SKAO

Large Satellite Constellations and Radio Astronomy

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RFI2022 – 14 Feb 2022

Agenda:

What is included:

- **Large Low Earth Orbit (LEO) Constellations**
- **Impacts on Radio Astronomy**
- **Mitigation Strategies**
- **Ongoing Efforts**

What is not included:

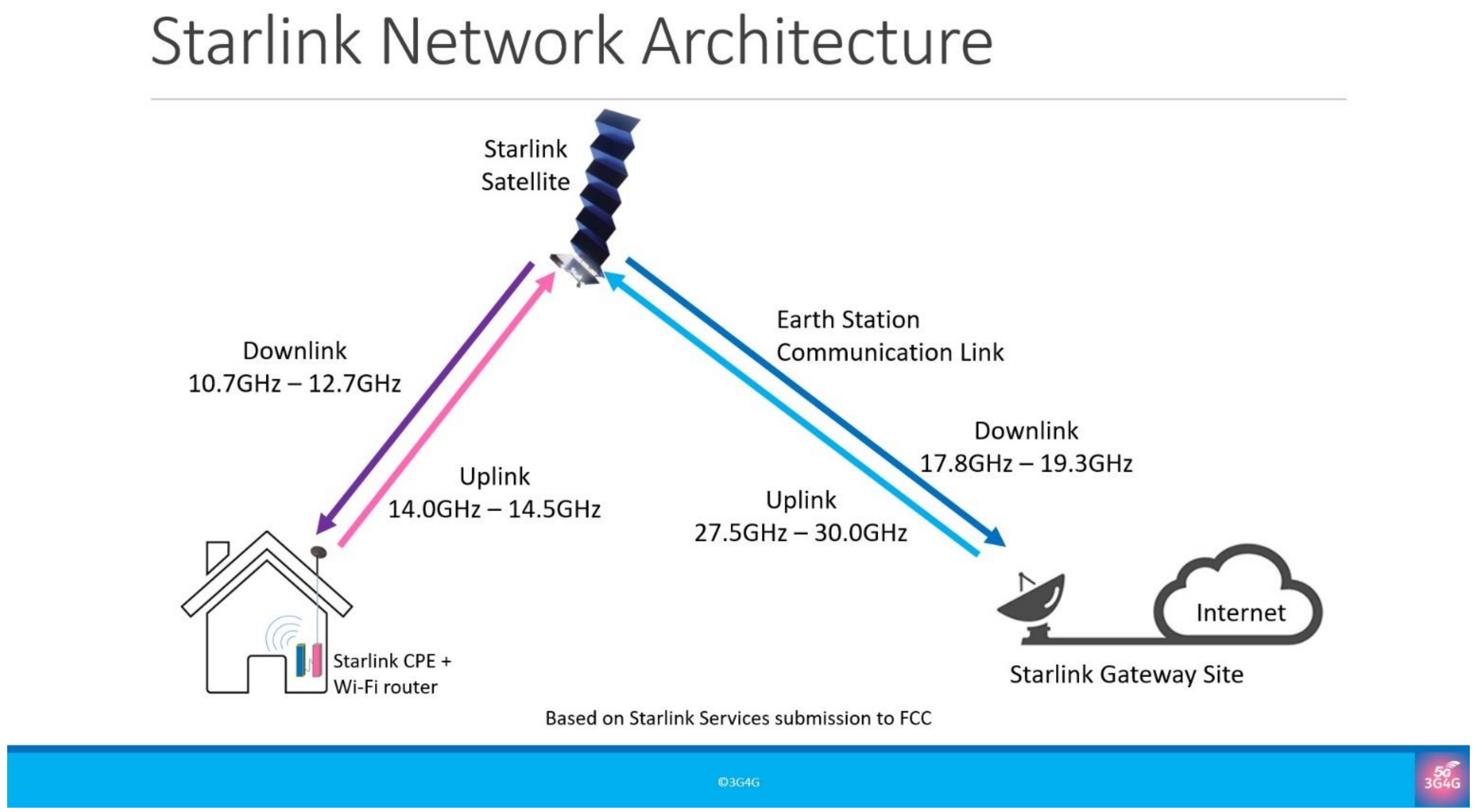
- **Details on calculations and simulations**
- **Measurement efforts**
- **Details on mitigation strategies**

Interested? Find me during the break:
gathertown/ federico.divruno@skao.int

Large LEO constellations

- Before: GPS (24), Iridium (66)…
- Lower cost of launches and new satellite manufacturing processes
- Now: 1000s of medium-size communication satellites
- **Low latency internet** (LEO: 300-2000 km)
- LEO means smaller beam footprints, more satellites needed
- Direct connection to users, gateways connections to the internet
- Sounds like a very good business model…

OneWeb constellation with ~700 satellites in phase 1. (credit: OneWeb)



Starlink business model description

Large LEO constellations

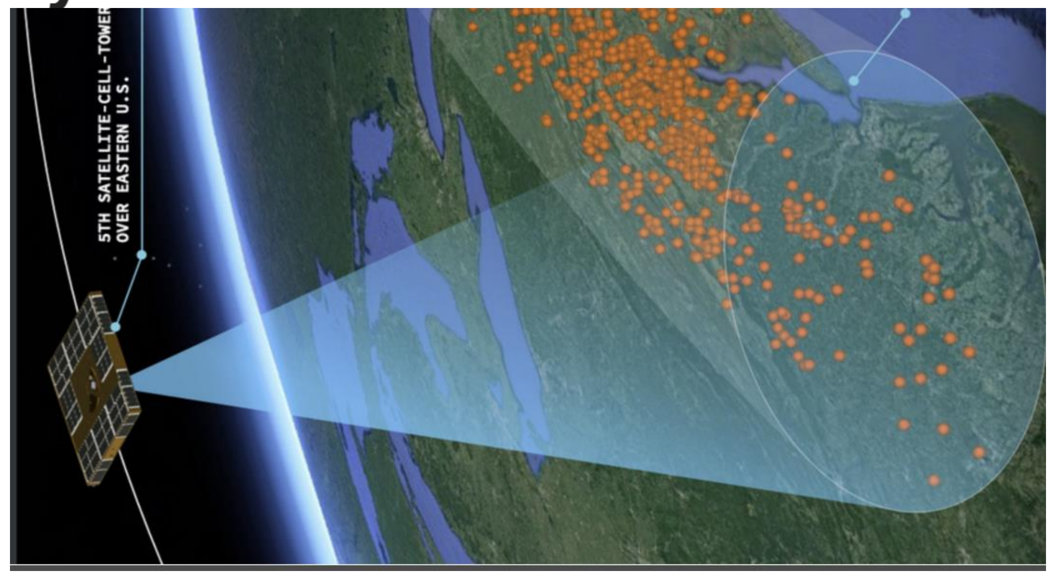
Some of the currently deploying and planned constellations:

Constellation	Number of Satellites	Downlink Frequencies	Altitude [km]
Starlink Phase 1	4,400	Ku, Ka	550
OneWeb Phase 1	648	Ku, Ka	1200
Amazon Phase 1	3,200	Ka	~600
Guo Wang (GW)	13,000	Ku, Ka	590 – 1145
Starlink VLEO	7600	V	340
Telesat	1,700	Ka	
Starlink Phase 2	30,000	Ku, Ka, E	328 – 614
OneWeb Phase 2	6,372	Ku, Ka, V	1200
Boeing	5,789		
Astra	13,620		
Amazon Phase 2	7,774		
Cinnamon-937	300,000	???	???

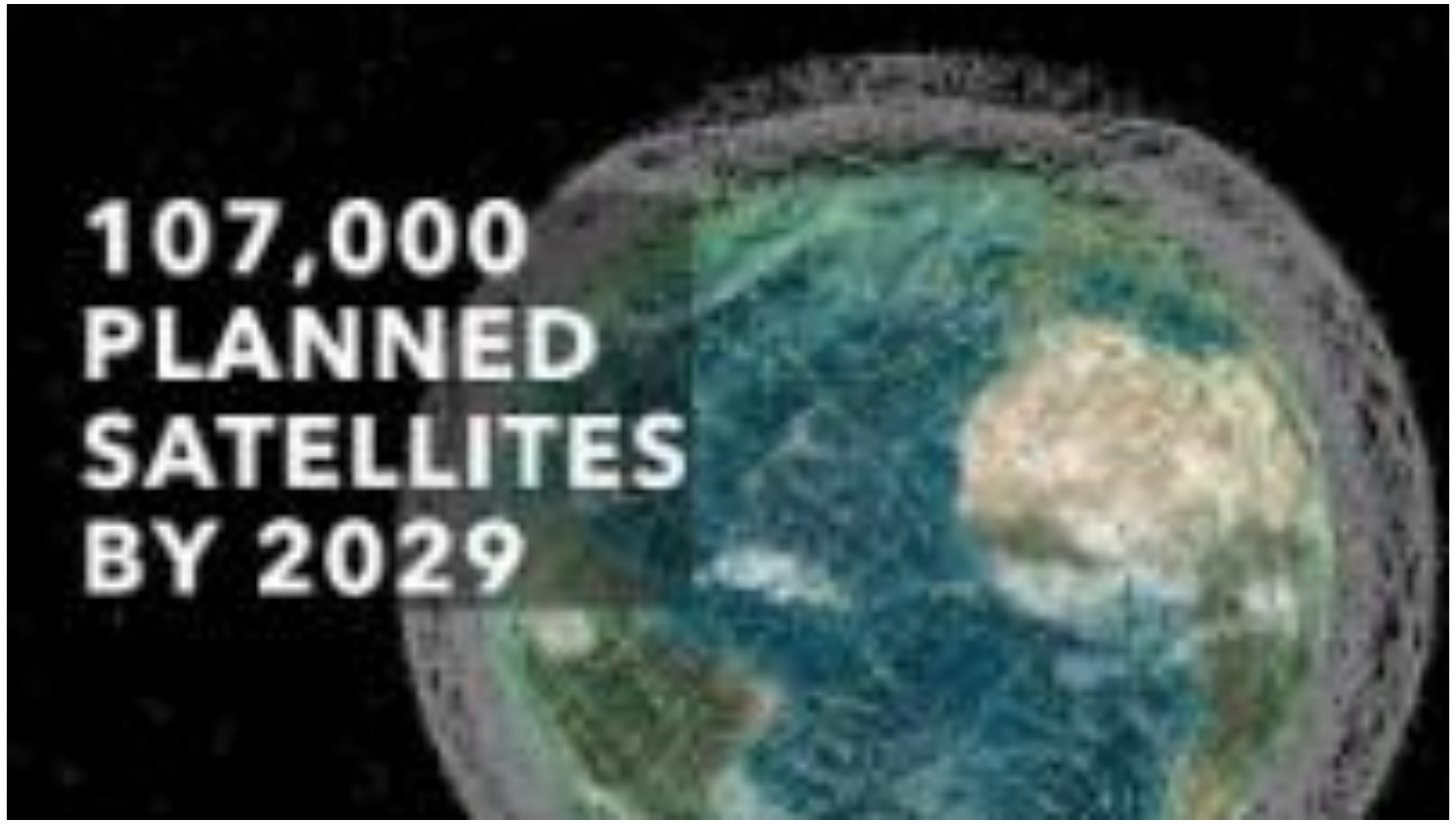
Cell phone towers in space!
663 – 960 MHz

SPACENEWS

Lynk satellites connect with thousands of devices



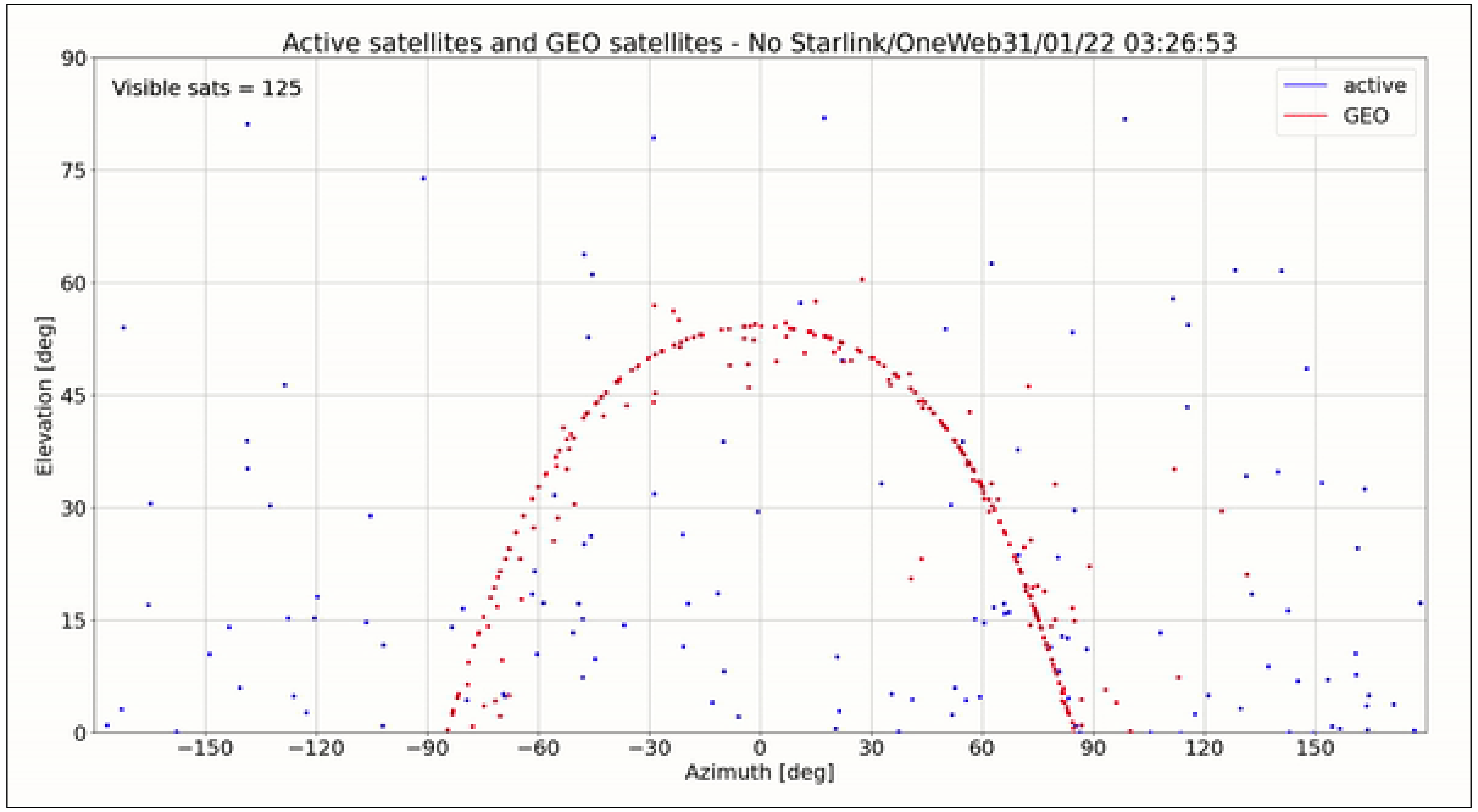
https://spacenews.com/lynk-satellite-testing/

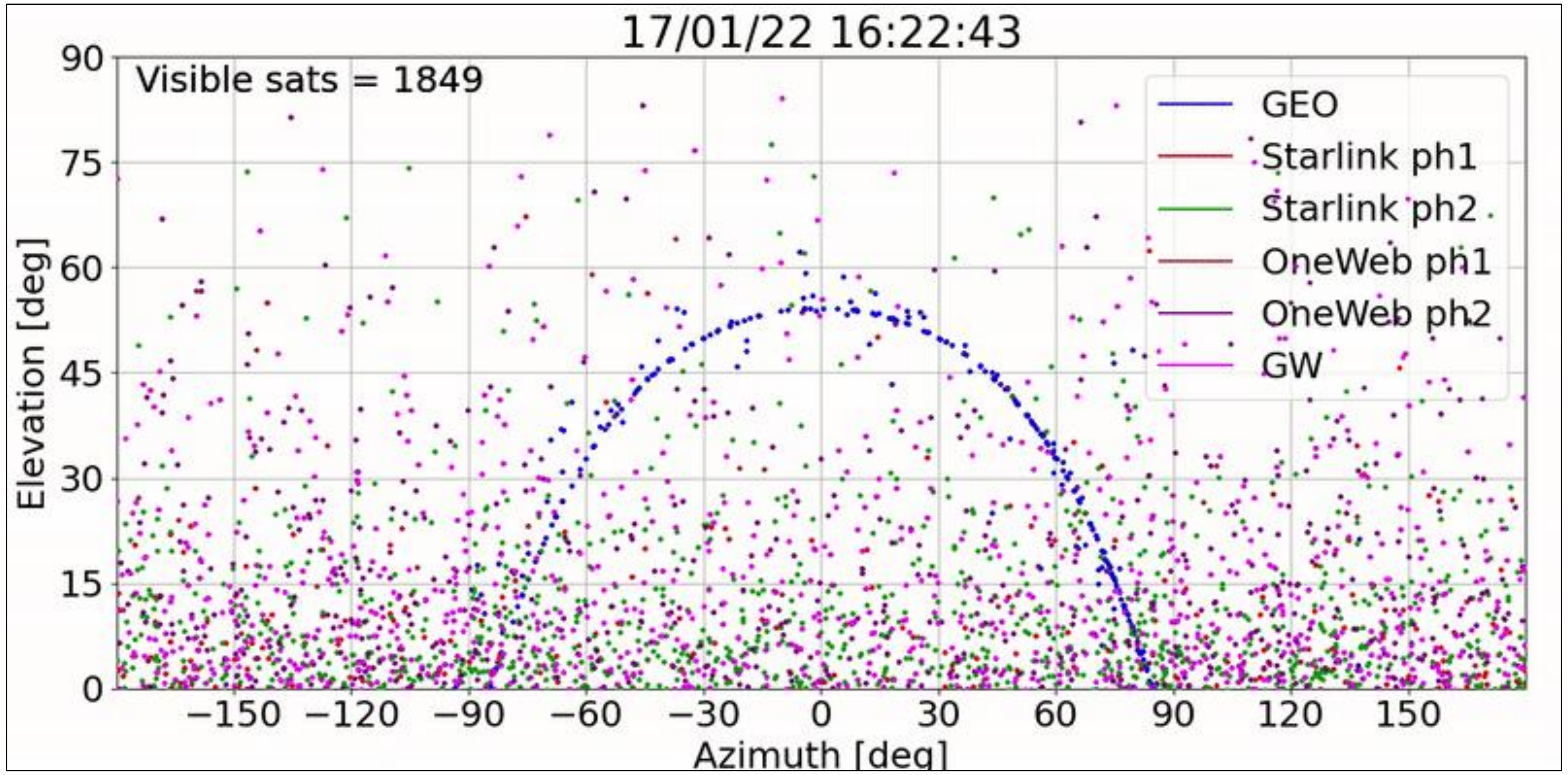


Youtube: [107,000 Planned Satellites by 2029]

