RFI: Sources, Identification, Mitigation

Brian Corey and Hayo Hase

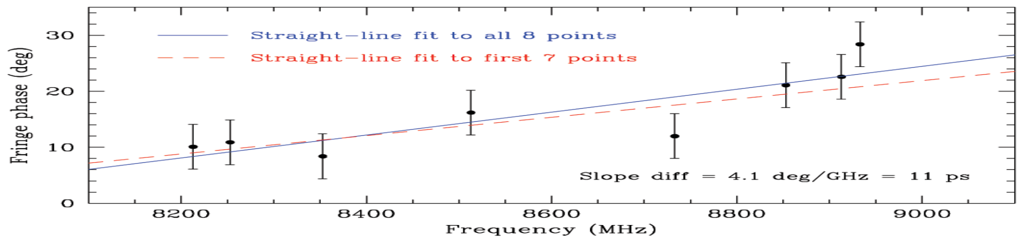
Effects of RFI on VLBI

- 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 Tsys 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

  sqrt[1 + (RFI power integrated over channel BW) / (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!

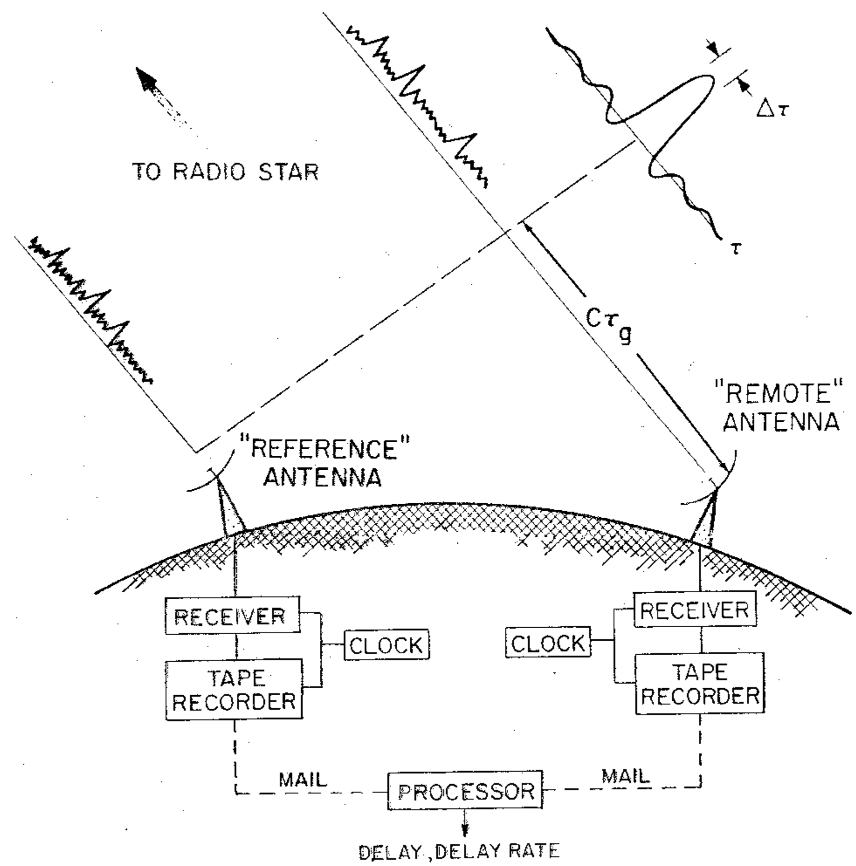
Effects of RFI on group delay

- 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://ivscc.gsfc.nasa.gov/publications/gm2000/shaffer/).



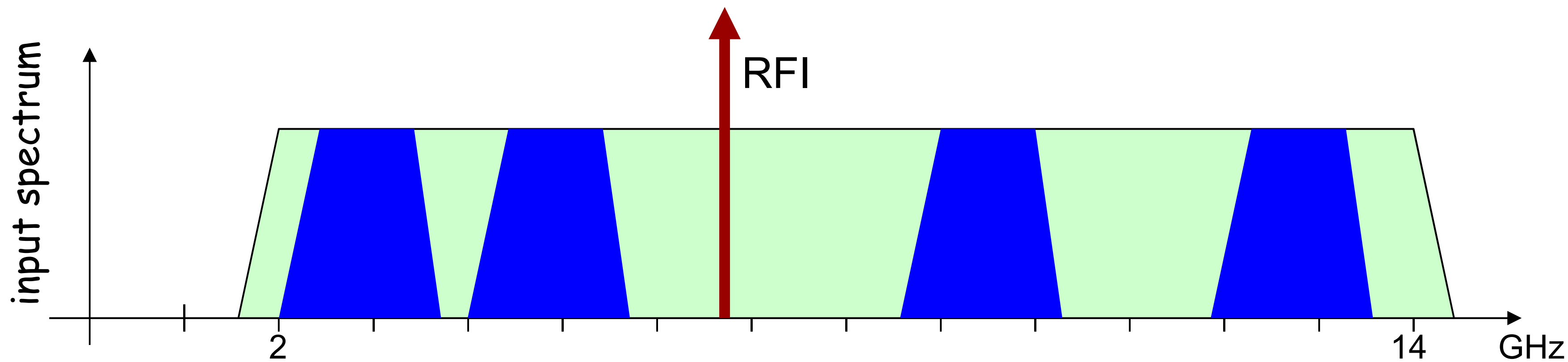
Non-effects of RFI on VLBI

- 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!),
  - $V_{out} = g V_{in}$
  - Output at frequency f_o is independent of input at $f \neq f_o$.
- For a real amplifier,
  - $V_{out} = g_1 V_{in} + g_2 V_{in}^2 + g_3 V_{in}^3 + \ldots$
  - Harmonics and intermodulation products of input signals appear in output.
  - Output at frequency f_o can depend on input signals at other frequencies.

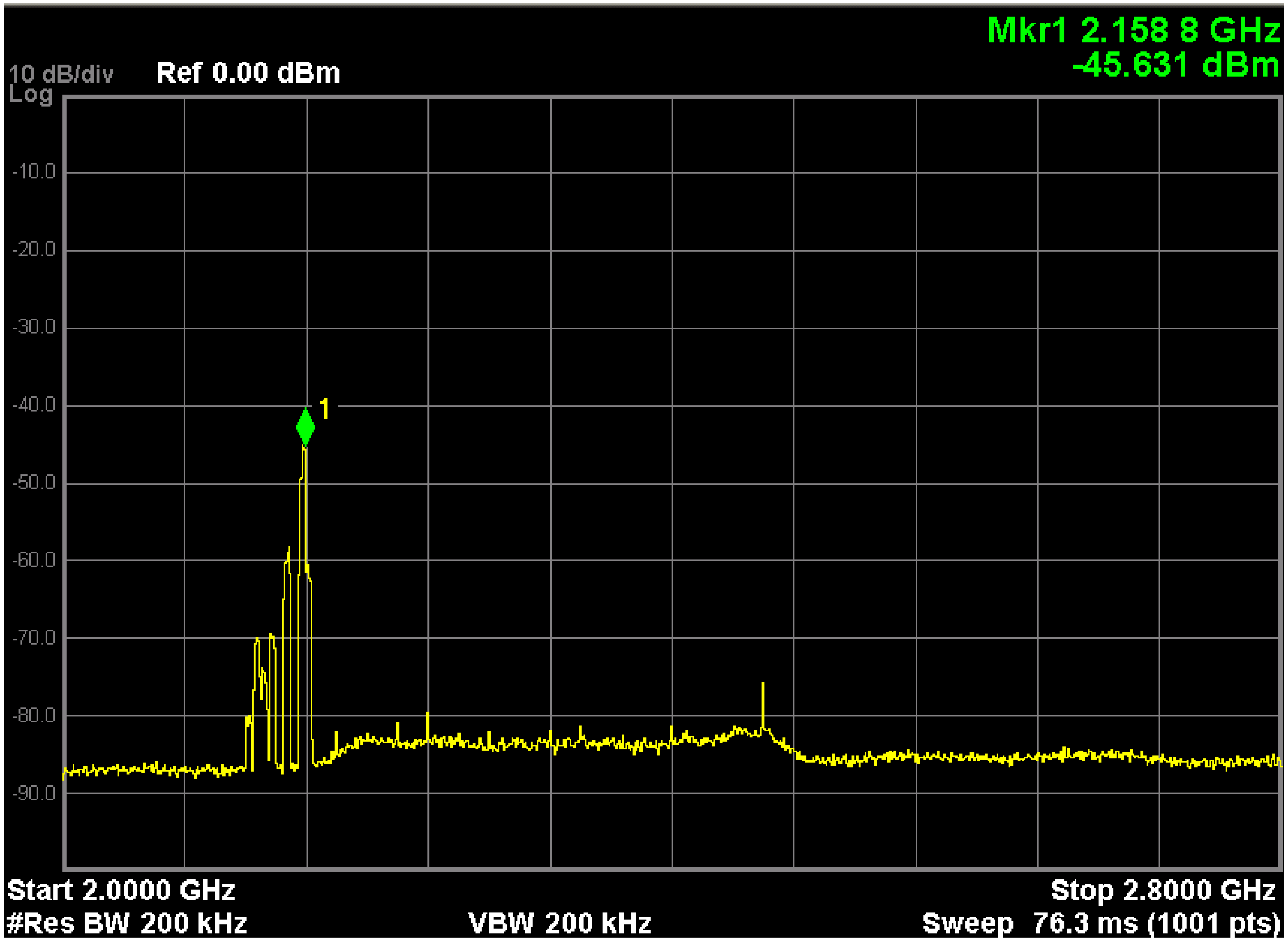


courtesy B. Petrachenko

- Output spectrum for above input spectrum includes signals at
  - $N f_{rfi}$
  - $N f_{rfi} \pm M f_{blue}$
- Tsys increases at these frequencies.

