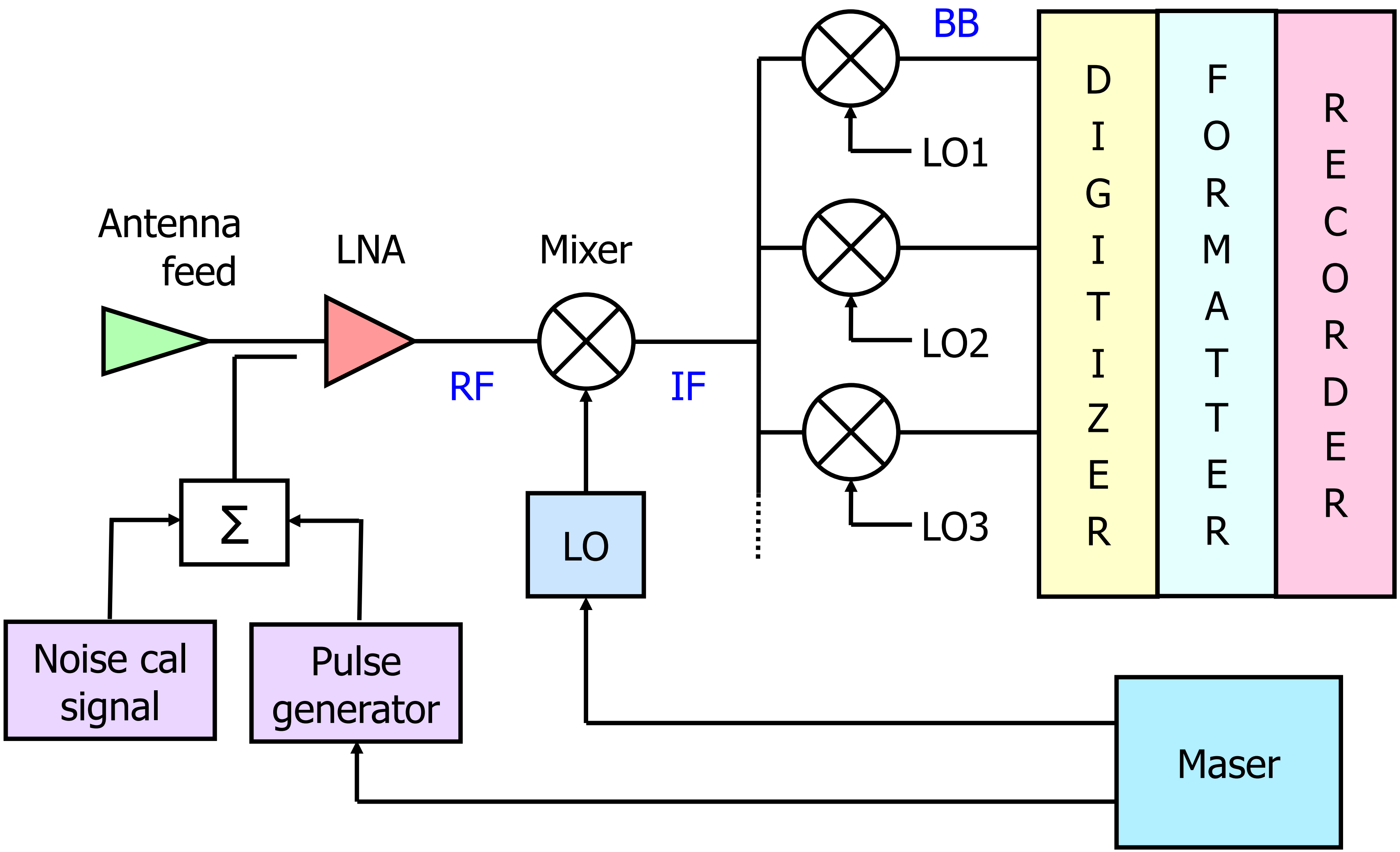
Advanced Pre-checks and Operations

Ed Himwich, *Ganesh Rajagopalan*

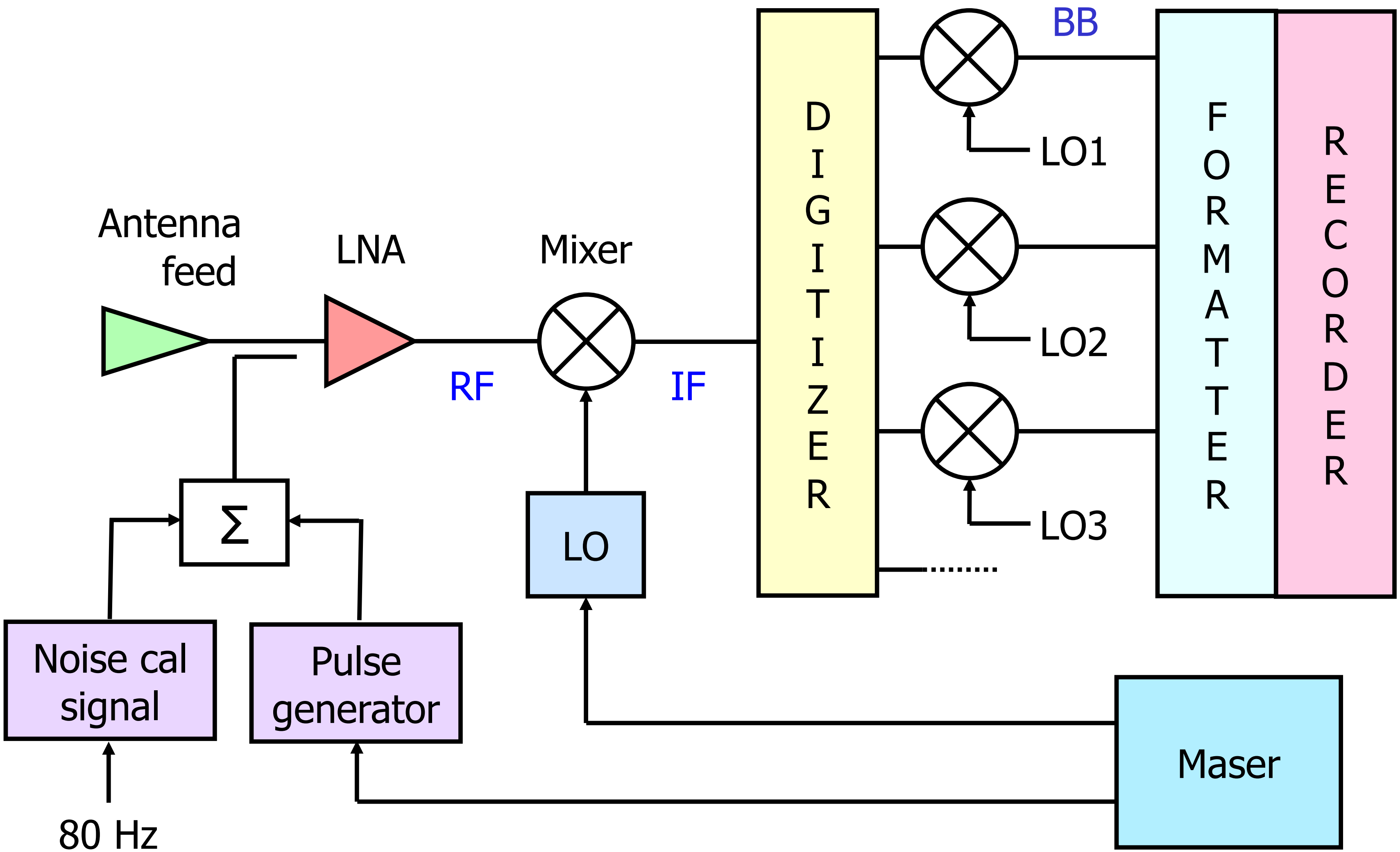
Overview

- This course covers VLBI equipment tests that are more extensive than those in the *Experiment Pre-checks and Operations* workshop.
- These tests should be carried out
  - after a major equipment change,
  - prior to a major, multi-day observing campaign such as CONT2#, or
  - at least annually, and preferably more frequently.
  - See TOW 2015 notebook for more information on *systests* software for analog systems
- Related Seminar and Workshops,
  - Campbell – Pointing and Amplitude Calibration Concepts
  - Lindqvist & Svoboda- RFI Sources, Identification, Mitigation
  - Rajagopalan – Phase Cal Basics & RF testing
  - Lindqvist –Antenna Gain Calibration

Simplified block diagram of VLBI electronics with ABEs



How does a system with DBE differ from one with ABE?



Antenna pointing offsets

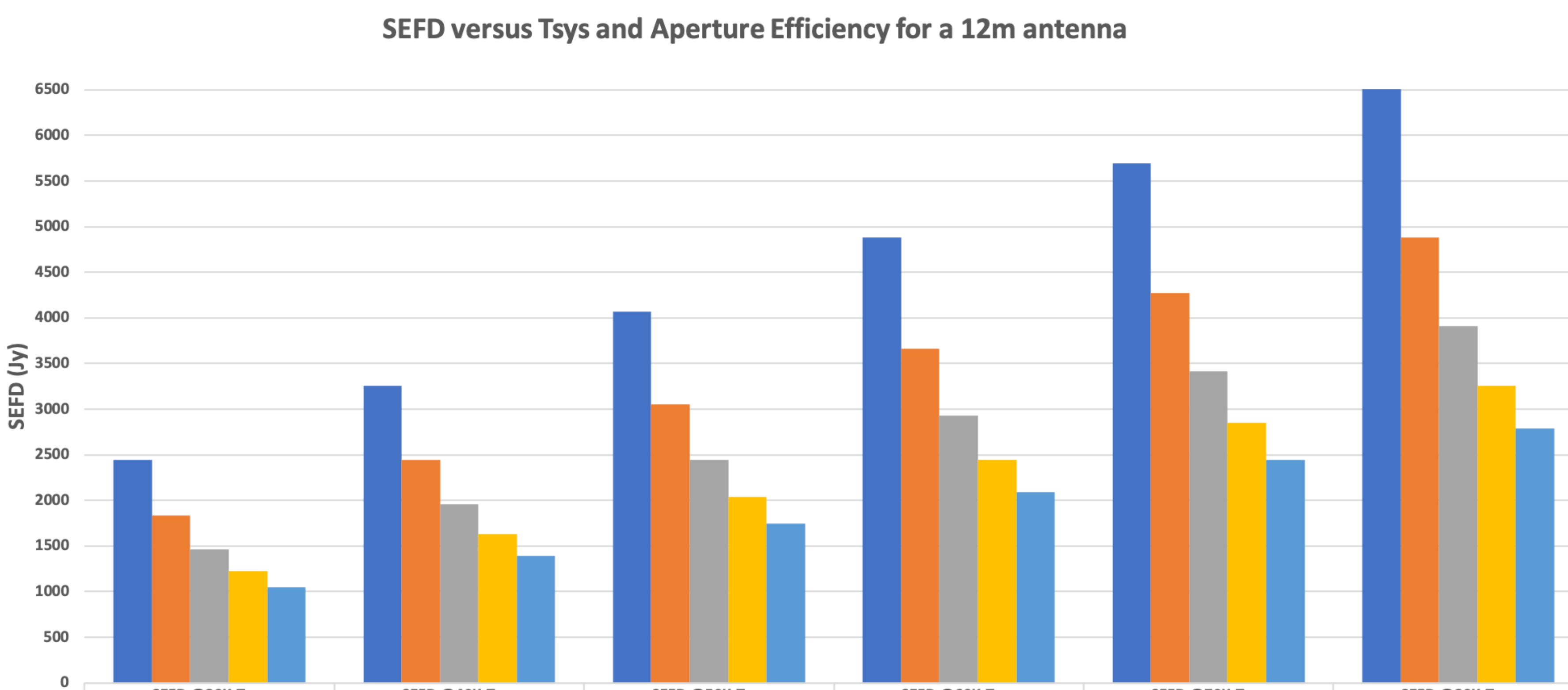
- Measure pointing offsets over the full az/el range of the antenna, by observing multiple sources over a wide range of declinations over a 24-hour period
  - Source size should be <~ X-band beamwidth
- Verify that pointing errors are
  - typically < 0.1 FWHM X-band beamwidth *(3% sensitivity loss)*
  - always < 0.3 FWHM X-band beamwidth *(22% sensitivity loss)*

System Equivalent Flux Density (SEFD)

- SEFD = flux density of a source that would double Tsys
- Measure SEFD in each frequency channel on a strong source of known flux density with angular size < X-band beamwidth.
  - Use FS **onoff** command.
  - Or measure system temperatures on and off source separately, and calculate:

