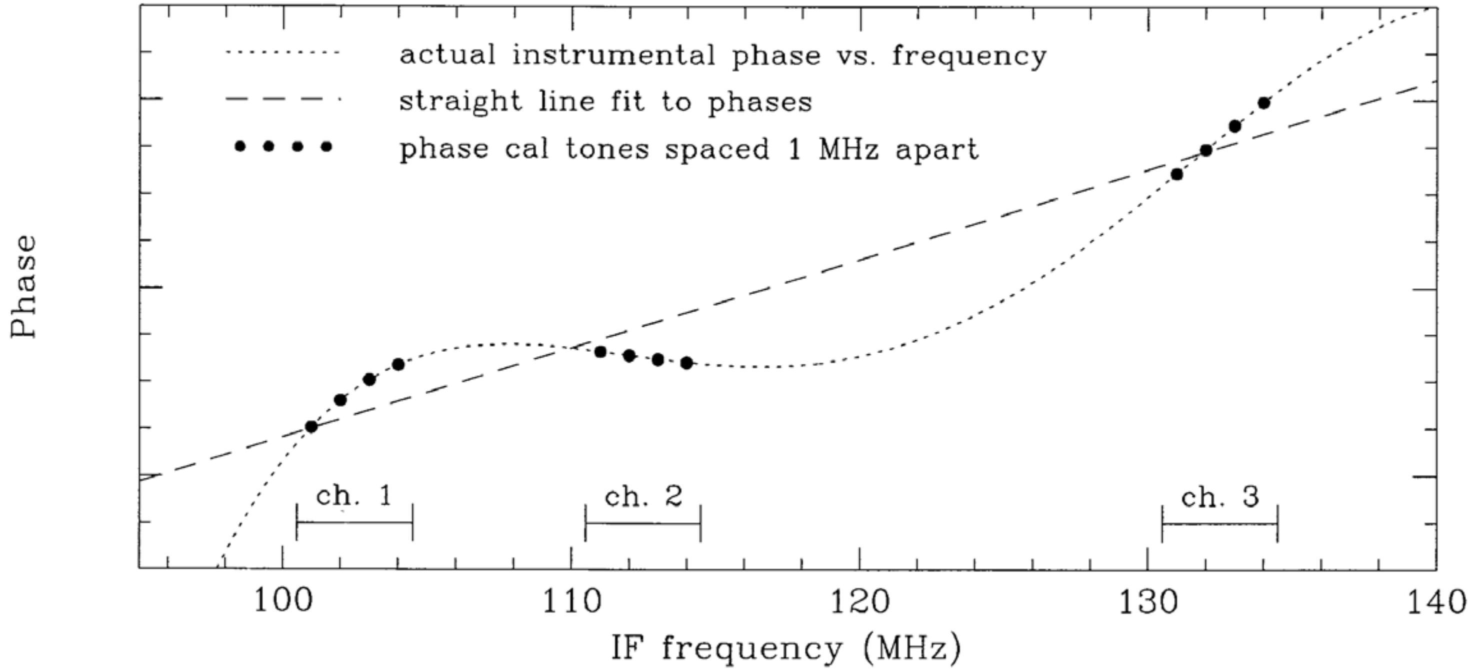
Phase calibration in VGOS

- Primary function remains as always: Measure instrumental phase variations over time and frequency.
- Phase differences between channels are far more stable in VGOS than in S/X VLBI, thanks to digital IF-to-baseband conversion in FPGAs.
- But digital back-ends have not made phase cal obsolete!
  - Phase cal needed in VGOS to measure
    - LO phase drifts between bands
    - Phase/delay drifts in RF/IF analog electronics and cables/fibers
- Increase pulse repetition rate from 1 to 5 or 10 MHz (and pcal tone spacing from 1 to 5 or 10 MHz), to avoid saturation.
  - Because baseband channels are wider (~32 MHz) than in S/X, each channel will still include many pcal tones.
- Options for pcal injection point:



Using multiple phase cal tones in each frequency channel

- With one phase cal tone per channel, only a phase offset can be estimated.
- But a simple phase offset may be inadequate if
  - instrumental phase varies rapidly over frequency, or
  - baseband tone frequency varies from channel to channel.
- Solution: Measure phase of multiple tones in each channel and solve for the frequency dependence of the phase.
- Advantages: Higher SNR and improved phase VLBI phase/delay stability.



VGOS 32 MHz channel data with phase cal tones

(Gruber, J., Nothnagel, A. and Böhm, J. (2021) 'VieRDS: A Software to Simulate Raw Telescope Data for very Long Baseline Interferometry', \pasp, 133(1022), p. 44503. doi: 10.1088/1538-3873/abeca4.

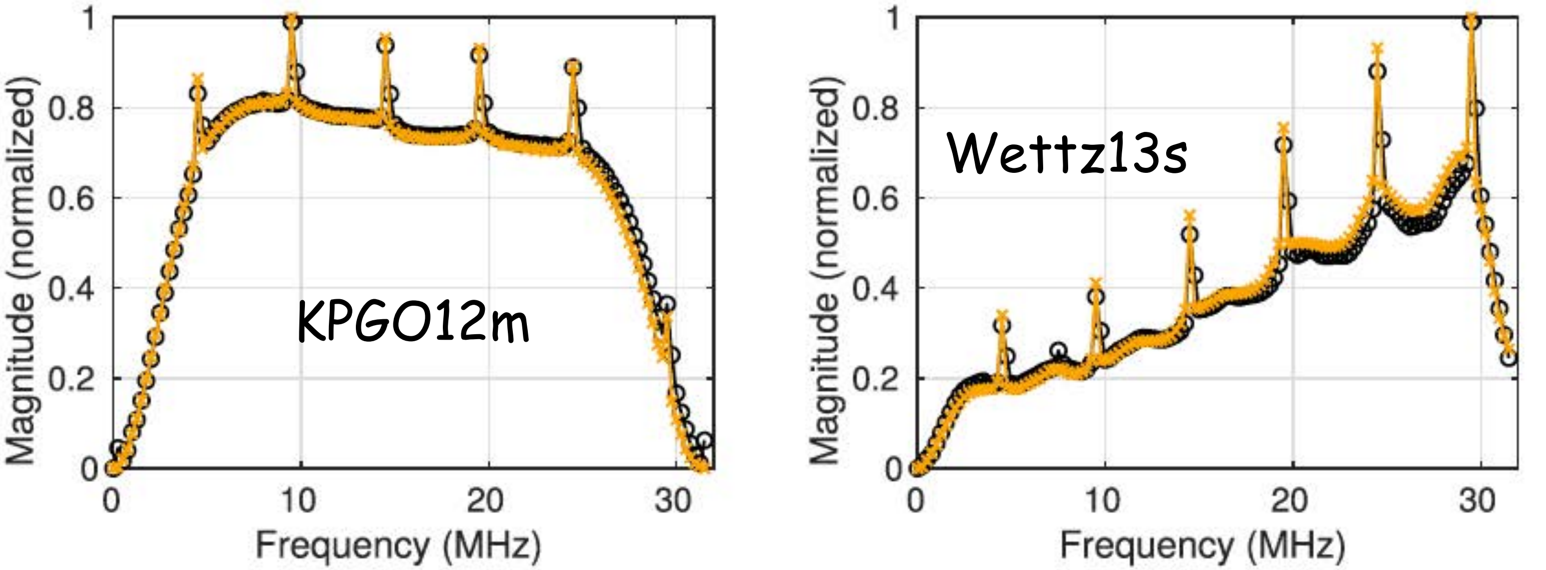


Figure 5. VieRDS is designed to simulate the characteristic frequency response of VLBI radio telescopes. The magnitudes of the frequency response of a 32 MHz channel for KOKEE12M (left) and WETTZ13S (right) is shown. The real observed frequency response is depicted in black color, whereas the simulated frequency response is depicted in orange color. The characteristic bandpass frequency response is clearly visible for both, real and simulated data, and reflects the characteristic bandpass response per station. The difference between real and simulated data is comparably small. Furthermore, the phase calibration signal with tones every 5 MHz are clearly visible for real and simulated data.

What is phase cal ***phase*** sensitive to?

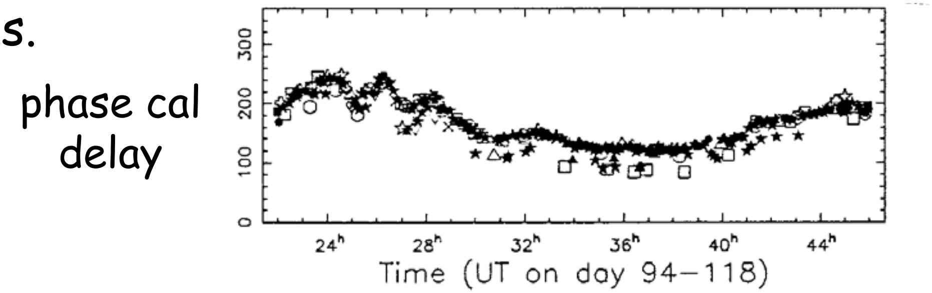
- Phase cal phase, measured at baseband/32 MHz channel, depends on:
  - 5 MHz phase at output of “ground unit” in control room
  - Electrical length of cable up to antenna unit
  - Phase delay through antenna unit, azimuth & elevation wraps
  - Phase delay from antenna unit to cal injection point
  - Phase of receiver LO
  - Phase delay through receiver, from cal injection point to IF output
  - Electrical length of RF/IF cable or fiber from receiver to control room
  - Phase delay through backend electronics (e.g., IF up- or down-converter, IF distributor, VC/BBC)
  - LO phase in backend mixers
- Any instrumental phase/delay that affects quasar (fringe) signal also affects phase cal signal except for
  - delay through antenna mechanical structure and
  - delay from feed to cal injection point.

What is phase cal ***amplitude*** sensitive to?

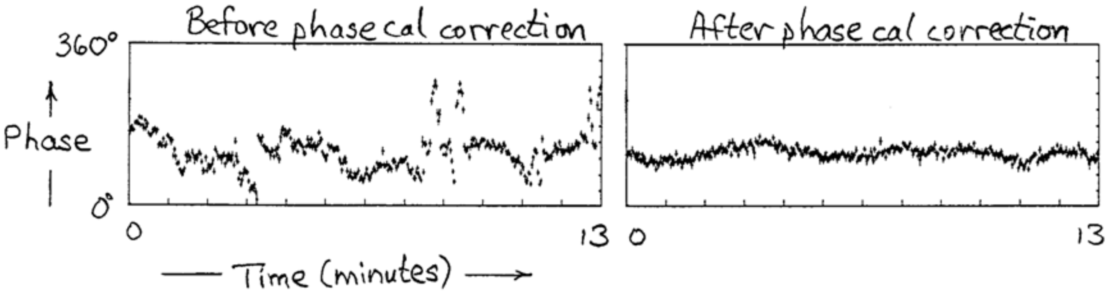
- Phase cal amplitude, as measured in baseband, depends on:
  - Phase cal voltage at antenna unit output
  - Loss between antenna unit and cal injection coupler
  - Coupling strength of cal injection coupler
  - Gain/loss through receiver, antenna cables, and backend
  - Coherence loss due to unstable LO in receiver or backend
  - Reflections in RF or IF path from antenna unit to backend
  - USB/LSB image rejection in downconverters (legacy S/X mainly)
  - Interference from spurious signals
- Phase cal amplitude, as measured in **digital** bit stream (sign bit or 2 bits with AGC), is the ratio between the analog phase cal amplitude and rms noise voltage.
  - Normalizing by the noise voltage makes the digital phase cal amplitude
    - insensitive to gain/loss through the receiver and backend (item 4 above), but now
    - sensitive to system temperature (including increase due to RFI).

Phase cal applications

- Measure changes in instrumental phase/delay during and between scans.
  - Example: Change in antenna RF/IF cable length at some antenna orientations.



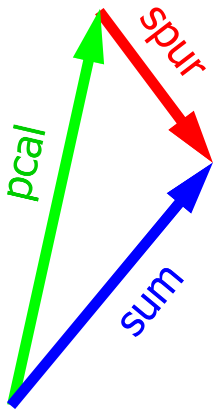
- Improve fringe phase coherence by correcting for LO phase variations
  - Example: Correction of LO jumps caused by intermittent cable connection.



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

- Test USB/LSB image rejection in downconverters, if still in use.

