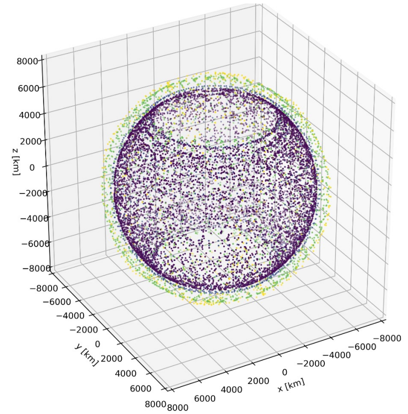
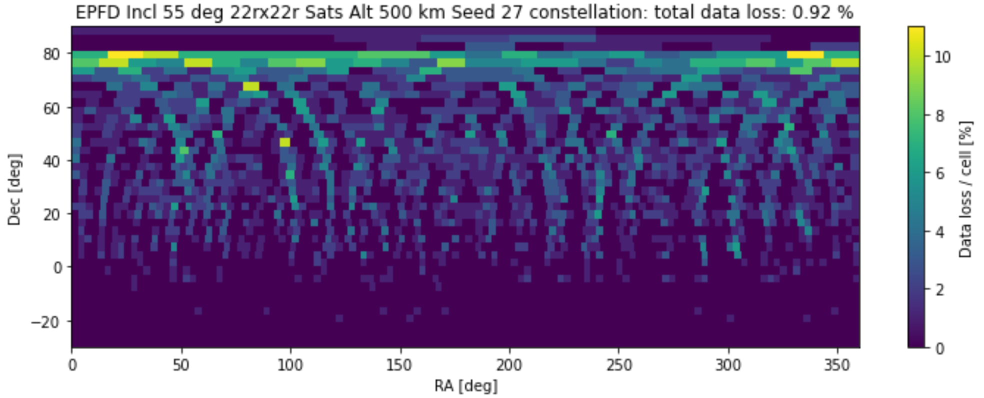
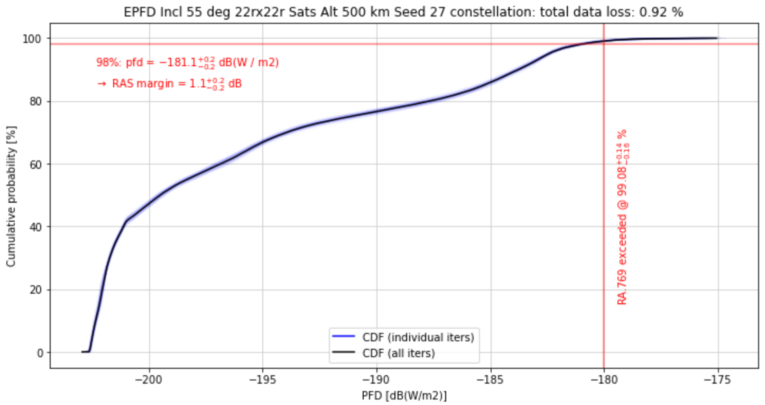
Spectrum management in Radio Astronomy







Gyula I. G. Józsa (MPIfR, ESF-CRAF, ORP)

and the Committee on Radio Astronomy Frequencies

CRAF

OPTICON RadioNet Pilot

MAX PLANCK INSTITUTE FOR RADIO ASTRONOMY

What is spectrum management?

- The operational, engineering, and administrative procedures to plan and coordinate operations within the electromagnetic operational environment. (DoD USA)

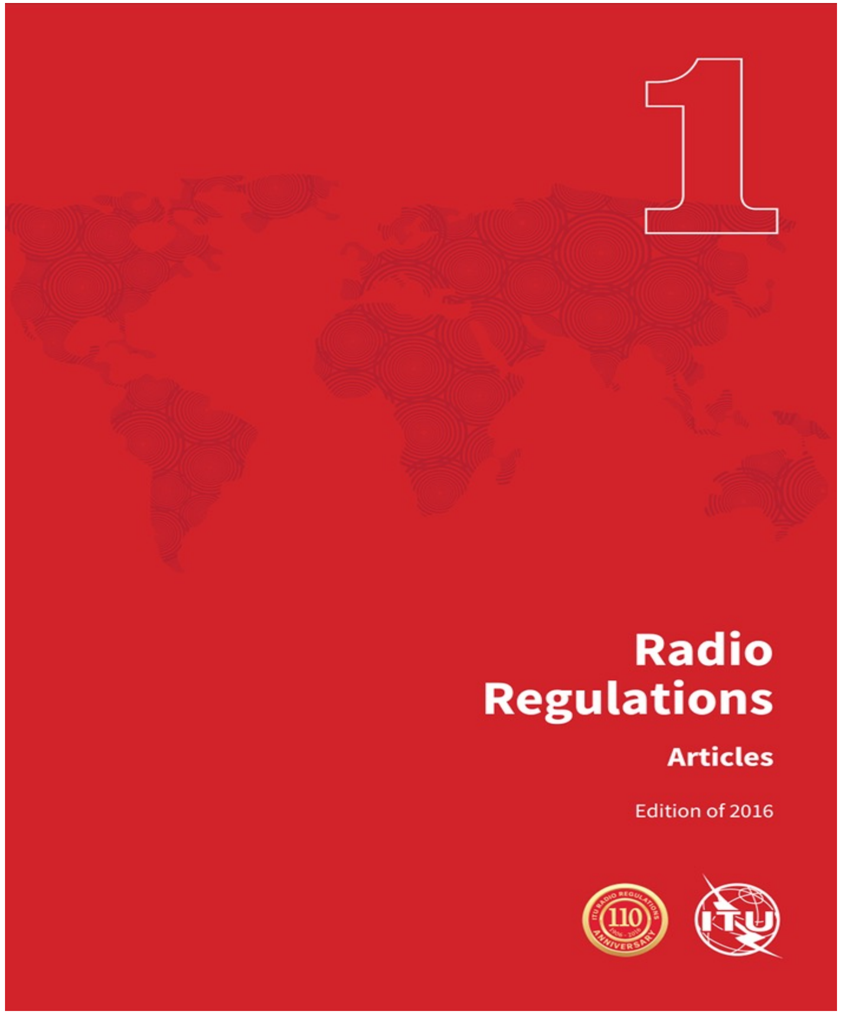
- The process of regulating the use of radio frequencies to promote efficient use and gain a net social benefit. The term radio spectrum typically refers to the full frequency range from 1 Hz to 3000 GHz. (Wikipedia: Cave, Doyle & Webb 2007)

- To ensure rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including those using satellite orbits, and to carry out studies and adopt recommendations on radiocommunication matters. (Mission statement of the International Telecommunication Union Radiocommunication Sector)

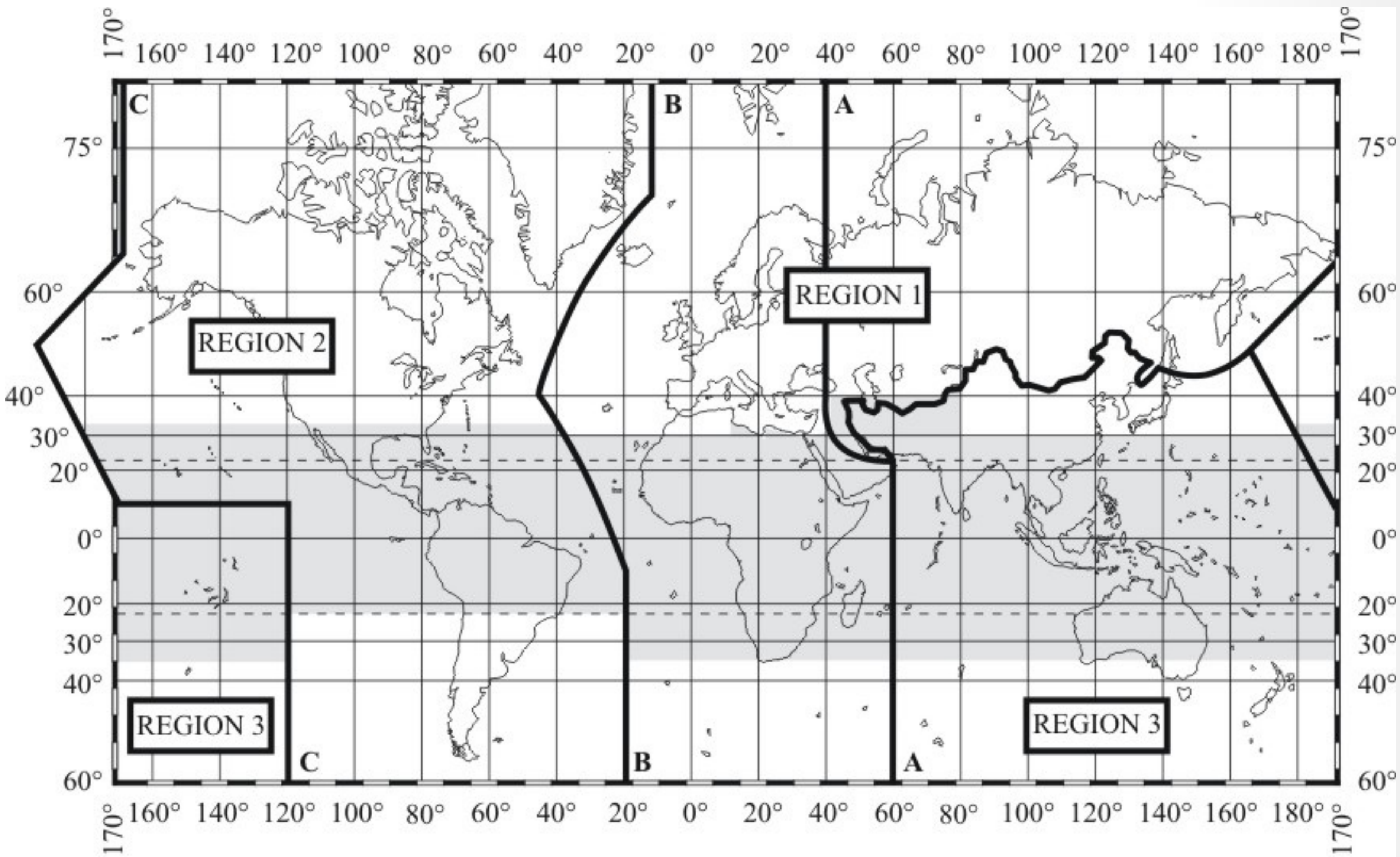
National and international spectrum management

- Nations normally regard the spectrum within their country as their property
- National authorities (spectrum agencies) regulate, police, and enforce spectrum usage
- In many cases the spectrum does not care about national bounderies and “harmful interference” can occur
- Therefore the United Nations International Telecommunication Union Radiocommunication Sector, founded on 17 May 1865, maintains
    - The Radio Regulations, an International Treaty containing radio allocations to services and rules how they should be applied
    - Standards to regulate spectrum usage (Radio Recommendations)
    - Study groups which study spectrum usage
    - Master International Frequency Register (MIFR) into which national agencies file service allocations

National and international spectrum management



ITU Regions


REGION 1
REGION 2
REGION 3
REGION 3
A
B
C
A
B
C
160° 140° 120° 100° 80° 60° 40° 20° 0° 20° 40° 60° 80° 100° 120° 140° 160° 180°
170°
75°
60°
40°
30°
20°
0°
20°
30°
40°
60°

ITU-R Regions

Allocation to services		
Region 1	**Region 2**	**Region 3**
47-50 BROADCASTING 5.162A 5.163 5.164 5.165	**47-50** FIXED MOBILE	**47-50** FIXED MOBILE BROADCASTING 5.162A
50-52 BROADCASTING Amateur 5.166A 5.166B 5.166C 5.166D 5.166E 5.169 5.169A 5.169B 5.162A 5.164 5.165	**50-54** AMATEUR 5.162A 5.167 5.167A 5.168 5.170	
52-68 BROADCASTING 5.162A 5.163 5.164 5.165 5.169 5.169A 5.169B 5.171	**54-68** BROADCASTING Fixed Mobile 5.172	**54-68** FIXED MOBILE BROADCASTING 5.162A
68-74.8 FIXED MOBILE except aeronautical mobile 5.149 5.175 5.177 5.179	**68-72** BROADCASTING Fixed Mobile 5.173 **72-73** FIXED MOBILE **73-74.6** RADIO ASTRONOMY 5.178 **74.6-74.8** FIXED MOBILE	**68-74.8** FIXED MOBILE 5.149 5.176 5.179
74.8-75.2	AERONAUTICAL RADIONAVIGATION 5.180 5.181	

ITU-R Study groups

• Study Group 1	Spectrum management
• Study Group 3	Radiowave propagation
• Study Group 4	Satellite services
• Study Group 5	Terrestrial services
• Study Group 6	Broadcasting service
• Study Group 7	Science services

Regional

ITU

European Conference of Postal and Telecommunications Administrations

– 48 European countries cooperating to regulate posts, radio spectrum and communications networks

ORGANIZATION OF AMERICAN STATES

OAS | CITEL

APT ASIA-PACIFIC TELECOMMUNITY

AFRICAN TELECOMMUNICATIONS UNION

ATU ★ UAT

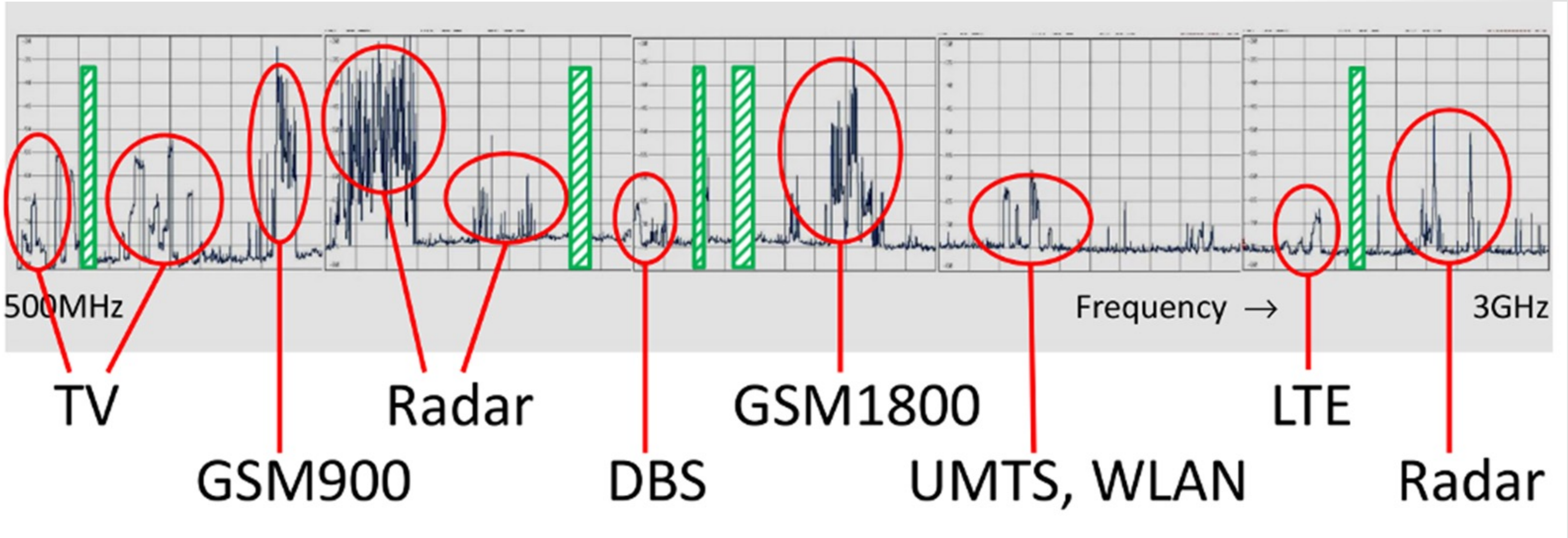
Radio Antennas

- Effelsberg 100-m telescope
  - Antenna gain: ~ 80 dBi
  - Receivers:
    - 0.3 – 90 GHz
    - cooled to 20 K
    - T_{sys}: 15 – 100 K
  - Long integrations to decrease noise; up to days
  - Sensitivity: < 10^{-32} W m^{-2} Hz^{-1} (1 µJy)

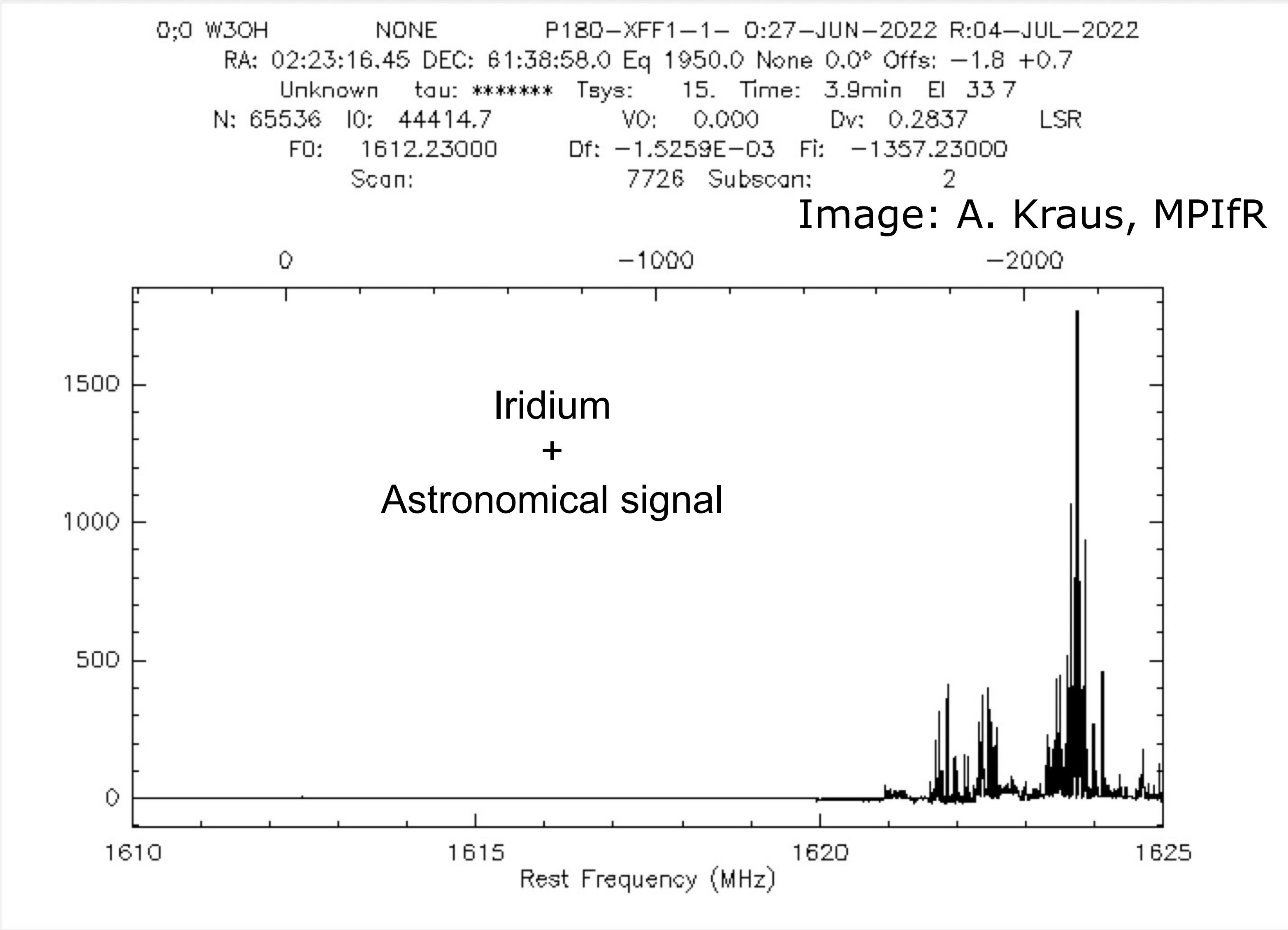
- Effelsberg 100-m telescope
  - Antenna gain: ~ 80 dBi
  - Receivers:
    - 0.3 – 90 GHz
    - cooled to 20 K
    - LNA noise figure ~0.04 dB
  - Long integrations to decrease noise; up to days
  - Sensitivity: < 10^{-32} W m^{-2} Hz^{-1} (1 μJy)