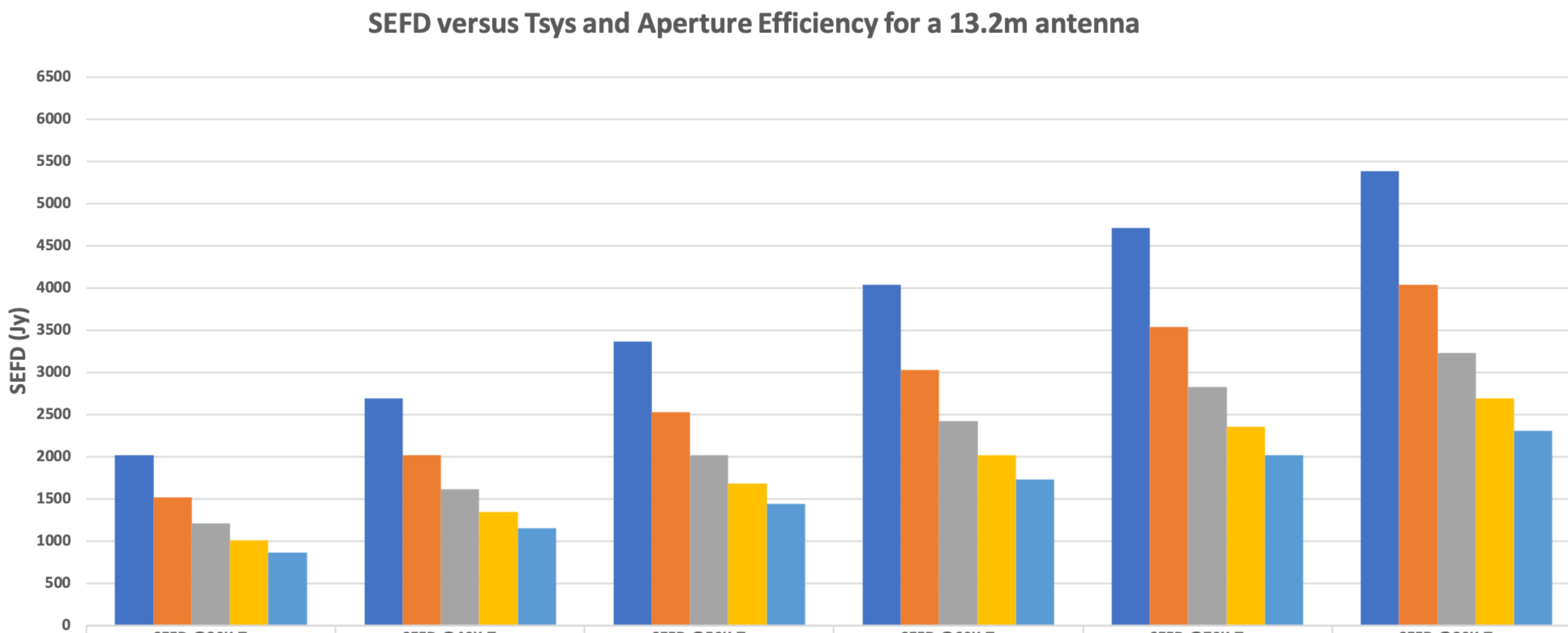
    SEFD = (source flux density) x Tsys_off / (Tsys_on – Tsys_off)
- Repeat measurements, on same source and other sources, to check consistency.
- Compare measured SEFD with SEFD inferred from VLBI observations.
  - VLBI SEFD much higher than single-dish SEFD means trouble (e.g., cross-polarization, maser instability, RF/IF signal blanking).

System Equivalent Flux Density (SEFD) for 12m antenna



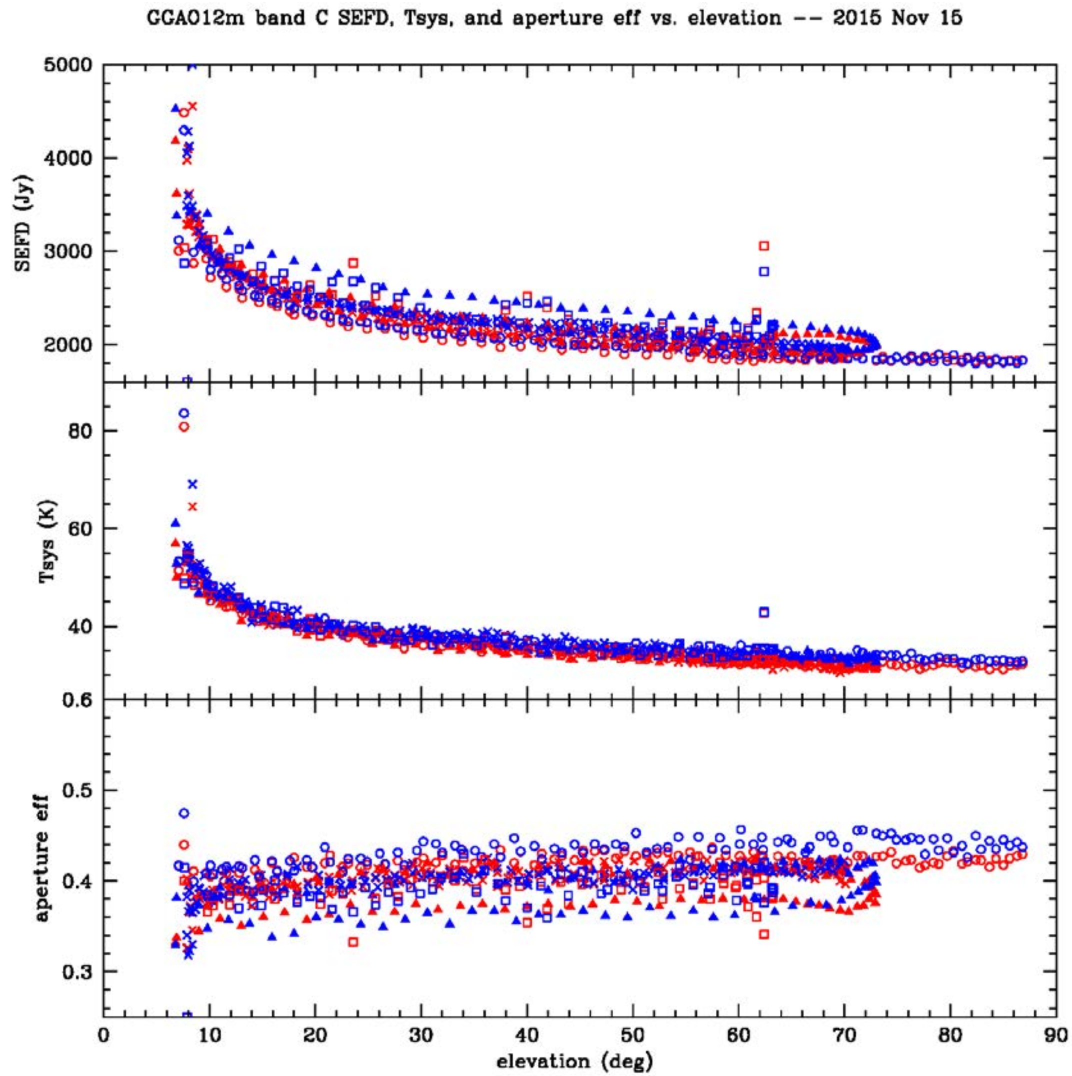
	SEFD @30K-Tsys	SEFD @40K-Tsys	SEFD @50K-Tsys	SEFD @60K-Tsys	SEFD @70K-Tsys	SEFD @80K-Tsys
30%	2442	3255	4069	4883	5697	6511
40%	1831	2442	3052	3662	4273	4883
50%	1465	1953	2442	2930	3418	3907
60%	1221	1628	2035	2442	2849	3255
70%	1046	1395	1744	2093	2442	2790

System Equivalent Flux Density (SEFD) for 13.2m antenna



	SEFD @30K-Tsys	SEFD @40K-Tsys	SEFD @50K-Tsys	SEFD @60K-Tsys	SEFD @70K-Tsys	SEFD @80K-Tsys
30%	2018	2690	3363	4036	4708	5381
40%	1513	2018	2522	3027	3531	4036
50%	1211	1614	2018	2421	2825	3229
60%	1009	1345	1682	2018	2354	2690
70%	865	1153	1441	1730	2018	2306

Tsys, Antenna Aperture Efficiency



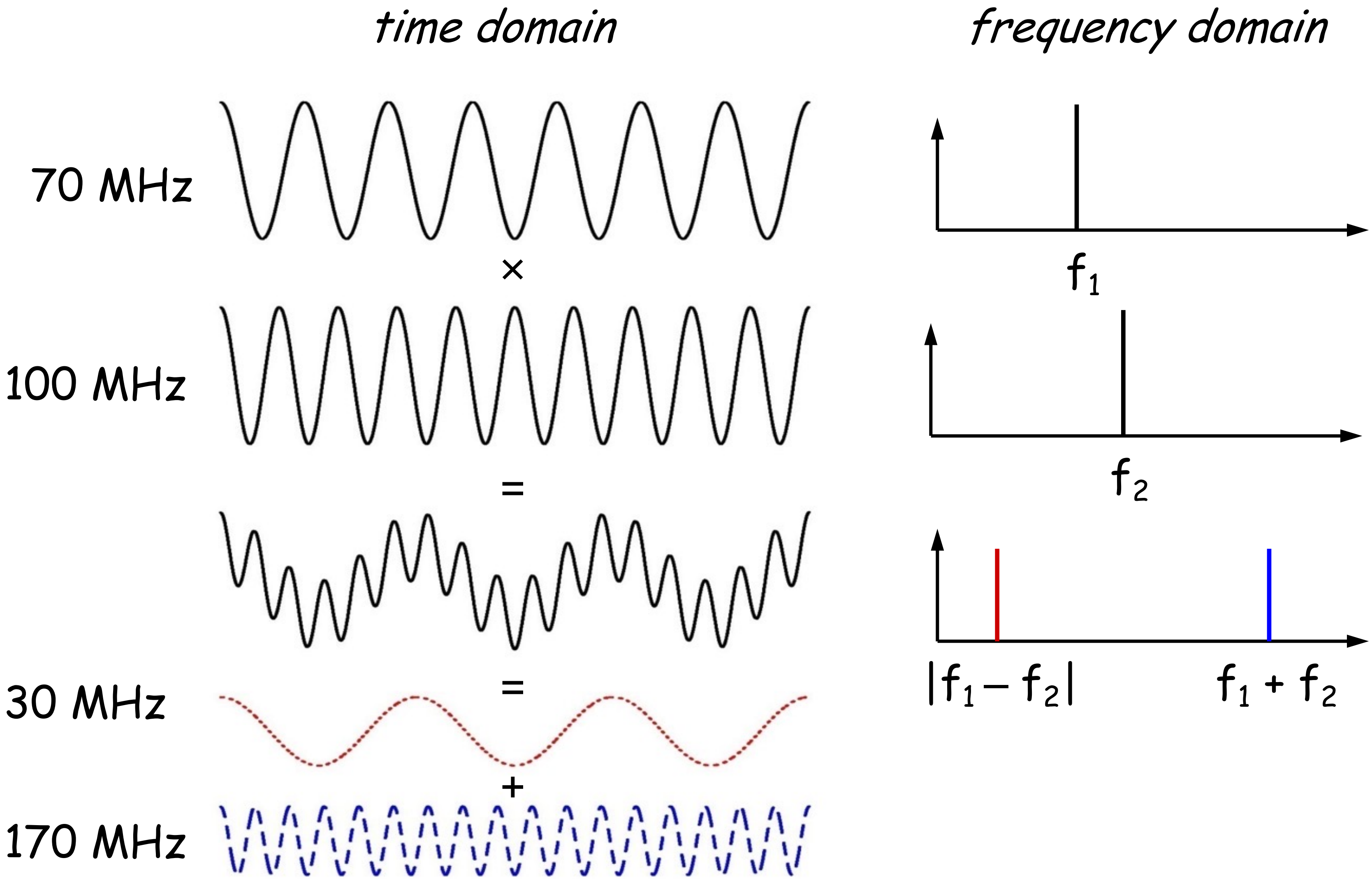
Phase cal power level

- Measure fractional power contributed by phase cal to total system power in each channel:
  - Measure broadband phase cal power.
    - Using **tpical** and **tpi** commands, measure baseband total power levels with phase cal on and off, respectively; then compute fractional power = (tpical – tpi) / (tpi – tpzero)
    - Should be about 0.1 - 1% of total power
    - Ideally should be compared to actual power in the pcal tones themselves to verify that pcal sidebands aren't getting power
      - *RDBE based systems can display pcal amp & phase from multicast data*

Spurious phase cal signals

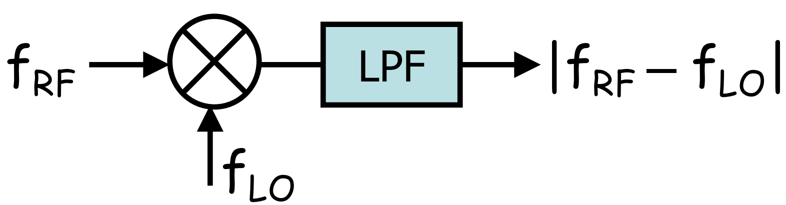
- pCal testing
  - phase cal on
  - phase cal off
    - by disconnecting 5 MHz signal to phase cal antenna unit
    - separately, by turning off ground unit switch, if available
    - by issuing command in case of MHO Phase Cal unit
  - phase cal on but receiver LO unlocked
- To dig deeper into noise, use low-frequency FFT analyzer to measure power of pcal tone at IF output, under same conditions as above.
- Ideally, power of each tone will drop by 50 dB when pcal is turned off, or LO is unlocked, compared with pcal on.