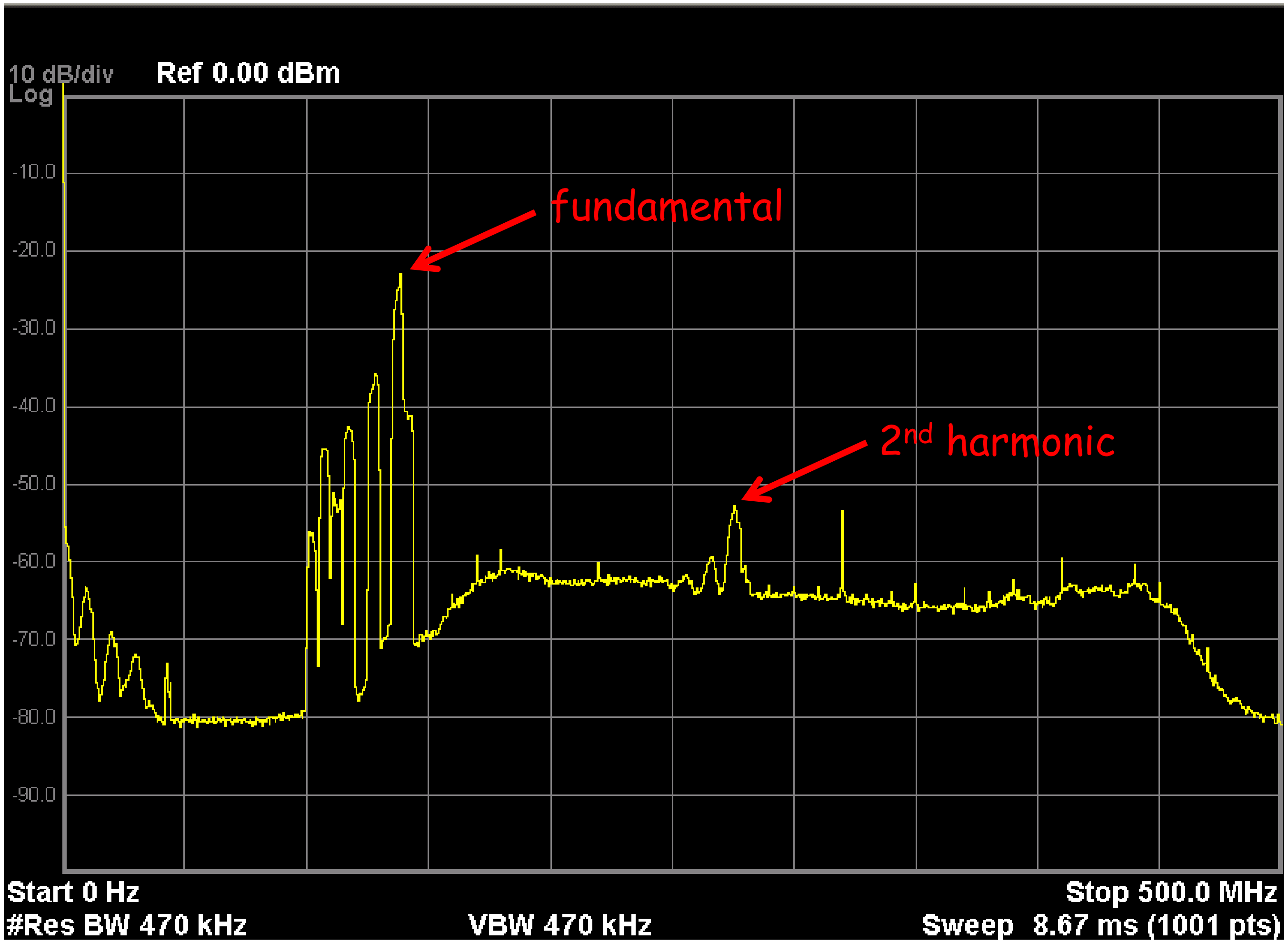
Example of harmonics generated from strong RFI – slide 1 of 2

S-band RF spectrum at input to mixer/preamp



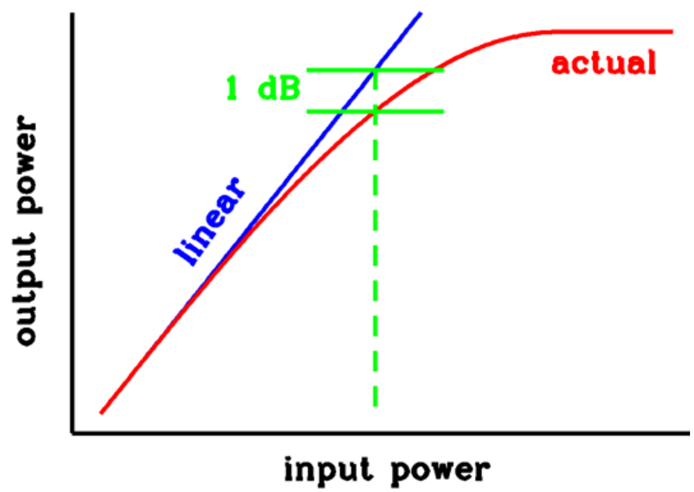
Example of harmonics generated from strong RFI - slide 2 of 2

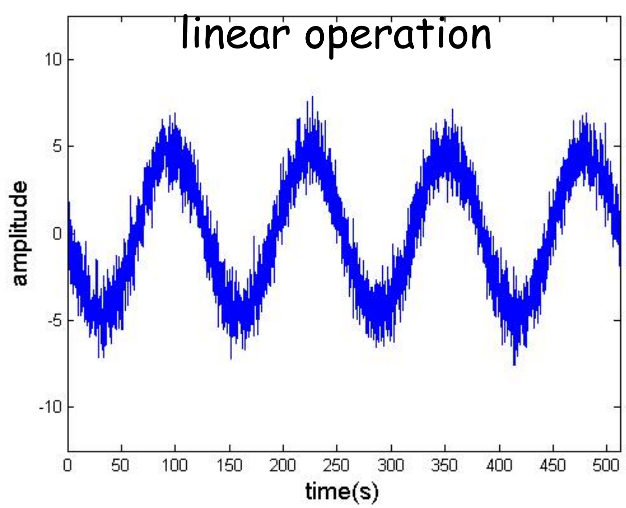
S-band IF spectrum at output from mixer/preamp (LO = 2020 MHz)

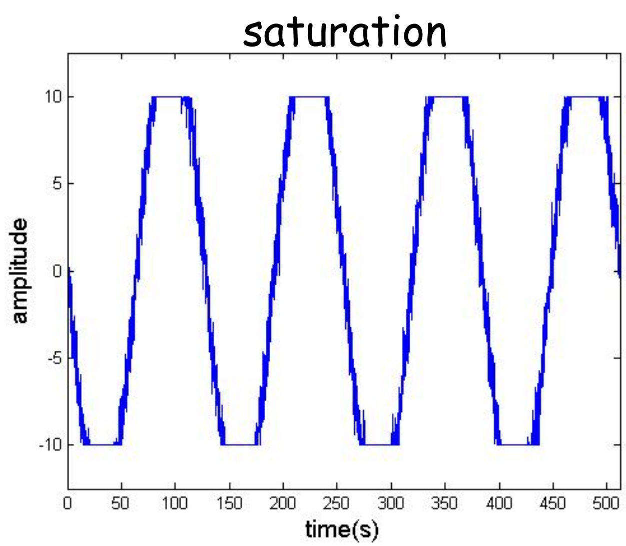


Gain compression / saturation

- 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 Tsys 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.







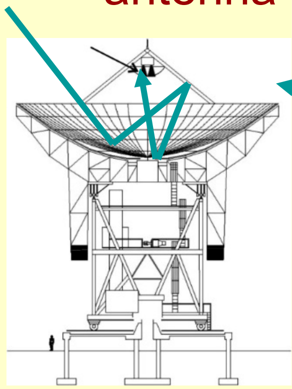
When should I worry that RFI is too strong?

You should worry when . . .

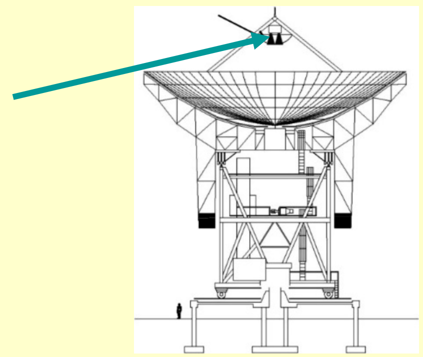
- RFI power raises system power in baseband frequency channel by >10%.
  - Effects:
    - SNR is reduced.
    - Group delay may be biased significantly.
  - Frequency of RFI may lie outside frequency channel, but gain nonlinearity in VLBI system can "move" RFI into frequency channel.
- RFI is at integer 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?

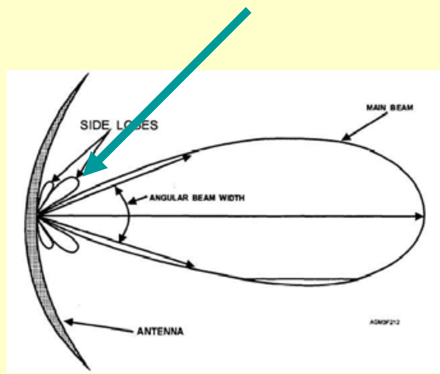
Multipath off objects and antenna structure



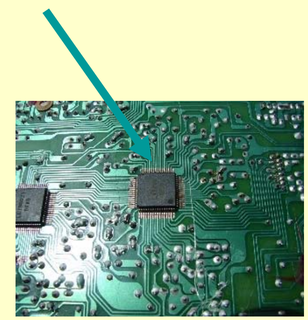

Spillover directly into the feed



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
    - Wireless/mobile/cell transmitters
    - TV/radio broadcast and relay
    - Radar
- 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.

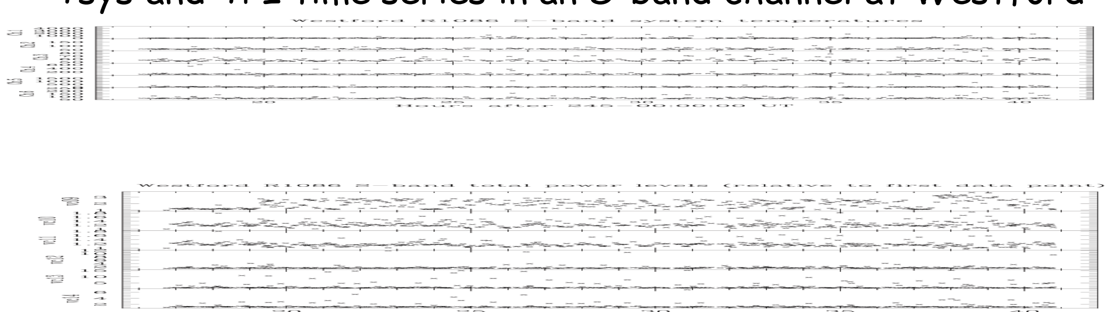
Detecting presence of RFI

- Spectrum analyzer is most efficient instrument to find narrowband RFI.
  - Reduce resolution BW to make narrowband signal stick higher above noise.
- RFI with bandwidth >~ 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.