Shared spectrum

Image: R. Keller et al., MPIfR



Shared spectrum



Shared spectrum


Image by B. Winkel

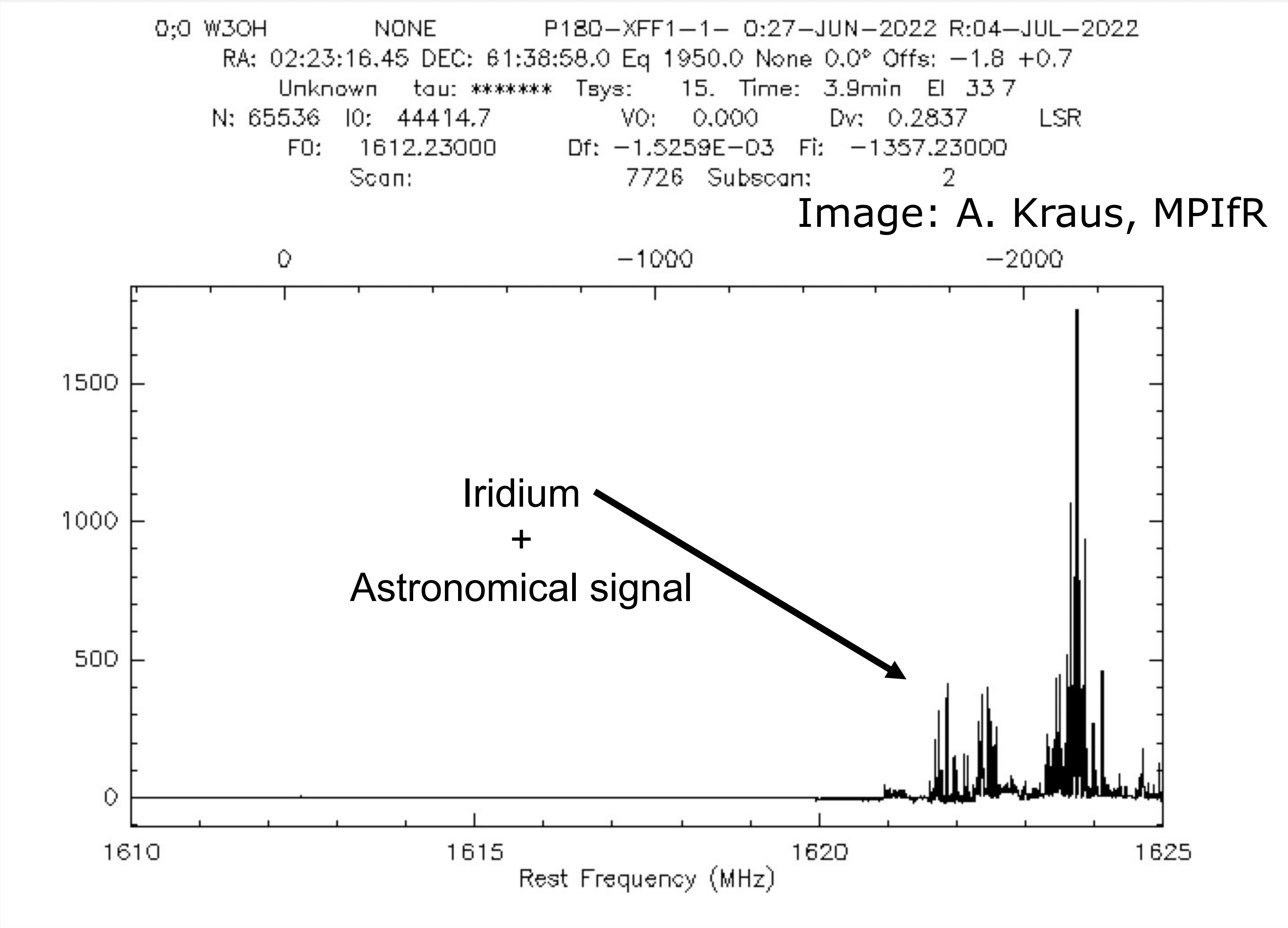
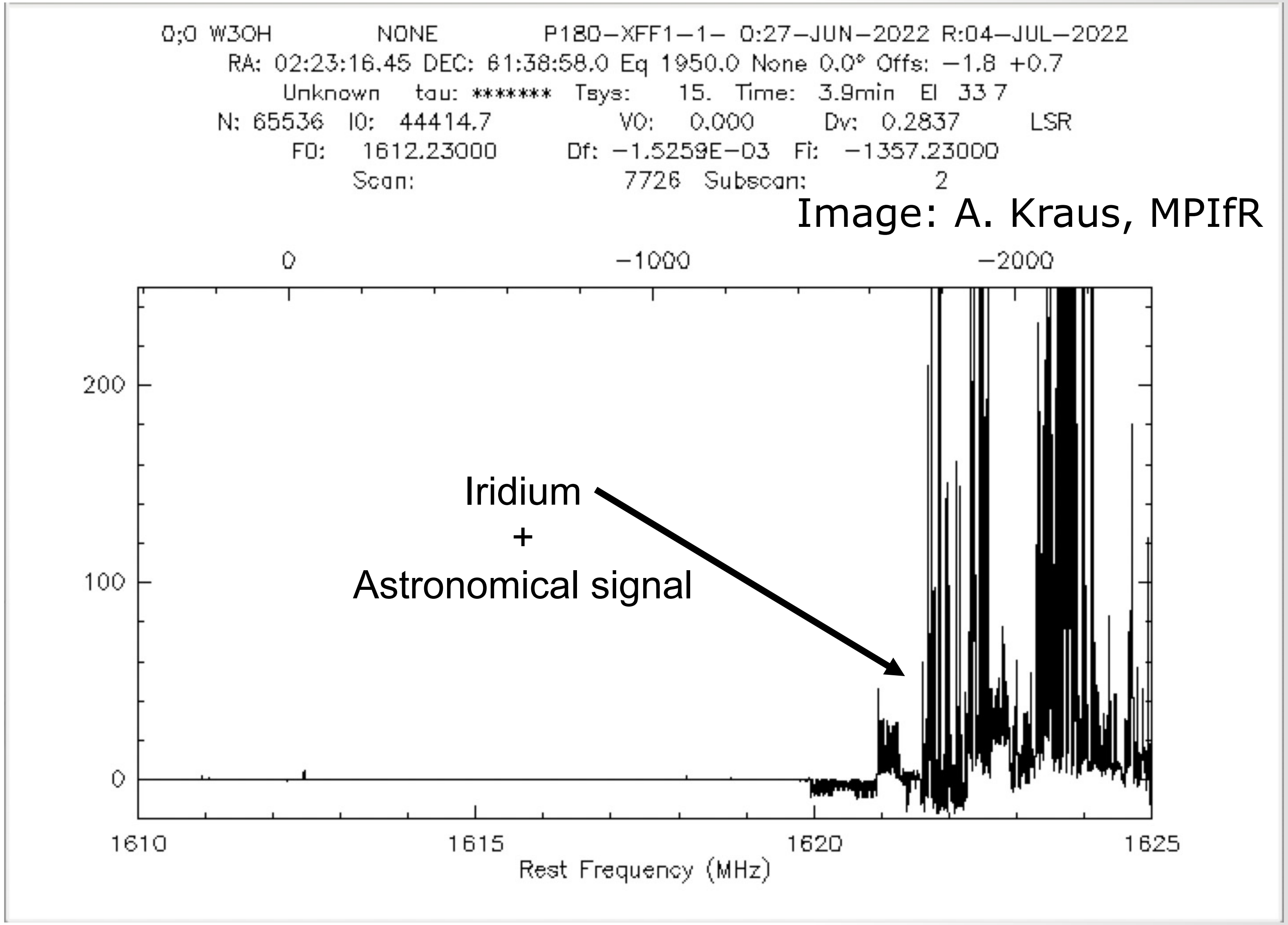
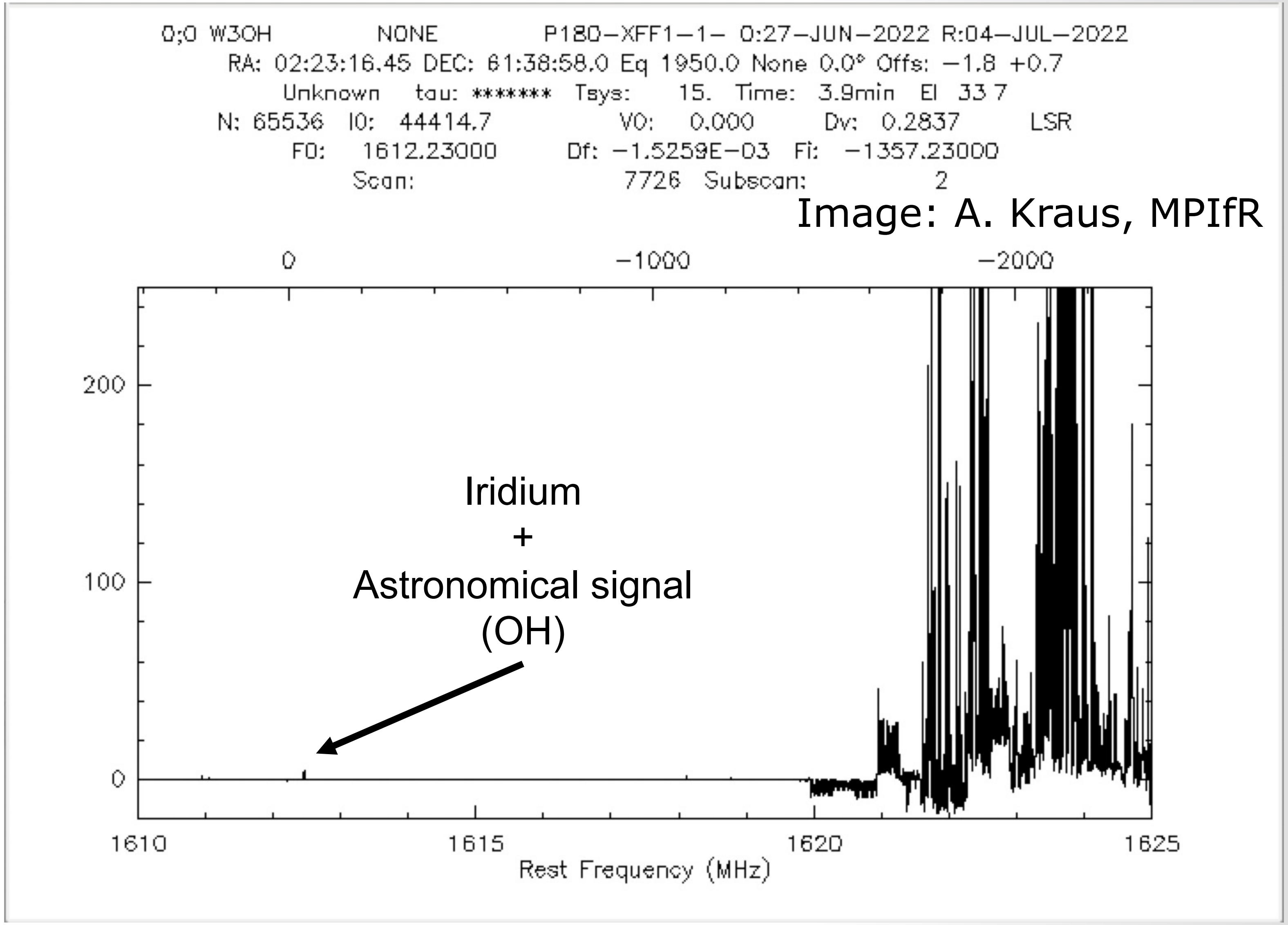


Image: A. Kraus, MPIfR

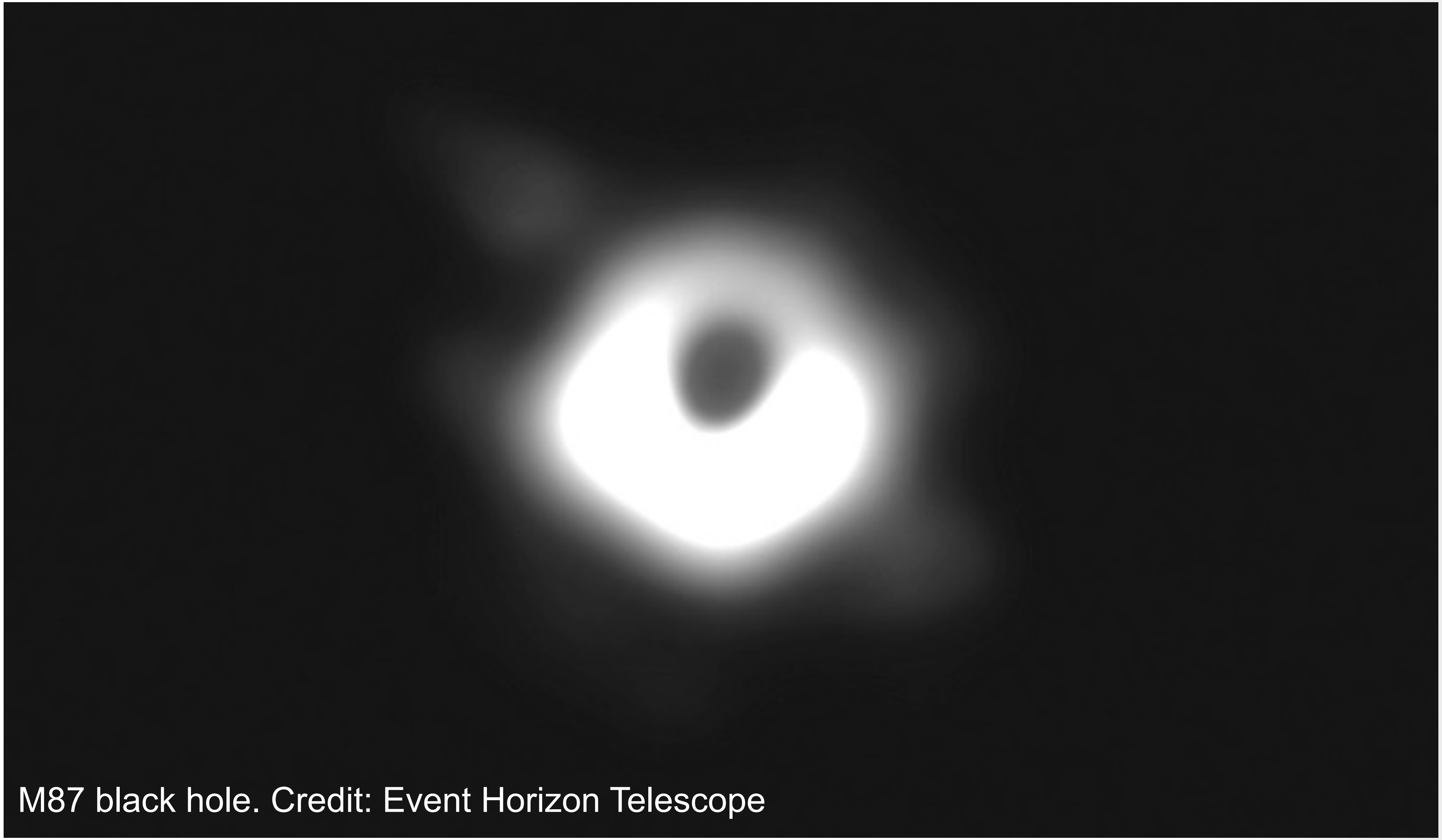
Shared spectrum



Shared spectrum

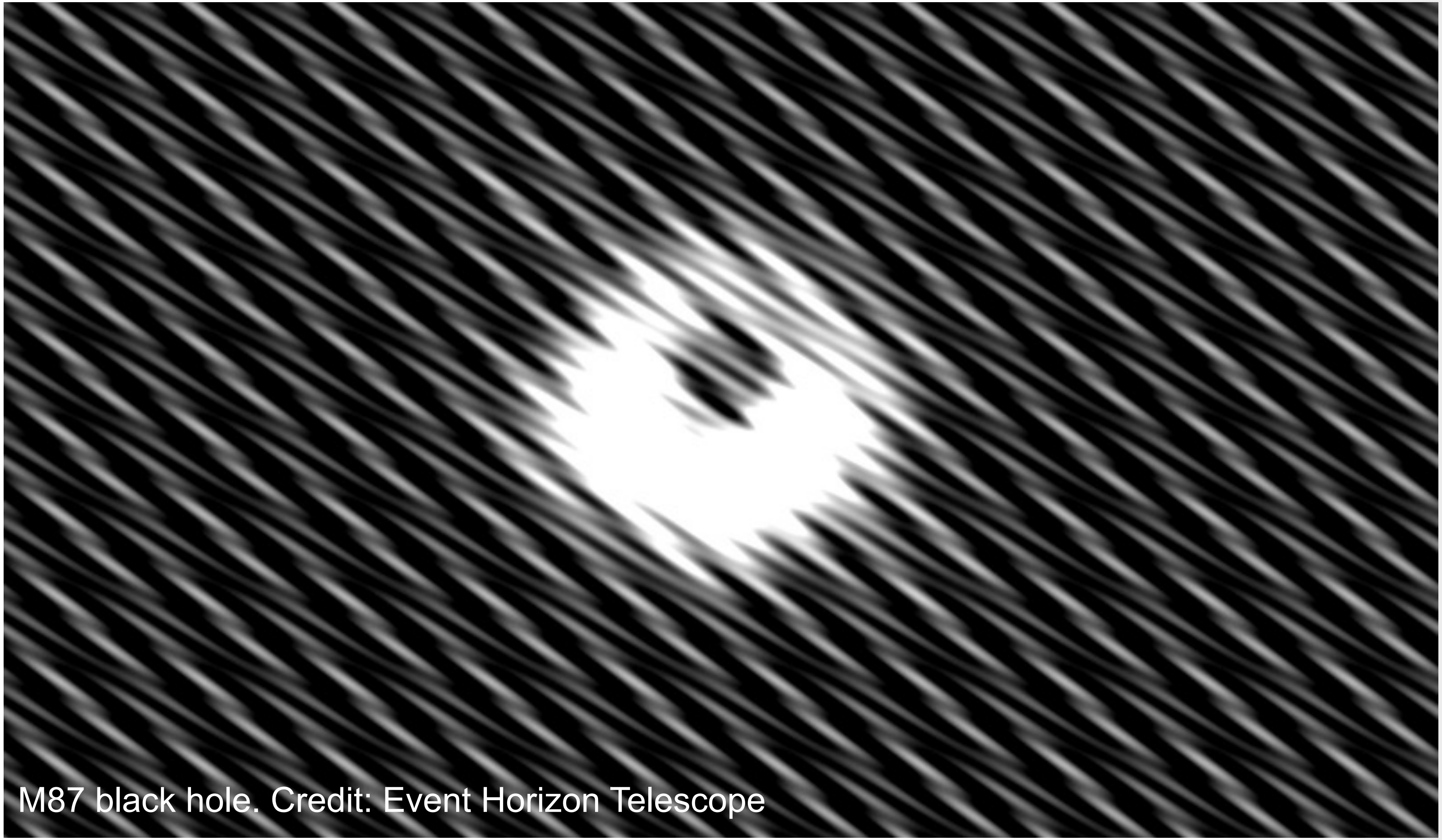


Radio Frequency Interference in imaging



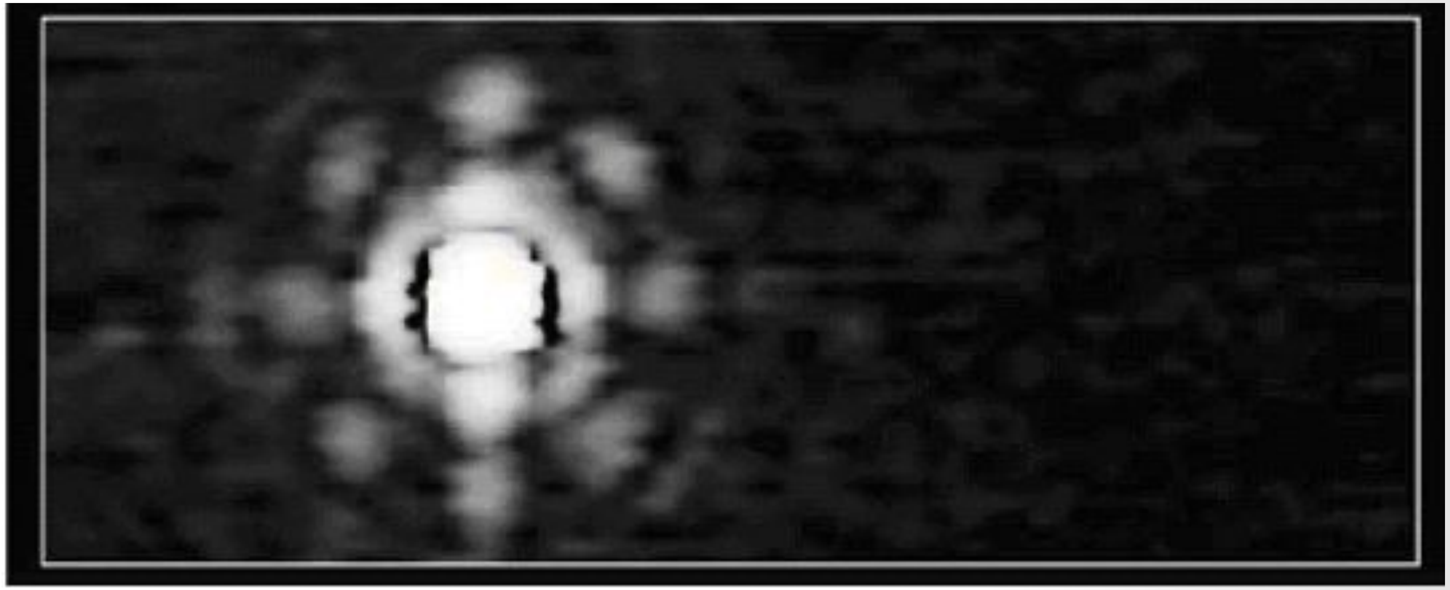
M87 black hole. Credit: Event Horizon Telescope

Radio Frequency Interference in imaging



Radio Frequency Interference in imaging

Radio source 3C84 in the 10.6-10.7 GHz band with the Effelsberg 100 m radio telescope (Image: A. Kraus, R. Keller)



• Sun @ 11 GHz:	300.000 Jy
• Moon @ 11 GHz:	6.000 Jy
• CAS A @ 11 GHz:	500 Jy
• 3C286 bei 11 GHz:	5 Jy