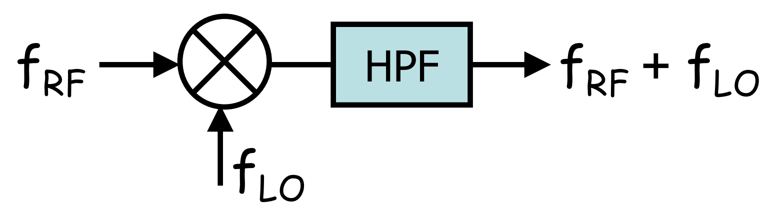
Mixer action



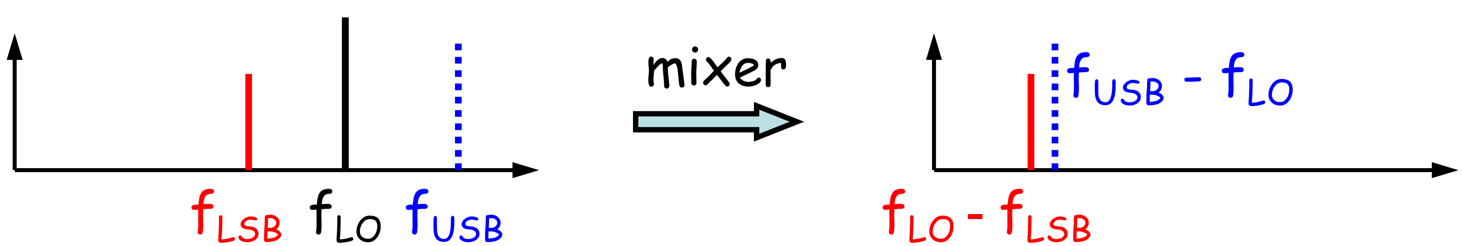
Sidebands and images

- From two input tones (sinewaves), a mixer creates output tones at the sum and difference frequencies.
- By filtering the output with a lowpass or highpass filter, the circuit becomes a downconverter or an upconverter:





- In a downconverter, $f_{RF} > f_{LO}$ → upper sideband (USB) conversion
  $f_{RF} < f_{LO}$ → lower sideband (LSB) conversion



- Image = RF signal from the undesired sideband that has the same IF frequency as the desired sideband.

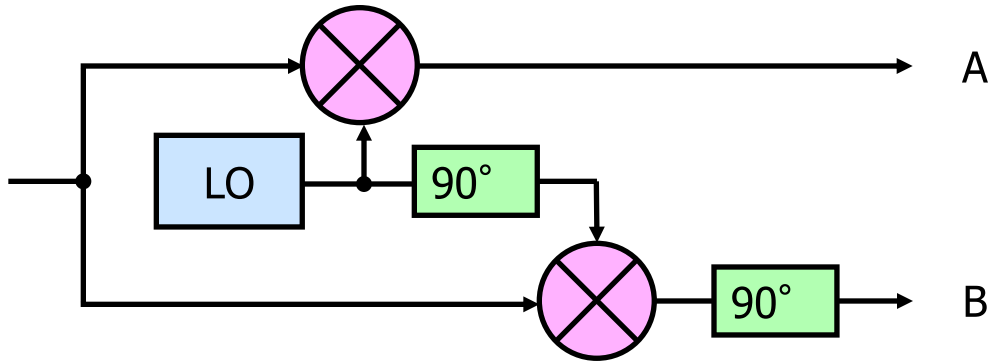
Image separation

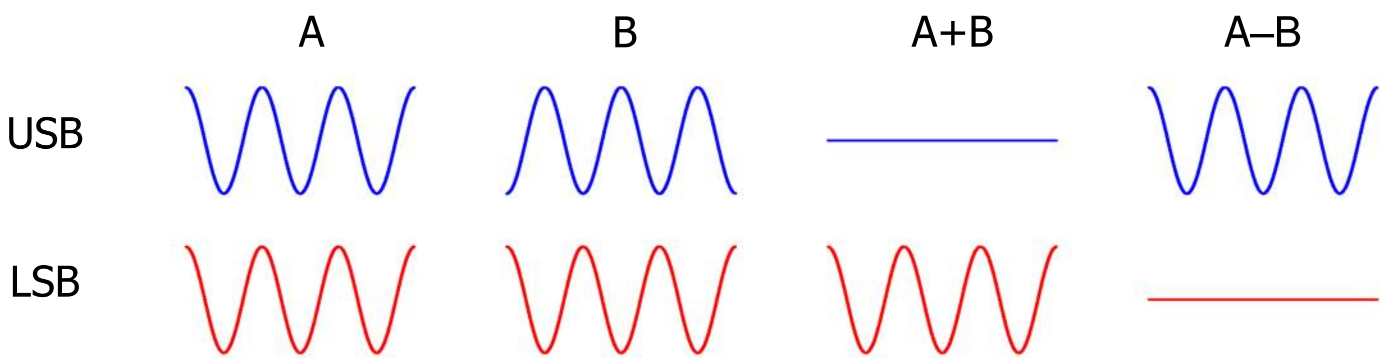
- A sideband-separating mixer (used in older VC/BBCs) puts downconverted sidebands out on separate lines, thereby reducing SNR loss that occurs if image and desired signals fall on top of each other in output.

$f_{RF,USB} = f_{LO} + f_{IF}$

+

$f_{RF,LSB} = f_{LO} - f_{IF}$



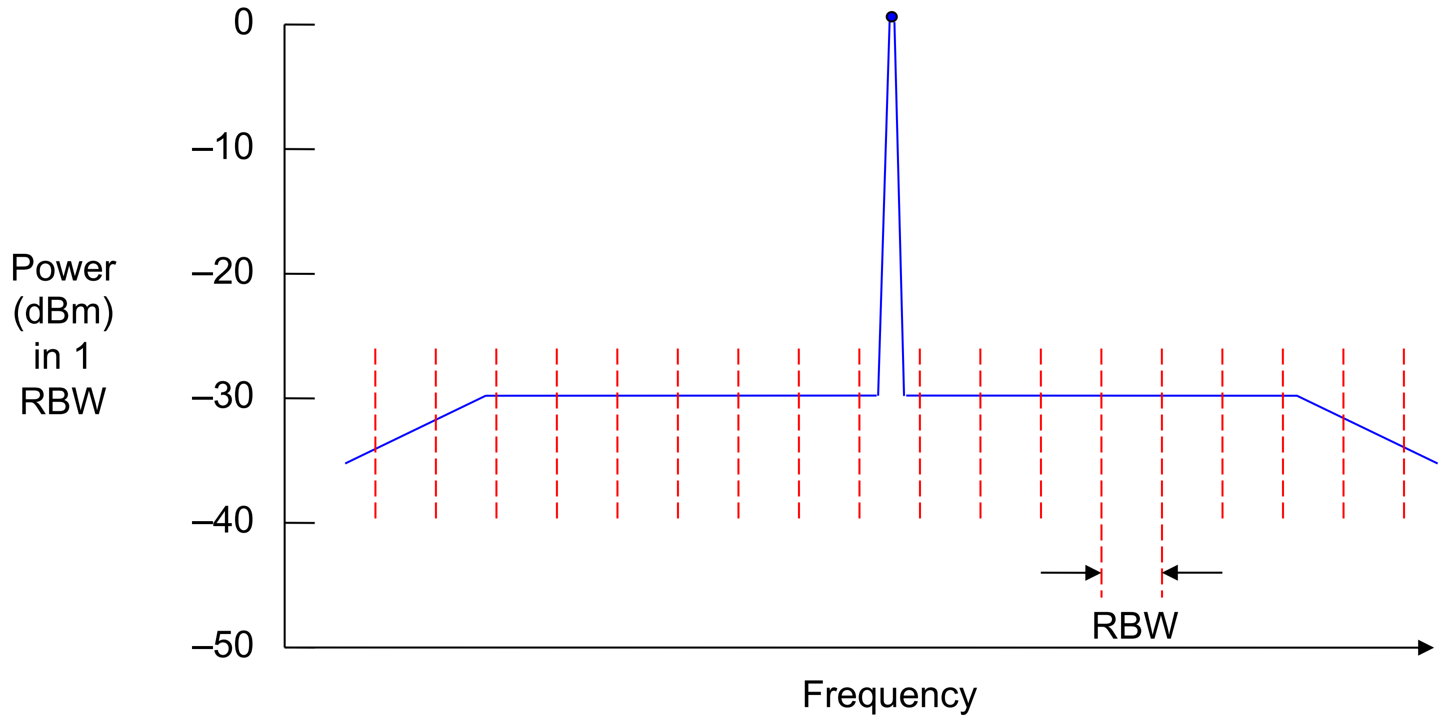


A+B gives downconverted LSB, A–B gives USB

LO phase noise

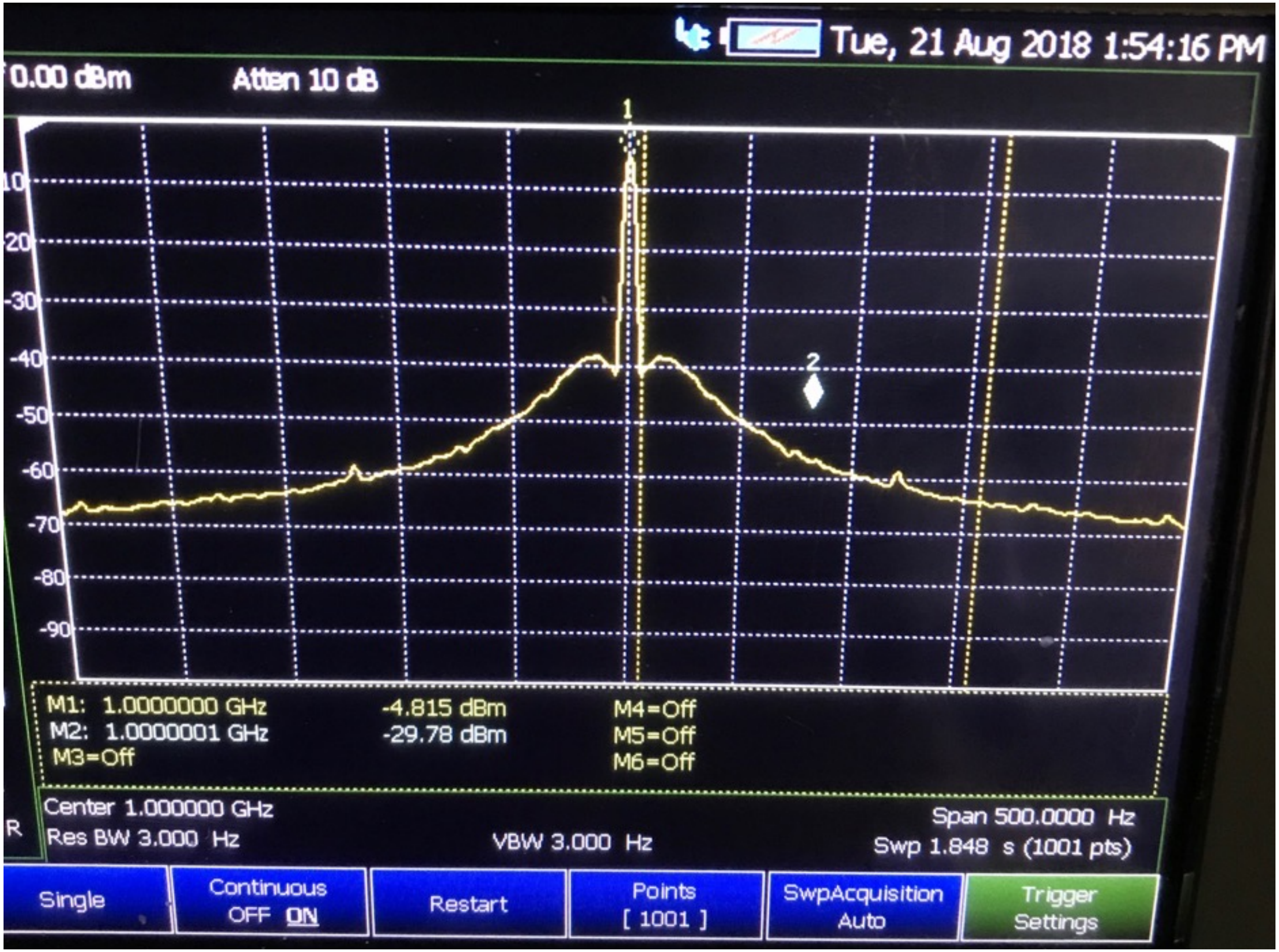
- Measure LO phase noise at 2-4 widely separated LO frequencies or in case of VGOS in each band.
  - Test tone method –
    - Turn off phase cal.
    - Set LO to xxx.xx MHz
    - Using a signal generator known to have low phase noise, inject a test tone at frequency xxx.xx + 0.01 MHz into IF.
    - Observe 10-kHz beat signal between test tone and LO in USB output on oscilloscope. Measure RMS jitter in zero-crossing time of signal, with scope triggered from an external, maser-synced time base.
  - Spectrum method –
    - Use method described in spectrum analyzer workshop to measure phase noise and RMS phase jitter.
- Compare measured jitter against LO specification:
  - Mk4: rms $< 4^\circ$ below 450 MHz, rms $< 9^\circ$ above 450 MHz
  - VLBA: rms $< 2^\circ$ VGOS: rms $< 10^\circ$ (1% coherence loss)
- Compare spectrum against reference spectrum.