Tsys and TPI time series in an S-band channel at Westford

Tsys

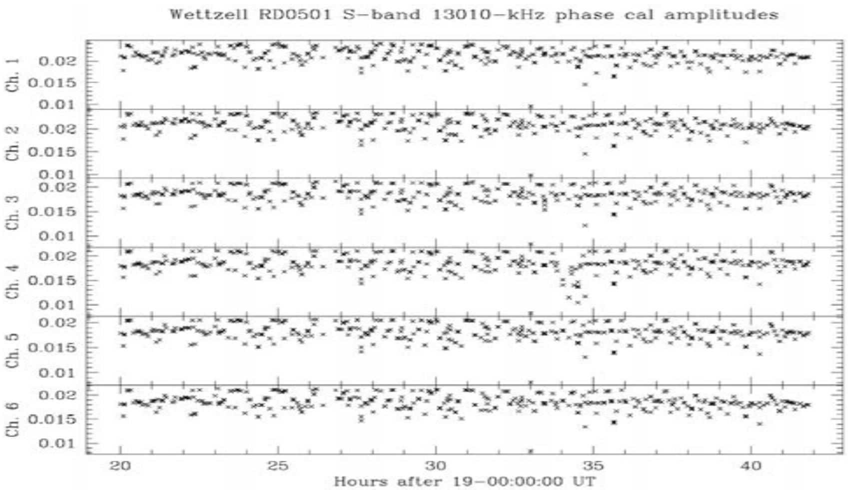
TPI



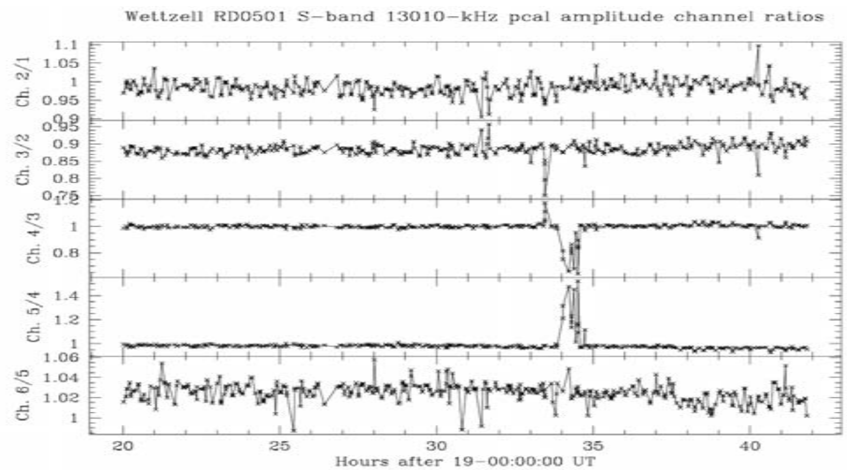
time

Detecting presence of RFI in phase cal amplitudes

Phase cal amplitudes in six S-band channels



Adjacent channel ratios of same phase cal amplitudes as at left



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

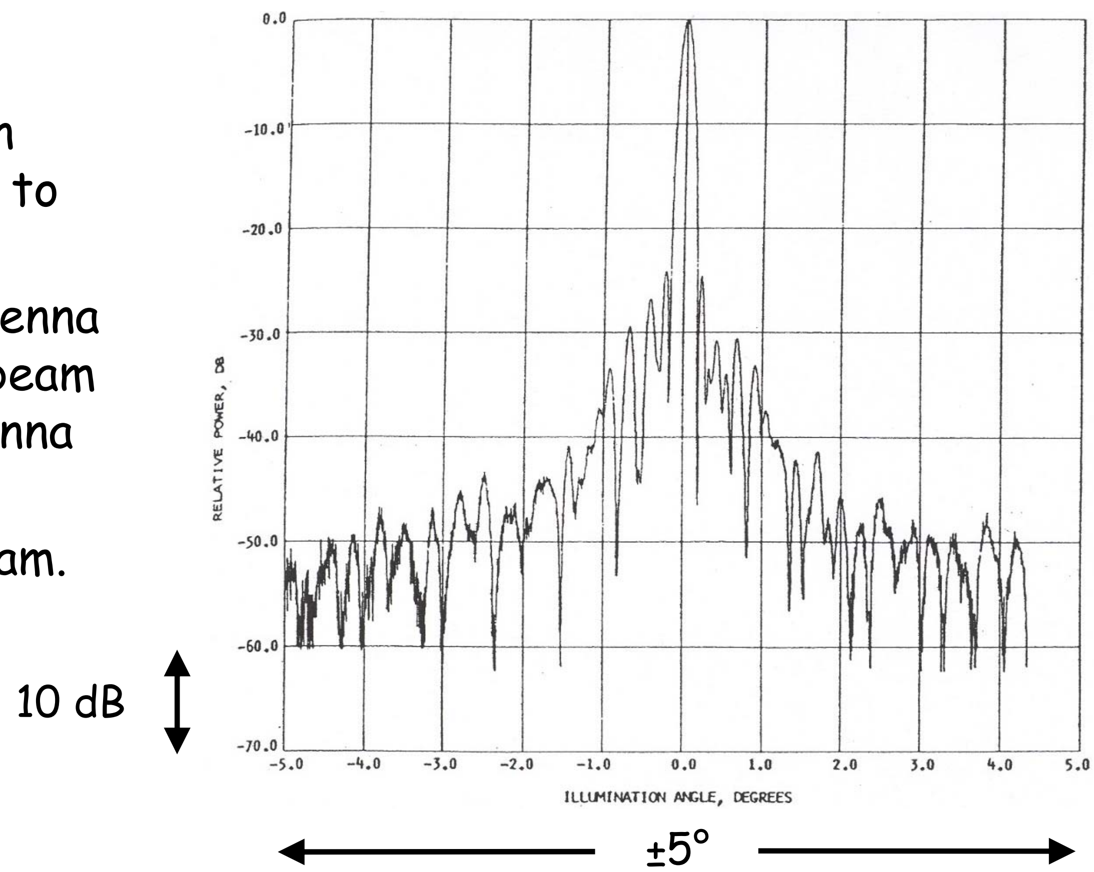
- RFI power at LNA input = RFI power density ($W\ m^{-2}$) at antenna
  x antenna effective area (m^2)
- For a transmitter with antenna gain $G_{transmit}$ and power $P_{transmit}$ located a distance R from the receiving antenna, in direct line of sight,

  power density = $P_{transmit}\ G_{transmit}\ /\ 4\pi\ R^2$
- For a receiving antenna with gain $G_{receive}$ in the direction toward source,

  effective area = $G_{receive}$ x (wavelength)^2 / 4π
  - For an isotropic antenna, $G_{receive} = 1$.
  - See next 2 slides for more on antenna gain.
- 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.

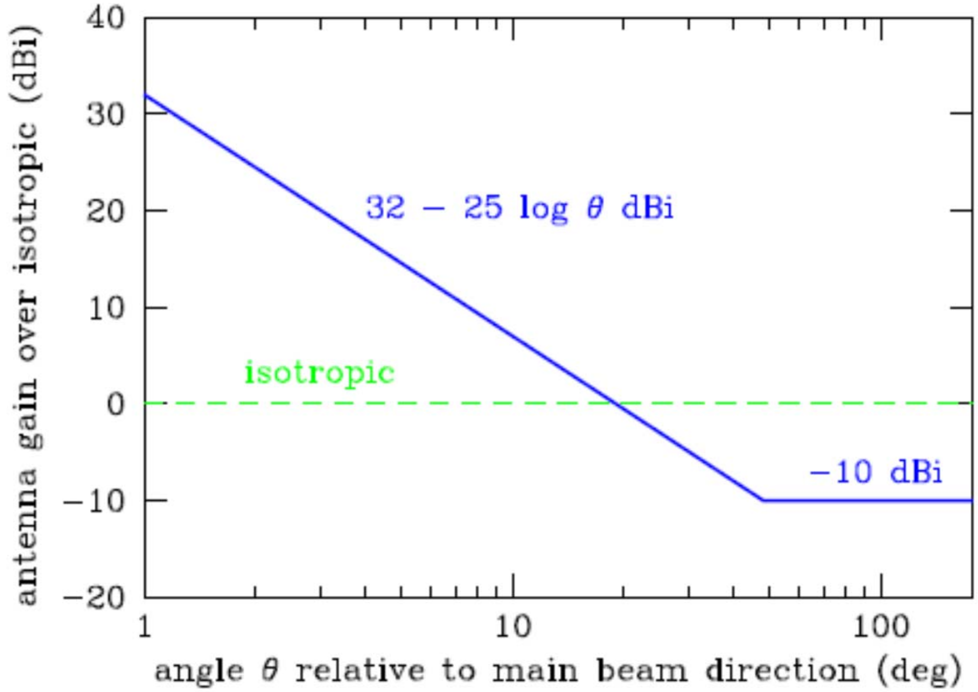
Antenna effective area

- 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.



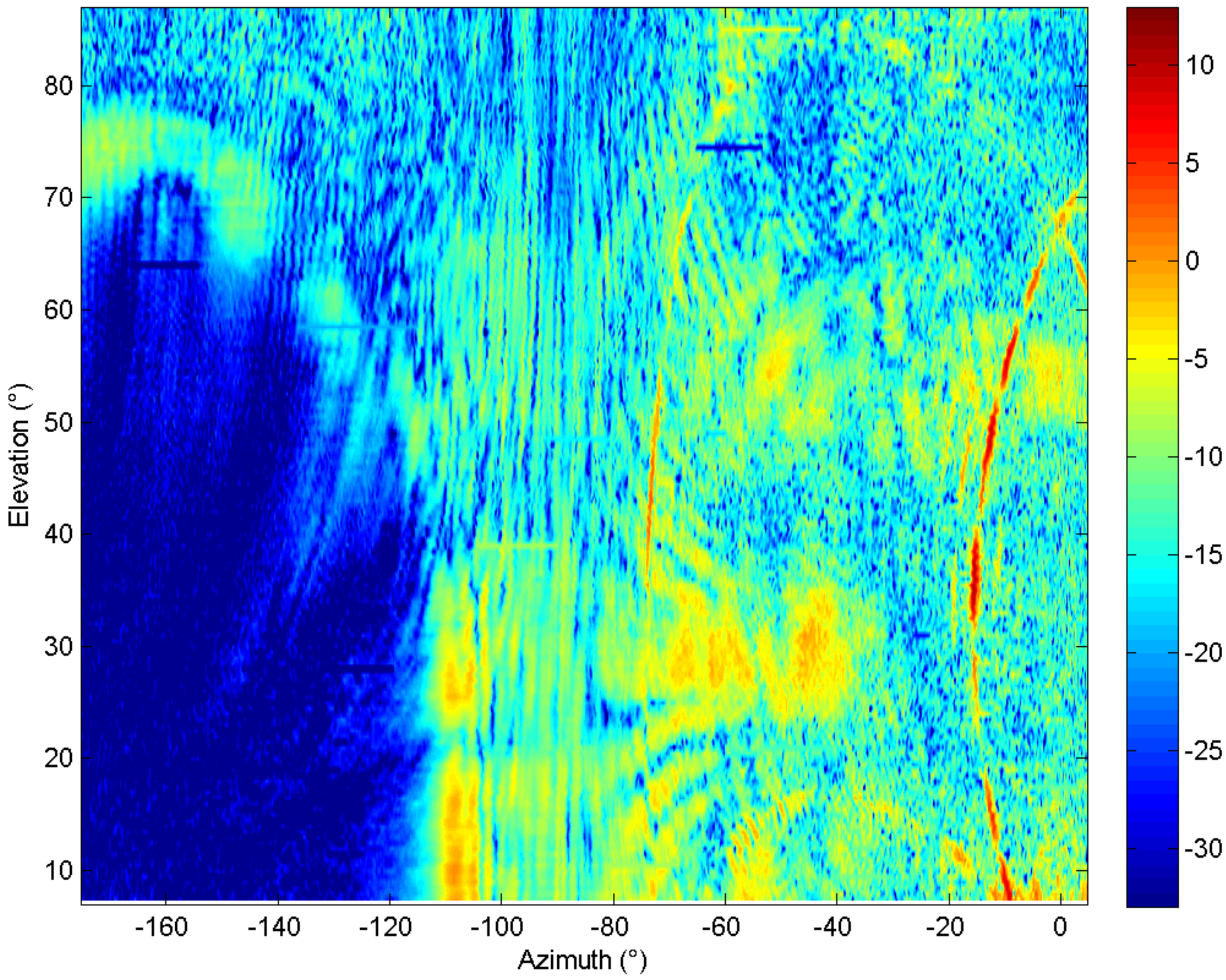
Antenna effective area – cont'd

- International Telecommunications Union (ITU) has developed an empirical model for sidelobe response of large (diameter > 100 wavelengths) parabolic antennas, such that 90% of sidelobe peaks lie below the curve.