Spurious phase cal signals



- Definition: Spurious signal is a monochromatic signal
  - at the same RF, IF, or baseband frequency as a pcal tone
  - coherent over at least ~1 second with the pcal tone
  - but not the pcal signal that traversed the desired signal path.
- Spurs corrupt measured phase cal phase and amplitude.
  - For a -20 dBc spur, error in measured pcal signal is up to
    - 6° in phase ↔ 33 ps over 500 MHz
    - 10% in amplitude
- Examples of spurious signal sources:
  - Maser-locked signals generated in VLBI electronics (e.g., 5 MHz harmonics)
  - Phase cal images
  - Phase cal intermodulation/saturation
  - Secondary injection paths from pulse generator
  - Multipath from radiated phase cal
  - Cross-talk from other polarization
- Goal: Spurious signals >40 dB weaker than phase cal.
- For details, see pages 31-35 of ftp://ivscc.gsfc.nasa.gov/pub/TOW/tow2013/notebook/Corey.MW2.pdf

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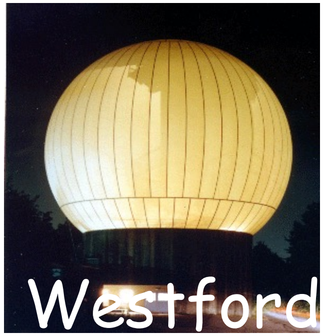
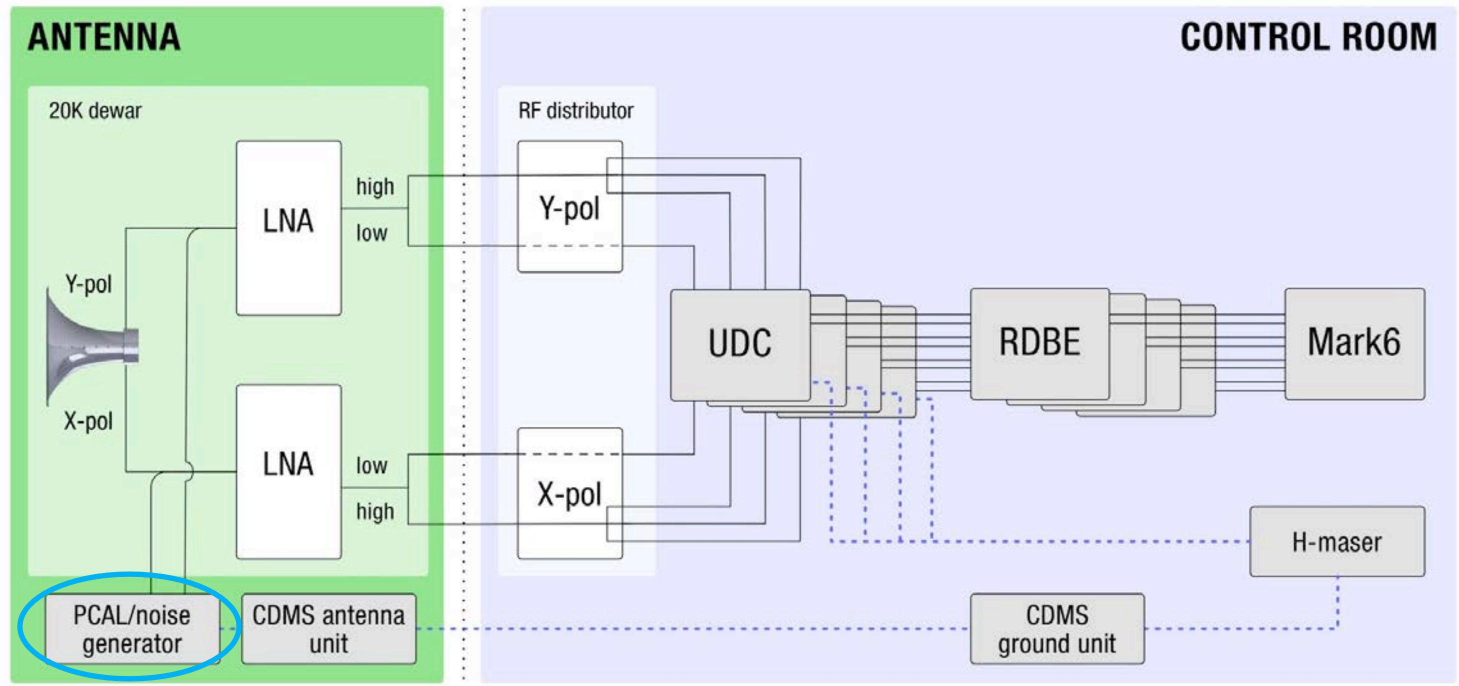
VGOS Signal Chain in the NASA network in the USA





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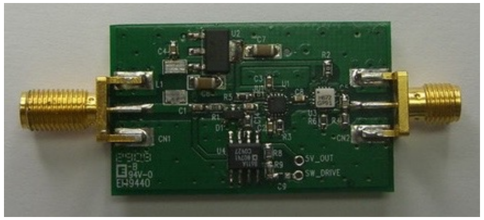
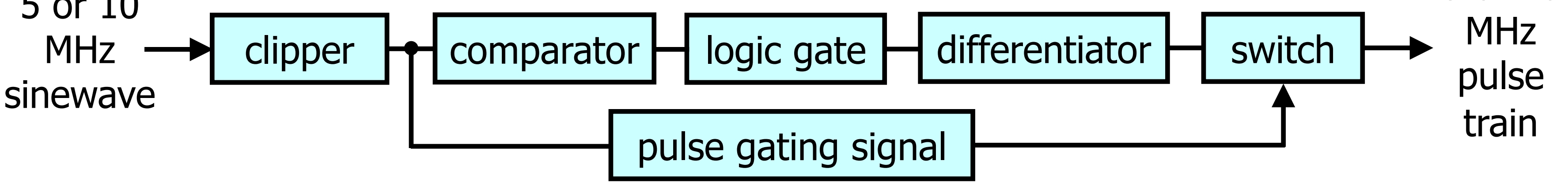
- Frequency Agile Up-Down Converter (UDC) enables tuning to different frequencies within the 2.2 to 14 GHz frequency range

Haystack "digital" phase calibrator

- Tunnel diodes at heart of many older pulse generators are no longer available.
- High speeds of today's logic devices allow a generator to be built around them.
- "Digital" phase calibrator designed by Alan Rogers (MIT Haystack).
- 5 or 10 MHz sinewave input; output pulse train at same frequency.
- Output spectrum flatter than in older tunnel diode design in legacy S/X.
- Pulse delay temperature sensitivity < 1 ps/°C with no external temp. control.
- Support for cable measurement system.
- Circuit diagram and details available at https://www.haystack.mit.edu/haystack-memo-series/vgos-memos/memo_VGOS_023/





5 or 10 MHz sinewave

clipper

comparator

logic gate

differentiator

switch

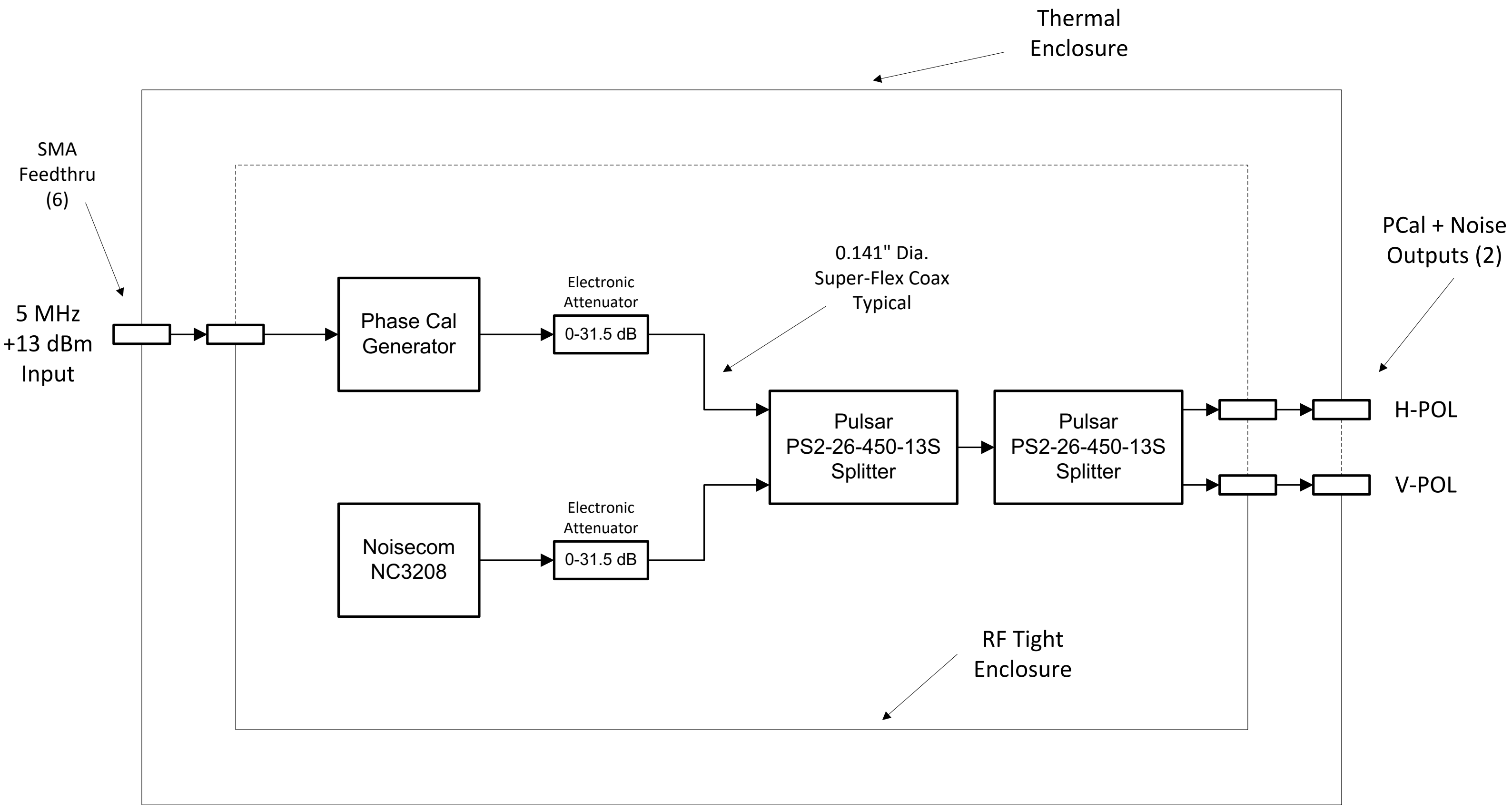
pulse gating signal

5 or 10 MHz pulse train

Broadband phase/noise calibration unit

- “Cal box” developed by Haystack Observatory for VGOS front-ends
- Cal box includes
  - digital phase calibrator
  - noise source
  - 0-31.5 dB programmable attenuators on phase and noise outputs
  - noise and phase cal gating
  - RF-tight enclosure
  - Peltier temperature controller ($\Delta T < 0.2$°C for 20°C change in ambient T)
  - monitoring of temperature, 5 MHz input level, attenuation, gating
- Two identical RF outputs with combined pcal+noise
- Equalizers for phase or noise cal signals can be added if necessary.

Broadband phase/noise cal box: RF connections

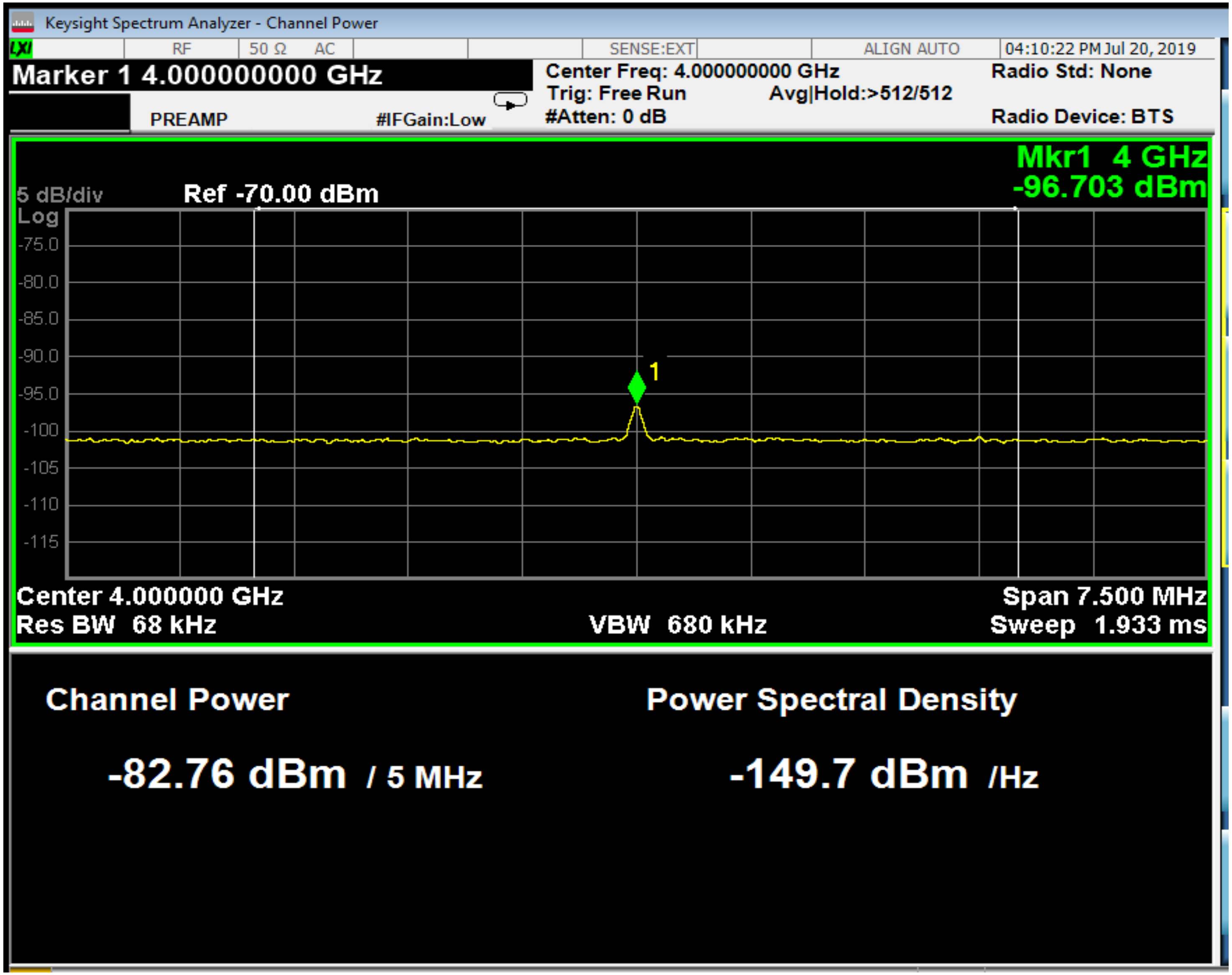


Broadband Phase/Noise Calibration Unit

RF Wiring Diagram

12th IVS Technical Operations Workshop - May 1-4, 2023

How to measure and adjust pCal to noise power ratio ?