Measuring LO phase noise on spectrum analyzer



- Phase noise = total power in two modulation sidebands, on either side of carrier
- RMS phase jitter (radians) = sqrt[(power in 2 sidebands) / (power in carrier)]

Sideband Power measurement using a Spectrum Analyzer

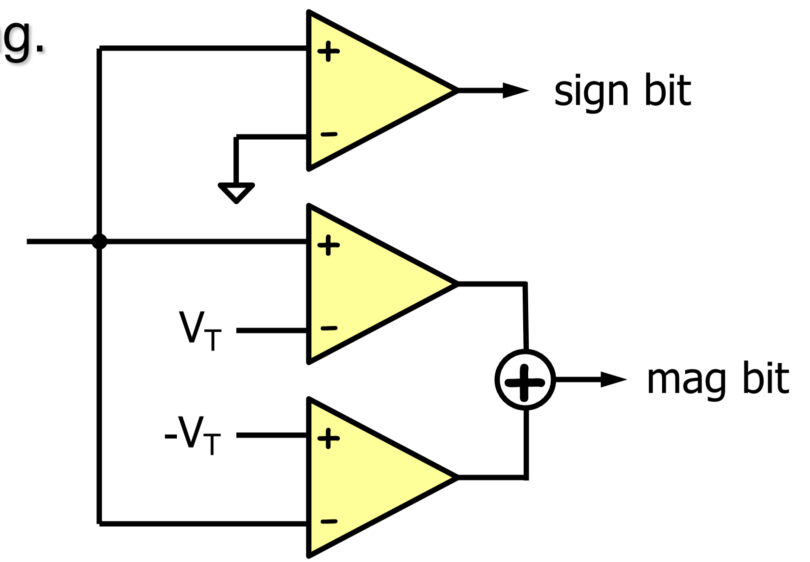


baseband / if bandpass shape

- Using spectrum analyzer, measure shape of baseband or in case of VGOS IF /RF spectrum in each frequency channel, and compare against expected.
- Shape may be affected by RF/IF filter characteristics, RFI, ripple due to impedance mismatches, etc.
- Make sure the total noise power output in the Nyquist zone of the ADC is within specs for the DBEs. Monitor the attenuator levels for any changes.

1- and 2-bit sampling

- For a **fixed** data rate (bits per second) in **continuum** observations:
  - 1-bit sampling (signal sign) gives maximum SNR.
    - Spread the samples over as much BW as possible.
  - 2-bit sampling (sign and magnitude) is almost as good as 1-bit.
    - Use half the BW as 1-bit sampling.



- In 1-bit sampling, rms input voltage simply must be >> sampler DC offset.
- In 2-bit sampling, SNR is maximized if 36% of samples are in high-mag state.
- Field System can monitor statistics via Mark 4 decoder or Mark 5B recorder.
- 2-bit samples become in effect 1-bit if
  - input level is too low and mag bit is always ‘0’, or
  - input level is too high and mag bit is always ‘1’.
- AGC in VC/BBC, or re-quantization in DBE, should maintain sampler input at proper 2-bit level.

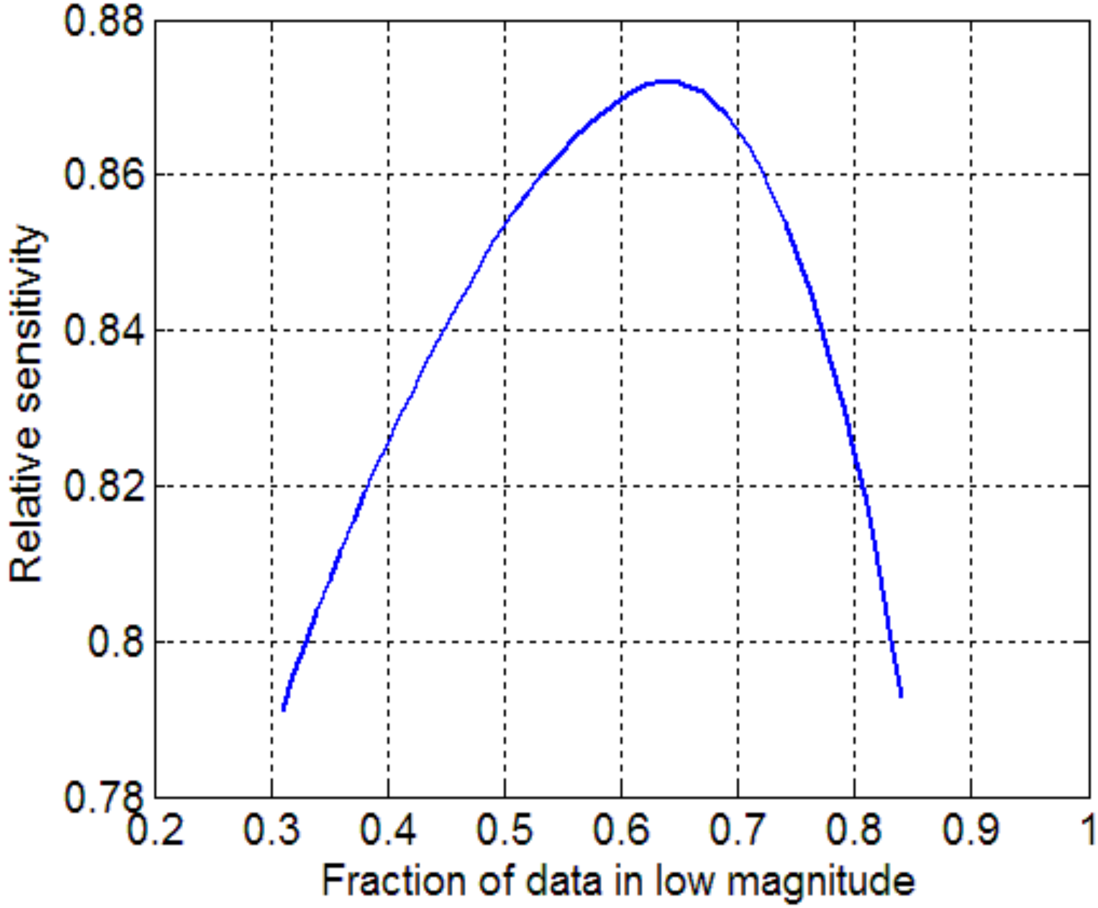
Sample state statistics

- Sample state statistics should be monitored via *systests* **samplestat** procedure & script, or Mk4 decoder **samples** command, to check for potential problems in analog or digital domain.
- Ideal distribution is

Sample state	*% of 1-bit samples*	*% of 2-bit samples*
– –	50%	18%
–		32%
+		32%
+ +	50%	18%

- Deviations from ideal may indicate…
  - Impedance mismatch in VC/BBC→formatter cable
  - No input to sampler
  - VC/BBC AGC circuit not working properly
  - DBE not re-quantizing sampled data properly
  - RFI varying on short time scales

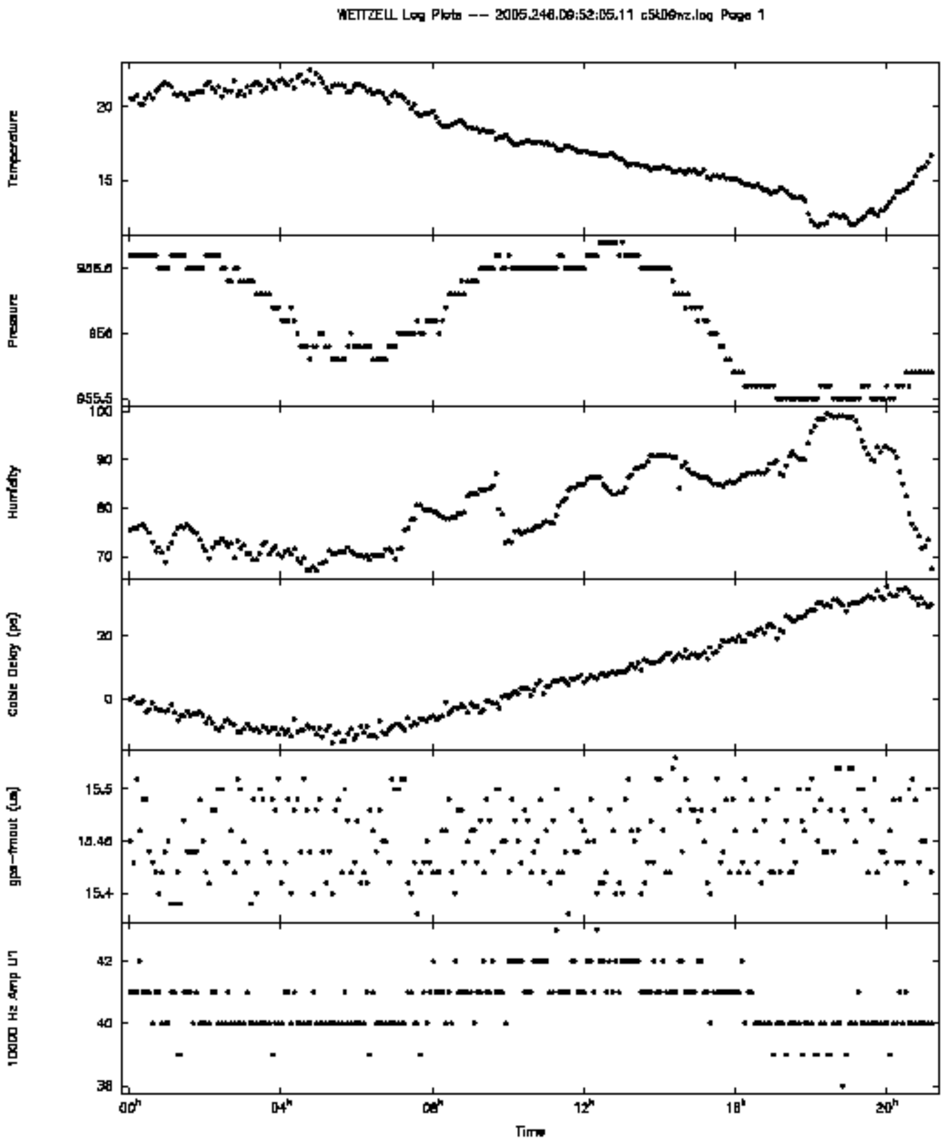
What if state count distribution deviates from ideal?



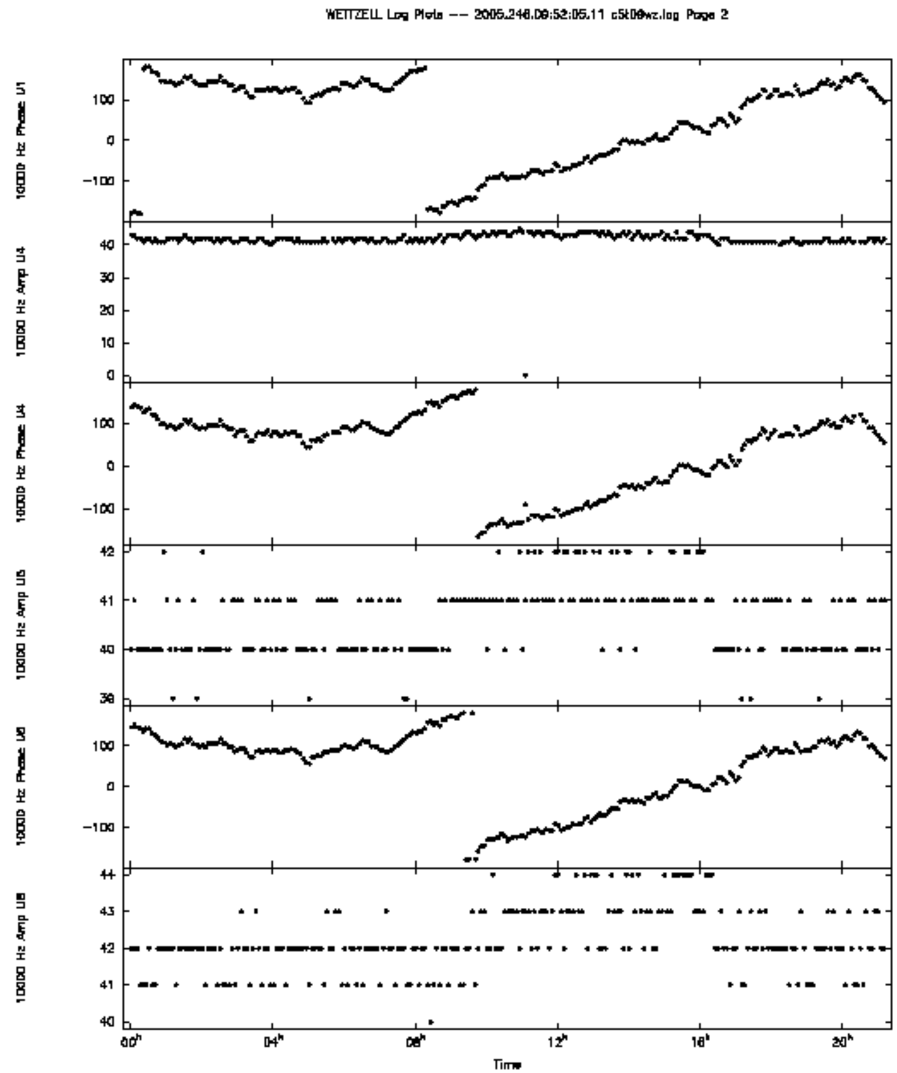
Diurnal behavior

- Park antenna at zenith.
- Use *systests* **overnite** procedure, or comparable one of your own devising, to log at least the following quantities at 5-minute (or shorter) intervals for 24 hours:
  - Phase cal phases and amps in 2 X-band channels
  - Phase cal phases and amps in 2 S-band channels
  - Cable cal
  - Formatter-GPS time interval
  - Weather data
  - Receiver monitor points
  - System temperatures in all channels
- Run *systests* **plotlog** script on log to look for unexpected variations.
  - Phase-cal extraction/plotting software for digital backends under development

