RFI: Sources, Identification, Mitigation

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Effects of RFI on VLBI

- RFI increases system temperature.
- Depending on strength of RFI, it may affect
  - only those frequency channels where RFI is present, or
  - all frequency channels if RFI is strong enough to overload electronics.
- Effects of increased $T_{sys}$ include:
  - Reduction in SNR and hence in geodetic/astrometric precision and astronomical source mapping quality
  - Systematic shifts in estimated group delay (see next slide)
  - Failure of geodetic bandwidth synthesis if too many frequency channels are severely affected by RFI
    - E.g., in T2075 RFI caused loss of channels S1 and S5 at station A and S2 and S3 in station B, leaving only two usable channels on baseline AB.
- SNR is inversely proportional to
  $$\text{SNR} \propto \frac{1}{\sqrt{1 + \frac{(\text{RFI power integrated over channel BW})}{(\text{non-RFI power})}}}.$$  
  - E.g., if RFI power = 50% of non-RFI, SNR drops by 18%.
  - In continuum VLBI, don’t worry about every little narrowband RFI spike, as its total power may be insignificant.
  - In spectral-line VLBI, do worry if spike falls on top of your spectral line!
Effects of RFI on group delay

- Besides degrading precision, RFI can bias group delay estimates.
- Example: If RFI increases in top channel in phase vs. frequency plot below, channel’s “weight” will decrease when fitting group delay to 8 channels.
  - If channel 8 phase is systematically biased (due to uncorrected instrumental effects) relative to other channels, group delay will be biased by an amount dependent on strength of RFI and size of phase bias.
- If RFI depends on direction (az/el), site position estimate is biased.
- Simulations show that S/X delay can be biased by >1 ps when RFI raises Tsys by >10% in one or more channels. See Dave Shaffer paper in 2000 IVS GM proceedings (http://ivsc.gsfc.nasa.gov/publications/gm2000/shaffer/).
Non-effects of RFI on VLBI

- Only rarely does RFI correlate between stations.
  - Wide geographic separation between stations precludes common visibility of RFI sources other than satellites.
  - If an antenna happens to point near a satellite, other antennas will be pointed far away because satellites are nearby.
- An RFI source visible on a baseline has a different delay and rate from the VLBI target; any correlated RFI signal will be strongly rejected at the correlator.
- Exception: short baselines (<~100 km), e.g., geodetic “ties” sessions, where local RFI and phase cal may correlate between stations.
Effect of gain nonlinearity on spectrum

- For a perfectly linear amplifier (which does not exist!),
  - $V_{\text{out}} = g V_{\text{in}}$
  - Output at frequency $f_o$ is independent of input at $f \neq f_o$.
- For a real amplifier,
  - $V_{\text{out}} = g_1 V_{\text{in}} + g_2 V_{\text{in}}^2 + g_3 V_{\text{in}}^3 + \ldots$.
  - Harmonics and intermodulation products of input signals appear in output.
  - Output at frequency $f_o$ can depend on input signals at other frequencies.

Output spectrum for above input spectrum includes signals at
- $N f_{\text{rfi}}$
- $N f_{\text{rfi}} \pm M f_{\text{blue}}$

$T_{\text{sys}}$ increases at these frequencies.
Example of harmonics generated from strong RFI

S-band IF spectrum at output from mixer/preamp (LO = 2020 MHz)
Gain compression / saturation

- Gain is less for strong signals than for weak signals. → gain compression
- 1-db compression point is power level at which gain is reduced by 1 dB.
- Simulations show $T_{sys}$ increases by > few % when input > 1-dB point - 10 dB.
  - Typical LNA input 1-dB = -70 dBW → keep $P_{in} < -80$ dBW to avoid SNR loss.
- If device saturates, all sensitivity to input is lost while signal is clipped.

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**Linear operation**

**Saturation**

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When should I worry that RFI is too strong?

You should worry when . . .