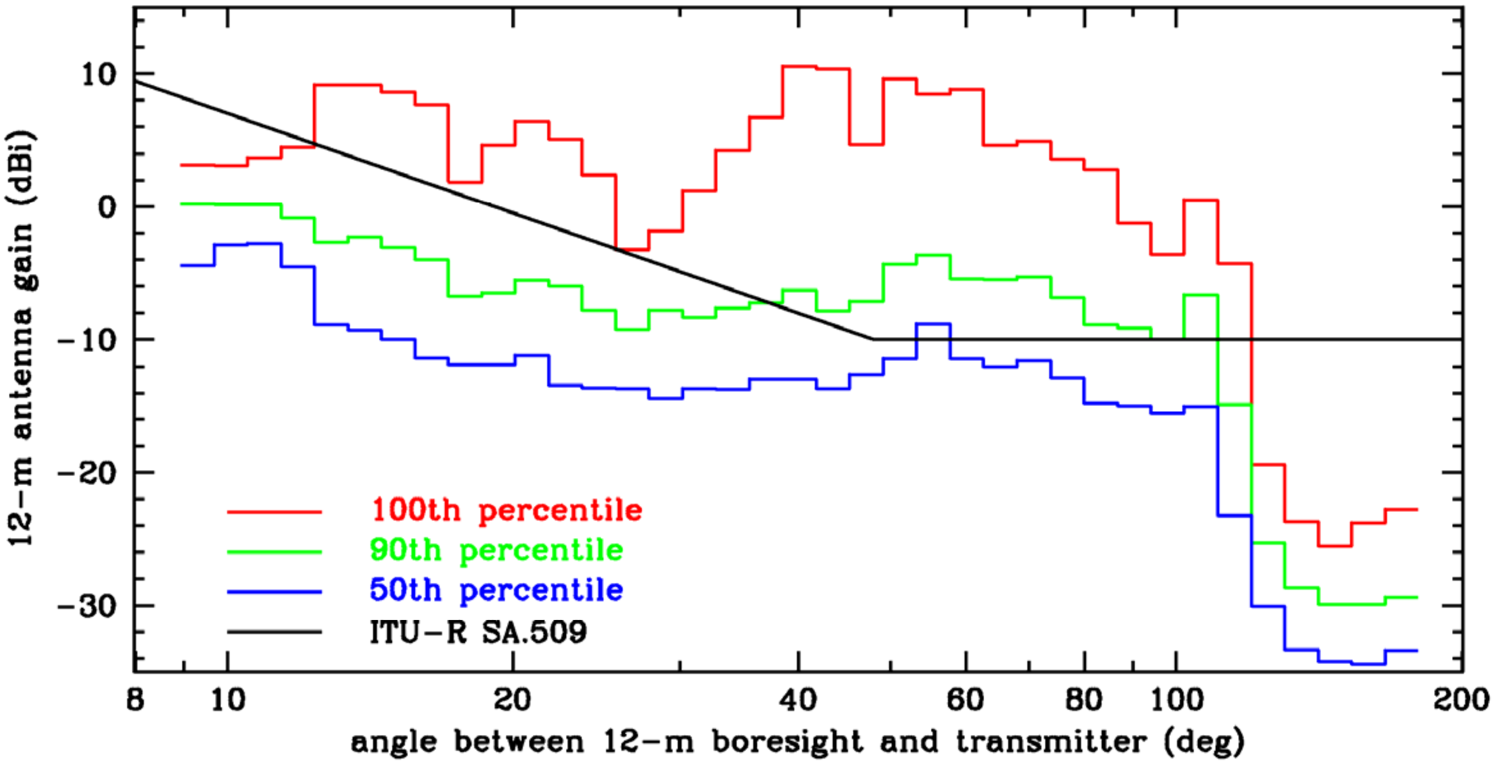


- Antenna area = (antenna gain over isotropic) x (wavelength)^2 / 4π
  - Example: For gain = 0 dBi, area = (1) x (3 cm)^2/4π = 0.7 cm^2 at 10 GHz.

GGAO 12m antenna sidelobe pattern (dBi) at 9 GHz



Gain vs. pointing angle for GGAO 12m at 9 GHz



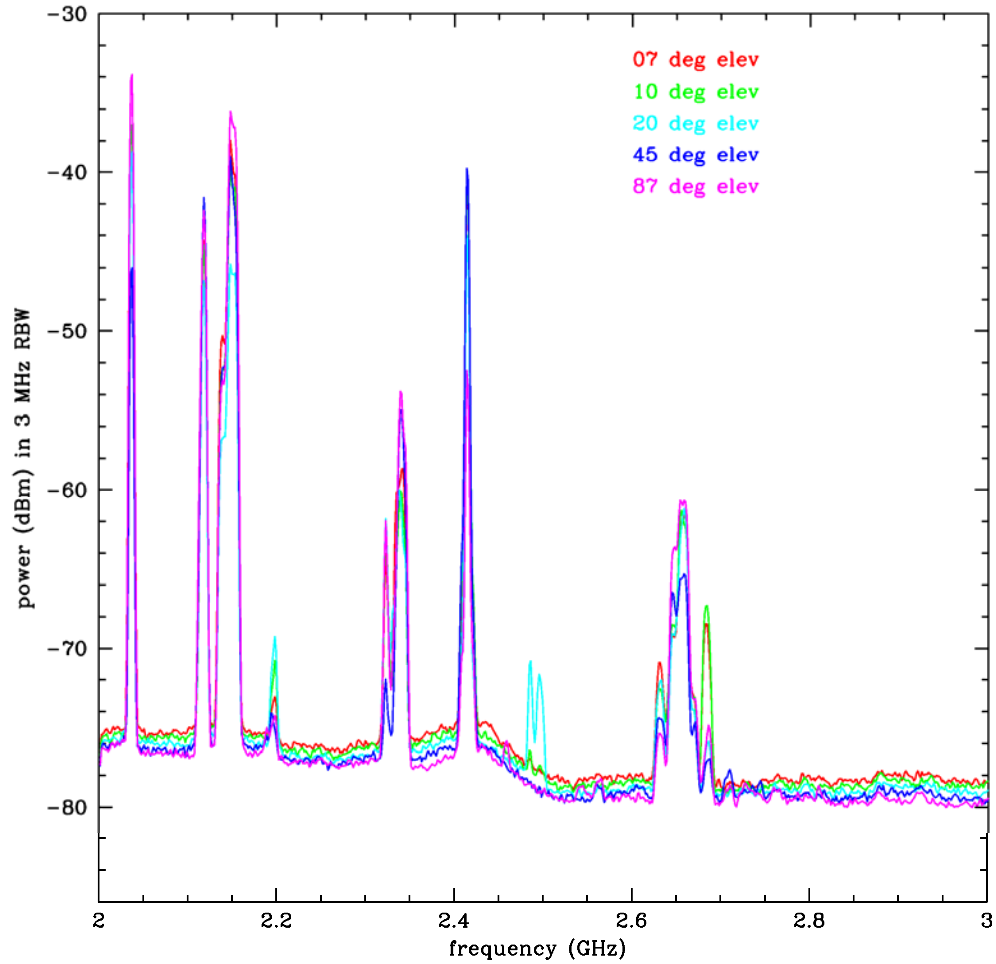
RFI and VGOS

- 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!

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.

GGAO 12m 2-3 GHz spectrum at 300° az



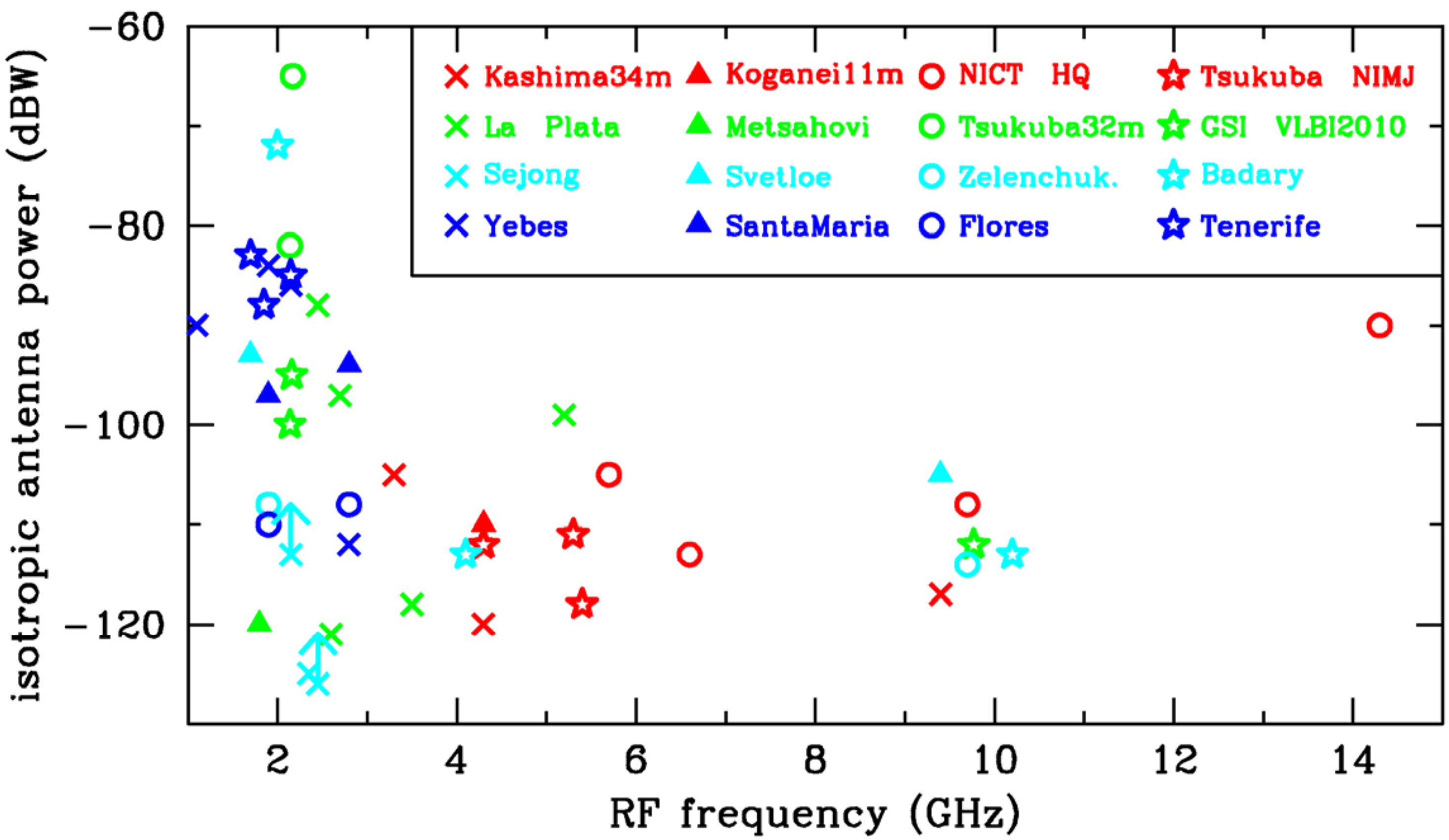
RFI surveys for VGOS

- In May 2012 the VGOS Project Executive Group (V2PEG) requested RFI information for existing and planned geodetic VLBI observatories.
  - Goal: Determine likelihood that RFI would saturate a broadband LNA.
  - Finding RFI-free (i.e., RFI power <10% or even <100% of Tsys) spectral windows for VGOS observations is a more difficult task – deferred to the future.
- Received RFI data from 9 organizations:
  - BKG (La Plata, Argentina)
  - GSI (2 sites in Japan)
  - IAA (3 QUASAR sites in Russia)
  - Metsähovi
  - NICT (4 sites in Japan)
  - RAEGE (10 sites in Spain, Açores, and Canary Islands)
  - Sejong
  - Shanghai
  - VLBA (10 sites in U.S.)

