Calibration systems: noise, phase, and cable

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Noise calibration system

- Function: Measure time variations & frequency dependence of system temp.
- Does not measure sensitivity loss from phase incoherence, cross-polarization, or antenna aperture efficiency variations

- Applications:
  - Frontend diagnostics
  - RFI detection
  - Radio source mapping

- Two standard techniques:
  - High-level cal signal ($T_{\text{cal}} \sim 0.1-0.3 T_{\text{sys}}$) fired momentarily before a scan, then power levels recorded with cal off during scan
    - Cal signal does not degrade system sensitivity during scan
  - Low-level cal signal ($T_{\text{cal}} \sim 0.02-0.05 T_{\text{sys}}$) fired continually with 50% duty cycle during scan and synchronously detected in backend (NAR method)
    - Higher precision $T_{\text{sys}}$ estimates if gain drifts during scan
    - No time lost to calibration at scan start
Noise calibration precision specification

- Need to calibrate in individual frequency channels (~32 MHz BW).
- Calibration for source mapping from geodetic observations:
  - Typical scan SNR = 10-30 per band, or ~3-10 per channel.
    - Fractional fringe amp std error = 0.1 – 0.3.
  - Cal precision should not limit source mapping capability.
    - Fractional $T_{sys}$ measurement error $<< 0.1 – 0.3$.
- Need to be able to detect RFI $> 0.1 \ T_{sys}$ to $> 5\sigma$.
- VLBI2010 scans may be as short as 1 second.

  $\Rightarrow \ \sigma(T_{sys}) < 0.01 \ T_{sys}$ in 1 second in each channel

- $\sigma(T_{sys}) / T_{sys} = 2 (1 + T_{sys}/T_{cal}) / \sqrt{BW \times t}$ for 50% duty-cycle NAR
  - For $T_{cal}/T_{sys} = 0.05$, $BW = 32$ MHz, & $t = 1$ sec, $\sigma(T_{sys}) / T_{sys} = 0.007$.
- Adjustable $T_{cal}$ level desirable for high $T_{sys}$ conditions (e.g., warm receiver).
- $T_{cal}$ and electronic gain ahead of cal injection point must be stable.
- $T_{sys}$ measurement accuracy of $\sim 10\%$ is sufficient.
Phase calibration system

- Primary function: Measure time variations of instrumental phase vs. frequency.
- Secondary functions:
  - Infer $T_{\text{sys}}$ variations from phase cal amplitude.
  - Phase/gain equalization for circular polarization generation from linear pol.
- Phase differences between channels will be far more stable in VLBI2010 than in S/X VLBI, thanks to digital IF-to-baseband conversion in FPGAs.
- But phase cal is still needed in VLBI2010 to measure
  - LO phase drifts between bands
  - Phase/delay drifts in RF/IF analog electronics
- Pcal phase 1-σ measurement precision should be $<\sim 1°$ in 1 second for each tone in a baseband channel ($\sim$32 MHz BW).
- Broadband pcal generator has been designed at Haystack Observatory and deployed in the NASA VLBI2010 test-bed receivers at GGAO and Westford.
- Broadband radiated pcal systems are under development at IAA and IRA-INAF.
Noise/phase cal signal injection points

- Radiated into feed –
  - Facilitates phase/gain equalization for linear-to-circular pol conversion.
  - Motion between feed & radiator mounted on subreflector can be measured.
  - Phase/delay characteristics of feed can be measured.
  - Phase calibration may be adversely affected by variable multipath.
- Injected via directional coupler between feed and LNA –
  - Conventional injection point in VLBI receivers.
  - Broadband stripline couplers have typical insertion loss of 0.5-1.0 dB.
    - Coupler must be cooled to cryogenic temperature to reduce added $T_{sys}$.
    - At 20 K physical temperature, added system noise is 2-5 K.
- Injected via directional coupler after LNA –
  - LNA gain and phase must be stable.
  - Cal signal level must be higher than for pre-LNA injection by LNA gain.
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 VLBI2010 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 –
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 tone that traversed the desired signal path.
- Spurs corrupt measured pcal phase and amplitude.
  - Phase error up to $|\text{spur}|/|\text{pcal}|$ radian for $|\text{spur}| << |\text{pcal}|$.
- For instrumental phase/delay measurements, only spurs that cause time-varying phase errors are a concern.
- 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
Case 1: To create \( \text{bbdelay} \), must extrapolate phase between two bands up to 5 GHz apart.

- Require extrapolated phase to be precise to < 1/10 radian. 
  \[ \text{delay error} < 0.1 / (2\pi \times 5 \text{ GHz}) = 3 \text{ ps} \]
- 3-ps delay = 0.02 radian (1°) over 1 GHz, or 0.01 radian over 500 MHz

Case 2: One fall-back option is to use group delay over 3 contiguous bands.

