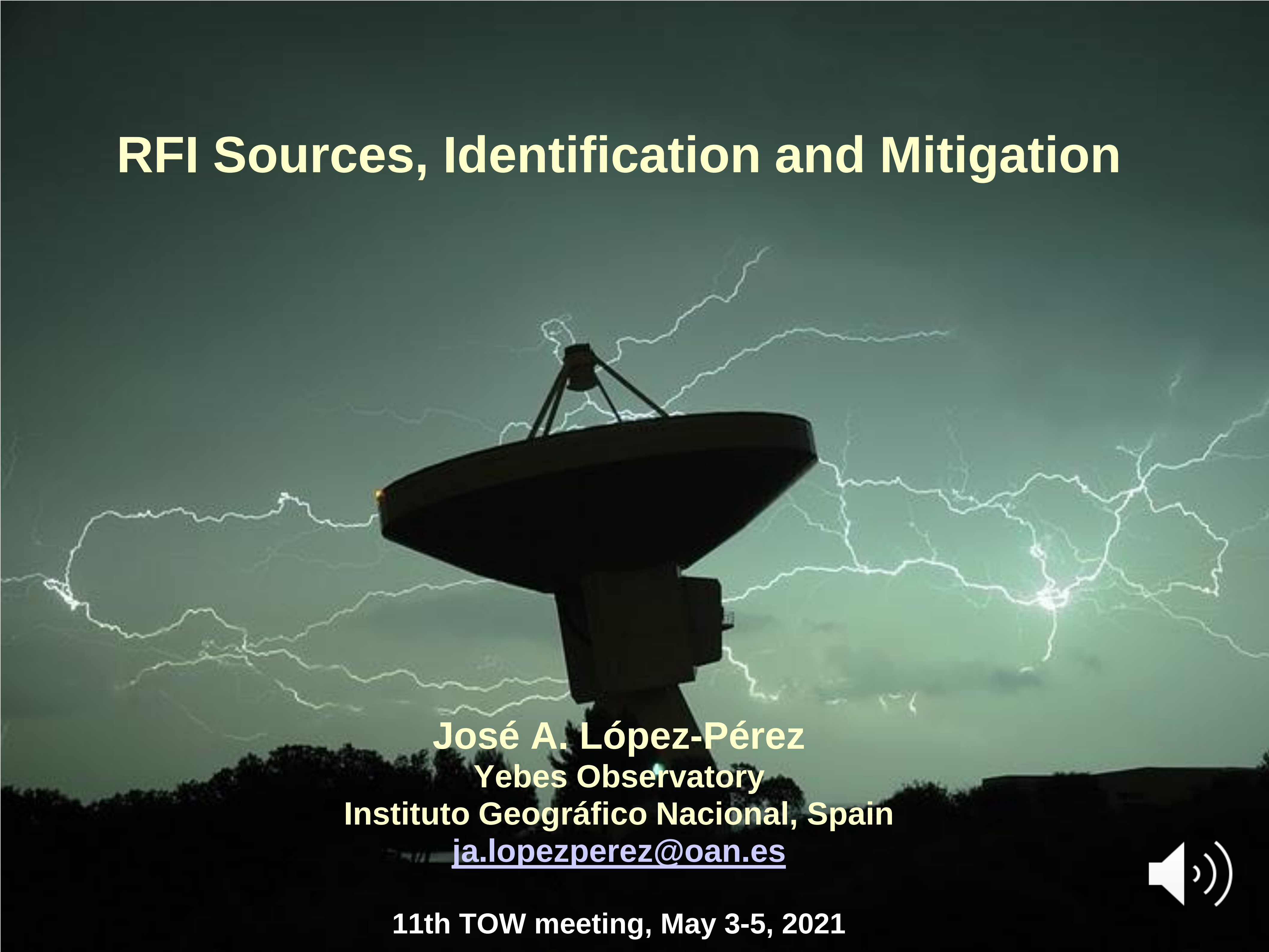


RFI Sources, Identification and Mitigation

José A. López-Pérez
Yebes Observatory
Instituto Geográfico Nacional, Spain
ja.lopezperez@oan.es

11th TOW meeting, May 3-5, 2021

Index

- Some ideas about Frequency Management
- What is RFI? Sources. Detection.
- RFI examples: external and self-generated
- Regulations and protection levels
- RFI effects on VLBI and receivers
- RFI mitigation and examples
- RFI measurement systems at Yebes
- Conclusions
- References

International Spectrum Management

The International Telecommunication Union (ITU) is an agency of the United Nations, whose responsibility is the **coordination of** the vast and growing range of radiocommunication services and the **harmonization** at international level of the radio-frequency spectrum

The allocation of frequency spectrum resources is the sovereign right of national governments

But radio waves do not respect national borders → International regulations are required!

Asia-Pacific Telecommunity (APT)

Arab Spectrum Management Group (ASMG)

African Telecommunications Union (ATU)

European Conference of Postal and Telecommunications Administrations (CEPT)

Inter-American Telecommunication Commission (CITEL)

Regional Commonwealth in the Field of Communications (RCC)

GOBIERNO DE ESPAÑA MINISTERIO DE FOMENTO
INSTITUTO GEOGRÁFICO NACIONAL

Frequency Allocation Chart

The value of the spectrum

In Spain, prices of licenses for 20 years:

- Vodafone paid **198 M€ for 90 MHz** in the 3.7 GHz band.
- Telefonica paid **107 M€ for 50 MHz** in the 3.6-3.8 GHz band
- Orange paid **132 M€ for 60 MHz** in the same range.

In Italy, Vodafone paid **€2.4 billion** for:

- 80 MHz of band in 3.7 GHz for 19 years
- 2 x 10 MHz of band in 700 MHz for 15.5 years
- 200 MHz in 26 GHz for 19 years

Range of price: 2 – 6 M€ / MHz

1 VGOS antenna ~ 1MHz

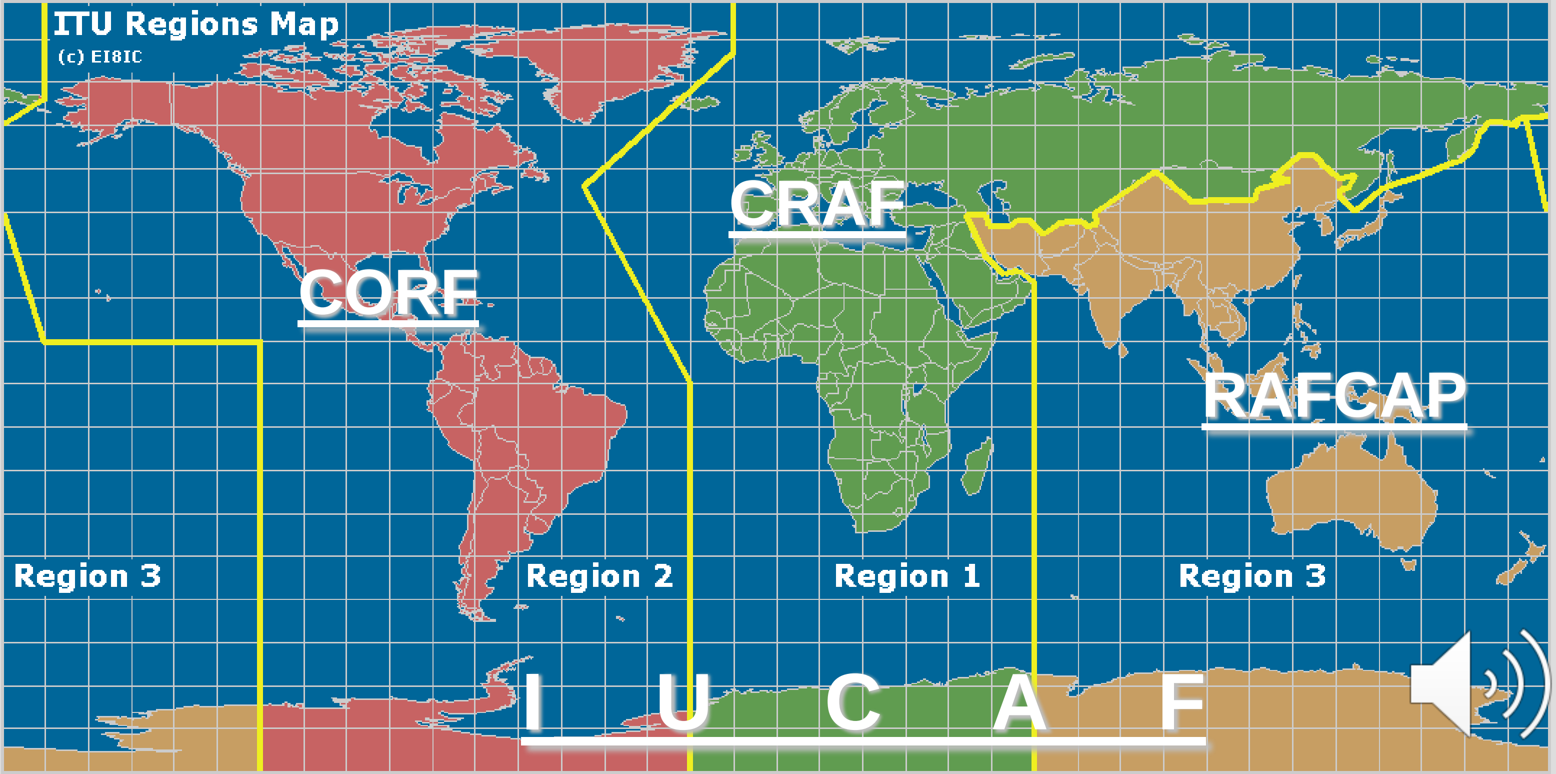
New frequencies in use

- 5G mobile networks:
  - USA: 3.1 – 3.55 GHz, 3.7 – 4.2 GHz
  - Europe: 3.4 – 3.8 GHz
  - Japan: 3.6 – 4.2 GHz, 4.4-4.9 GHz
  - China: 3.3-3.6 GHz, 4.4-4.5 GHz, 4.8-4.99GHz
- Starlink (SpaceX): 4,425 LEO sats in 11/14 GHz and 20/30GHz (1,300 in orbit)
- OneWeb consortium: 650 LEO sats (145 in orbit)
- Project Kuiper (Amazon): 3,236 LEO sats
- High Altitude Platform Stations (HAPS) at 20Km

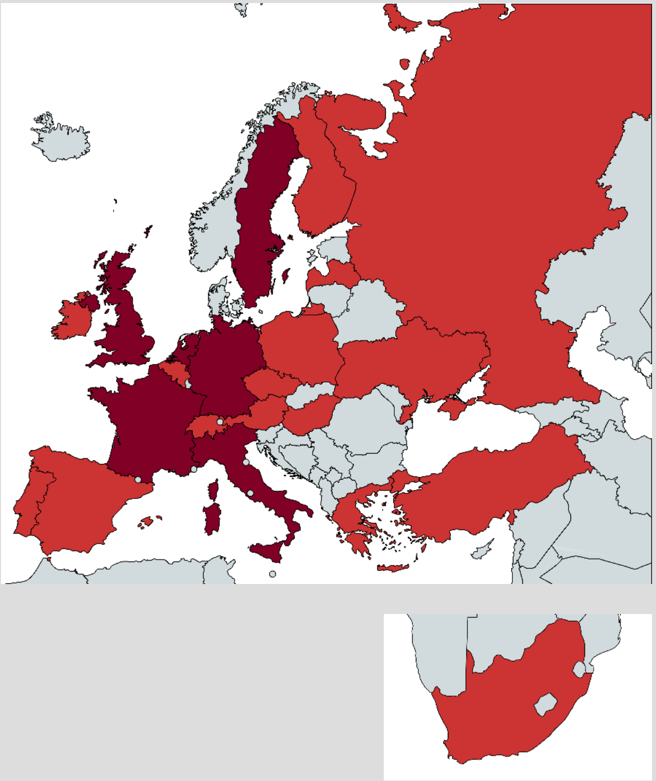
Radioastronomy Service (RAS)

- In 1959, Radio Astronomy was recognised as a "radiocommunication service" creating a legal basis to seek protection against "harmful" interference.
- A series of frequency bands were allocated to the Radio Astronomy Service. Some bands provide an exclusive allocation ("All emissions are prohibited") to passive services.
- Geo-VLBI is a radioastronomy service from ITU perspective.

