MIT HAYSTACK OBSERVATORY

RFI Sources, Identification and Mitigation

Part 3: Impacts and Mitigations

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RFI Impact and Mitigation

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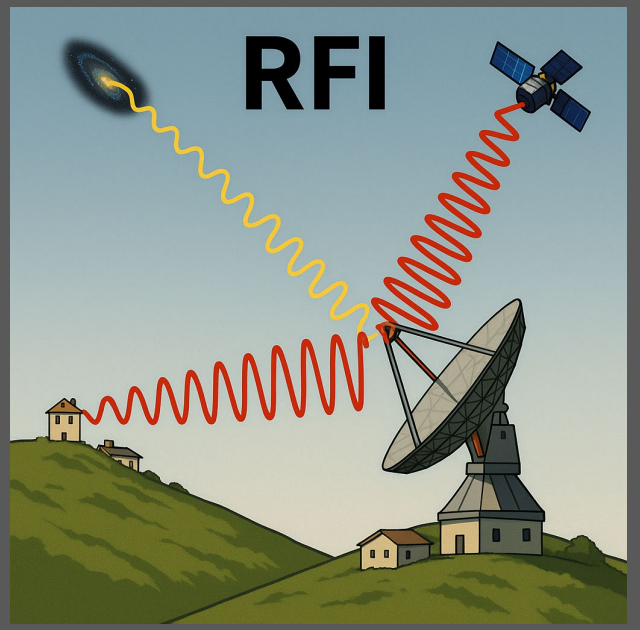
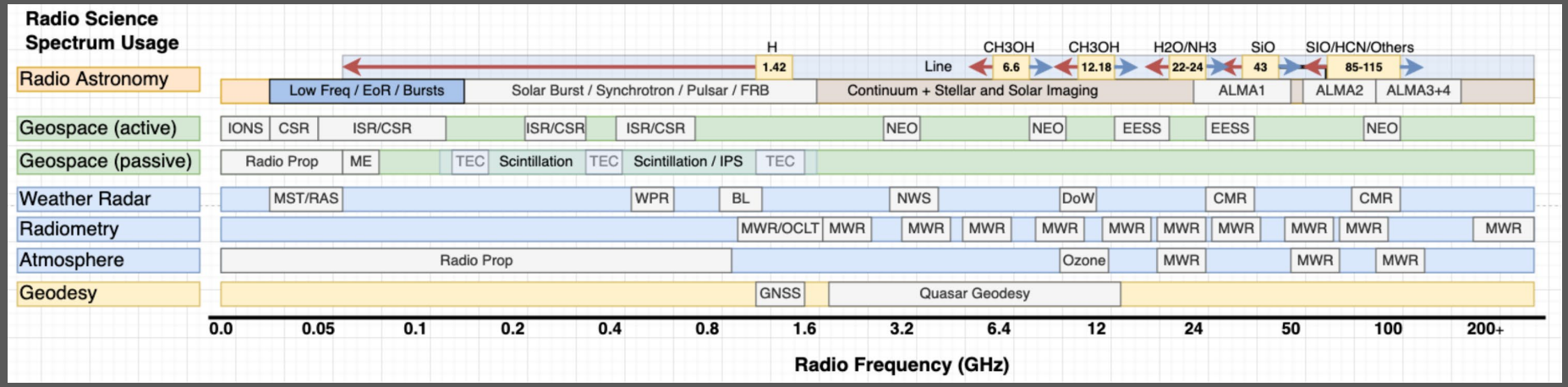
- RFI Impact
  - Receiver
  - Single dish observation
  - Interferometry
  - Geodesy VLBI