Large LEO constellations

- Numbers! Satellites seen from South Africa (Az,el)



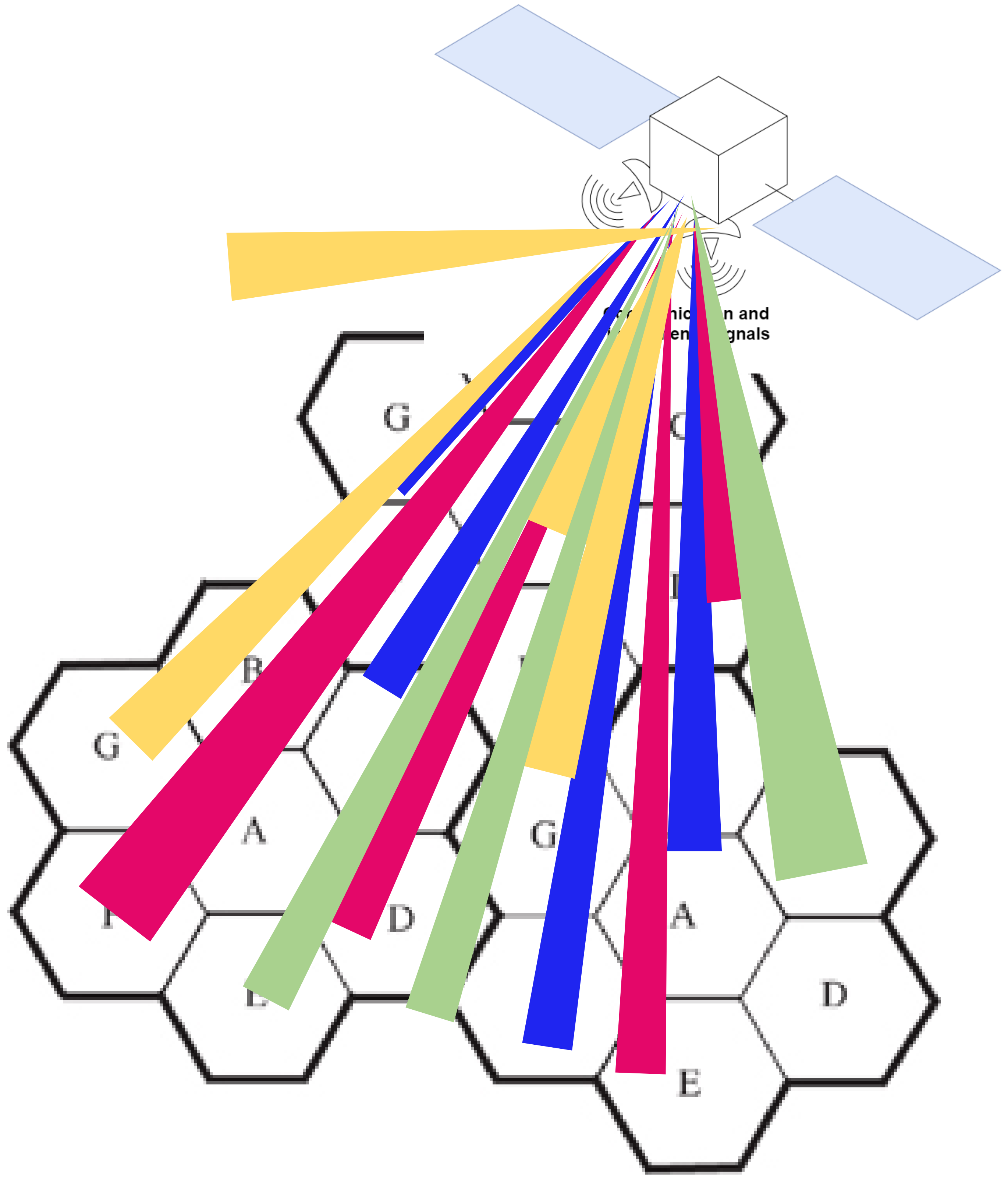


GEO: 35786 km
LEO: 300 – 2000 km

Large LEO constellations
Satellite as transmitters

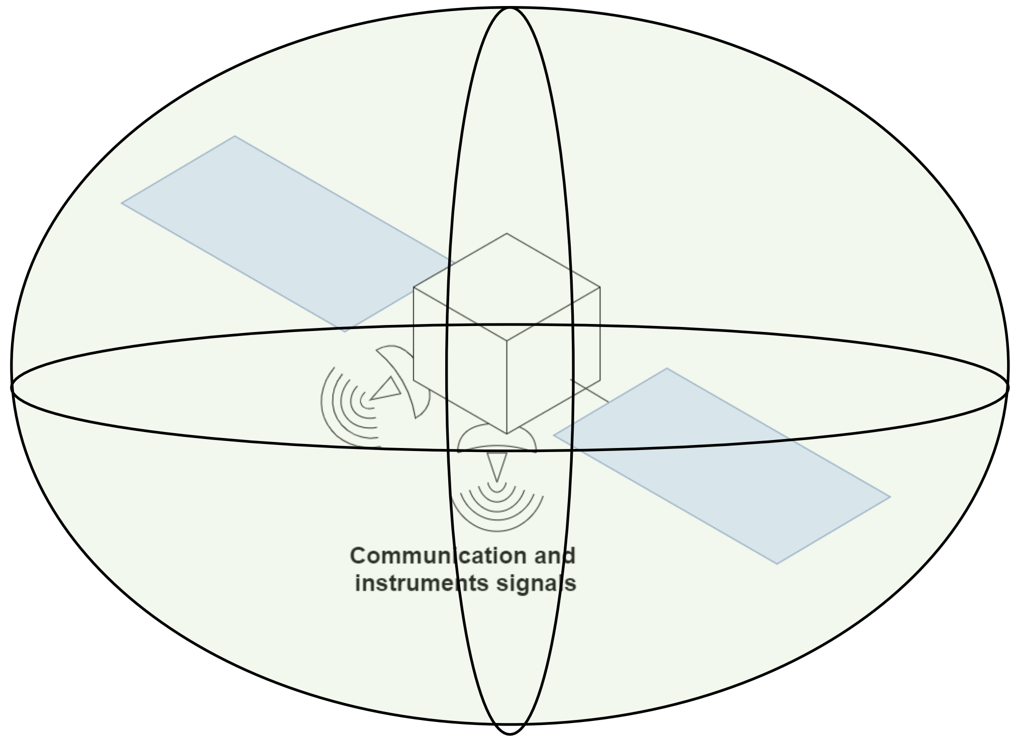
Steerable beams

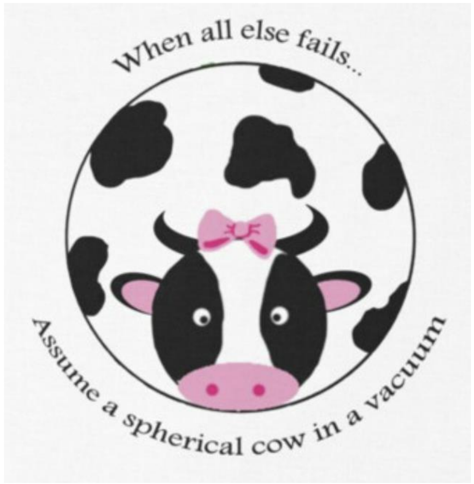
- N channels
- M beams per channel – moving in real time (cell phone tower equivalent)
- Active antenna modelling needed, or probabilistic model



Isotropic model:

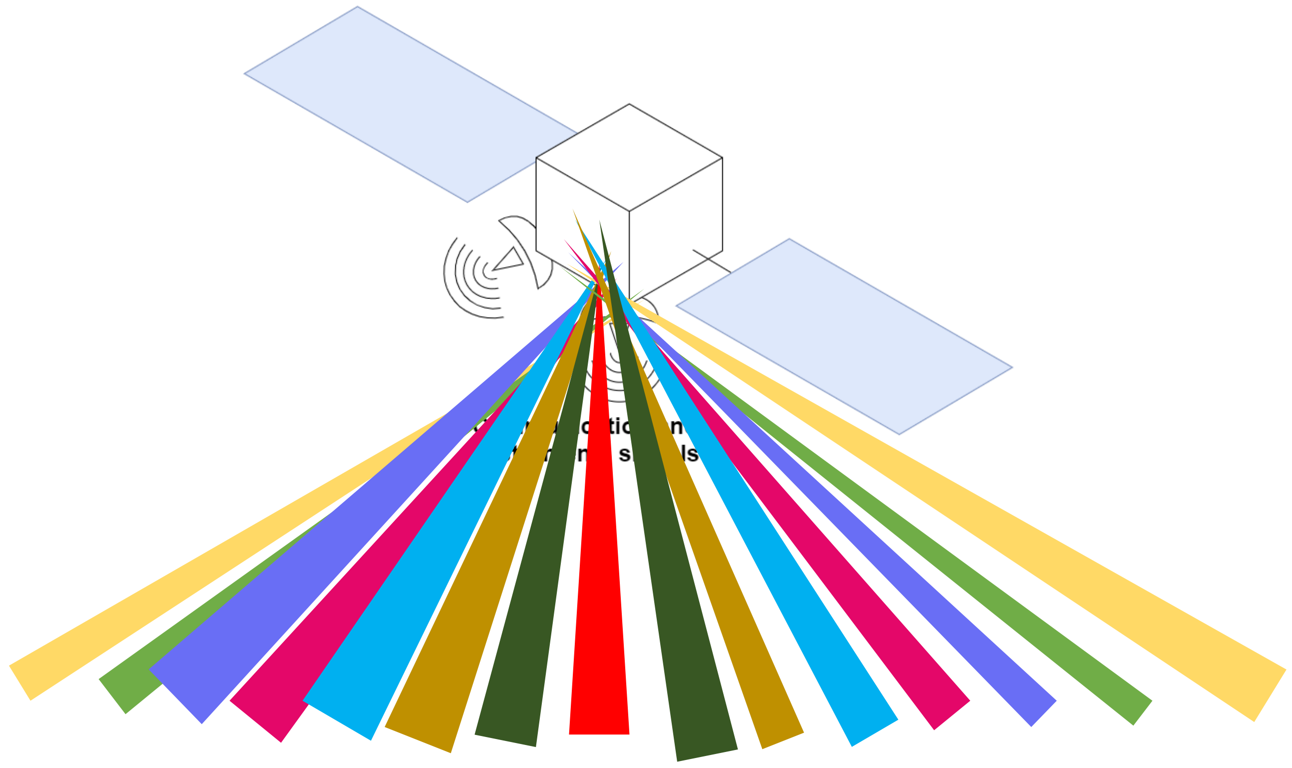
- Seen as a sphere, radiating the EIRP in all directions
- N channels





Fixed beams

- N channels
- M beams per channel (predictable position)

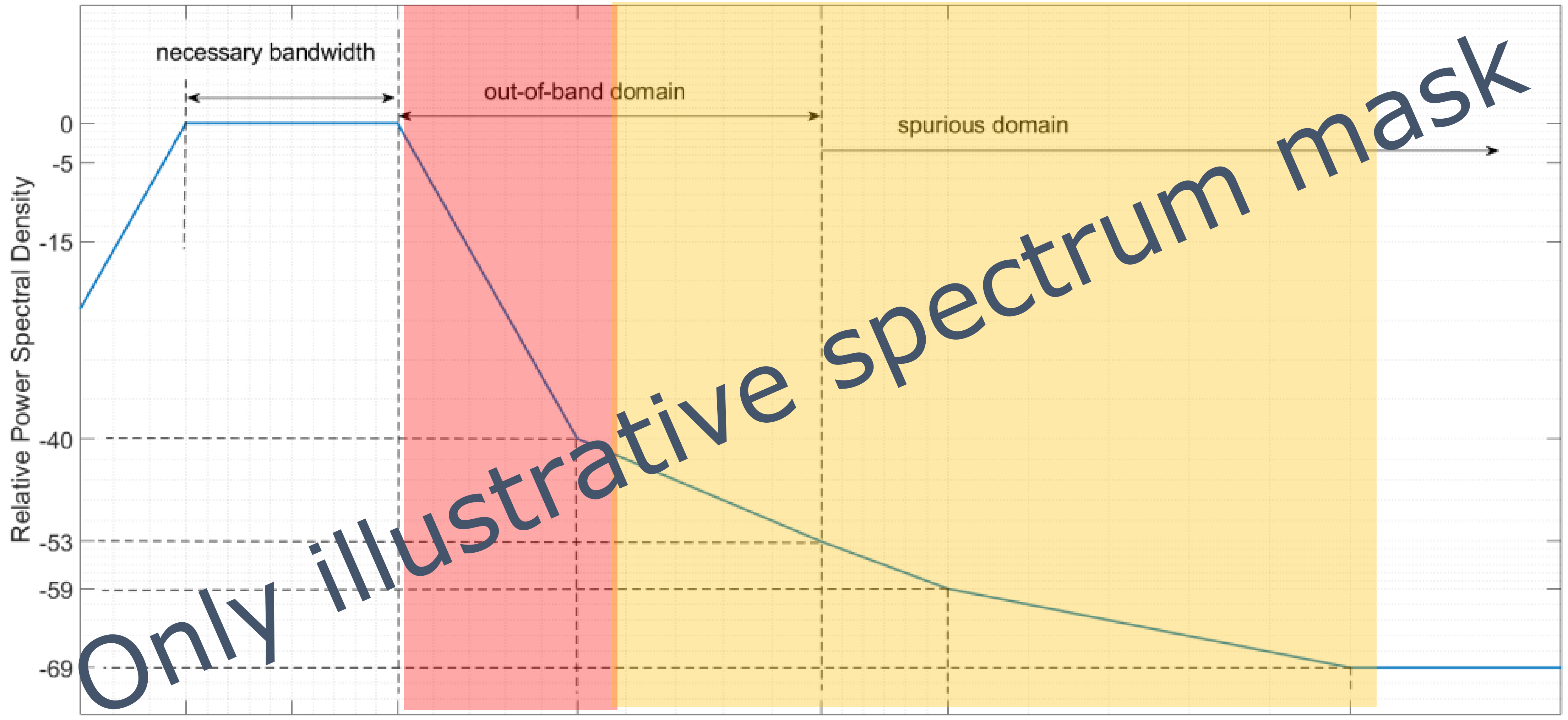


Frequency usage (downlinks)

Planned frequency bands for Internet Satellite Constellations:

Frequency	Band	Use	Protected RAS bands (primary)
10.7 – 12.75 GHz	Ku	Users	(p) 10.6-10.7 GHz
19.7 – 20.2 GHz	Ka	Users/GW	(p) 22.21 – 22.5 GHz
37.5 – 42.5 GHz	V	Gateways	(p) 42.5 – 43.5 GHz
71.0 – 76.0 GHZ	E	Gateways	(p) 76 – 77.5 GHz

Out-of-band emissions:



Adjacent
Near by

Agenda:

What is included:

- Large LEO Constellations
- **Impacts on Radio Astronomy**
- Mitigation Strategies
- Ongoing Efforts

Impacts on Radio Astronomy from Satellite Constellations

I. High power into analog or digital signal chains

II. RFI into the RAS protected bands

III. RFI into wideband observations (even in RQZs)

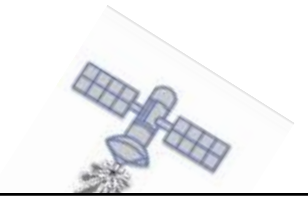
IV. Potential unintentional electromagnetic radiation from satellites (see B. Winkel's talk later!)