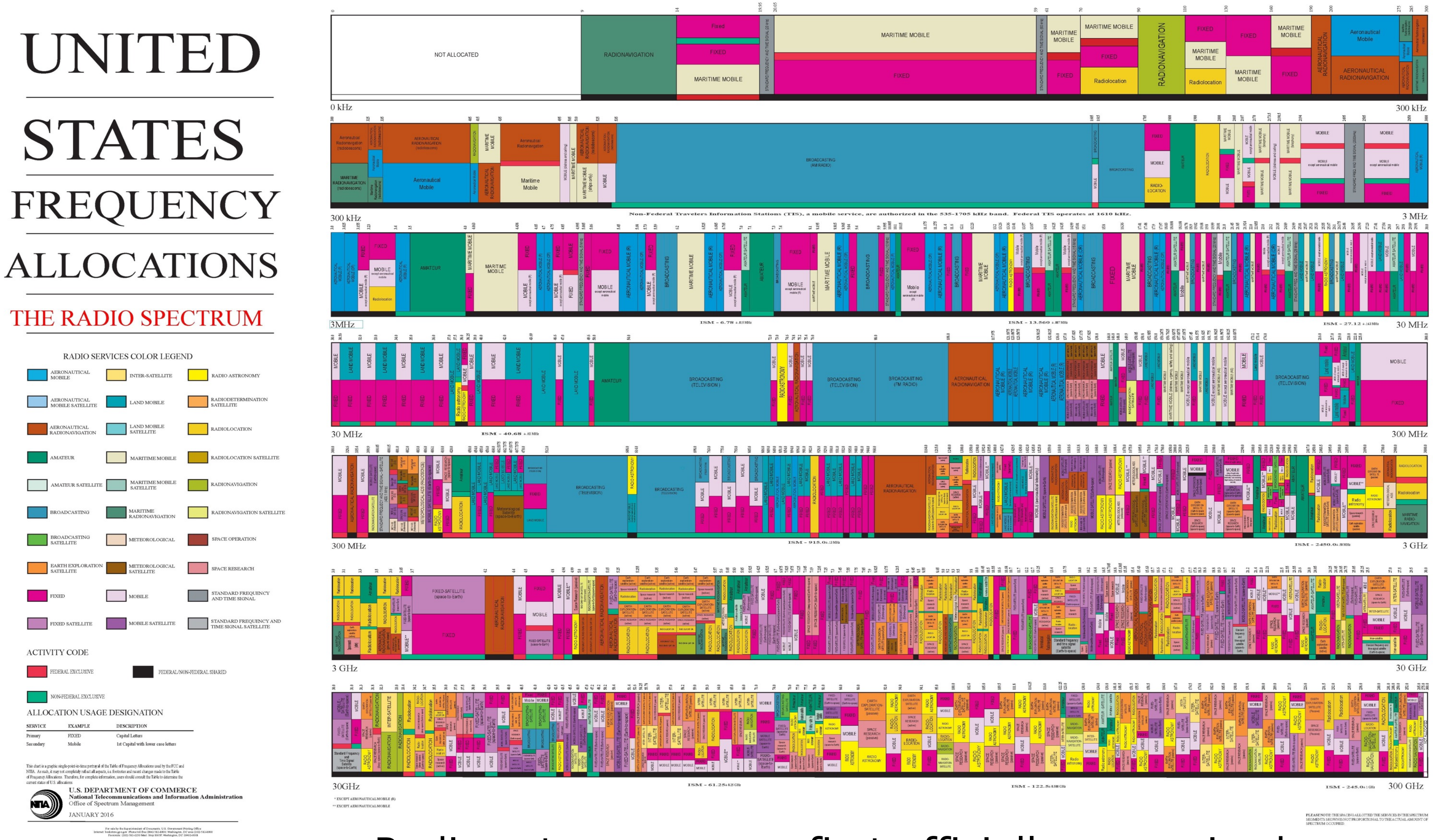
Radio Frequency Interference in imaging

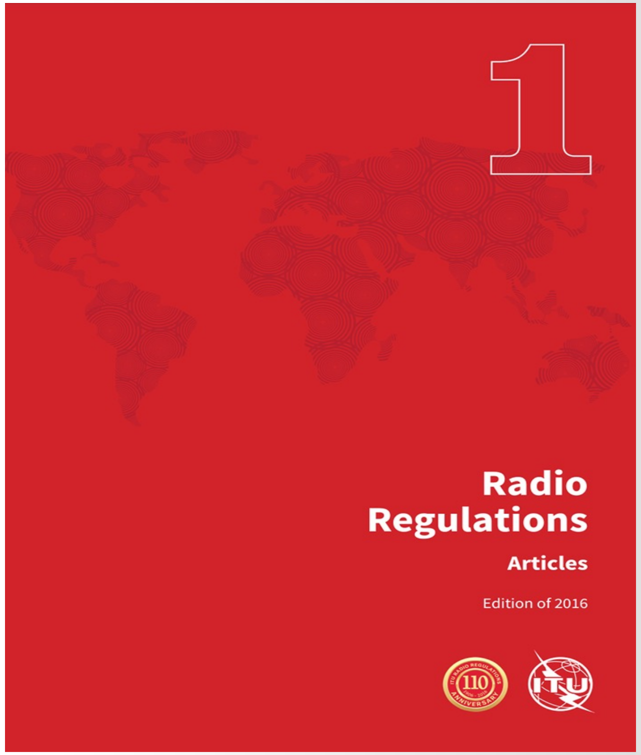
ASTRA 1E (Image from compendium.infotip.de)

Radio source 3C84 in the 10.6-10.7 GHz band with the Effelsberg 100 m radio telescope (Image: A. Kraus, R. Keller)

• Sun @ 11 GHz:	300.000 Jy
• Moon @ 11 GHz:	6.000 Jy
• CAS A @ 11 GHz:	500 Jy
• 3C286 bei 11 GHz:	5 Jy
• ASTRA:	~1.900.000 Jy

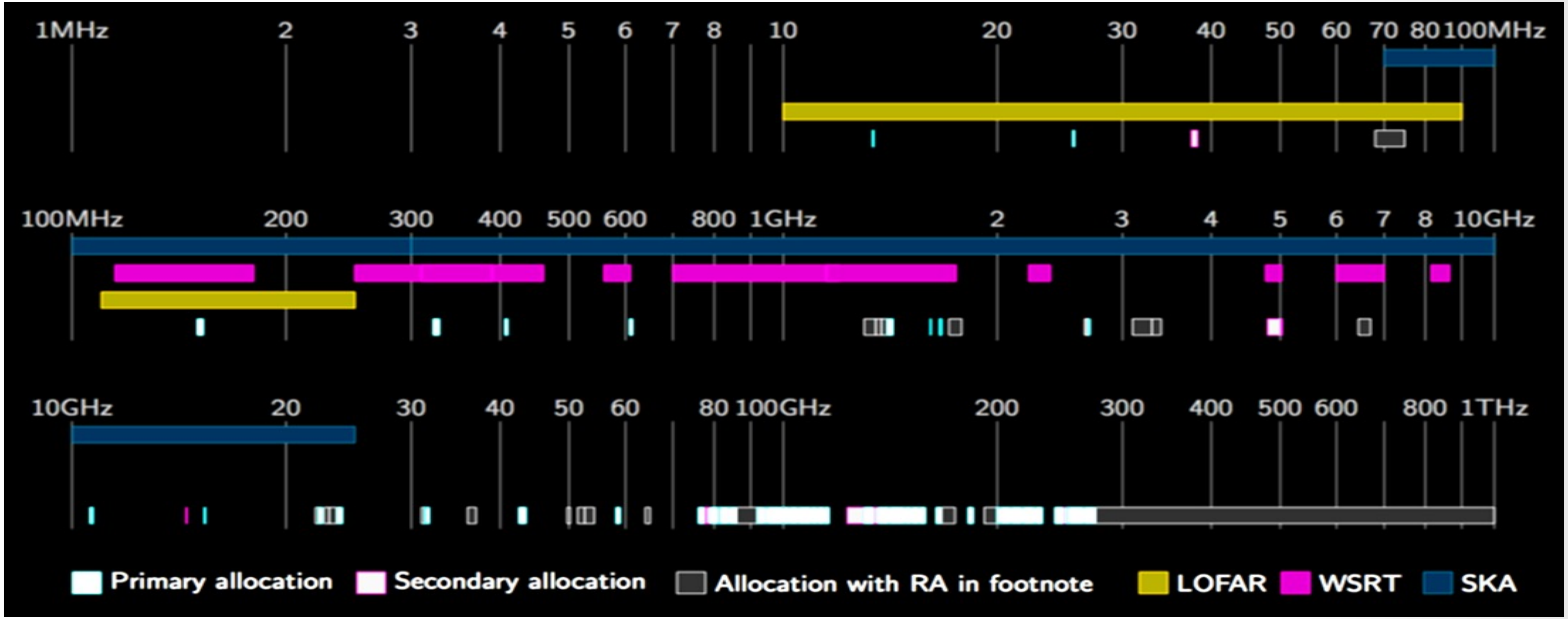
Shared spectrum





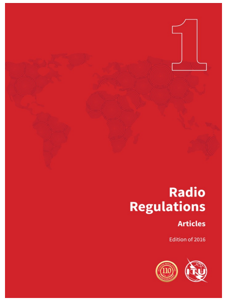
- Radio astronomy was first officially recognized as a radiocommunication service at the WARC-59

Shared spectrum



ITU-R Radio Regulations
- Frequency table
- Footnotes
- Procedures

ITU-R Recommendations



World Radio Conference
- Updates RRs
- Meets every 3-4 years
- Next: Nov-Dec 2023

Radio Astronomical Associations

- Inter-Union Commission for the Allocation of Frequencies for Radio Astronomy and Space Science (IUCAF)

IUCAF

- Committee on Radio Astronomy Frequencies (CRAF, Region 1)

- Committee on Radio Frequencies of the National Academy of Sciences (CORF, US)

CORF

- Radio Astronomy Frequency Committee in the Asia-Pacific Region (RAFCAP, Region 3)

RAFCAP

- National organisations

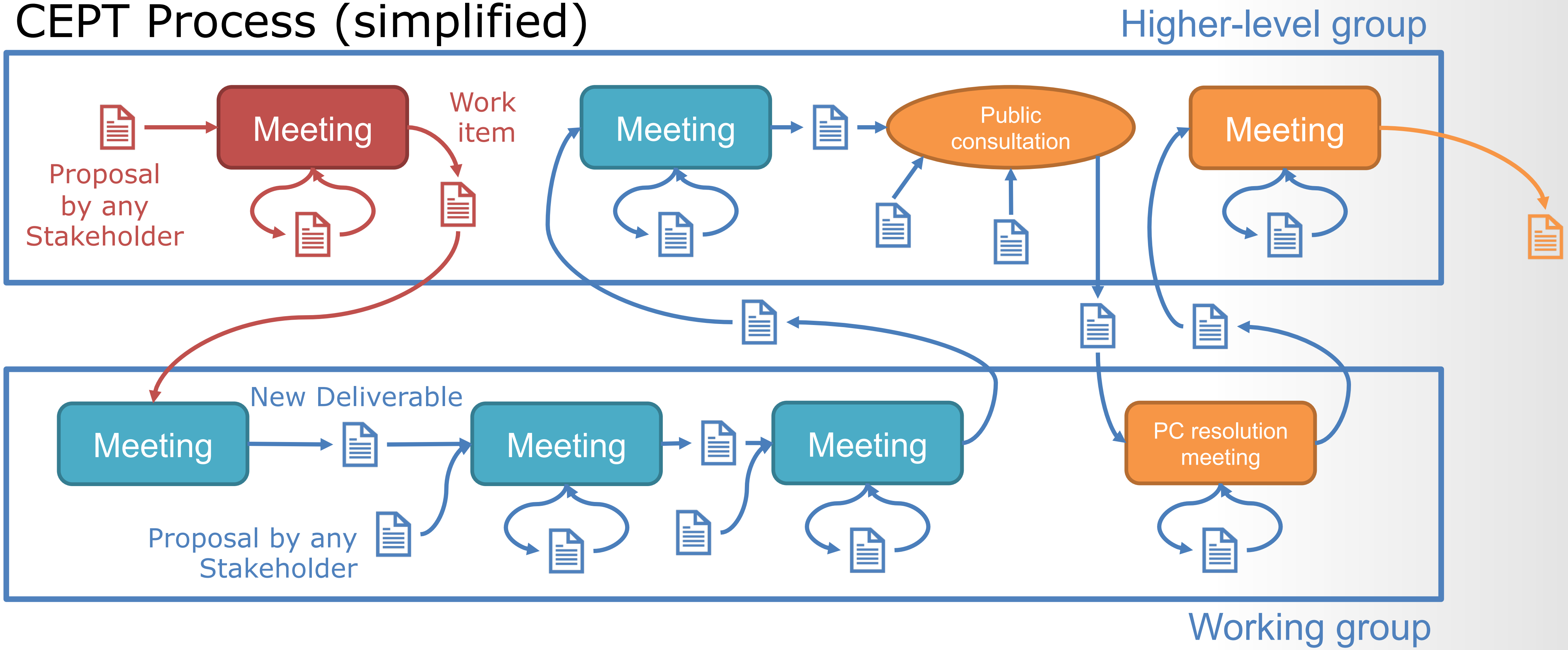
CRAF Mission:

- Keep the allocated radio astronomy frequency bands free from interference
- Ensure access to and availability of the radio spectrum for scientific needs
- Support the scientific community in their needs for passive use of interference free bands

Activities in several teams:

- Intervention in regulatory processes at national and international level
- Software for compatibility studies
- Harmonized RFI Monitoring (new)
- Handbook
- Outreach
- CPS
- ORP

CEPT Process (simplified)



- Regulation process formalized, document driven
- Requires attention at all times

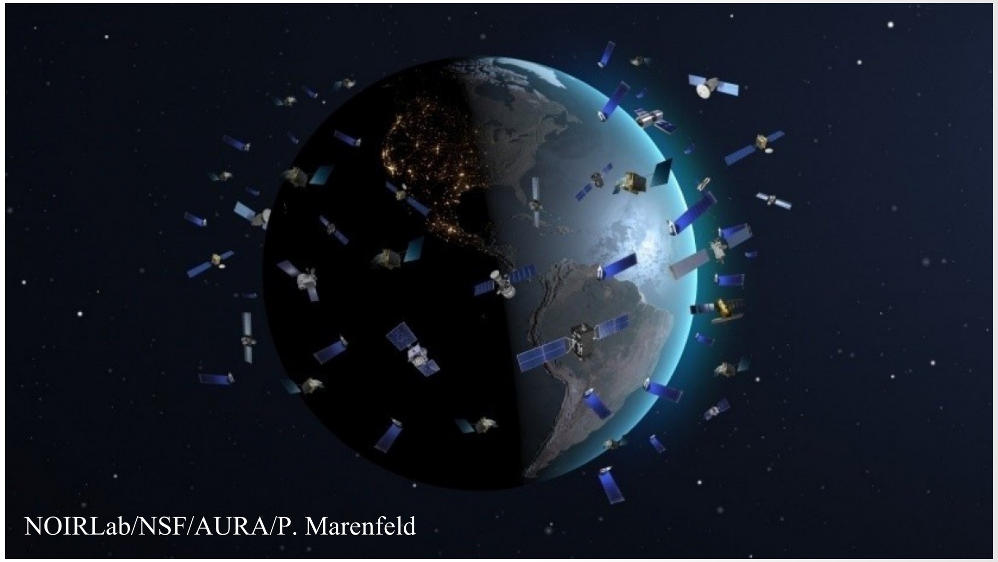
Frequency management

ITU WRC-23

- More IMT allocation (GHz)
  - AI 1.1: 4.8-4.99
  - AI 1.2: 3.5-3.8, 6.425-7.025, 7.025-7.125
  - AI 1.3: 3.6-3.8
  - AI 1.4: HIBS 0.694-0.96, 1.71-1.885, 2.5-2.69
  - AI 1.5: 0.47-0.694

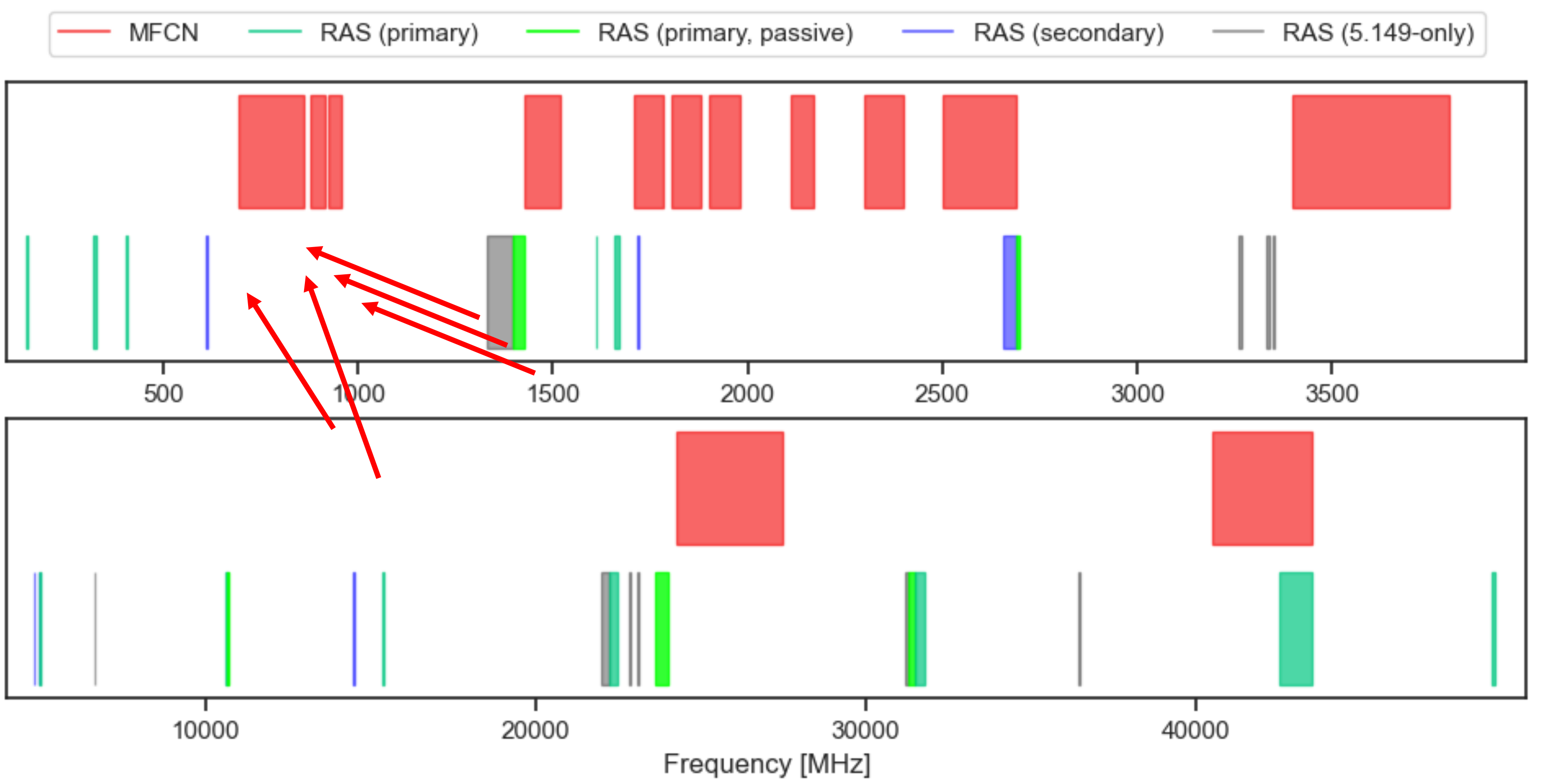
- NGSO Satellites
  - AI 1.16: FSS ESM 17.7-18.6, 18.8-19.3, 19.7-20.2, 27.5-29.1, 29.5-30
  - AI 1.17: inter-satellite 11.7-12.7, 18.1-18.6, 18.8-20.2, 27.5 - 30

Via Satellite/Jeffrey Hill



NOIRLab/NSF/AURA/P. Marenfeld

Cellphone spectrum



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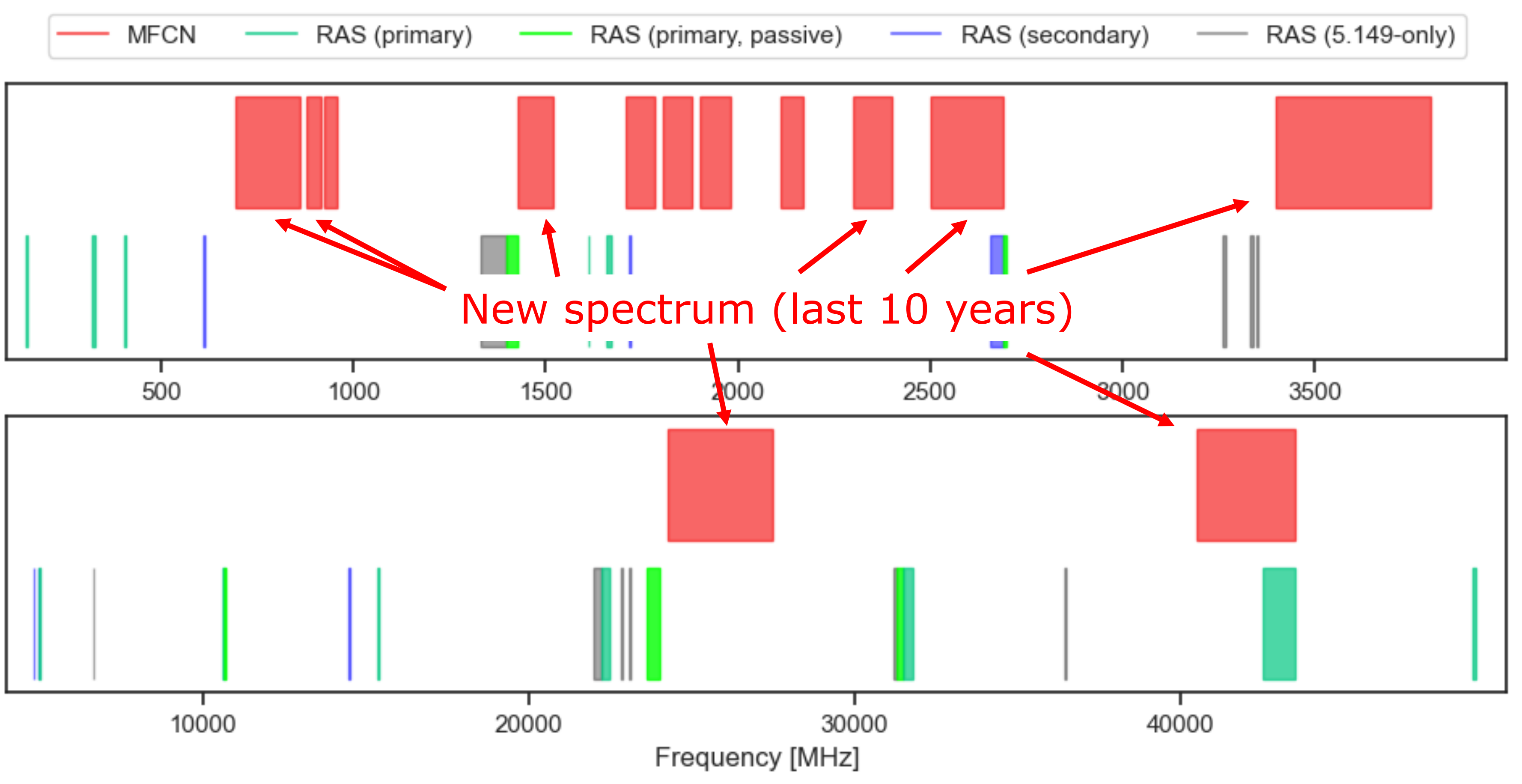