Keysight Spectrum Analyzer - Channel Power

RF | 50 Ω AC | SENSE:EXT | ALIGN AUTO | 04:10:22 PM Jul 20, 2019

Marker 1 4.000000000 GHz

PREAMP #IFGain:Low

Center Freq: 4.000000000 GHz
Trig: Free Run Avg|Hold:>512/512
#Atten: 0 dB

Radio Std: None
Radio Device: BTS

Mkr1 4 GHz
-96.703 dBm

5 dB/div Ref -70.00 dBm
Log

Center 4.000000 GHz
Res BW 68 kHz
VBW 680 kHz
Span 7.500 MHz
Sweep 1.933 ms

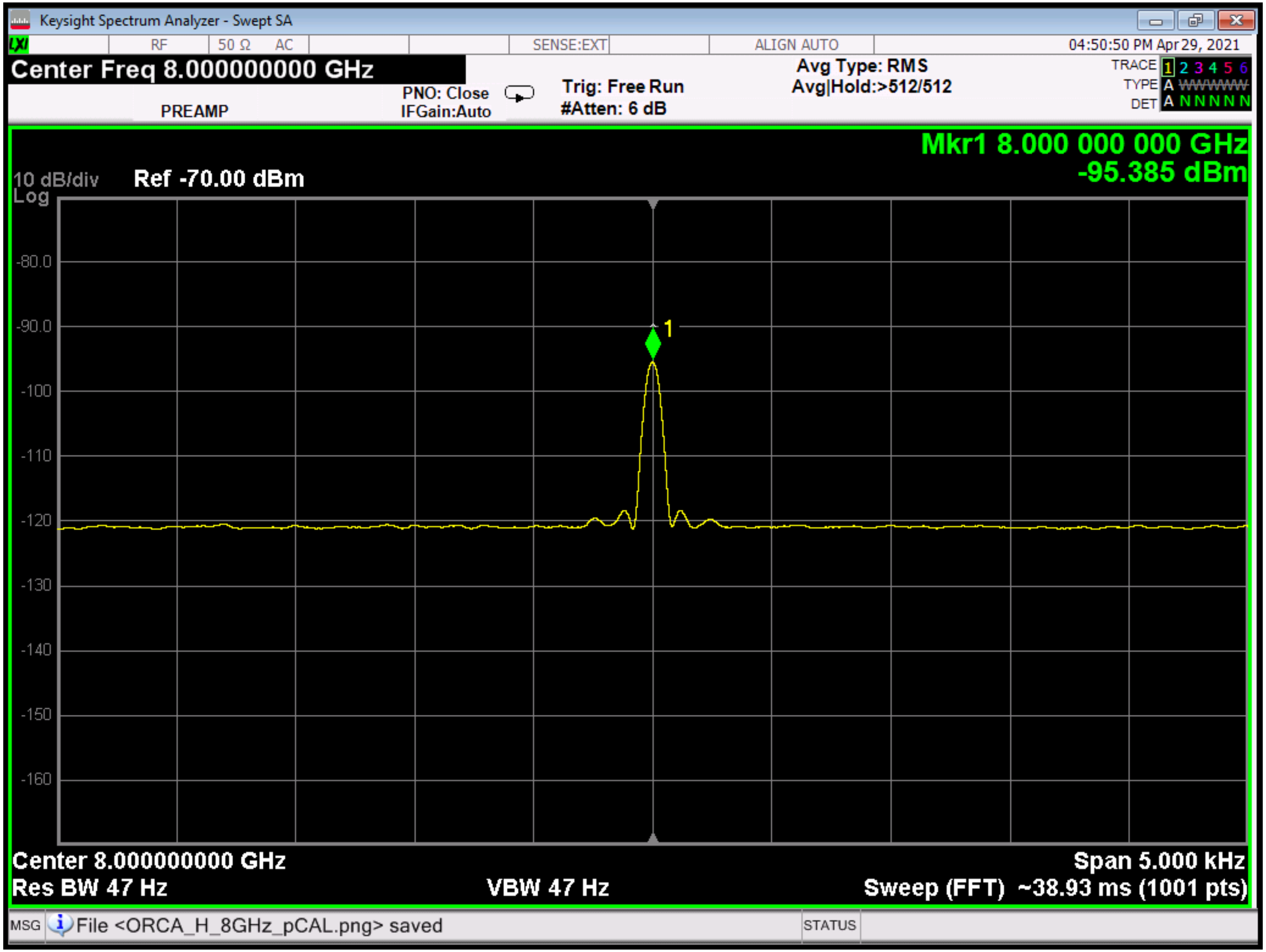
Channel Power

-82.76 dBm / 5 MHz

Power Spectral Density

-149.7 dBm /Hz

More accurate measurement of a single pCal tone



SENSE:EXT

ALIGN AUTO

04:50:50 PM Apr 29, 2021

Center Freq 8.000000000 GHz

PREAMP

PNO: Close
IFGain:Auto

Trig: Free Run
#Atten: 6 dB

Avg Type: RMS
Avg|Hold:>512/512

Mkr1 8.000 000 000 GHz
-95.385 dBm

Ref -70.00 dBm

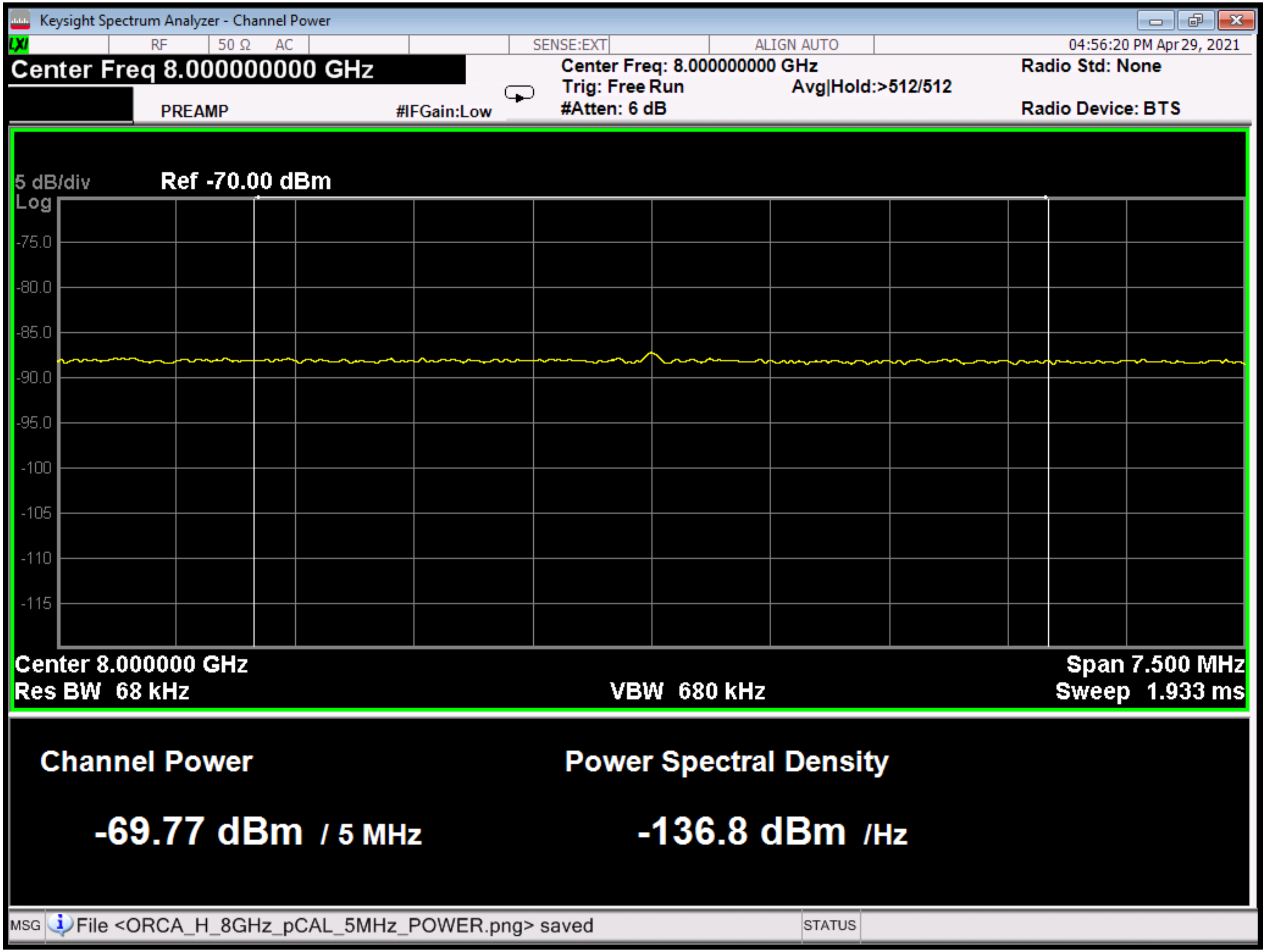
Center 8.000000000 GHz
Res BW 47 Hz

VBW 47 Hz

Span 5.000 kHz
Sweep (FFT) ~38.93 ms (1001 pts)

File <ORCA_H_8GHz_pCAL.png> saved

5 MHz noise power using Channel Power mode



Keysight Spectrum Analyzer - Channel Power

RF 50 Ω AC SENSE:EXT ALIGN AUTO 04:56:20 PM Apr 29, 2021

Center Freq 8.000000000 GHz

PREAMP #IFGain:Low

Center Freq: 8.000000000 GHz
Trig: Free Run Avg|Hold:>512/512
#Atten: 6 dB

Radio Std: None
Radio Device: BTS

Center 8.000000 GHz
Res BW 68 kHz
VBW 680 kHz
Span 7.500 MHz
Sweep 1.933 ms

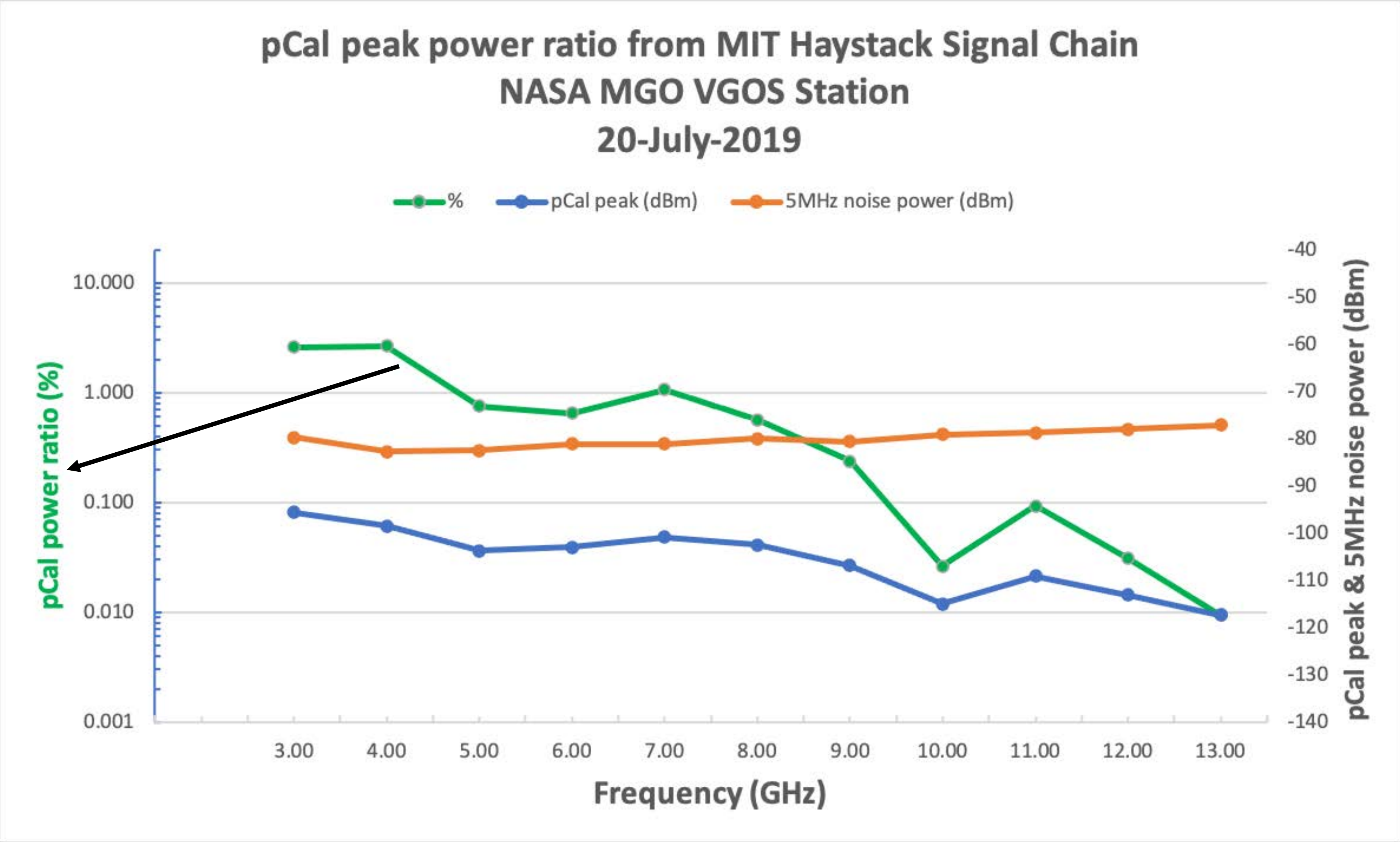
Channel Power

-69.77 dBm / 5 MHz

Power Spectral Density

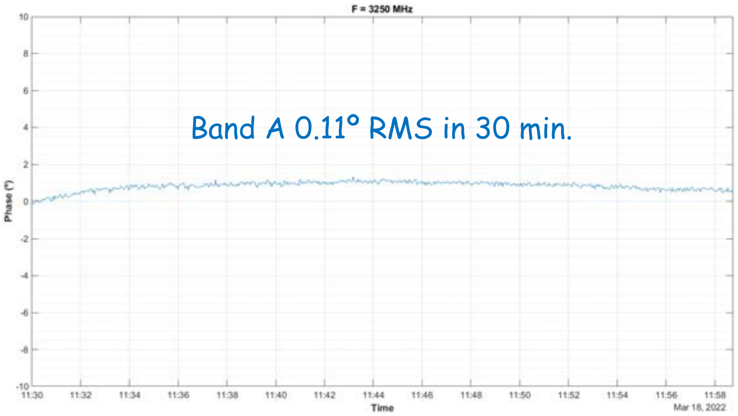
-136.8 dBm /Hz

MSG File <ORCA_H_8GHz_pCAL_5MHz_POWER.png> saved STATUS

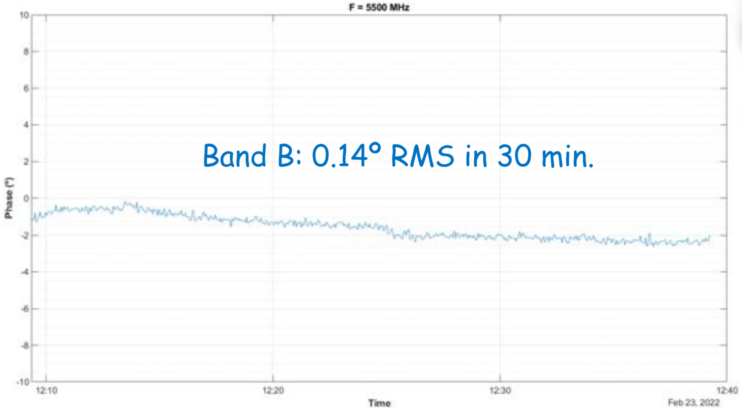

pCal peak power ratio from MIT Haystack Signal Chain
NASA MGO VGOS Station
20-July-2019
%
pCal peak (dBm)
5MHz noise power (dBm)
pCal power ratio (%)
10.000
1.000
0.100
0.010
0.001
pCal peak & 5MHz noise power (dBm)
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
13.00
Frequency (GHz)