- For SNR = 20, \( \sigma(\text{group delay}) \approx 10 \text{ ps} \).
- Want instrumental error \(< \sigma\). \( \rightarrow \) instrumental error < 1 ps.
- 1-ps delay = 0.02 radian over 3 GHz

Specification for spurs that do not depend on antenna orientation:

- **Sufficient condition:** spurs < -40 dB relative to \( \text{pcal} \)
- **Necessary condition:** delay error < 3 ps over 1 GHz and < 1 ps over 3 GHz
Spec for spurious signals dependent on antenna orientation

- Spurs that vary systematically with antenna orientation need their own spec.
- Possible origins:
  - Varying multipath affecting pcal radiated (intentionally or not!) into feed
  - Elevation-driven thermal variations in pulse generator
- VLBI2010 goal is 1-mm 3-D station position accuracy in 24 hours.
- Orientation-dependent systematic errors...
  - map into station position, and therefore
  - should be kept < 0.1 mm = 0.3 ps.
- 0.3 ps error can arise from spur-induced phase error of
  - 0.004 radian at 2 GHz (broadband delay case), or
  - 0.006 radian change over 3 GHz (case 2 of previous slide).
- Specification for spurs that vary with antenna orientation:
  - Sufficient: spurs < -50 dB relative to pcal
  - Necessary: phase error < 0.004 radian & delay error < 0.3 ps over 3 GHz
- Simulations of subreflector-feed multipath indicate that -50 dB spec is more restrictive than necessary for path length changes < a few cm.
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 (Haystack).
- 5 or 10 MHz sinewave input; output pulse train at same frequency.
- Output spectrum flatter than in tunnel diode design.
- Pulse delay temperature sensitivity < 1 ps/°C with no external temp. control.
- No support for cable measurement system (unlike previous pcal designs).

```
5 or 10 MHz sinewave clipper comparator logic gate differentiator switch
pulse gating signal
5 or 10 MHz pulse train
```
Digital phase calibrator output power spectrum

Digital pcal generator tone power with 5 MHz input

-70
-80
-90
-100
-110

pcal tone power (dBm)

2011 Mar 11 spot checks
bbdev memo #034

2 4 6 8 10 12 14 16 18

frequency (GHz)
Broadband noise/phase calibration unit

- “Cal box” has been developed by Honeywell Technical Solutions Inc (HTSI) and Haystack Observatory for use in broadband frontends.
- 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 (ΔT < 0.2°C for 20°C change in ambient T)
  - monitoring of temperature, 5 MHz input level, attenuation, gating
- Equalizers for phase or noise cal signals could be added if necessary.
Broadband noise/phase cal box: RF connections

1-2 March 2012
VLBI2010 TecSpec Workshop
Broadband noise/phase cal box: cal signal generators
Broadband noise/phase cal box: RF-tight inner enclosure
Broadband noise/phase cal box: outer thermal enclosure
Broadband noise/phase cal box: complete unit
Cable calibration system

- Electrical length of cable carrying phase cal reference signal (or phase cal signal itself) from control room to frontend must be
  - stable or, if not,
  - measured for post-observation data correction.
- Whether a cable measurement system (or “cable cal”) is necessary for VLBI2010 systems has not yet been determined.
  - Answer will depend on measured stability of coax cable or optical fiber.
- Specifications on cable cal performance:
  - 1-σ measurement precision < 1 ps
  - Allan std dev < $10^{-15}$ @ 50 minutes
  - On other time scales, ASD scales with typical maser performance.
- Absolute length measurement is not necessary, just relative.
Representative cable cal systems deployed or under development

- Some system 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?
- Modulation in the frontend allows the return signal to be distinguished from a reflected signal on a single coax or fiber.

<table>
<thead>
<tr>
<th>System</th>
<th>Cable no./type</th>
<th>Frequencies</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark 4</td>
<td>1 coax</td>
<td>5 MHz &amp; 5 kHz</td>
<td>Does not meet VLBI2010 spec.</td>
</tr>
<tr>
<td>VLBA</td>
<td>2 coax</td>
<td>500 MHz &amp; 2 kHz</td>
<td>Modulates 500 MHz in frontend.</td>
</tr>
<tr>
<td>Kokee Park</td>
<td>2 fibers</td>
<td>500 MHz</td>
<td></td>
</tr>
<tr>
<td>NRAO 14-m</td>
<td>2 fibers</td>
<td>500 MHz</td>
<td></td>
</tr>
<tr>
<td>JPL DSN</td>
<td>1 fiber</td>
<td>modulated 1 GHz</td>
<td>Phase stabilization</td>
</tr>
<tr>
<td>EVLA</td>
<td>2 fibers</td>
<td>512 MHz</td>
<td></td>
</tr>
<tr>
<td>Arecibo</td>
<td>2 fibers</td>
<td>1.45 GHz</td>
<td></td>
</tr>
<tr>
<td>KVG</td>
<td>1 coax or fiber</td>
<td>2 near 700 MHz</td>
<td>Phase stabilization or meas.</td>
</tr>
</tbody>
</table>
Cable cal performance: Green Bank 14-m system