RFI surveys for VGOS – cont'd

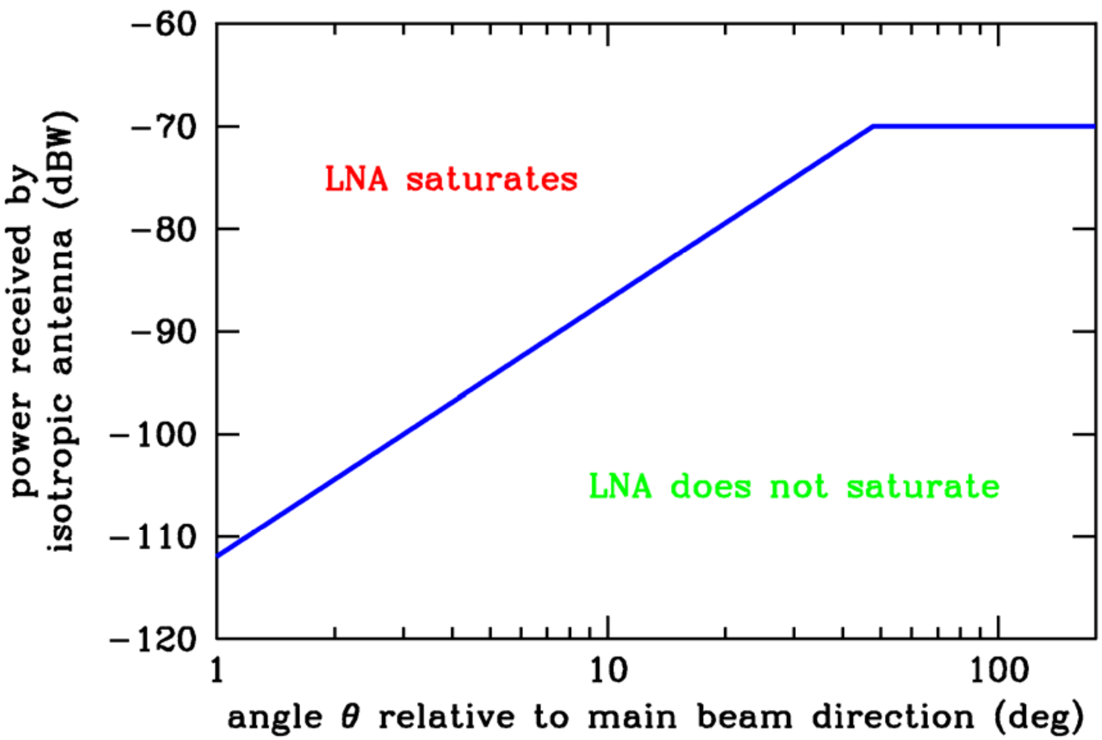
- Survey data are **highly** heterogeneous!
- Surveys were taken in different ways:
  - Most involved 360° of azimuth coverage (using 4 or 8 azimuth directions or continuous sweep with max hold on spectrum analyzer) around horizon.
    - VLBA recorded data near North Celestial Pole.
  - Most involved a fairly short spot measurement of RFI.
    - La Plata recorded continuous automated observations over 1 month.
  - Frequency range was restricted at some sites, e.g., only S- or S/X-band or >3 GHz.
  - Most data were taken with special-purpose RFI survey equipment (e.g., broadband horn antenna + amplifier + spectrum analyzer).
    - Sejong and VLBA data were taken with VLBI antennas.
- Survey data were reported in many different units:
  - Power (dBm)
  - Power flux density (W m^{-2} Hz^{-1})
  - Antenna temperature (K)
  - Electric field strength (μV m^{-1})
- Power at LNA input of hypothetical VLBI antenna was calculated for 2-3 strongest emitters at each site, assuming isotropic VLBI antenna gain (0 dBi).

RFI power calculated for VLBI antenna from RFI survey data: 1-15 GHz



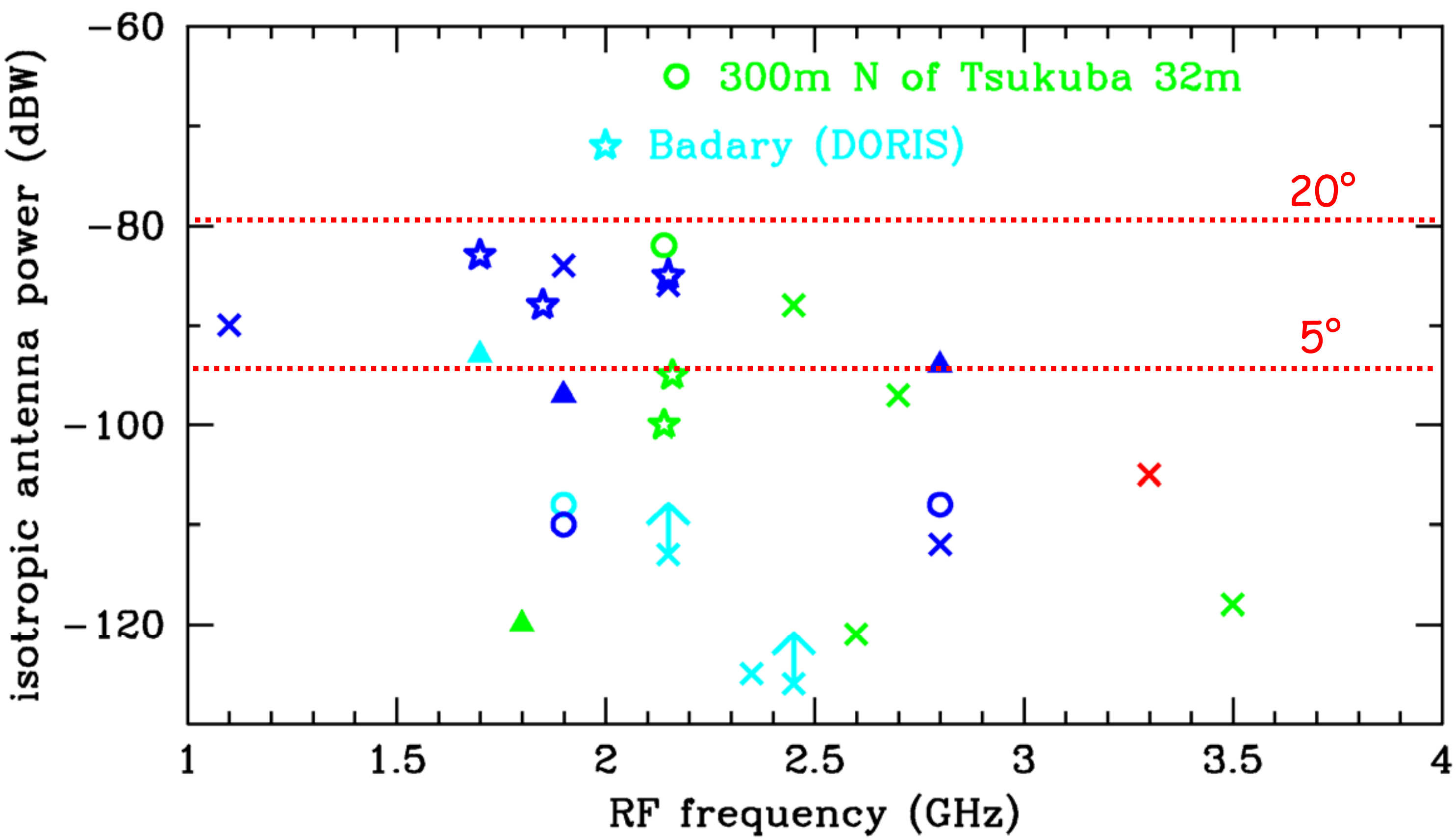
RFI survey results interpretation

- Survey yielded estimates of RFI power P_{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.
- Assume ITU model is true. → Can calculate, for a given P_{iso}, how close to RFI source an antenna can point without SNR loss (90% of the time).



P_{iso} (dBW)	θ
-95	> 5°
-87	> 10°
-79	> 20°
-70	> 50°

RFI power calculated for VLBI antenna from RFI survey data : 1-4 GHz



Comments on RFI survey techniques

- Distinguish two types of surveys:
  - Low-sensitivity, for identifying strong RFI that could saturate LNA
  - High-sensitivity, for identifying "RFI-free" spectral windows
- For low-sensitivity surveys . . .
  - Scan horizon repeatedly and save individual spectra.
    - Option 1: point antenna at discrete set of azimuths spaced one 3-6 dB beamwidth apart and record spectrum at each azimuth.
    - Option 2: scan antenna around 360° with analyzer on max hold.
  - Compute statistics on spectra: max, 90th percentile, median, min.
  - Resolution BW ~ 1 MHz
- For high-sensitivity surveys . . .
  - Use option 1 scan strategy and compute statistics.
  - Include LNA between antenna and analyzer to keep receiver noise < 300 K.
  - Resolution BW ~ 0.1-1 MHz
  - Sensitivity challenge: survey Tsys ~ 10 x VLBI Tsys
    - Decreasing RBW makes narrowband RFI more visible, but not wideband.
    - Increasing survey antenna gain helps, but at cost of more az pointings.

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I A R
CCT La Plata
CONICET

Instituto Argentino de Radioastronomía

Excerpts from . . . .

Radio Frequency Interference Observations at IAR La Plata

Guillermo Gancio, Daniel Perilli, Juan José Larrarte, Leonardo Guarrera, Leandro Garcia

Instituto Argentino de Radioastronomía

Hayo Hase, Gerhard Kronschnabl, Christian Plötz

Bundesamt für Kartographie und Geodäsie

21st EVGA Meeting, Espoo – Finland, March 5-8, 2013

Wettzell RFI Measurement System

overall gain: 70dB at 2 GHz
incl. ~7 dbi antenna directivity
positioning manually

Rohde&Schwarz-Antenna HL024A1

- frequency range: 1-18 GHz,
- input signal: horizontal + vertical polarization

Antenna box

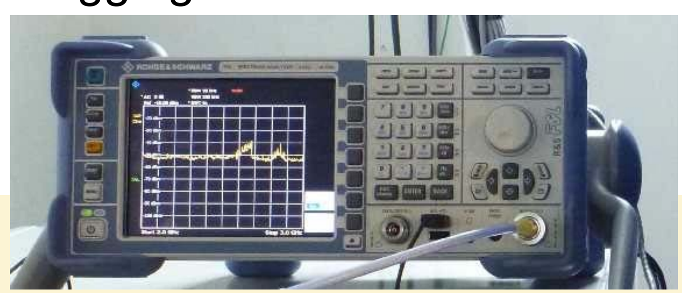
- 1 LNA for each polarization, 3 postA
- relays for noise cal injection
- noise cal diode NC346B

Receiver Box

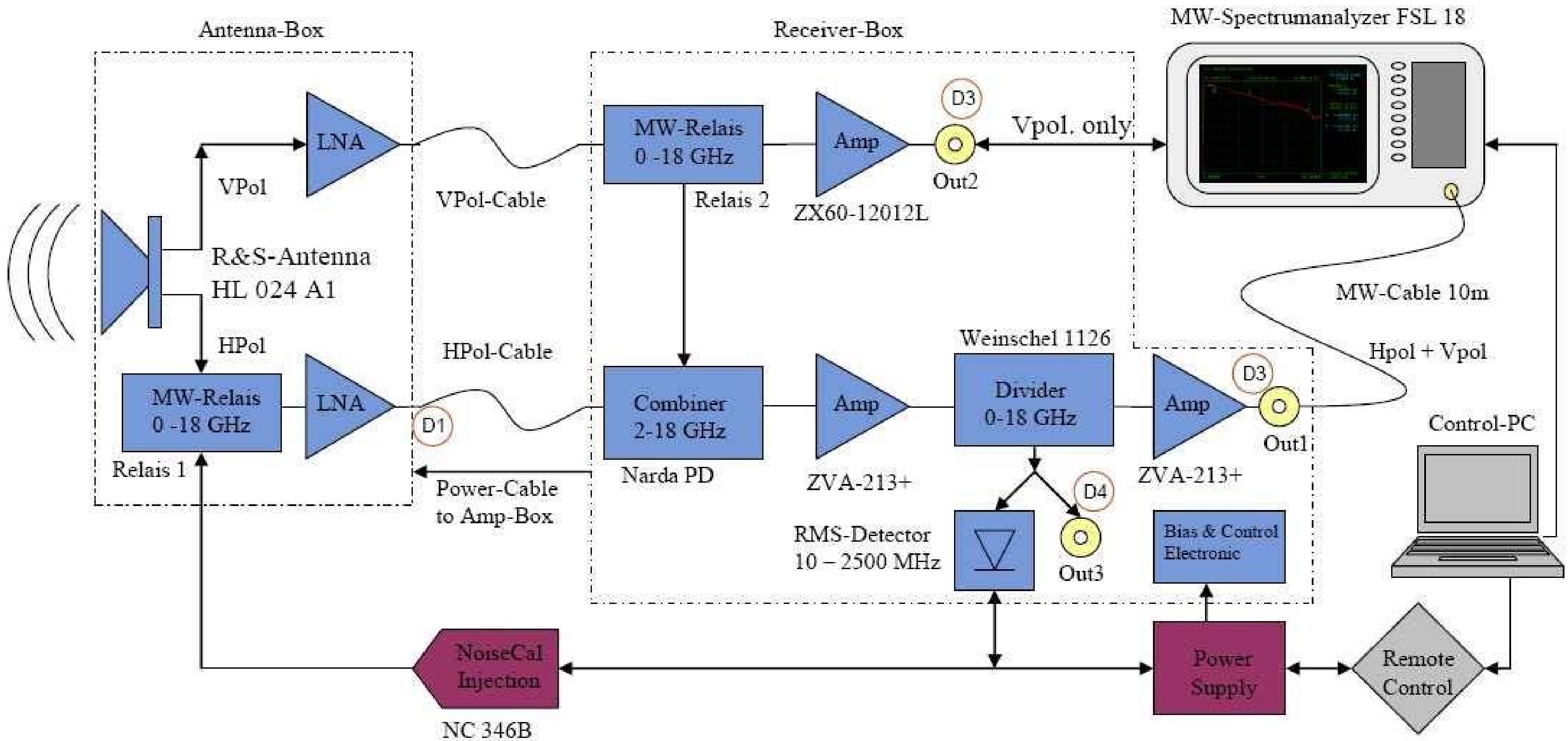
- power combiner for both polarizations
- amplifier