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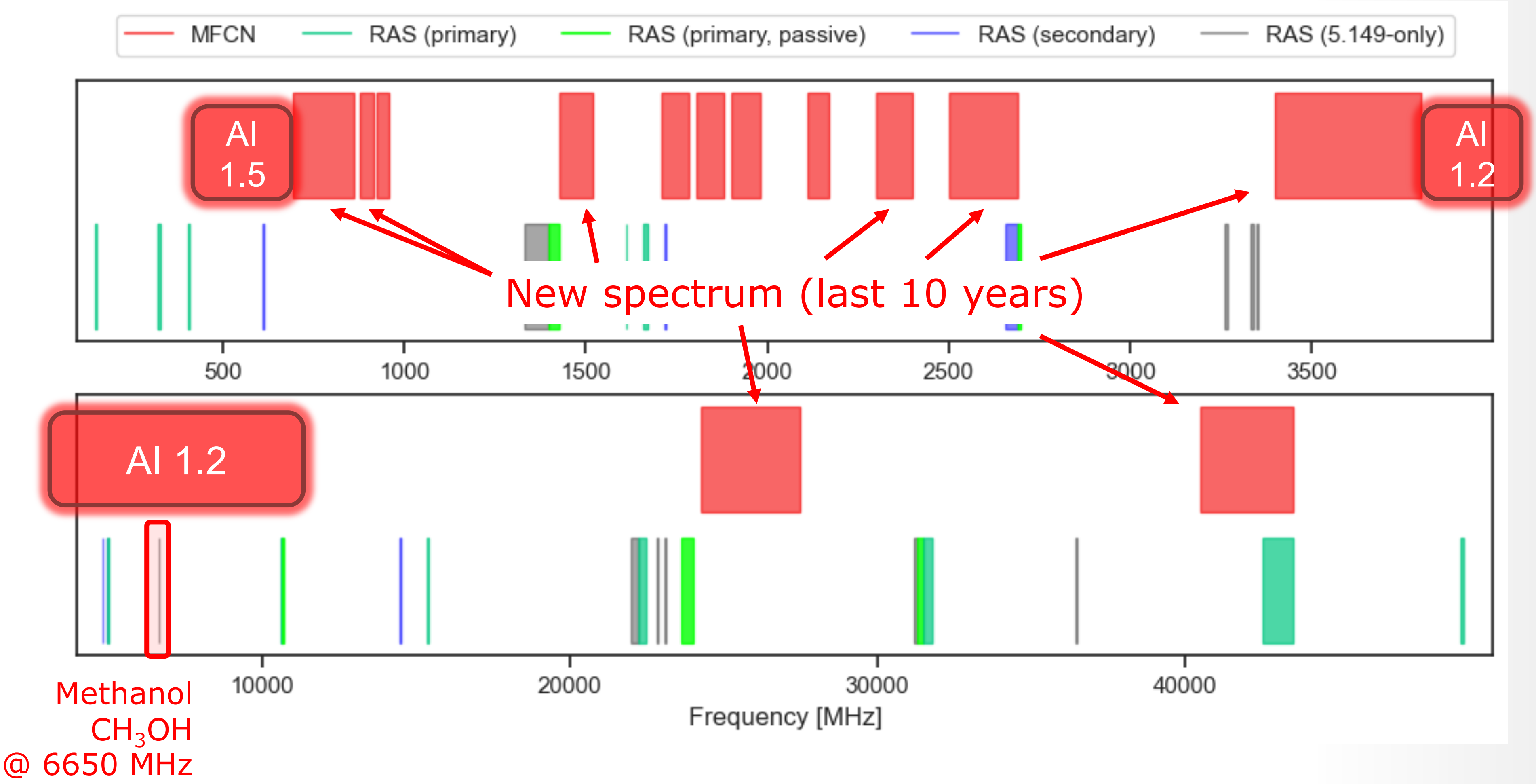


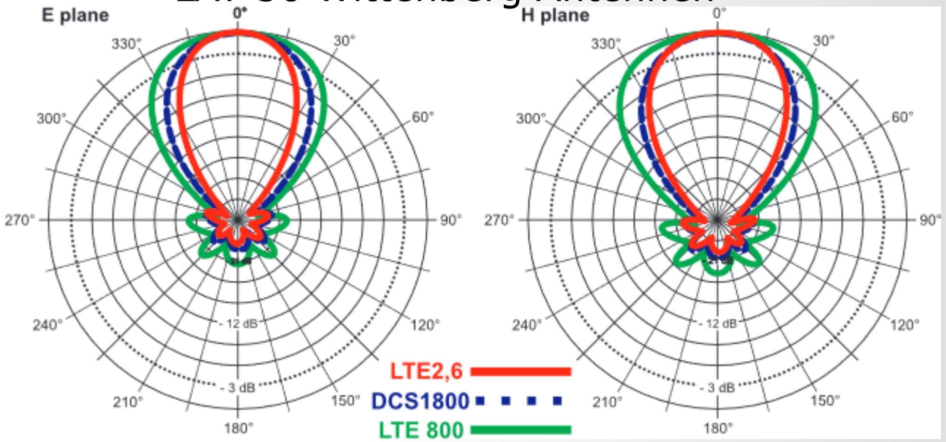
Software-supported compatibility studies

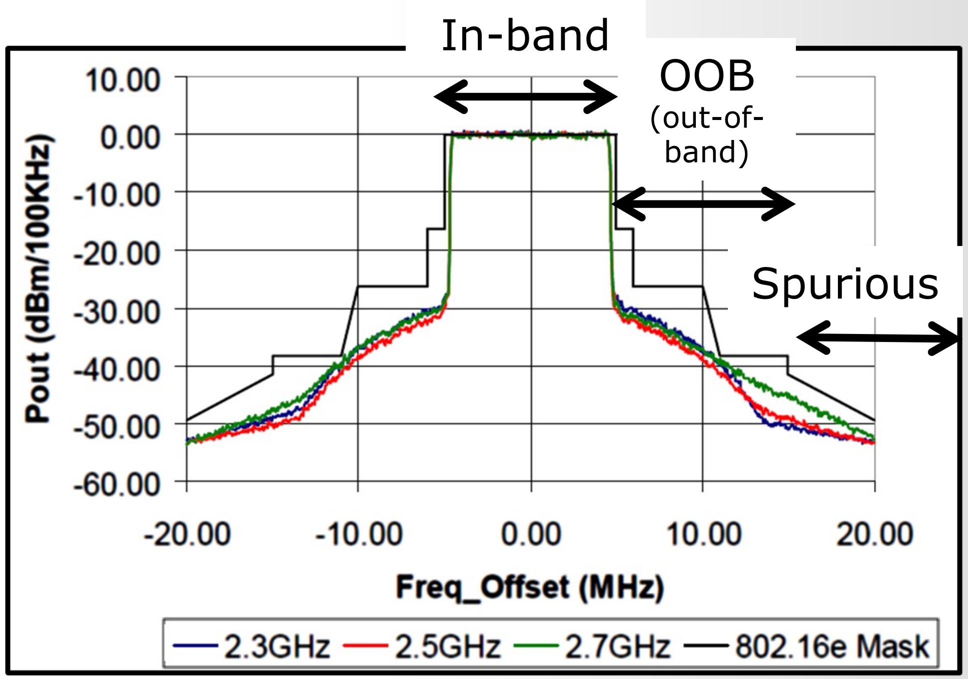
- Calculate un-/wanted emission levels of interferer
- Path propagation: implement ITU-R recommendations
  - (Generate topographic information first)
- Infer received power flux densities/E-field strengths at victim receiver
- Infer received power levels
- Compare with limits recommended by ITU-R RA.769
- Infer statistical data loss following recommended procedures (e.g. ITU-R M.1583 and RA.1513)
  - Limits:

    5% aggregate data loss

    2% data loss from single systems

LAT-56 Wittenberg Antennen





Software-supported compatibility studies

- **Calculate un-/wanted emission levels of interferer**
- Generate topographic maps (height profiles) from SRTM data
- Path propagation: implement ITU-R recommendations
- Infer received power flux densities/E-field strengths at victim receiver
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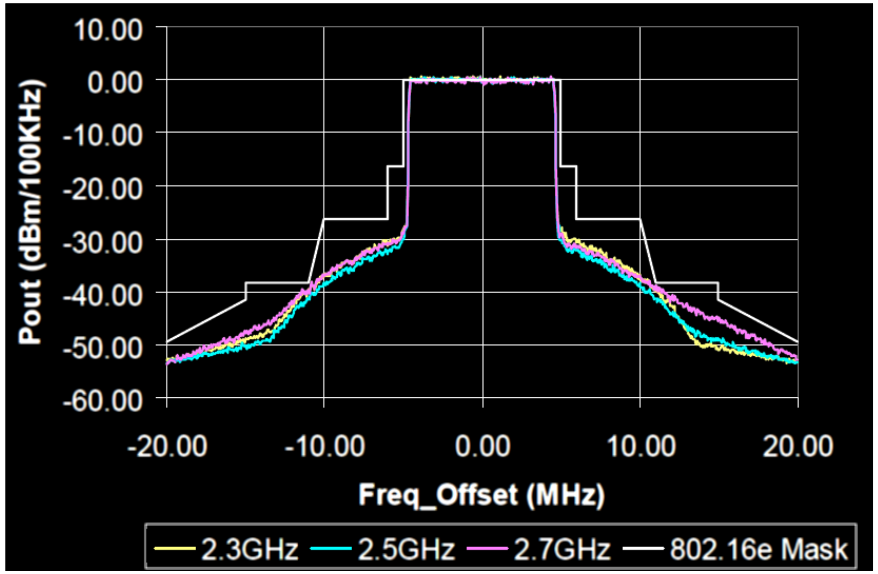
- Compare with recommended limits



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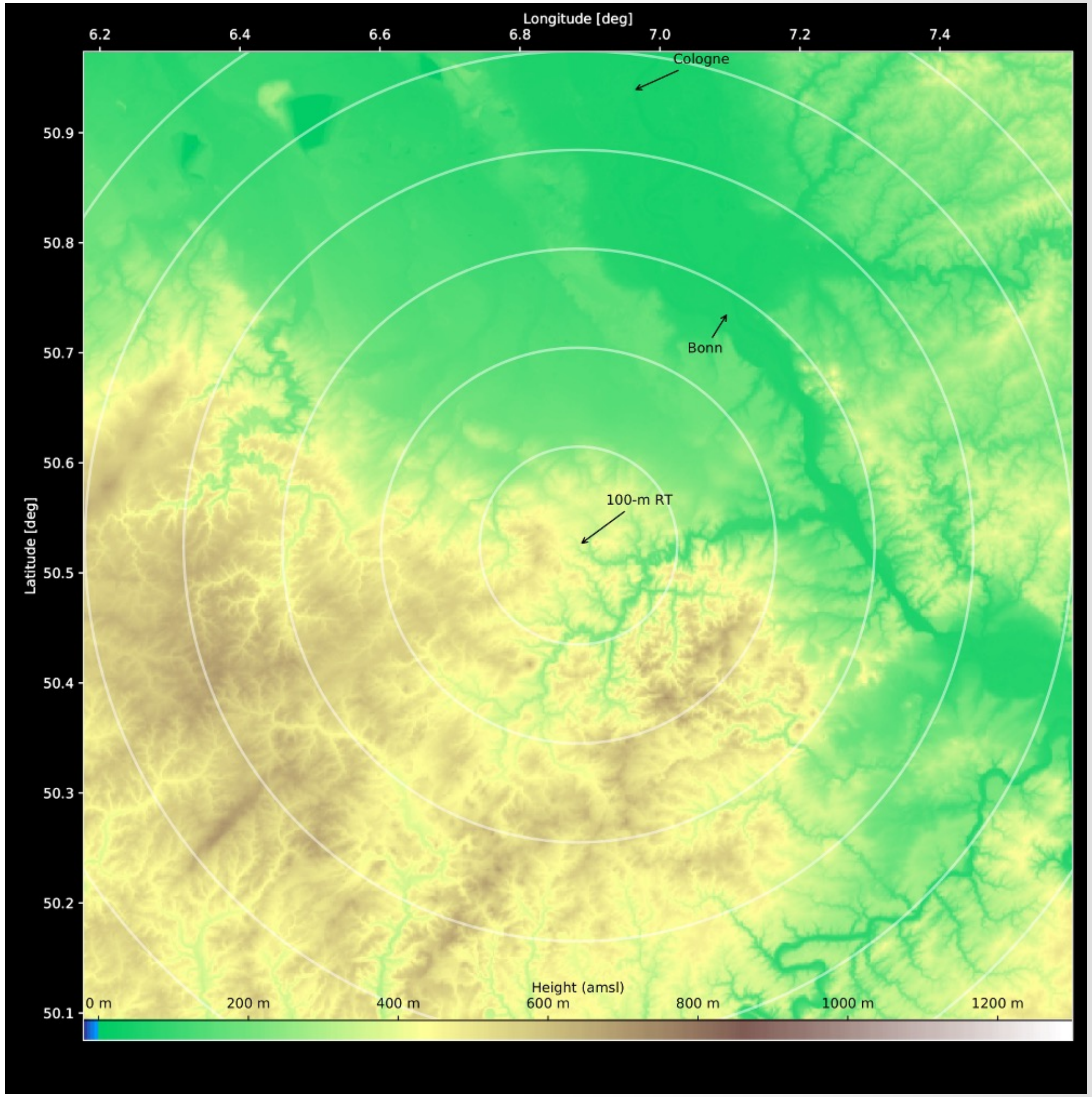

https://github.com/bwinkel/pycraf

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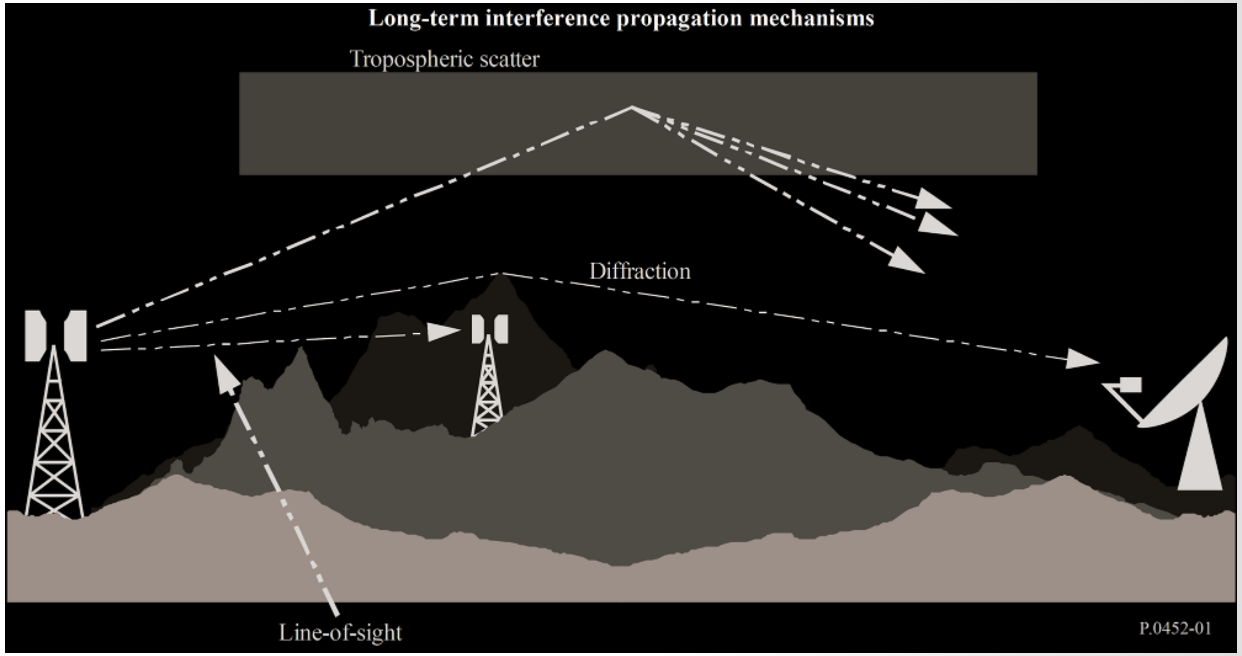

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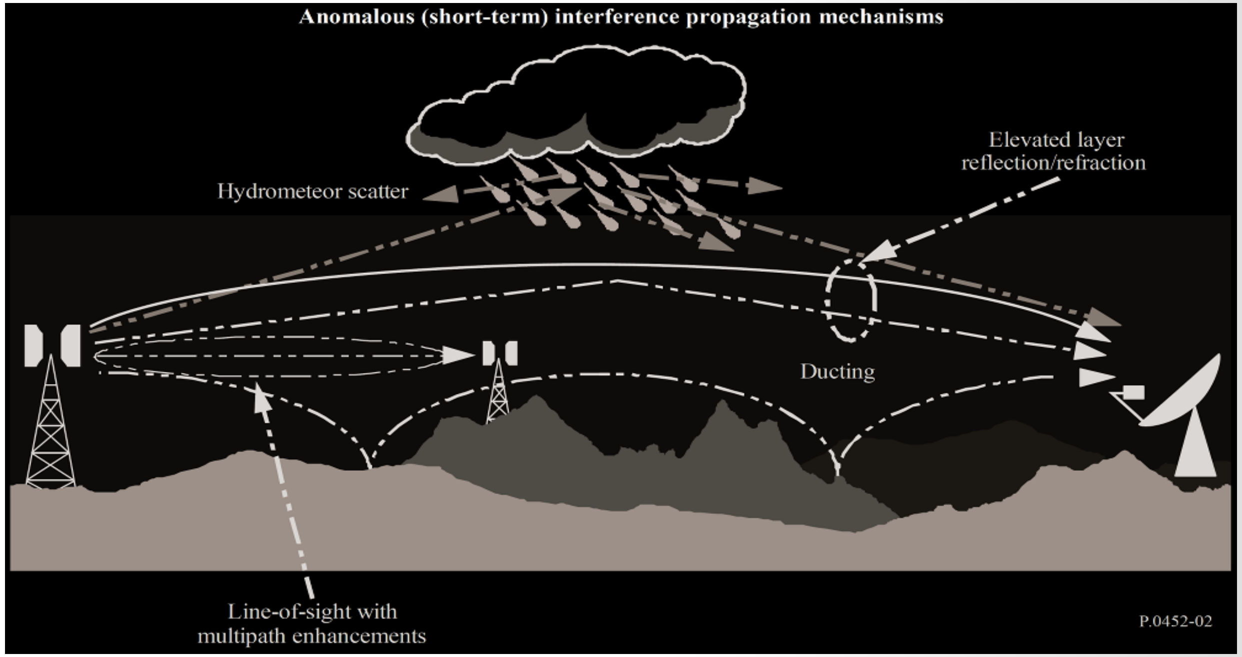

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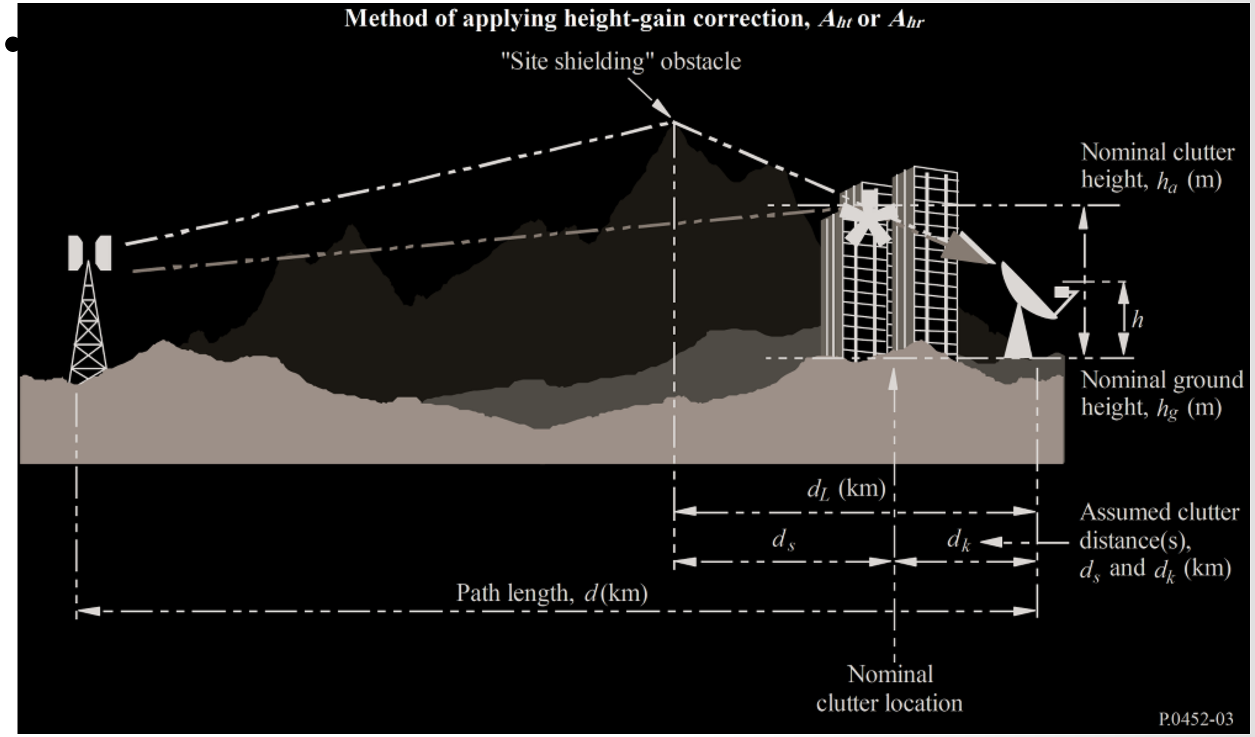