V. Impacts on Optical and InfraRed astronomy

I - High power into receivers

- The power flux density of one channel -146 dBW/m² in 4 kHz bandwidth
- In 250 MHz channel represents a power flux of -98 dBW/m²
- Considering direct beam-to-beam coupling :

Diameter [m]	100	60	30	15
Gain [dB] eta=60% f = 11 GHz	79	75	68	62
Effective Area [m²]	4712	1700	424	106
P_{rx} [dBW]	-31	-36	-42	-47



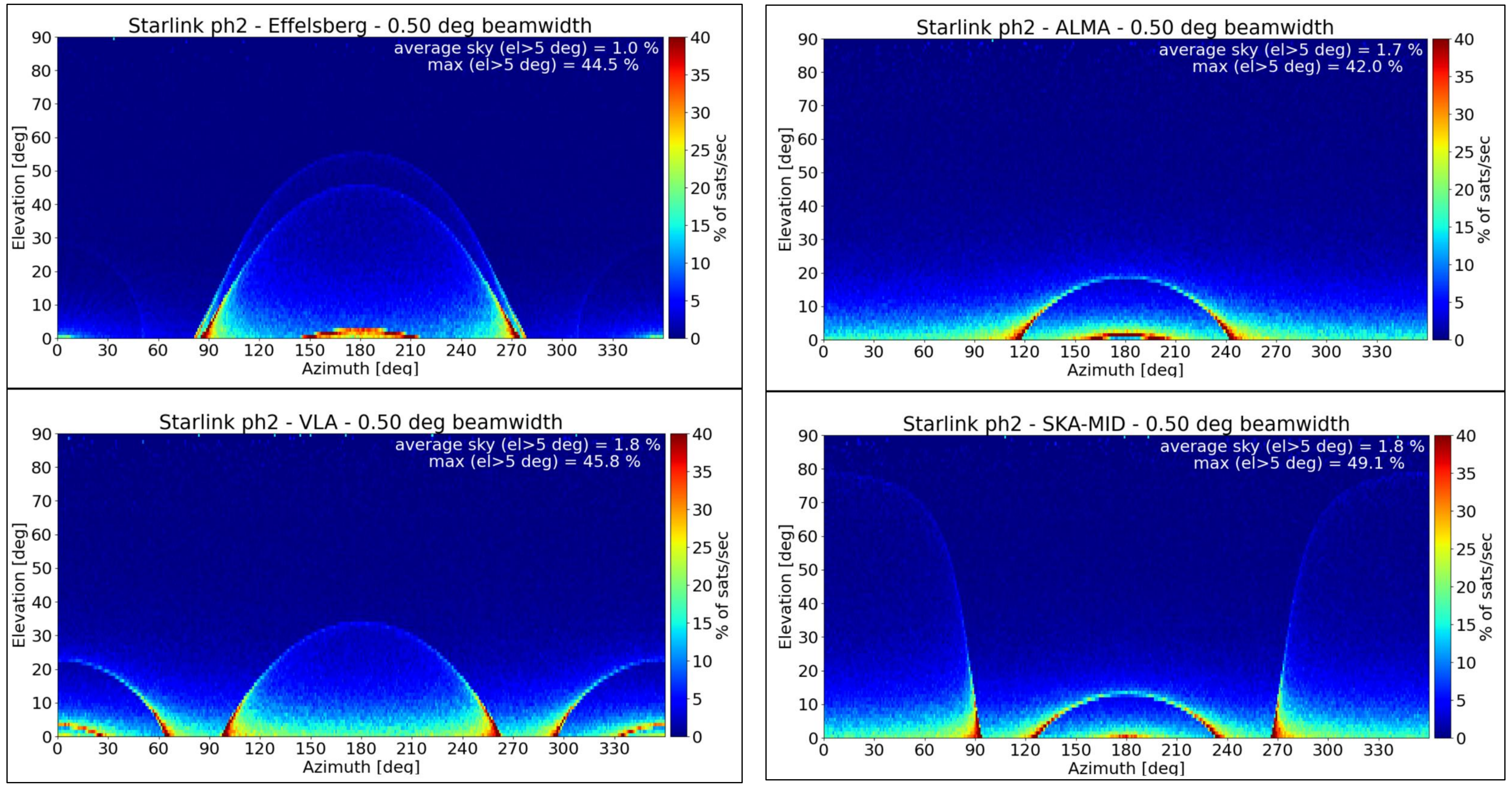
Receiver with 20 K system temperature in 250 MHz:

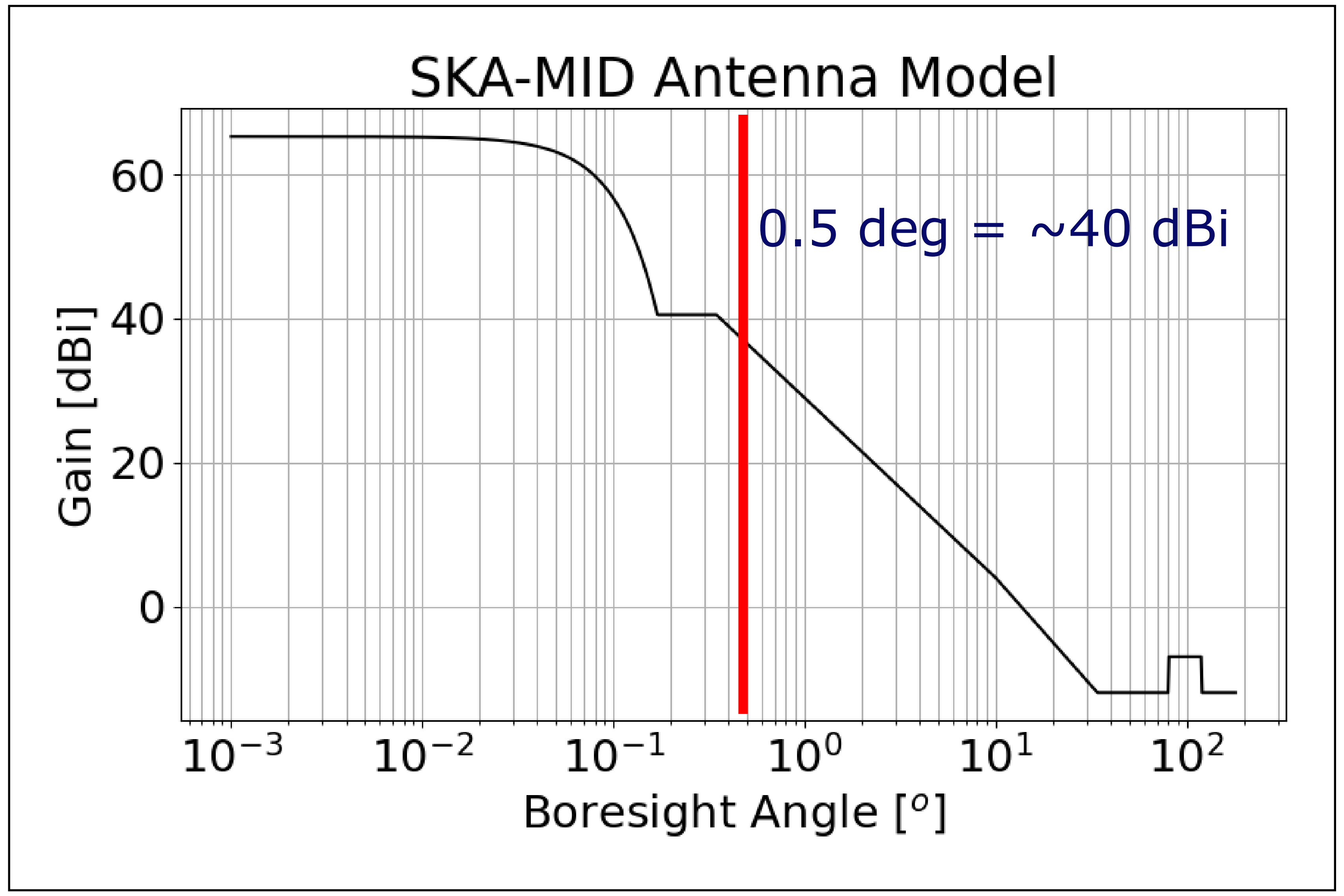
P_{noise} = -101 dBm

> 50 dB of dynamic range for RFI

If my beam is 1 deg across, 20dB (or more) less Gain, how many **satellites/second** will I see?

Starlink ph2
N=30000





Antenna model based on Recommendation ITU-R RA.1631

II- RFI into protected RAS bands

Satellite band		Protected RAS bands (primary)
10.7 – 12.75 GHz	Users	(p) 10.6-10.7 GHz
19.7 – 20.2 GHz	Users/GW	(p) 22.21 – 22.5 GHz
37.5 – 42.5 GHz	Gateways	(p) 42.5 – 43.5 GHz
71.0 – 76.0 GHZ	Gateways	(p) 76 – 77.5 GHZ

- Out of band emissions into RAS bands
- Max interference thresholds defined in Rec. ITU-R RA.769
- Rapidly moving satellites in the local sky, aggregation of all is calculated through an epfd* calculation (Rec. ITU-M.1584-3)
- ECC report 271 studied OneWeb and Starlink phase 1 (adjacent to the 10.6-10.7 GHz band)
    - High data loss in some regions of the sky but compliant to total data-loss requirement (**condition not to use the first 250 MHz**)
- Other bands and other operators will conduct these studies…?
- **Verification?** Remember IRIDIUM case with 66 sats