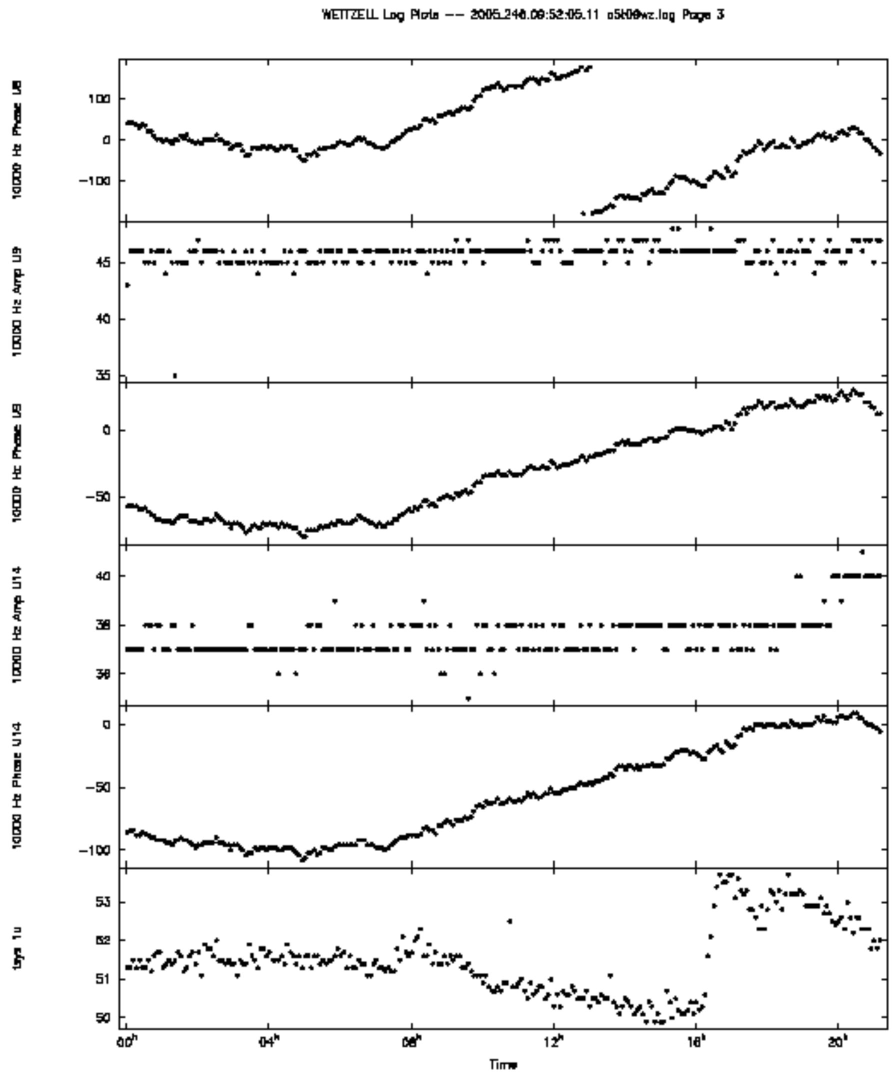
output example – overnite and plotlog



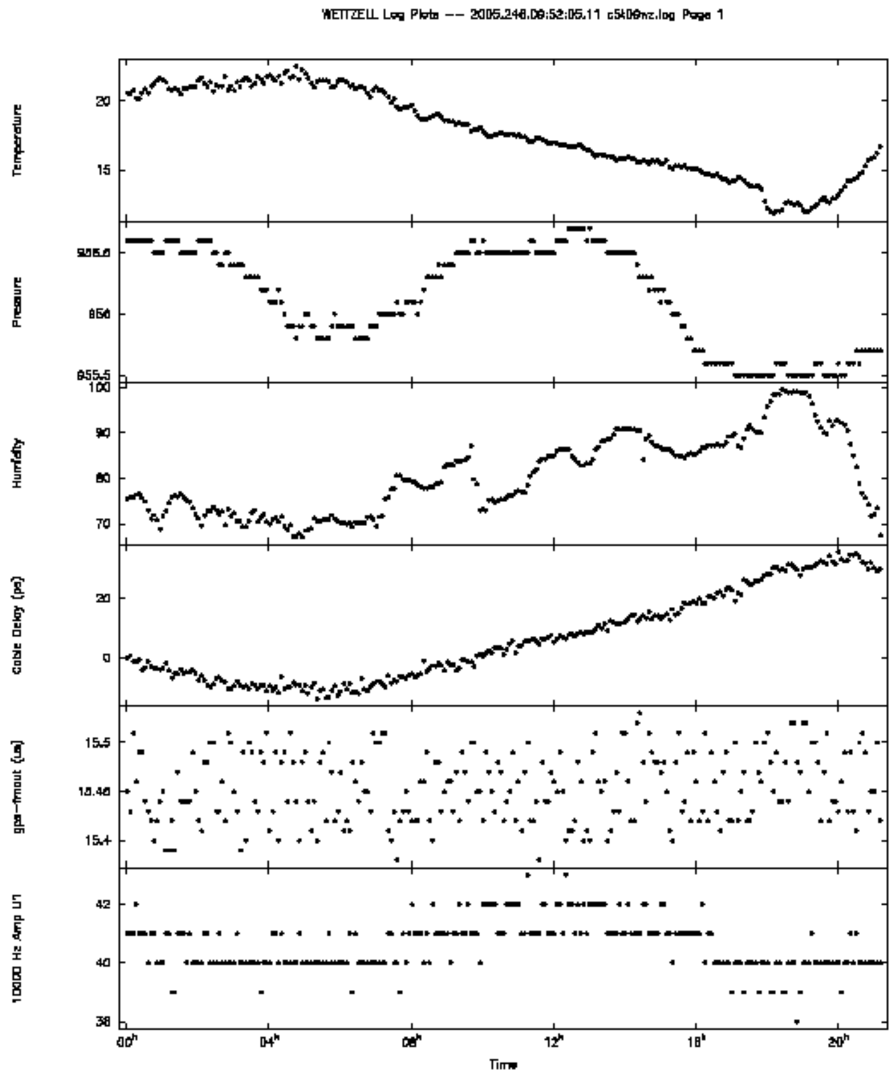
systests output example – overnite and plotlog



systests output example – overnite and plotlog

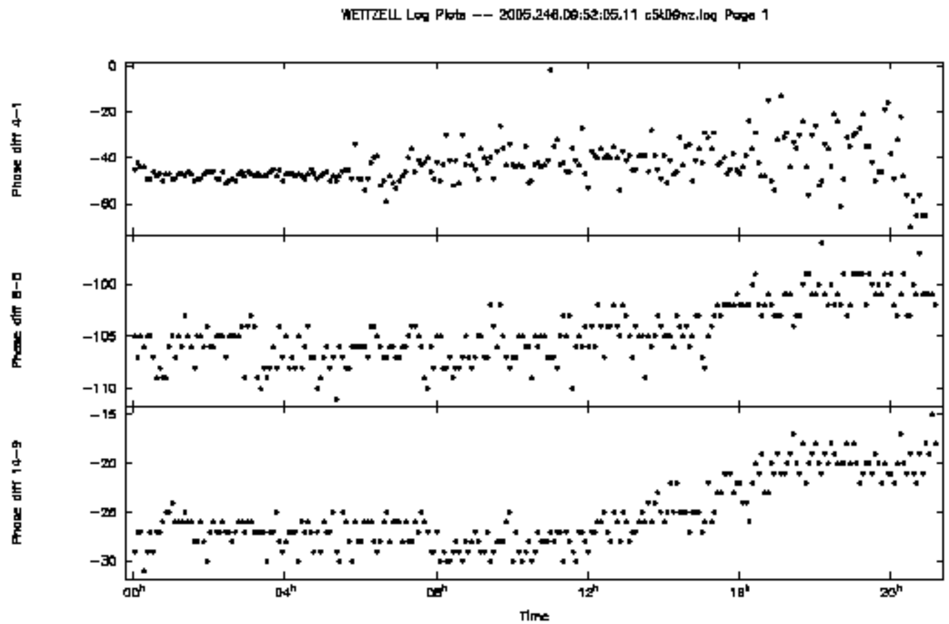


systests output example – overnite and plotlog



systests output example –

overnite and plotlog



Short-term variations

- Park antenna at zenith.
- Use *systests* **rapid** procedure, or comparable one of your own devising, to log at least the following quantities at 15-second (or shorter) intervals for at least 10 minutes:
  - Phase cal phases and amps in 2 X-band channels
  - Phase cal phases and amps in 2 S-band channels
  - Cable cal
- Run *systests* **plotlog** script on log to look for systematic variations or unusual short-term variations.
  - Phase-cal extraction/plotting software for digital backends under development
- In principle, this can be done for RDBEs with some modification of the scripts

Antenna orientation-dependent effects

- As the antenna is slewed slowly in azimuth and elevation over its full range of motion…
  - Use the FS to record cable cal and phase cal amplitude and phase rapidly, with at least 20 sets of data points per azimuth or elevation slew.
    - FS *systests* **rapid** procedure may be used to acquire data, and *systests* **plotlog** script to examine the logged data for unstable behavior.
  - Observe each IF with a spectrum analyzer and look for in-band RFI and strong out-of-band RFI.
  - Watch cable cal counter for jumps or rapid drifts. (e.g. Westford)
  - Watch S and X phase cal phases on oscilloscope for jumps, rapid drifts, or unusual jitter that might be missed in FS log readings.

Timing between devices and relative to UTC

- Good practice is to measure time offsets to < 10 ns accuracy regularly between
  - maser
  - samplers/DBEs
  - recorders
  - GPS
- Can use external counters or counters internal to some devices.
- Goals:
  - Measure offset between time tags on data samples and UTC, to help the correlator find fringes.
  - If a shift in 'fmout-gps' occurs, understand its origin.

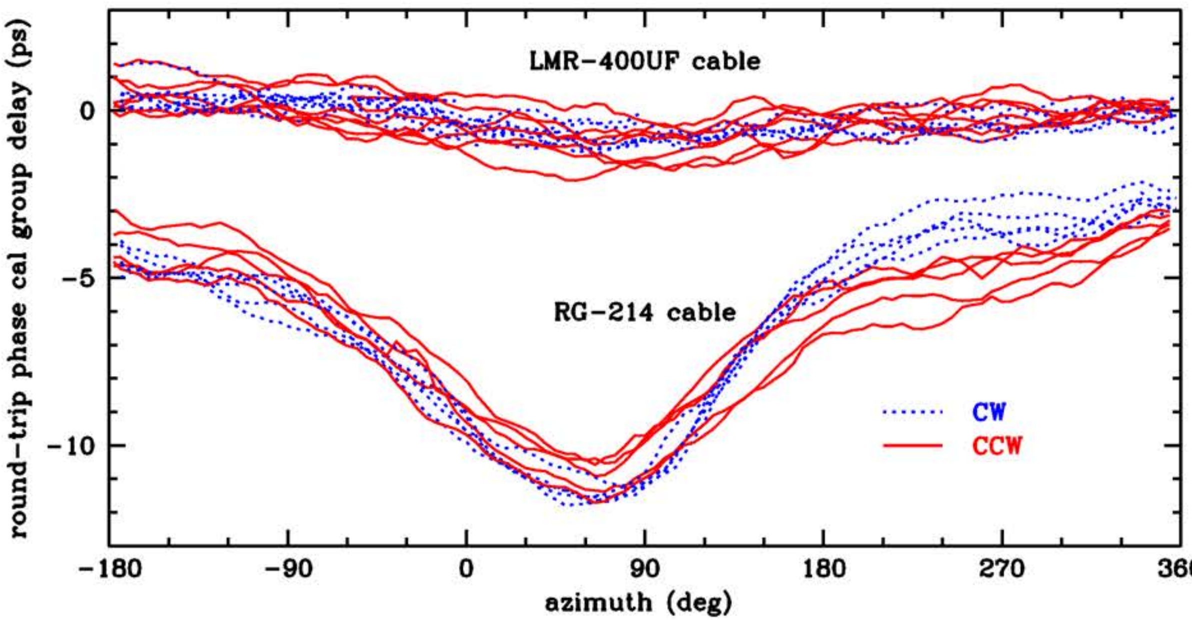
Cable cal

- Legacy Mark4 system: Is cable reading stable to < 2 microsec peak-peak on time scales of 1-30 seconds?
  - It should not be necessary to operate counter in averaging mode to achieve this level of stability. Counter should be operated in single-sample mode.
- With test cable of known length inserted, does counter reading change by correct amount?