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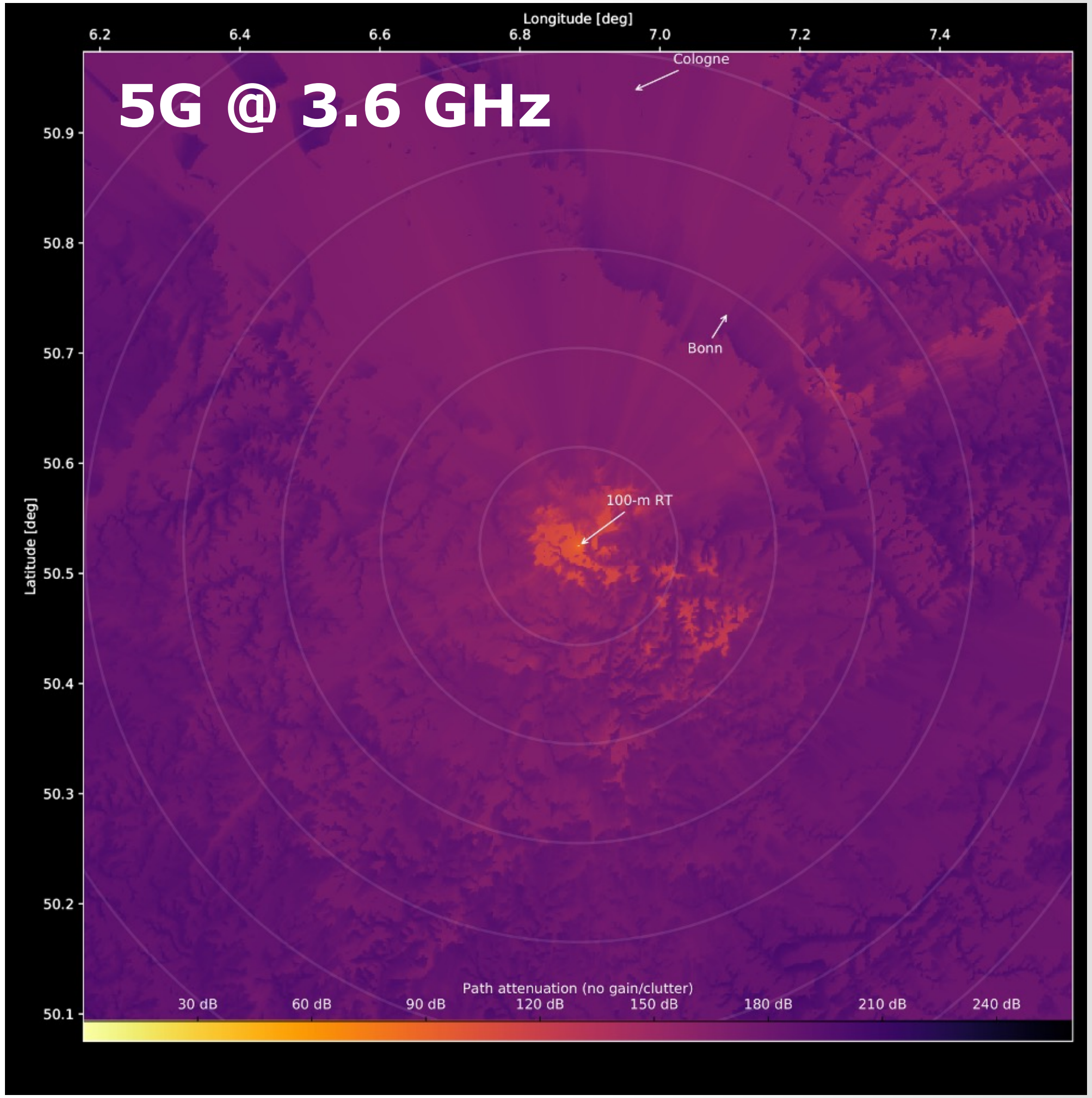

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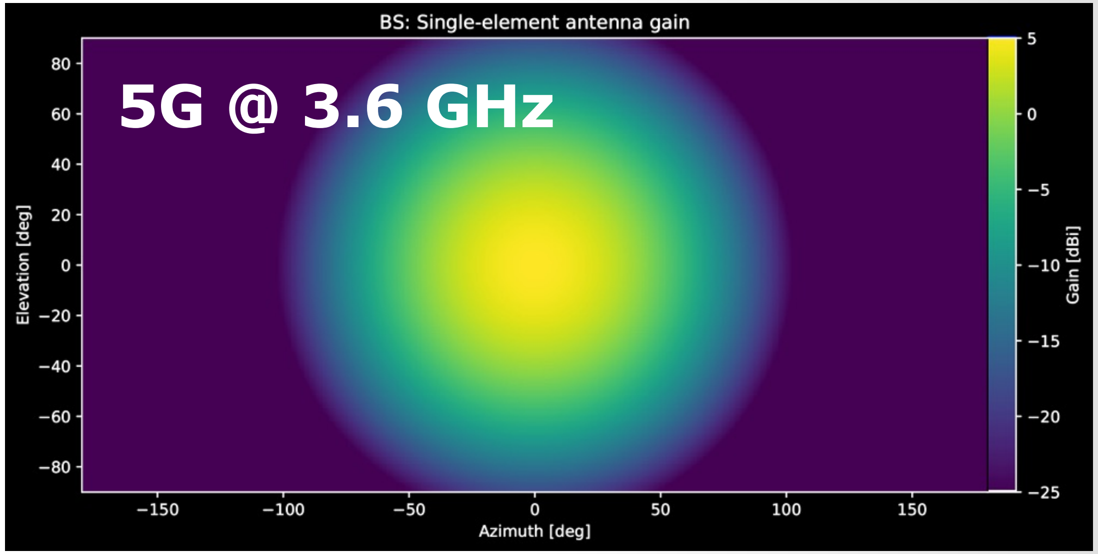

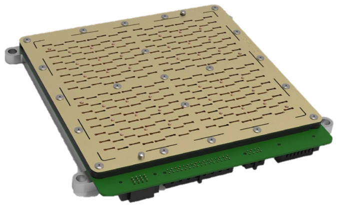

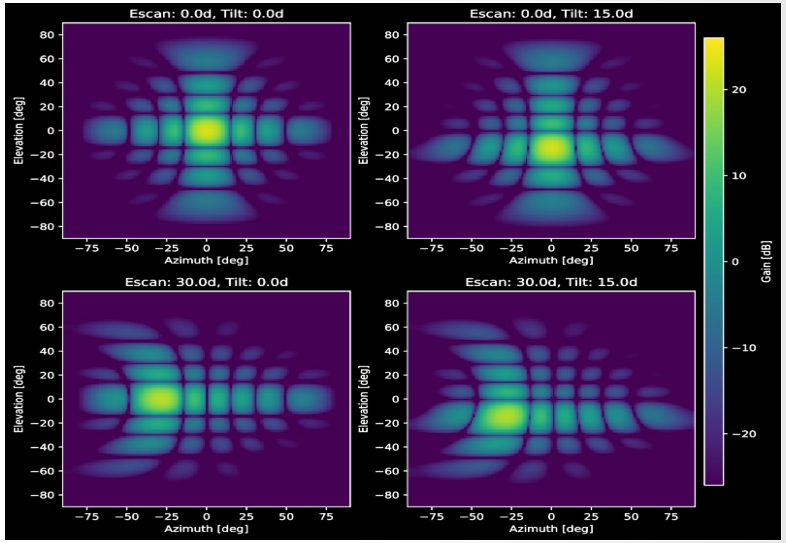

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TABLE 1

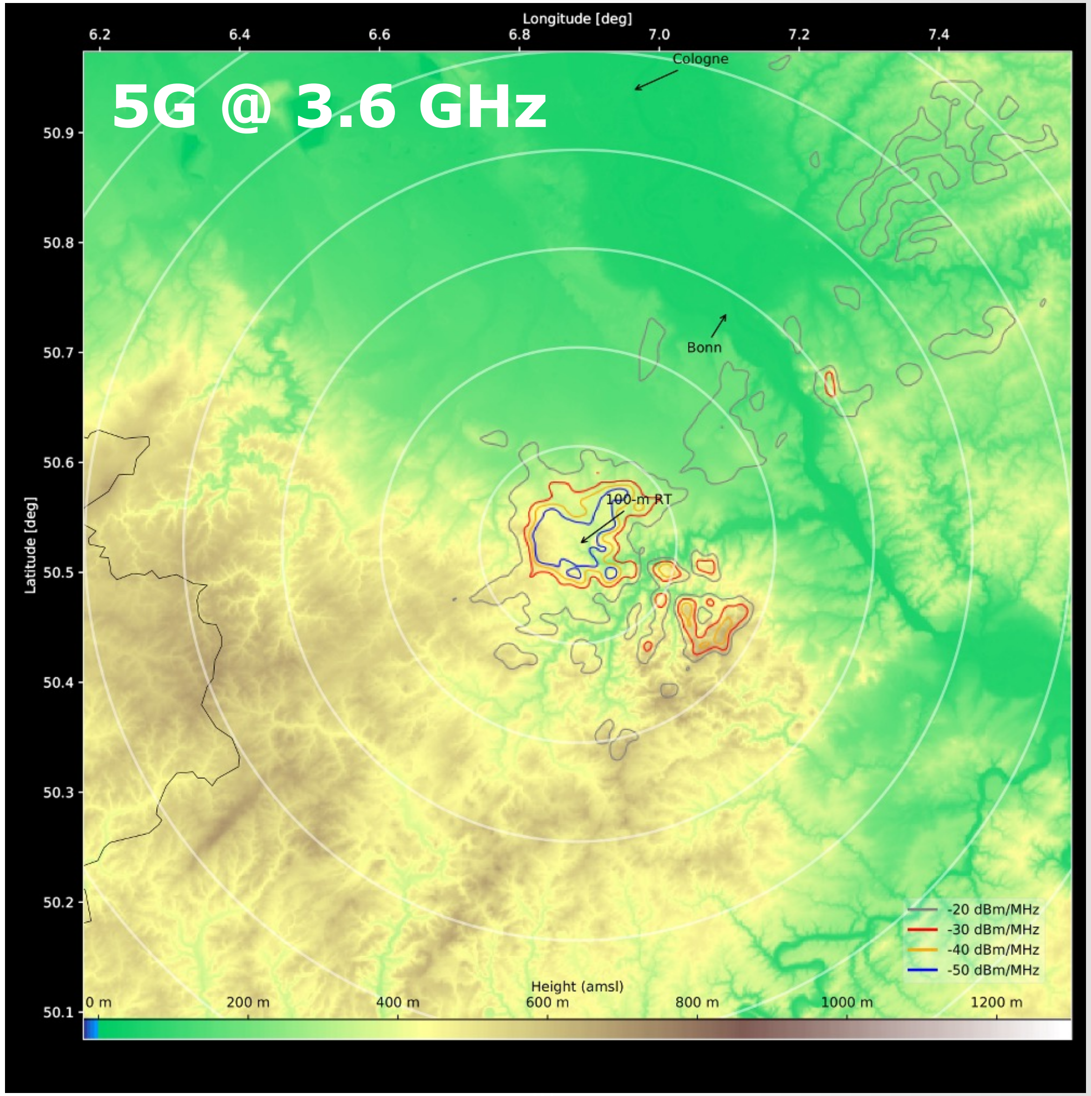
Threshold levels of interference detrimental to radio astronomy continuum observations

Centre frequency [(1)] f_c (MHz)	Assumed bandwidth Δf (MHz)	Minimum antenna noise temperature T_A (K)	Receiver noise temperature T_R (K)	System sensitivity[(2)] (noise fluctuations): Temperature ΔT (mK)	System sensitivity[(2)] (noise fluctuations): Power spectral density ΔP (dB(W/Hz))	Threshold interference levels[(2) (3)]: Input power ΔP_H (dBW)	Threshold interference levels[(2) (3)]: pfd $S_H \Delta f$ (dB(W/m^2))	Threshold interference levels[(2) (3)]: Spectral pfd S_H (dB(W/(m^2 · Hz)))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
13.385	0.05	50 000	60	5 000	–222	–185	–201	–248
25.610	0.12	15 000	60	972	–229	–188	–199	–249
73.8	1.6	750	60	14.3	–247	–195	–196	–258
151.525	2.95	150	60	2.73	–254	–199	–194	–259
325.3	6.6	40	60	0.87	–259	–201	–189	–258
408.05	3.9	25	60	0.96	–259	–203	–189	–255
611	6.0	20	60	0.73	–260	–202	–185	–253
1 413.5	27	12	10	0.095	–269	–205	–180	–255

- Defines RAS thresholds
- Usually: **2000 s** integration time

Software-supported compatibility studies

- Calculate un-/wanted emission levels of interferer
- Generate topographic maps (height profiles) from SRTM data
- Path propagation: implement ITU-R recommendations
- Infer received power flux densities/E-field strengths at victim receiver
- Infer received power levels
- **Compare with recommended limits:**
    - **Coordination zones**



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Software-supported compatibility studies

Single 4G BS

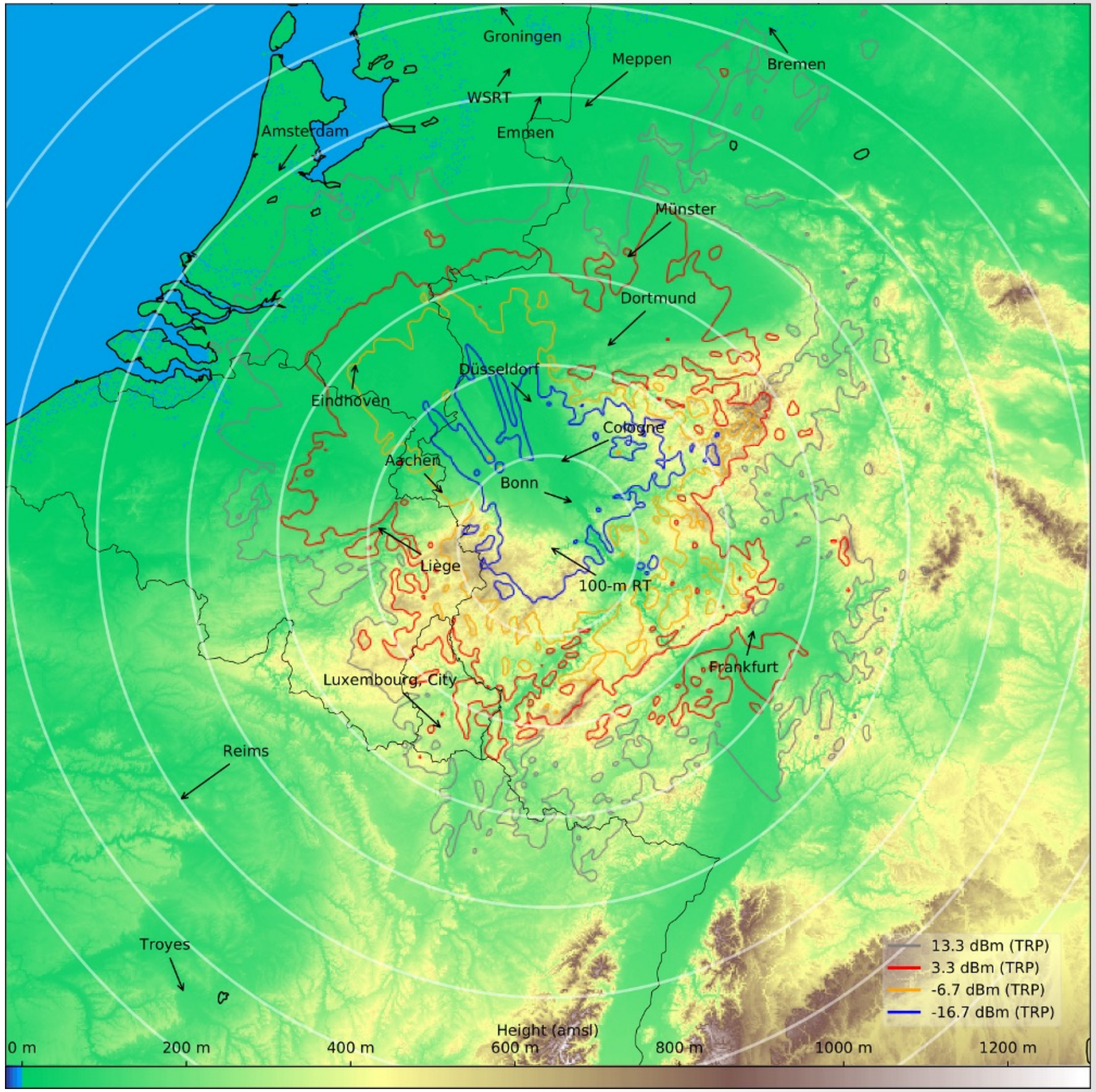
f = 2.7 GHz

Out-of-band: 3.3 dBm (TRP)

RAS limits: −177 dBm

Worst case: Beam towards RAS

(Gain: ~18 dBi)



https://github.com/bwinkel/pycraf

Software-supported compatibility studies

Single 5G BS

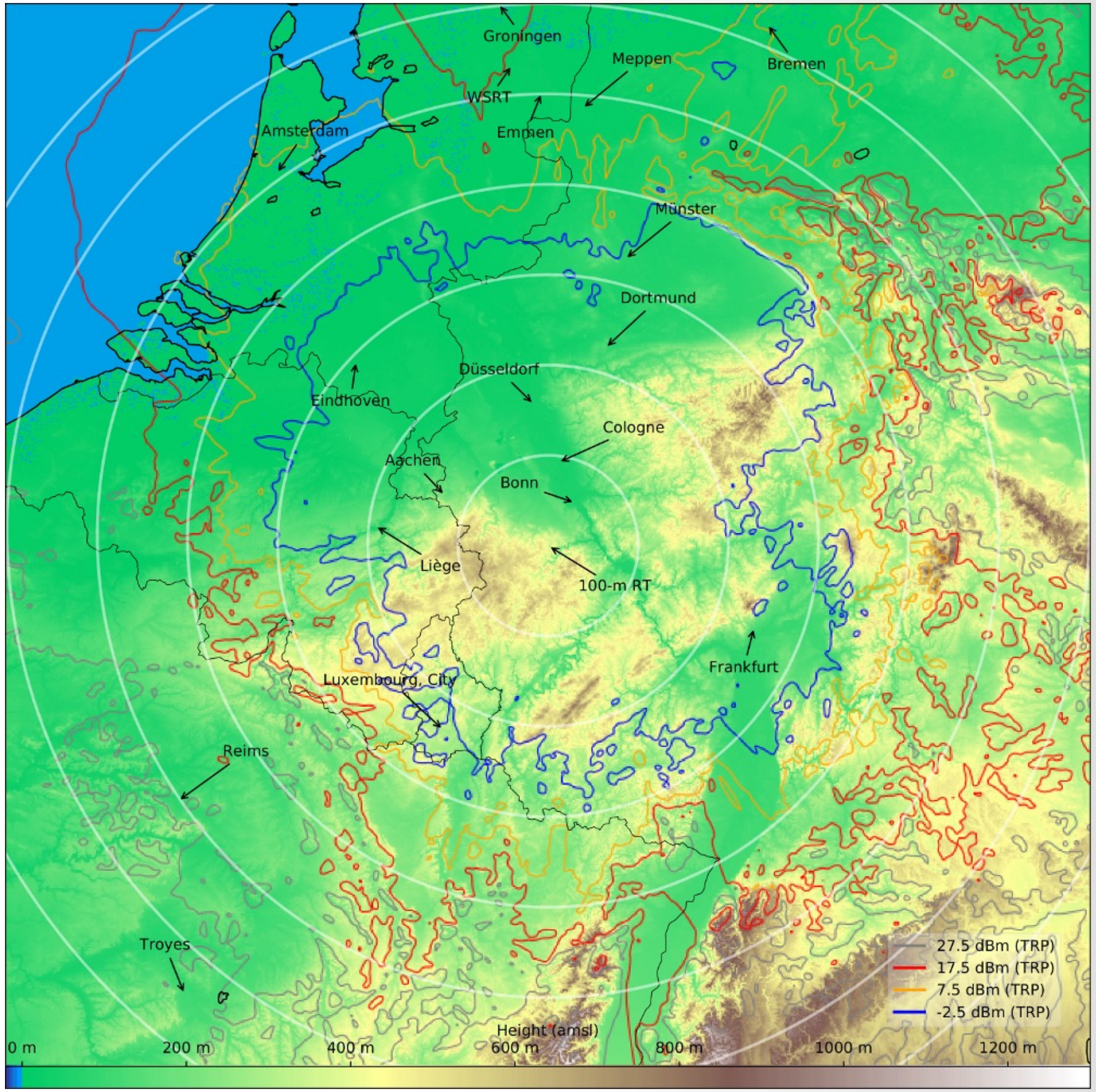
f = 2.7 GHz

Out-of-band: 17.5 dBm (TRP)

RAS limits: −177 dBm

Worst case: Beam towards RAS

(Gain: ~25 dBi)