*epfd: equivalent power flux density

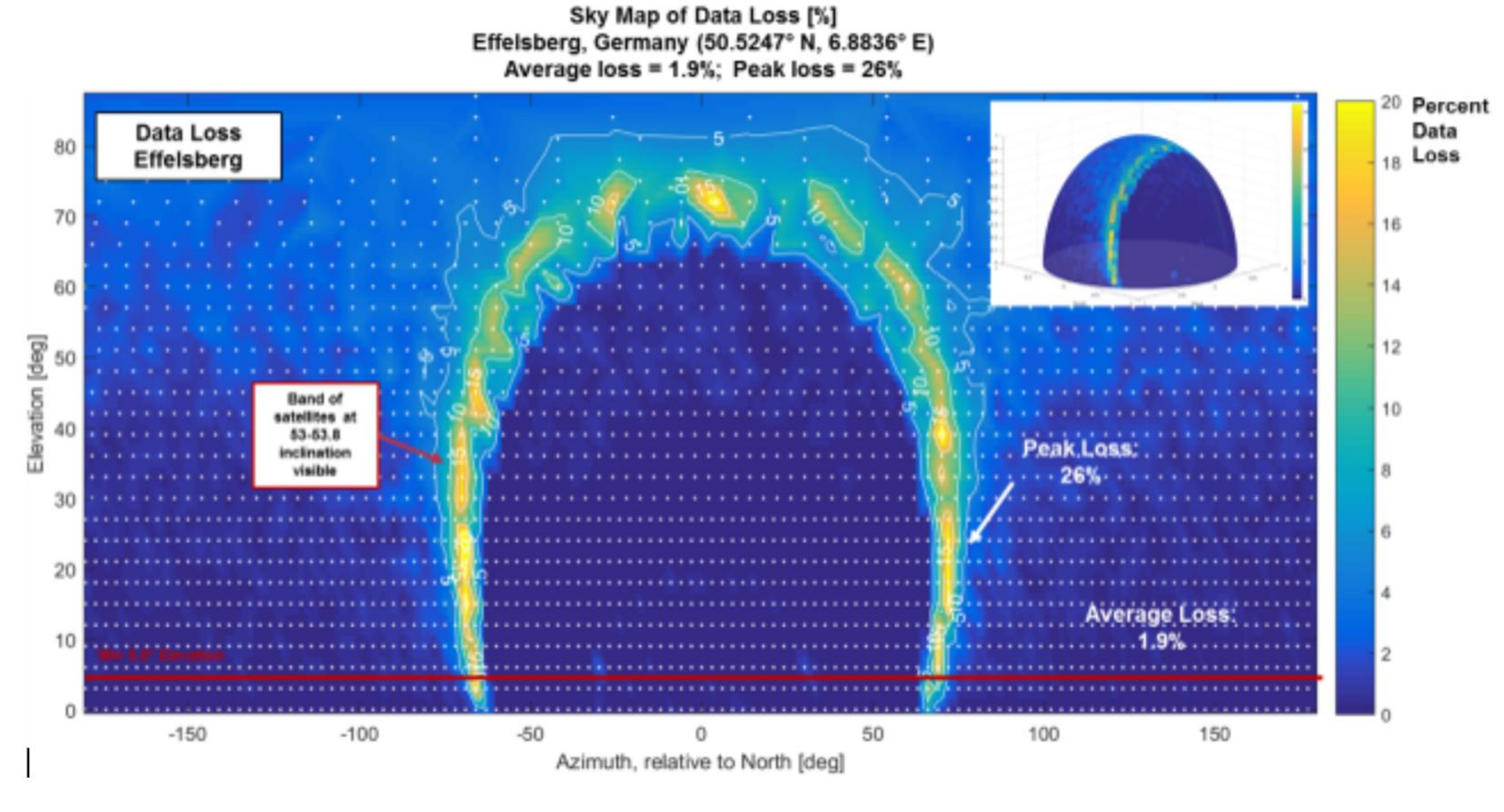


Figure 64: Effelsberg – Sky Map of Percent Data Loss

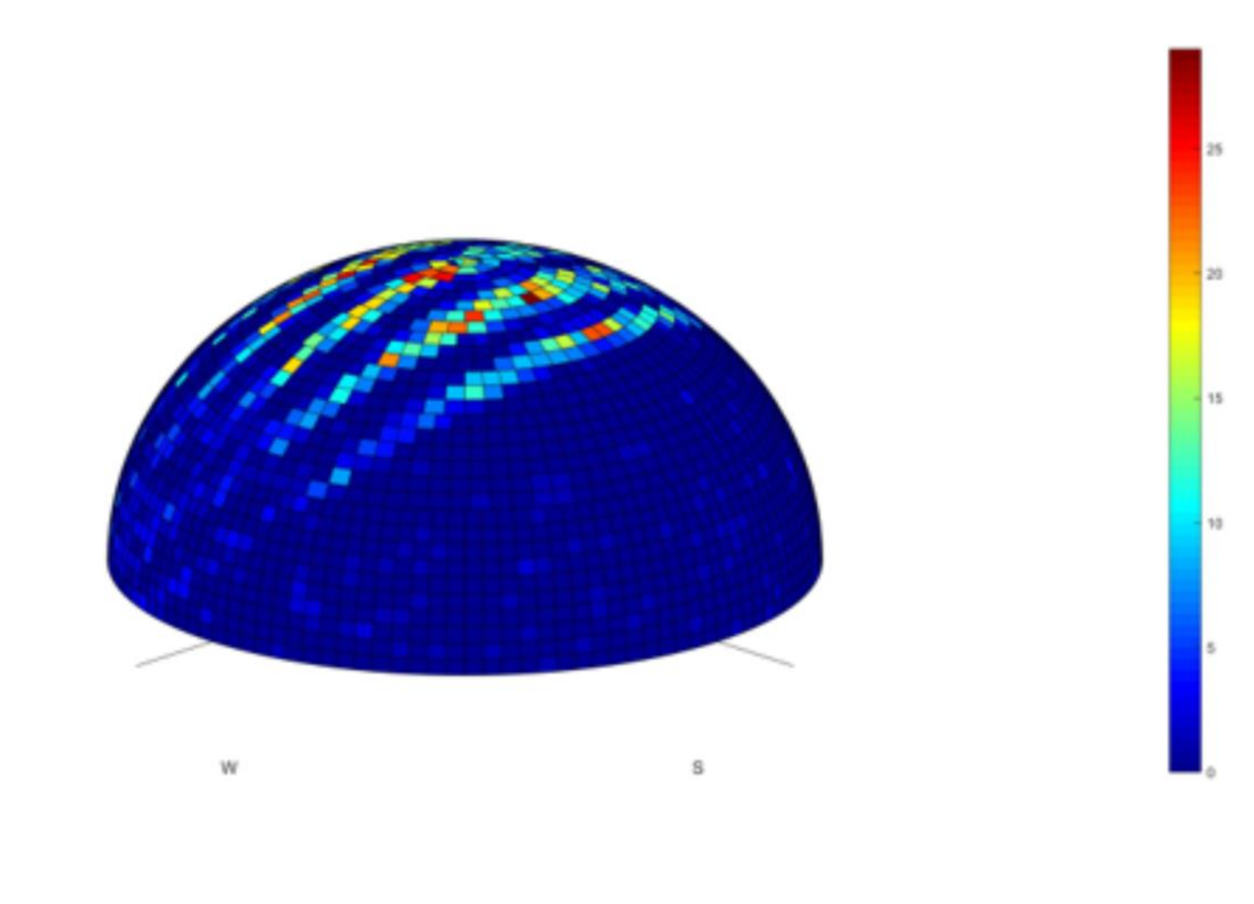


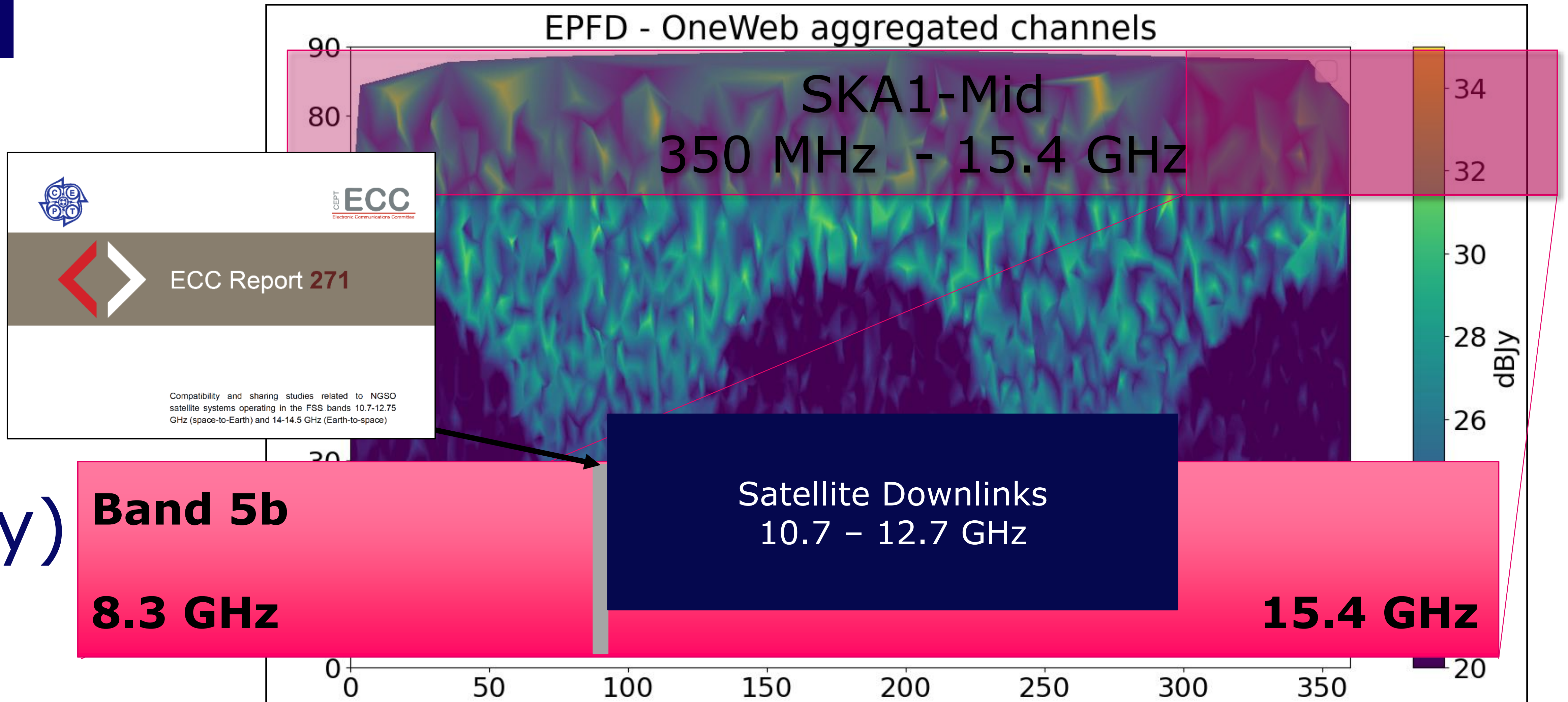
Figure 14: Plot of the data loss over sky

Data loss in 10.6-10.7 GHz band. Starlink #1 (top), OneWeb #1 (bottom). ECC report 271

III- Implication for wideband observations

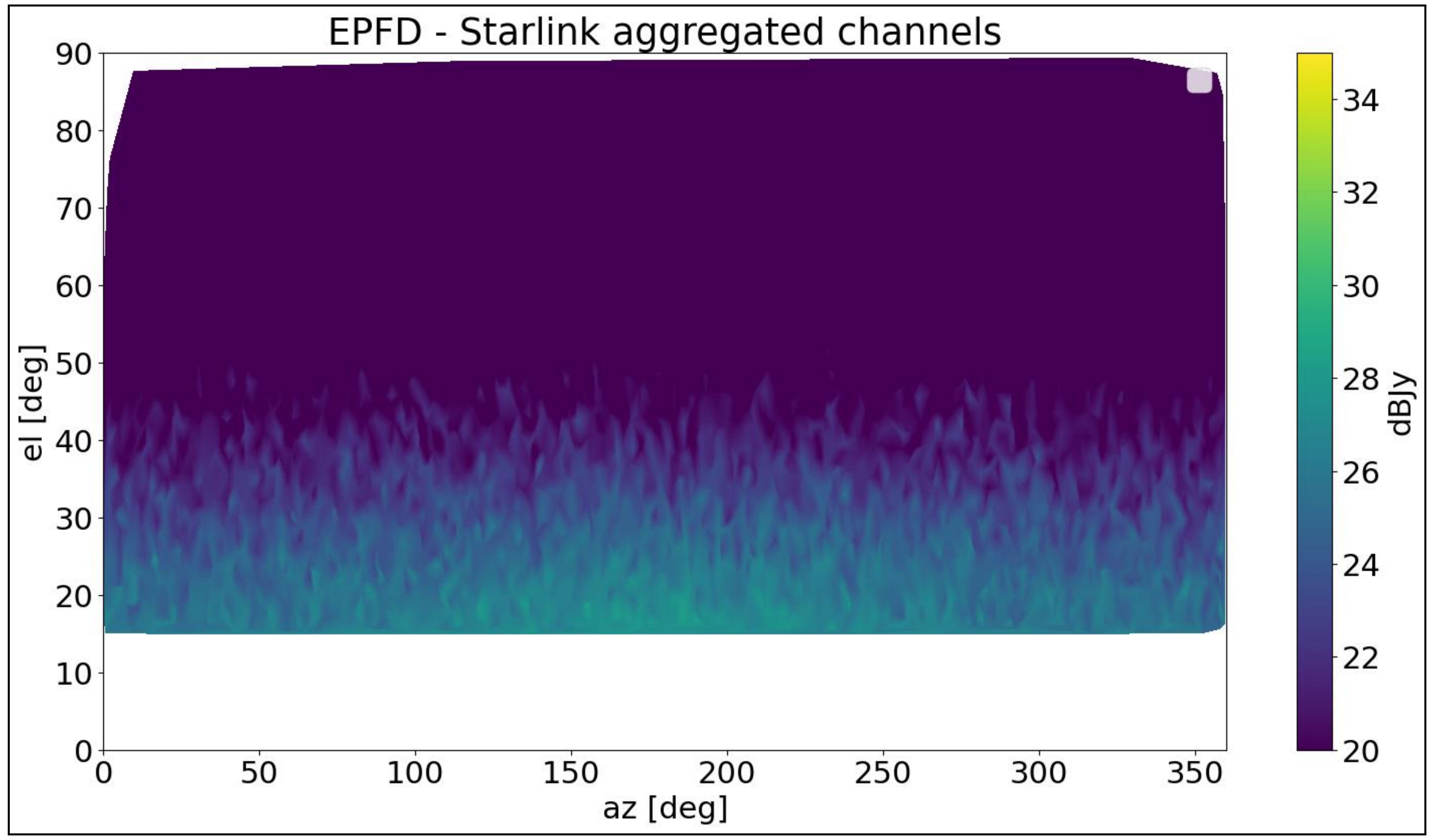
- In-band signals, much higher power
- Strong RFI could temporarily saturate a receiver (<1s but depends on satellite density)
- Example:
  - EPFD calculation in the SKA-Mid telescope.
  - Average RFI received about 30 dB higher than strong radio sources (without any mitigation).
  - Mitigations at telescope and operator level are possible. Some national protections are granted to telescopes in Europe and US

Source code: https://gitlab.com/ska-telescope/rfims/ska-rfi-satellites
Orbit propagations: https://github.com/bwinkel/cysgp4



Frequency coverage of SKA-Mid B5b (blue), RAS protected band in 10.6-10.7 GHz (green) and satellite downlinks (red)

Average EPFD for OneWeb ph1 constellation. All channels are included in the same plot. (15 deg is the minimum elevation of an SKA antenna)

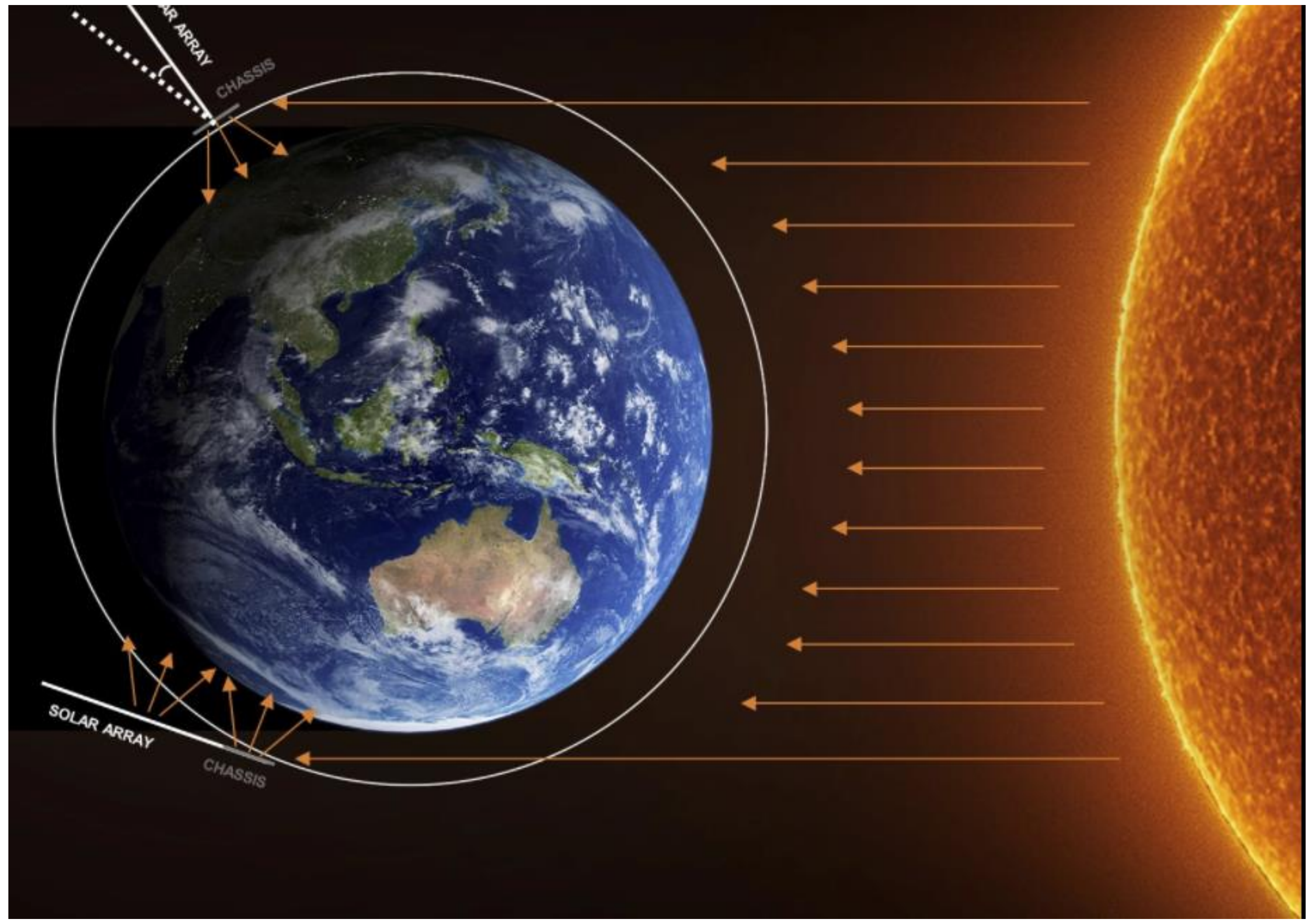


Average EPFD for Starlink ph1 constellation.

See Benjamin Winkel’s talk later today!!!

V - Impacts to OIR astronomy

- Specular surfaces on the satellites reflect sunlight low on the horizon and in twilight
- Can be brighter than most stars in the night sky, affecting wide field of view instruments
- There is no regulatory framework for this effect, can potentially have even larger implications for wildlife
- Ongoing engagement with industry to mitigate satellite brightness (Starlink Darksat and Visorsat)



Satellites reflect sunlight, especially in dawn and dusk
Credit: Starlink

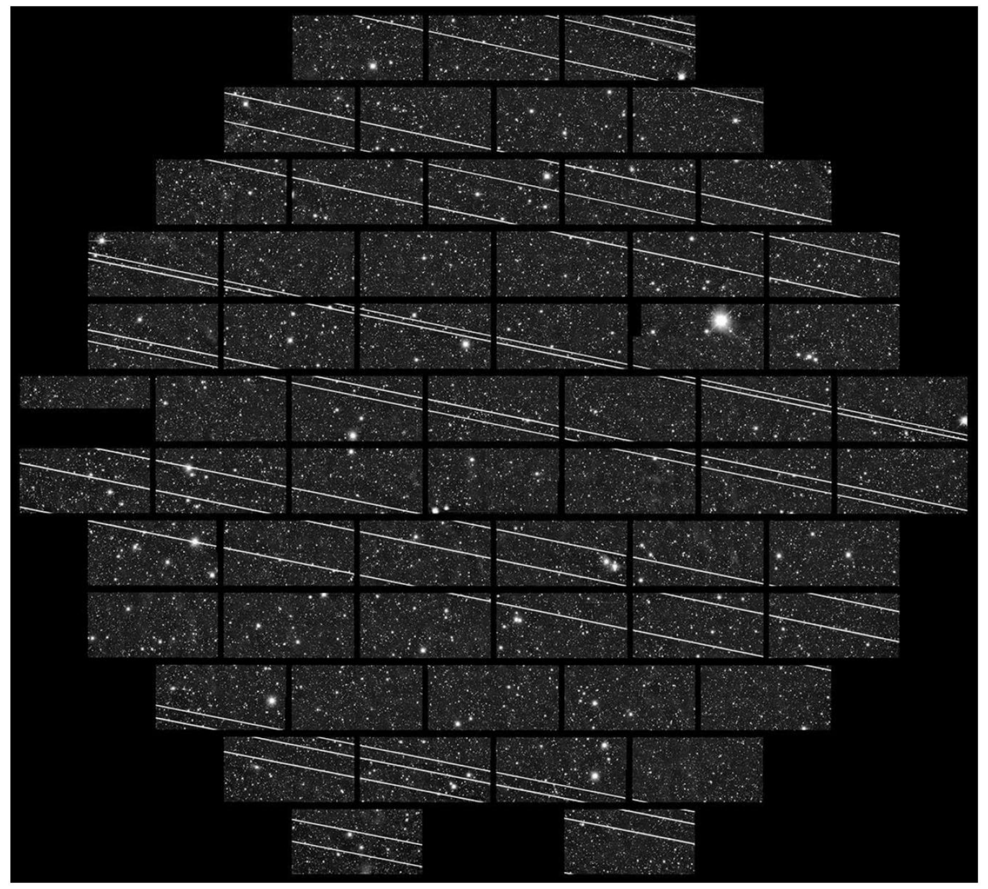


Figure A.1. A wide-field image (2.3 degrees across) from the Dark Energy Camera on the Víctor M.