Rohde&Schwarz Spectrum Analyzer FSL18

Data logging: Notebook PC



Wettzell RFI Measurement System Block Diagram



Design: Gerhard Kronschnabl, BKG

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La Plata RFI Measurement System

developed for SKA site finding in Argentina in 2005, reconditioned in 2012

overall gain: 75dB at 2 GHz
incl. ~8dbi at 2 GHz antenna directivity

Dual ridge horn antenna, Emco 3115

- frequency range: 1 - 18 GHz
- polarization change mechanically
- 359° spatial coverage 5° resolution

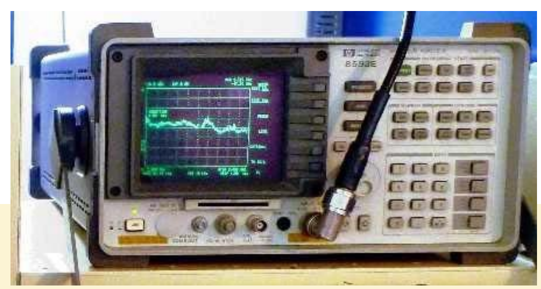
Antenna box

- 3 LNA from Miteq, 2 - 8 GHz
- relays for 50 ohm reference load used for Cal

HP9583E Spectrum Analyzer

- Tsys: 400-700°K, due to high display average noise level of spectrum analyzer

Data logging: PC with custom software



positioning automatized

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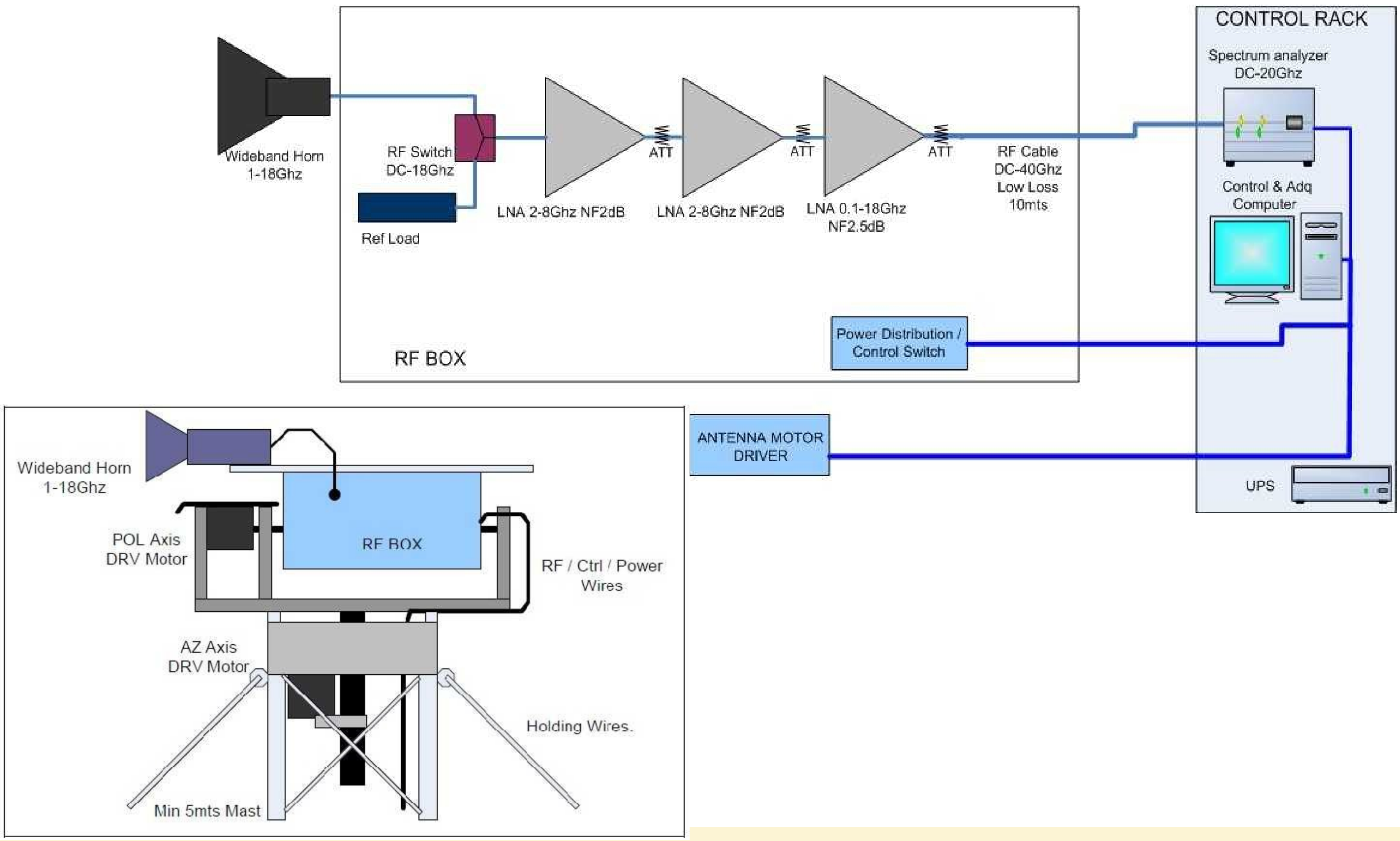
IAR RFI Measurement System Block Diagram



Design: IAR

Wettzell RFI measurement system mounted on La Plata motorized pedestal

combination of RFI-monitoring systems
BKG Wettzell and IAR La Plata
14.09.-14.10.2012

Measurement

- 30kHz resolution bandwidth
- 2-14 GHz range divided in 1GHz bands
- each 1GHz band requires 2.5s sweeptime (12 bands = 30s)
- 8 directions (N, NE, E, SE, S, SW, W, NW) + 1 Cal. = 15min

=> 96 azimuth scans/day

=> 768 images/day

After 30 days of measurement (14.09.-14.10.2012):

=> 21776 images of the spectrum analyzer recorded

most dense RFI data set known to the IVS

1 image = 9600 amplitude data points spaced by 1.25 MHz. => 209 million data points.

Flux Density of electro-magnetic spectrum

$$S_{dB} = P_{SA.dBm} - 10\log_{10}(B_S) - G_{R.dB} + k_{A.dB} - 35.77 \quad [dBWm^{-2}Hz^{-1}]$$

$$k_{A.dB} = 20\log_{10}(f_{MHz}) - G_{dBi} - 29.79$$

where:

$P_{SA.dBm}$ = power in [dBm] read at spectrum analyzer = measurement

B_S = signal bandwidth (resolution bandwidth) = 30 kHz

$G_{R.dB}$ = receiver system gain = median value from calibration measurement

$k_{A.dB}$ = antenna factor = computed

f_{MHz} = antenna frequency = 2000...14000 MHz

G_{dBi} = antenna isotropic gain = ~7 dBi (data sheet)

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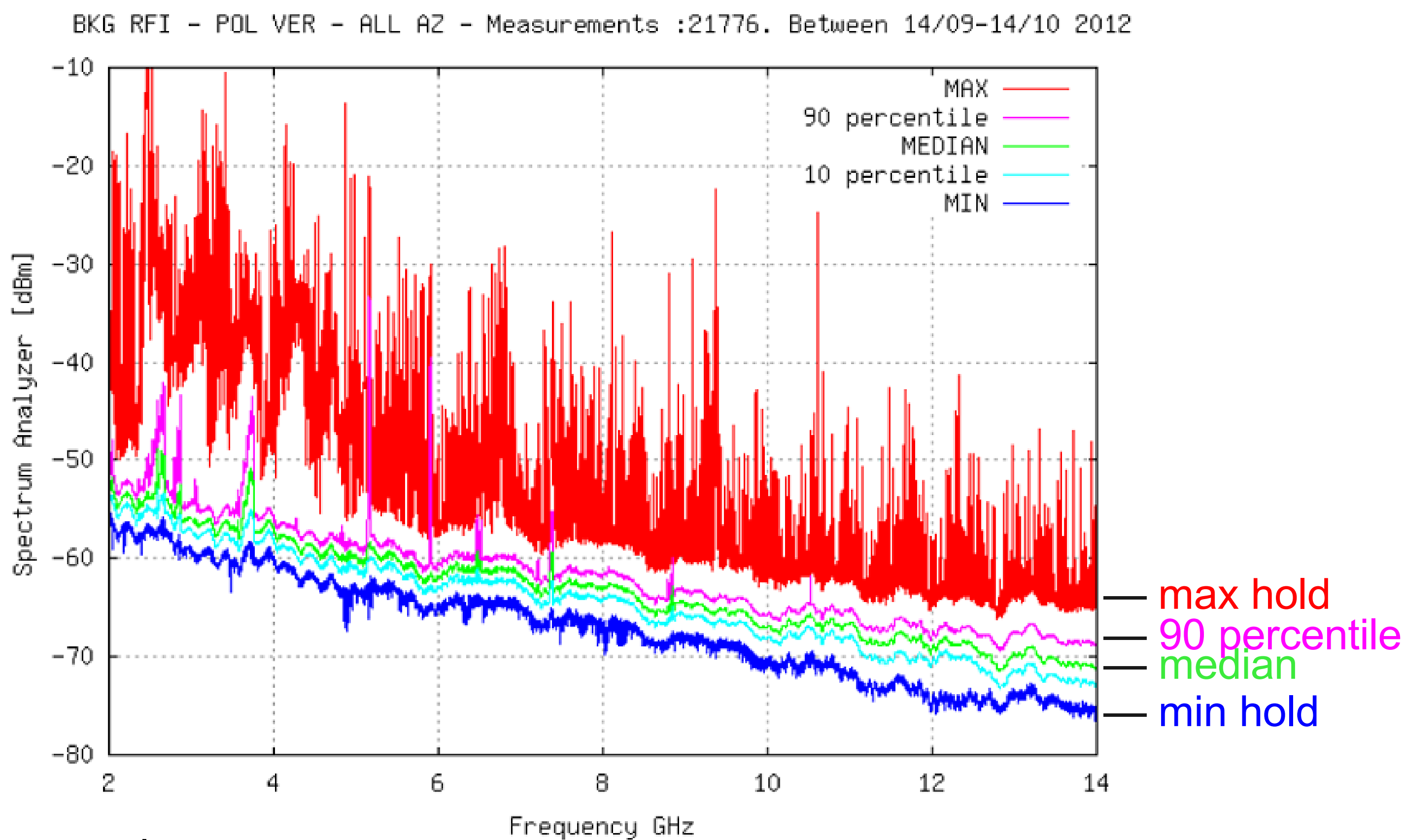
Power at Spectrum Analyzer [dBm] vs. Frequency [GHz]