RAS is represented by regional committees



CRAF



- CRAF was established in 1988 and it acts as an ESF Expert Committee
- CRAF: ITU sector member & observer status in CEPT
- 22 Member Countries (incl. Russia, Ukraine, Turkey and South Africa) + International organizations, which have an observer status: ESA, IRAM, IVS and SKA.
- Missions:
  - to keep the frequency bands used for radio astronomical observations free from interference;
  - to argue the scientific needs of the European research community for continued access to and availability of the radio spectrum for radio astronomy;
  - to support related science communities in their needs concerning interference-free radio frequency bands for passive use.
- Funding by MoU: 130 k€
- CRAF employes one full-time Frequency Manager

Telescope registration

- To obtain administrative protection
- To avoid direct illumination from strong transmitters
- To be taken into accout by space agencies
- To claim losses due to RFI
- To complain to the responsible of RFI

See H. Hase, V. Tornatore, B. Corey: “How to register a VGOS radio telescope at ITU and why it is important”. IVS 2016 GM Proc.

Watch TOW video “Radiotelescope Registration at ITU-R” by Marta Bautista

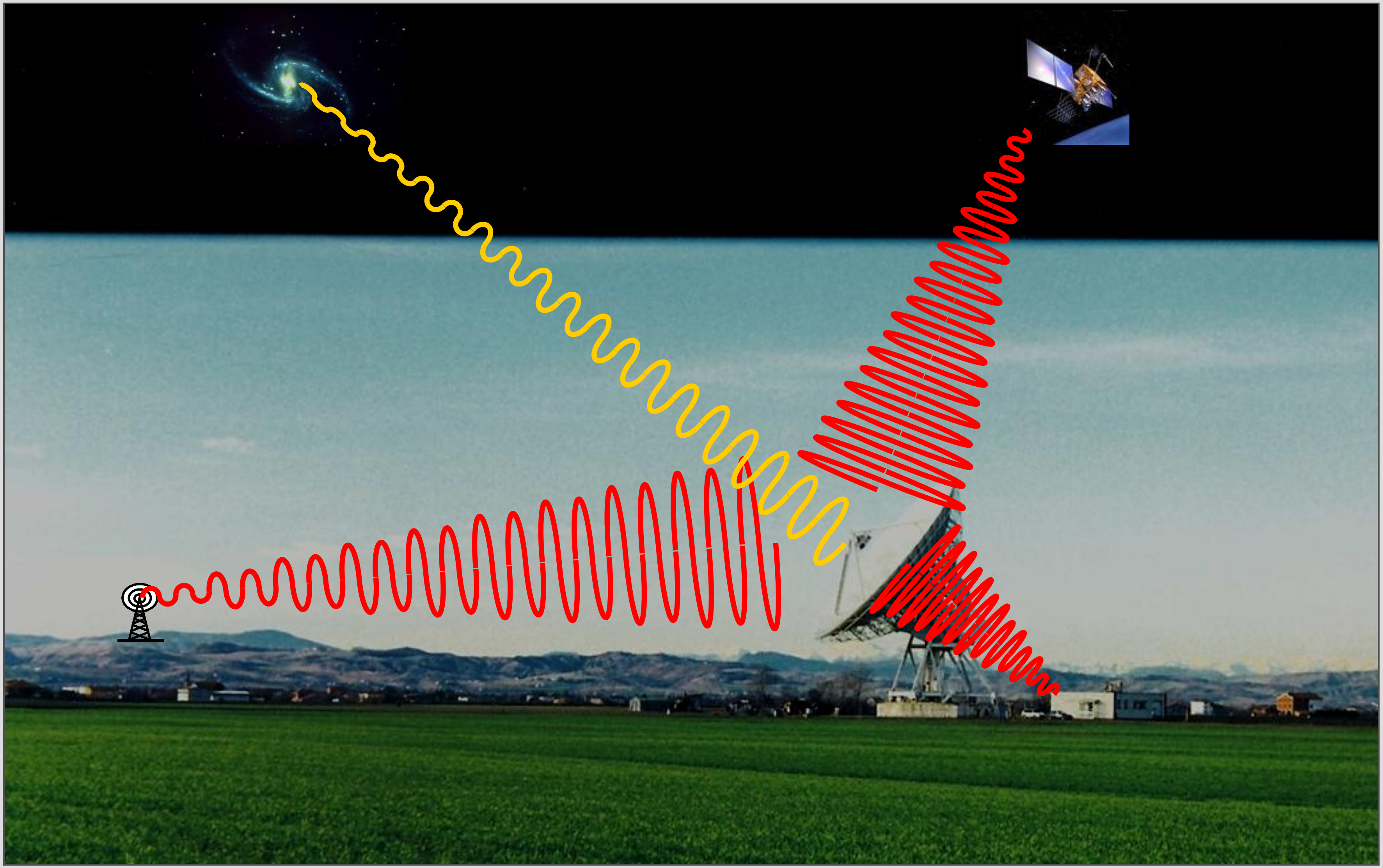
What is RFI?

- According to ITU Radio Regulations Section IV, Radio Stations and Systems – Article 1.166 *interference:*

> The effect of unwanted energy due to one or a combination of **emissions, radiations or inductions** upon reception in a radiocommunication system, **manifested by any performance degradation, misinterpretation or loss of information** which could be extracted in the absence of such unwanted energy.

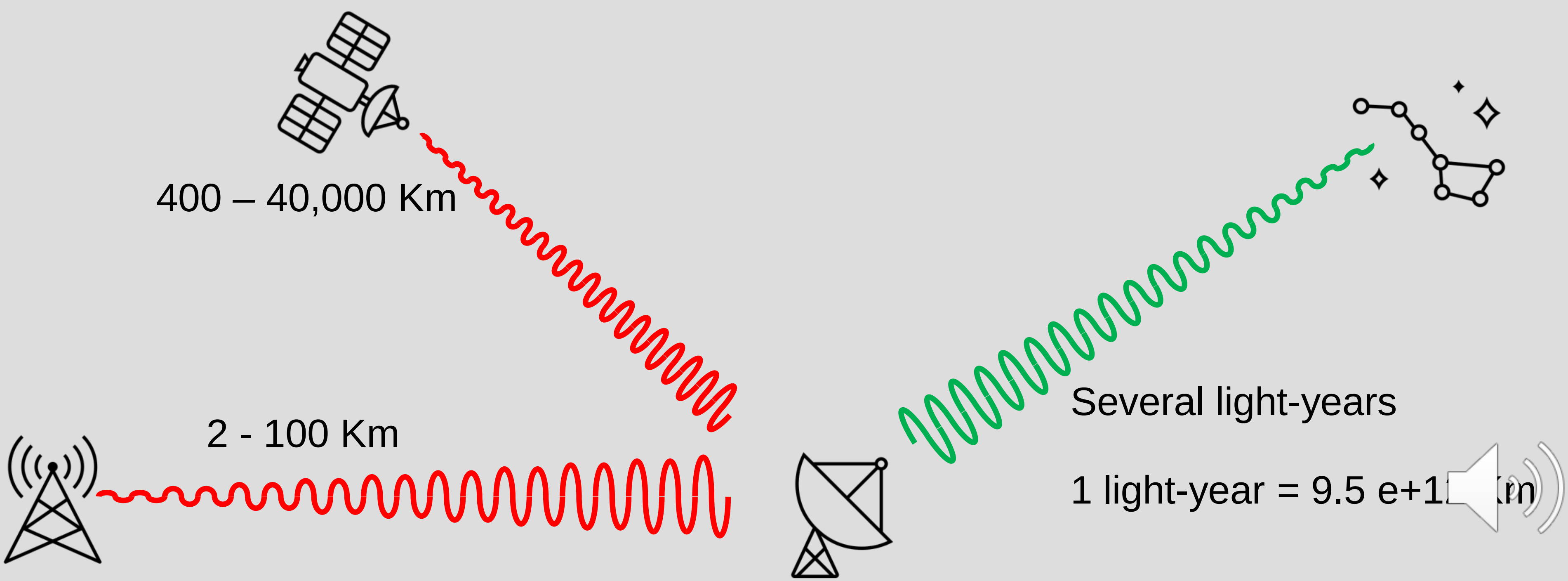
- Types of interferences:
  - Permissible interference
  - Accepted interference
  - **Harmful interference**

RFI environment



RFI signal properties

- Non-thermal origin
- Variable in time: persistent, intermittent or burst-like
- Variable in space: stationary or mobile
- Variable in spectrum: narrowband or broadband
- Variable in polarization: H, V, RCP, LCP
- Many orders of magnitude stronger than cosmic signals