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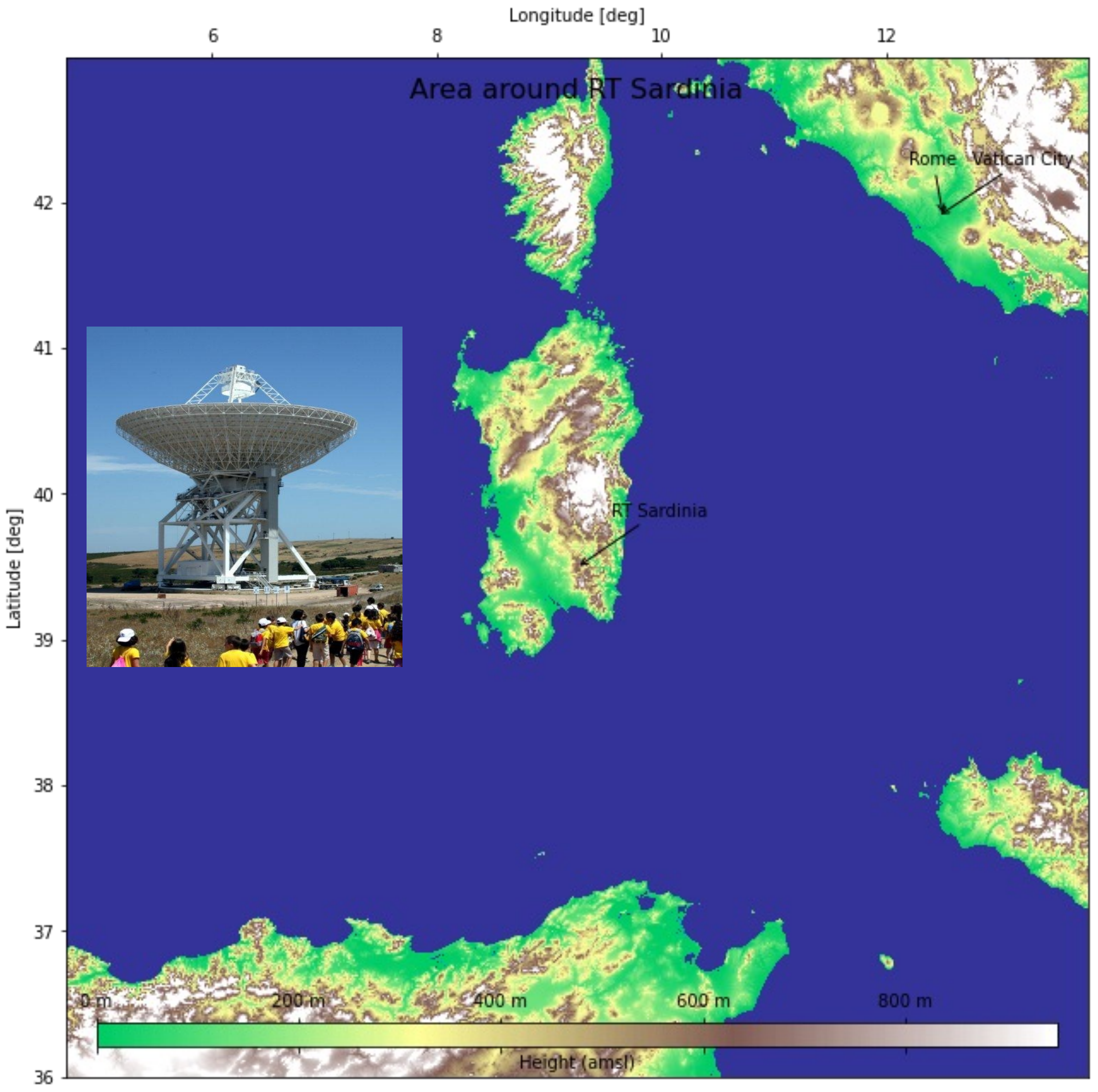
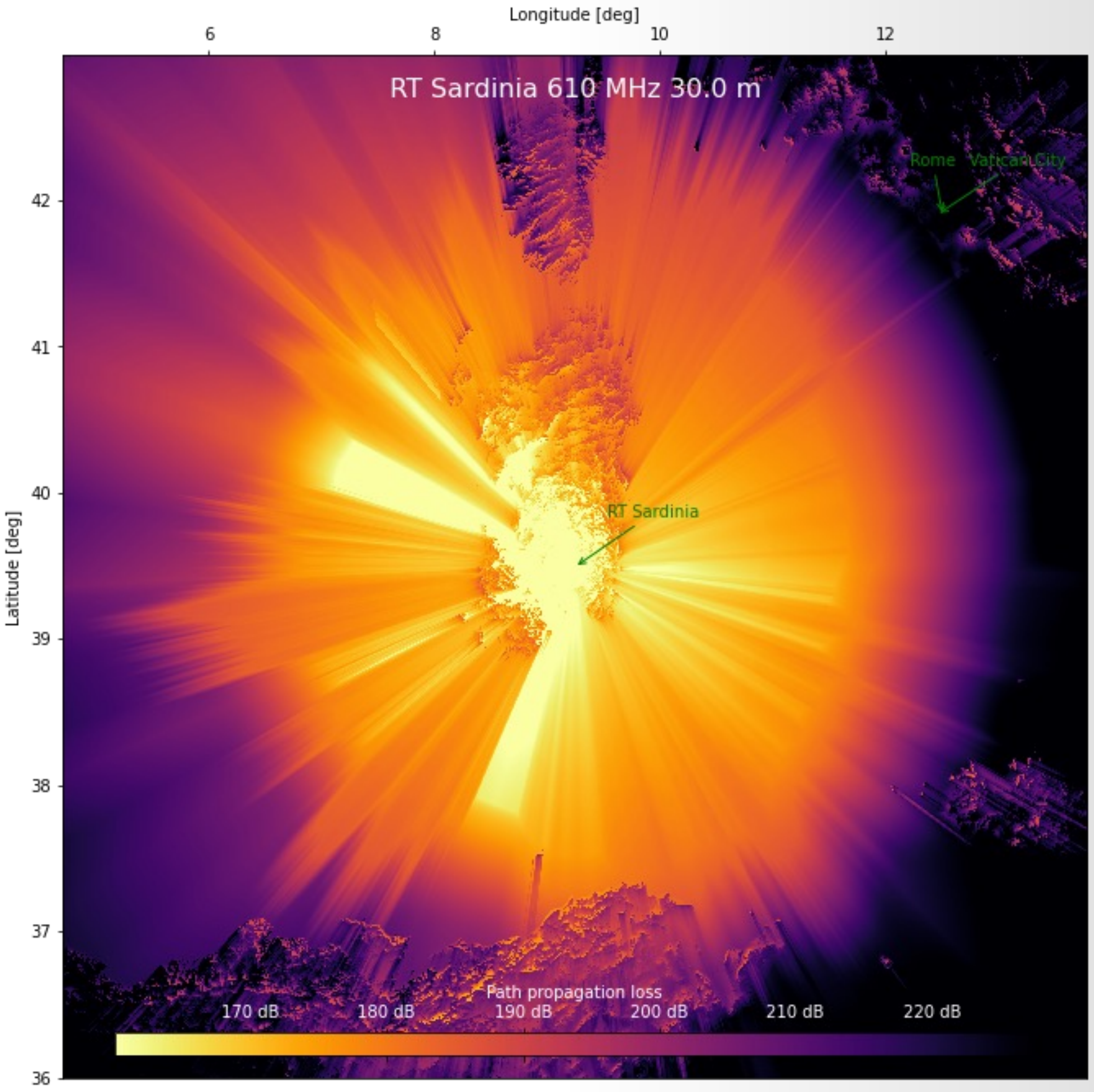
Can we assume a flat earth?





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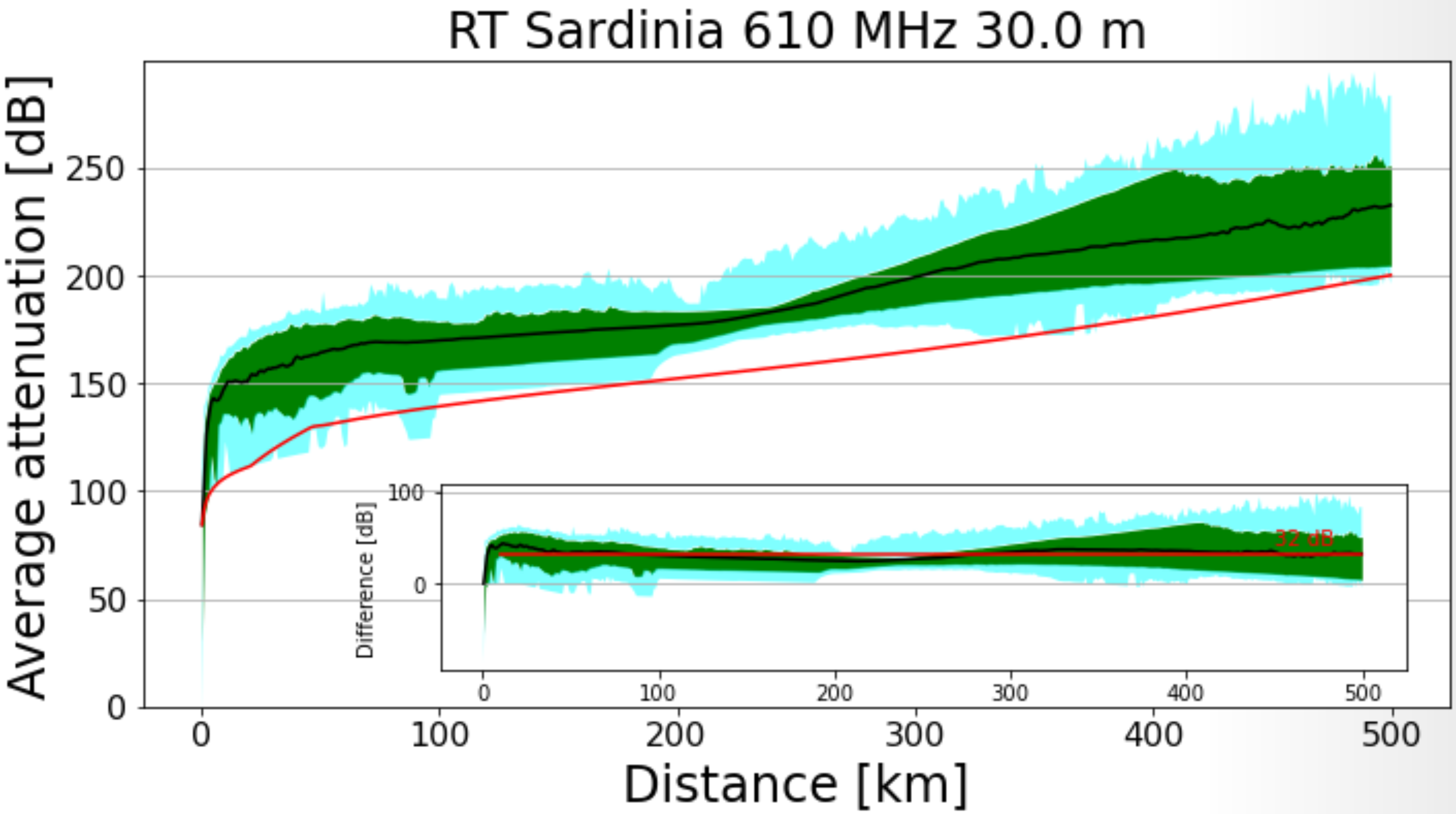

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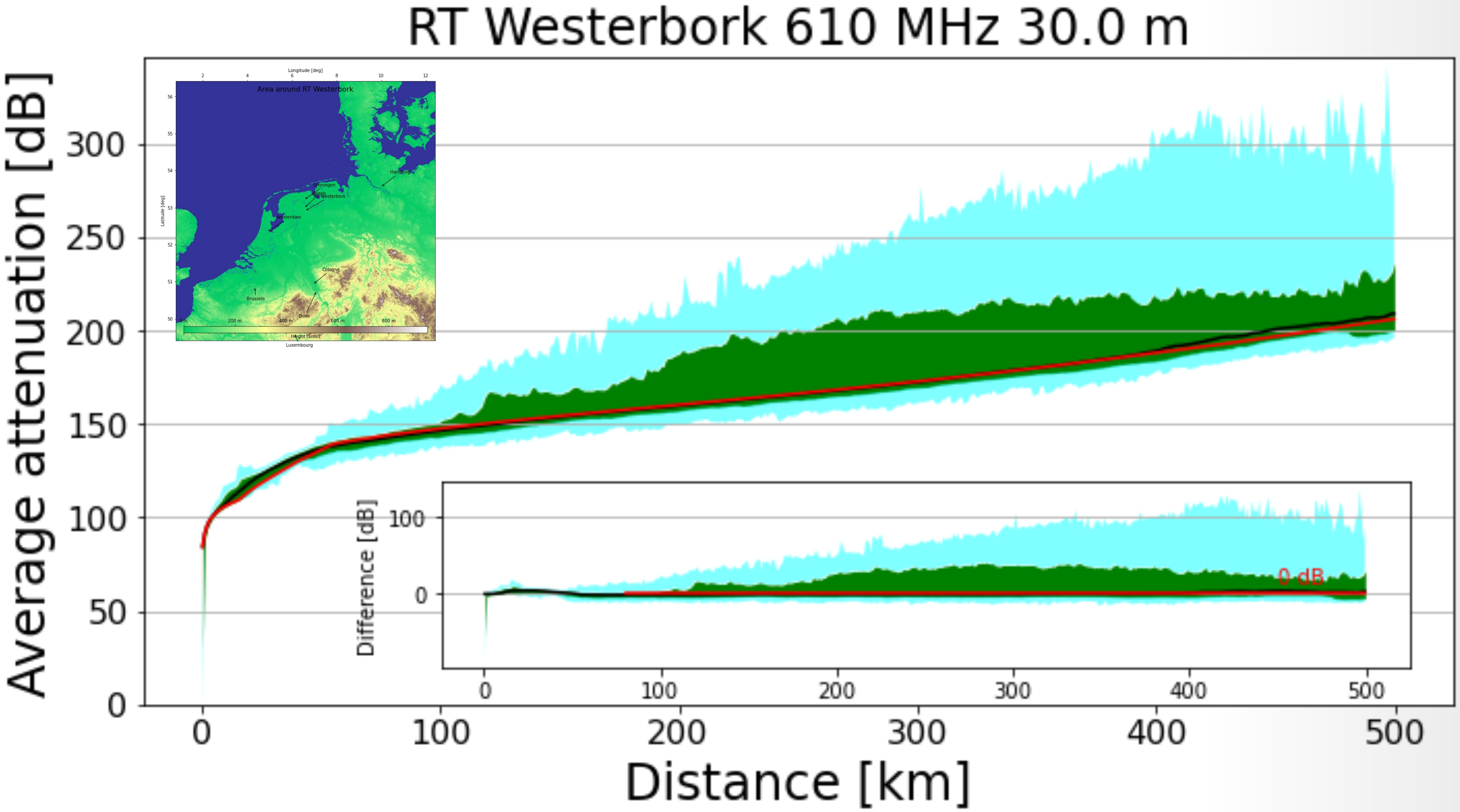


CRAF

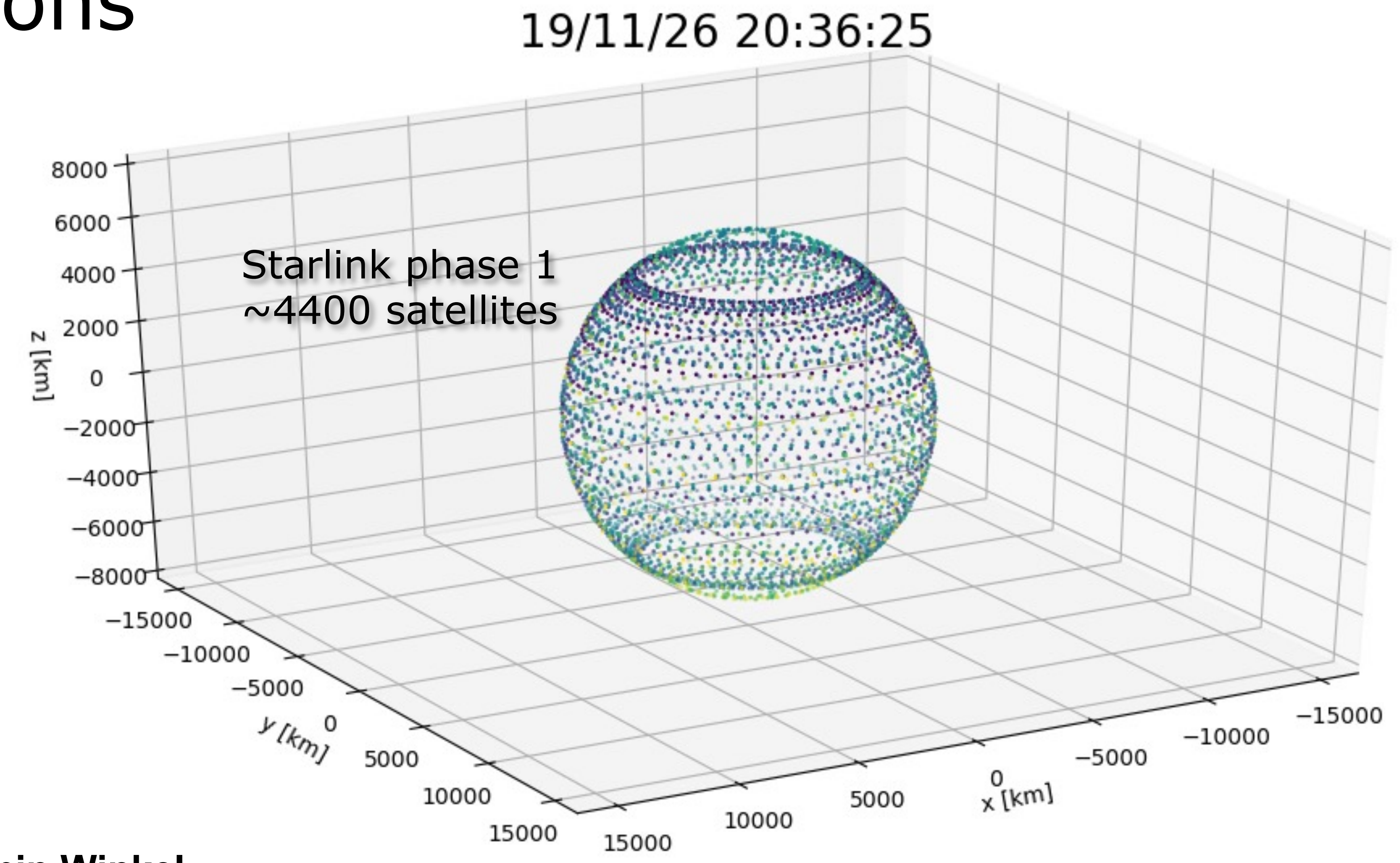
Can we assume a flat earth?

MAX PLANCK INSTITUTE FOR RADIO ASTRONOMY

RAS station	Latitude	Longitude	Height above ground	Average difference in attenuation 610 MHz 30 m/1.5 m	Average difference in attenuation 6.65 GHz 20 m/1.5 m
	(deg)	(deg)	(m)	(dB)	(dB)
Effelsberg	50.52483	6.88361	50	29/31	27/30
Westerbork	52.91474	6.60334	22.5	0/1	0/2
Sardinia	39.49278	9.24500	32	32/31	34/33
Yebes	40.52467	-3.08694	20	25/26	25/26
Jordrell Bank	53.23611	-2.30722	38	20/19	18/18
Onsala	57.39306	11.91778	12.8	10/12	9/11
Nançay	47.37333	2.197222	2.0	20/21	23/26