Yebes Observatory, Spain
PhaseCal upgrade (I): New pulse generator

https://www.amcad-engineering.com/product/harmonic-phase-reference-hpr/



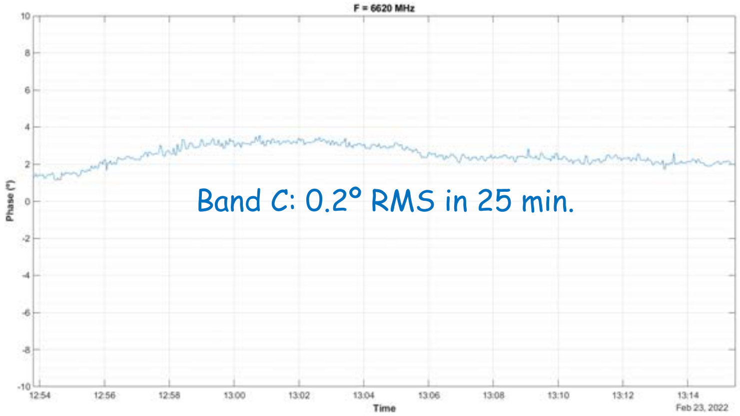
Band A 0.11° RMS in 30 min.



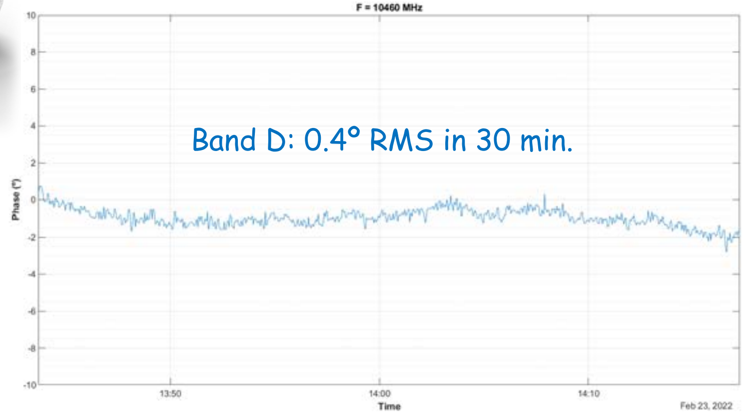
Band B: 0.14° RMS in 30 min.

Phase stability of single PhaseCal tone in each VGOS band

(@ room temp. w/o temp control)

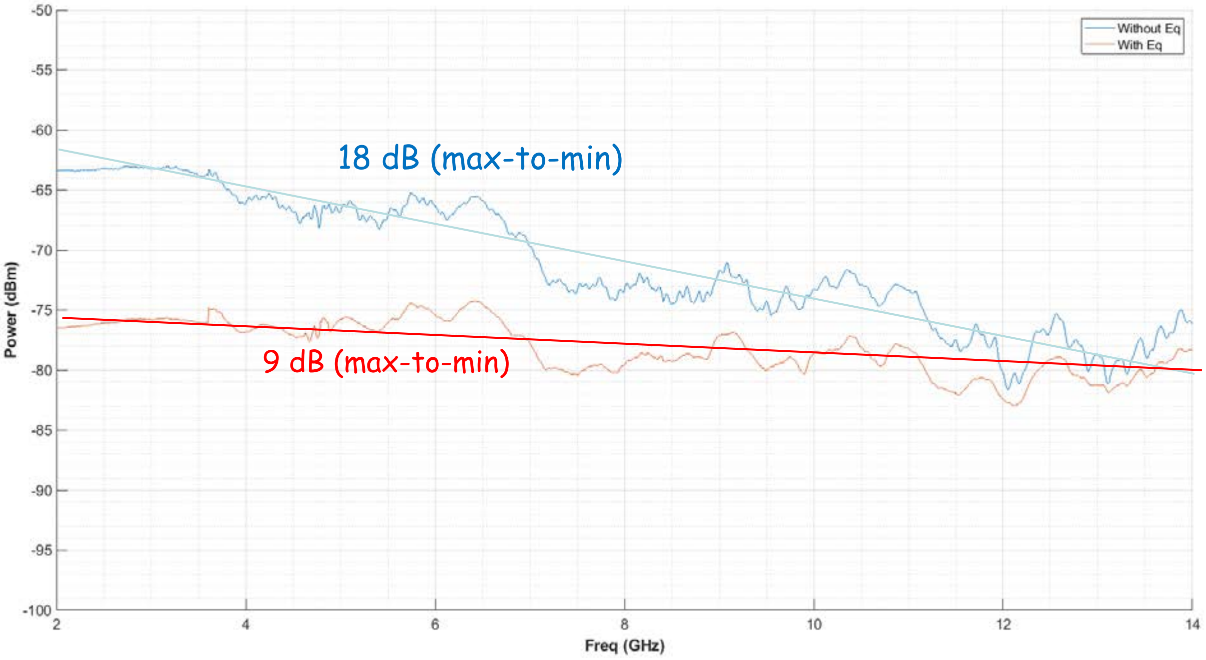


Band C: 0.2° RMS in 25 min.



Band D: 0.4° RMS in 30 min.

Yebes Observatory, Spain
PhaseCal upgrade (II): Equalizer

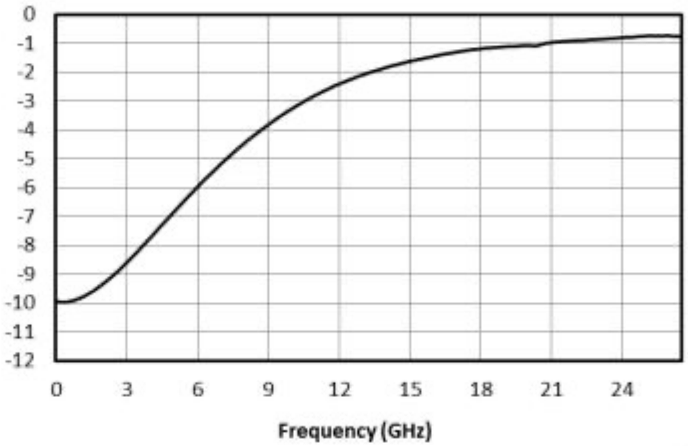


18 dB (max-to-min)

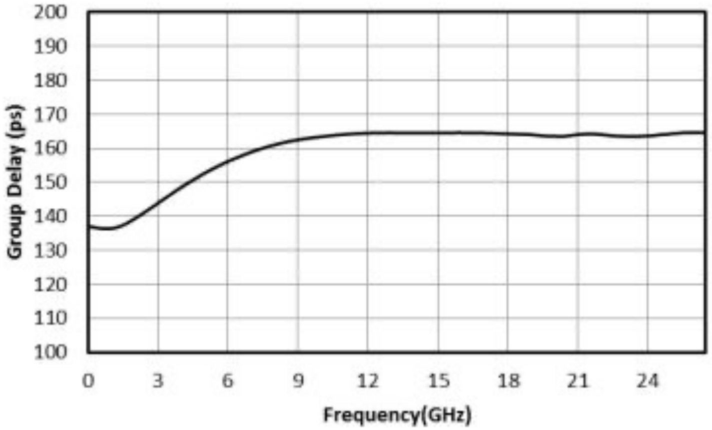
9 dB (max-to-min)