- RFI power raises system power in baseband frequency channel by >10%.
  - Effects:
    - SNR is reduced.
    - Group delay may be biased significantly.
  - Frequency of RFI may lie outside frequency channel, but gain nonlinearity in VLBI system can “move” RFI into frequency channel.
- RFI is at integer MHz, coherent with maser, and > -50 dB relative to phase cal signal.
  - RFI = spurious phase cal signal, which degrades calibration.
- RFI power > device survival limit
  - Typical input limit for LNA is ~ -20 dBW.
- Do not worry about every little blip on a spectrum analyzer!
  - A signal 10 dB above the noise and 10 kHz wide adds only 1% to total power of an 8-MHz-wide channel. → not a problem for continuum VLBI
How does RFI get into VLBI system?

- Multipath off objects and antenna structure
- Spillover directly into the feed
- Antenna sidelobes
- Direct coupling into cables and circuits

courtesy B. Petrachenko
Sources of RFI

- **RFI external to VLBI system**
  - Usually originates at RF frequencies and is picked up in feed.
  - Can be at image frequency if RFI is strong enough to overcome image rejection in receiver or backend.
  - Can be picked up at IF frequencies if RFI is exceptionally strong, especially if an IF cable has a broken shield or bad connector.
- **Common RFI sources:**
  - Satellites (plans for 1000’s of small sats for broadband internet)
  - Wireless/mobile/cell transmitters (5G to include Millimeterwaves)
  - TV/radio broadcast and relay
  - Radar, now includes *automotive radars*
- **Internally generated RFI**
  - RF or IF amplifiers may oscillate.
    - LNAs are especially prone to oscillation, which may occur at RF or IF frequency.
  - Backends (especially high-speed digital logic) generate maser-coherent tones.
  - Good practice: Set LOs of unused BBCs to frequencies outside observing band.
Detecting presence of RFI

- Spectrum analyzer is most efficient instrument to find narrowband RFI.
  - Reduce resolution BW to make narrowband signal stick higher above noise.
- RFI with bandwidth $\gtrsim$ channel BW is hard to identify by looking at the channel power spectrum.
  - If RFI has stable level, it can be seen in elevated Tsys or reduced phase cal amplitude.
    - Tsys may vary from scan to scan due to legitimate causes such as changing tropospheric or ground pickup noise.
      - Such effects are removed by calculating ratios between channels.
  - If RFI is unstable on time scale of noise cal on-off cycle, total power levels (FS ‘tpi’) are a better indicator of RFI strength than is Tsys.
What can be done about RFI?

- To reduce out-of-band RFI, install filters with sharp cutoffs or notches.
  - Options are limited if RFI drives LNA close to saturation.
- Operate analog electronics and sampler at lowest level consistent with negligible impact on SNR, to maximize headroom and minimize potential for saturation.
- Try to get cooperation of agency operating interferer, e.g. time multiplexing.
- Change observing frequencies to avoid persistent RFI.
  - Has been done in geodesy to accommodate RFI at Matera, Medicina, and Westford, among others.
- Avoid observing in direction toward interferer.
  - Will have negative impact on geodetic results.
- If RFI is internally generated . . .
  - Fix the oscillating LNA.
  - Fix the broken shield on the IF cable coming into the rack.
Estimating received power level from a known RFI source

- RFI power at LNA input = RFI power density \( (W \, m^{-2}) \) at antenna times antenna effective area \( (m^2) \)

- For a transmitter with antenna gain \( G_{transmit} \) and power \( P_{transmit} \) located a distance \( R \) from the receiving antenna, in direct line of sight,
  
  \[ \text{power density} = \frac{P_{transmit} \, G_{transmit}}{4 \pi R^2} \]

- For a receiving antenna with gain \( G_{receive} \) in the direction toward source,
  
  \[ \text{effective area} = \frac{G_{receive} \times \text{(wavelength)}^2}{4\pi} \]
  
  - For an isotropic antenna, \( G_{receive} = 1 \).

- If the received signal lies within passband of feed and LNA . . .
  - It may damage LNA if too strong.
  - At lower levels, it may saturate LNA.
  - If it lies within post-LNA passband, it may saturate electronics downstream.
- Effective area (or gain) of antenna depends strongly on direction of source relative to main beam.
  - To right: example of antenna sidelobes close to main beam of a large parabolic antenna
- RFI is usually picked up in sidelobes > 5° from main beam.

![Graph showing relative power dB vs illumination angle degrees]
How can we tell if 2-14 GHz LNA at a site is safe from saturation?