- Mitigation Procedure
  - Analog stage
  - Digital stage
  - Policy stage





Impact on Frontend/Receiver

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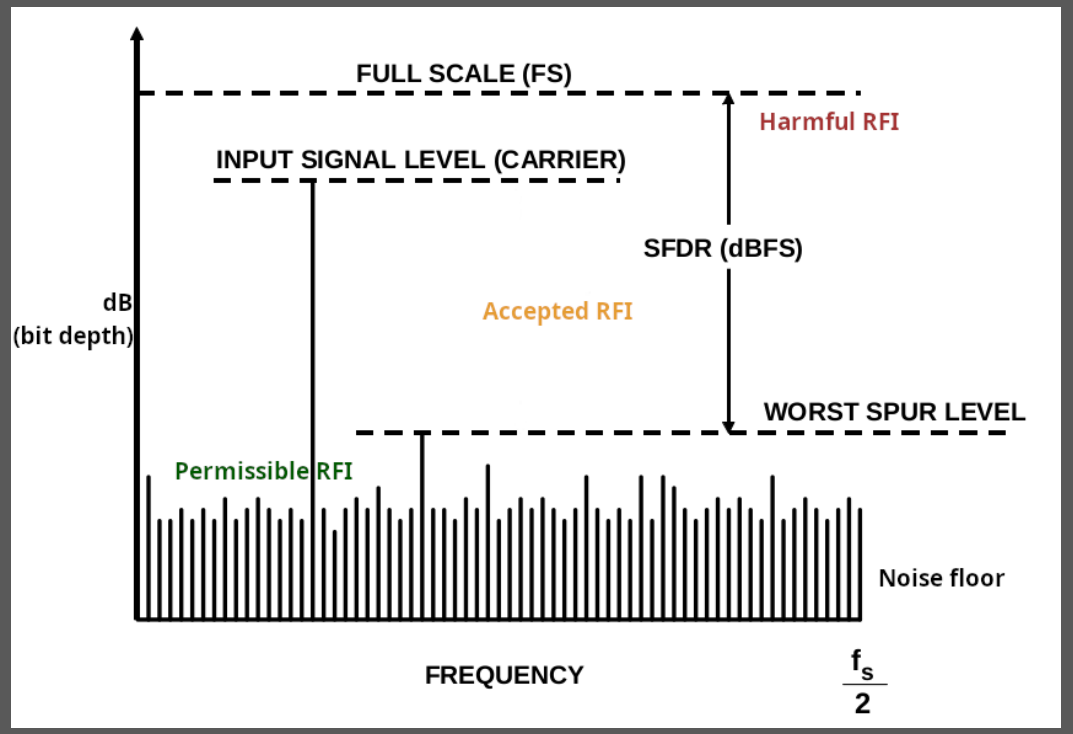
- Different RFI
  -> Bit depth gives flexibility
- Gain compression/Saturation
  -> Creates intermodulation products and harmonics
  -> Rise of noise floor
- Non-linearities
  -> Constrain input power to < -40 dBm
- Low Noise Amplifier damage
  -> First stage of the receiver that sets the gain
  -> Very sensitive (power < 12 dBm)



Impact on Single Dish Observations

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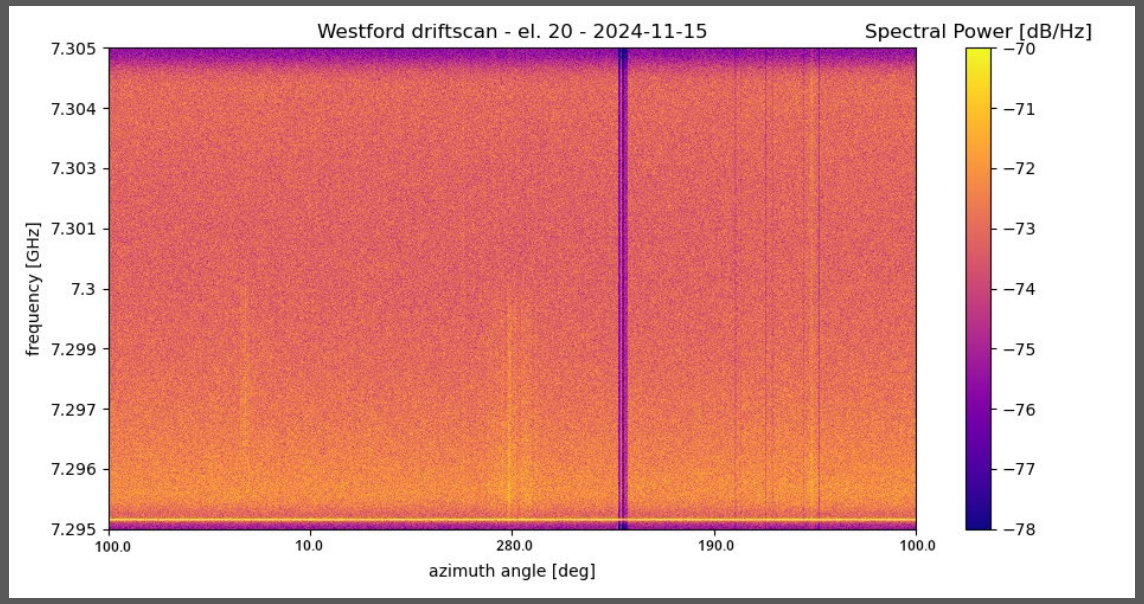
- Broadband RFI