Onsala Observatory, Sweden
PhaseCal upgrade: Equalizer

Equalizer Amplitude Response

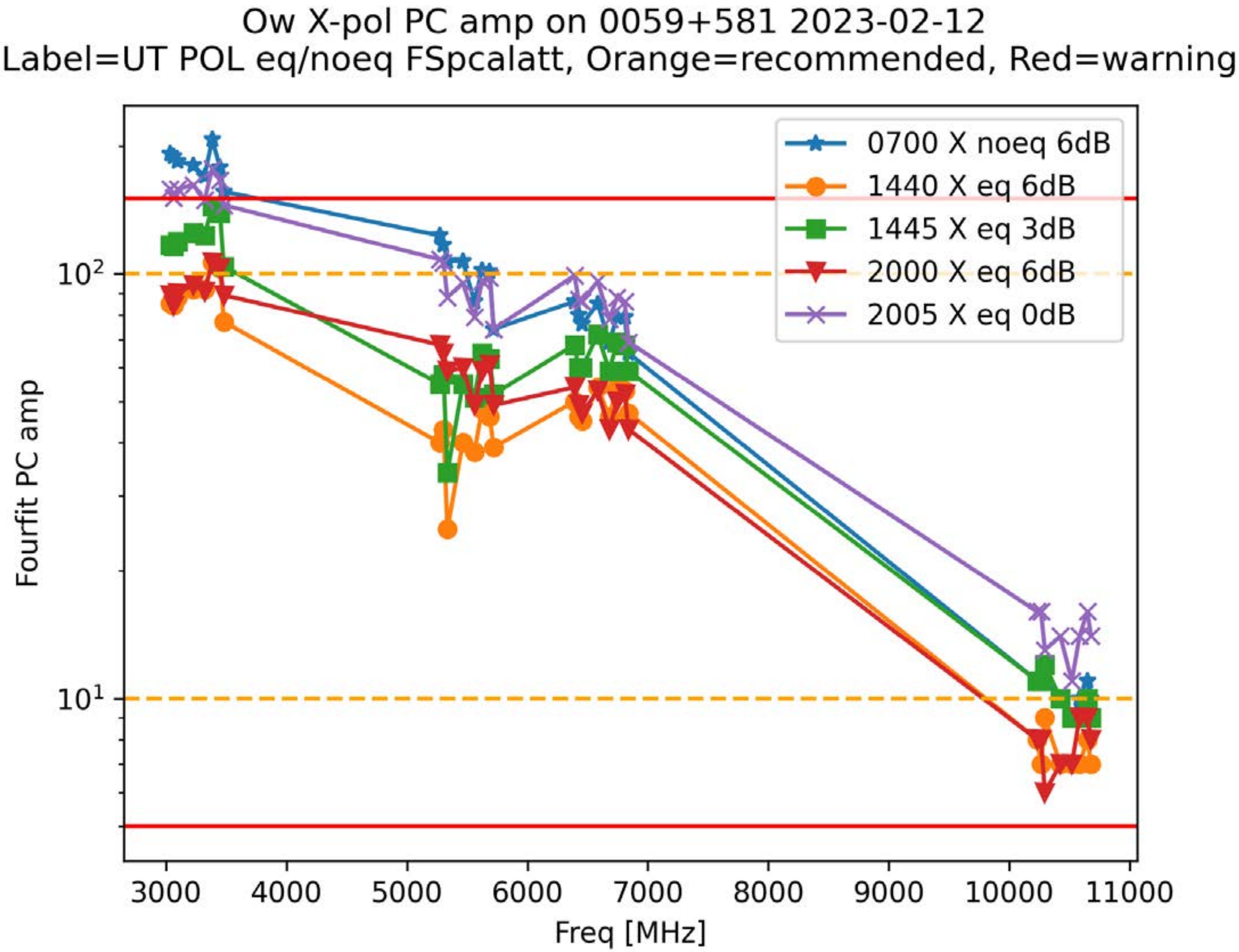


Equalizer Phase/Delay Response



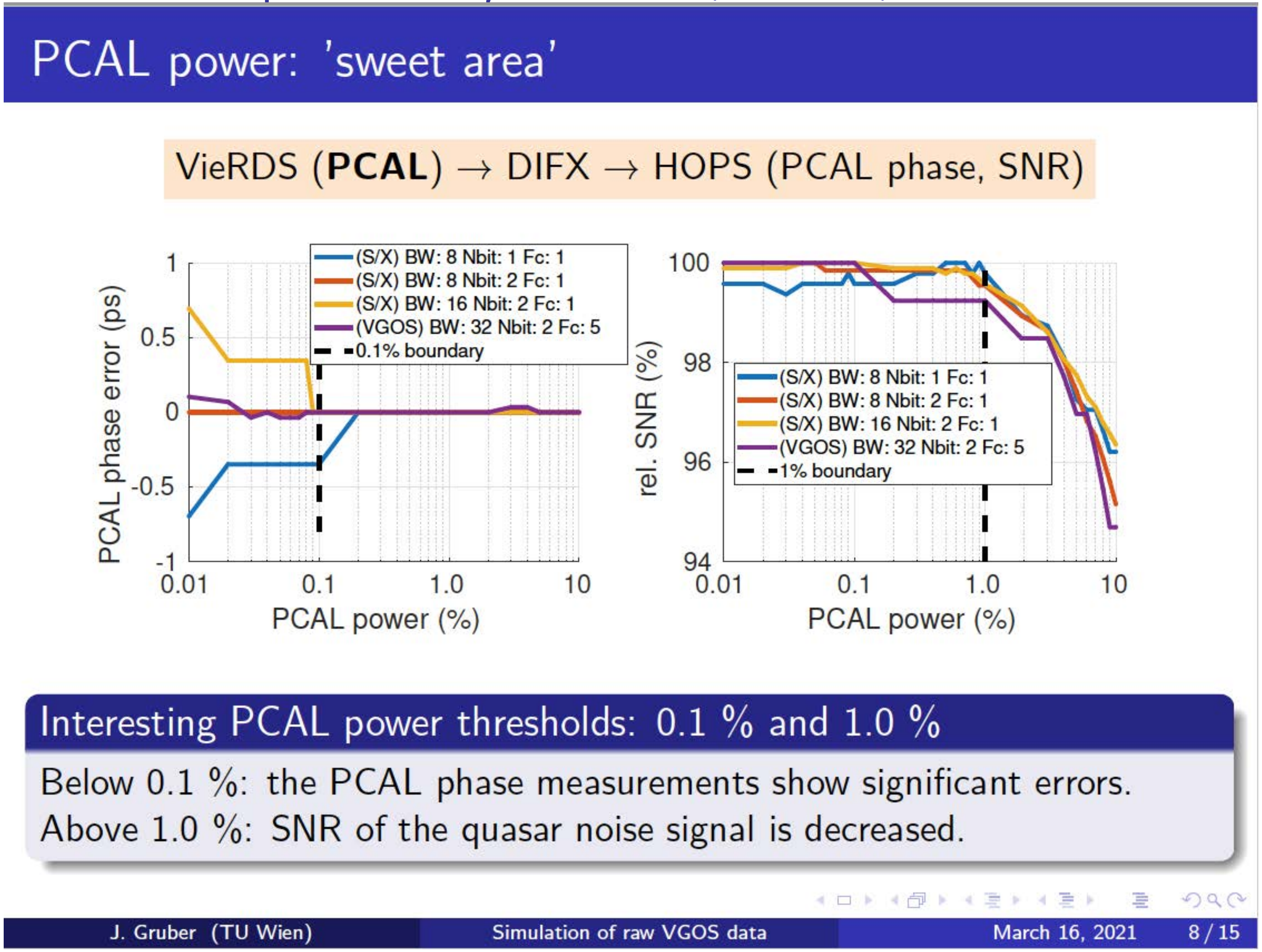
Caution: the dispersion in the equalizer output (group delay a function of frequency) looks to be highly correlated with the TEC effect. Needs to be small enough and absorbed into station clock parameter

Onsala Observatory, Sweden
PhaseCal upgrade: Equalizer



pCal peak power to noise ratio- ‘sweet spot’

presented by J. Gruber (TU Wien) at EVGA2021, Mar 16, 2021



PCAL power: ’sweet area’

VieRDS (**PCAL**) → DIFX → HOPS (PCAL phase, SNR)

Interesting PCAL power thresholds: 0.1 % and 1.0 %

Below 0.1 %: the PCAL phase measurements show significant errors.
Above 1.0 %: SNR of the quasar noise signal is decreased.

J. Gruber (TU Wien) | Simulation of raw VGOS data | March 16, 2021 | 8 / 15

BBDev-031 Notes on phase cal extraction, power levels, total rail count, and SNR (2010)
BBDev-034 Phase Cal Amplitude RF Frequency Dependence (2009)
https://www.haystack.mit.edu/haystack-memo-series/vgos-memos/

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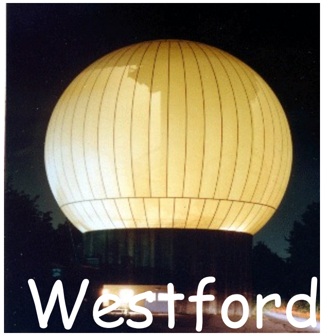
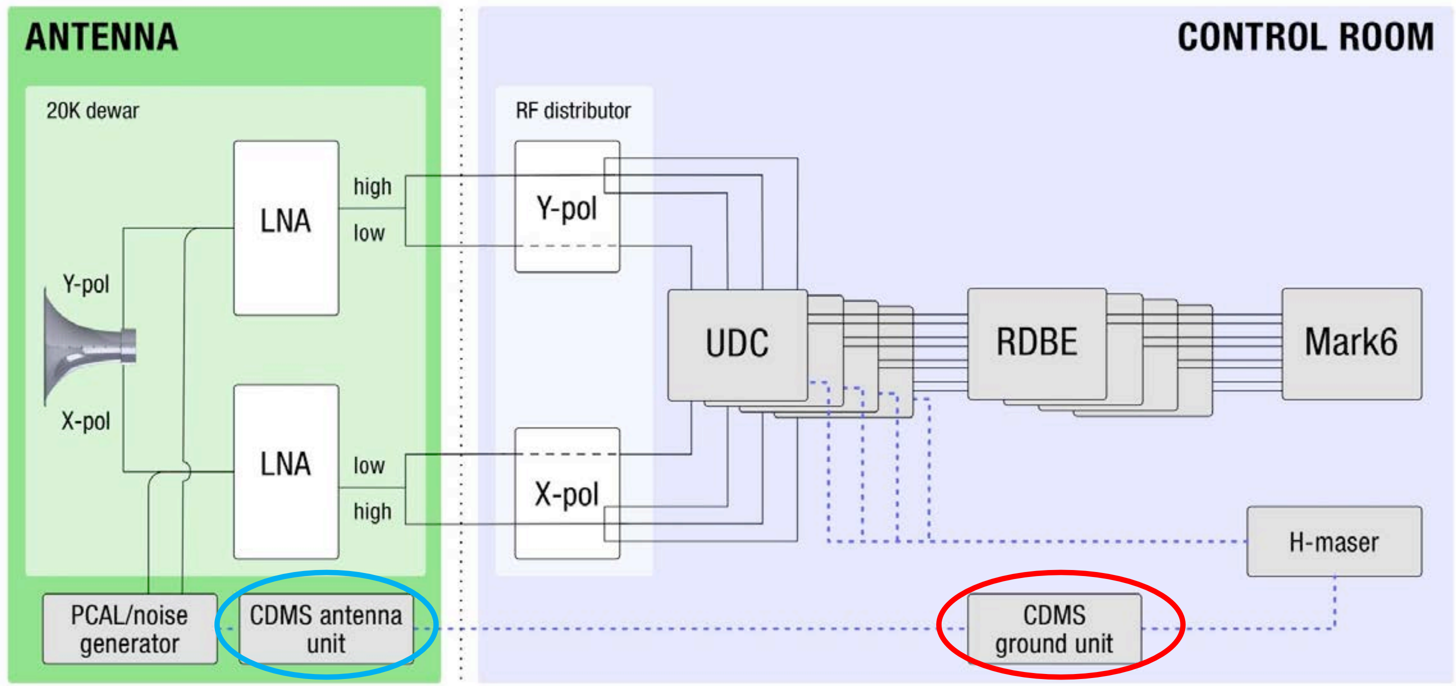
VGOS Signal Chain in the NASA network in the USA





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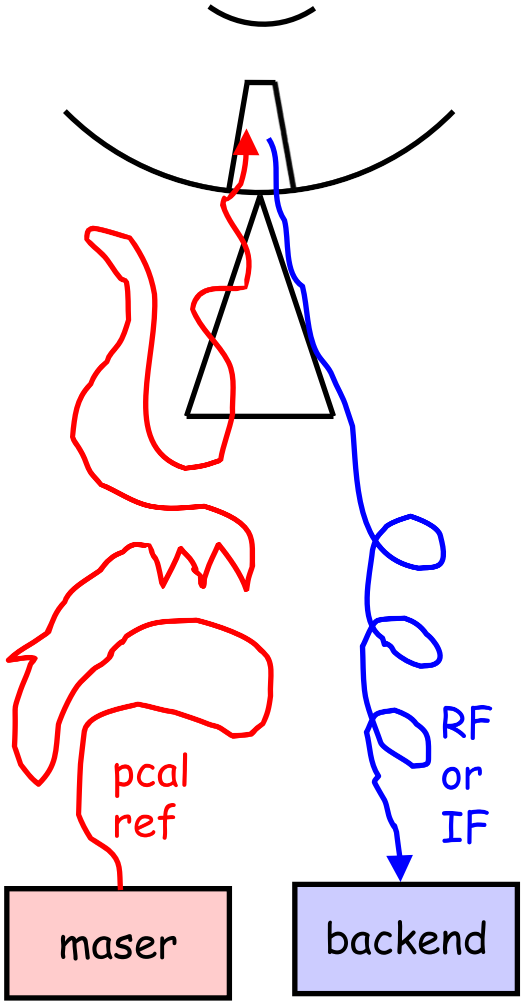
- Frequency Agile Up-Down Converter (UDC) enables tuning to different frequencies within the 2.2 to 14 GHz frequency range

Why cable calibration?

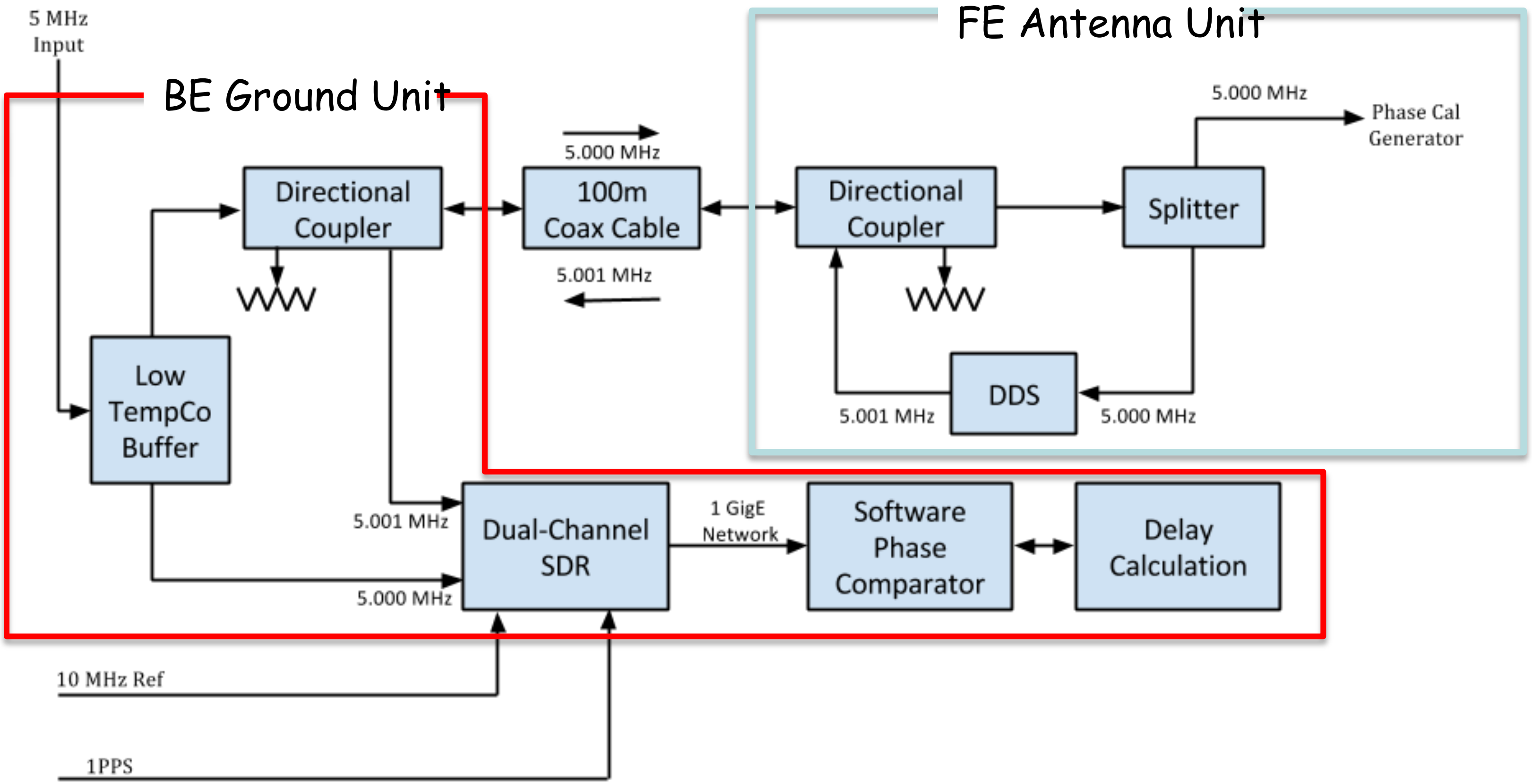
- Where is the VLBI station?
  - On the antenna, at the intersection of axes,
  - **not** at the backend or maser.
- For **absolute** UT1 (= Earth rotation angle relative to Universe) measurements, absolute length of uplink and downlink must be measured.
  - We're not doing absolute (yet), so relax!
- For relative UT1 & other geodetic measurements, only variations in downlink (measured with phase cal) and uplink must be accounted for.
- Electrical length of uplink must be
  - stable or, if not,
  - measured for post-observation correction.