Wide field image affected by streaks (left), Orion with satellite steaks (right)

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Mitigation strategies

- Satellite RFI is not a new situation for **Radio Astronomy**
  I. Satellite predictors: Planning and masking
  II. Online and post-processing RFI detection and flagging
  III. Interferometers will be less affected (>10km baselines)

- **Regional regulatory groups** conducted studies and implemented protections (e.g. ECC Decision 17(04))

- **National regulators** included conditions in licenses to mitigate negative effects on radio telescopes (Germany[1] and Spain)
  - No 10.95-12.75 GHz downlinks in a radius of 12.5 km from the Observatory
  - No use of 14.47-14.5 GHz uplink in a defined contour

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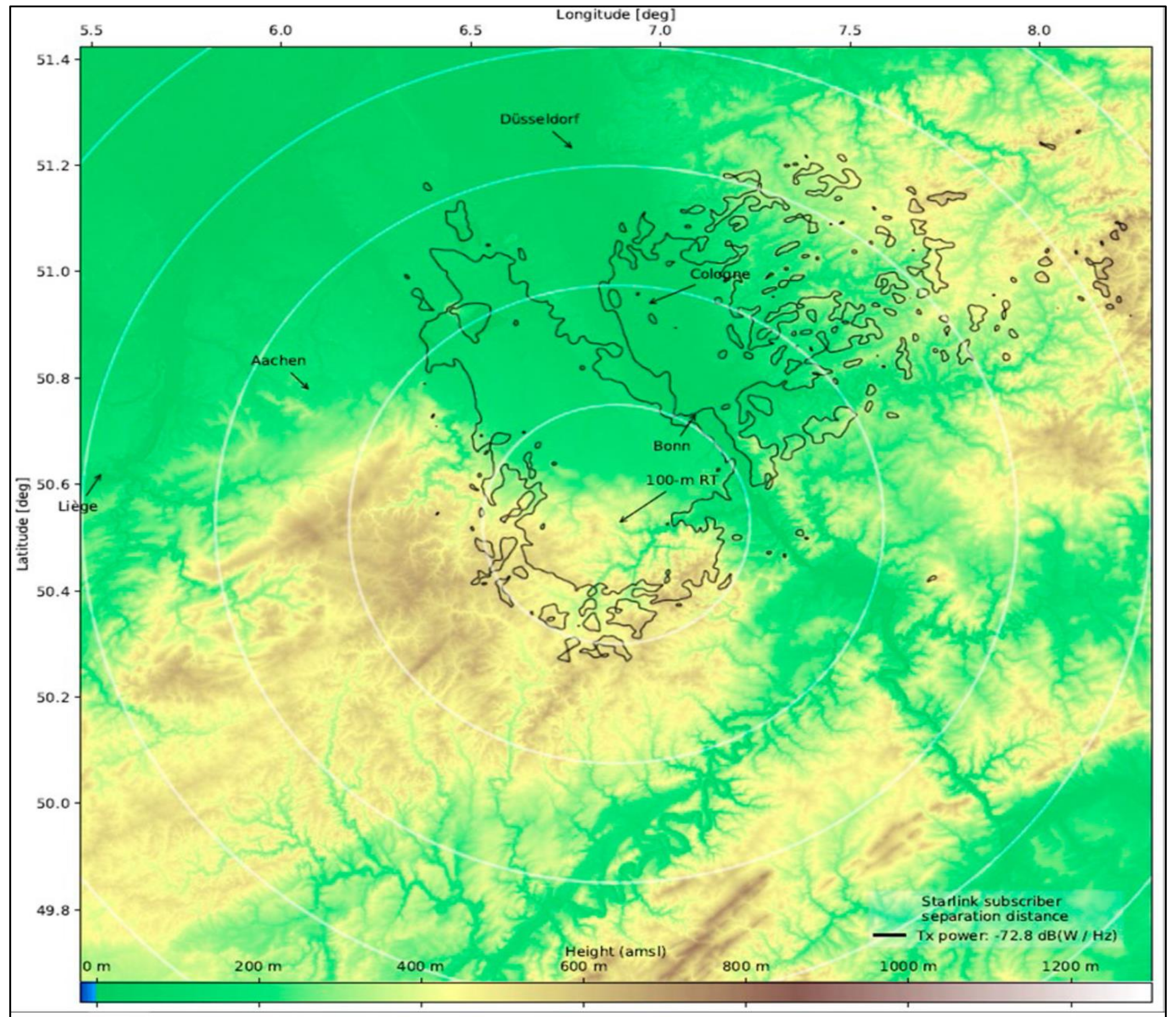

Abbildung 1
(Hinweis: Die weißen Ringe befinden sich in n x 25 km Abstand um die RAS-Station in Effelsberg)

https://www.bnetza-amtsblatt.de/download/73

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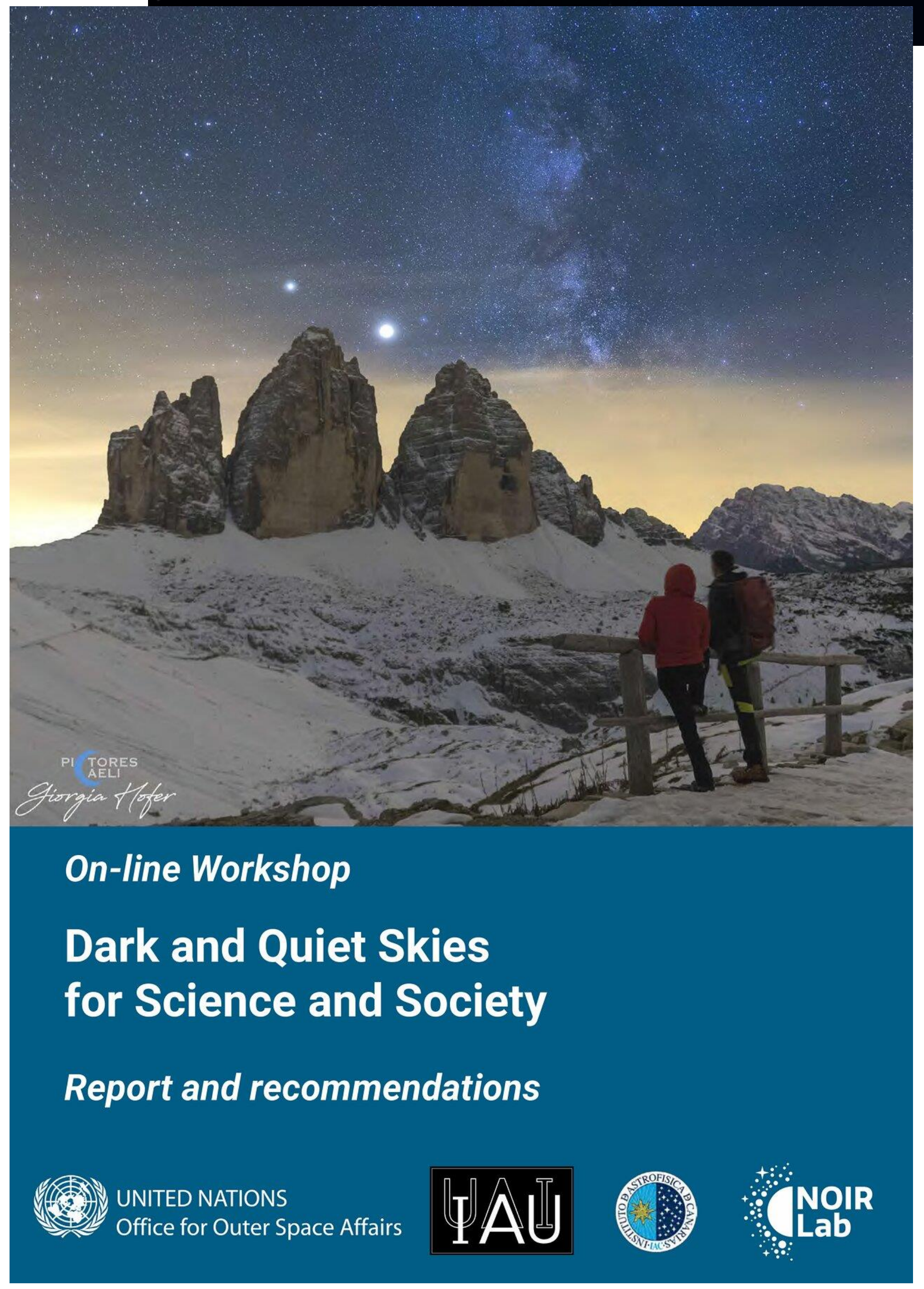
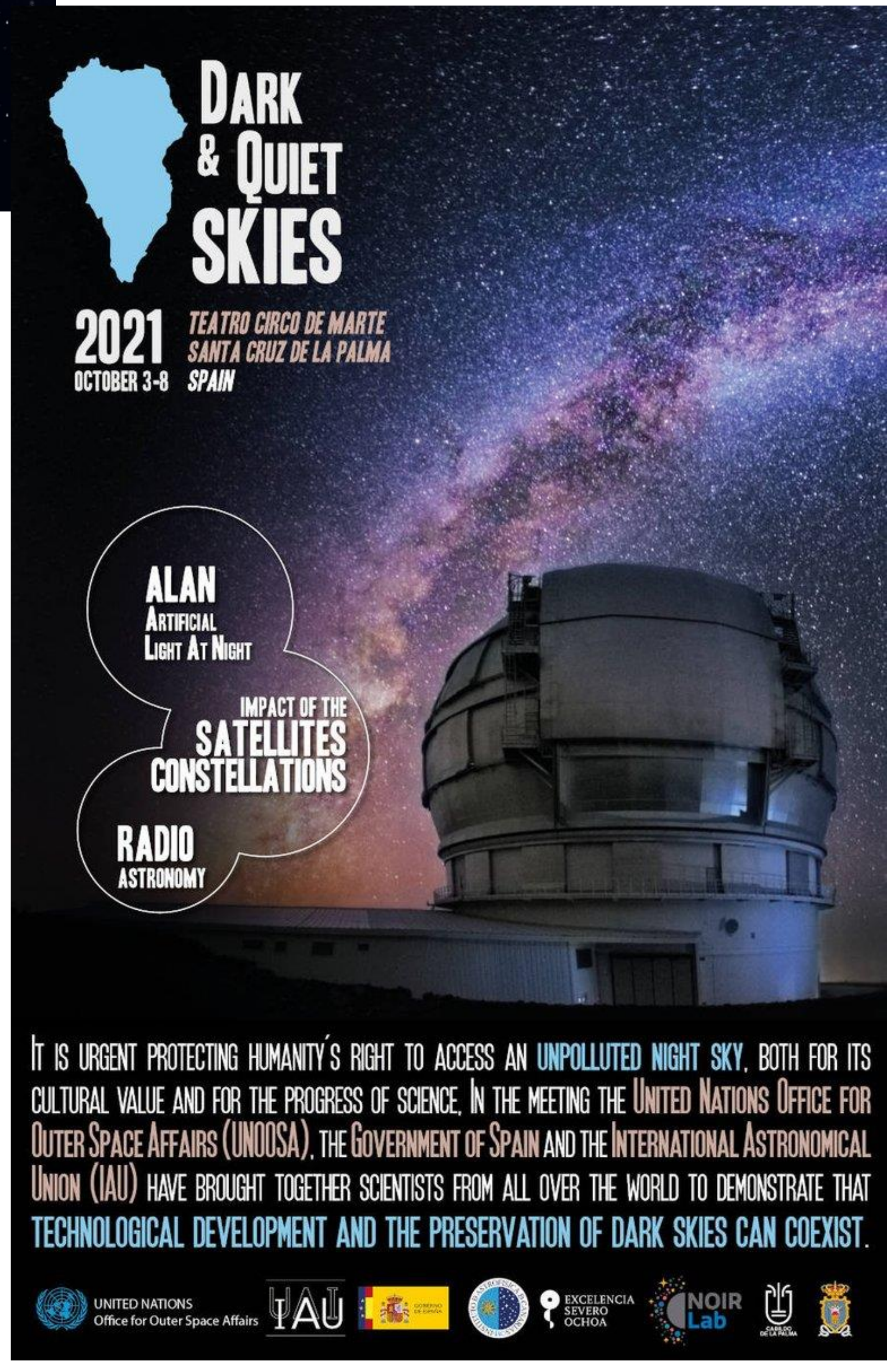
Ongoing efforts in the community

- The astronomical community has self organized in several workshops, started with US initiatives and then became global with the sponsorship of UN Office of Outer Space Affairs (UN OOSA)
- Not only the effects of Satcons on astronomy were discussed, but wider effects such as the modification of the night sky as human heritage
- Technical mitigations:
  - Software: orbital predictions, observation planning, post observation detection and flagging
  - Hardware mitigations at telescope and satellite level
- Policy developments:
  - At ITU where RAS is represented since long (only RAS bands)
  - Several papers into UN COPUOS* regarding the effects of Satcons





*UN COPUOS: United Nations Committee on the Peaceful Uses of Outer Space

Ongoing efforts in the community

- Efforts from the IAU and astronomical community have obtained for the first time a dedicated agenda item in the STSC* of UNCOPUOS about **“Dark and Quiet Skies” (earlier today!)**

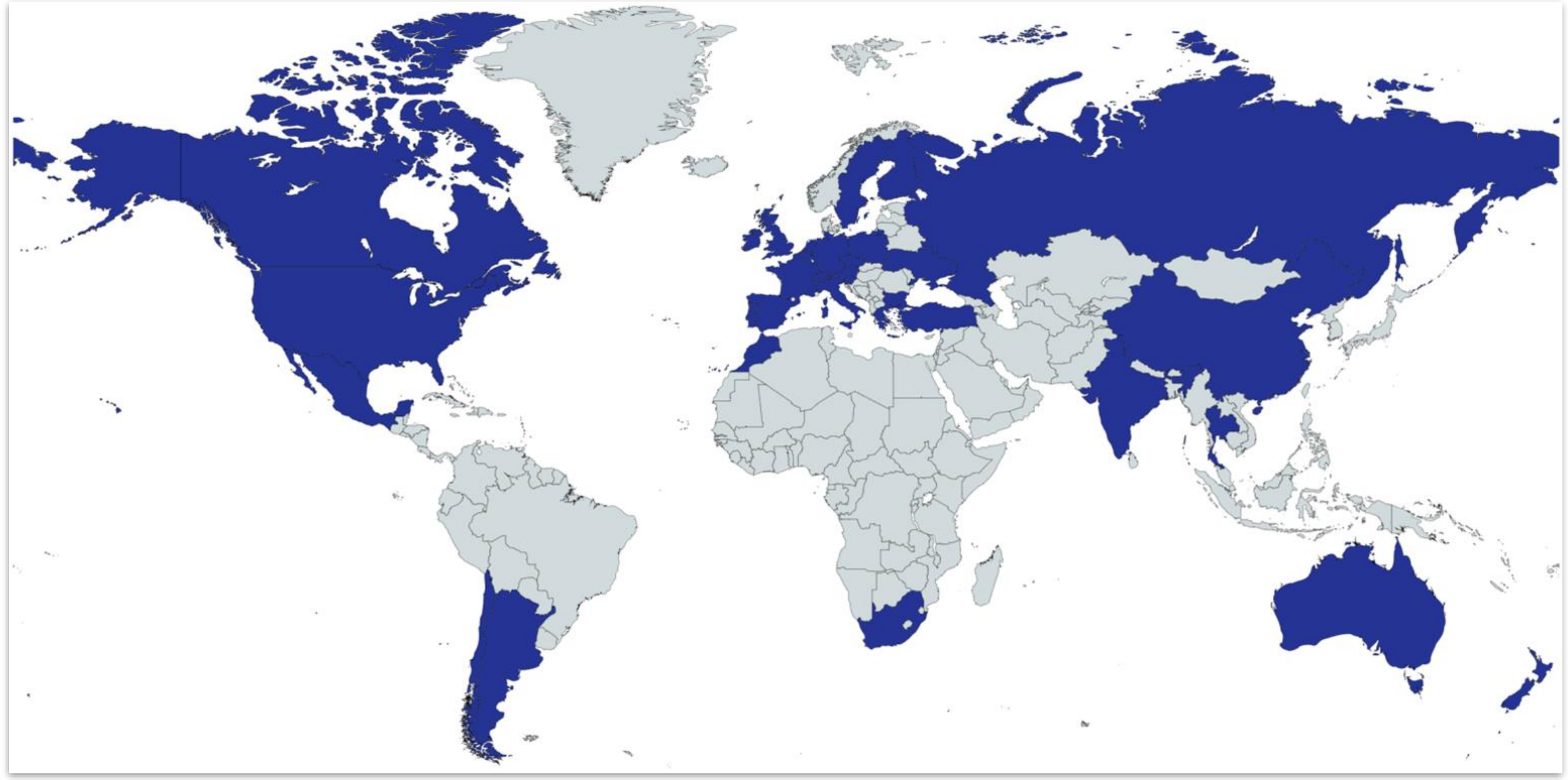
- **Countries expressing their opinions about how space activities affect the D&QS**

- Creation of an **IAU Centre for the protection of the Dark and Quiet Sky from Satellite Constellation Interference**