In general we should... **In individual cases we should not...**

Satellite simulations



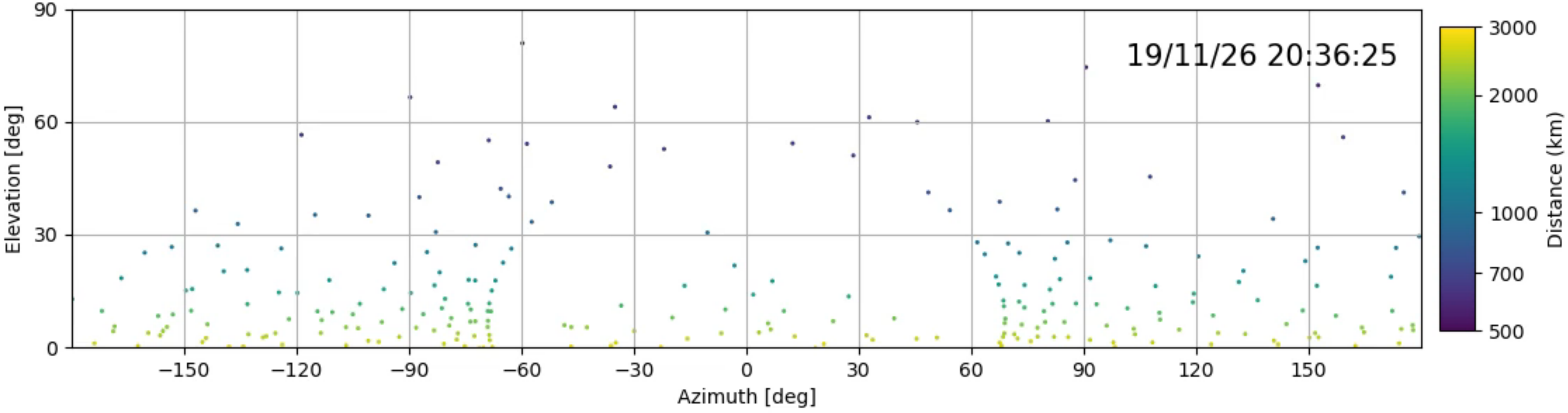
Courtesy: Benjamin Winkel

Orbit calculations powered by cysgp4

https://github.com/bwinkel/cysgp4

Satellite simulations

Observer at geographical latitude of 50°



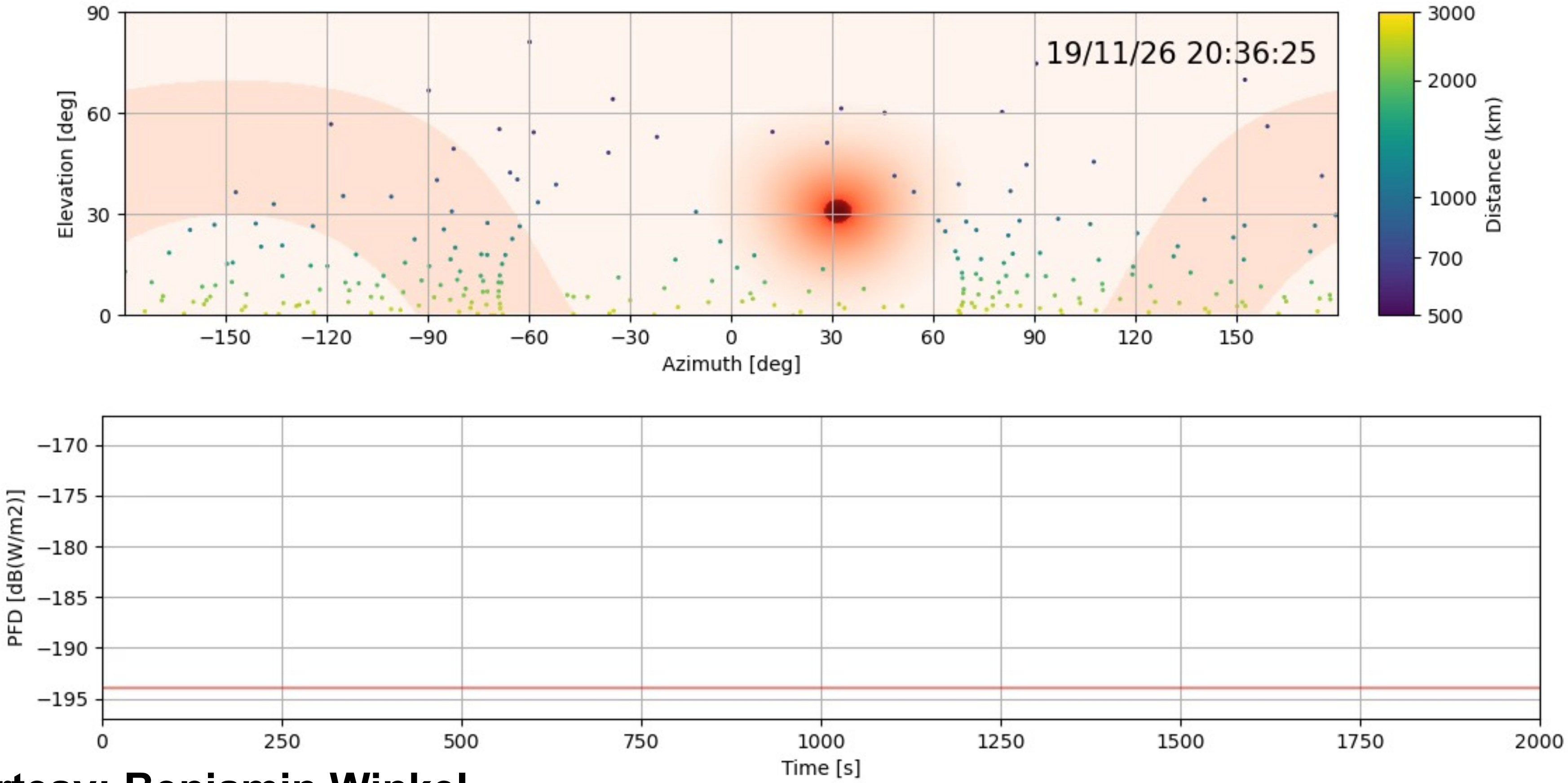
Courtesy: Benjamin Winkel

Orbit calculations powered by cysgp4

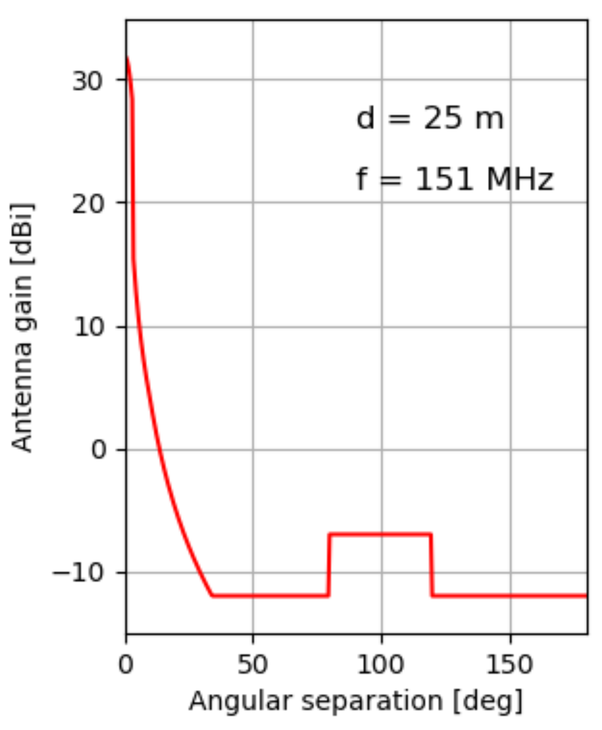
https://github.com/bwinkel/cysgp4

Satellite simulations: received power

Convolution of sky “brightness” with telescope antenna pattern



Rec. ITU-R RA.1631

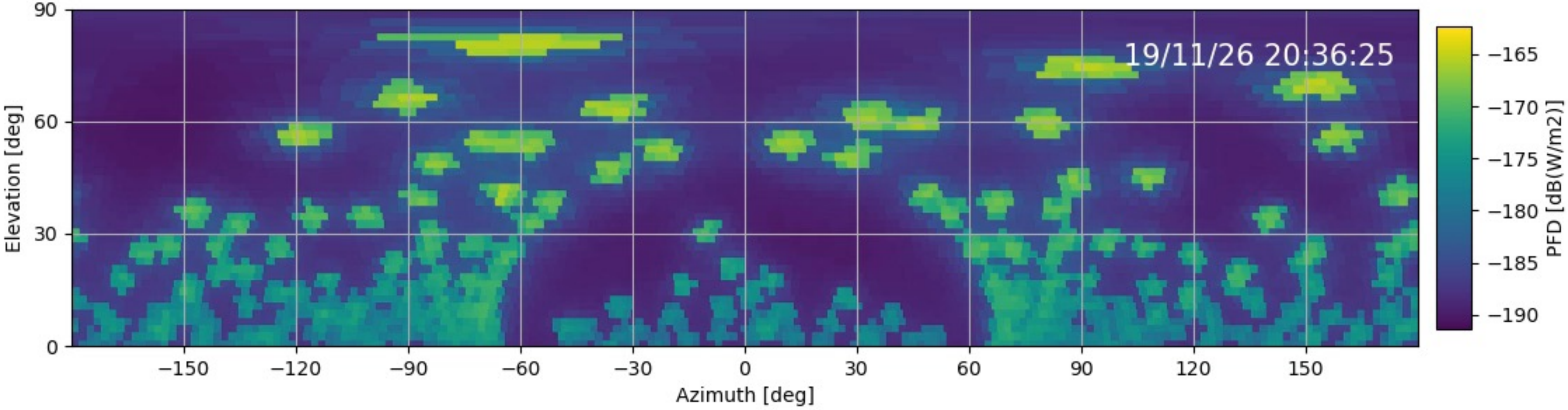


Courtesy: Benjamin Winkel

Orbit calculations powered by cysgp4 https://github.com/bwinkel/cysgp4

Satellite simulations: received power

Repeat for all positions on the sky



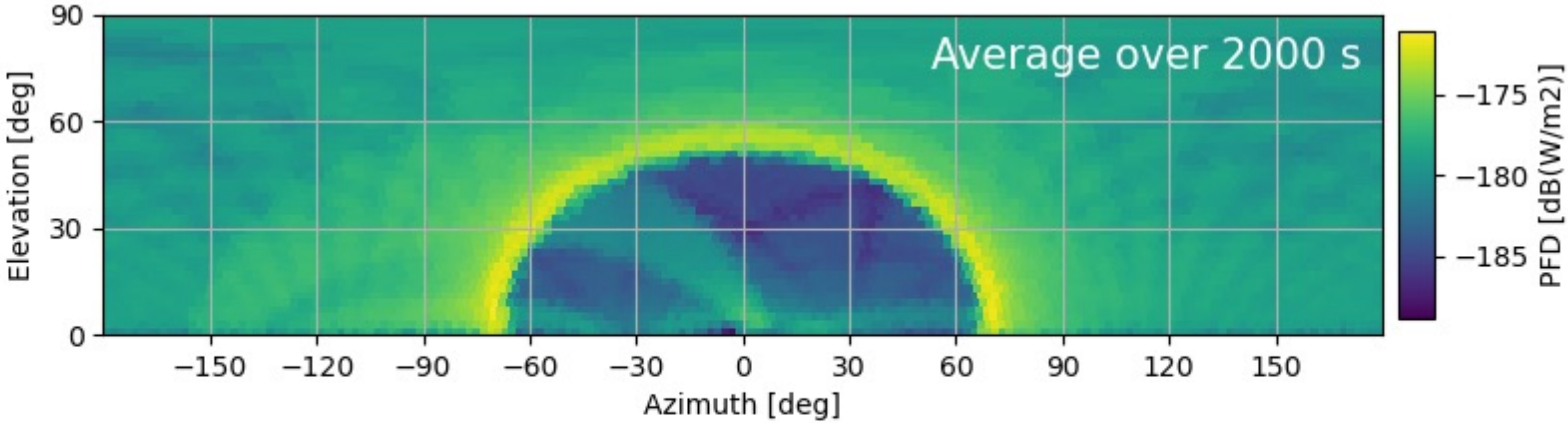
Courtesy: Benjamin Winkel

Orbit calculations powered by cysgp4

https://github.com/bwinkel/cysgp4

Satellite simulations: received power

Integrate over time



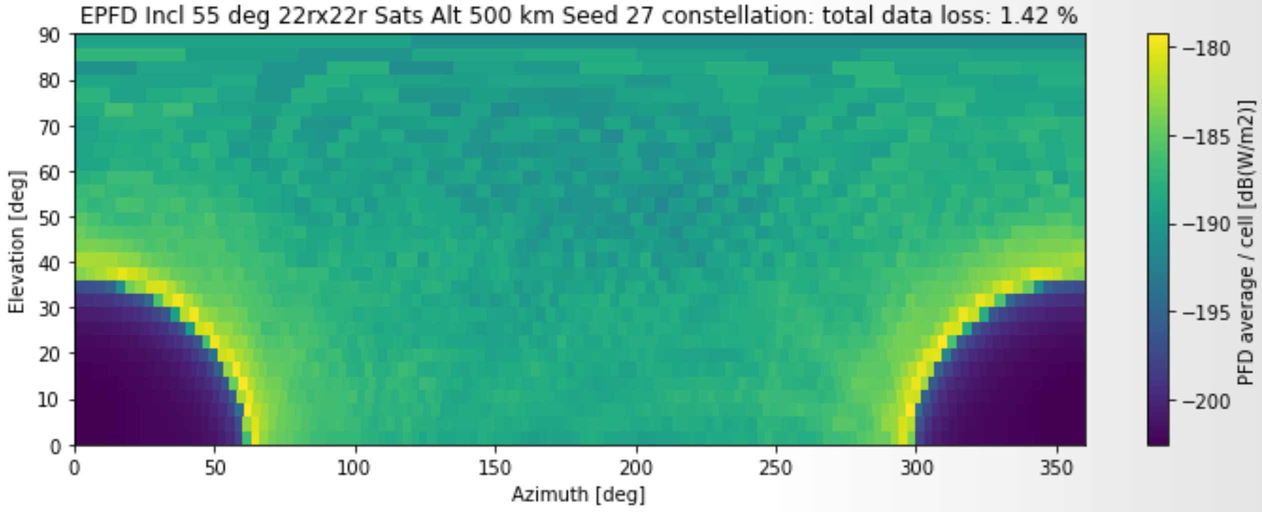
Courtesy: Benjamin Winkel
Orbit calculations powered by cysgp4
https://github.com/bwinkel/cysgp4

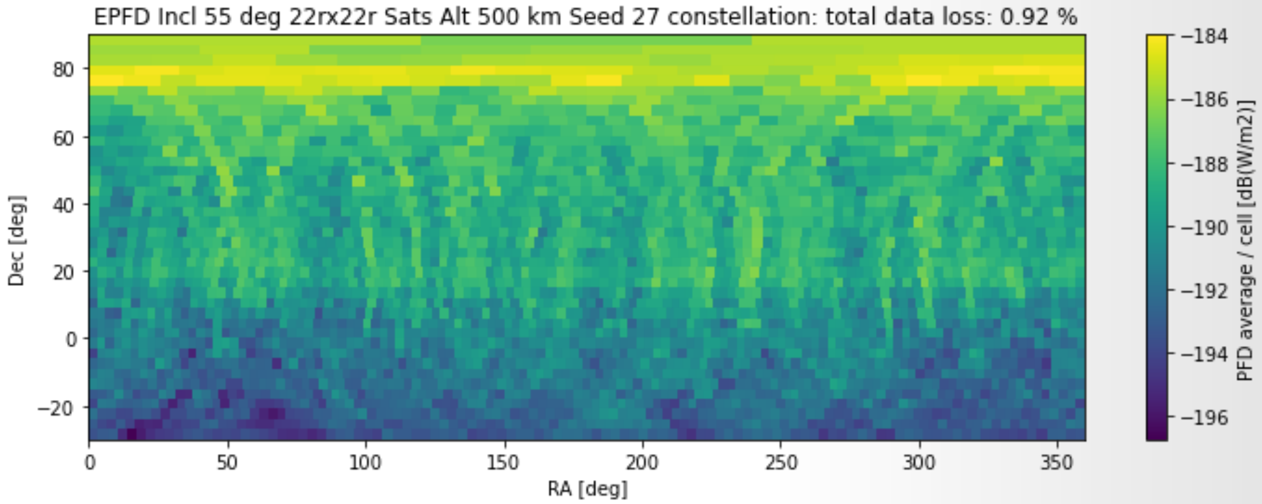
Satellite simulations: statistics (ITU-R M.1583) and reference systems

Example:

- 22 equidistant orbital planes
- Circular orbits
- 55° inclination
- 22 Satelites per plane
- 500 km altitude
- Emitting isotropically
- Telescope diameter 25m
- Geographical latitude 50°
- 100 simulations

- 2 h processing on average workstation





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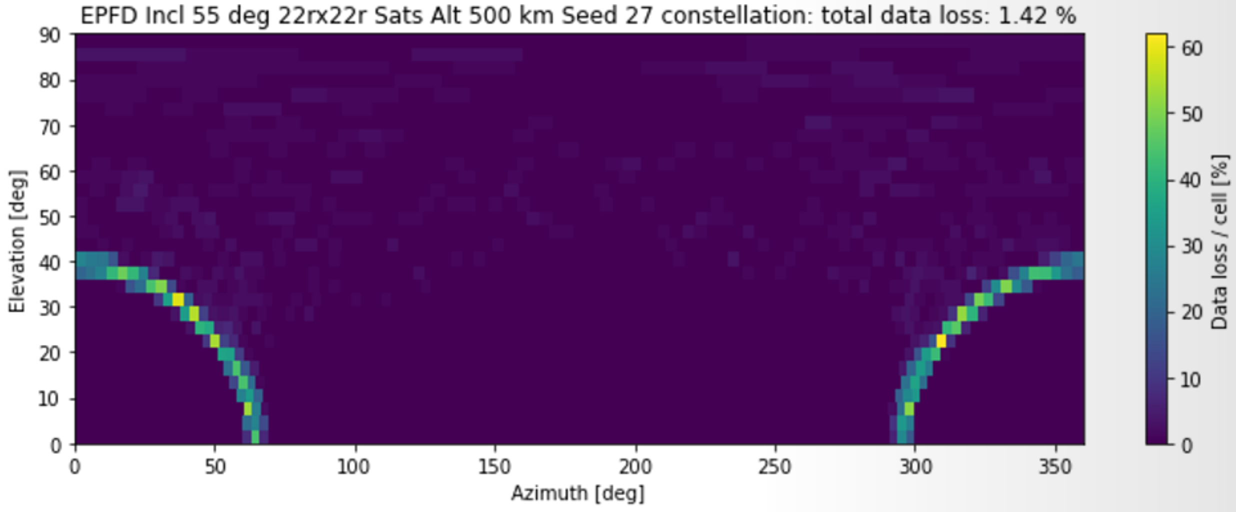
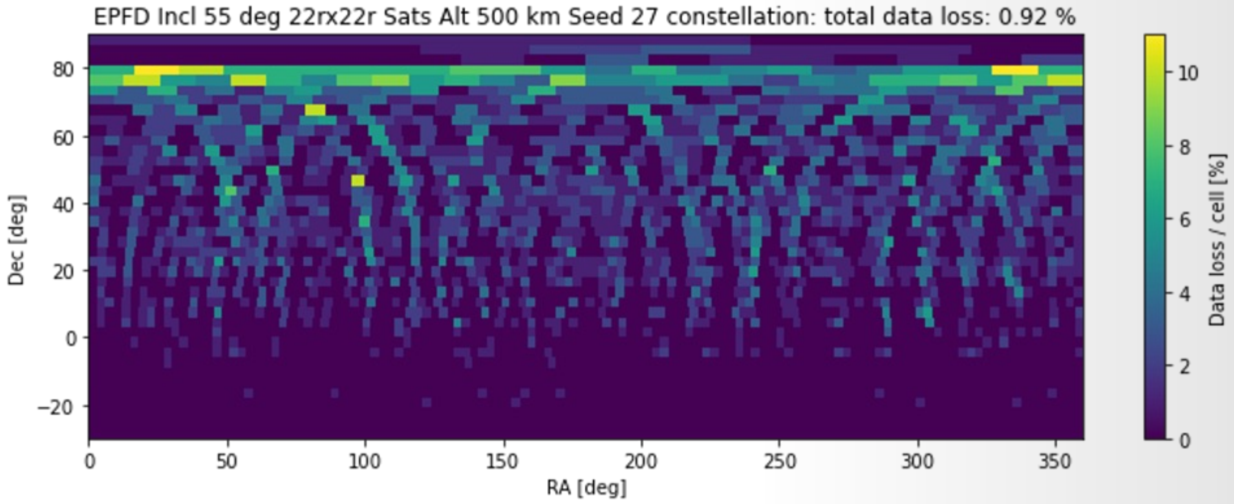
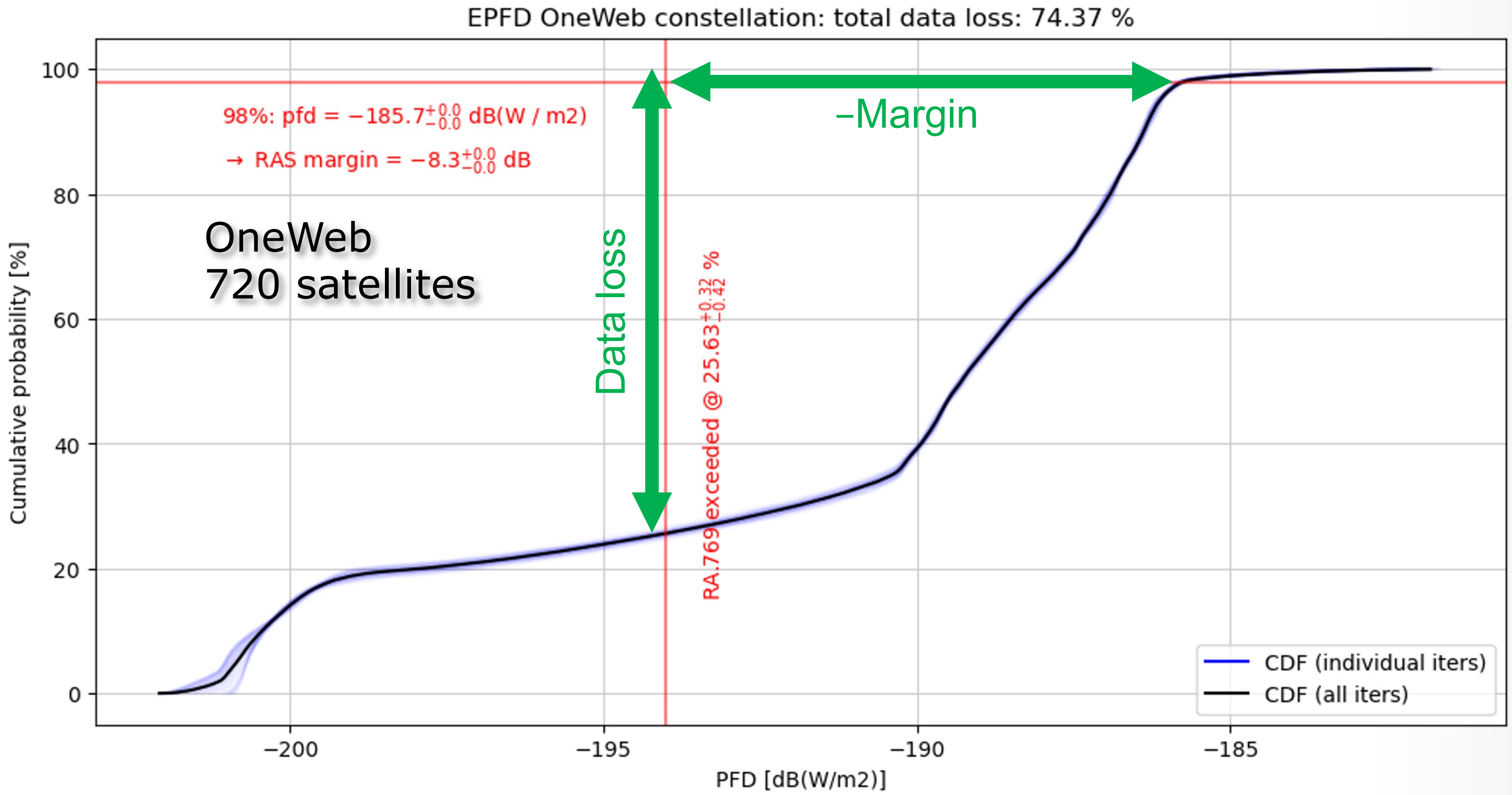




Satellite simulations: statistics (ITU-R RA.1513)

Cumulative distribution: how many samples are below a given PFD value?