RFI sources

External

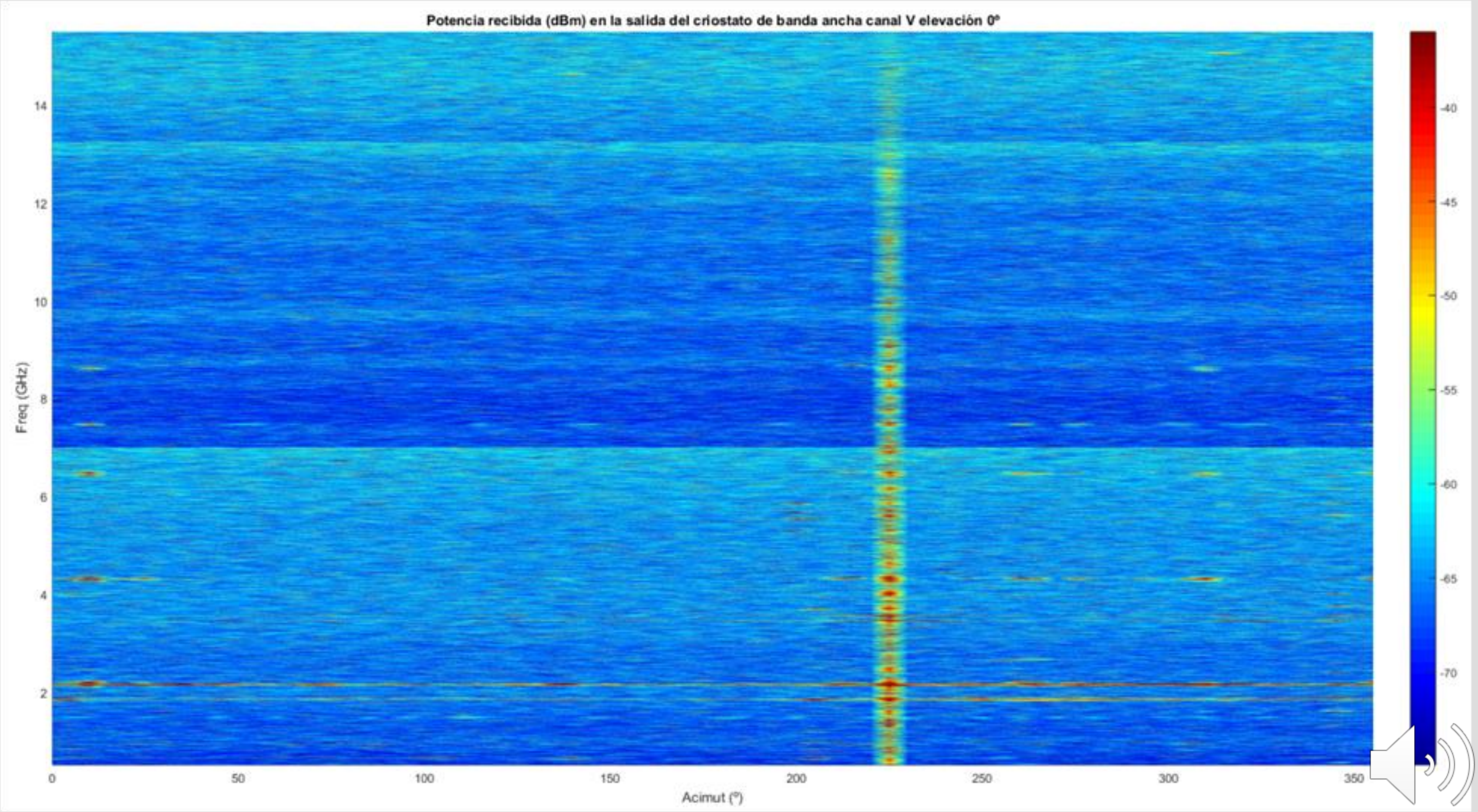
- Satellite downlinks
- Cellular networks
- Radio & TV networks
- Radio-links
- Radars
- Wind-mills
- Spark plugs
- Home appliances
- Electric fences
- Lightnings
- LED light drivers
- Consumer electronics

Self-generated

- Servo electronics
- Control buses: Profibus, CANbus
- Leaky connectors
- Leaky cables
- Leaky racks
- Amplifier oscillation - instability
- Signal distributors
- Digital back-ends
- LAN/Ethernet equipment
- Computers
- UPS
- Auxiliary equipment

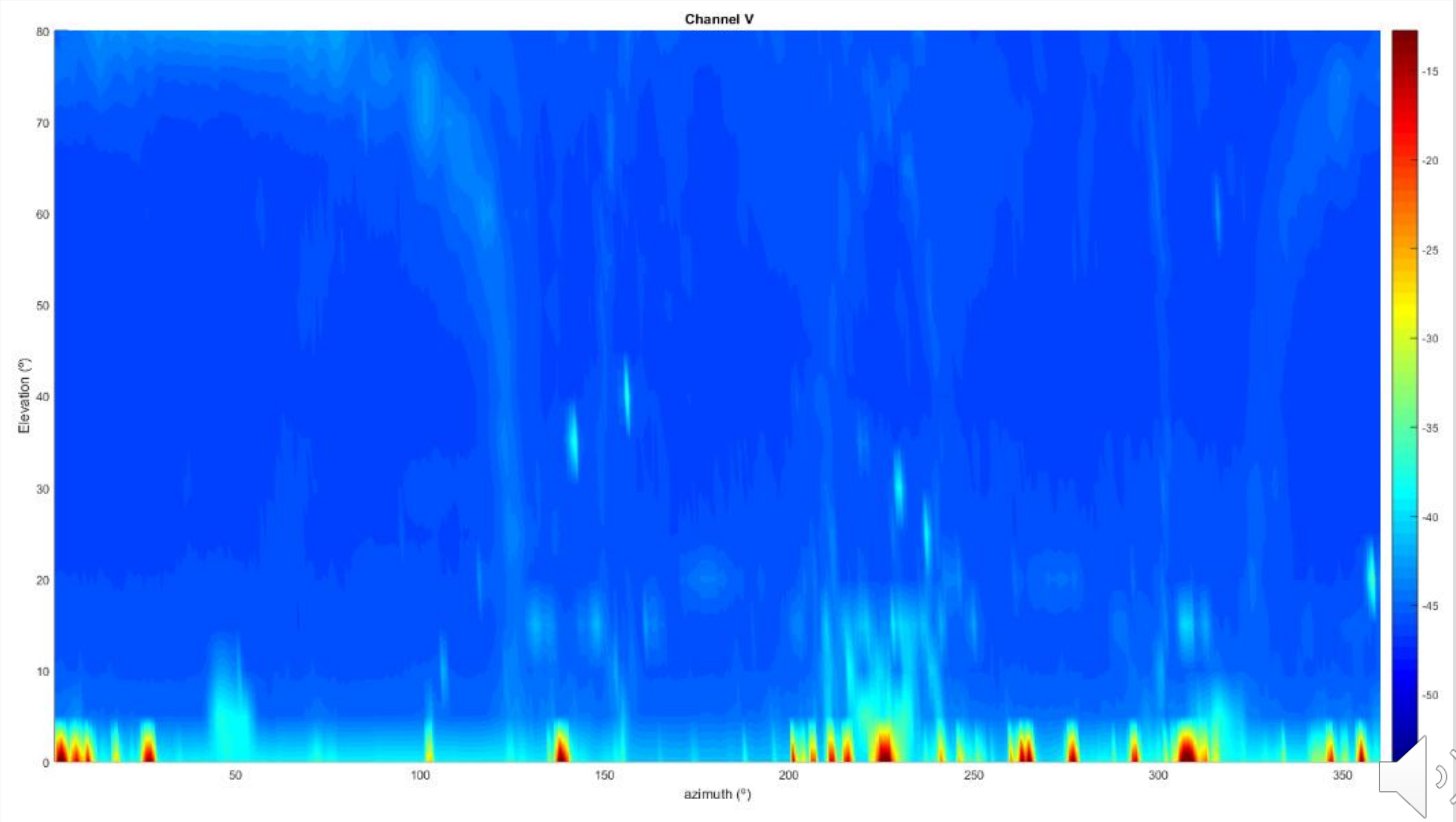
Detecting RFI with your radiotelescope (1)

RFI frequency vs. Azimuth map



Detecting RFI with your radiotelescope (2)

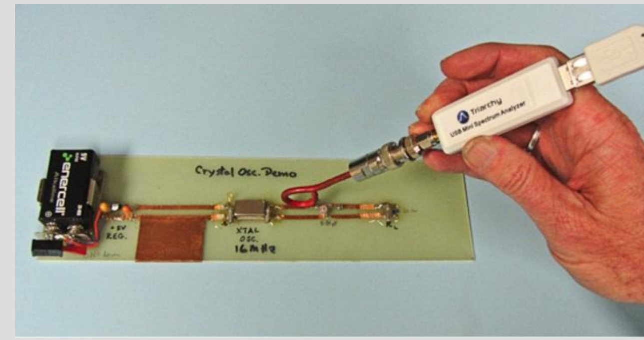
Elevation over Azimuth RFI power maps

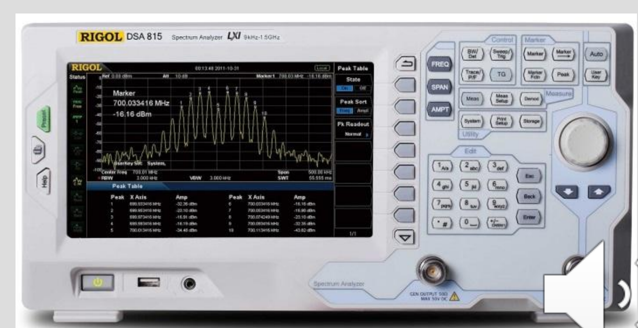


GOBIERNO DE ESPAÑA MINISTERIO DE FOMENTO
INSTITUTO GEOGRÁFICO NACIONAL

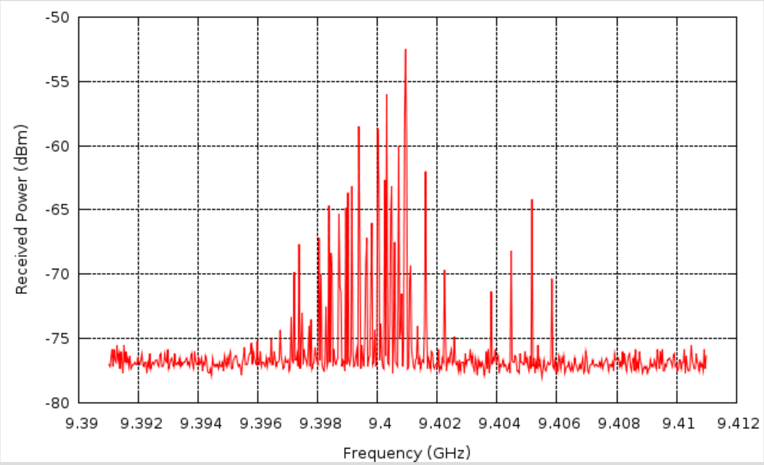
Detecting RFI

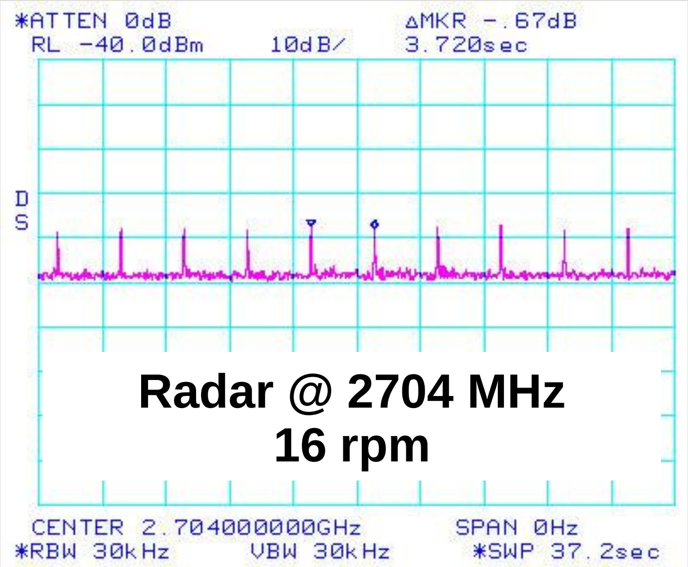
- Field probes & sniffers
- Antennas
- Pre-amplifiers
- Spectrum Analyzers
- Receivers
- Preselectors
- Software Defined Radios