- For an existing antenna with broadband frontend, can measure spectrum directly.
- For imaginary antennas, can calculate expected power: RFI power at LNA input = RFI power density (W m$^{-2}$) x antenna effective area (m$^2$), where RFI power density comes from RFI survey.
  - Already looked at antenna gain; now look at surveys.
RFI power calculated for VLBI antenna from RFI survey data: 1-15 GHz
RFI survey results interpretation

- Survey yielded estimates of RFI power $P_{\text{iso}}$ at terminals of an isotropic antenna.
- To avoid SNR loss from gain nonlinearity, LNA input power must be < -80 dBW.
  - Assume post-LNA filter is present to remove RFI that could saturate downstream electronics.
- Using an ITU model → Can calculate, for a given $P_{\text{iso}}$, how close to RFI source an antenna can point without SNR loss (90% of the time).

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<thead>
<tr>
<th>$P_{\text{iso}}$ (dBW)</th>
<th>$\theta$</th>
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<tbody>
<tr>
<td>-95</td>
<td>&gt; 5°</td>
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<td>-87</td>
<td>&gt; 10°</td>
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<td>-79</td>
<td>&gt; 20°</td>
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<td>-70</td>
<td>&gt; 50°</td>
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RFI and VGOS

- VGOS frequency range of 2-14 GHz presents challenges from RFI.
- Mitigation strategies include:
  - Use flexible tuning of updown converters to place radio-quiet observing bands (500-1000 MHz wide) in between RFI-loud regions.
  - Exclude RFI-loud regions within a band by recording selected narrow-BW (e.g., 32 MHz) channels in each band.
  - Use highly frequency selective techniques (e.g., high image rejection and inter-channel isolation) in downconversion, Nyquist zone filtering and channel definition to keep RFI at one frequency from infecting another.
  - Use physical barriers to reduce interference from DORIS beacons and SLR aircraft surveillance radar at integrated geodetic sites.
  - Do not attempt to support observations below 2.2 GHz, where RFI is particularly strong; take advantage of highpass character of feed.
    - GNSS observations may be precluded for main VGOS antenna; they may be supported with a smaller reference antenna.
  - But these strategies are useless if strong RFI in 2.2-14 GHz VGOS band saturates LNA!
Plenty of RFI in the bands of VGOS interest
VGOS Signal Chain

MIT Haystack designed and built the VGOS Signal Chain: Frontend, Backend, Delay Calibration, MCI
Front Ends with Low & High Band Filters covering 2.3 -14 GHz

Vacuum Chamber

Power Supply Requirements
+5 VDC: 200 mA
5 VDC: 100 mA
+15 VDC: 5.34 A

Low Band Section designed to drive 85' LMR-400UF (FE to pedestal) + 275' LMR-400 (pedestal to control room)

From SCC
From Calibration Signal

RF-over-Coax

RF-over-Fiber

RF-over-Coax

RF-over-Fiber
And we see them all the time

Spectra taken in the low band channel with Westford antenna slewing full 360 deg in Azimuth at 10 deg Elevation. Yellow: MaxHold & Cyan: Averaged

Without a 2200 MHz High Pass Filter

After inserting a 2200 MHz High Pass Filter at the dewar output
9.41GHz radar from the SLR station within GGAO can damage the LNA.
Notch filter to cut off the NGSLR’s 9.4 GHz radar for 100% the sky coverage

- Design & fabrication of High Temperature Superconducting 9.4 GHz Notch Filters in front of the cryogenic LNAs in collaboration with colleagues at GSFC. *Prototype fab is in progress*
RFI measurements at MGO, site of next VGOS antenna at the McDonald Observatory in Texas (ref: Larry Hilliard, GSFC)

BroadBand_TX VLBI site 1 radar take 12_7212016_1, 2 and 3=> radar on elevation 10.4 degrees elev, 269.9 azi, 12:00:17 AM→12:03:10 AM

-76.3 dBm was highest measured RFI at operational worst case elevation

-76 dBm translates to about -16 dBm signal at the LNA input - below the damage level but enough to saturate the output.

- Synchronous Blanking at the output will also be needed

- GGAO operates with a sky mask, losing 20% coverage for both the SLR and VLBI stations