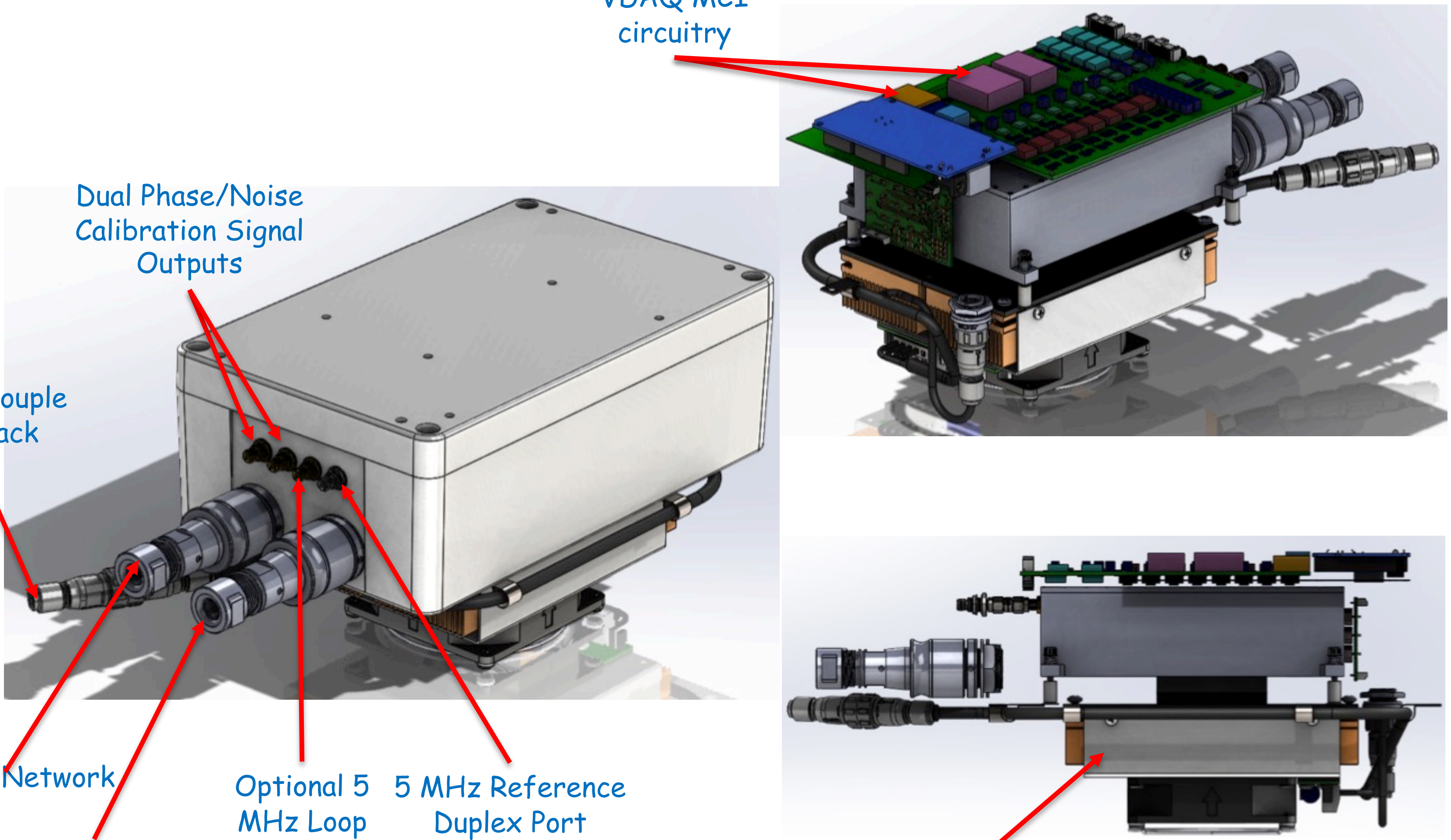
Cable calibration systems

- Measurement techniques include:
    - Use vector voltmeter in control room to measure phase difference between reference signals sent to receiver and returned from receiver.
        - If a single cable is used for transmitting both directions, reflections along the way can cause measurement errors.
        - If two cables are used, they may not behave in same manner.
    - Modulate reference signal in antenna unit before returning it to control room, to distinguish it from a reflected signal.
        - This is method used in Mark4 cable cal system
- A cable measurement system is certainly needed for VGOS systems with a coaxial cable uplink.
    - VGOS limit on orientation-dependent uplink cable delay variations = <0.3 ps
    - Observed delay variations in RG-214 and LMR-400UF 5 MHz cables on GGAO and Westford antennas are >~1 ps at best, and can increase over time.
- KPGO & MGO Signal Chains incorporate the new integrated calibrator module and cable delay is used in deriving the geodetic results.