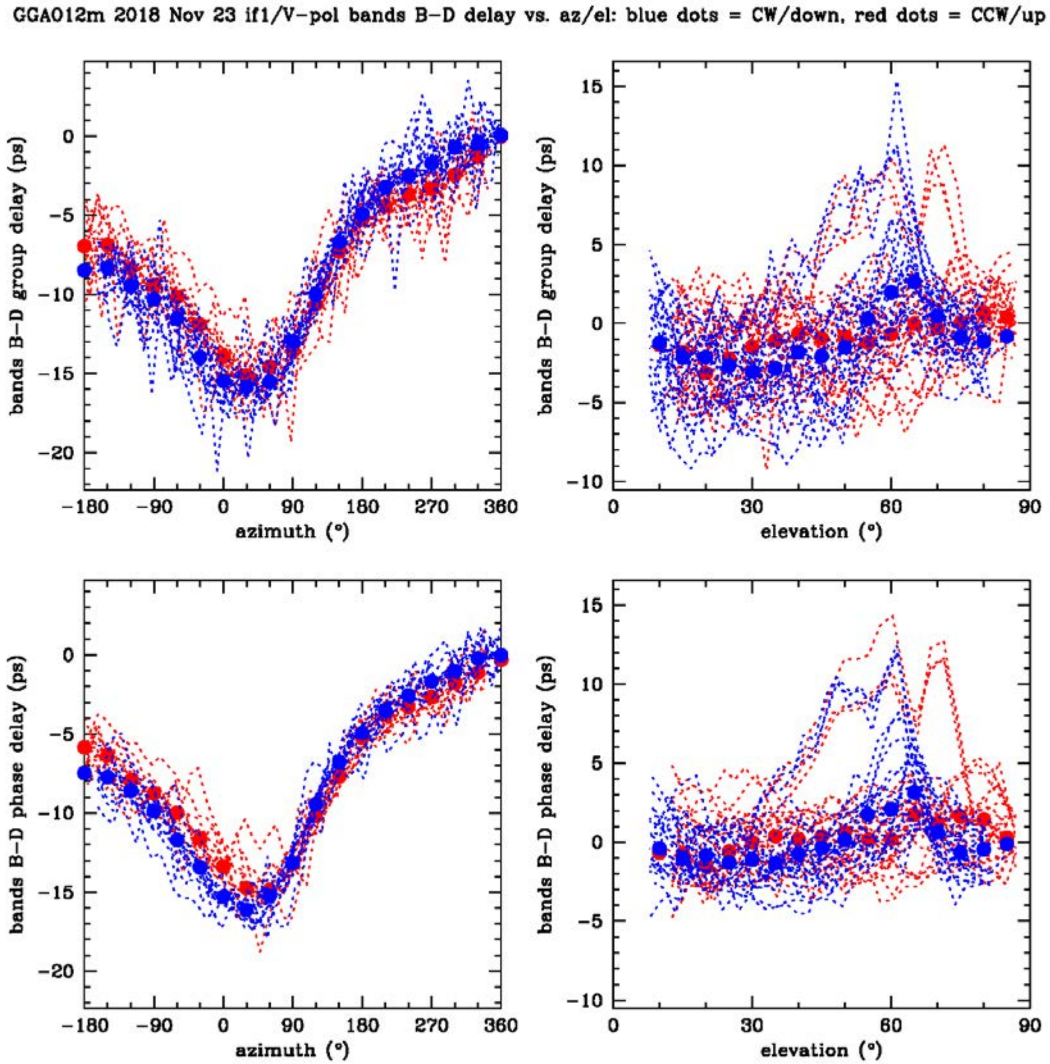
- Modern SDR based Cable Delay Measurement System: Periodically record orientation dependent relative delay and observe for larger than normal values. If not using fiber to transmit 5 MHz reference, replace the 5MHz uplink coax cable, when required.

Cable delay orientation dependence in absence of cable cal

- For station with no cable measurement system, upper bound can be set on cable delay orientation dependence by recording phase cal phase in one or more frequency channels as antenna is slewed in az/el.
- Delay can be estimated from
  - phase delay = phase / frequency, or
  - group delay = (phase1 – phase2) / (freq1 – freq2)
- Observed delay = desired "uplink" delay + "downlink" delay



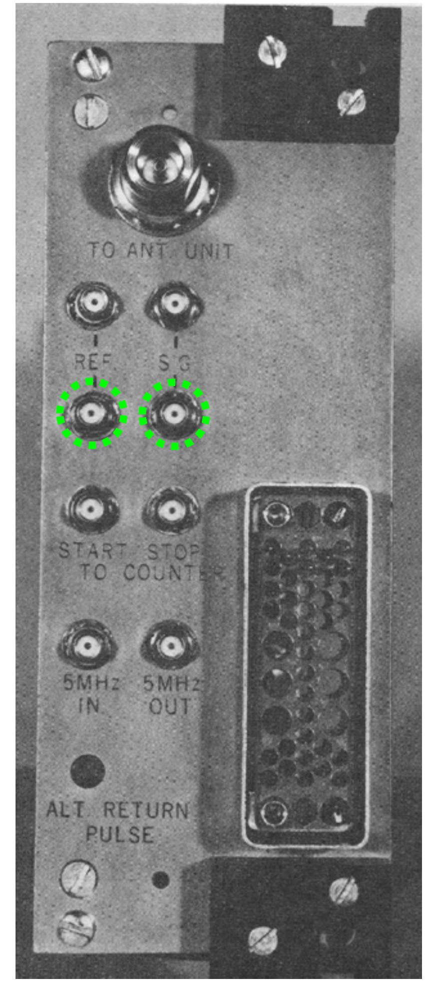
GGAO Cable delay measurement (Nov 2018)



Phase comparators for reference frequency tests

- Phase instabilities in an LO or phase cal often result from instabilities at the reference frequency (e.g., 5 or 500 MHz).
- Vector voltmeters can be used to check the phase stability of a suspect signal against a known-to-be-good signal.
- At sites with a Mk4 delay cal ground unit, the relative phases between two 5 MHz signals can be measured by
  - Feeding them into the lower REF and SIG jacks on the rear panel (circled connectors in figure to right), and
  - Recording the cable cal counter readings in the usual way in a FS log.

Mk4 ground unit rear panel



Rack power

- Use oscilloscope to measure ripple and noise on DAT/DAR power supplies.
  - Low-frequency ripple should be < 10 mV pk-pk.
  - Total noise should be <100 mV pk-pk.
- Use multimeter to measure DC supply voltages *at the modules*, not at the power supply terminals, as there may be significant IR voltage drop from the supply to the module. Measured voltage should be within 0.1 V of design voltage.

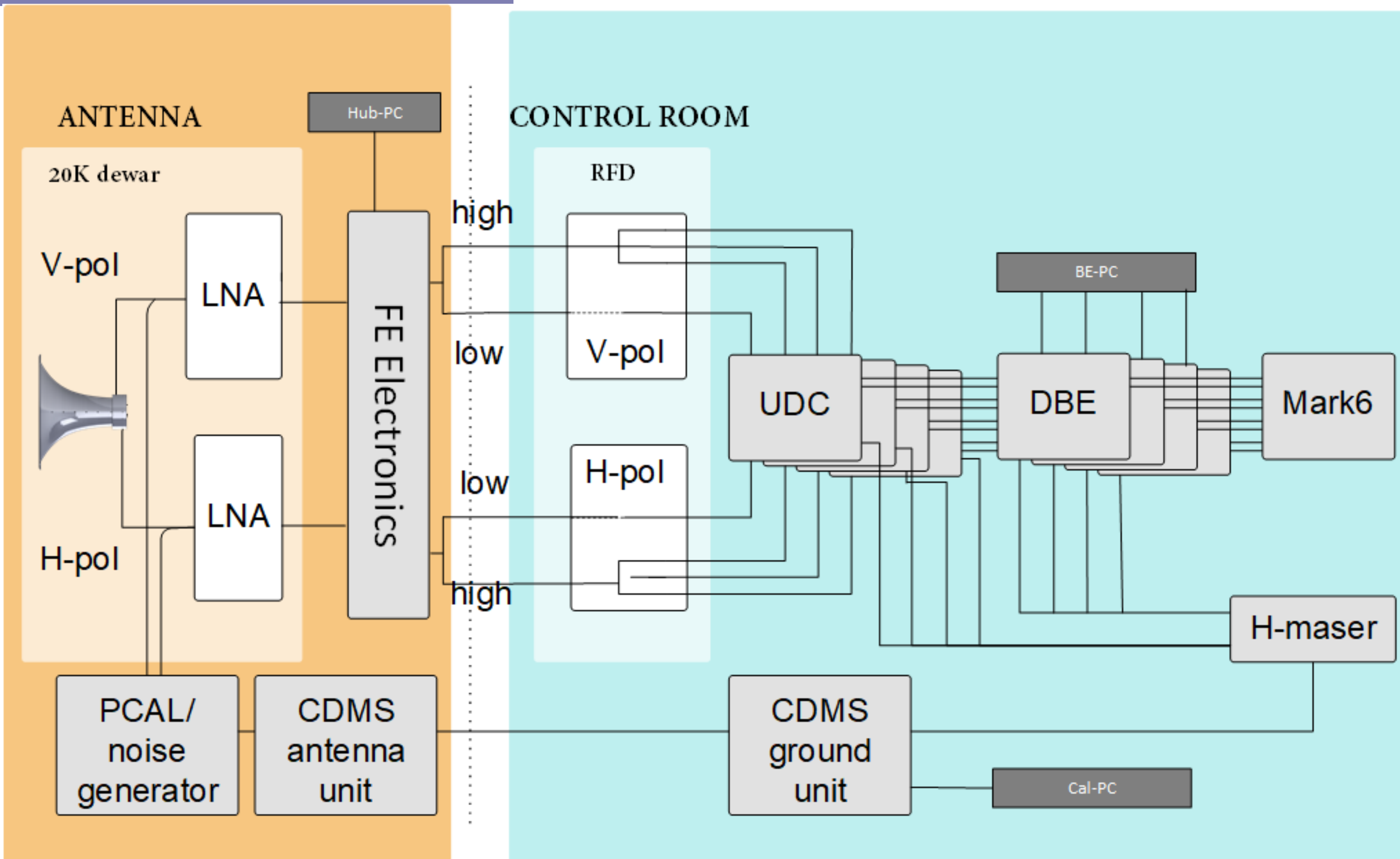
Meteorological sensors

- Temporal stability
  - Barometer should be stable to 0.1 mb over a few minutes.
  - Temperature should be stable to 0.1 ° C over a few minutes.
- Barometer should be calibrated annually.
- Measure barometer offset relative to a local authority, e.g., airport.

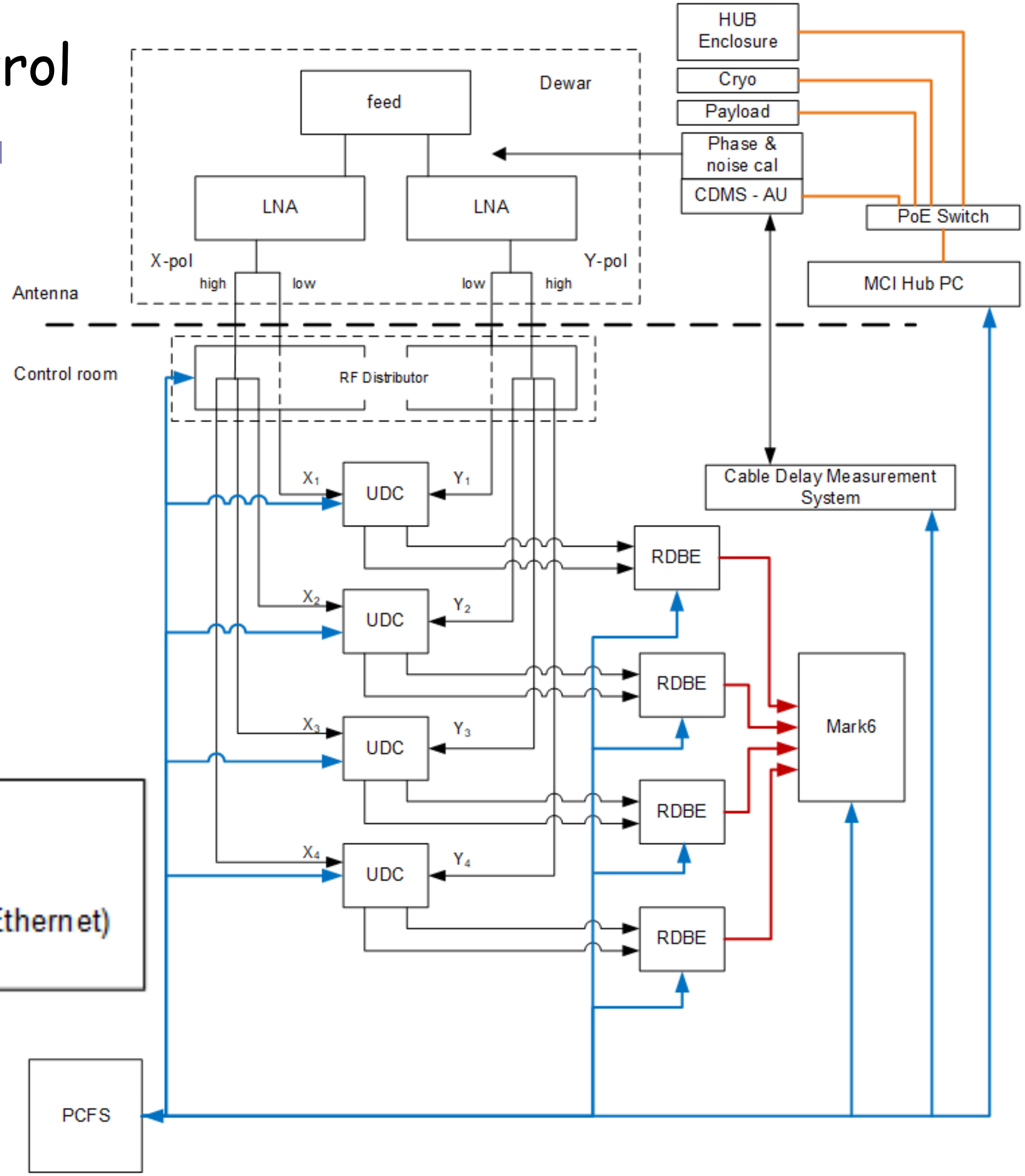
Non-*systests* software tools for testing DBEs (or ABEs)

- For systems with Mark5B recorders –
  - **bpcal** to measure phase cal amplitudes and phases
  - **bstate** to measure sample statistics
  - **vlbi2** to calculate auto-correlation (and cross-corr) spectra
- use plotlog routinely for plotting everything (wx, cable, fmout-gps, pCal amp/phase, pcal phase diffs, Tsys, rx parameters, etc.)