21776 measurements



$$S_{dB} = P_{SA.dBm} - 10\log_{10}(B_S) - G_{R.dB} + k_{A.dB} - 35.77 \quad [dBWm^{-2}Hz^{-1}]$$

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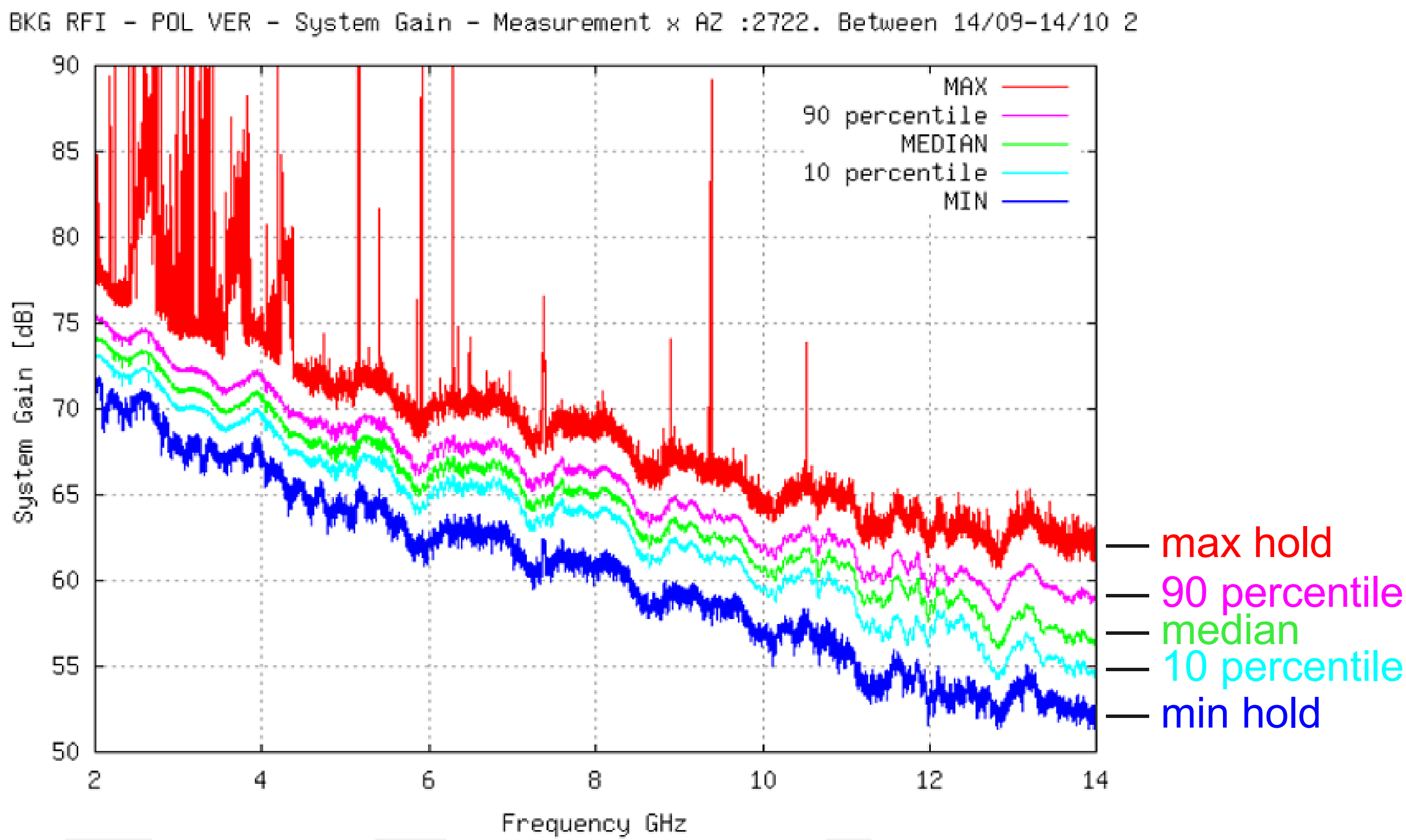
System Gain [dB] vs. Frequency [GHz]

21776 measurements



$$S_{dB} = P_{SA.dBm} - 10\log_{10}(B_S) - G_{R.dB} + k_{A.dB} - 35.77 \quad [\mathrm{dBWm^{-2}Hz^{-1}}]$$

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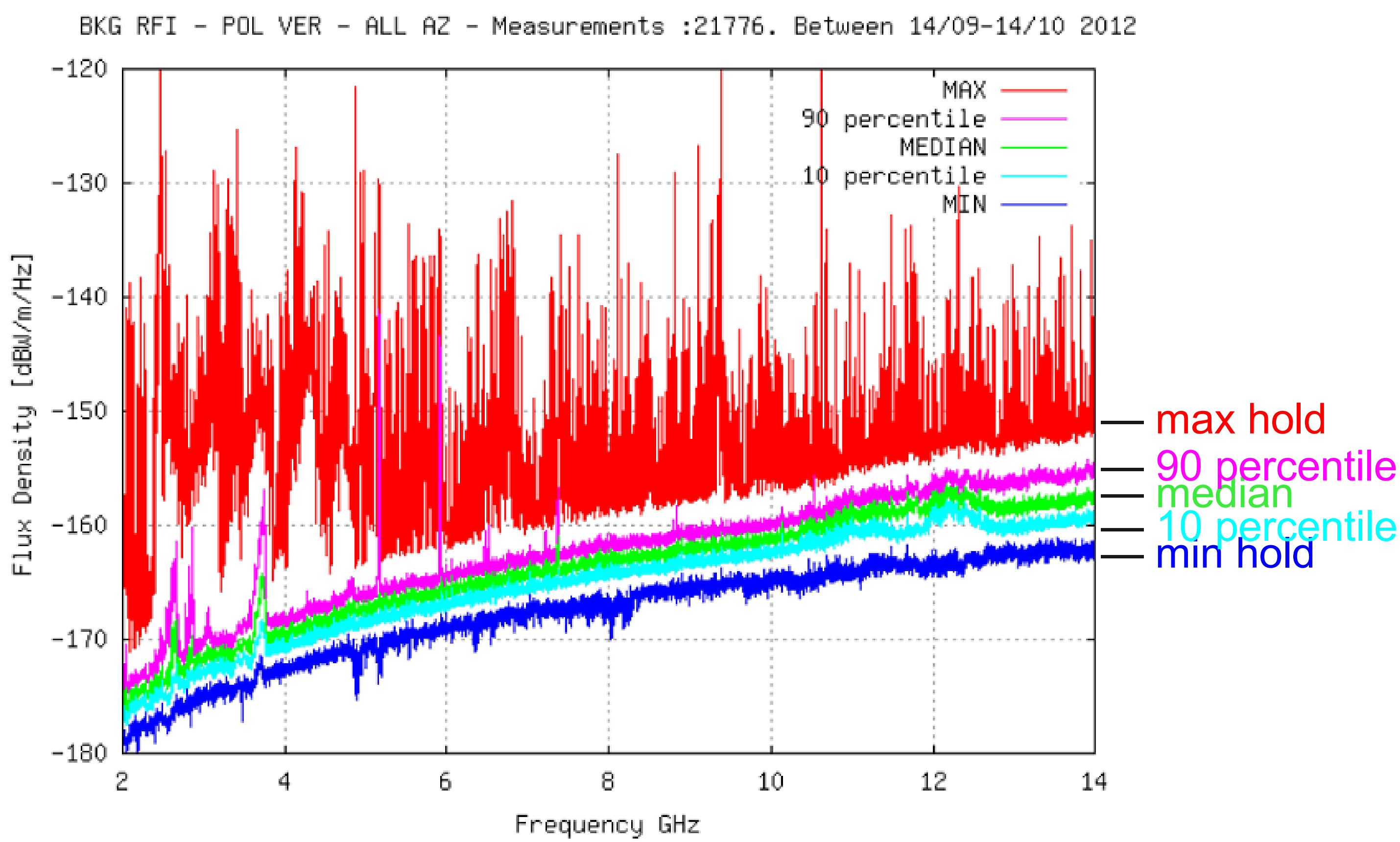
Flux Density [dBW/m²/Hz] vs. Frequency [GHz]

all directions: 21776 measurements

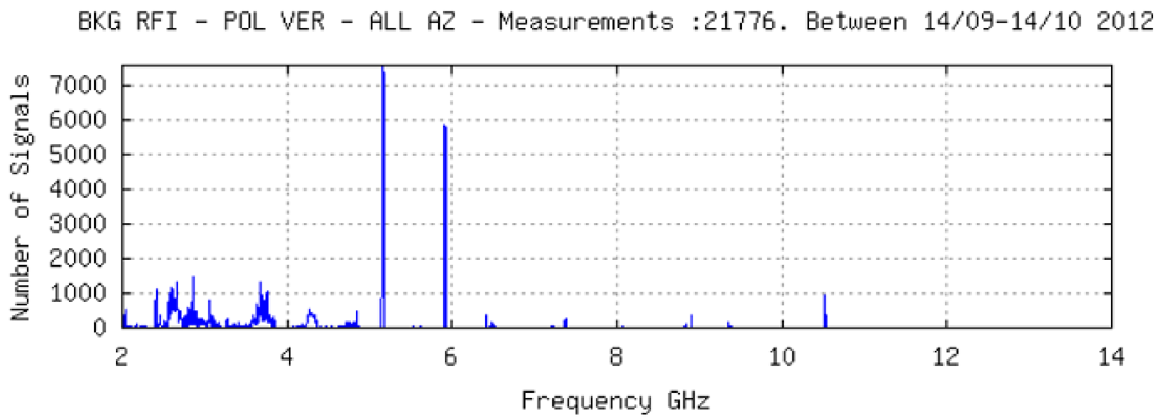


$$S_{dB} = P_{SA.dBm} - 10 \log_{10}(B_S) - G_{R.dB} + k_{A.dB} - 35.77 \quad [dBWm^{-2}Hz^{-1}]$$