ECC Report 271 and consequences

“Compatibility and sharing studies related to NGSO satellite systems operating in the FSS bands 10.7-12.75 GHz (space-to-Earth) and 14-14.5 GHz (Earth-to-space)”

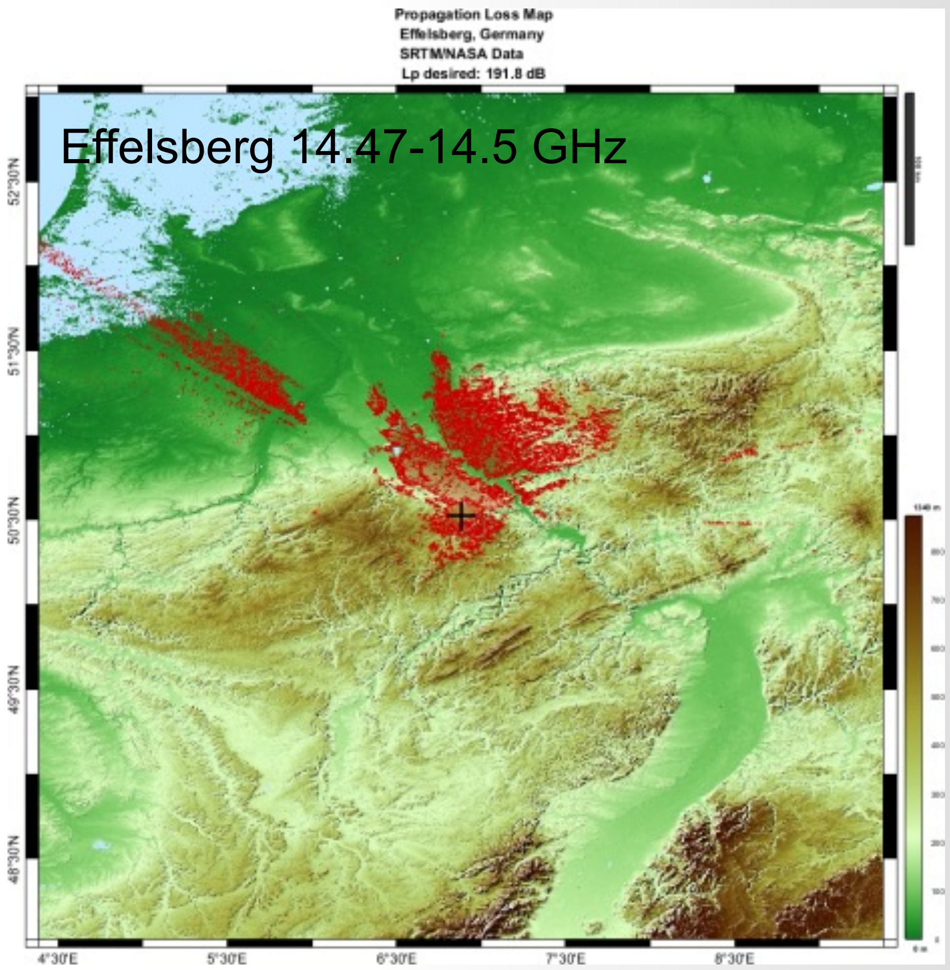
- ECC report -> EU regulatory framework
- Last update: 23 April 2021
- OneWeb and SpaceX
- No aggregate effects of the two systems
- RAS bands 10.6 – 10.7 GHz (primary and secondary) and 14.47 – 14.5 GHz (secondary)

Results:

- Requirement to switch off downlink between 10.7 and 10.95 GHz in visibility of RAS stations
- Protection zone for uplink required (depending on telescope)

Furthermore:

- Additional protection in Effelsberg, Wettzell, Yebes:
    - No direct illumination by Starlink



Satellite simulations: unintended radiation

Unintended Radiation:

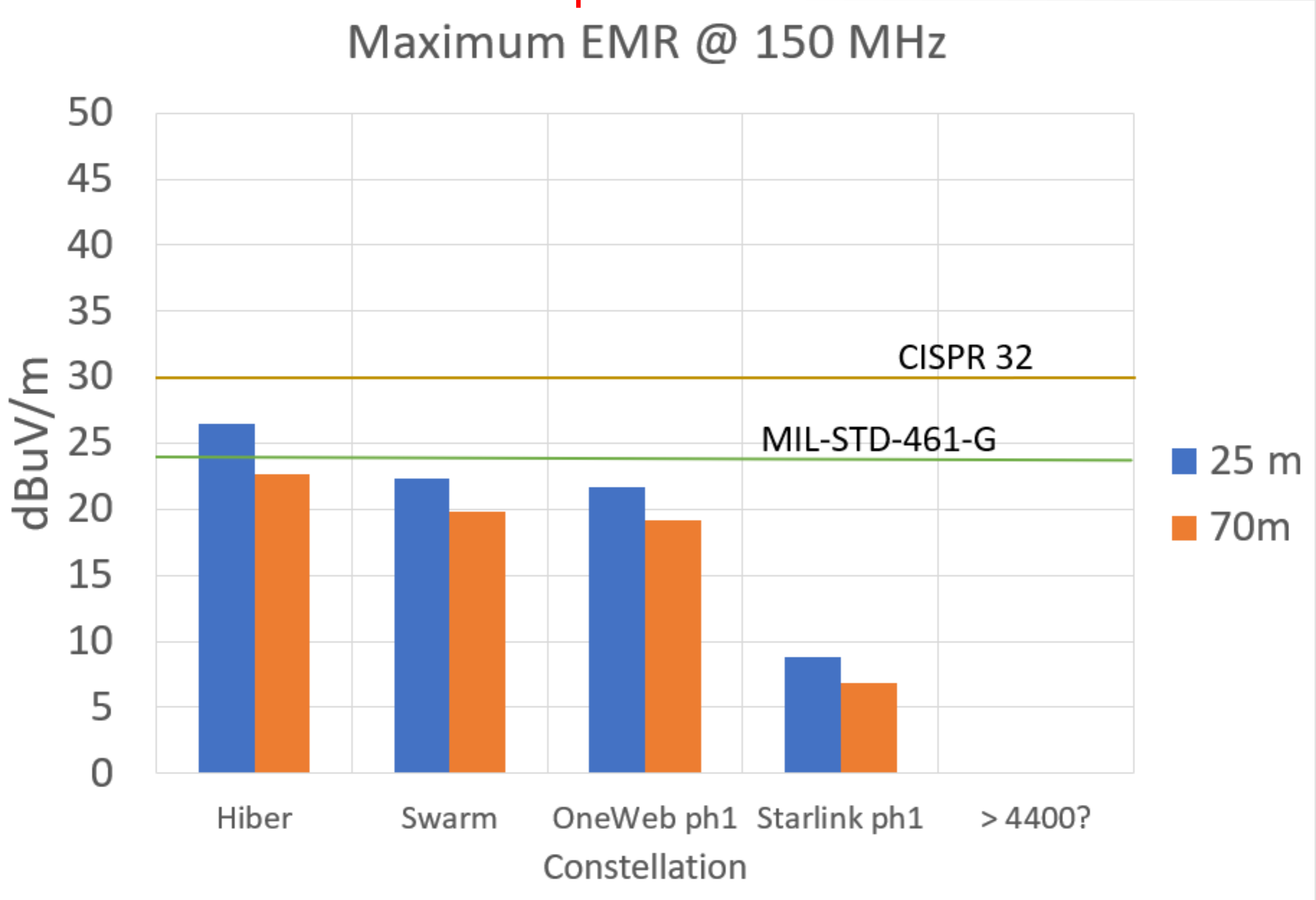
- Satellites do not emit from the transmitting devices -> unintended radiation
- Due to the sheer numner of satellites unintended radiation may cause problems for RAS

CRAF simulations indicate potential problem

- Stricter emission standards necessary
- Lab measurements should be mandatory
- Consider RAS bands (not only for applications/services regulated by ITU-R)

Measurements underway

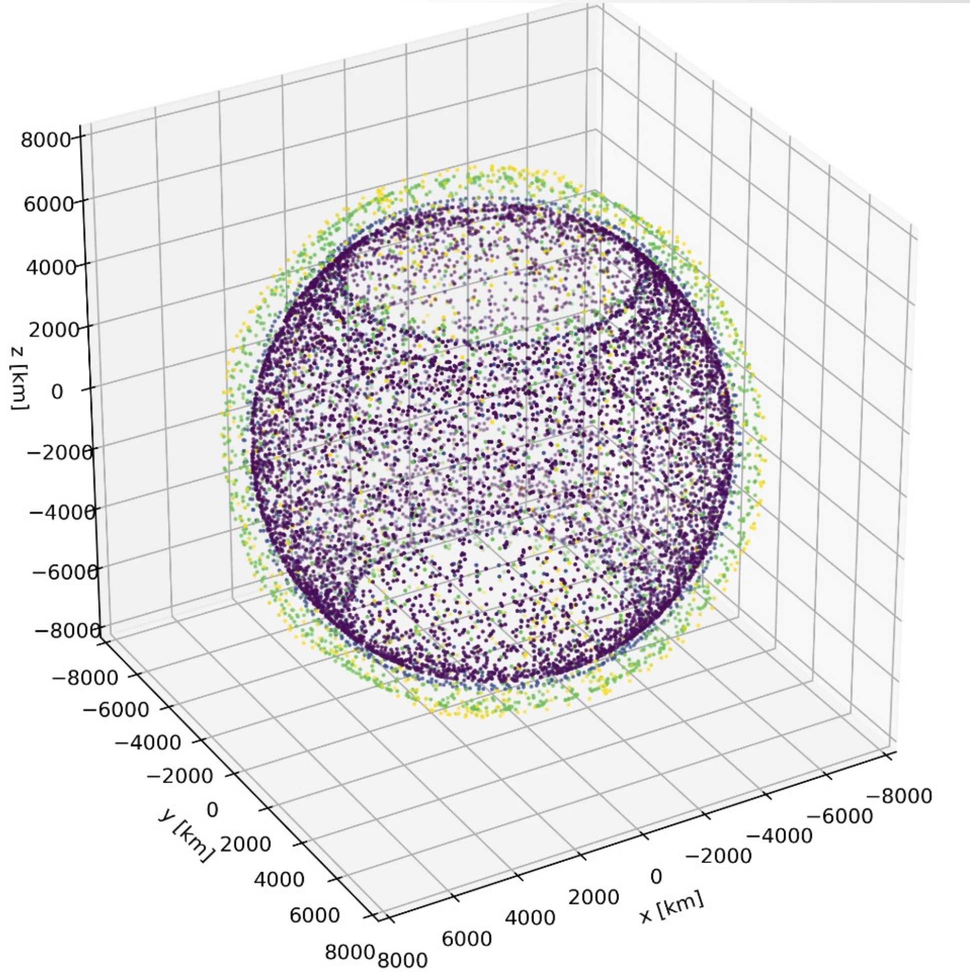
Required



Beyond the regulations

- Outer space largely unregulated
- Uncontrolled launches of satellites
- Aggregate effects partly unregulated
- High demand for unused frequencies

  → Less space for opportunistic observations or even secondary and footnote allocations under pressure



→ Need for other means to protect the skies

- Networking
- Public Awareness
- Direct political interventions

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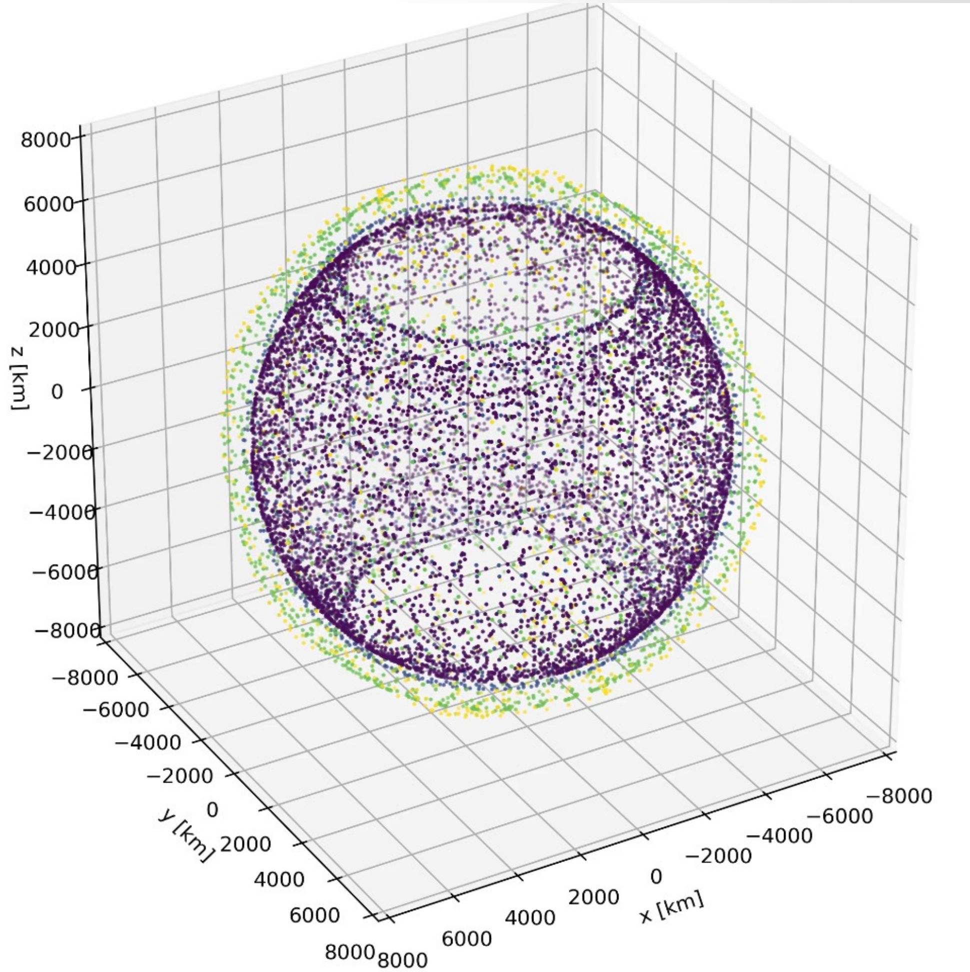


→ Need for other means to protect the skies

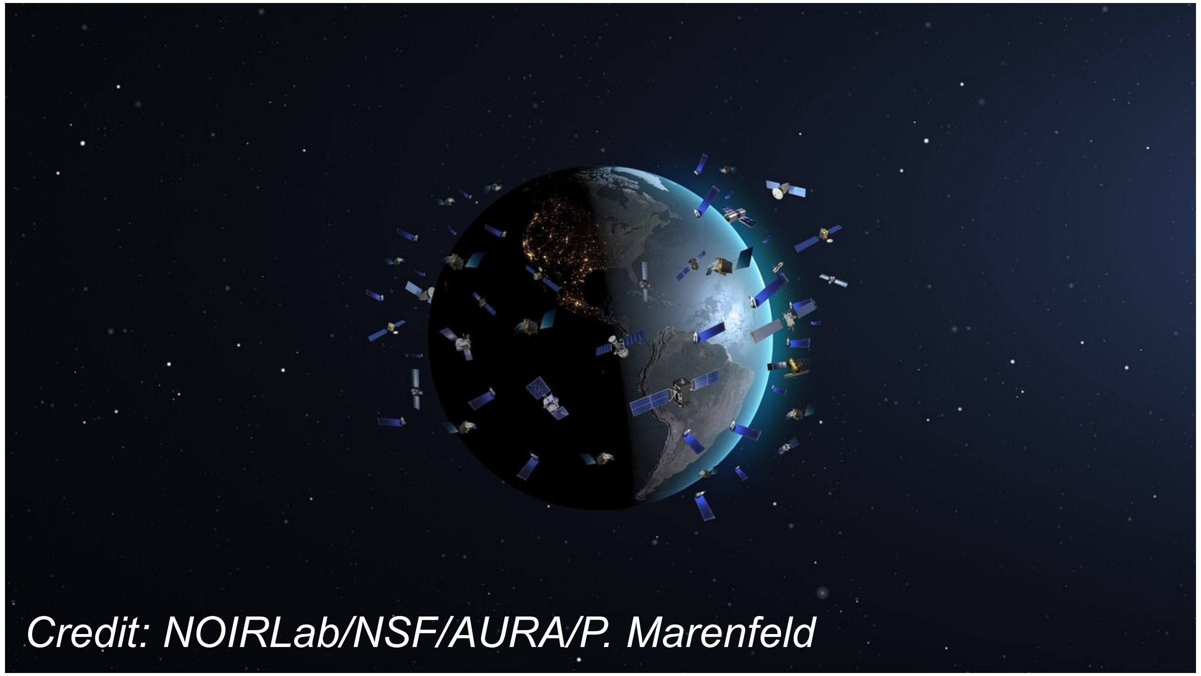
- Networking
- Public Awareness
- Direct political interventions

CRAF

IAU centre for the protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS)

MAX PLANCK INSTITUTE FOR RADIO ASTRONOMY

- Inaugurated in April 2022
- Optical and Radio Astronomy
- CRAF (members) participating
- ORP (members) participating
- Involvement in Committee On Peaceful Uses Of Outer Space



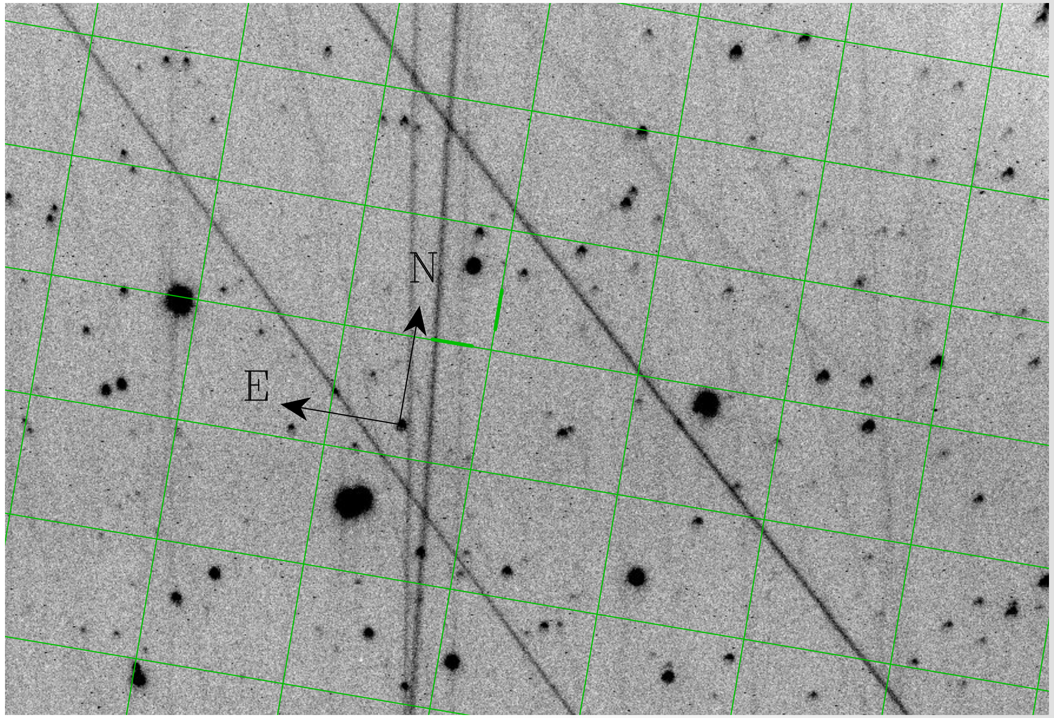
Credit: NOIRLab/NSF/AURA/P. Marenfeld

Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference

CPS

IAU NOIRLab SKAO

And optical astronomy?



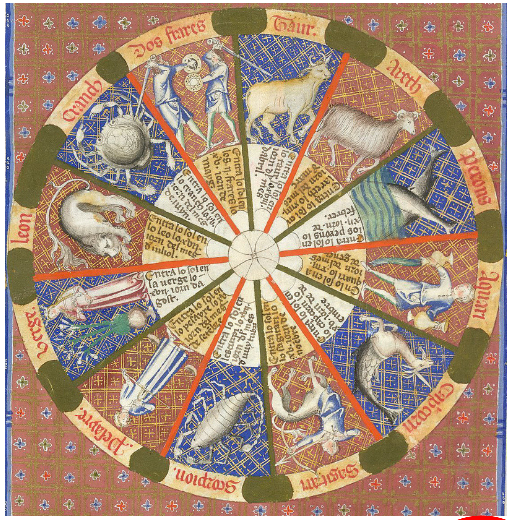
And optical astronomy?

Sutherland night sky (Credit: Sterland Stargazing)

And culture?

Threatened

Credit: Marie-Lan Nguyen



Inanna (Sumerian goddess of love and fertility)

Credit: Fæ

Venusplates Ammi-saduqas (in original um 1680 B.C.)

Sky disc of Nebra (2100-1700 v.Chr.)

And biodiversity and human health?

Credit: Moshe Spinel

Fo... (partly hidden)

Credit: Chad Fitz

Threatened

Summary

- The task to preserve radio astronomical frequencies for scientific work is demanding and requires intensive work and collaboration across national borders
- Several astronomical committes engage in regulatory processes
- Harmful interference from satellites is predictable using regulatory prescriptions
- Due to permanent use of the spectrum International Mobile Telecommunication (IMT) is a threat to radio astronomy
- Megaconstellations may become a threat through unintended radiation.
- Measurements of RFI required and will be streamlined
- Regulatory processes might not provide sufficient protection

  → Establishment of extended advocacy tools (**CPS**)
- Not only radio astronomy is threatened but also other astronomical disciplines

M87 black hole. Credit: Event Horizon Telescope

Literature and assignments

- ITU Handbook on Radio Astronomy
- CRAF Handbook for Radio Astronomy (3rd edition, 2005)
- ITU-R Radio Regulations
- ITU-R WWW pages
- CPS
- gjozsa@mpifr-bonn.mpg.de (Josh)

- pycraf
- cysgp4

- Determine the name of your country's spectrum agency
- Determine the name of the spectrum manager of your favourite observatory (and send it to Josh)
- Check in the ITU-R Radio Regulations whether your observation is protected
- Prepare your story why you are proud to be an astronomer and prepare an explanation why (radio-) astronomy needs to be protected (it is worth it!)
- Engage!