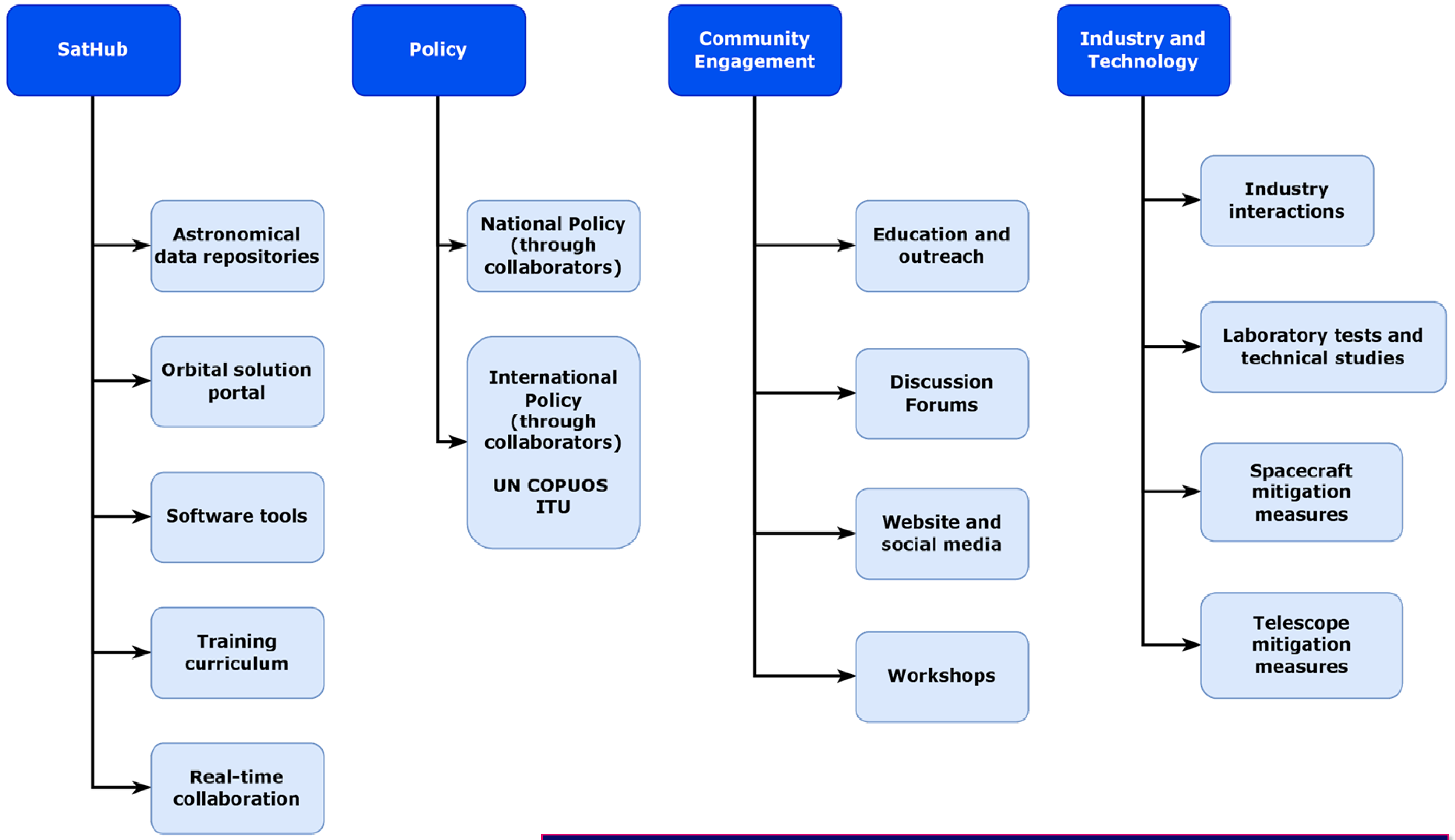
*STSC: Scientific and Technical Sub Committee

IAU Centre for the protection of the Dark and Quiet Skies from satellite constellations

- SKAO + (NSF's) NOIRLab
- Coordinate the efforts in mitigation of negative effects
- 76 letters of support from Institutions & individuals



Four Hubs:



Interested? Find me during the break:
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Thank you for listening! Questions?

federico.divruno@skao.int

MeerKAT L-Band Milky Way centre
SARAO, Heywood et al. (2022) / J.C. Muñoz-Mateos

EXTRA SLIDES

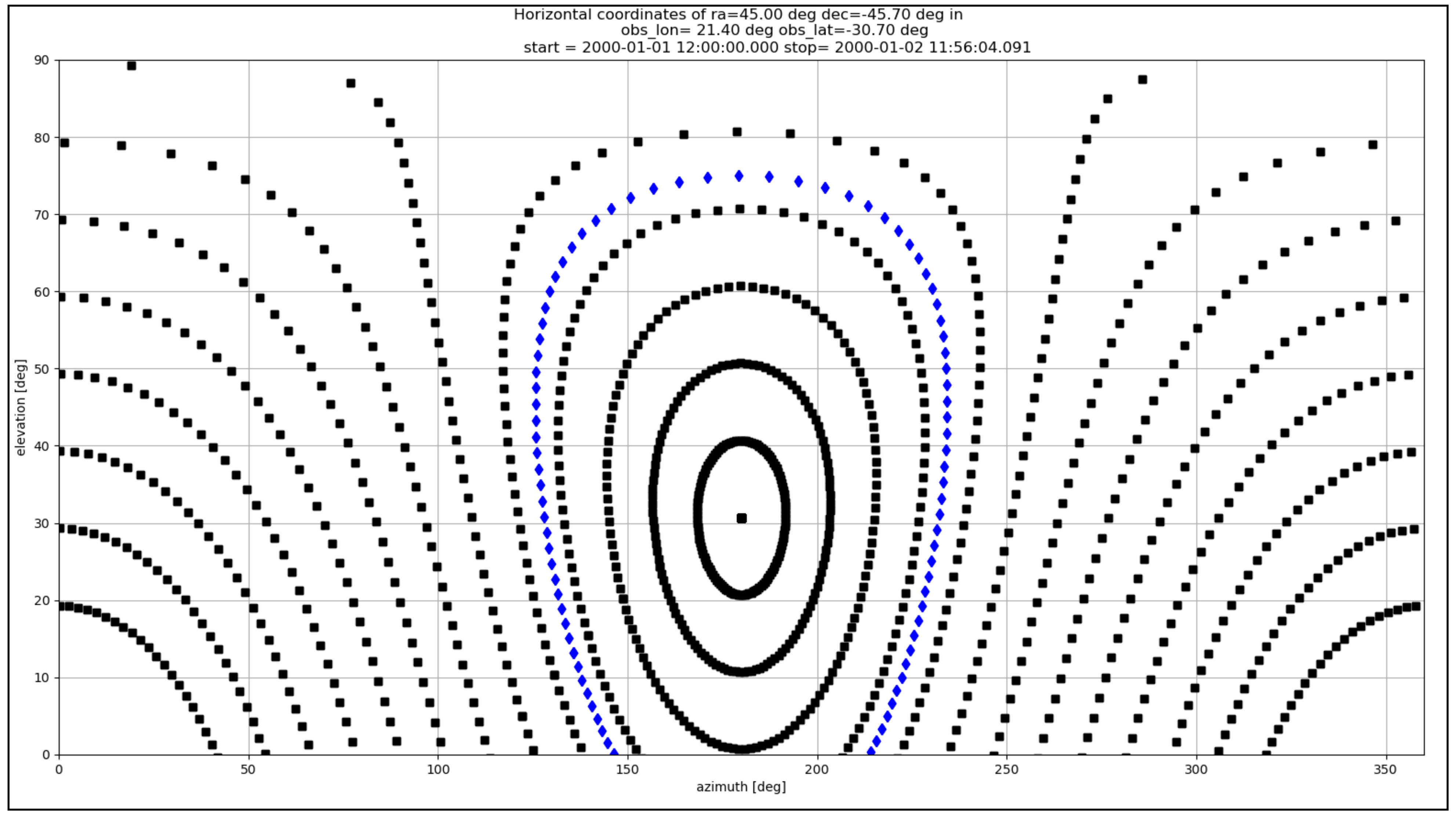
We recognise and acknowledge the Indigenous peoples and cultures that have traditionally lived on the lands on which our facilities are located.

SKAO

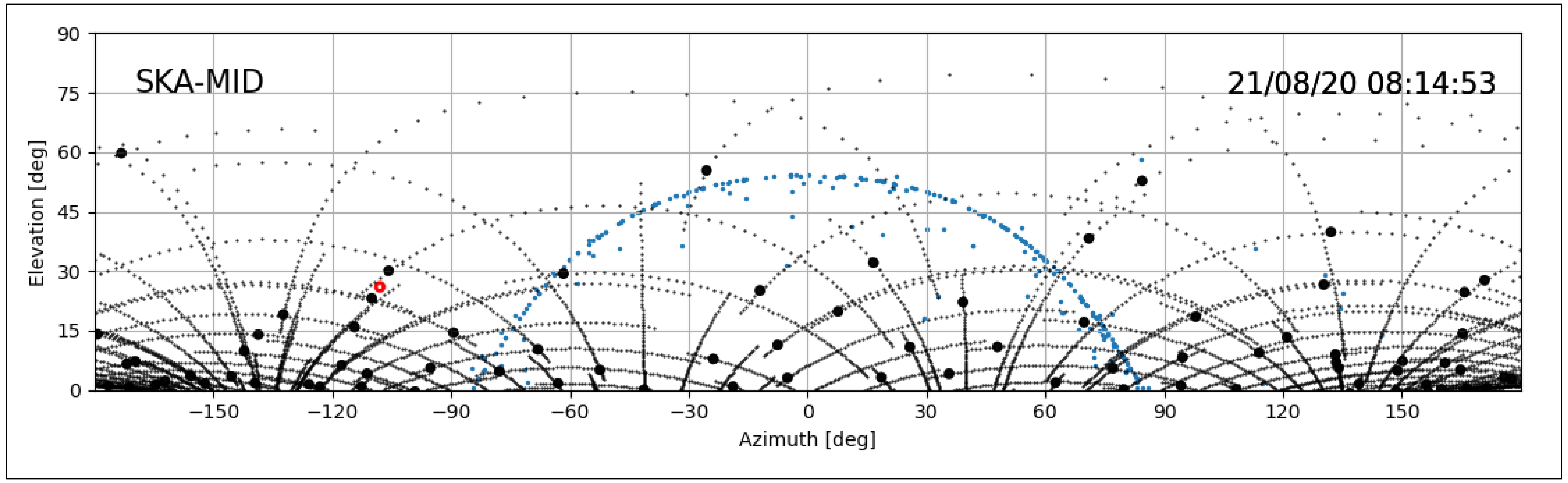
www.skao.int

SKA Mitigation measures
No 1: Prediction tool

- Satellite prediction tool to minimize observing in high RFI zones
- The predictor will also be able to identify moments where a satellite was in the main beam
- Needs high accuracy TLEs



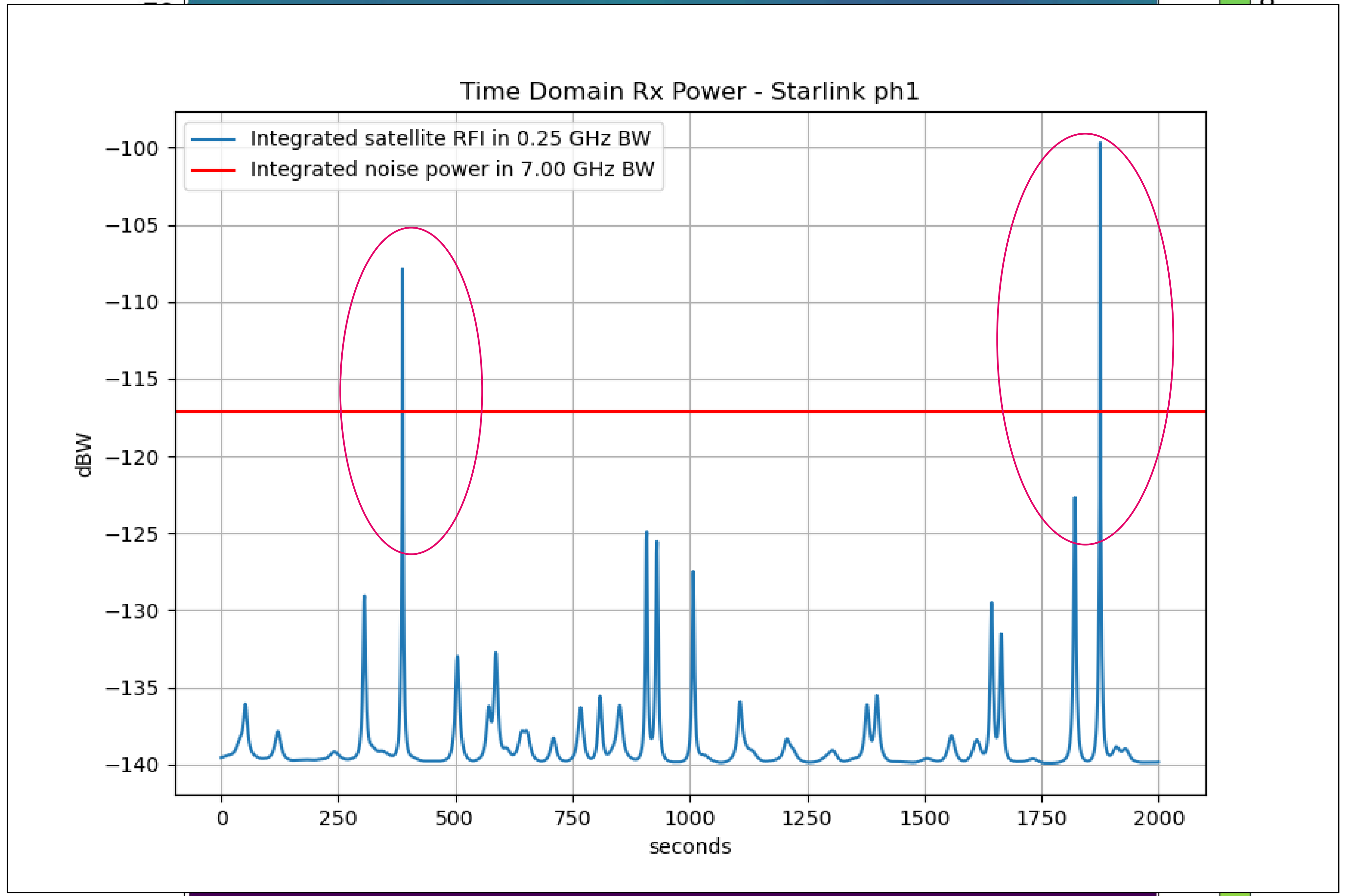
Projection of the celestial sphere in the South African sky in steps of 10 deg, Pictor A locus in blue (dec aprox -45 deg)



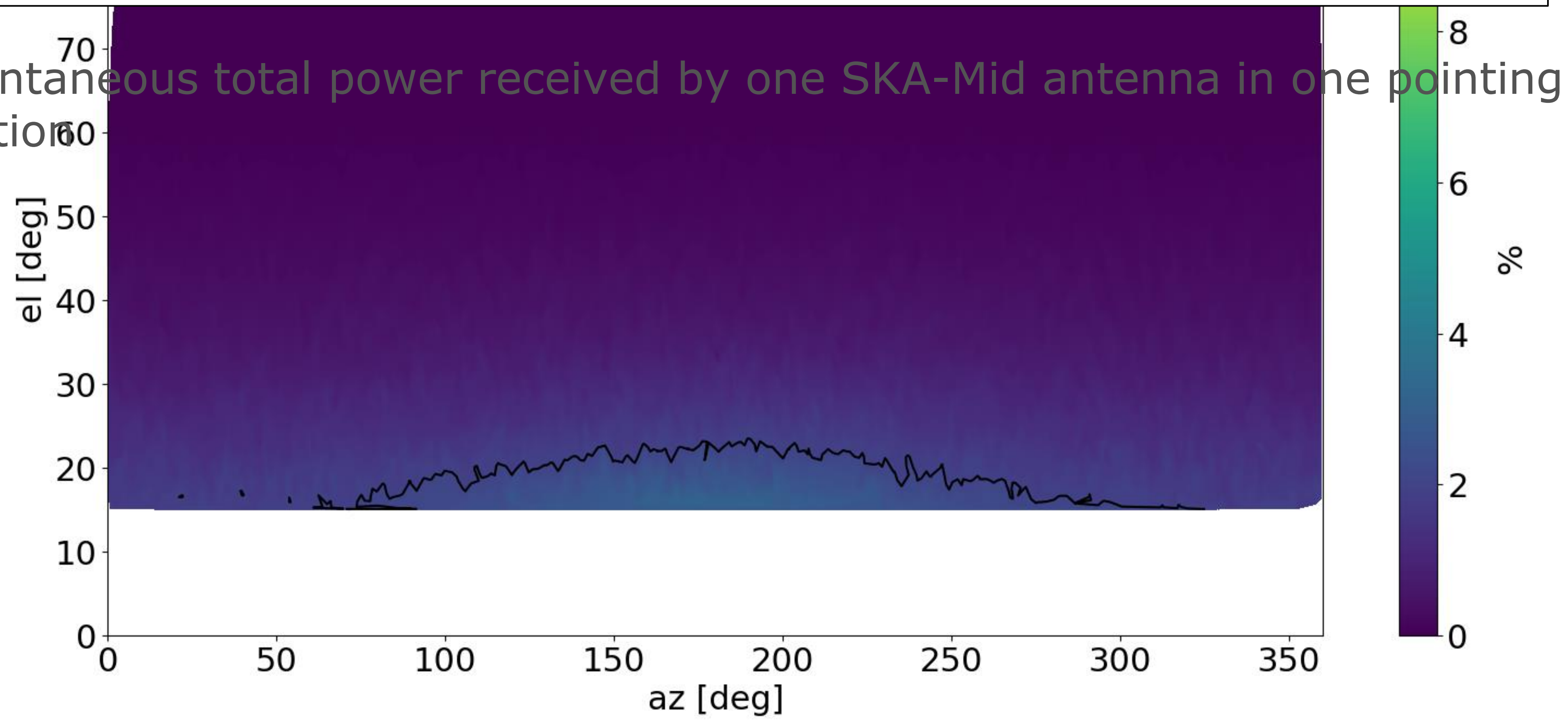
Real time tool showing geosynchronous satellites (blue) and Starlink satellites (black dots). Small black dots are projected trail in 30 minutes.
Credit: M. Bautista and B. Winkel

SKA Mitigation measures
No 2: RFI flagging and excision

- RFI detection and flagging (different timescales and BWs)
- Can avoid strong RFI events corrupting the integrated visibilities
- Flagged data represents a loss in observing time and bandwidth
- For Starlink phase 1 and OneWeb phase 1 **combined**, flagging due to high power events is estimated < 4% of the time in any direction in the South African sky