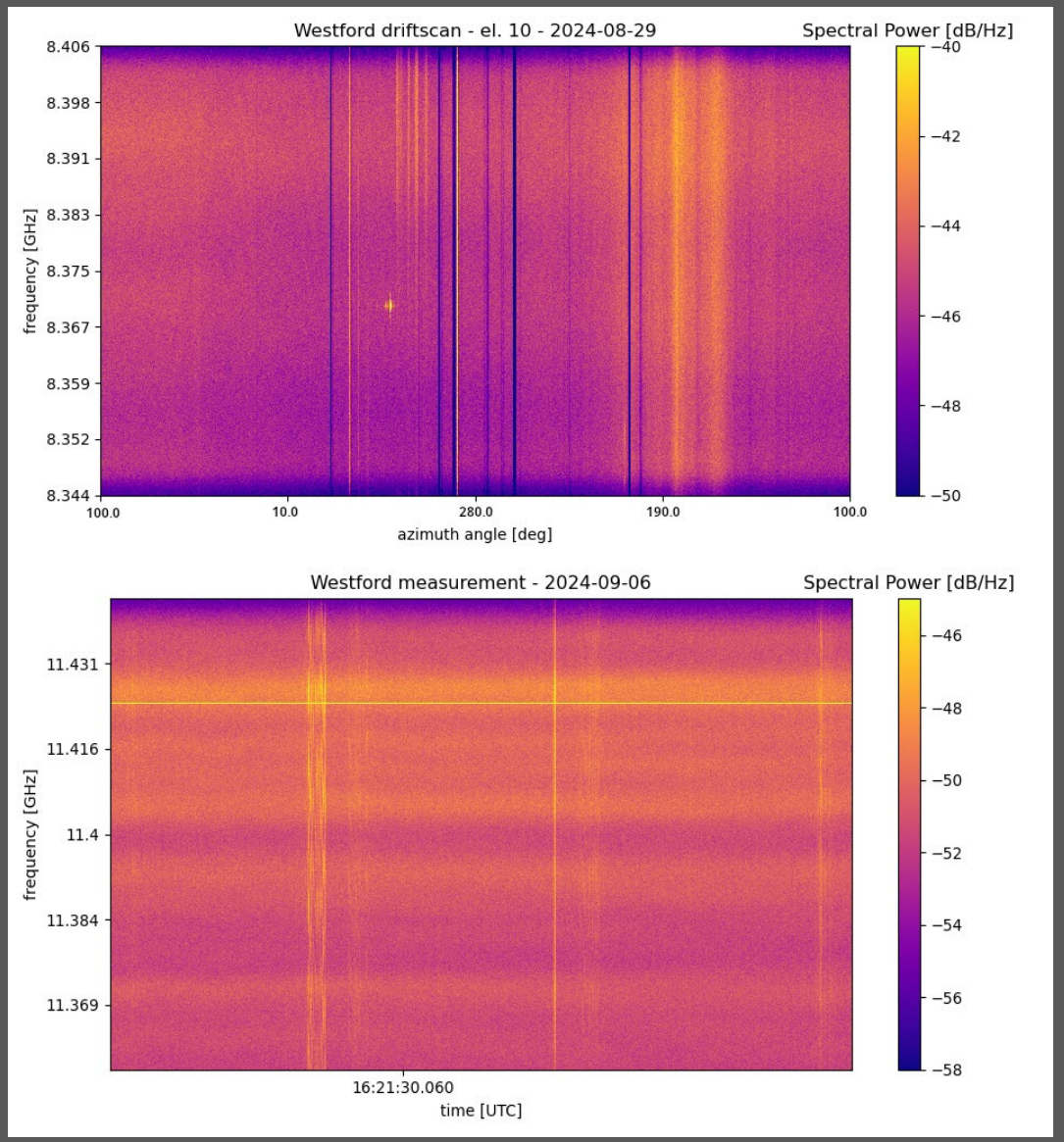
  -> Rise noise floor/Bias in total power, decrease sensitivity