NASA VGOS Signal Chain



PC Field System control



Key

--- IF (Analog)
--- Digital Data (10G Ethernet)
--- Command and Control (1G / 100M Ethernet)
--- POE (private subnet – non routable)

NASA VGOS Stations – SDE – Single Dish Experiments

- Led by Leonid Petrov and post doc Nlingi Habana
  - antenna slewing model to avoid being late on source and reduce unnecessary idle time for highly efficient scheduling
  - develop a realistic model of SEFD prediction
  - provide amplitude calibration for source imaging
  - understand the origin of abnormal antenna characteristics, if any
  - tune system so that it meets specifications

Scheduling single dish experiments (SDE):

- Schedule is defined using single dish scheduling (SDS) language.
- SDS contains experiment name, code, type, experiment description, procedure file, and a schedule.
- The sds file is set to a station.
- Program sds_to_snap converts an sds schedule to a pair snap a proc file for the specified start time.
- Full logging is turned on

```
# Single Dish VLBI schedule. Format version #1.00  of 2021.01.12 ... #
```

```
station  KOKEE12M
exper    k20004   2
type     ZenTsys
pi_name  Leonid Petrov
pi_email Leonid.Petrov@nasa.gov
duration 79207 seconds ( 22.00 hours)
#
description_begin
...
description_end
procedure_begin
...
procedure_end
...
require_sds_to_snap_version 2021.08.27
require_stp_version         2021.08.27
#
```

SDE analysis

- Full log is transformed to anc format
- Datafile in anc format is transformed to a binary format (bts)
- A set of tools for processing data in bts format is being developed

Slewing model estimation SDE

Slewing model: accel --→ slew --→ decel --→ settle

A special schedule to estimate 4 parameters per axis

Achieved accuracy: $< 1s$ for Mg and K2; $\sim 2s$ for Gs.

Slewing parameters

	Gs	Mg	K2	Kk	
SLEW_AZ:	5.00	12.0	11.97	1.80	deg/sec
SLEW_EL:	1.23	6.1	6.12	1.96	deg/sec
ACCL_AZ:	1.33	3.43	3.05	0.80	deg/sec^2
ACCL_EL:	1.41	2.58	2.33	0.20	deg/sec^2
TSETTLE_AZ:	2.35	5.6	5.43	6.60	sec
TSETTLE_EL:	2.04	5.3	5.09	2.60	sec

Max error: better 1s, except El for Gs (2s).

Tsys at Zenith across 2.2-12 GHz by sweeping GGAO UDCs

These are the frequency setups used at GGAO12M in Bands [A], [B], [C], and [D]: (Low Band 2.2-5 GHz; High Band 4-12 GHz)

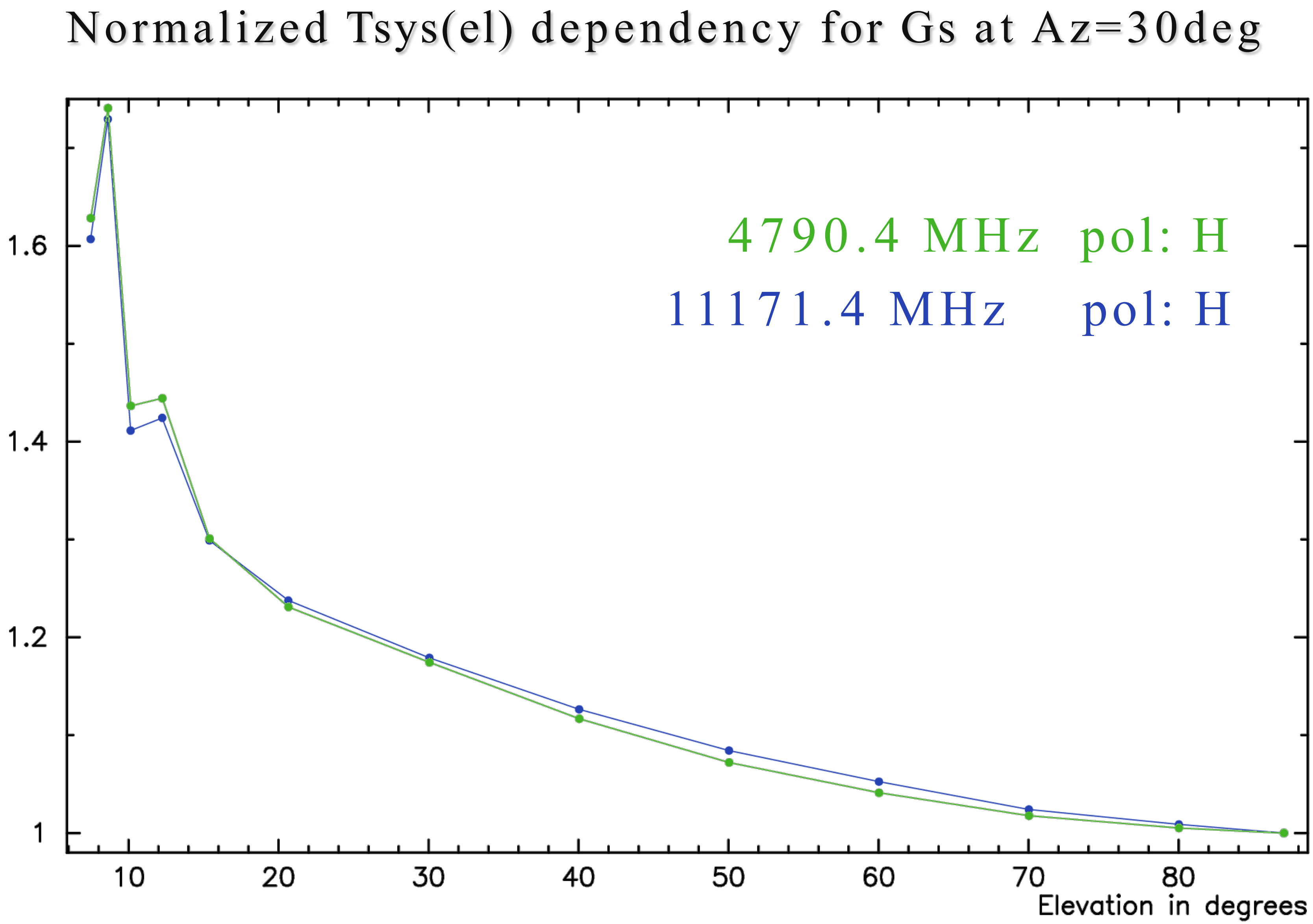
- freq_001 [2200.4, 2680.4] [5000.4, 5480.4] [5480.4, 5960.4] [5960.4, 6440.4]
- freq_002 [2680.4, 3160.4] [6440.4, 6920.4] [6920.4, 7400.4] [7400.4, 7880.4]
- freq_003 [3160.4, 3640.4] [7880.4, 8360.4] [8360.4, 8840.4] [8840.4, 9320.4]
- freq_004 [3640.4, 4120.4] [9442.4, 9922.4] [9922.4, 10402.4] [10402.4, 10882.4]
- freq_005 [4120.4, 4600.4] [4518.4, 4998.4] [10882.4, 11362.4] [11026.4, 11506.4]

60 sec integration at any given frequency, then switch to the next, gather data for 24 hours

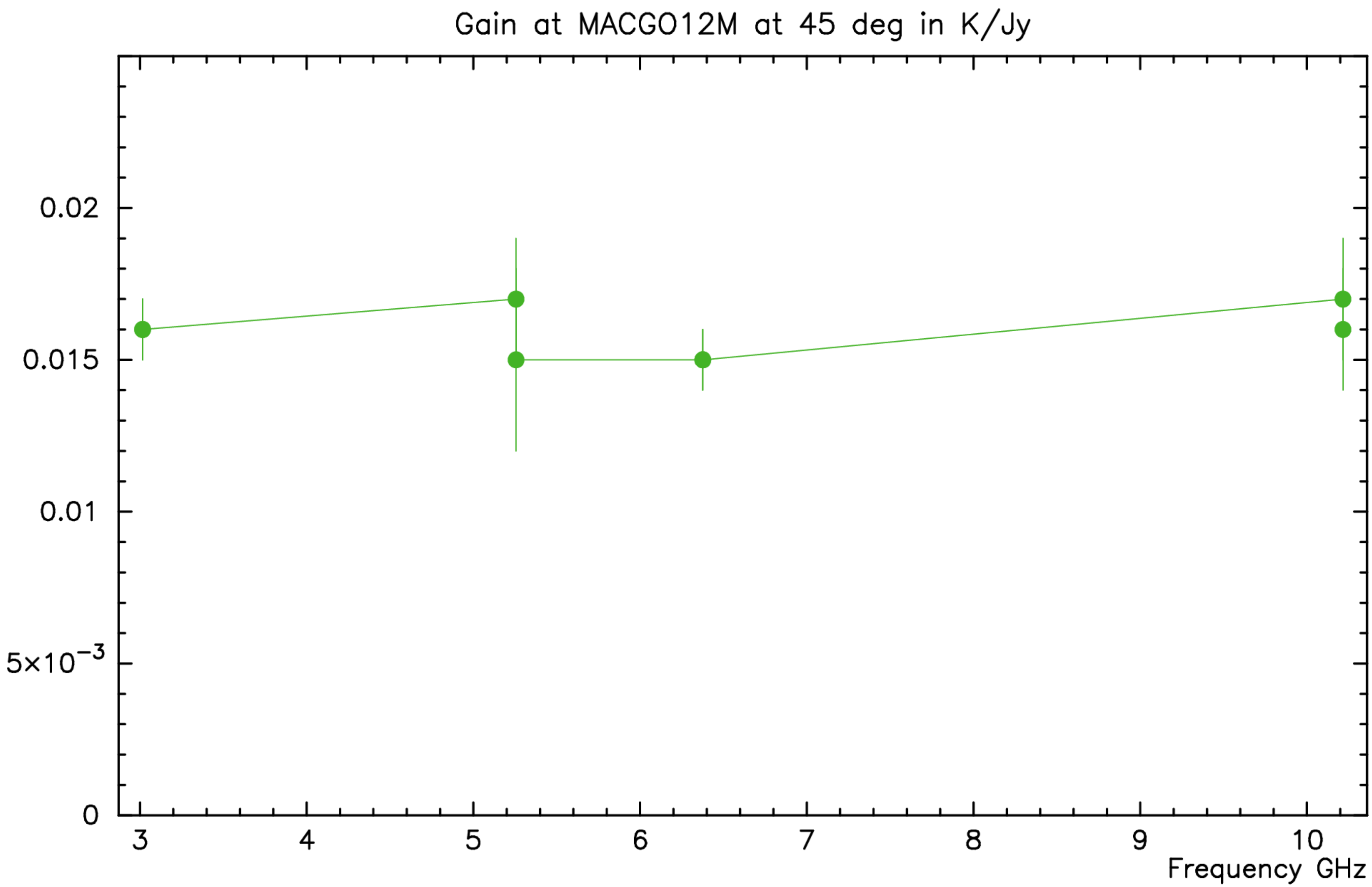
Status of SDE

	Gs	Mg_warm	Mg_cold	K2	Kk	Ws
Slewing	Yes	n/a	Yes	Yes	Yes	NO
ZenTsys	Yes	Yes	Yes	Yes	Yes	NO
ElTsys	Yes	Yes	Yes	Yes	Yes	NO
Gain	Yes	Fail	Yes	Yes	Yes	NO