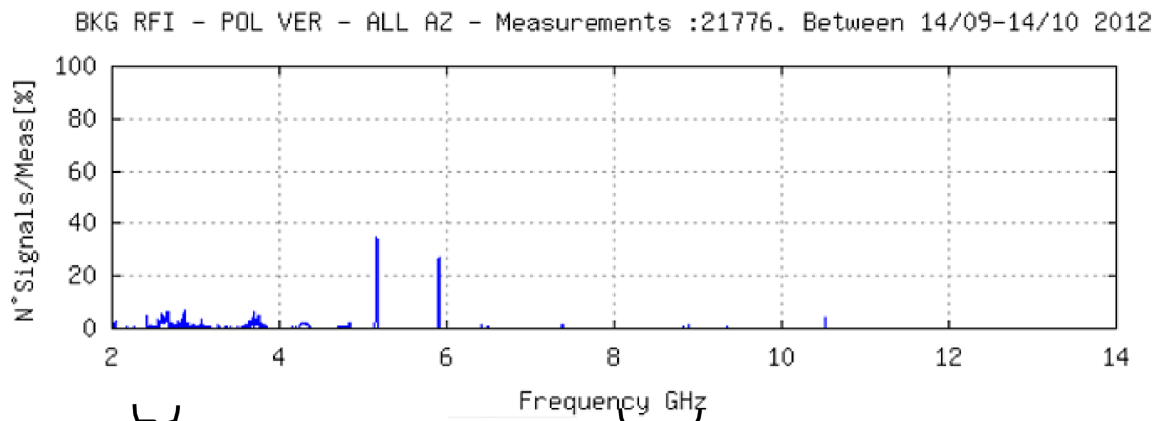
RFI detections (+6dB > median) vs. Frequency [GHz]

all directions: 21776 measurements

absolute number



percentage of total number



S-band

X-band

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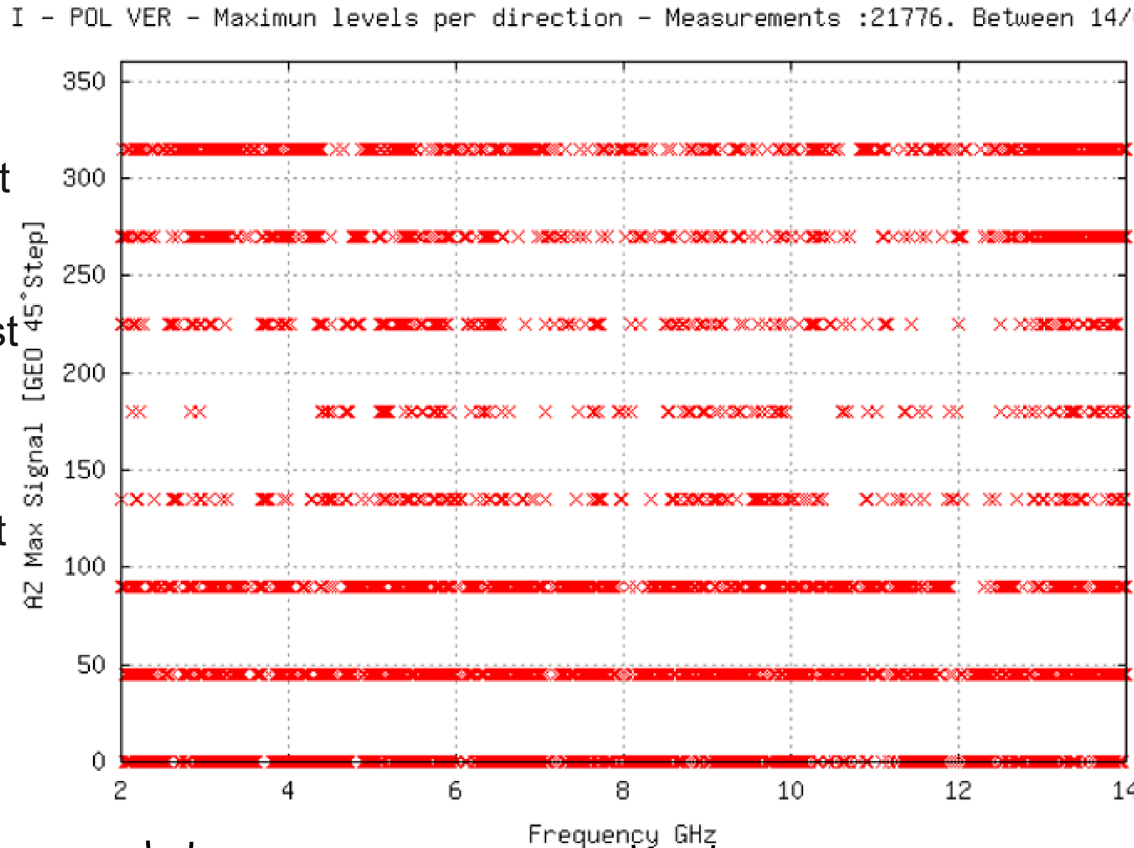
RFI detection (+6dB > median) directions vs. Frequency [GHz]

all directions: 21776 measurements

North-West
West
South-West
South
South-East
East
North-East
North



S-band
X-band

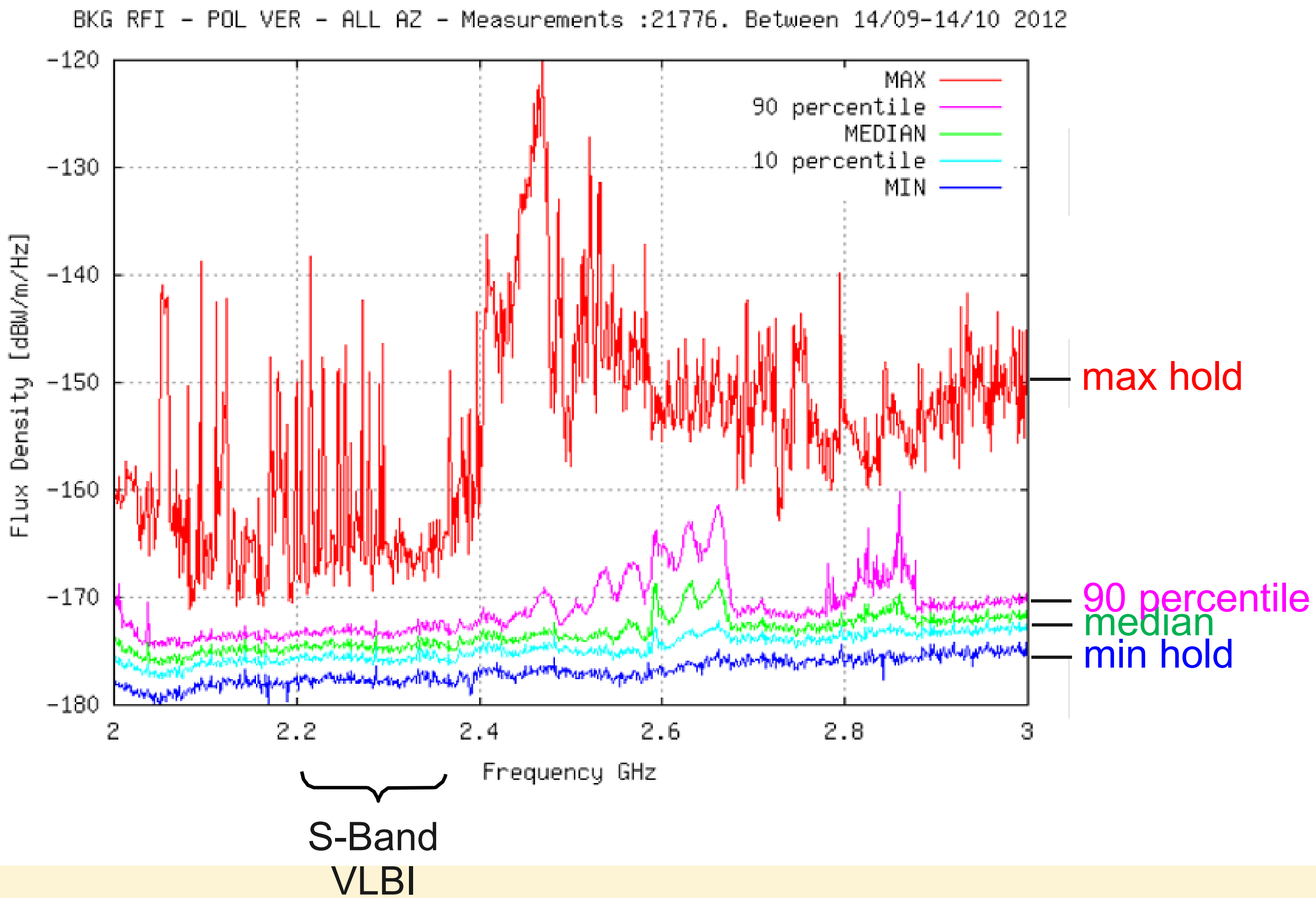
Buenos Aires

rural area

La Plata

S-Band - Flux Density [dBW/m²/Hz] vs. Frequency [GHz]

all directions: 21776 measurements



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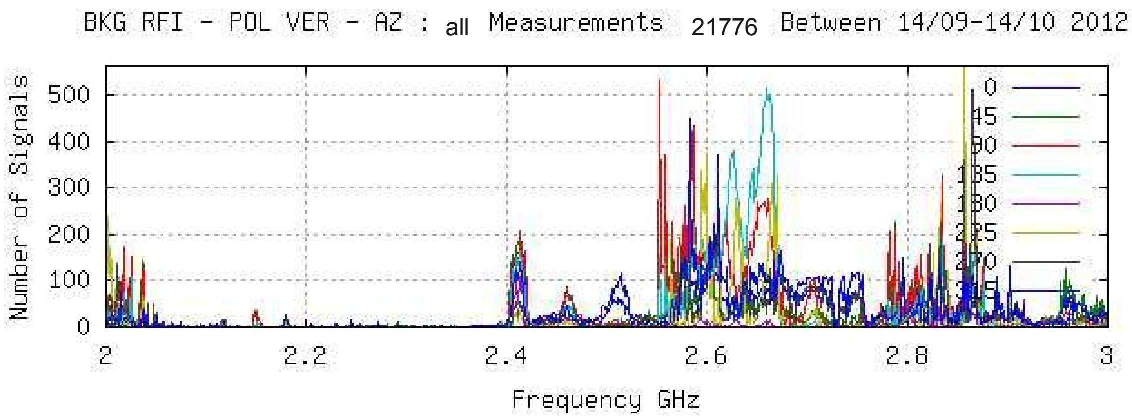
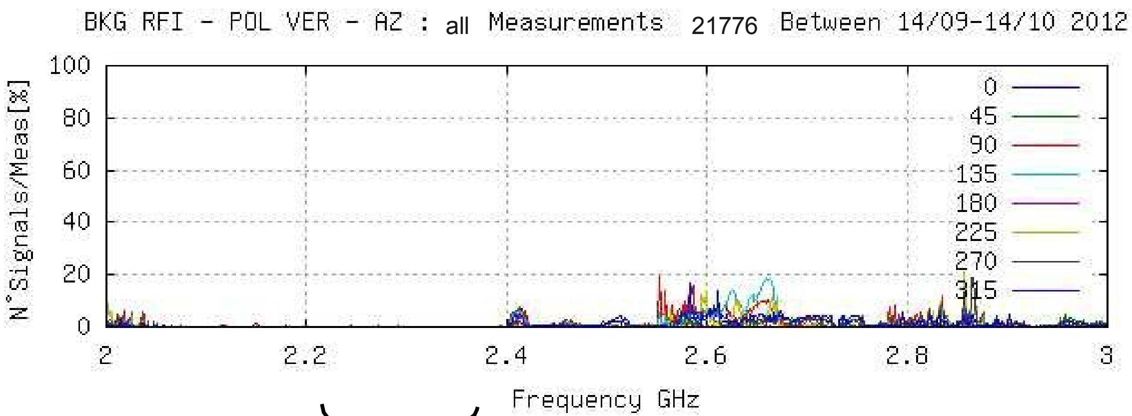
S-Band - RFI detections (+6dB > median) vs. Frequency [GHz]

8 directions: 21776 measurements





S-Band VLBI

color coded directions

Conclusions

- The Wettzell RFI-measurement system was used for one month continuously in an automatized RFI-monitoring campaign in La Plata, Argentina.
- 21776 radiation images in the spectrum from 2.0-14.0 GHz were taken and processed.
- RFI-signals had been detected, i.e. 2.4-2.9 GHz.
- Most RFI signals appear sporadically and are absent most of the time as shown by the 90 percentile.
- Permanent RFI is mostly generated locally.
- **S-Band and X-Band used by geodetic VLBI are almost free of RFI** and hence IAR is a suitable site for a future IVS-network station.
- RFI-monitoring should become a permanent task in order to protect observatories against new transmitters.