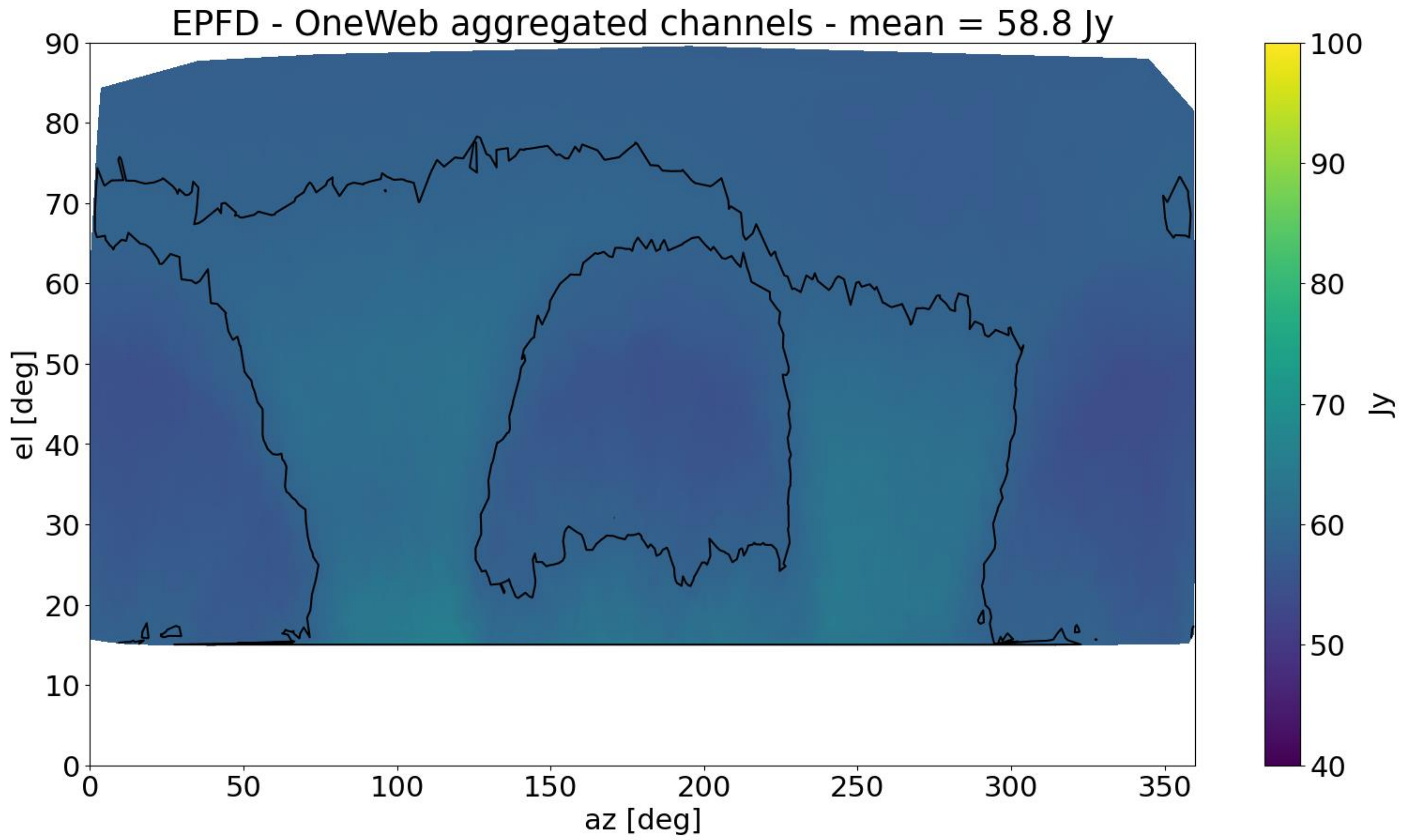
Instantaneous total power received by one SKA-Mid antenna in one pointing direction



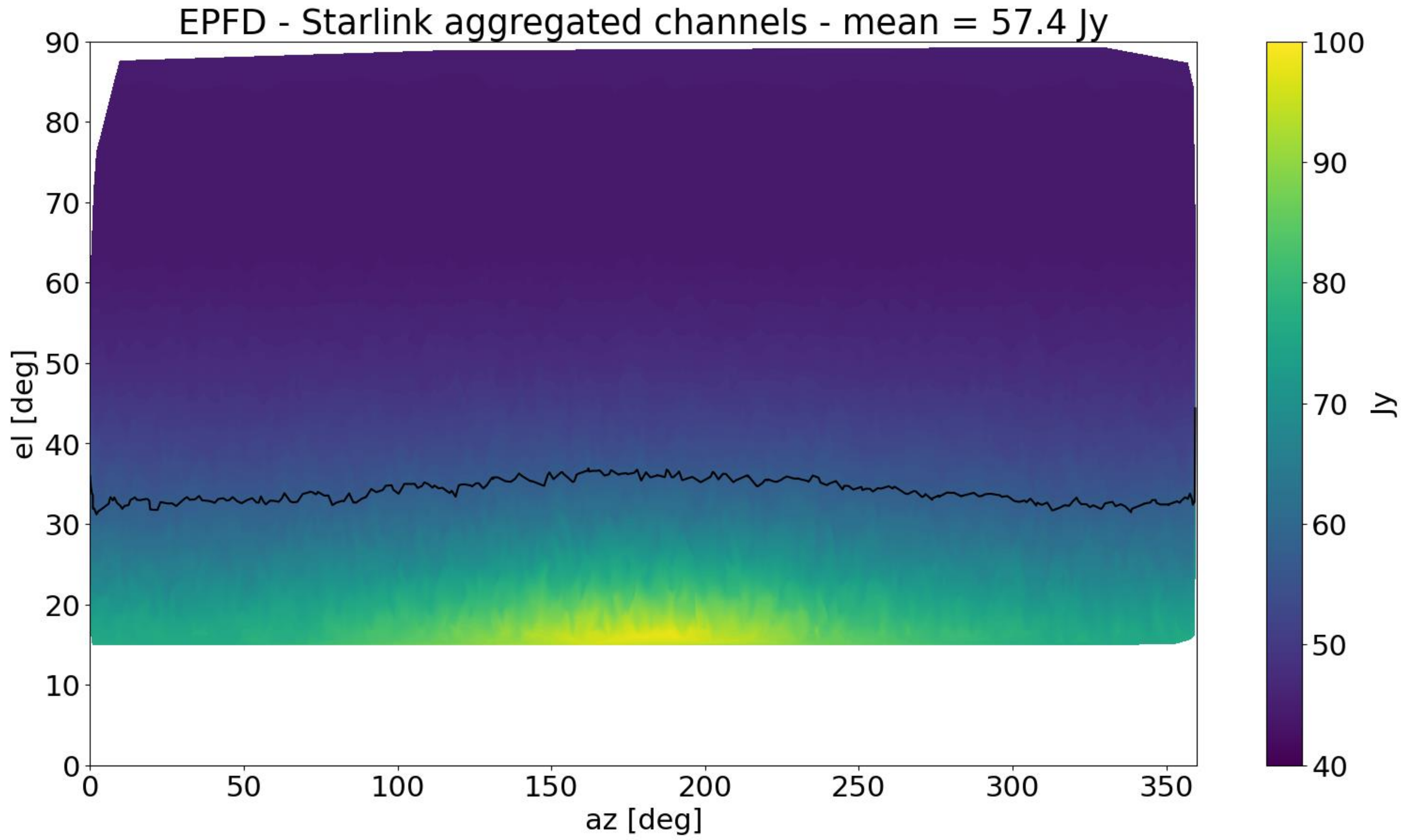
Percentage of time flagged (discarded) in the local sky for Starlink ph1

SKA Mitigation measures
No 2: RFI flagging and excision

- **Residual RFI** is the "leftover RFI" that the automatic flagging would not be able to detect
- Power received through sidelobes, coming from satellite sidelobes…
- Residual RFI can affect observations:
  - Incoherently:
    - Increasing Tsys
    - Less available bandwidth
    - Resulting in more observing time for equal sensitivity
  - Coherently:
    - Residual RFI after cross correlations

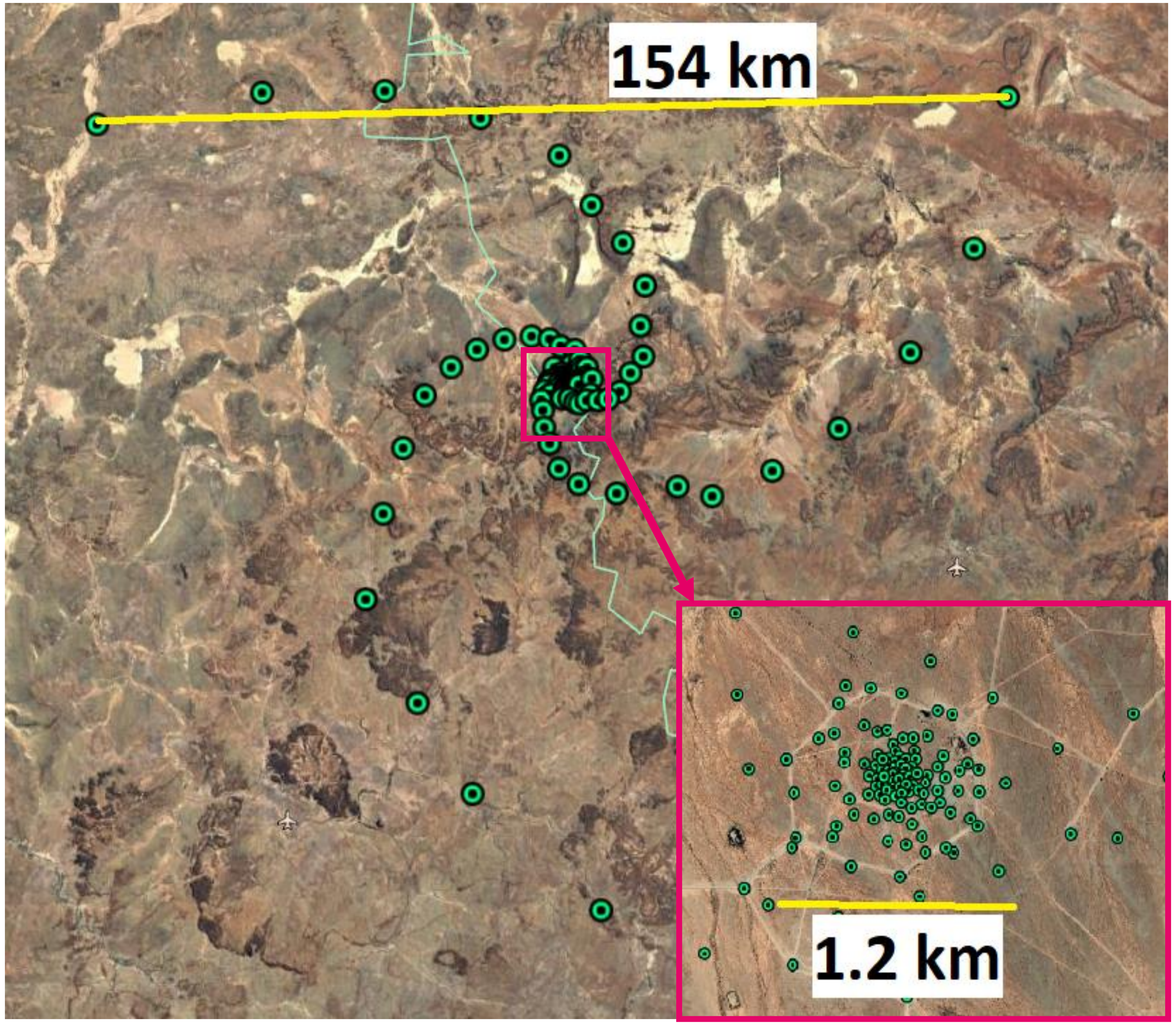


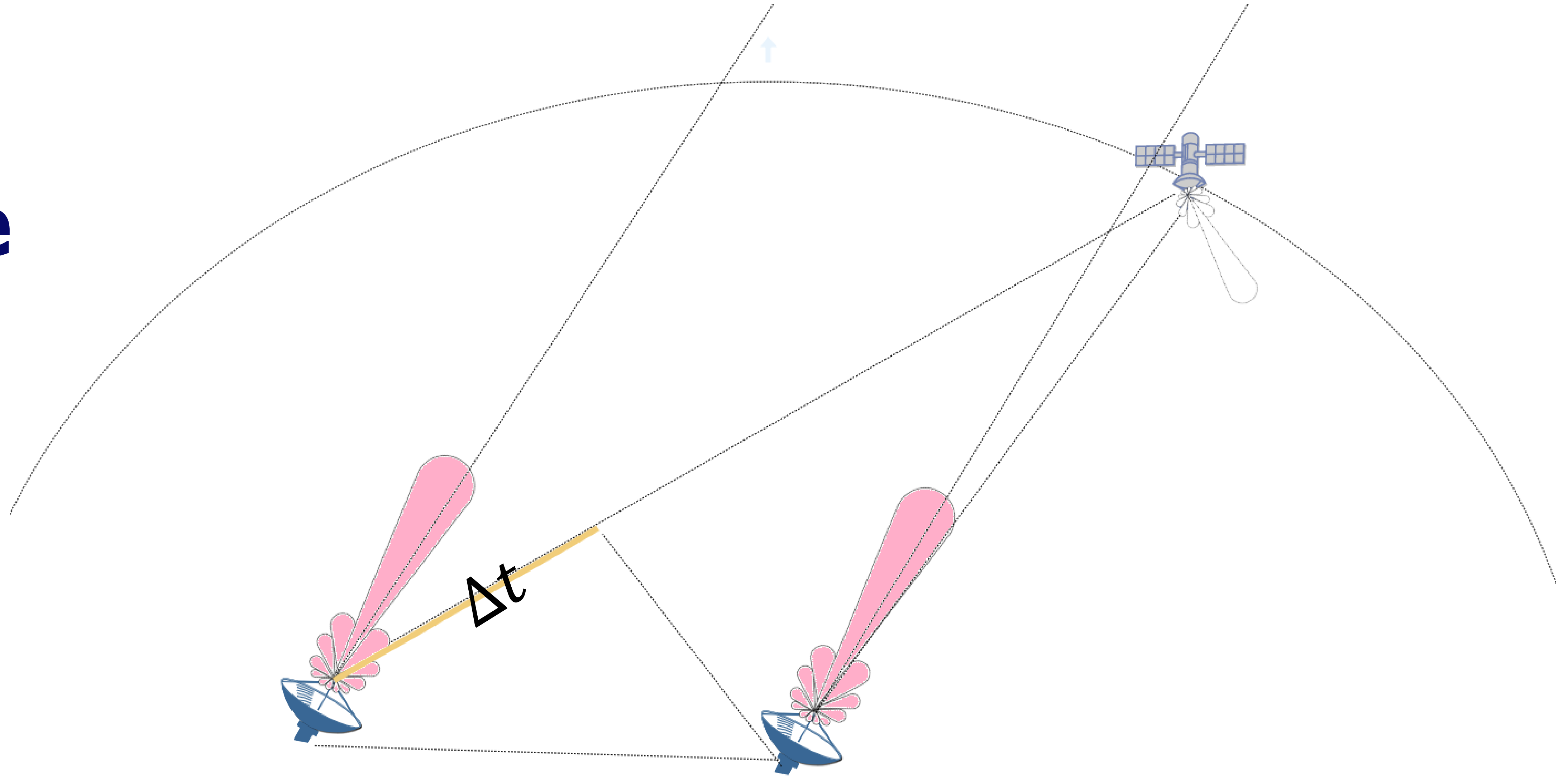
Percentage of time flagged (discarded) in the local sky for OneWeb ph1