Cable Delay Measurement System (CDMS) Block Diagram



Calibration – Antenna Unit



VDAQ MCI circuitry

Dual Phase/Noise Calibration Signal Outputs

Thermocouple Feedback

Shielded Network

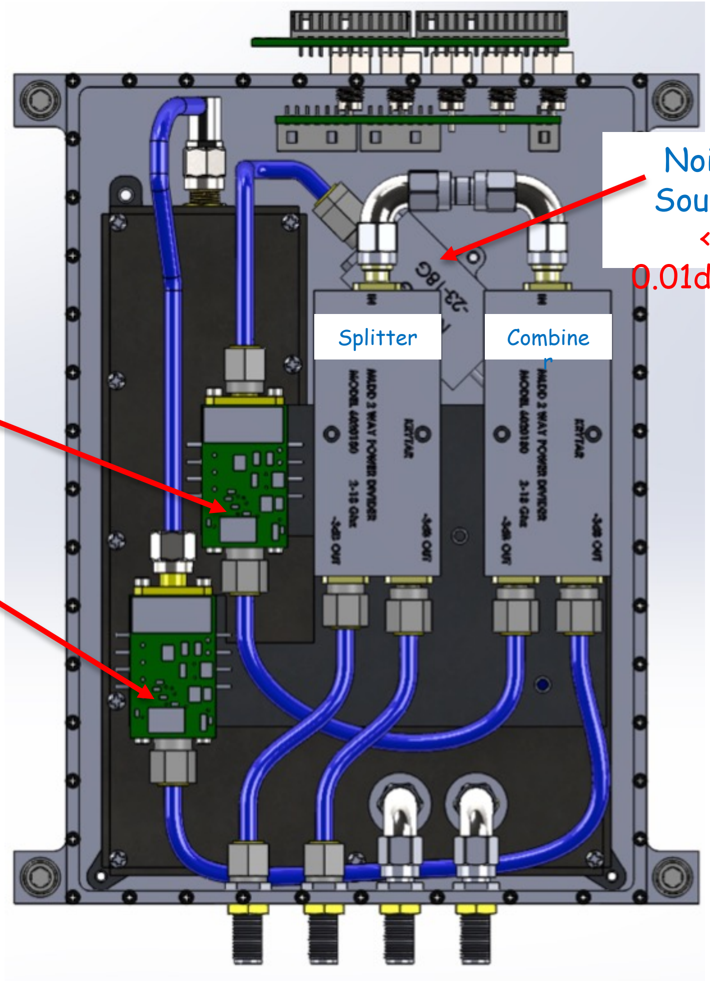
Main Power Sync Noise Drive

Optional 5 MHz Loop Back

5 MHz Reference Duplex Port

TE Heater

Calibration – Antenna Unit



Power/Control Entry

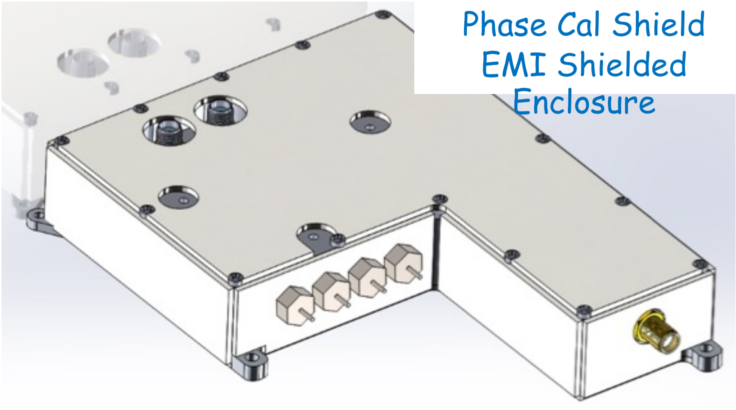
Noise Source < 0.01dB/°C

Splitter

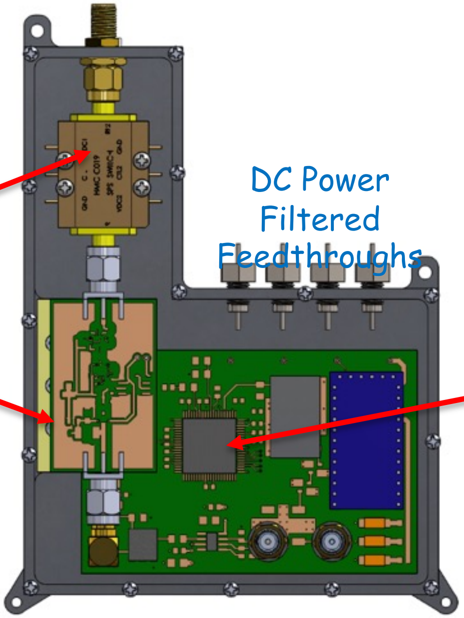
Combiner

Noise Level Control

Pcal Level Control



Phase Cal Shield EMI Shielded Enclosure



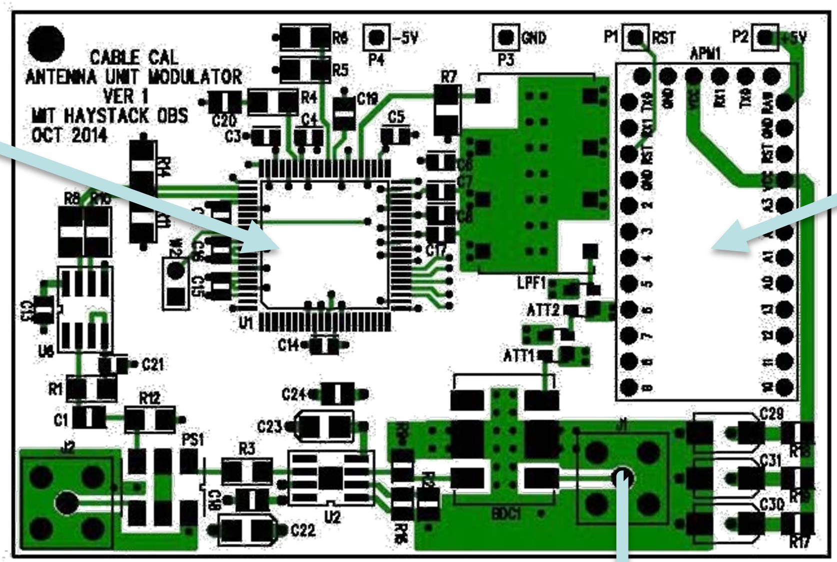
DC Power Filtered Feedthroughs

Pcal Generation ~1ps/°C

Antenna Reference Modulator

Calibration – Antenna Unit

Antenna Reference Modulator



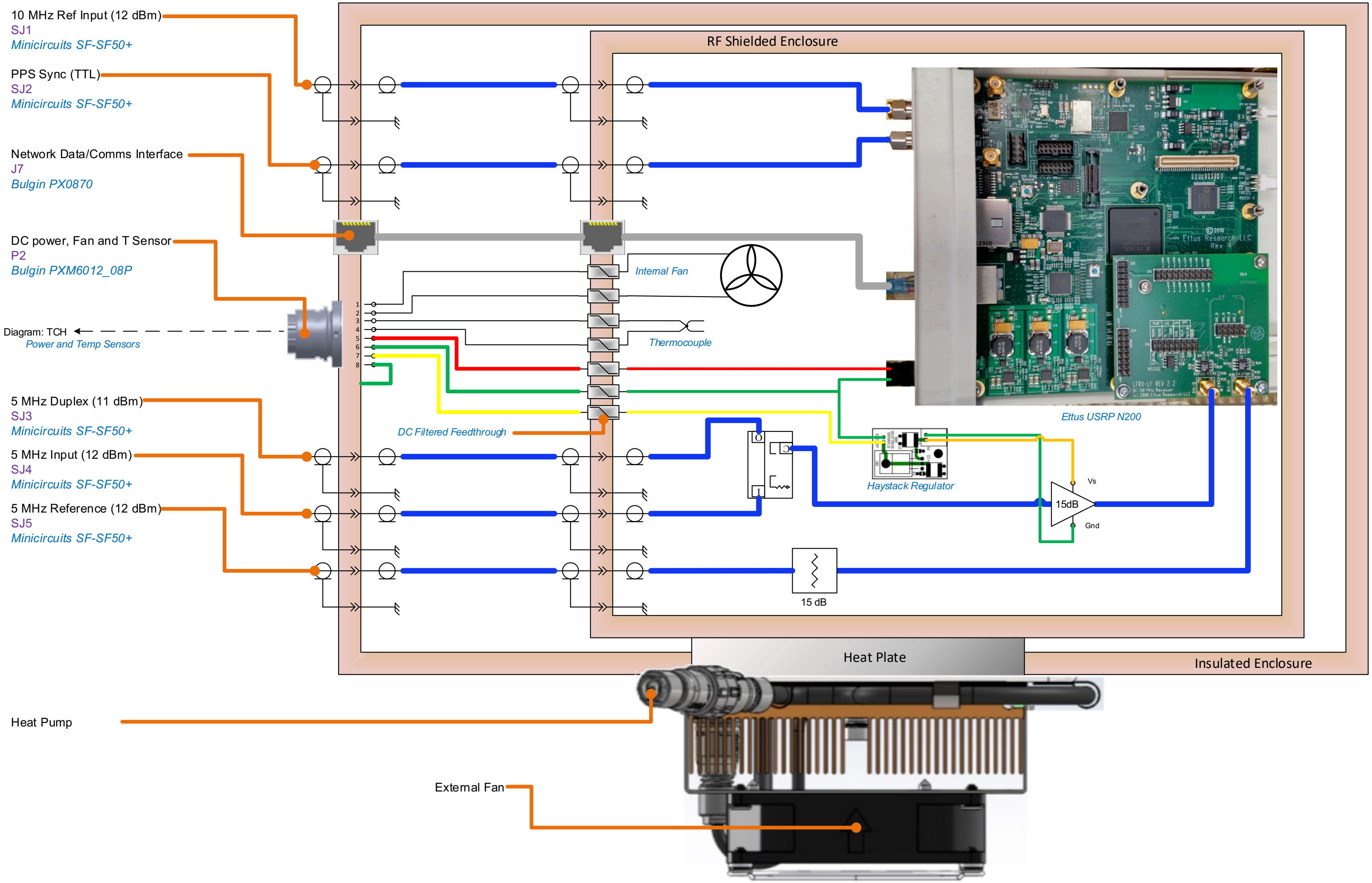
Modulation Synthesizer

Programming uCom

Cable Reference

Pulse Generator

Calibration - Ground Unit



10 MHz Ref Input (12 dBm)
SJ1
Minicircuits SF-SF50+

PPS Sync (TTL)
SJ2
Minicircuits SF-SF50+

Network Data/Comms Interface
J7
Bulgin PX0870

DC power, Fan and T Sensor
P2
Bulgin PXM6012_08P

Diagram: TCH
Power and Temp Sensors

5 MHz Duplex (11 dBm)
SJ3
Minicircuits SF-SF50+

5 MHz Input (12 dBm)
SJ4
Minicircuits SF-SF50+

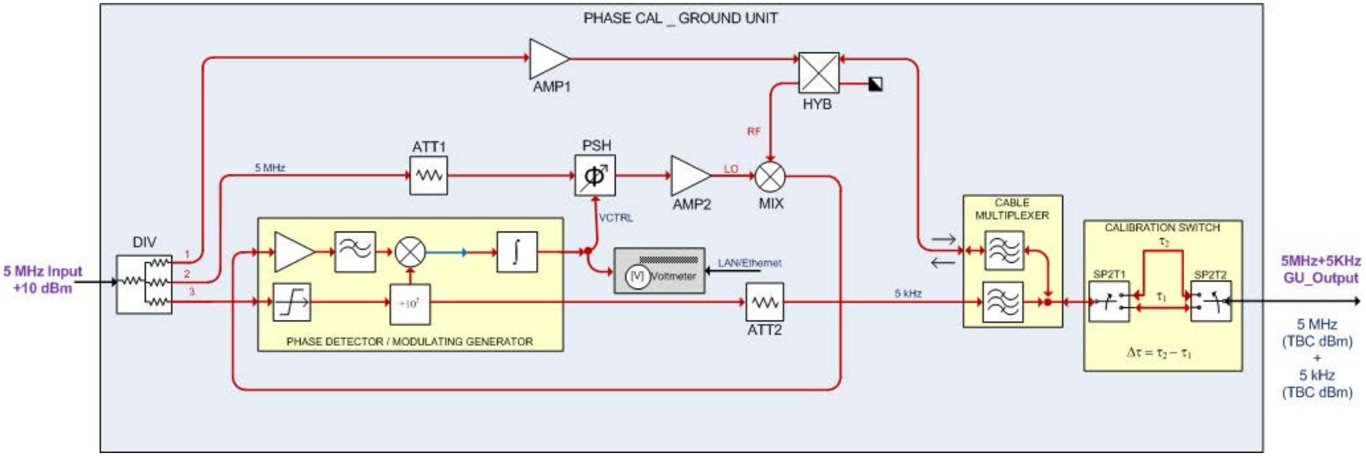
5 MHz Reference (12 dBm)
SJ5
Minicircuits SF-SF50+

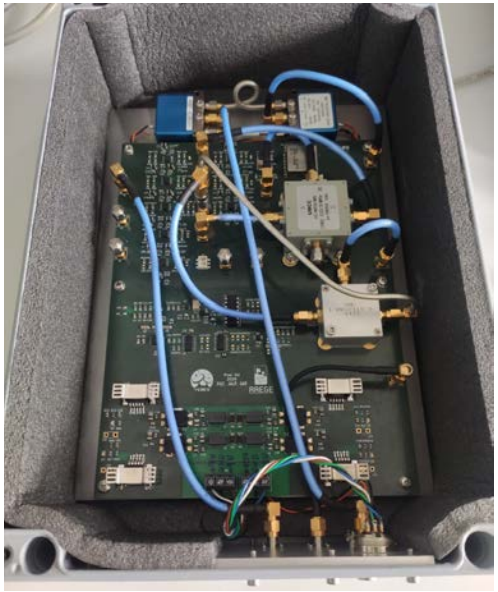
Heat Pump

External Fan

12th IVS Technical Operations Workshop - May 1-4, 2023

Yebes Observatory, Spain CDMS upgrade (I)





García-Carreño, P.; González-García, J.; Patino-Esteban, M.; Beltrán-Martínez, F.J.; Bautista-Durán, M.; López-Espí, P.L.; López-Pérez, J.A. **New Cable Delay Measurement System for VGOS Stations**. *Sensors* **2022**, *22*, 2308. https://doi.org/10.3390/s22062308

Representative cable cal systems deployed

- Some systems stabilize the transmitted phase rather than measure variations.
- Most optical fiber systems send the same frequency up and down separate fibers due to directional crosstalk in a single fiber.
  - Do lengths of up and down fibers change by the same amount?
  - Possible to use WDM on one fiber –send at one wavelength & receive at another

System	*Cable no./type*	*Frequencies*	*Comments*
Mark 4	1 coax	5 MHz & 5 kHz	Does not meet VGOS spec.
VLBA	2 coax	500 MHz & 2 kHz	Modulates 500 MHz in frontend.
Kokee Park	2 fibers	500 MHz	
NRAO 14-m	2 fibers	500 MHz	
JPL DSN	1 fiber	modulated 1 GHz	Phase stabilization
EVLA	2 fibers	512 MHz	
Arecibo	2 fibers	1.45 GHz	For existing 12m antenna
KVG	1 coax or fiber	2 near 700 MHz	Phase stabilization or meas.
NASA VGOS	1 coax or fiber	5 MHz	In operation at Westford, KPGO, OSO, MGO, soon at FGO
Yebes VGOS	1 coax	10 MHz	In operation at Yebes 13m, ..

Time and frequency distribution for the Onsala twin telescopes

Helldner L., Johansson K.-Å., Pettersson L. E. & Hobiger T.
Onsala Space Observatory, Chalmers University of Technology, Sweden

Motivation

In order to realize the full potential of twin telescopes it is crucial to operate a time and frequency (T&F) distribution system which ensures that both signal chains are connected to a single frequency standard. For the Onsala Twin Telescopes (OTT) time and frequency are obtained from the H-maser which is also shared with the 20 m telescope.

System description

The core of the frequency transfer to the telescopes is based on a pair of custom made WDM (Wavelength Division Multiplexer) fiber optical transceivers from RFOptics Ltd, enabling 5 MHz bidirectional transfer in a single fiber over the distance of 850 m. These links are complemented with a slightly modified KPGO type Cable Delay Measuring System (CDMS) from MIT-Haystack Observatory.

One-direction fiber tests with OTT-N: short-term stability

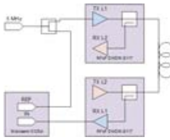


Fig. 1: Schematics of the one-direction optical transfer test setup, using two fibers, looped in the telescope, with a total distance of about 1700 m, with received signal compared with H-maser 5 MHz using a Microsemi 5125A test set.

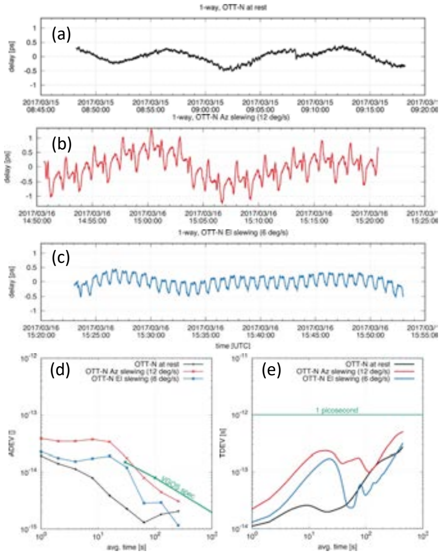


Fig. 2: One-direction phase measurement results with telescope at rest (a) and while slewing fast (b–c). The corresponding Allan and time deviation results are depicted in (d) and (e), respectively.

Bidirectional fiber tests with OTT-N: long-term stability

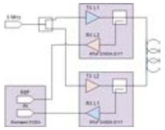


Fig. 3: Schematics of the bidirectional optical transfer test setup with differential measurement of the received signals propagating through the same fibers used in the one-direction test.

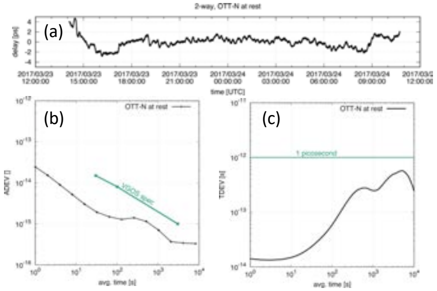


Fig 4: Bidirectional fiber test phase measurement results with the telescope at rest (a). The corresponding Allan and time deviation results are depicted in (b) and (c), respectively.

CDMS tests with OTT-S: long-term stability

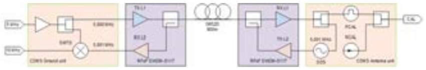


Fig. 5: Final test setup, bidirectional transfer through one fiber, 850 m long, using the CDMS.

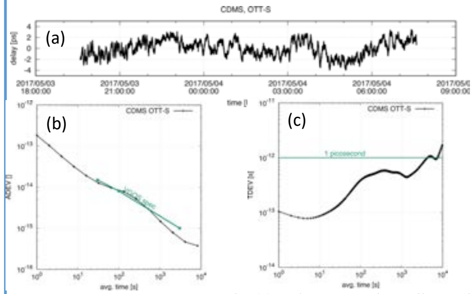


Fig. 6: CDMS measurement results (a) and corresponding Allan and time deviation results shown in (b) and (c), respectively.

Conclusions

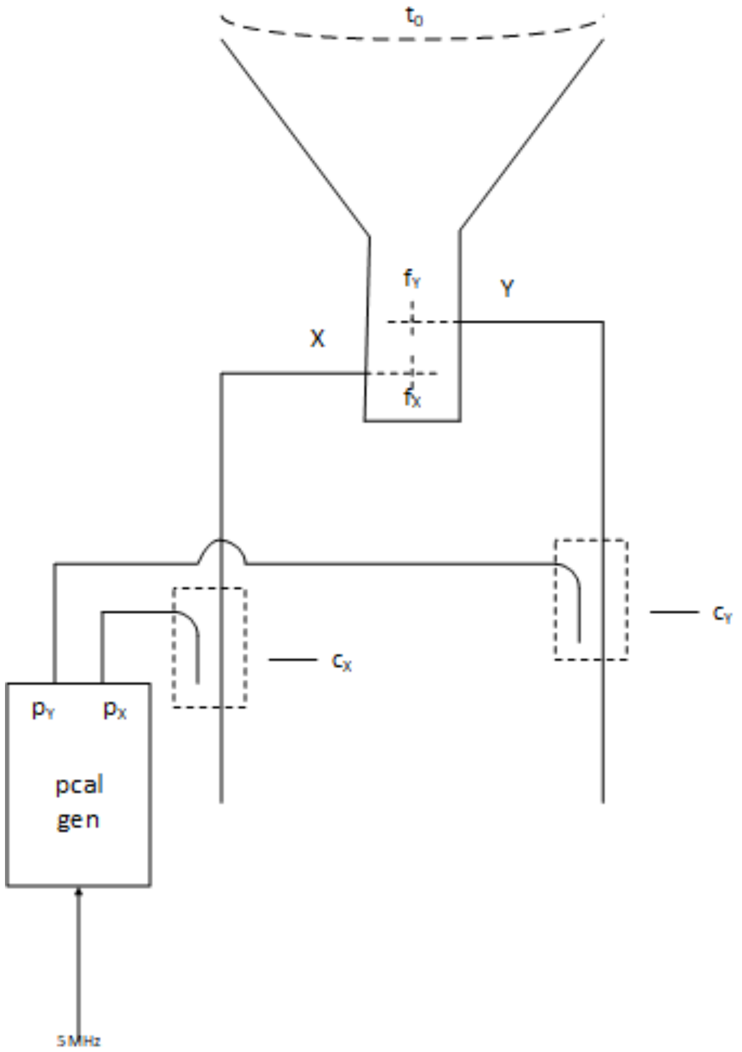
Frequency and time stability of the optical fiber meet the VGOS specifications. Furthermore, tests with the CDMS confirm that phase changes are monitored sufficiently accurate over a distance > 800 m.

Memos related to Phase Cal available online

- MIT Haystack Mark 5 development Memo series (https://www.haystack.mit.edu/haystack-memo-series/mark-5-memos/)
  - Mk5-020 Simulation of phase cal and low fringe rate phase error using a polyphase filter bank
  - Mk5-021 Phase Cal Extraction for the Mark 5B
  - Mk5-051 Measurements of cross-talk and spurious signals levels after
  - Mk5-065 Proposed phase calibration scheme
  - Mk5-066 Measurements of cable delay with temperature and flexure
  - Mk5-071 Test of Hittite Logic gate
  - Mk5-074 Phase calibrator pulse distortion in UDC
  - Mk5-075 Preliminary circuit for the new phase cal
- MIT Haystack Broadband Memo series (https://www.haystack.mit.edu/haystack-memo-series/vgos-memos/)
  - BBDev-017 Modification to NASA/Honeywell pcal for 5 MHz repetition rate
  - BBDev-021 Phase cal performance during 2008 May 23 GGAO-Westford BBD test
  - BBDev-023 Tests of new “digital” phase calibrator
  - BBDev-031 Notes on phase cal extraction, power levels, total rail count, and SNR
  - BBDev-032 Phase Cal Channel-to-Channel Phase Discontinuities
  - BBDev-034 Phase Cal Amplitude RF Frequency Dependence

What does pCal not correct ?

Delays ahead of pcal injection are not calibrated and must be determined from the data (Y-X offsets).