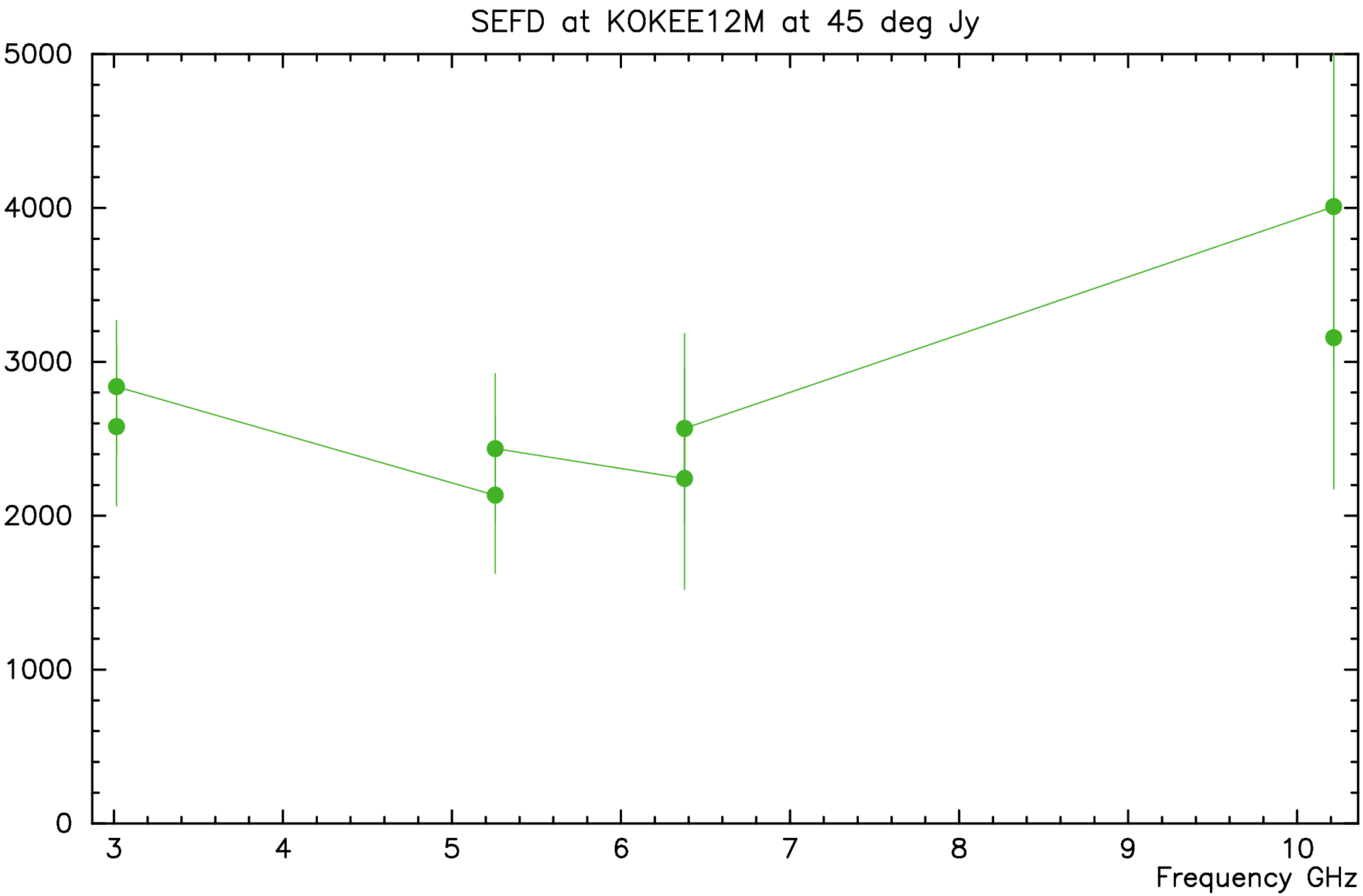
Normalized Tsys vs elevation of Gs



Mg gain curve

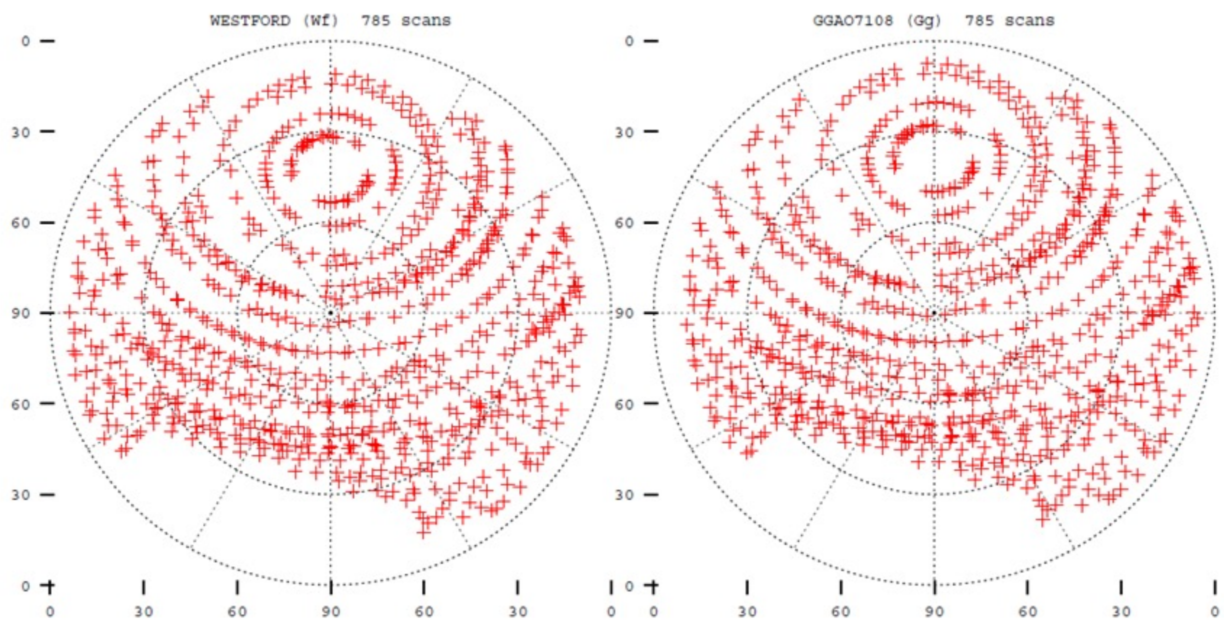


SEFD of K2 as a function of frequency

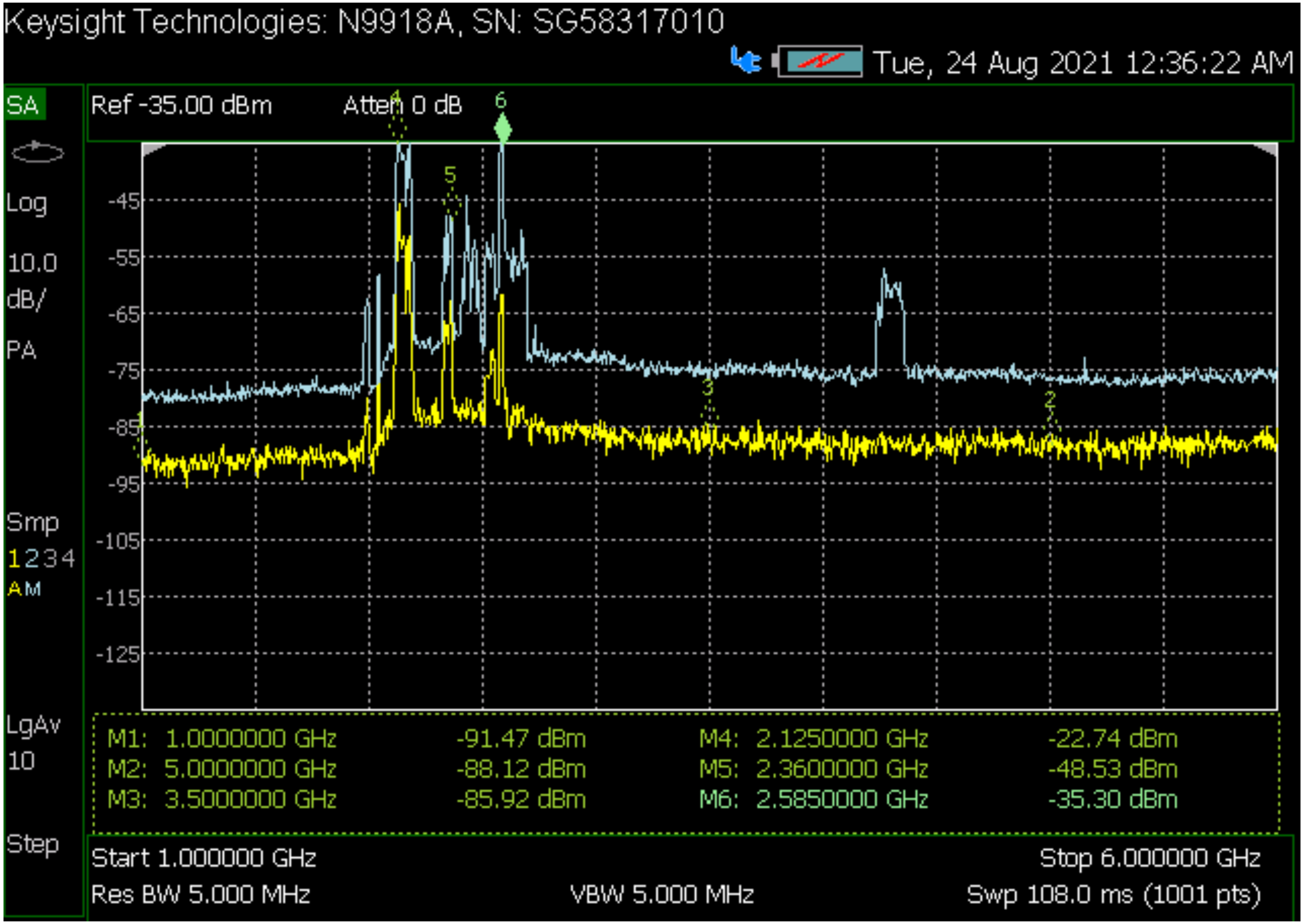


Do RFI survey periodically

- RFI is increasingly becoming a serious problem at many stations
  - Survey RFI in the receiver by scanning in Az & El, while measuring Tsys using 80 Hz winking cal
  - Be prepared to lose sky coverage if RFI is affecting the linearity of the signal chain. Example: At GGAO, ~20% of sky for both the VGOS & SLR telescopes is lost due to a 9.4 GHz aircraft avoidance radar.



GGAO Band A signal chain bandpass



- Ever increasing RFI levels in low band

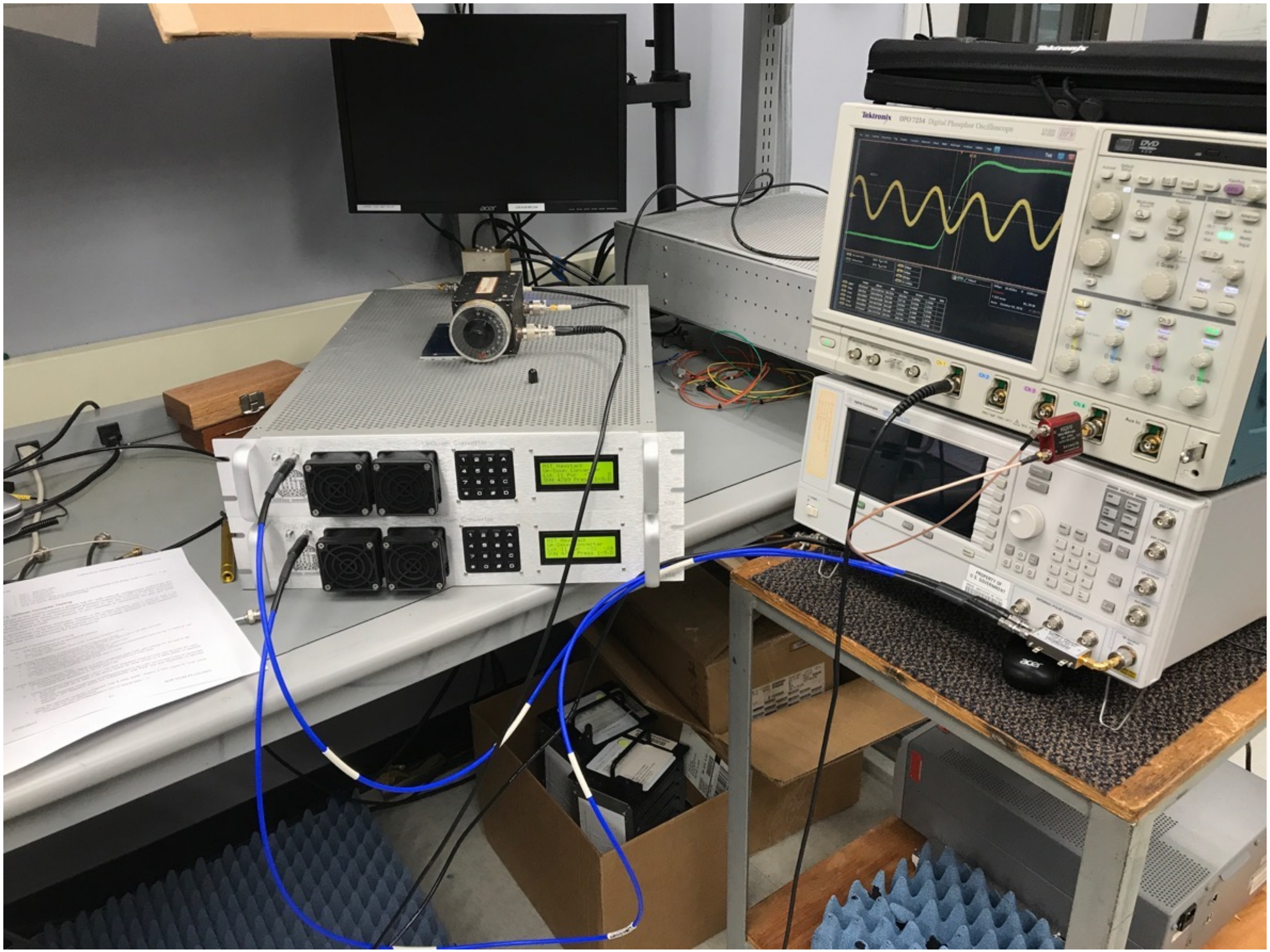
Complementary VLBI data checks at correlator (discussion in presence of Mike Titus)

- Do fringe phases line up between channels?
- Are fringe amplitudes the same in all channels?
- Do the following quantities vary during scans, or between scans?
  - Fringe phase difference between channels
  - Fringe amplitude ratio between channels
  - Phase cal phase difference between channels
  - Phase cal amplitude ratio between channels
- Is the scatter in the estimated delays reasonable?
- Is there evidence of RFI?
- Etc.
- But volume of data passing through correlators is so massive . . . .

  Correlators need all the help they can get from stations in identifying (and fixing!) problems.

Thank you

Typical setup for phase noise measurements



Time Domain Jitter using High Speed Oscilloscope

Fundamentals of antenna calibration

Tsys — power of received emission within the unit bandwidth

Tant = **Trec + Tcmb + Tatm + Tspil + Trfi** + **Tsrc**

SEFD — flux density of the observed source that doubles Tant

Gain = Tsys/SEFD

Gain = $\eta \cdot 2.84 \cdot 10^{-4} D^2$

Gain = $\eta \cdot 0.041$ for VGOS antennas.