RFI example: Radars

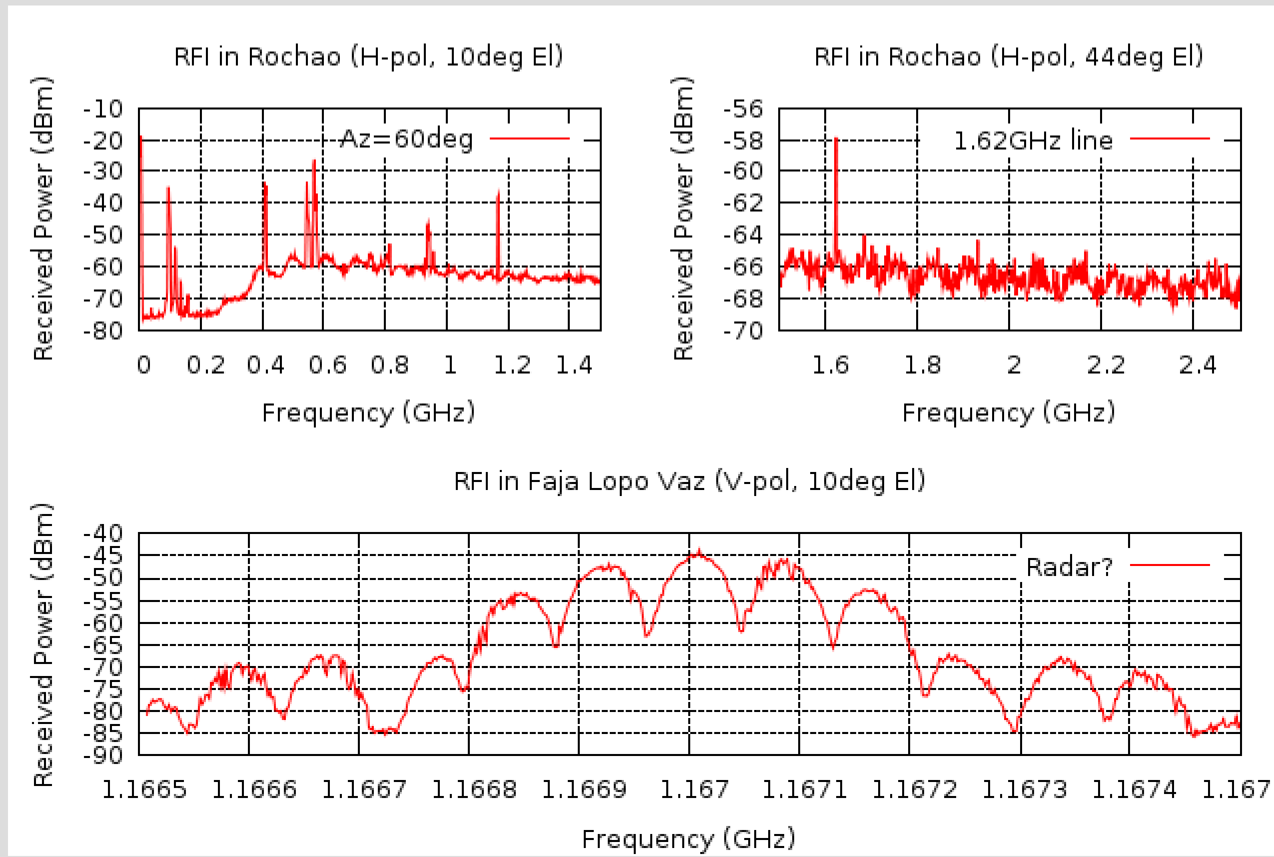




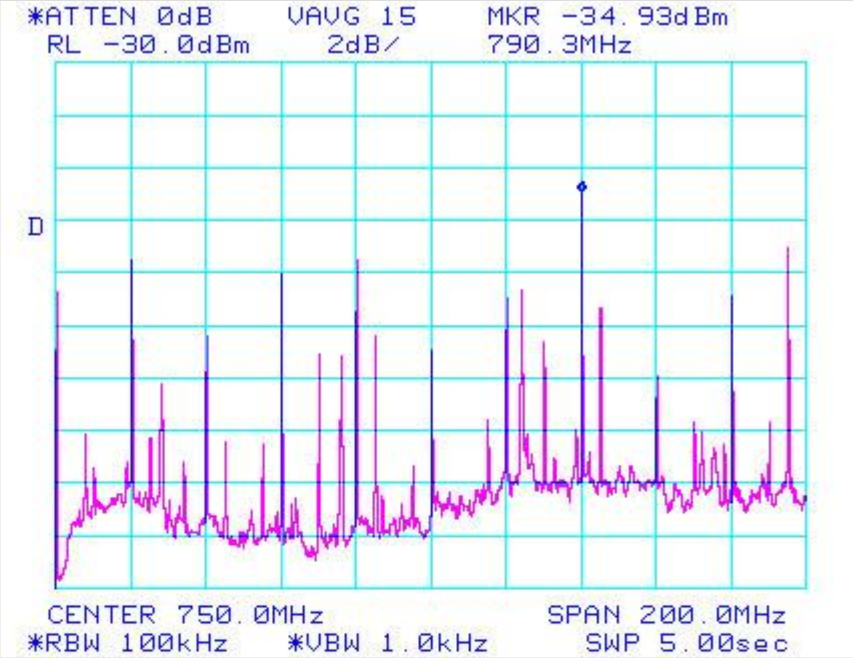
- **Destruction of 4 units of Yebes X-band cryogenic LNAs in tri-band receiver at Ny-Alesund !!**

- **Similar event in Onsala on one of their broad-band receivers**

RFI example: radio-repeaters and radio-links



RFI example: servo electronics

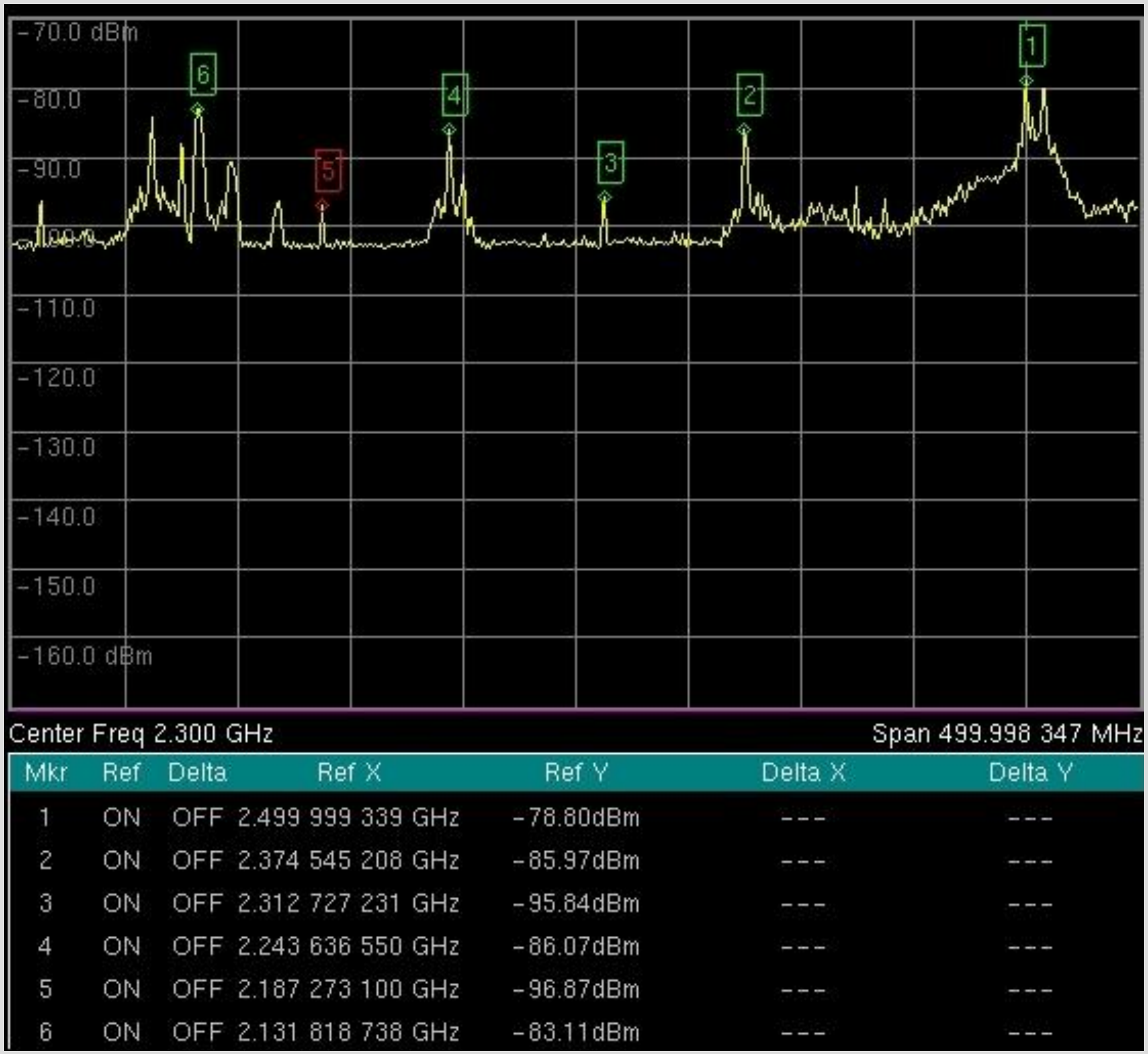


RFI spectrum in S band under normal 40-m antenna and Rx's operation

Main sources of interference from antenna servos are:

- **Local Control Panels (train of 20 MHz spaced lines).**
- **Hand-Held panel for service operations.**
- **Profibus modules for sensor M&C (train of 16 MHz & 48 MHz spaced lines).**
- **Power supply from servo racks to servo equipment in Rx room.**

RFI example: LAN/Ethernet switch



Signals radiated by LAN Ethernet Switch in S-band

Reduction of LAN speed to 100MHz or 10MHz doesn't show significant improvement.

ITU regulations to protect RAS

- Thresholds for detrimental interference in RAS bands are given in ITU-R RA.769 .
- Percentage of acceptable data loss ITU-R RA.1513.
- In exclusive passive bands (RR footnote No. 5.340), all emissions are prohibited.
- Other bands: administrations are urged to take all practical steps to protect RAS from interference.

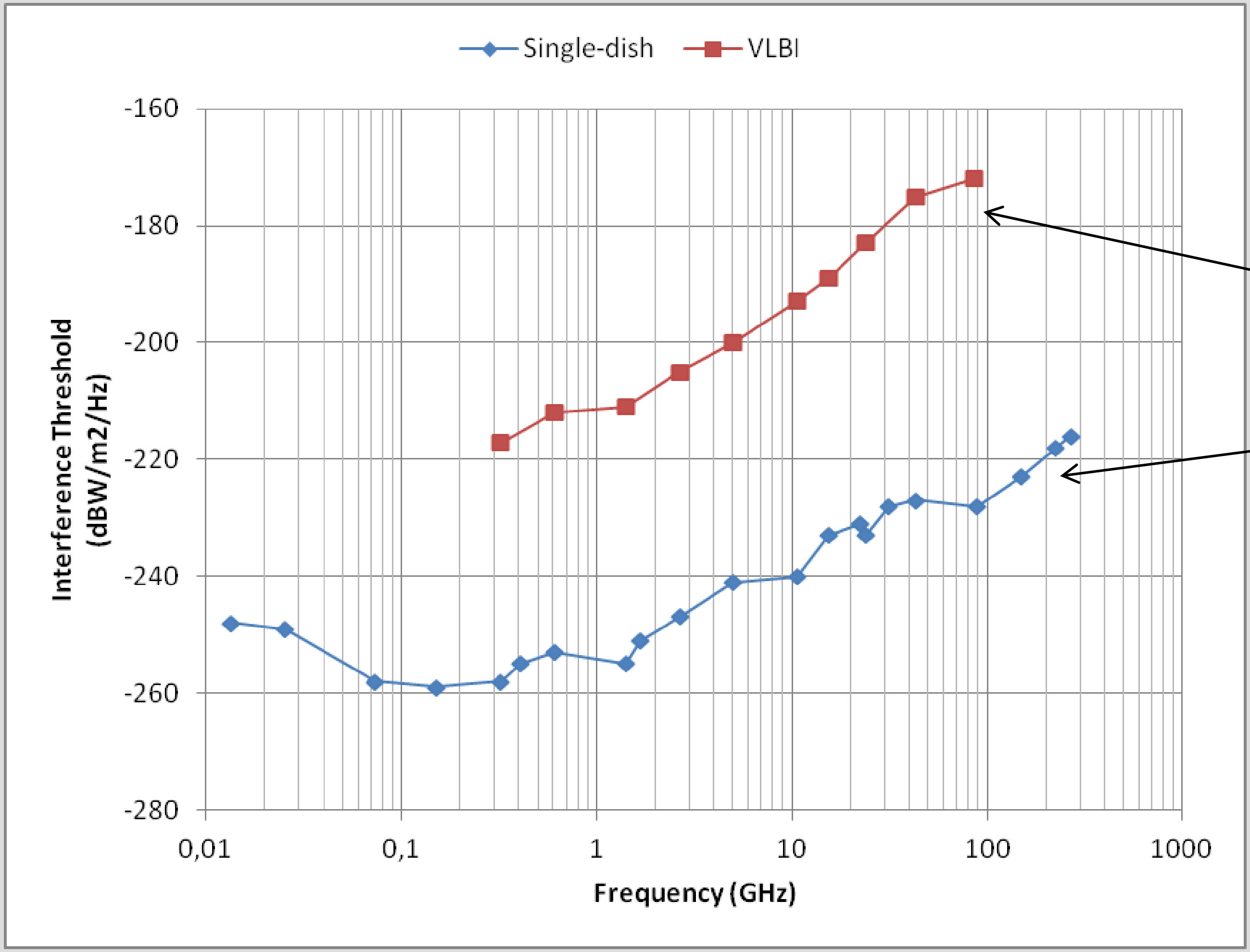
However, ITU regulations only consider RFI received through telescope sidelobes (0 dBi telescope gain).

If RFI were received through the main beam (50 dBi typical telescope main beam gain), the ITU limit for spectral line observations would be exceeded for any RFI with a flux larger than 10 Jy.

GOBIERNO DE ESPAÑA MINISTERIO DE FOMENTO INSTITUTO GEOGRÁFICO NACIONAL

Criteria for Harmful Interference

For VLBI, ITU-R criterion is that **RFI should add no more than 1% to the receiver noise** (ITU-R RA.769), which is the typical uncertainty of “well-calibrated” VLBI data.



VLBI is more inmune to uncorrelated RFI that single-dish

RFI effects on single-dish

- In total power mode, the presence of RFI will distort/bias the total power measurements, unless it is very narrowband.
- In spectral line observations, RFI can obscure, distort or degrade the profile of the molecular lines under observation.
- These effects are even worse if RFI changes with time/frequency/position, because “substraction” techniques for calibration are invalidated (position or frequency switching) .

GOBIERNO DE ESPAÑA · MINISTERIO DE FOMENTO · INSTITUTO GEOGRÁFICO NACIONAL

The Guardian

Microwave oven to blame for mystery signal that left astronomers stumped

Australian scientists first detected interference in 1998, which they assumed was from lightning strikes, but earlier this year they finally found the real culprit

▲ The source of 'suspicious perytons' that caused headaches for astronomers at the Parkes radio telescope for years has finally been identified. Photograph: Julian Chang/Guardian Australia

The mystery behind radio signals that have baffled scientists at Australia's most famous radio telescope for 17 years has finally been solved.

The signals' source? A microwave oven in the kitchen at the Parkes observatory used by staff members to heat up their lunch.

RFI effects on VLBI (1)

- Unless it overloads the receiver, arrays are less sensitive to RFI, because it is not present in all sites and, therefore, is not correlated between telescopes.

- RFI will not have the characteristic fringe frequency and delay of a cosmic source, so “fringe stopping” will decorrelate RFI signal

- Raw cross-correlation coefficient:

$$\frac{P_i * P_j}{\sqrt{P_i^2 \cdot P_j^2}}$$

RFI added to signal “Pi” will reduce the coefficient and can drive to fringe amplitude errors

RFI effects on VLBI (2)

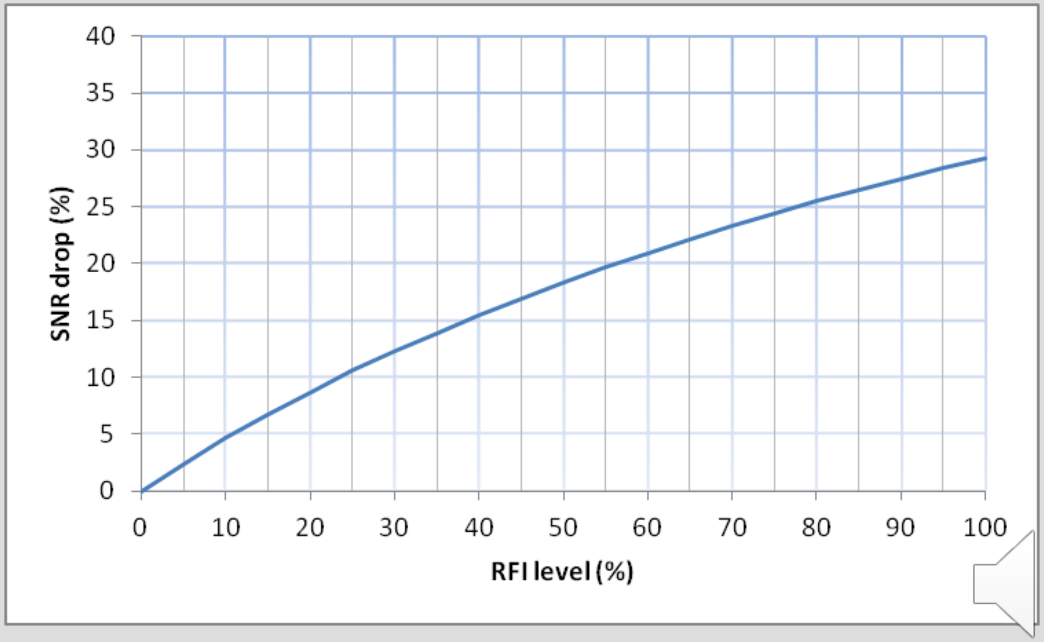
- RFI increases Tsys, which implies:
  - less sensitivity, i.e., SNR reduction
  - Higher System Equivalent Flux Density

$$SEFD[Jy] = \frac{2kT_{sys}}{A_e} \cdot 10^{26}$$

- Artifacts in source mapping
- Failure of geodetic bandwidth synthesis if several channels are affected by RFI
- SNR is given by:

$$SNR = \frac{S_{source} \cdot \sqrt{N_{bits}}}{\sqrt{SEFD_i \cdot SEFD_j}}$$

If RFI is 50% of system noise power , SNR drops by 18%



RFI effects on group delay

According to Shaffer simulations (2000 IVS GM paper):

- RFI effects look like a variable clock offset
- RFI bias group delay estimates, rather than delay noise
- RFI from one particular direction tends to “pull/bias” site position estimation in that direction
- **RFI levels (> 10 % of Tsys) will cause delay errors > 1 ps which implies a geometric error > 1 mm**

- **Less accuracy in geodetic/astrometric measurements**

RFI effects on receivers

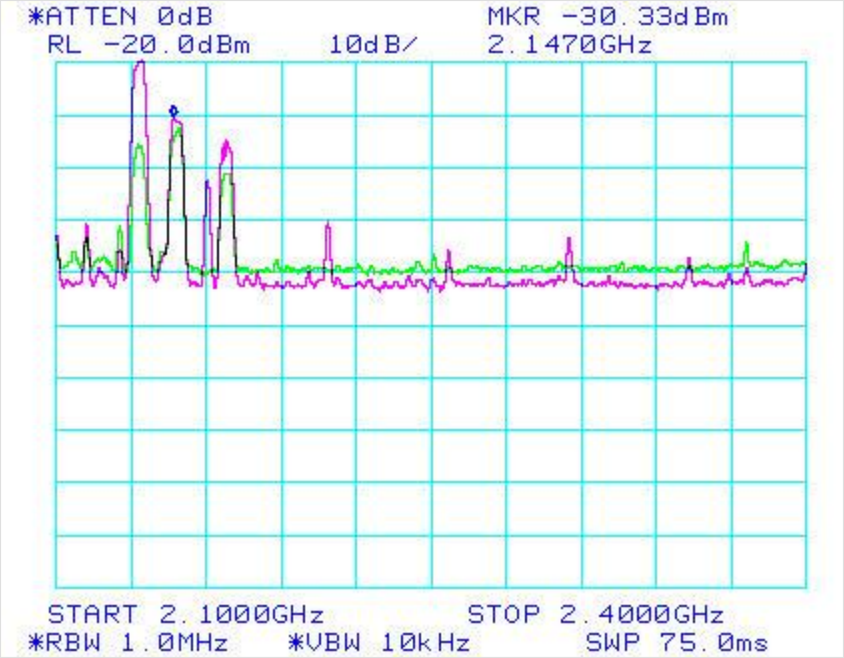
- LNA damage !!
  - It is the first and most sensitive amplifier in the Rx chain.
  - Typical damage level is 15 mW (12 dBm) => PFD threshold of -38 dB(W/m2) for a VGOS antenna.
  - Typical Pi1dB = -30 dBm => max. input power < -40 dBm to guarantee operation in linear regime

- Gain compression at some point of the receiver’s chain:
  - Intermodulation + harmonics => spurious signals
  - Tsys increase => less sensitivity.
  - Lack of linearity in the receiver

RFI mitigation

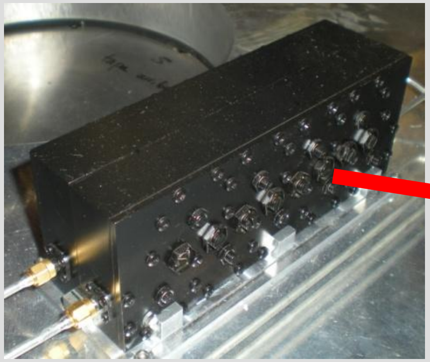
- Diode power limiters at LNA input (degrades sensitivity and may generate intermodulation)
- HTS filters at LNA input (less degradation than limiters)
- Shielding of noisy devices
- Dynamic schedule to avoid direct pointing to transmitter
- Blanking of transmitters
- Software tools: AOFlagger (https://gitlab.com/aroffringa/aoflagger)

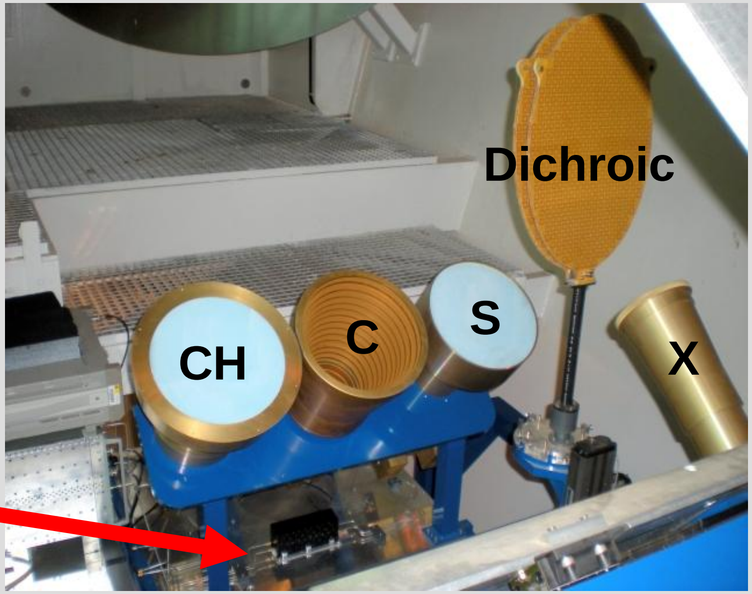
RFI mitigation: radio-link filtering



Three 4 MHz BW lines coming from fixed-service radiolink.

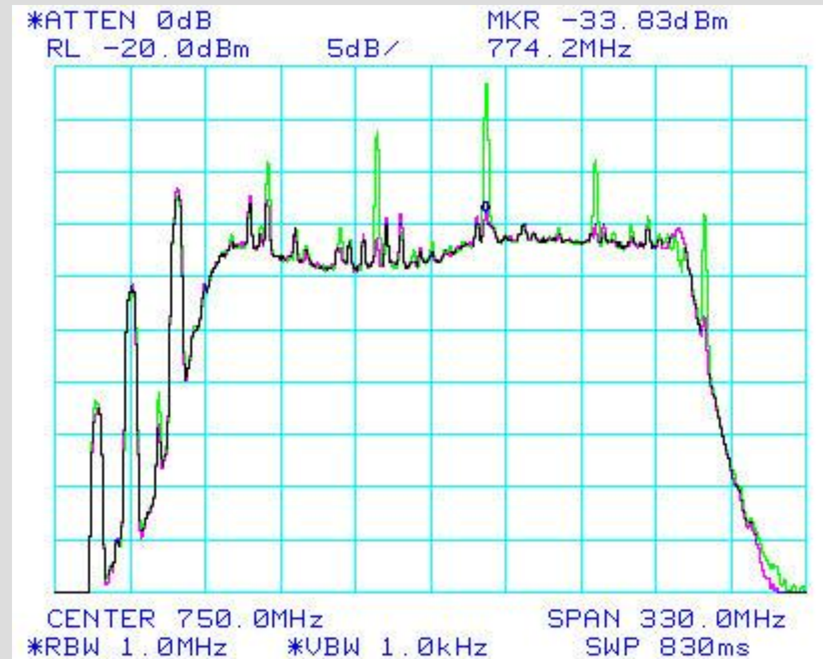
They were filtered out using high-selectivity customized 8-sections band-pass filters





RFI mitigation:
Servo electronics shielding

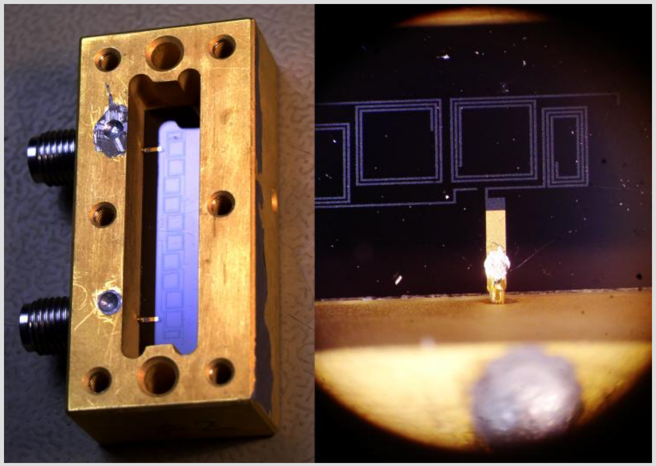
M3 Mirror Profibus Module inside shielded box



Some improvement …

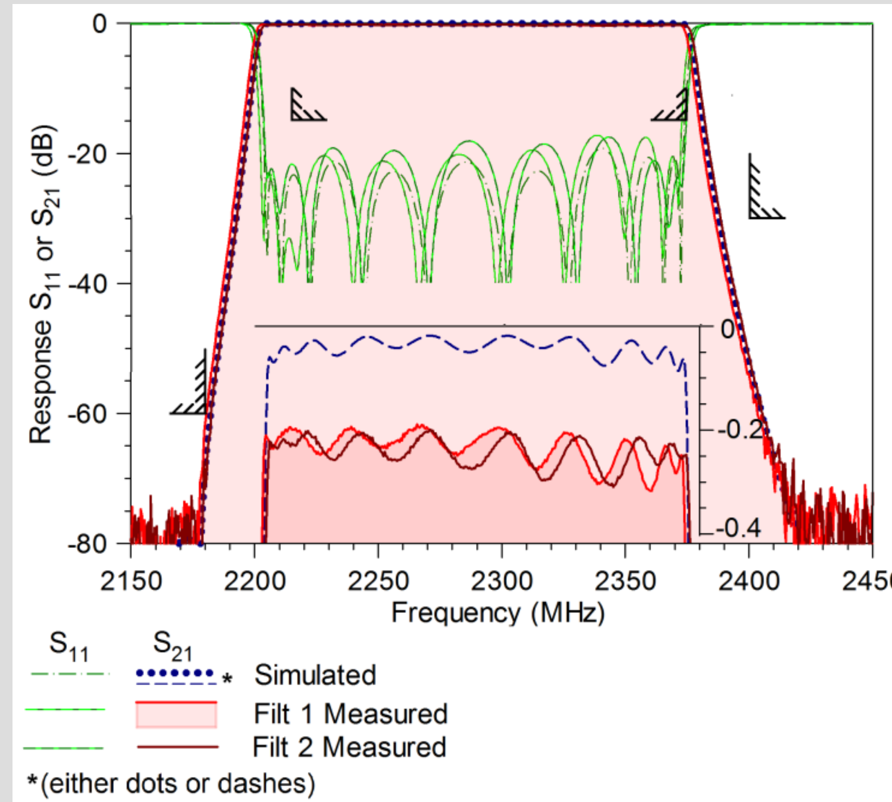
but not enough !

RFI mitigation: HTS filters



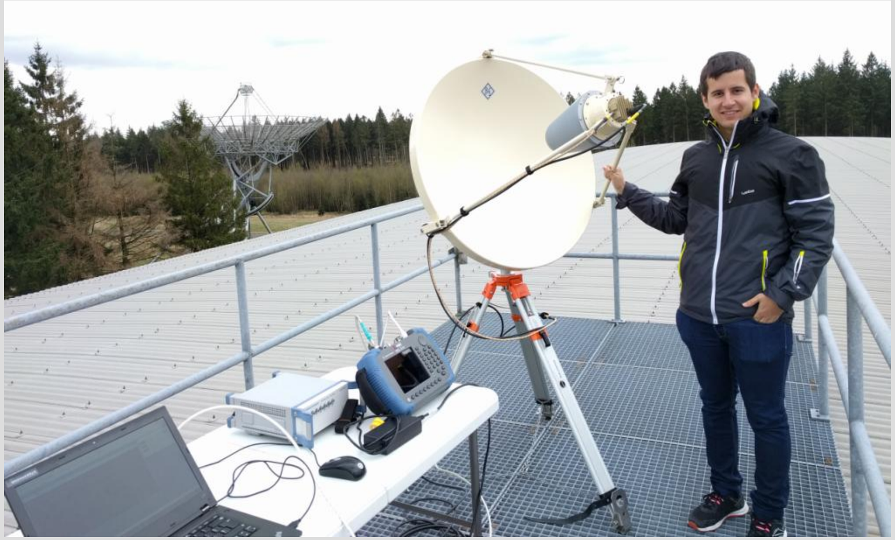
S-Band: 2.2-2.37 GHz
9 poles band-pass filter

Fo = 2295 MHz
BW= 2215 - 2375 MHz
Max. insertion loss: **0.1dB @ 20 Kelvin**
Rejection **> 60 dB at 2115 <= f <= 2180**
Rejection **> 30 dB at f > 2400 MHz**
Max. VSWR in/out: 1.4:1



Frederick Huang, Pietro Bolli, Luca Cresci, Sergio Mariotti, Dario Panella, Jose A. Lopez-Perez, Pablo Garcia: **Superconducting spiral bandpass filter designed by a pseudo-Fourier technique.** *IET Microw. Antennas Propag., 2018, Vol. 12 Iss. 8, pp. 1293-1301*

Yebes RFI portable measurement system



- Wideband 0.9m parabolic antenna AC008 from RS on a tripod
- Wideband 1 - 18 GHz crossed log-periodic antenna HL024S5 from RS, as the feed of the parabola, with internal pre-amplifiers
- GB016S5 feed control unit for polarization (H or V) and pre-amplifiers control.
- DC - 20 GHz Keysight N9344C spectrum analyzer with internal pre-amplifier
- Low loss coaxial cables
- Lap-top for data acquisition
- Auxiliary equipment
- It has been used for the evaluation of candidate RAEGE-VGOS sites in Azores and Canary islands
- It has been used for the measurement of RFI environment in Yebes (Spain), Westerbork (Netherlands), Effelsberg (Germany) and Onsala (Sweden)

GOBIERNO DE ESPAÑA | MINISTERIO DE FOMENTO | INSTITUTO GEOGRÁFICO NACIONAL

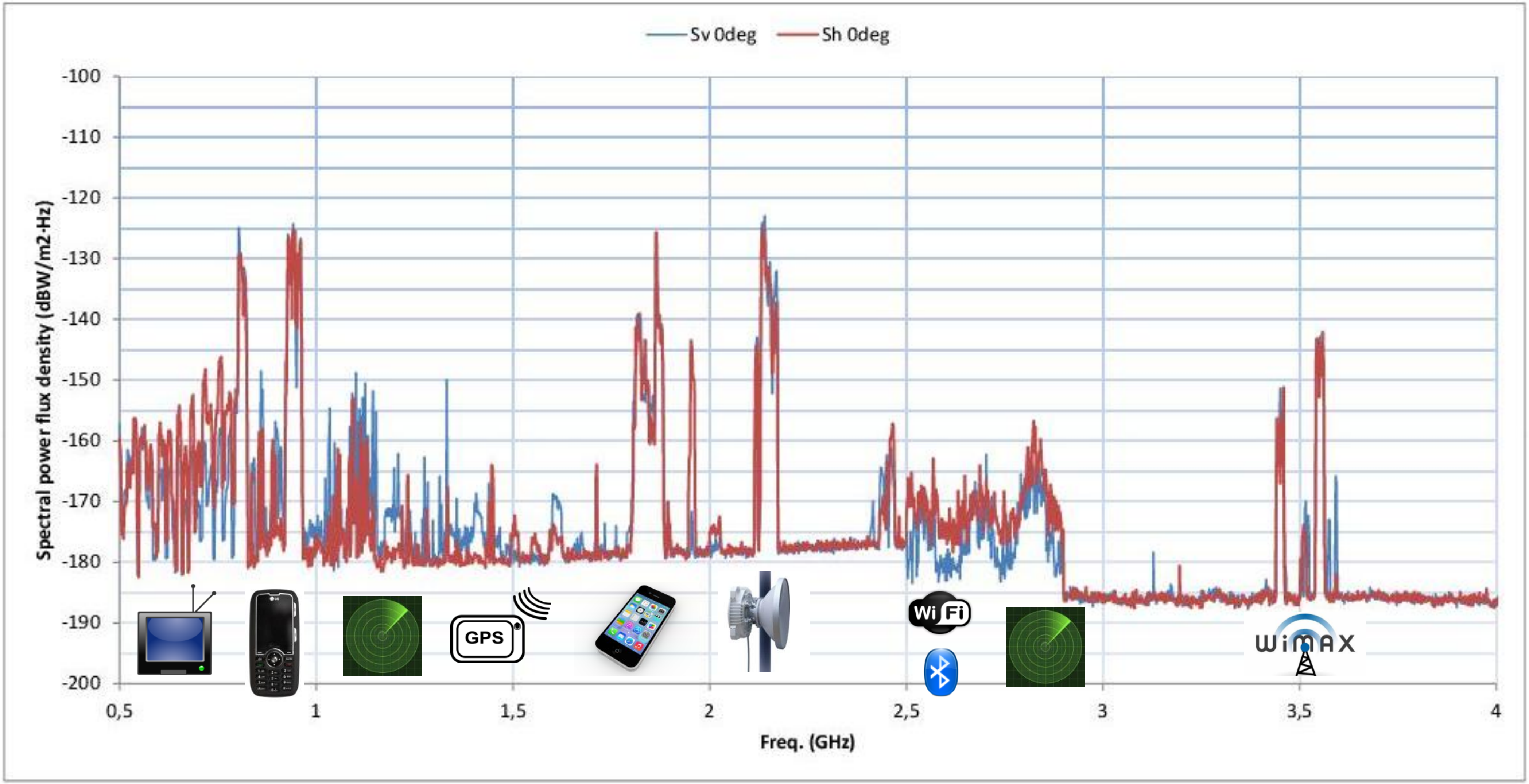
Measurement procedure

1. **Install and set-up RFI measurement system in desired location**
2. **Set parabolic antenna elevation angle (0º worst case)**
3. **Set feed polarization and select feed pre-amplifier**
4. **Set spectrum analyzer parameters and MAX-HOLD mode**
5. **Turn the parabolic antenna by 360º in azimuth while analyzer accumulates data**
6. **Read/save accumulated spectrum with lap-top**
7. **Repeat from step 3 for each polarization and desired band**

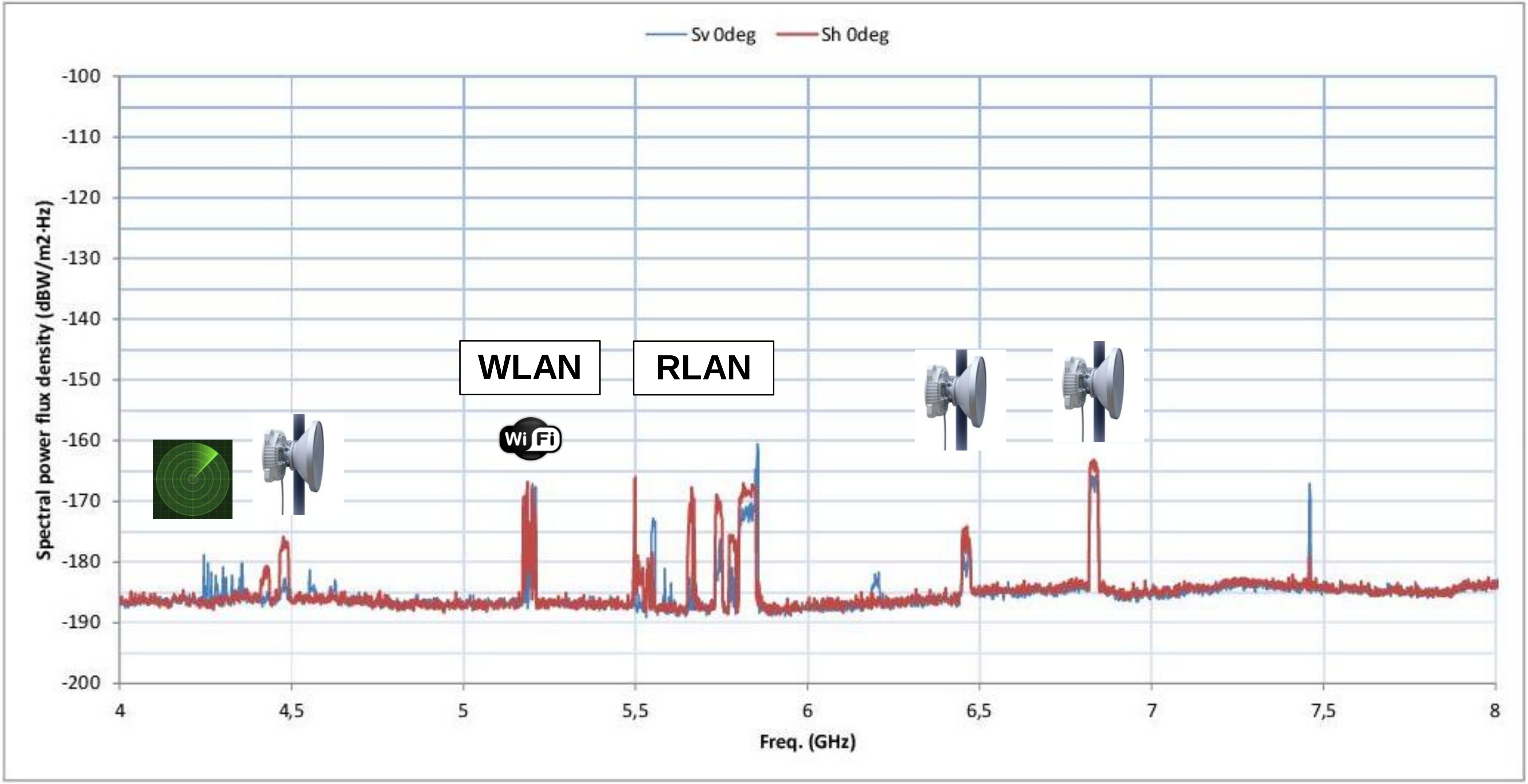
Typical spectrum analyzer parameters:
- RBW = 1MHz
- VBW = 100 KHz
- Number of points = 461 (fixed)
- Sweep time = 150 ms (depends on span and RBW)
- Pre-amplifier: ON/OFF depending on RFI level

GOBIERNO DE ESPAÑA
MINISTERIO DE FOMENTO
INSTITUTO GEOGRÁFICO NACIONAL

0.5 – 4 GHz zoom

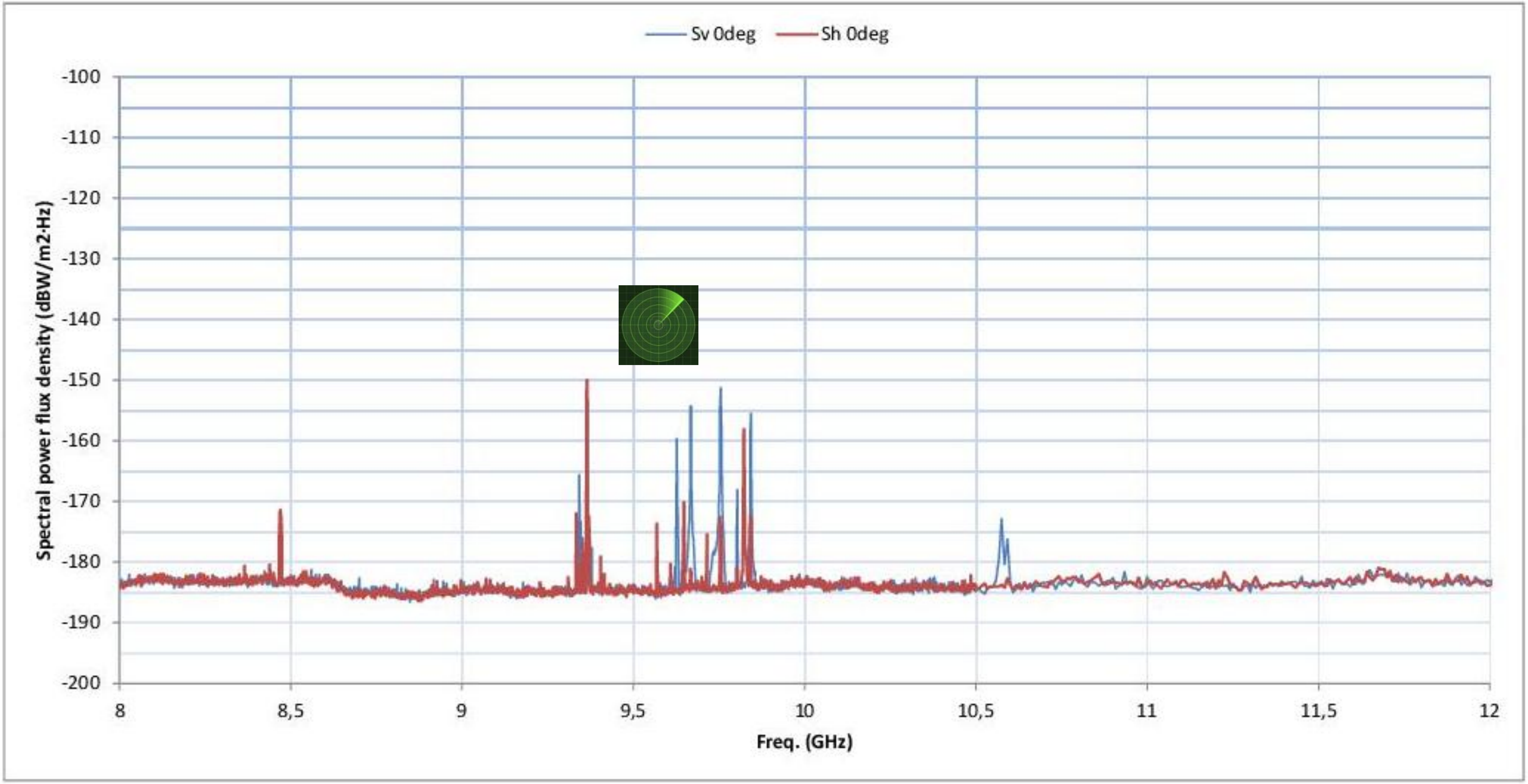

Sv 0deg
Sh 0deg
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
Spectral power flux density (dBW/m2·Hz)
0,5
1
1,5
2
2,5
3
3,5
4
Freq. (GHz)
GPS
Wi Fi
WiMAX

4 – 8 GHz zoom



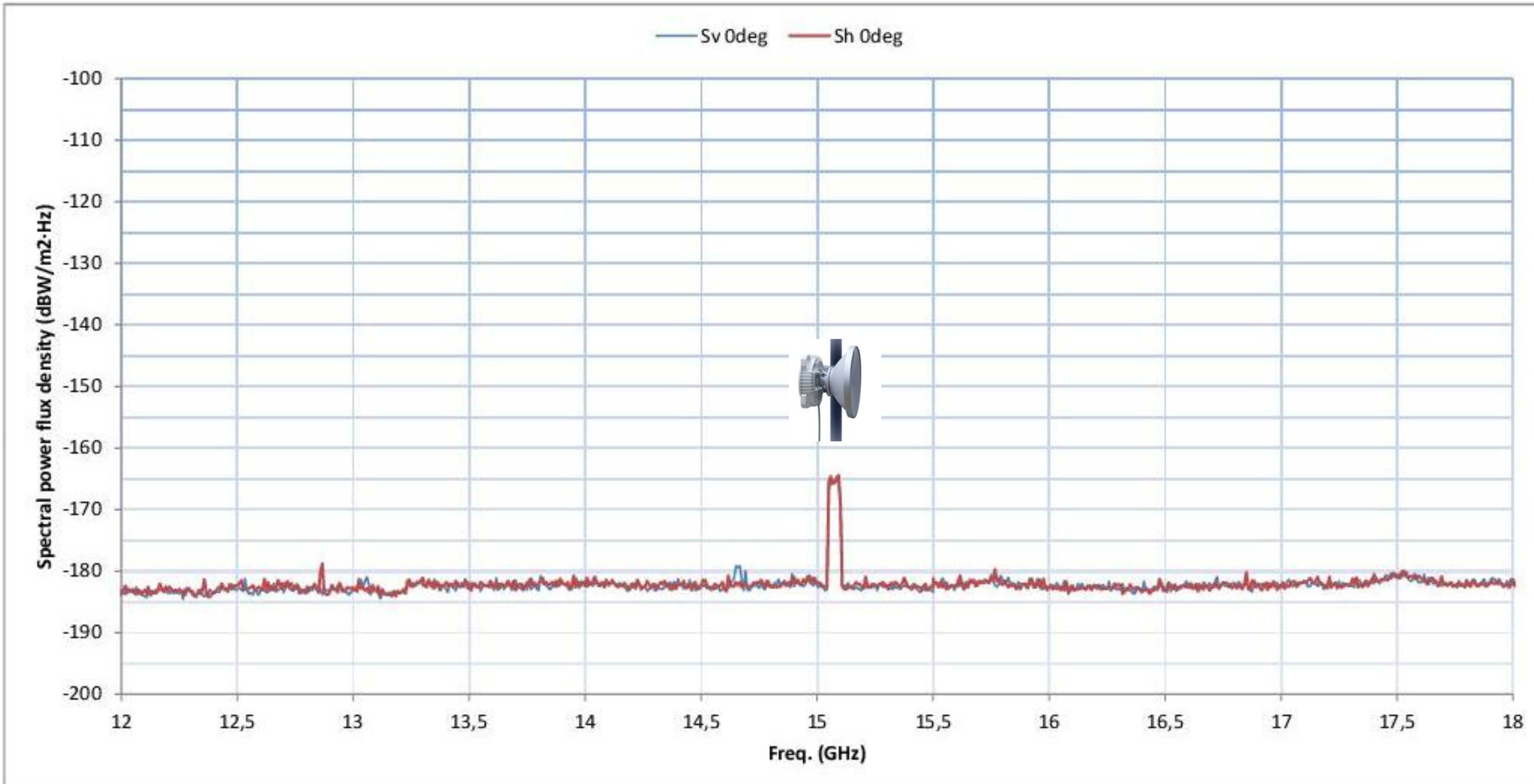
Sv 0deg
Sh 0deg
Spectral power flux density (dBW/m2·Hz)
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
4
4,5
5
5,5
6
6,5
7
7,5
8
Freq. (GHz)
WLAN
RLAN
Wi Fi

8 – 12 GHz zoom



Sv 0deg
Sh 0deg
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
Spectral power flux density (dBW/m2·Hz)
8
8,5
9
9,5
10
10,5
11
11,5
12
Freq. (GHz)

12 – 18 GHz zoom

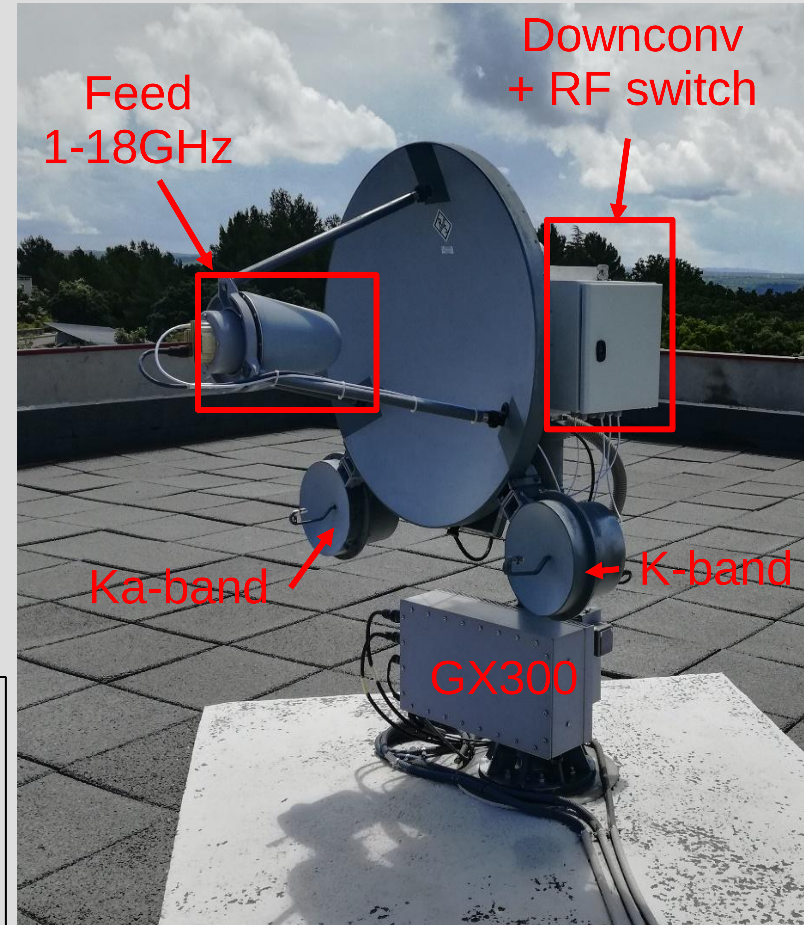


Yebes RFI fixed monitoring system

AC308R2 0.25m dish
Freq: 18 – 26.5 GHz
Gain: 29 – 33 dBi
HPBW: 4.5º - 3º

AC308R3 0.25m dish
Freq: 26.5 – 40 GHz
Gain: 33 – 36 dBi
HPBW: 3º - 2º

AC090 SHF 0.9m dish
Log-periodic feed HL024S7
Freq: 1 - 18 GHz
Gain: 15 – 40 dBi
HPBW: 19º - 1.1º
Surface < 430 um
Az: 0º - 360º
El: -5º - 95º
Accuracy: +/-0.2º



Wideband parabolic antenna
AC090 from R&S
on Az over El rotor

Conclusions

It’s been shown that:

- RFI degrades VLBI observations and geodetic products accuracy
- RFI levels are going to increase in the future (5G, mega-constellations)

So:

- Register your radio telescope in ITU database (contact national authority to do it)
- Support your commitee (CORF, CRAF or RAFCAP)
- Install an RFI measurement system to detect RFI and claim for protection in RAS bands if required.

References

- ITU-R RA.2188: Power flux-density and EIRP levels potentially damaging to radio astronomy receivers.
- ITU-R RA.2428-0: Parameters for the registration of distributed radio astronomy systems
- ITU-R RA.RA-769: Protection criteria used for radioastronomical measurements
- ITU-R RA-314: Preferred frequency bands for radioastronomical measurements
- ITU-R RA-1513: Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy on a primary basis
- ITU-R RA-2126: Techniques for mitigation of radio frequency interference in radio astronomy
- B. Corey: RFI Measurement Techniques. IVS 2000 GM Proceedings P.397-401
- D. Shaffer: RFI Effects on Bandwidth Synthesis. . IVS 2000 GM Proceedings P.402-406
- **PyCRAF software from Benjamin Winkel: https://github.com/bwinkel/pycraf**
- J. A. López-Pérez, F. Tercero: "Report on recommendations for individual EVN antennas". BRAND-EVN work package deliverable 6.1. H2020-INFRAIA-2016-2017/H2020-INFRAIA-2016-1. 2017-06-22.
- J. A. López-Pérez, P. García-Carreño: "Recommendations on RFI frequencies to be filtered in BRAND prototype receiver for the 100-m Effelsberg radio telescope". Report, H2020-INFRAIA-2016-2017/H2020-INFRAIA-2016-1. 2017-06-22.
- *Frederick Huang, Pietro Bolli, Luca Cresci, Sergio Mariotti, Dario Panella, Jose A. Lopez-Perez, Pablo Garcia:* **Superconducting spiral bandpass filter designed by a pseudo-Fourier technique**. *IET Microw. Antennas Propag., 2018, Vol. 12 Iss. 8, pp. 1293-1301*
- **H. Hase, V. Tornatore, B. Corey: "How to register a VGOS radio telescope at ITU and why it is important". IVS 2016 GM Proc.**
- SFCG-31 SF31-9/D R1 NASA: Potential Damage to RAS site by EESS (active). 7-15 June 2011.
- **TOW video "Radiotelescope Registration at ITU-R" by Marta Bautista**

Thanks !!