Percentage of time flagged (discarded) in the local sky for OneWeb ph1

SKA Mitigation measures
No 3: Interferometry on long baseline

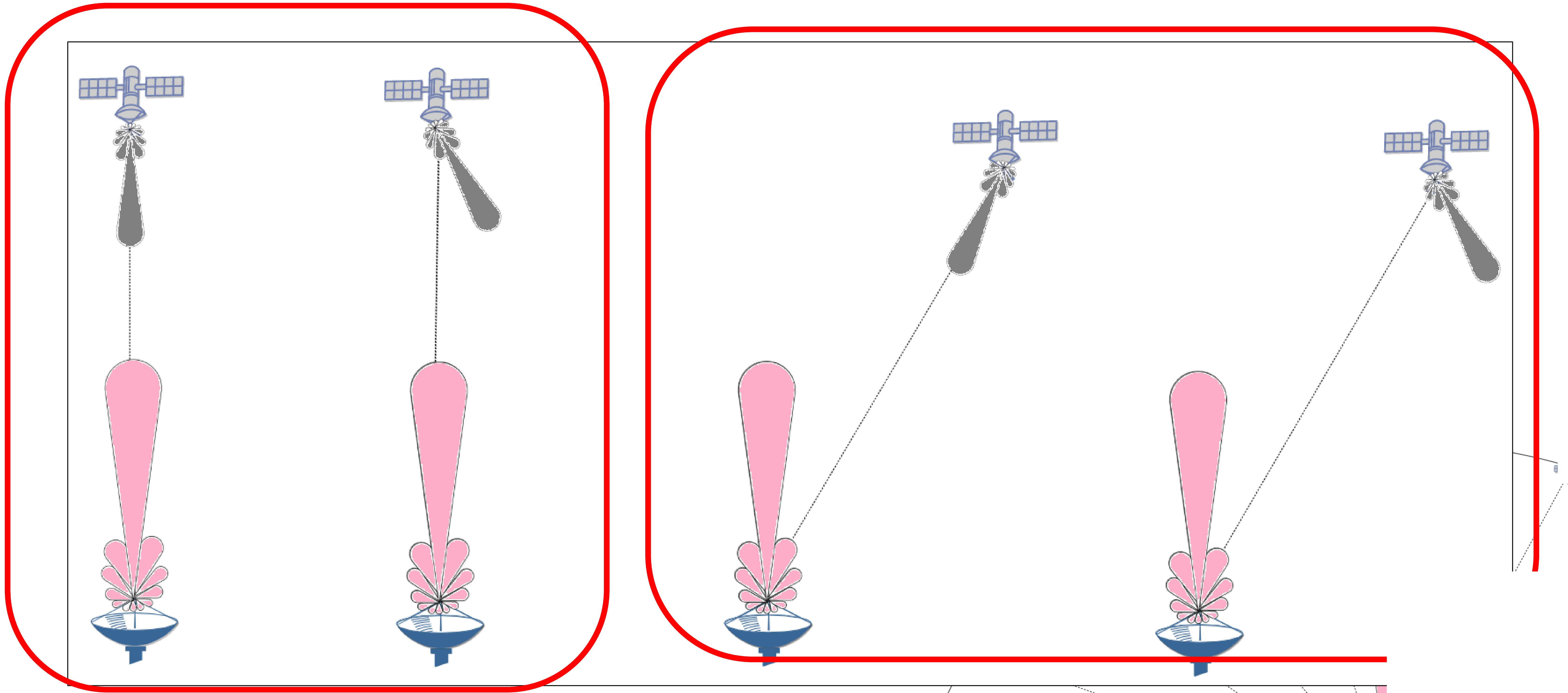




One baseline of an interferometer. The yellow line shows the path delay that the RFI experiences, satellites move much faster than astronomical sources

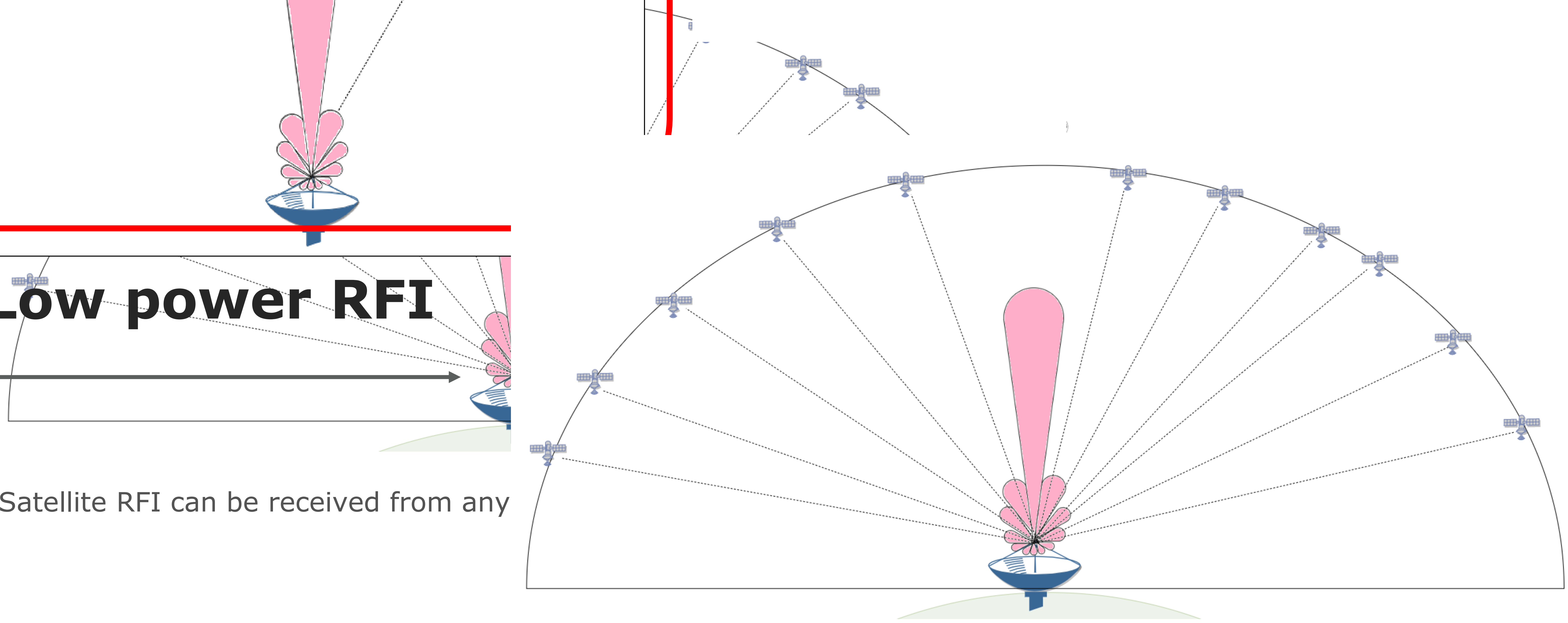
- Long baselines (10s kms) can de-correlate low level RFI
- Preliminary calculations estimate >20 dB suppression of low level RFI for the longest BLs (from 50 Jy to 0.5 Jy)
- The dense central of the SKA-Mid would not benefit from this effect
- Some science cases may use only individual antennas

Radio interference from satellites



High power RFI

Low power RFI



Satellite RFI can be received from any

RECOMMENDATION ITU-R S.1586-1

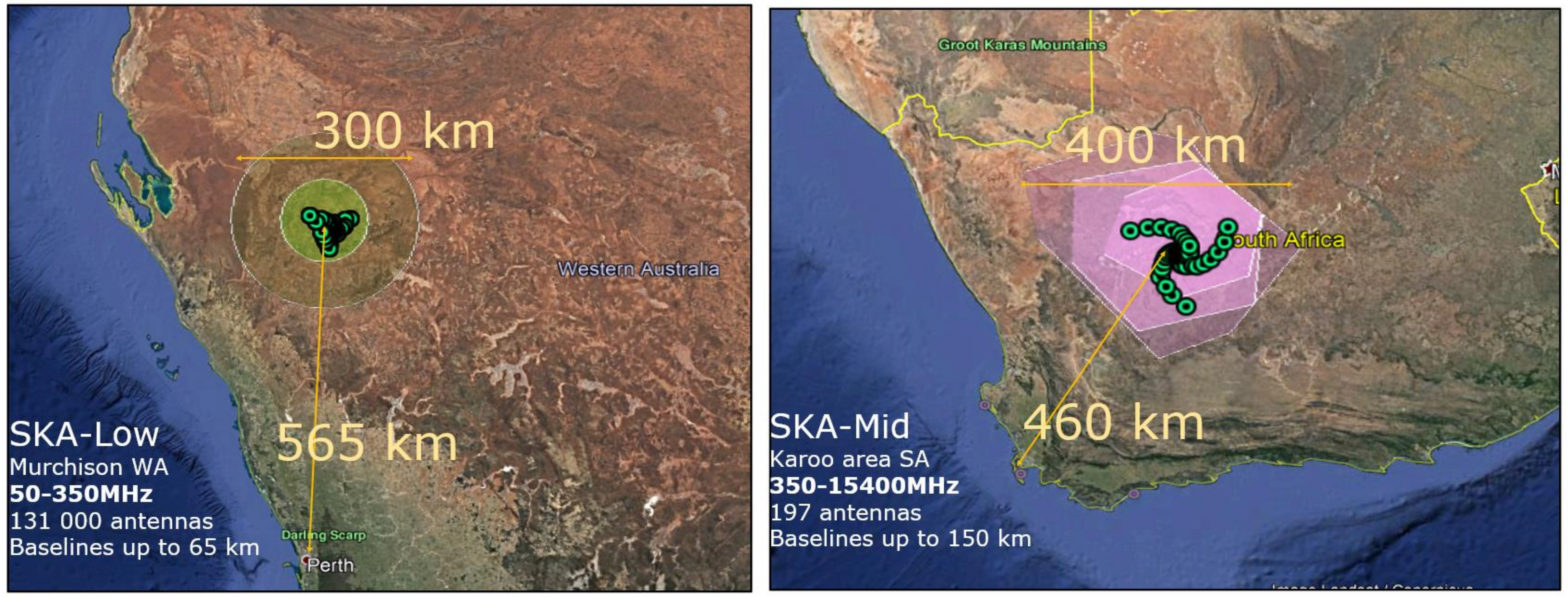
Calculation of unwanted emission levels produced by a non-geostationary fixed-satellite service system at radio astronomy sites

(Question ITU-R 236/4)

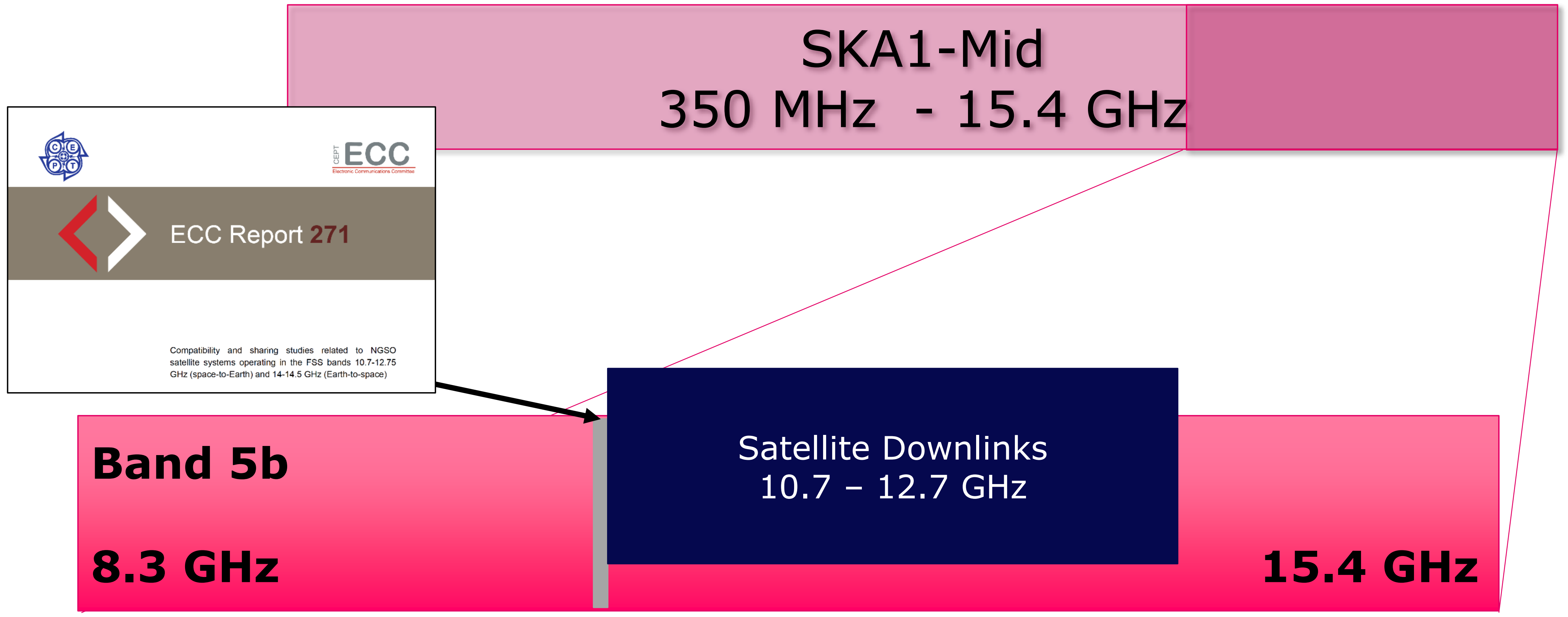
$$epfd = 10\log_{10}\left(\sum_{i=1}^{N_a} 10^{\frac{P_i}{10}} \cdot \frac{G_t(\theta_i)}{4\pi\, d_i^2} \cdot \frac{G_r(\varphi_i)}{G_{r,max}}\right)$$

The SKA telescope and mega-constellations

- Observation outside of RAS bands:
  - red-shifted spectral lines
  - explore newly discovered spectral line emissions
  - Increase sensitivity of observations
  - Detect transients and other wideband phenomena
- SKA’s Radio Quiet Zones cover 70 MHz to 25.5 GHz
- RQZ control terrestrial radio sources, have no power over satellite transmissions



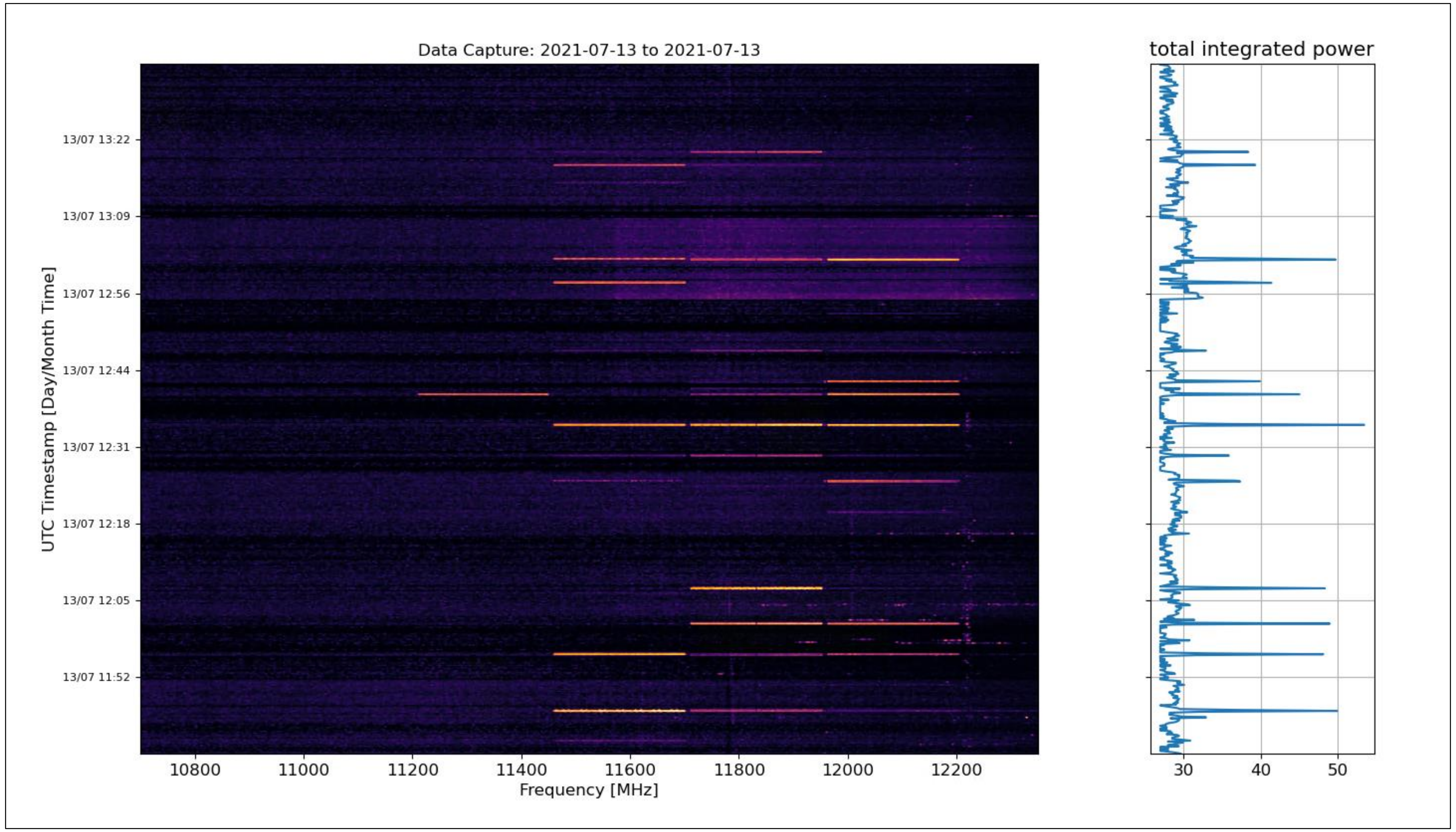
SKA-Low and SKA-Mid sites with their respective RQZs and antenna configurations



Frequency coverage of SKA-Mid B5b (blue), RAS protected band in 10.6-10.7 GHz (green) and satellite downlinks (red)

Measurements

- Continue interaction with industry and the astronomical community
- Measurements to adjust simulations
- Baselines of the radio sky
- Satellite monitoring, not by radio telescopes, is crucial for continuous compliance check



Waterfall plot for one antenna (low sensitivity) located at JBO Manchester in a fixed pointing for 2 hours approximately (left), integrated total power in the measurement band (right).