- RFI changing with time or frequency or position

  -> Cannot calibrate out

- Spectral lines can be distorted or degraded by RFI
- Calibration contaminated -> Bias in the absolute flux





Impact on Interferometers

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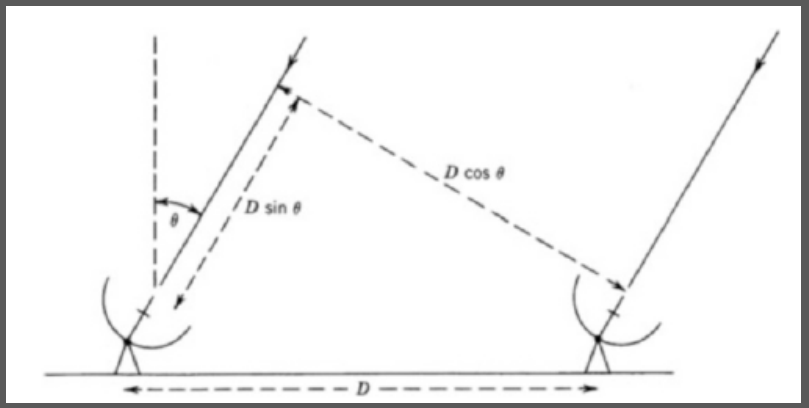

- If RFI seen by only antenna i can lead to fringe amplitude errors

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

delay $\tau = \frac{D}{c} \sin\theta$

- Sensitivity of this antenna will be lower

  -> All baselines involving antenna i will have their SNR reduced

$$SEFD = \frac{2kT_{sys}}{A_{eff}} \quad \Rightarrow \quad SNR \propto \sqrt{\frac{INTEG}{SEFD_i \cdot SEFD_j}}$$

- Flagging for strong RFI

  -> Losing observation time/integration time

Impact on Geodesy VLBI

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- **Group delay** : difference in time of arrival of same signal on two antennas.

  -> Changes with Earth rotation

- Error on delay: $\sigma = \frac{1}{2\pi B \cdot SNR}$ with B : effective bandwidth

  And precision needed ~ 1ps

  -> either high SNR or high B needed

- **Bandwidth Synthesis**: estimate phase slope between multiple smaller frequency channels
- If RFI in one or more small channels -> Impact the phase slop estimation

Table 1. Effects of RFI at X-band

Single Antenna RFI Level	Relative Baseline SNR	Group Delay Offset
No RFI	1.000	16.9 picosec
10% RFI	0.953	15.9
20% RFI	0.913	15.0
30% RFI	0.977	14.2
40% RFI	0.845	13.4
50% RFI	0.816	12.8
100% RFI	0.707	10.3

Frequency Sequence is 0-1-4-10-21-29-34-36, multiplied by 10 MHz
RFI and a 5° phase offset occur in channel 8 only (frequency spacing 360 MHz)

Shaffer, 2000

Impact from Mega-Constellations of Satellites

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- Remote location is no longer an option (except in space...)

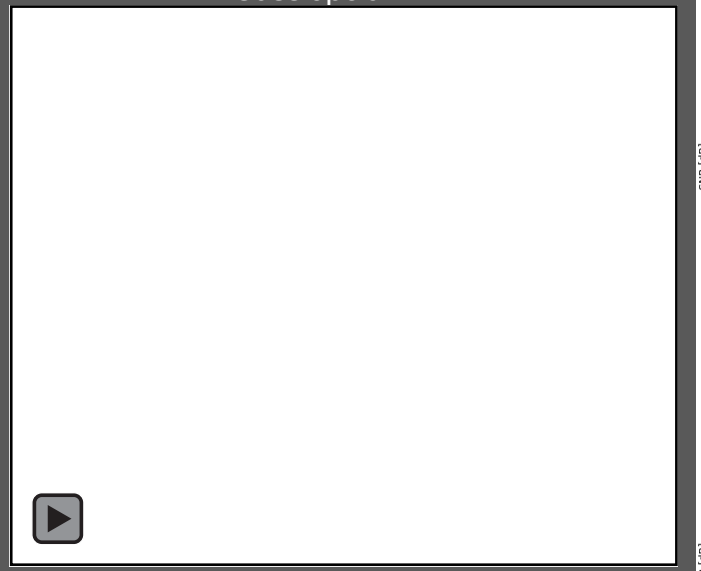
  -> Currently, ~60 Starlink satellite above our heads at any given time

- Sidelobes interactions are becoming important

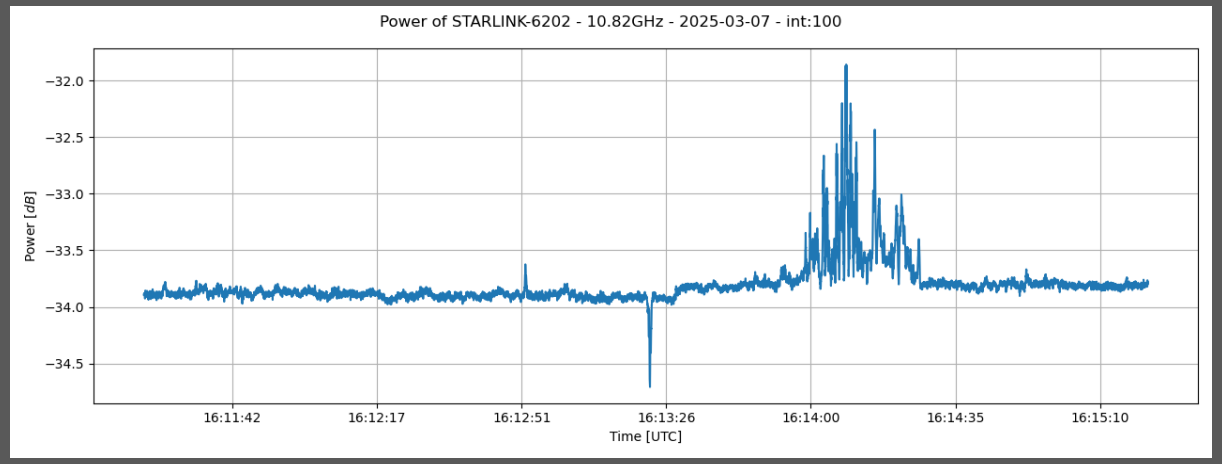
  -> Aggregated power for single dish observation

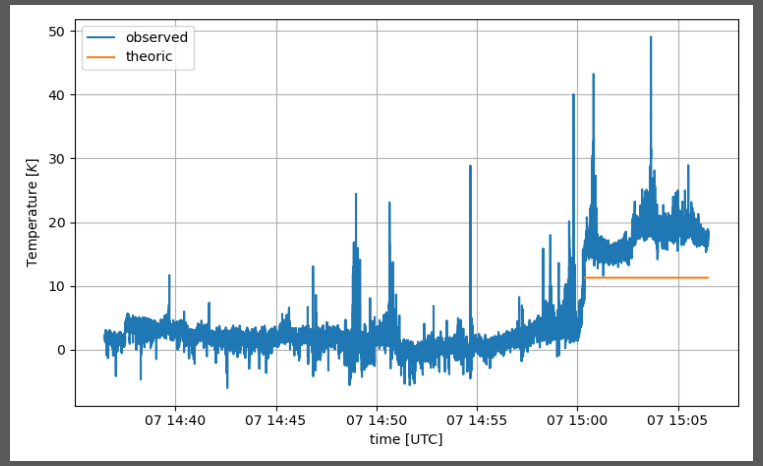
  -> Correlated noise for short baseline **is possible** through mainlobes but also sidelobes

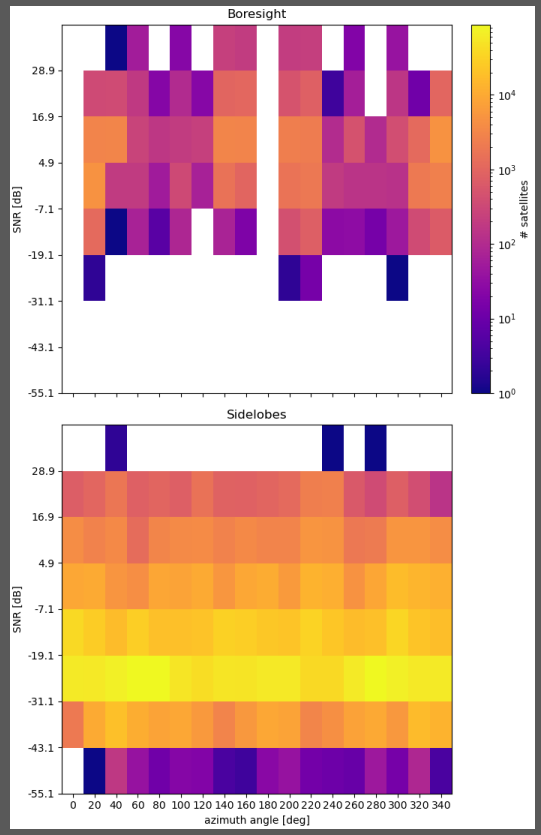
sky map estimated power accounting for satellites trajectories and Cassiopeia A.



Cas A Off-On 10.82GHz 2025-03







number of satellites during a week at a given SNR and position for mainlobe and sidelobe interactions.

Mitigation Procedure

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- Different steps to mitigate RFI for different strategies

Analog stage

- Pre-detection methods related to the receiver/frontend

→ Diode Power Limiter and Filters
→ Physical Shielding
→ Phased Array Feeds
→ Auxiliary Measurement Equipment

Digital stage

- Detection and digital filtering before and/or after correlation

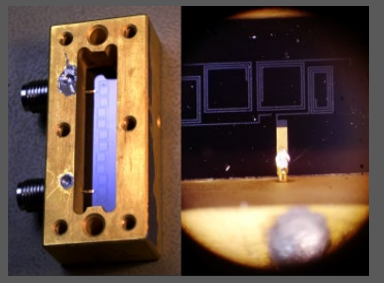
→ Calibration Strategies
→ Fringe Stopping
→ Robust Fring Fitting
→ Machine Learning

Policy stage

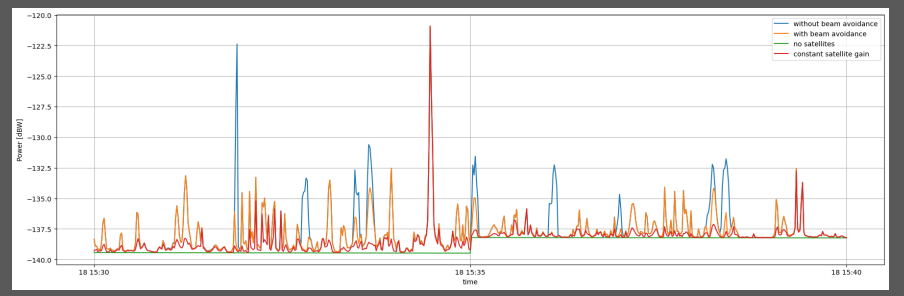
- Policies and agreements to coexist between different systems

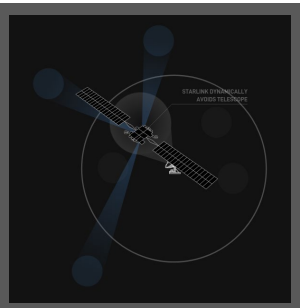
→ Terrain Shielding
→ Radio Quiet Zones
→ Dynamic Spectrum Management
→ Beam Avoidance Strategies

S-band HTS filter
0.1dB insertion loss



Estimated power of Cassiopeia A observations, on and off source, with different scenarios. These account for Starlink satellites, using a beam-avoidance strategy, with a low and constant gain hypothesis and without any satellites).





Nhan et al. 2024
VGOS MEMO #062

Conclusion

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- RFI have impacts on multiple scales of our systems
- We have ways to defend ourselves, especially in interferometry
- Mega-constellations of satellites are a new challenge
- Instrument design, digital processing and international agreements need to **work together** to coexist!

References

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- Nhan et al., "Toward Spectrum Coexistence: First Demonstration of the Effectiveness of Boresight Avoidance between the NRAO Green Bank Telescope and Starlink Satellites", 2024 *ApJL* **971** L49
- Shaffer, "RFI: Effects on Bandwidth Synthesis", *IVS 2000 GM Proceedings*
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Questions?