More online resources

- For more advanced treatment of the subject, refer to notes and presentations from
  - VGOS Correlation Workshop, Thursday May 9th and 10th, 2019
  - https://www.haystack.mit.edu/conference-2/past-conferences/10th-ivs-technical-operations-workshop/
    - A. Neill on "Phase cal and sampler delays"
- Presentations at IVS VLBI 2010 Workshop on "Future Radio Frequencies and Feeds held at Wettzell / Hoellenstein (Germany), March 18 - 20, 2009"
  - http://www.wettzell.ifag.de/veranstaltungen/vlbi/frff2009/frff2009.html
    - "Broadband Delay Tutorial" by B Petrachenko
- Presentations at IVS VLBI2010 Workshop on Technical Specifications (TecSpec) Bad Kötzting/Wettzell (Germany), March 1 - 2, 2012
  - http://www.fs.wettzell.de/veranstaltungen/vlbi/tecspec2012/index.html

MIT
HAYSTACK
OBSERVATORY

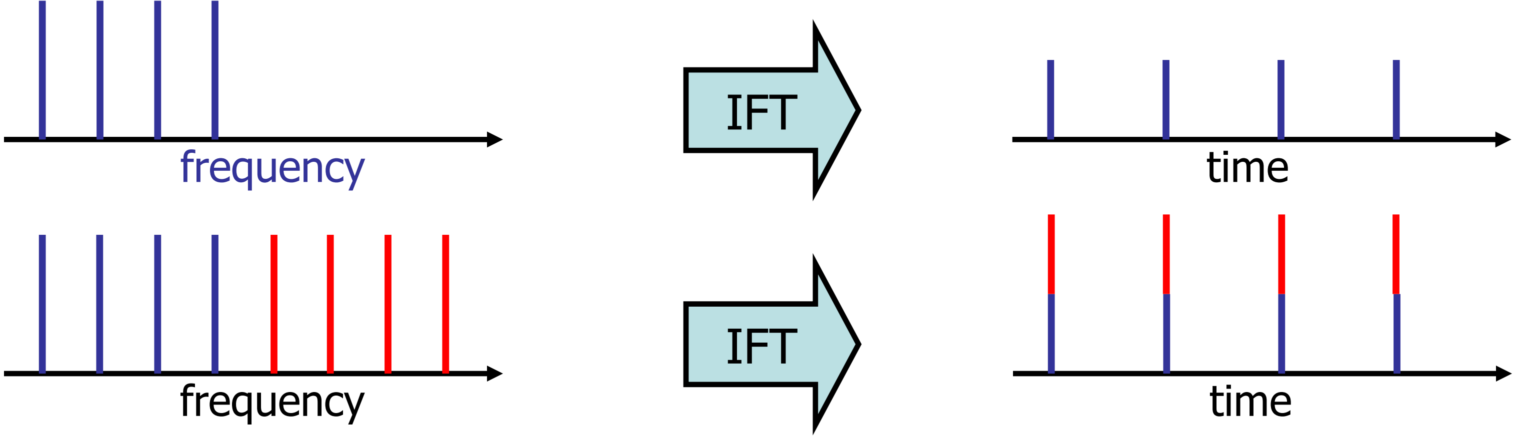
Thank you

Pulse repetition rate and headroom

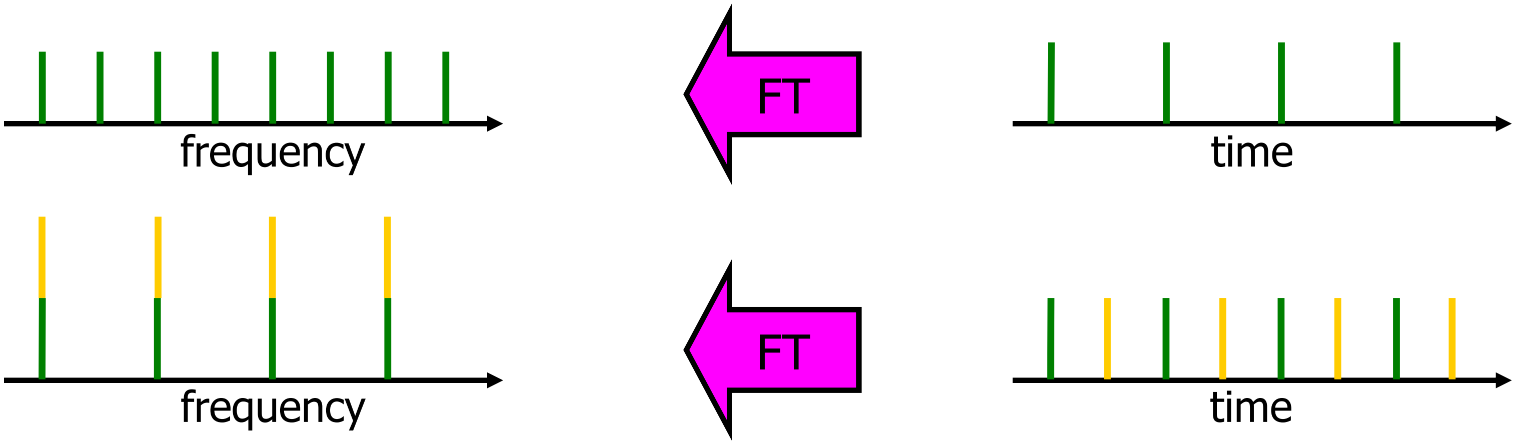
- As RF bandwidth increases, pulse intensifies.
  - For 1-MHz pulse rep rate & 1-GHz BW, peak pulse voltage ~ 10× rms noise.
  - For VGOS RF BW of 12 GHz, peak pulse voltage >> 10× rms noise.
- With insufficient analog headroom, pulse drives electronics into nonlinear operation. → spurious signals generated that corrupt undistorted pcal signal
- Options to avoid driving electronics into saturation:
  - Reduce pulse strength
    - Phase cal SNR reduced → noisier phase extraction
    - More prone to contamination by spurious signals
  - Reduce pulse strength *and* increase pulse repetition rate to 5 or 10 MHz
    - Fewer tones spaced 5 or 10 MHz apart
- With 5 or 10 MHz rep rate, baseband tone frequencies can differ from channel to channel when channel separation = 2^N MHz.
  - Fringe-fitting is more complicated if only one tone per channel is extracted .
  - Software solution: Use multiple tones per channel and correct for delay within each channel, as well as between channels.
- General recommendation: peak pcal pulse power / P1dB < -10 dB

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 –



Origin of pcal amp vs. phase quasi-sinusoids

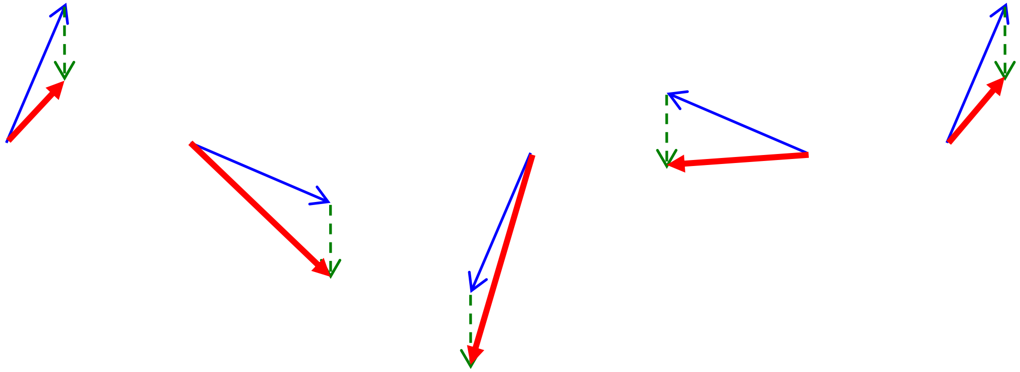
Legend:

→ True phase cal, rotated in steps of 90°

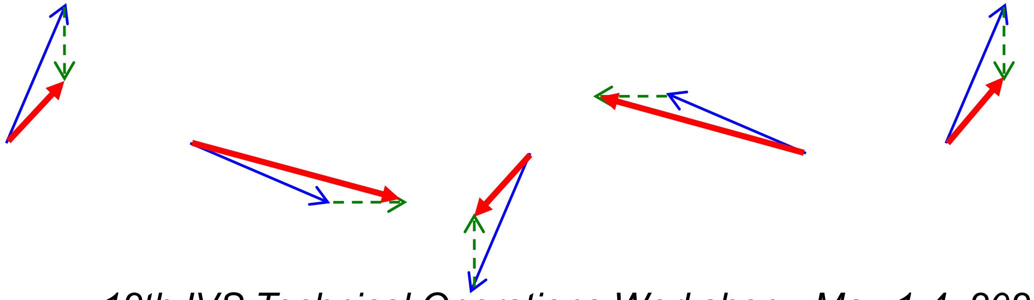
⇢ Spurious signal

➡ Vector sum of true phase cal & spurious signal

- Case 1: Spurious signal of constant amplitude and phase
  - Amplitude of vector sum varies by one cycle as pcal phase varies 360°.

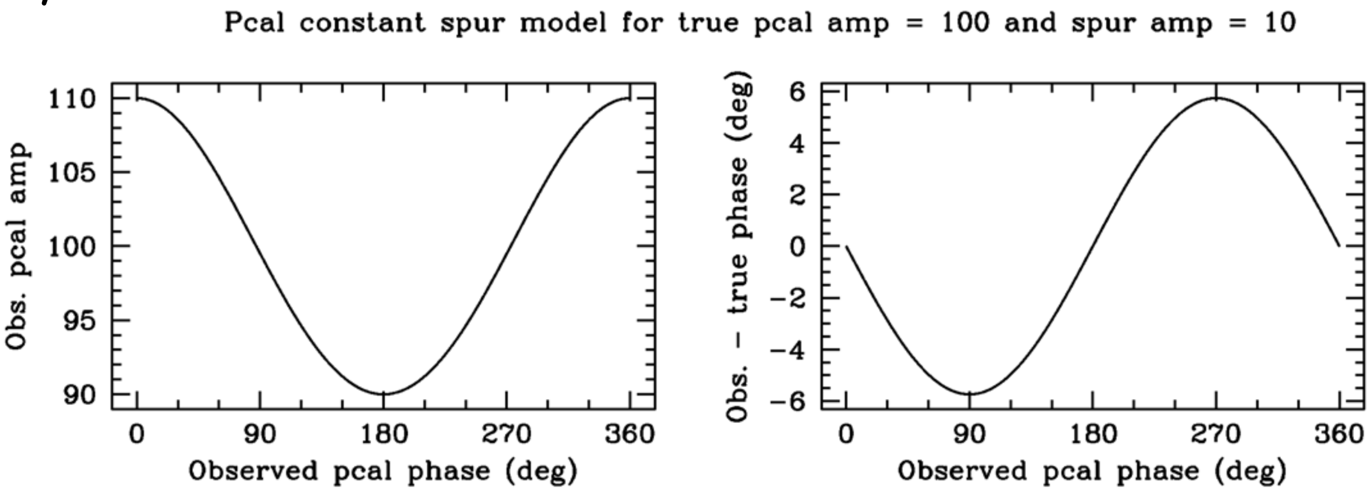


- Case 2: Spurious signal = phase cal at image frequency
  - Amplitude of vector sum varies by two cycles as pcal phase varies 360°.

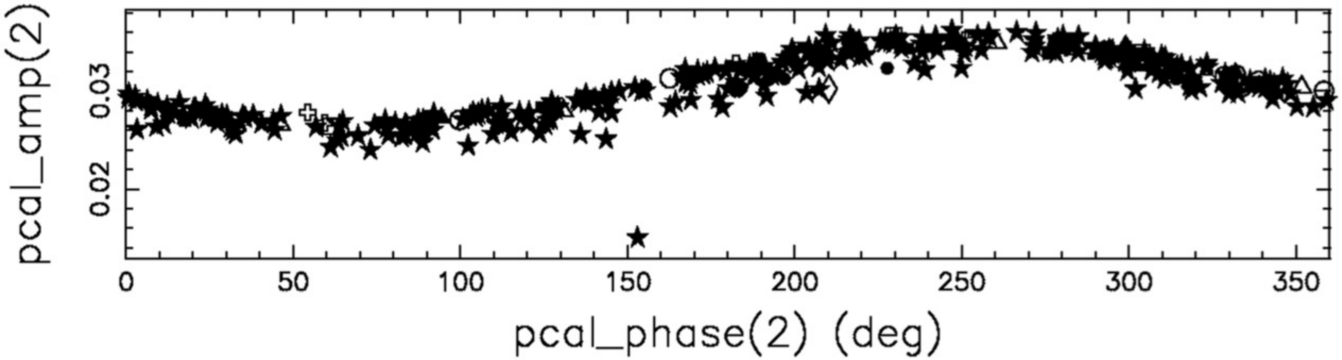


Spurious signal example: constant spur

Theory:

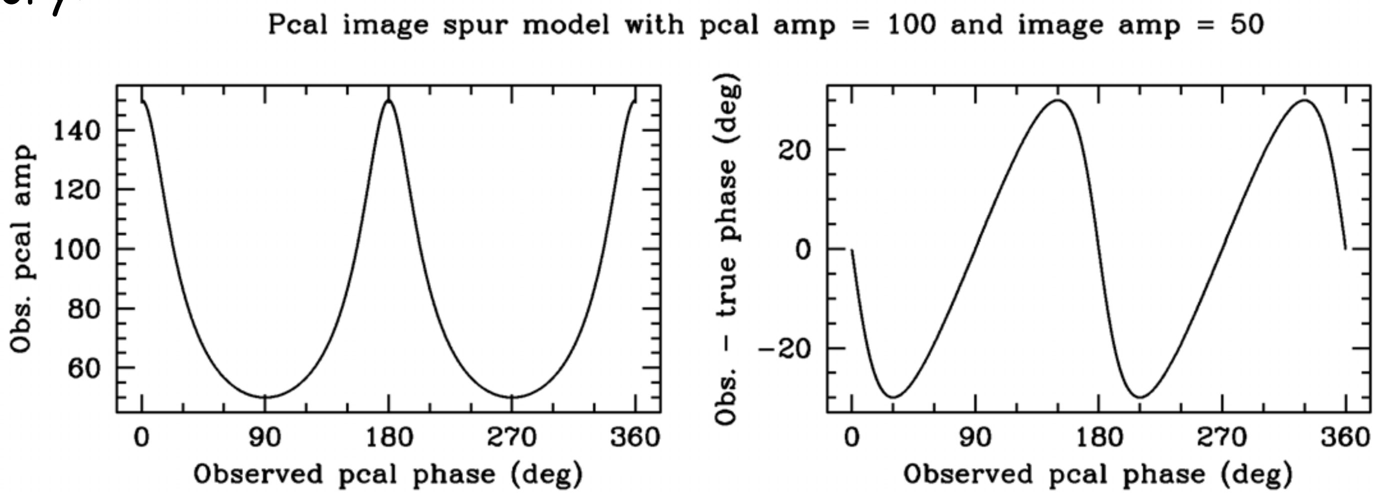


Observation:



Spurious signal example: image spur

Theory:



Observation: