Towards VLBI with ESA's Genesis satellite

Rüdiger Haas

for ESA GSET WG-3 (VLBI)

IVTW IX2024

Genesis

- ESA mission, co-location satellite:
  - VLBI sender
  - GNSS receivers
  - SLR reflectors
  - DORIS receiver
- Orbit:
  - height h=6000 km
  - inclination i=95°
  - orbital period ≈T= 3.8 h
  - angular velocity η=0.026 °/s
  - horizon-2-horizon @ 5 deg: 68 min

2+ year mission, lauch planned 2028

Genesis ESA project team

- Sara Gidlund – Head of the GENESIS Project
- Gaia Fusco – System and Operations Manager
- Evelyn Honoré-Livermore – Platform Principal Engineer
- Pierre Waller – Payload Principal Engineer
- Evelina Sakalauskaite – System Engineering Support
- Werner Enderle – Head of Navigation Support Office
- Vicente Navarro – Senior System Engineer (GSSC)

Genesis Science Exploitation Team (GSET)

Lead science coordinator
Özgür Karatekin (ROB)

Lead science co-coordinator
Francesco Vespe (ASI)

WG-1:
ITRF and combinations
Zuheir Altamimi (IGN)
Florian Seitz (DGFI – TUM)

WG-2:
GNSS
Rolf Dach (UBern)
Benjamin Männel (GFZ)

WG-3:
VLBI
Rüdiger Haas (Chalmers)

WG-4:
DORIS
Guilhem Moreaux (CLS)

WG-5:
Laser Ranging
Clément Courde (Géoazur)

WG-3 Members

- Simone Bernhart – BKG/MPIfR correlator Bonn, DEU
- Johannes Böhm – TU Vienna, AUT
- Patrick Charlot – CNRS Bordeaux, FRA
- Pablo de Vicente – IGN Yebes Observatory, ESP
- Claudia Flohrer – BKG Frankfurt, DEU
- Susana Garcia-Espada, Kartverket, Ny-Ålesund Observatory, NOR
- Luciano Garramone – ASI, Matera Observatory, ITA
- Jakob Gruber – BEV Wien, AUT
- Rüdiger Haas, Chalmers, SWE
- Masafumi Ishigaki, GSI, JAP
- Shinobu Kurihara , GSI, JAP
- Lucia McCallum – University of Tasmania, Hobart Observatory, AUS
- Alexander Neidhardt – TU München, Wettzell Observatory, DEU
- Axel Nothnagel – TU Vienna, AUT
- Almine Ozyildirim, RoB Brussels, BEL
- Chet Ruszczyk – MIT Haystack Observatory, USA
- Matthias Schartner – ETH Zürich, CHE
- Harald Schuh – GFZ Potsdam, DEU
- Gino Tuccari – INAF Italy & MPIfR Bonn, ITA/DEU

Ex-officio (ESA GSET coordinator)

- Özgür Karatekin, RoB, Brussels, BEL

ESA

- Gaia Fusco, ESTEC, NLD
- Werner Enderle, ESOC, DEU
- Pierre Waller, ESTEC, NDL
- Evelina Sakalauskaite, ESTEC, NDL
- Sara Bruni, ESOC, DEU

The tasks of WG-3

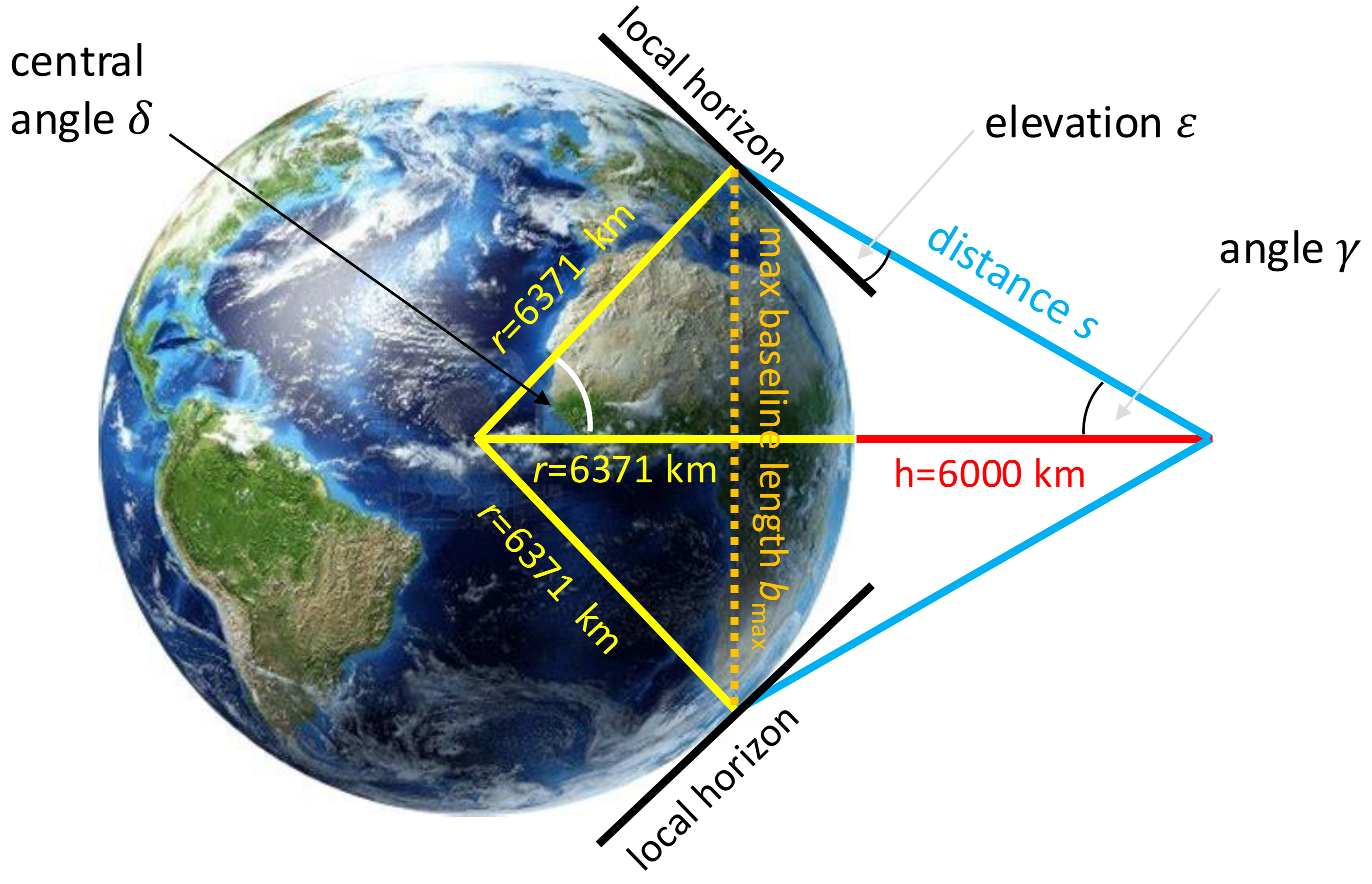
- Advise and support ESA in design of the Genesis VLBI transmitter
- Investigate and prepare for compatibility with normal IVS operations and IVS product generation
- Scientific exploitation of Genesis VLBI data

- Goals:
  - include Genesis in IVS operations to strengthen TRF
  - BUT do not ”harm”, i.e. deteriorate any other IVS products (!)
  - find ”good compromises” to achieve a “win-win-situation”
  - do not harm radio astronomy as such

Seven Work Packages in WG-3

- WP-1: frequencies, signals etc.
- WP-2: ground station fidelity, etc.
- WP-3: delay resolution and correlation, etc.
- WP-4: scheduling
- WP-5: end-to-end simulations
- WP-6: test observations
- WP-7: PRN-option

Some Genesis geometry



Assuming a spherical earth.

$$\frac{\sin(90° + \varepsilon)}{(r+h)} = \frac{\sin\gamma}{r} = \frac{\sin\delta}{s}$$

$$\sin\gamma = \frac{r}{(r+h)}\sin(90° + \varepsilon)$$

$$\delta = 90° - \varepsilon - \gamma$$

Distance *s* between Genesis and ground station:

$$s = \frac{\sin\delta}{\sin(90° + \varepsilon)}(r+h)$$

Max baseline length *b* between two ground stations at ”opposite sides” :

$$b_{max} = 2 \cdot r \cdot \sin\delta$$

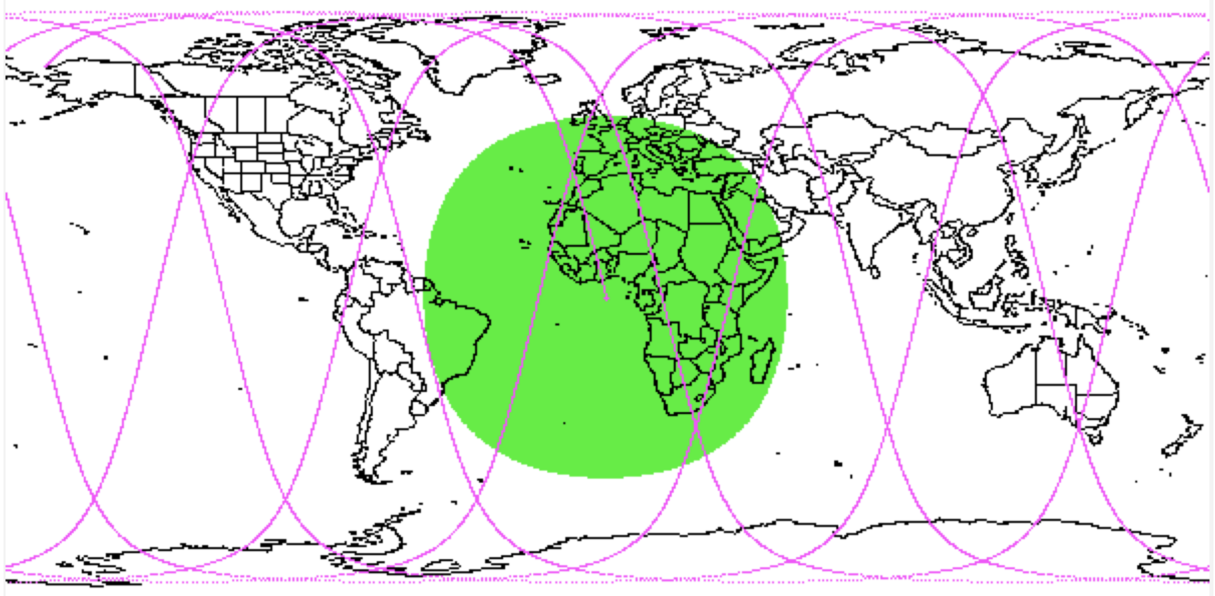
Area *A* of Genesis’ ”visibility cap”:

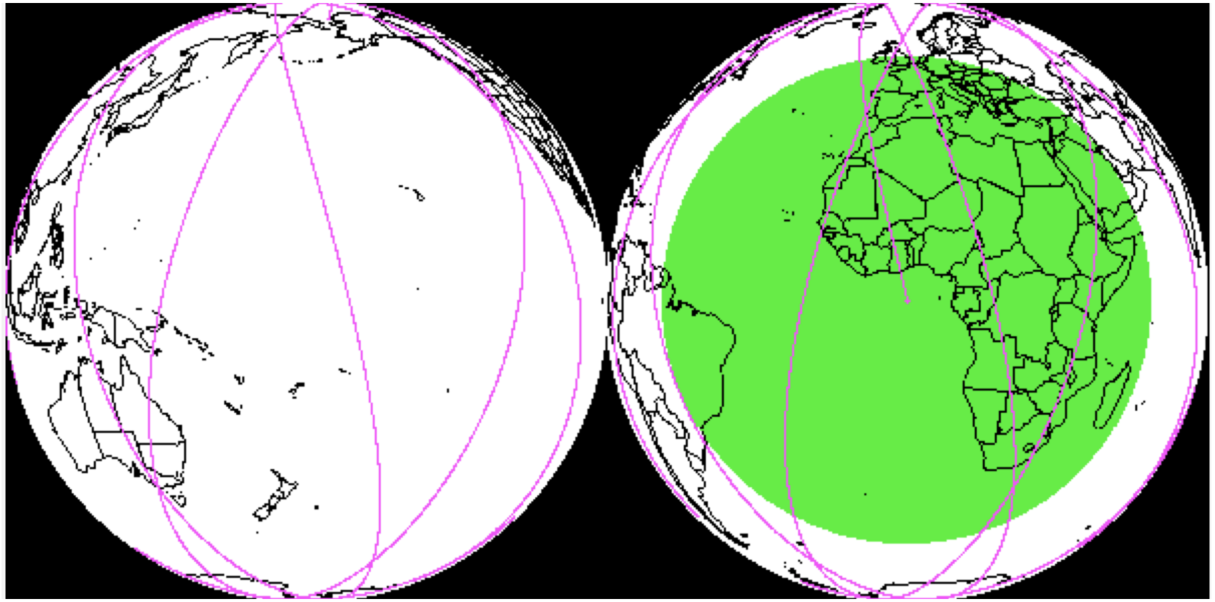
$$A = 2 \cdot \pi \cdot r^2(1 - \cos\delta)$$

Genesis visibility measures

Station elevation cutoff angle ε_{min}	Genesis antenna opening angle 2γ	Distance satellite–ground station s (km)	Max baseline length between ground stations at ”opposite sides” b_{max} (km)	Percentage of earth surface illuminated p (%)
5˚	61.732˚	10063.597	10325.956	20.705
10˚	60.951˚	9555.579	9692.621	17.544
15˚	59.662˚	9082.839	9036.457	14.749
20˚	57.886˚	8646.889	8369.094	12.297

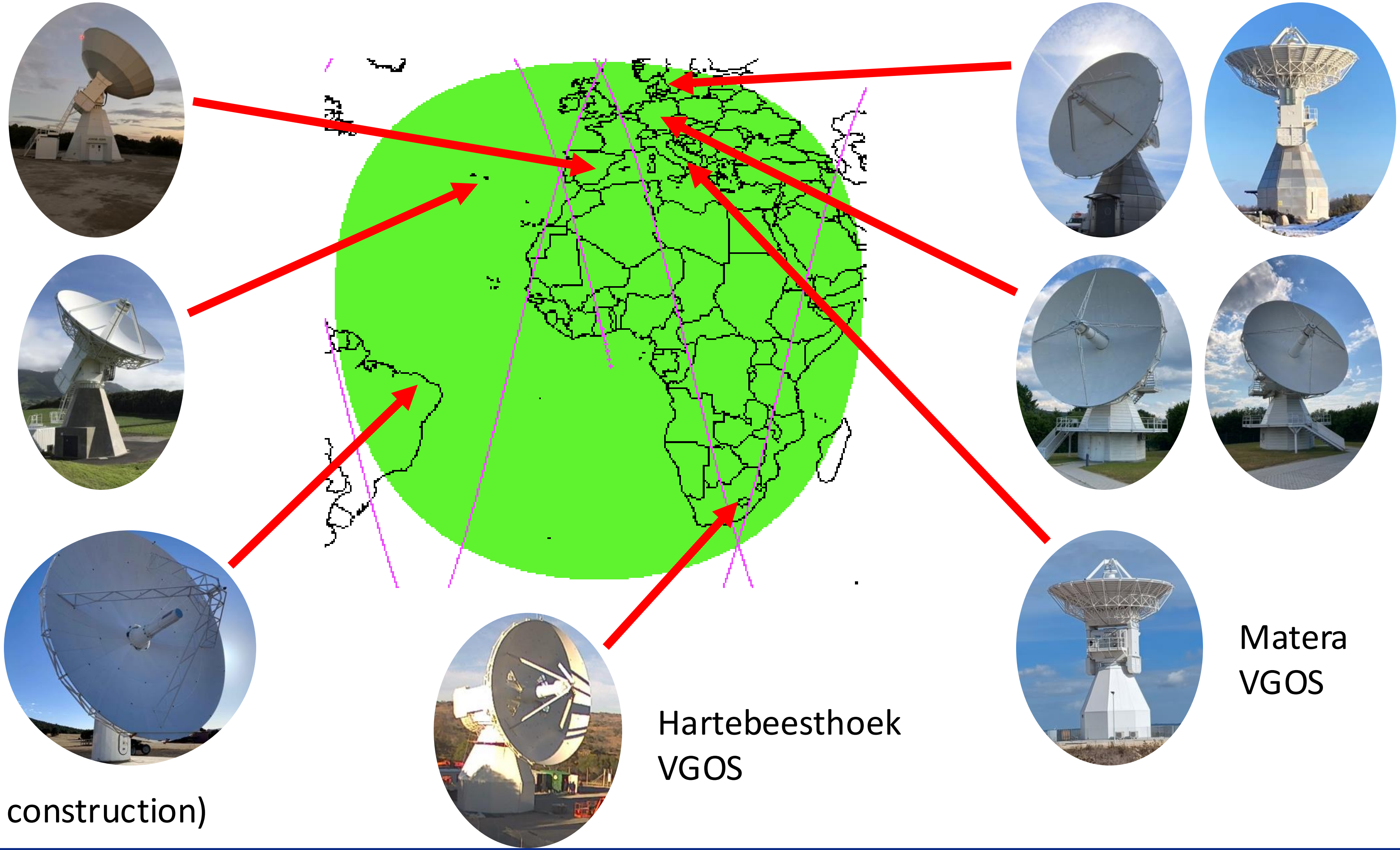
One day of Genesis





Pink: Ground track during 1 day.
Green: "Visibility cap" , i.e. instantaneous visibility assuming a minimum elevation $\varepsilon_{min} = 5^\circ$ at the ground stations.

Genesis snap-shot visibility



Yebes
VGOS

Santa Maria
VGOS

Fortaleza
VGOS (under construction)

Hartebeesthoek
VGOS

Onsala
VGOS
twins

Wettzell
VGOS
twins

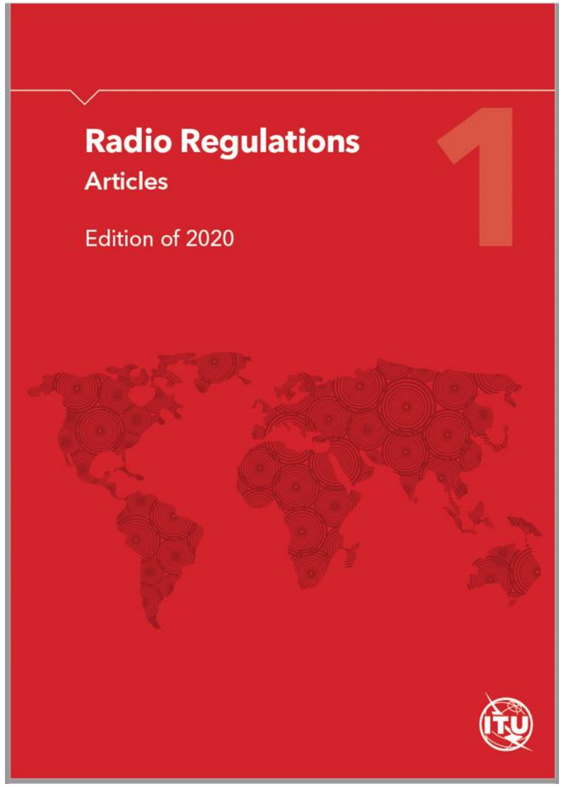
Matera
VGOS

WP-1

frequencies, signal strength, etc.

The Genesis VLBI frequencies

Band-1 3100–3300 MHz	Radiolocation, Earth exploration-satellite (active), Space research (active)
Band-2 5250–5570 MHz	Radiolocation, Earth exploration-satellite (active), Space research (active)
Band-3 8200–8400 MHz	Earth exploration-satellite (space-to-Earth)
Band-4 9300–9800 MHz	Earth exploration-satellite (active), Radiolocation, Radionavigation, Space Research (active)



See: https://www.itu.int/en/publications/ITU-R/pages/publications.aspx?parent=R-REG-RR-2020&media=electronic

Genesis VLBI signal

Standard VLBI equation relating signal strength (spectral flux density *F*), station sensitivities (*SEFD*), bandwidth *B*, number of channels *N*, and observation time *t :*

$$SNR = \frac{1}{\eta} \frac{F}{\sqrt{SEFD_1 \cdot SEFD_2}} \sqrt{2 \cdot B \cdot N \cdot t}$$

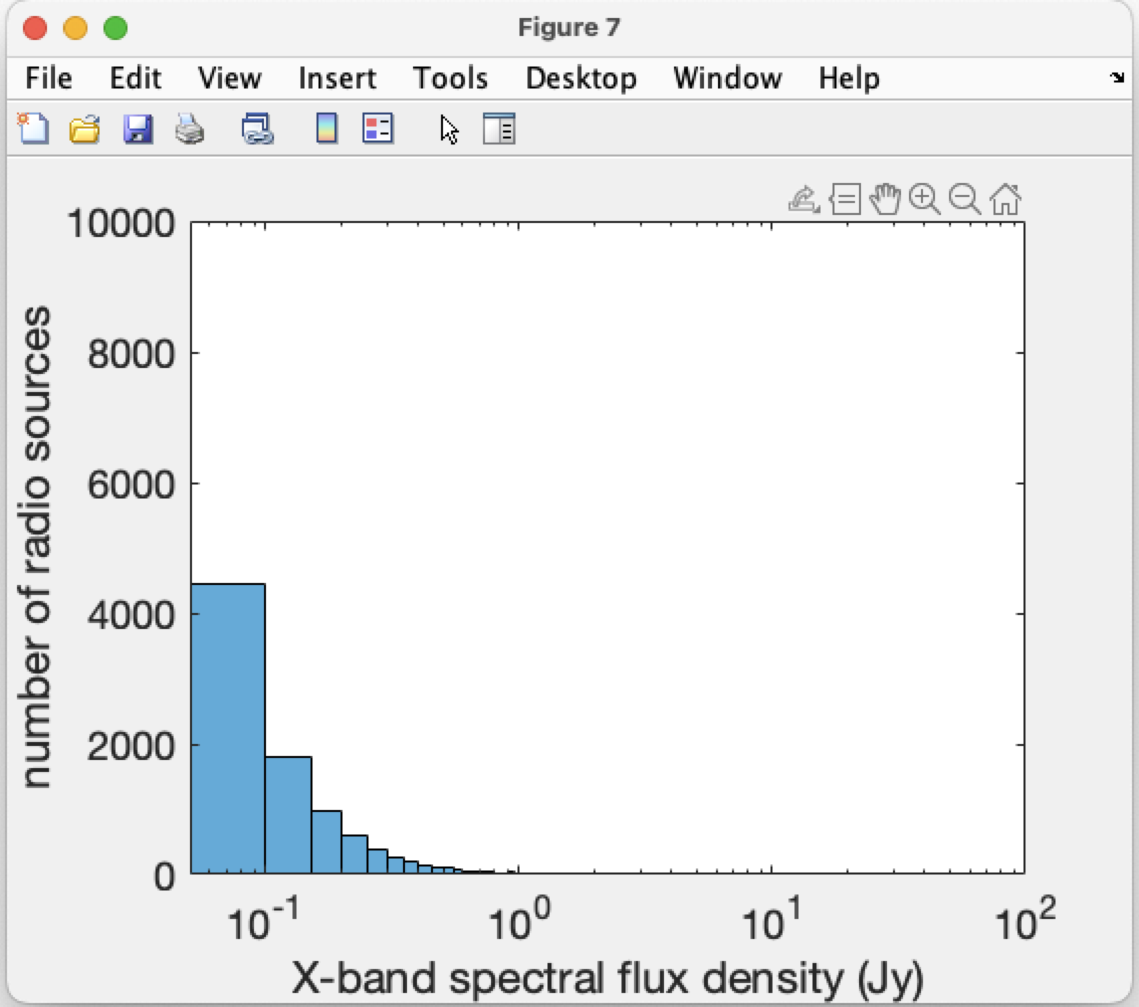
Genesis VLBI signal should be:

- ”White noise”, i.e. flat spectrum
- Same spectral flux density *F* at all stations
- Tuneable and on/off possibility

Genesis signal strength?

- In VLBI we usually express the spectral flux density in Jy
- 1 Jy = 10^{-26} W m^{-2} Hz^{-1}

- Histogram of spectral flux density of natural radio sources at X-band



Genesis: Tuneable signal strength

- Logarithmic tuning
- Max. spectral flux density F_{max} = 10 Jy
- Attenuation in 21 steps: A= [0 20] dB
- on/off switch possibility

$$F = F_{max} \cdot 10^{\frac{-A}{10}}$$

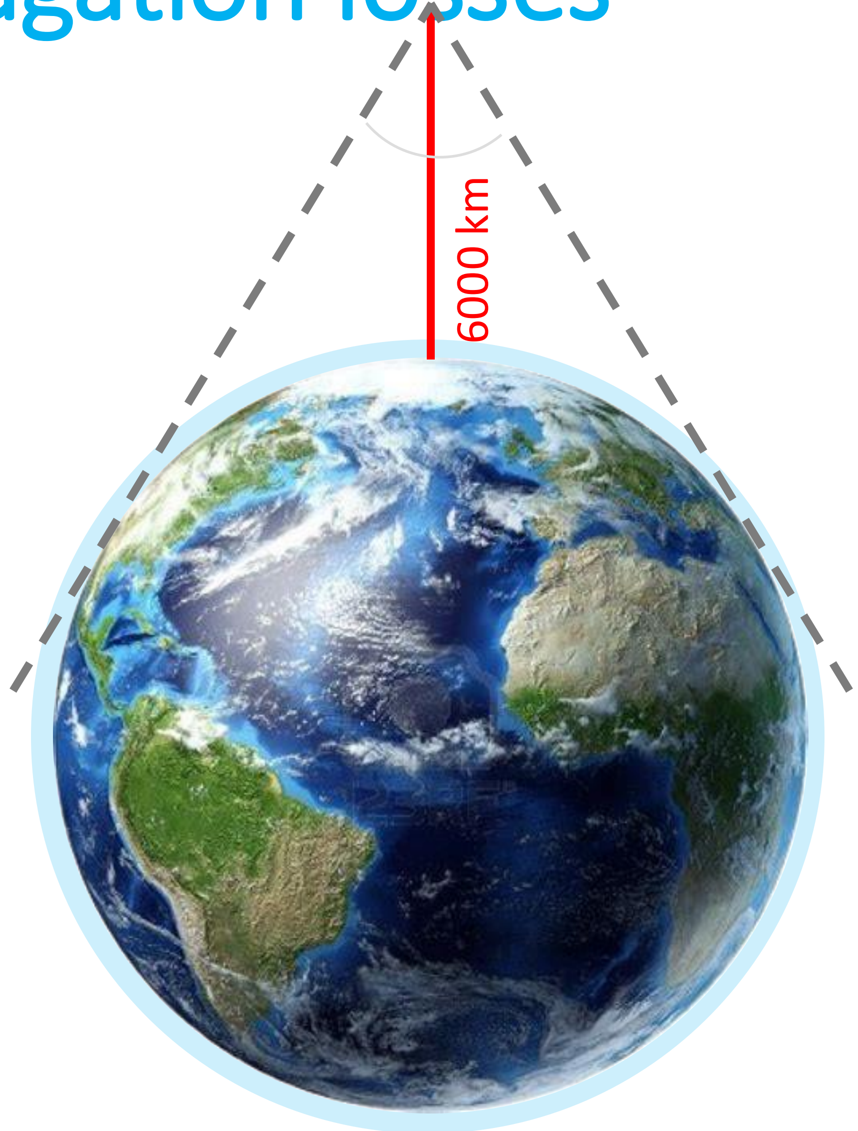
A (dB)	F (Jy)	A (dB)	F (Jy)
0	10.0	11	0.7943
1	7.9433	12	0.6310
2	6.3096	13	0.5012
3	5.0119	14	0.3981
4	3.9811	15	0.3162
5	3.1623	16	0.2512
6	2.5119	17	0.1995
7	1.9953	18	0.1585
8	1.5849	19	0.1259
9	1.2589	20	0.1
10	1.0		

Signal strength and propagation losses

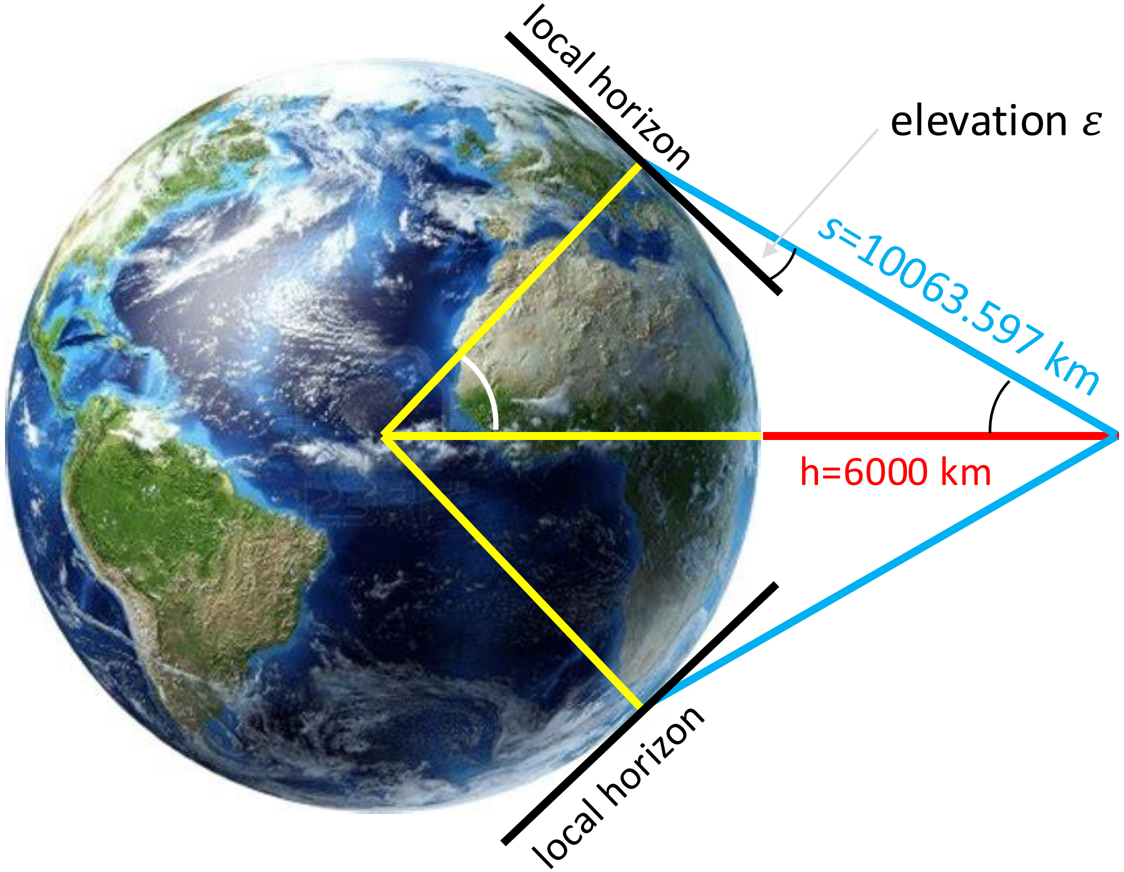
- Antenna pattern
  - Usually 3 dB between bore sight and HPBW edges
- Free space loss
  - Distance and frequency dependent

- Atmospheric losses
  - Frequency and weather dependent
    - Atmospheric gas attenuation
    - Cloud attenuation
    - Scintillation attenuation

    - Rain attenuation



Free space loss effect:



Free space loss:

$$L_{FS} = \left(\frac{4 \cdot \pi \cdot R \cdot f}{c}\right)^2$$

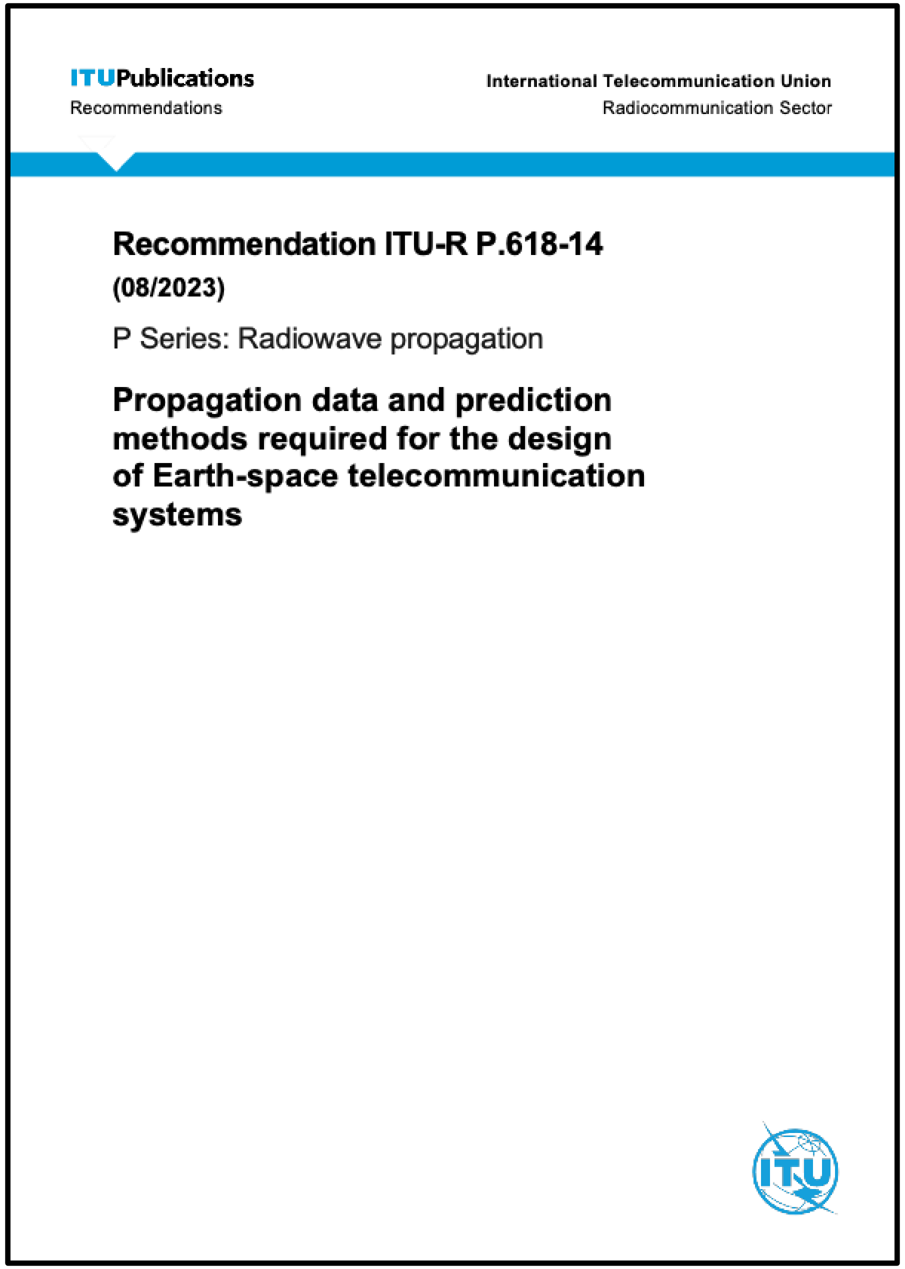
Frequency	3.2 GHz	5.41 GHz	8.3 GHz	9.55 GHz
$L_{FS\_(nadir)}$	178.1 dB	182.7 dB	186.4 dB	187.6 dB
$L_{FS\_(edge)}$	182.6 dB	187.2 dB	190.9 dB	192.1 dB
ΔL_{FS}	4.5 dB	4.5 dB	4.5 dB	4.5 dB

Assuming an HPBW opening angle of 61.732˚, i.e. corresponding to ε_{min}= 5˚

Atmospheric losses

- ITU-R recommendation
  - ITU-R P.618

- Attenuation due to
  - Atmospheric gases
  - Clouds
  - Scintillation
  - Rain


ITUPublications
Recommendations

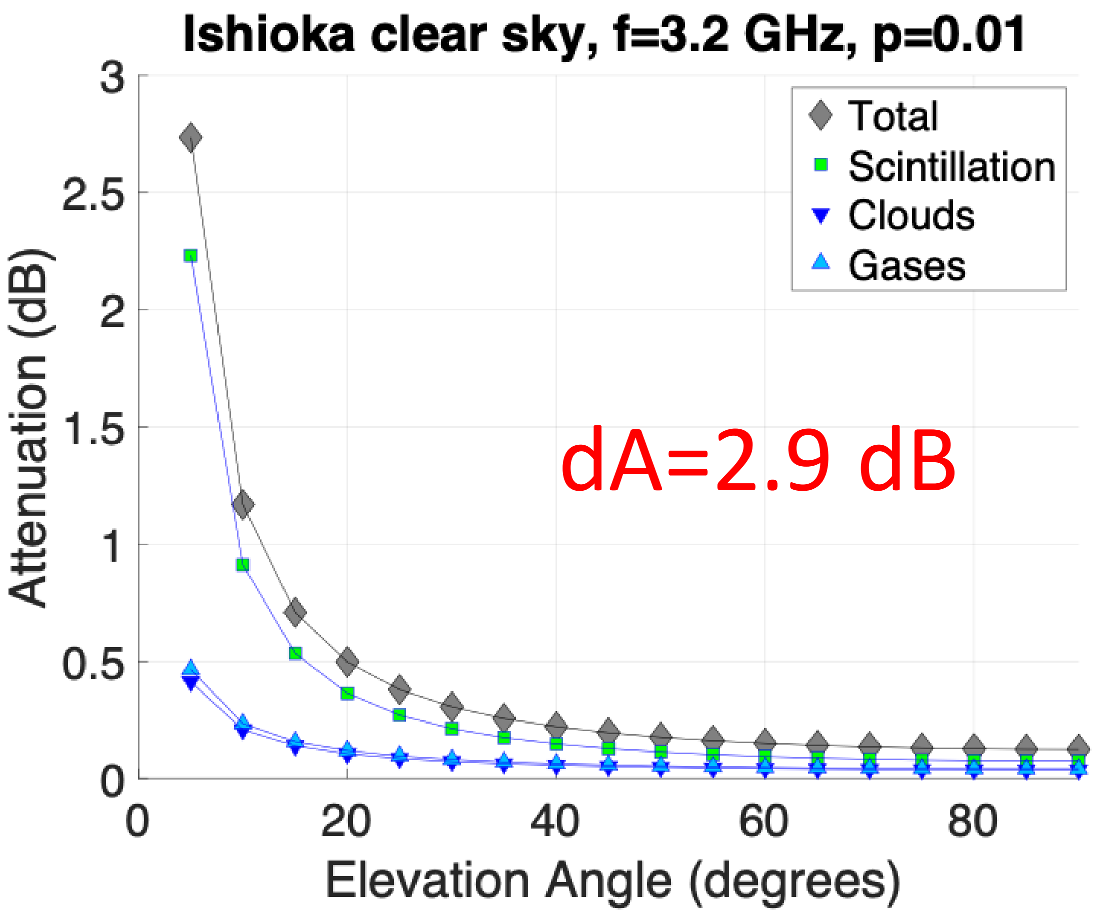
International Telecommunication Union
Radiocommunication Sector

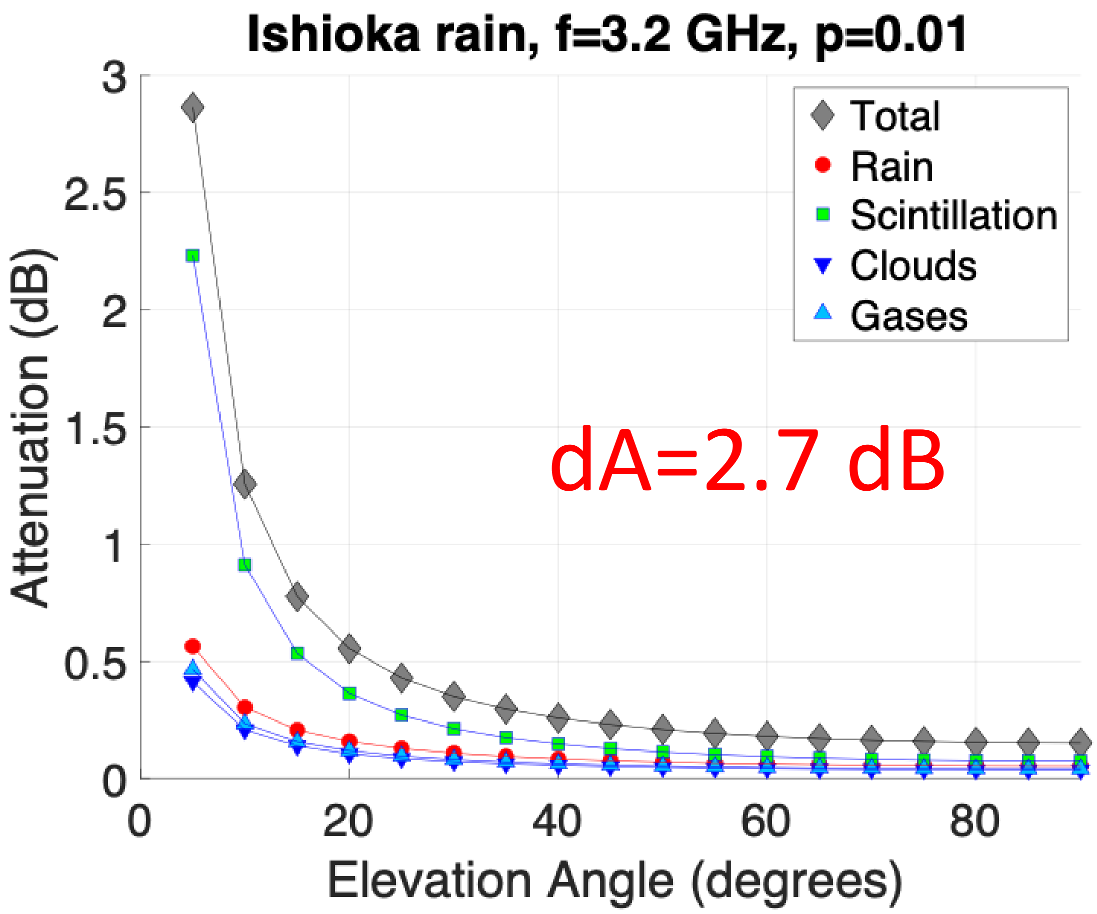
Recommendation ITU-R P.618-14
(08/2023)

P Series: Radiowave propagation

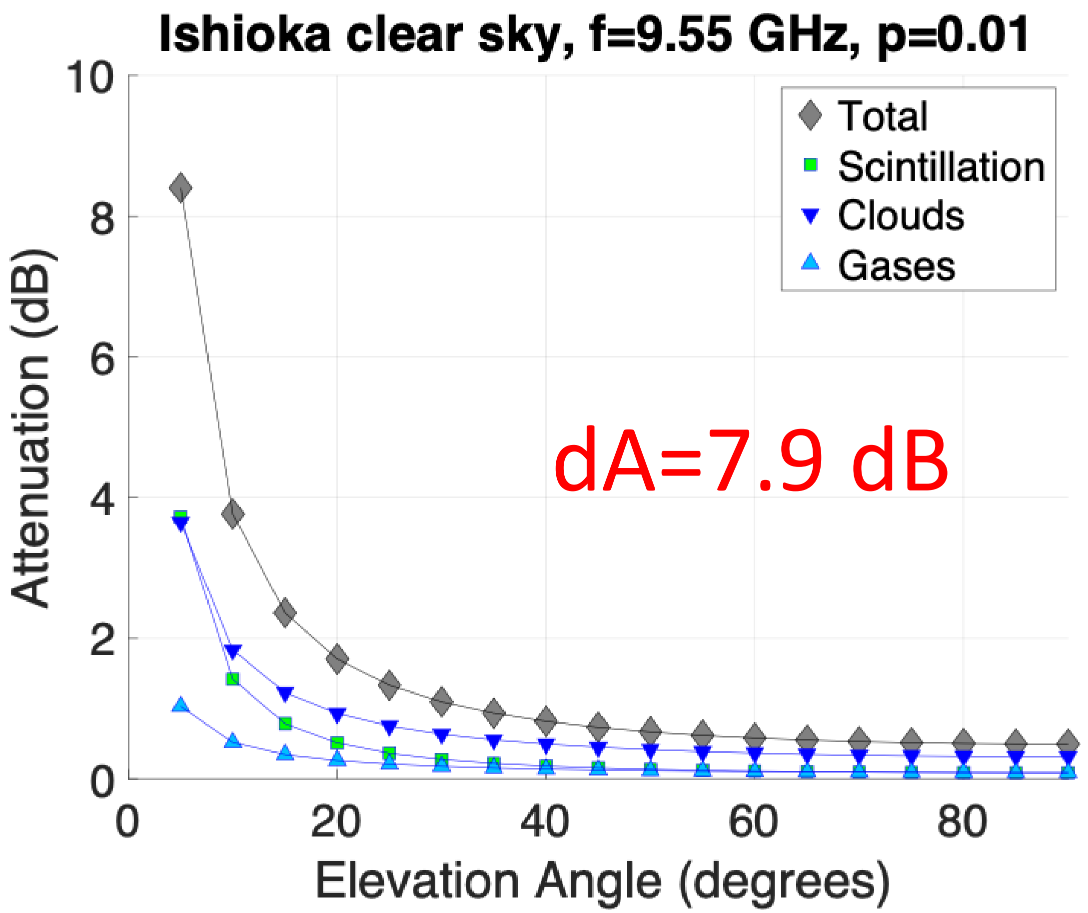
Propagation data and prediction methods required for the design of Earth-space telecommunication systems

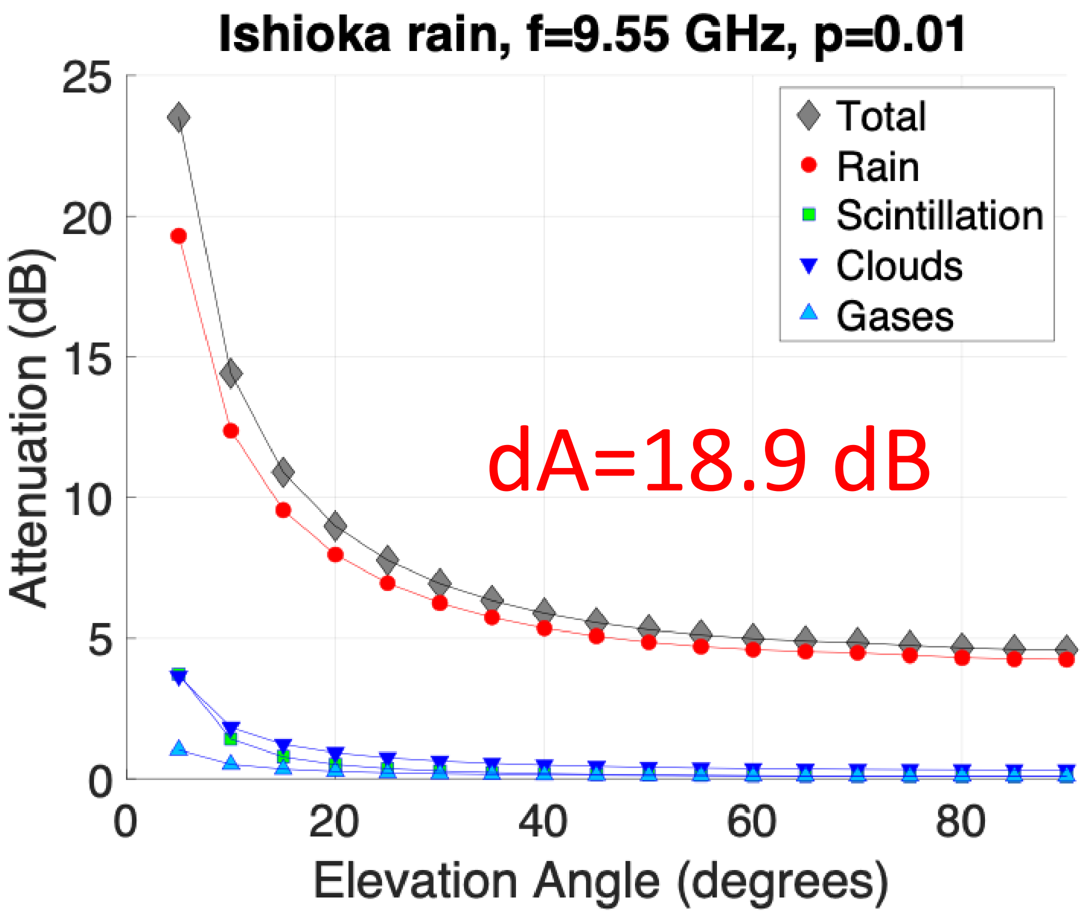
Example: Ishioka, f=3.2 GHz





Example: Ishioka, f=9.55 GHz





Differential losses 5° vs. 90° elevation

Station	Ishioka		Onsala		
Frequency (GHz)	3.2	9.55	3.2	9.55	
Genesis antenna pattern	–3 dB	–3 dB	–3 dB	–3 dB	Genesis specific
Free space loss	–4.5 dB	–4.5 dB	–4.5 dB	–4.5 dB	
Atmosphere	–3.0 dB	–7.9 dB	–2.5 dB	–5.4 dB	”normal”
Rain attenuation	–0.5 dB	–15.1 dB	–0.1 dB	–6.1 dB	
Total clear sky	– 13.3 dB	–15.6 dB	–12.8 dB	– 12.9 dB	
Total in rain	– 13.8 dB	–30.7 dB	–12.9 dB	– 19.0 dB	

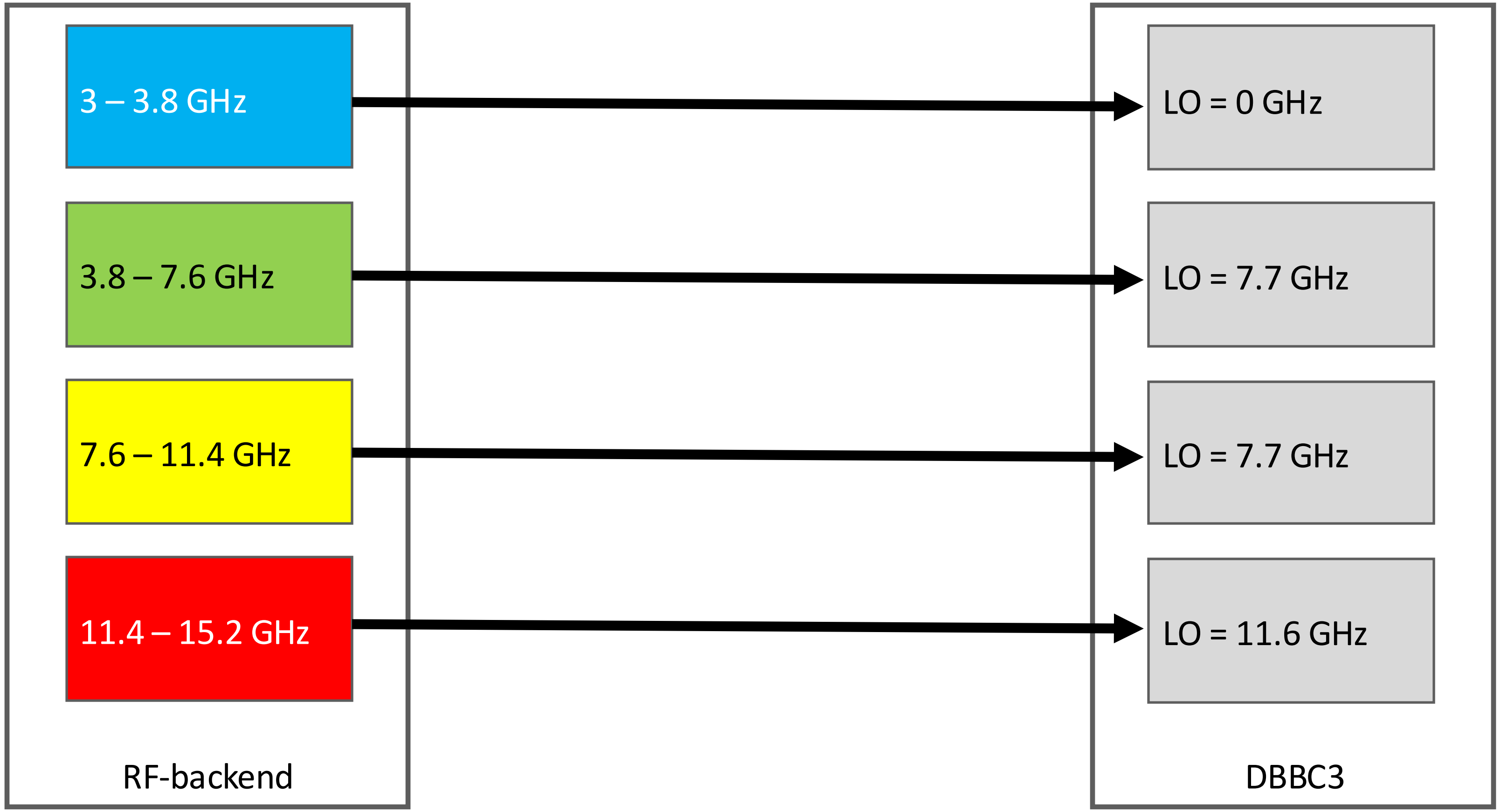
Open questions

- Can one single transmit antenna be realized?
- How to minimize / treat impact of antenna phase center variation?
- How to achieve ISO-flux?
- How to handle non-ISO flux in scheduling?

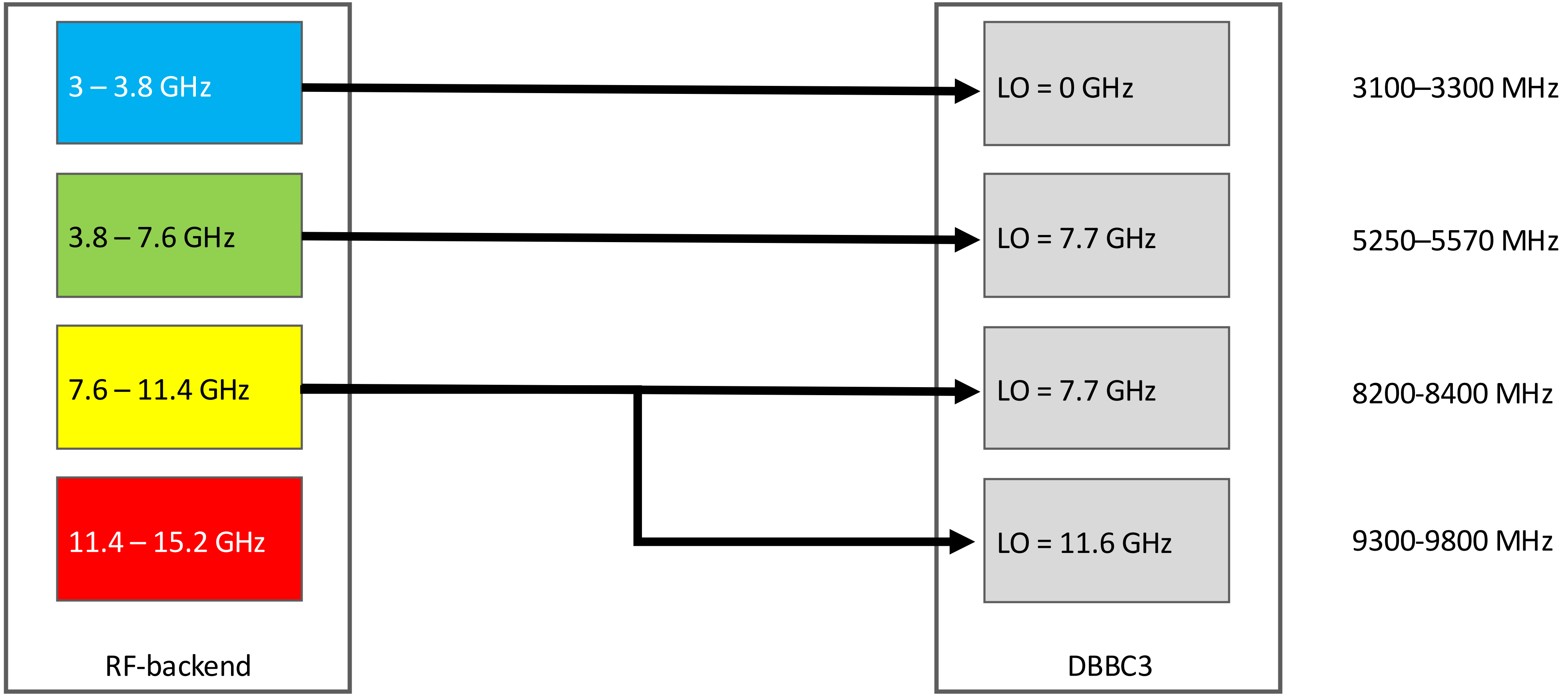
WP-2

ground station fidelity, etc.

Example: VGOS @ OSO as planned originally

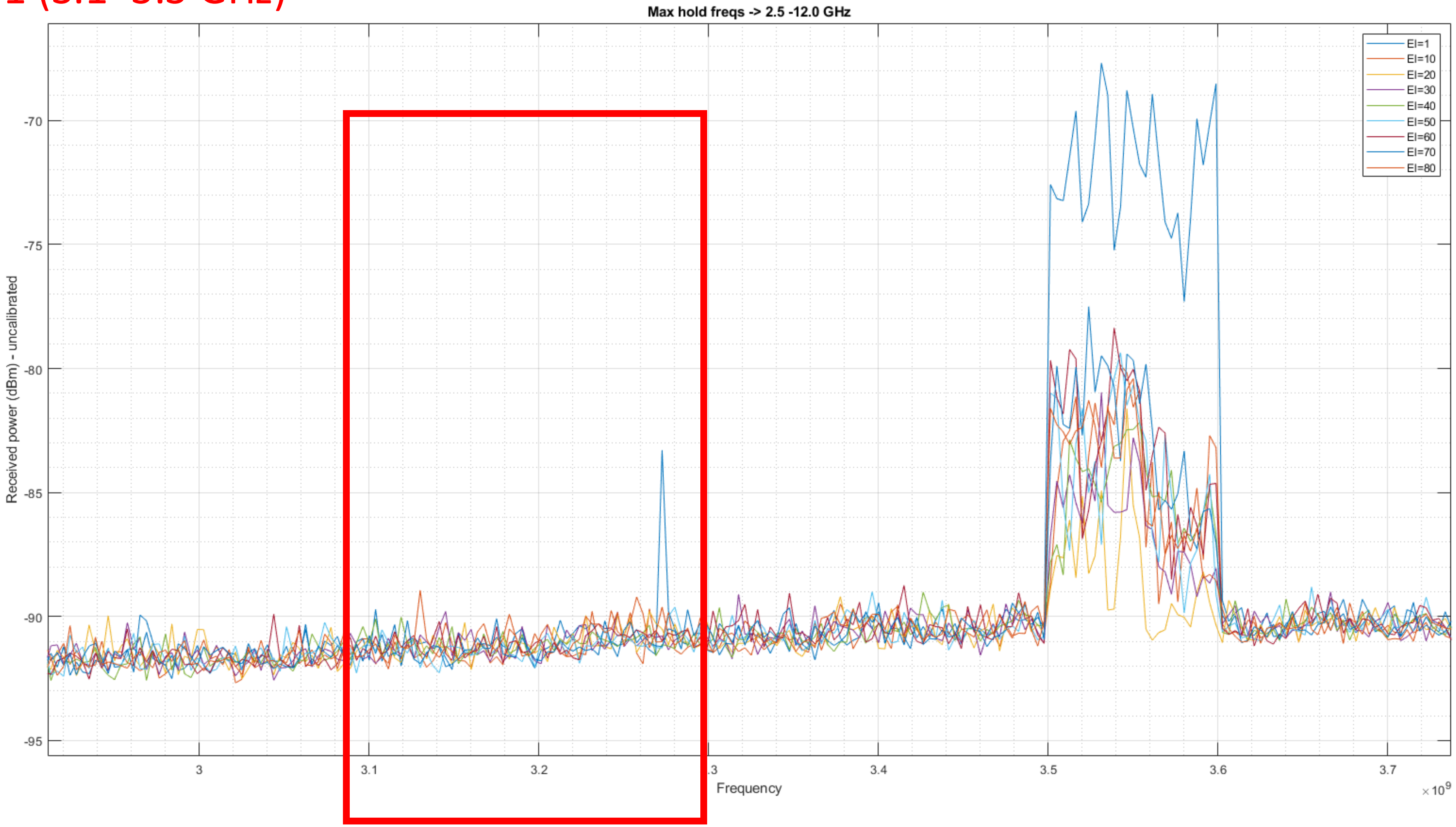


”Genesis-VGOS” @ OSO



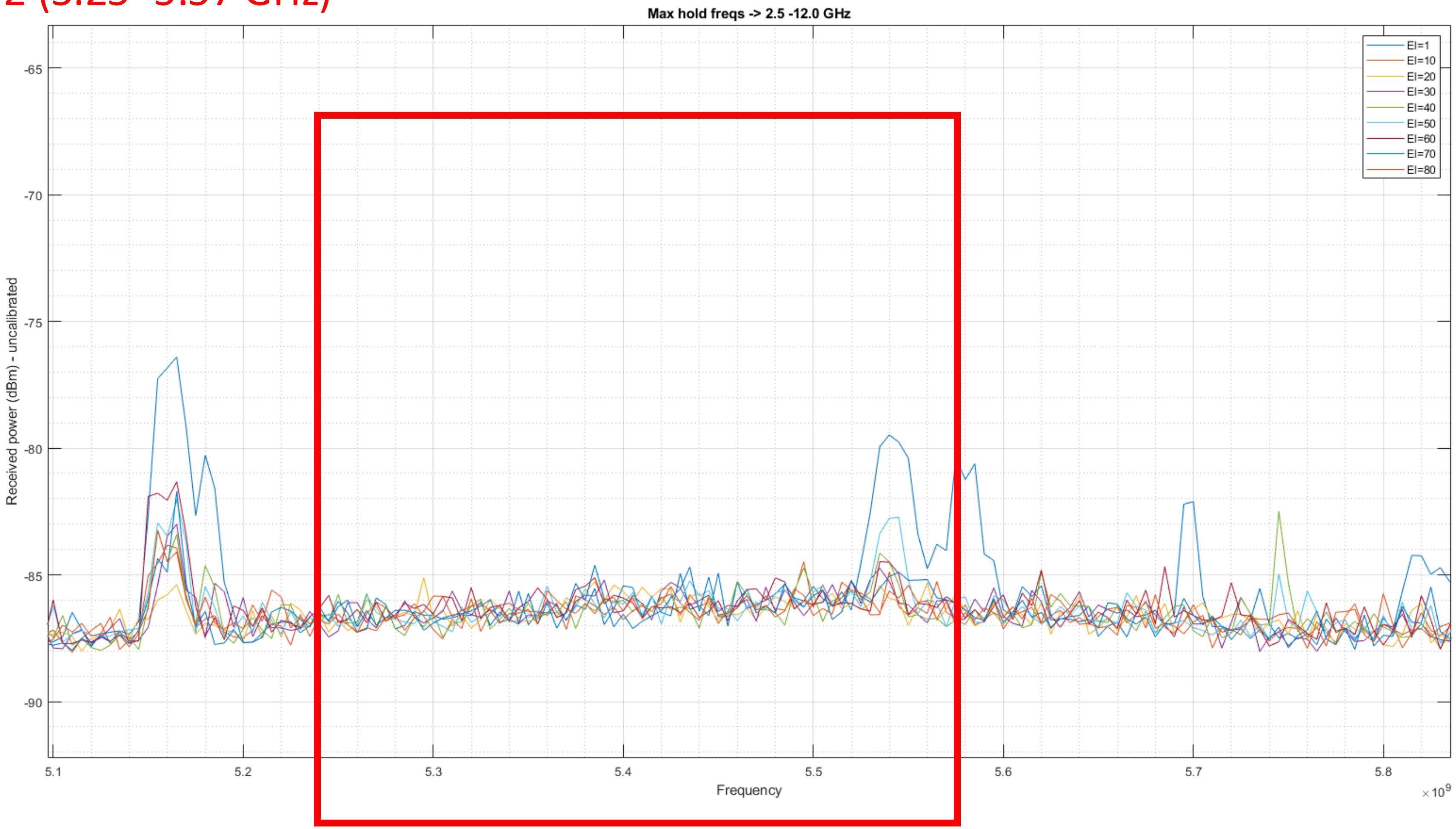
Example: RFI situation at Yebes

Genesis band-1 (3.1–3.3 GHz)



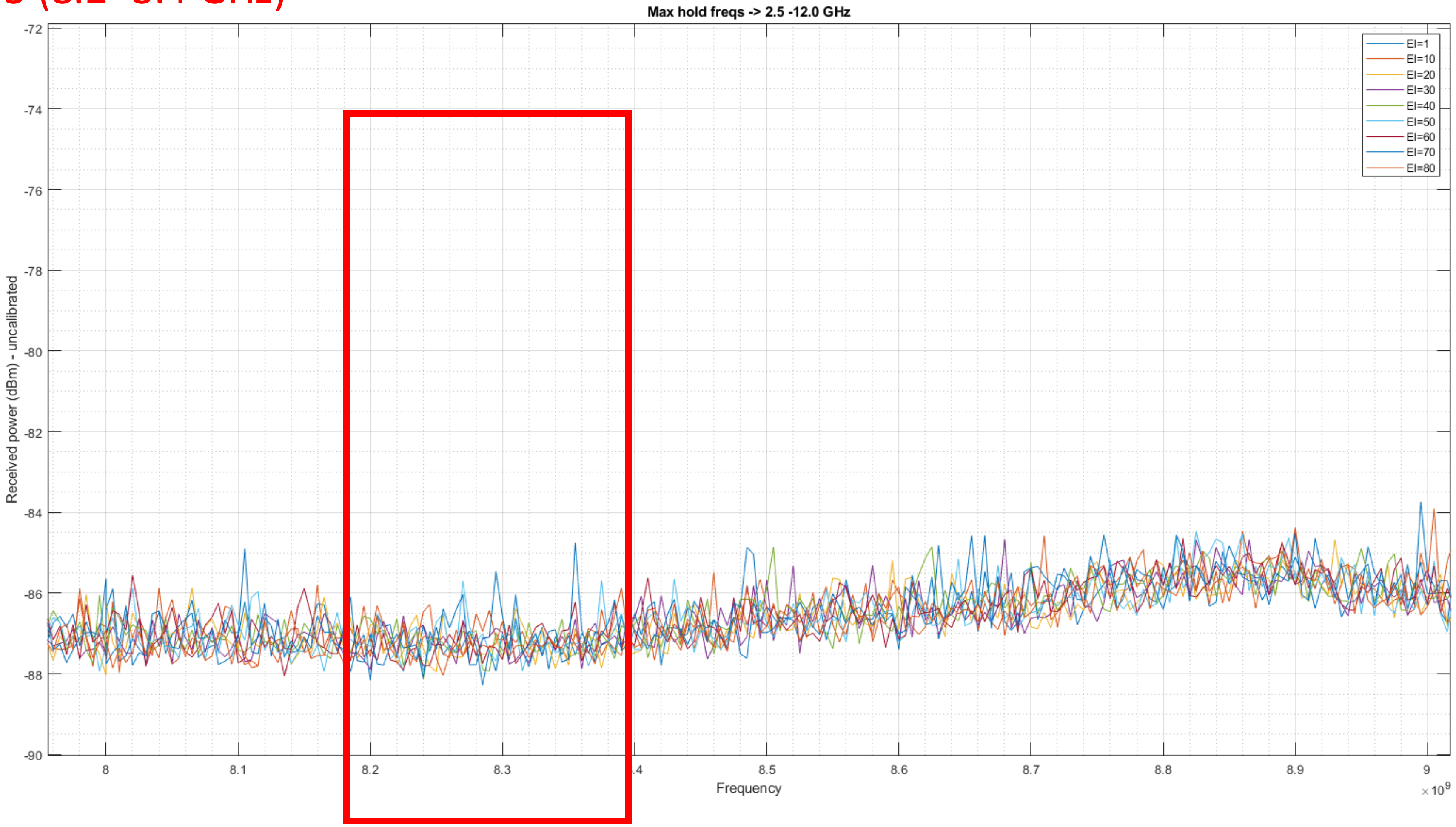
Example: RFI situation at Yebes

Genesis band-2 (5.25–5.57 GHz)



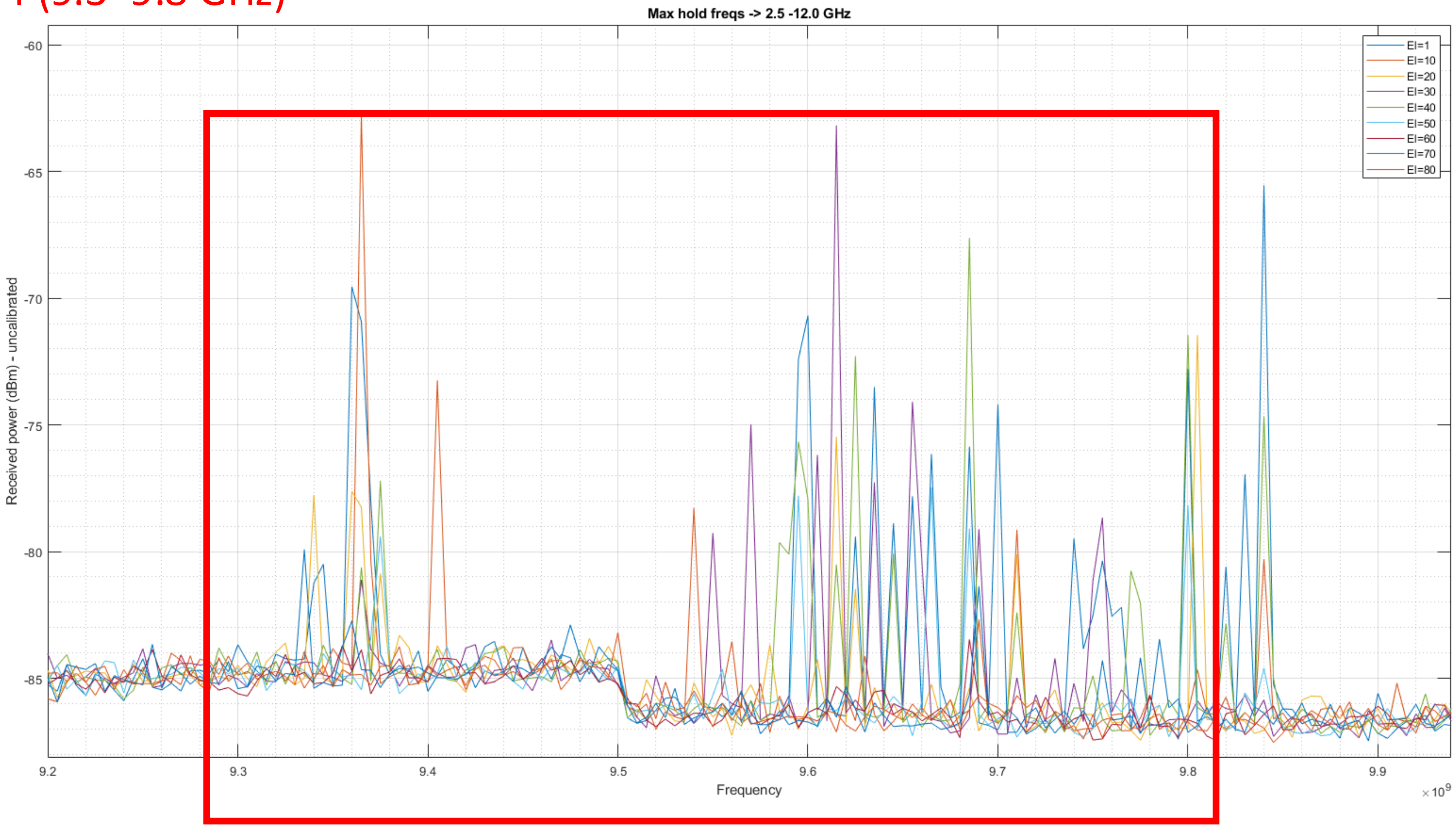
Example: RFI situation at Yebes

Genesis band-3 (8.2–8.4 GHz)



Example: RFI situation at Yebes

Genesis band-4 (9.3–9.8 GHz)



So far we know

- Most/all VGOS stations will need to install new equipment to be able to observe the Genesis frequencies
  - switches for the signal chain necessary
    - should be controlable from the VLBI FS
  - potentially additional filters
- Stations might have different RFI situations at the Genesis frequencies

To do list

- Collect ”station fidelity” information for as many as possible VGOS stations worldwide
- Start testing Genesis frequency setup with quasar observations
- Test also ”mode switching” approaches, i.e. switching between standard VO and Genesis setups

WP-3

delay resolution and correlation, etc.

Channel selection for Genesis frequencies

3100-3300 MHz

BAND	A	3132.4	32.0	L
BAND	A	3164.4	32.0	L
BAND	A	3196.4	32.0	L
BAND	A	3260.4	32.0	L
BAND	A	3292.4	32.0	L

5 channels

5250–5570 MHz

BAND	B	5276.4	32.0	L
BAND	B	5308.4	32.0	L
BAND	B	5340.4	32.0	L
BAND	B	5372.4	32.0	L
BAND	B	5404.4	32.0	L
BAND	B	5468.4	32.0	L
BAND	B	5500.4	32.0	L
BAND	B	5532.4	32.0	L
BAND	B	5564.4	32.0	L

9 channels

8200–8400 MHz

BAND	C	8220.4	32.0	L
BAND	C	8252.4	32.0	L
BAND	C	8316.4	32.0	L
BAND	C	8348.4	32.0	L
BAND	C	8380.4	32.0	L

5 channels

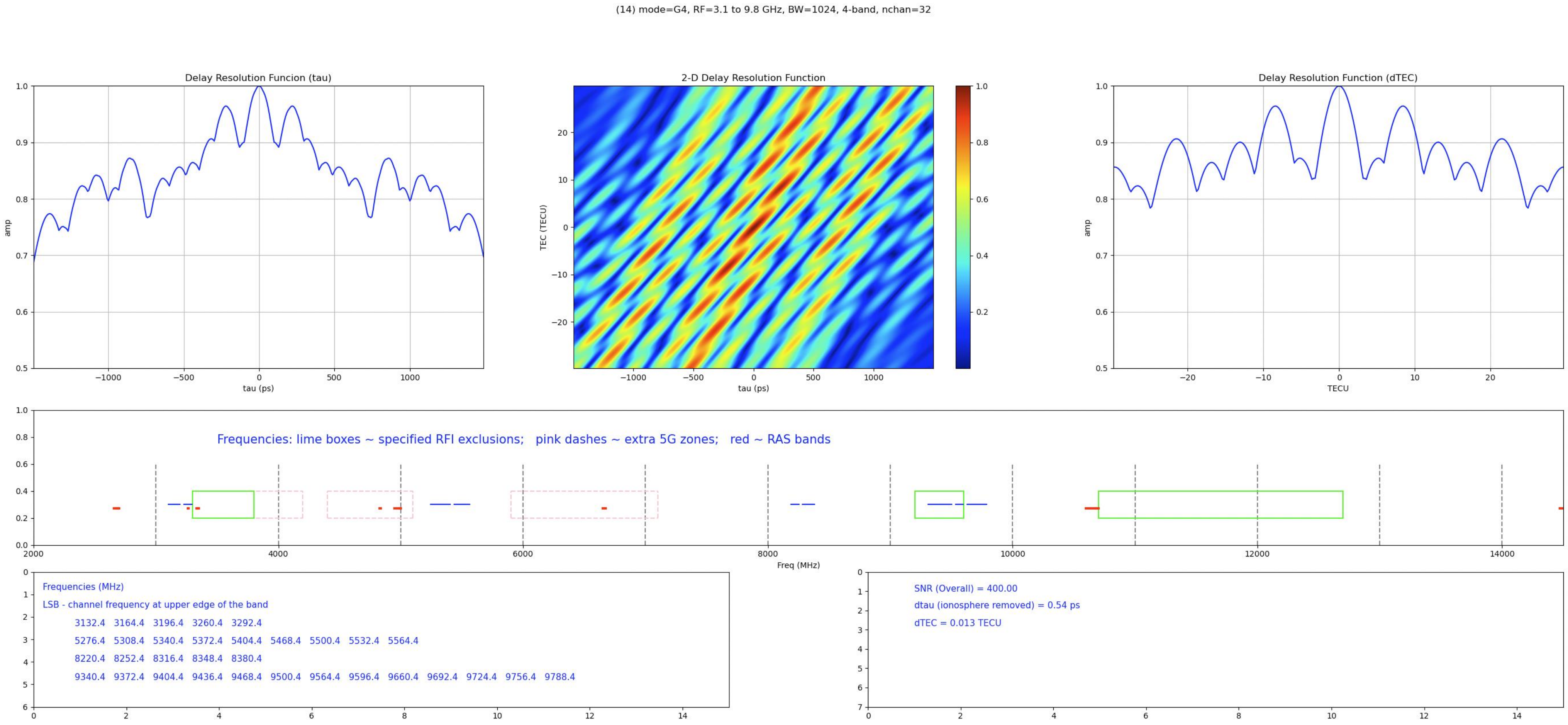
9300–9800 MHz

BAND	D	9340.4	32.0	L
BAND	D	9372.4	32.0	L
BAND	D	9404.4	32.0	L
BAND	D	9436.4	32.0	L
BAND	D	9468.4	32.0	L
BAND	D	9500.4	32.0	L
BAND	D	9564.4	32.0	L
BAND	D	9596.4	32.0	L
BAND	D	9660.4	32.0	L
BAND	D	9692.4	32.0	L
BAND	D	9724.4	32.0	L
BAND	D	9756.4	32.0	L
BAND	D	9788.4	32.0	L

13 channels

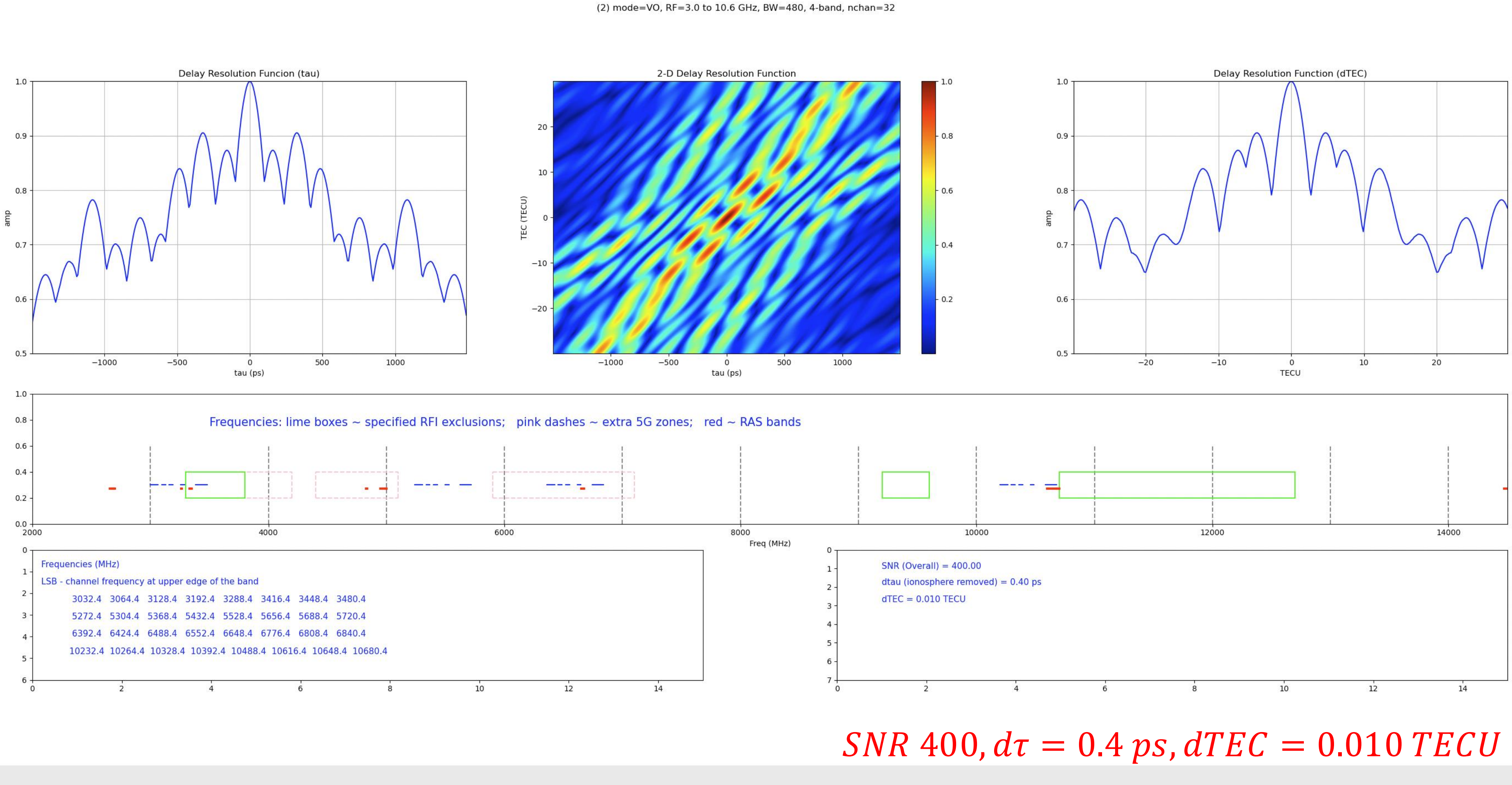
=> In total 32 channels, total BW covered 1024 MHz in 4 bands.

Delay resolution function with Genesis frequencies

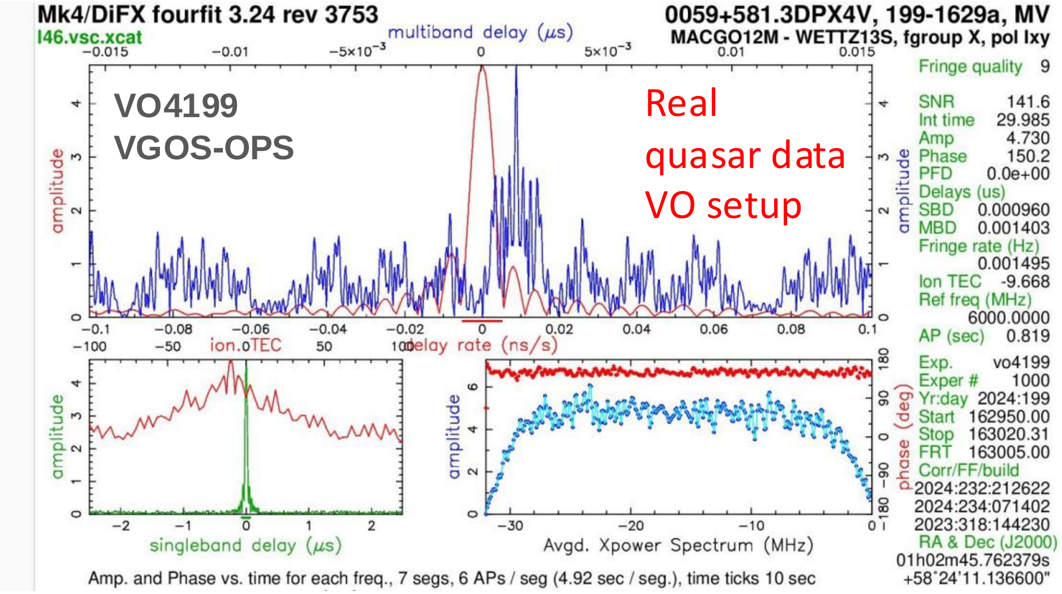


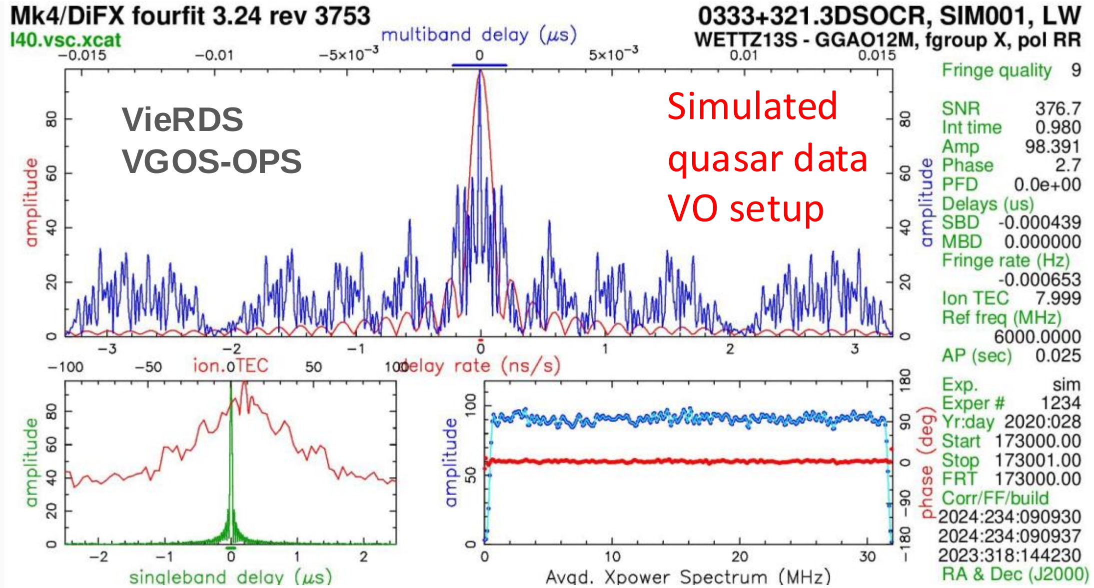
$SNR\ 400, d\tau = 0.5\ ps, dTEC = 0.013\ TECU$

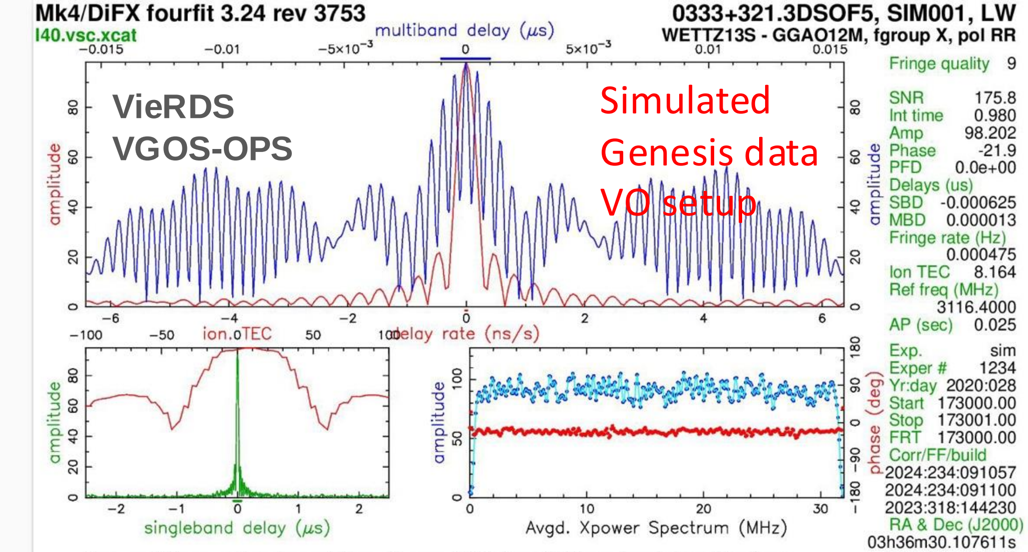
Comparison: standard VGOS setup (VO)

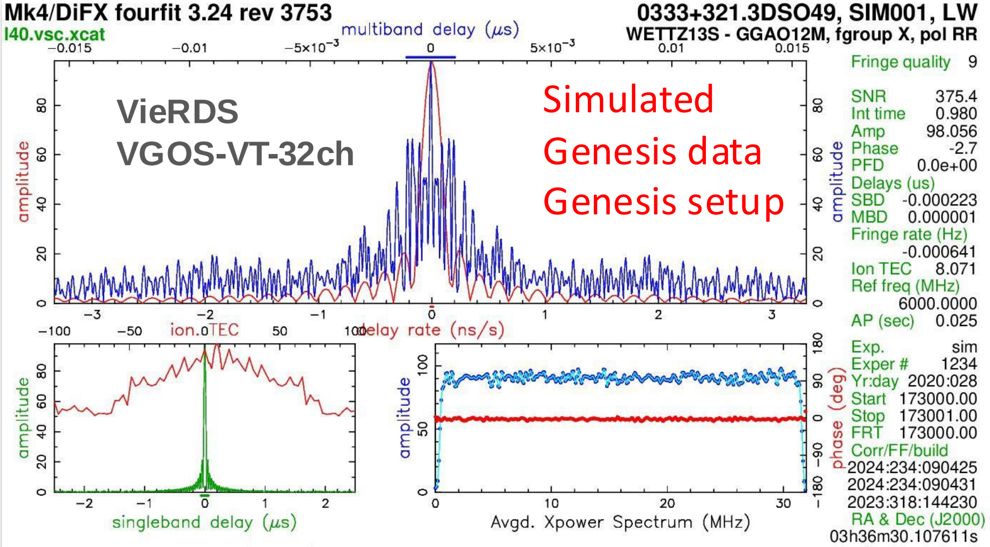


$SNR\ 400, d\tau = 0.4\ ps, dTEC = 0.010\ TECU$









Ref. Jakob Gruber, BEV, Austria

To do list

- Simulations with more realistic values
  - station SEFD and
  - signal spectral flux density
- Study also potential phase center variation effects

WP-5

simulations

General goals

- Realistic simulations
  - Realistic orbit
  - Realistic ground station network

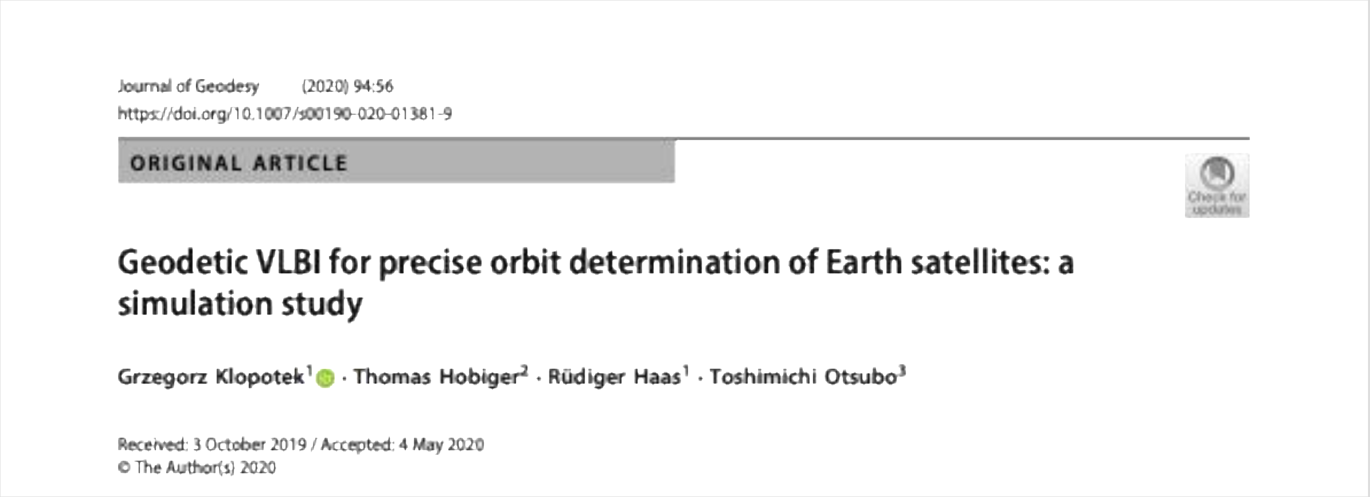
- Study determination of ”geodetic parameters” from Genesis-VLBI
  - Station positions and satellite orbit
  - Earth orientation parameters
  - Signal propagation parameters

Important:

- There should be no harm on ”standard” VLBI products, e.g. EOP!

Some previous work

- Klopotek et al., JOGE, 2020, 10.1007/s00190-020-01381-9
  - Lageos-1/-2 (also Galileo)
  - Legacy S/X VLBI (Cont17) schedules
  - VGOS simulated schedules



Journal of Geodesy (2020) 94:56
https://doi.org/10.1007/s00190-020-01381-9

ORIGINAL ARTICLE

Geodetic VLBI for precise orbit determination of Earth satellites: a simulation study

Grzegorz Klopotek[1] · Thomas Hobiger[2] · Rüdiger Haas[1] · Toshimichi Otsubo[3]

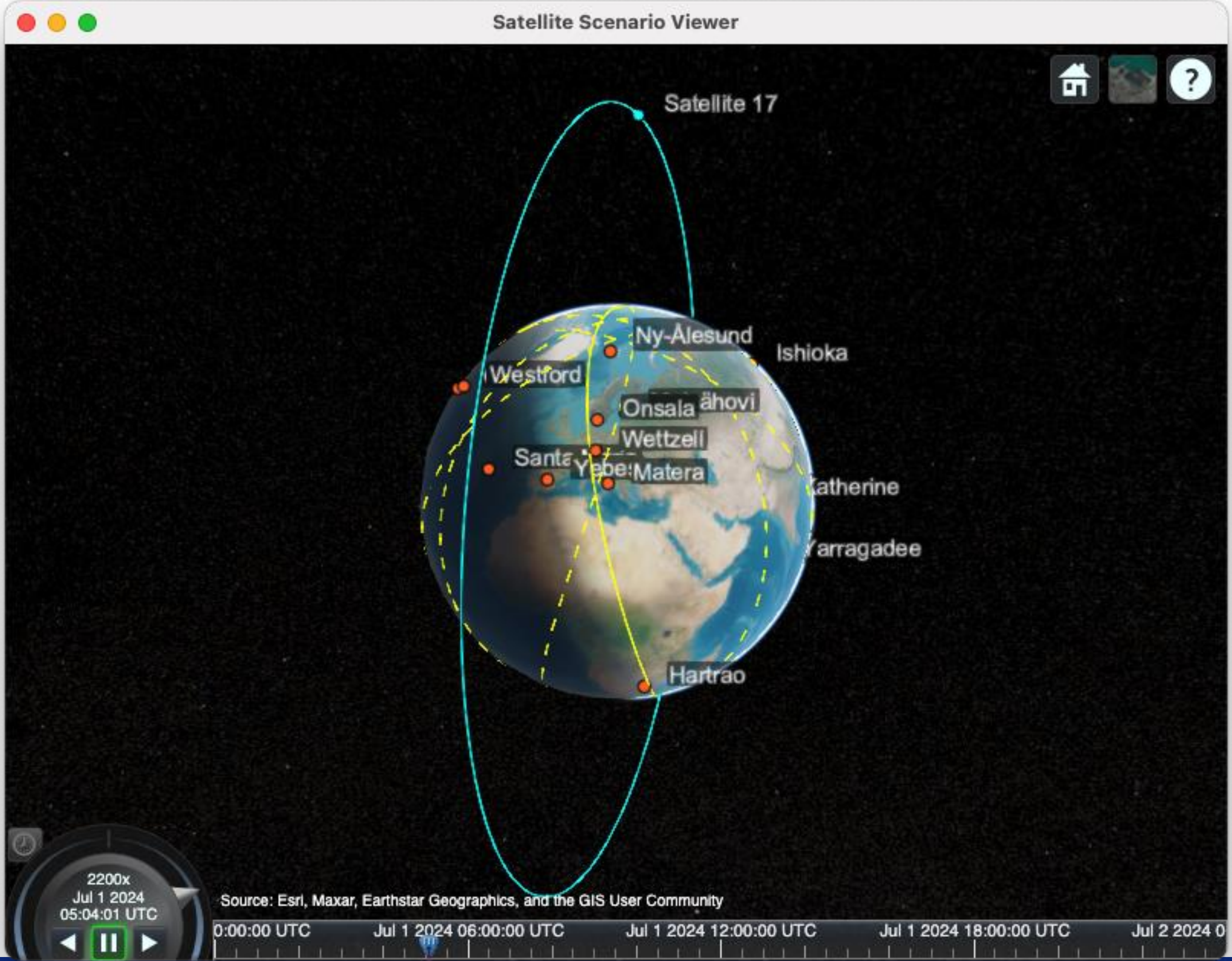
Received: 3 October 2019 / Accepted: 4 May 2020

- Estimation of
  - Satellite orbit and geocenter
  - Station positions
  - Earth Rotation Parameters
  - Clock parameters and tropospheric parameters

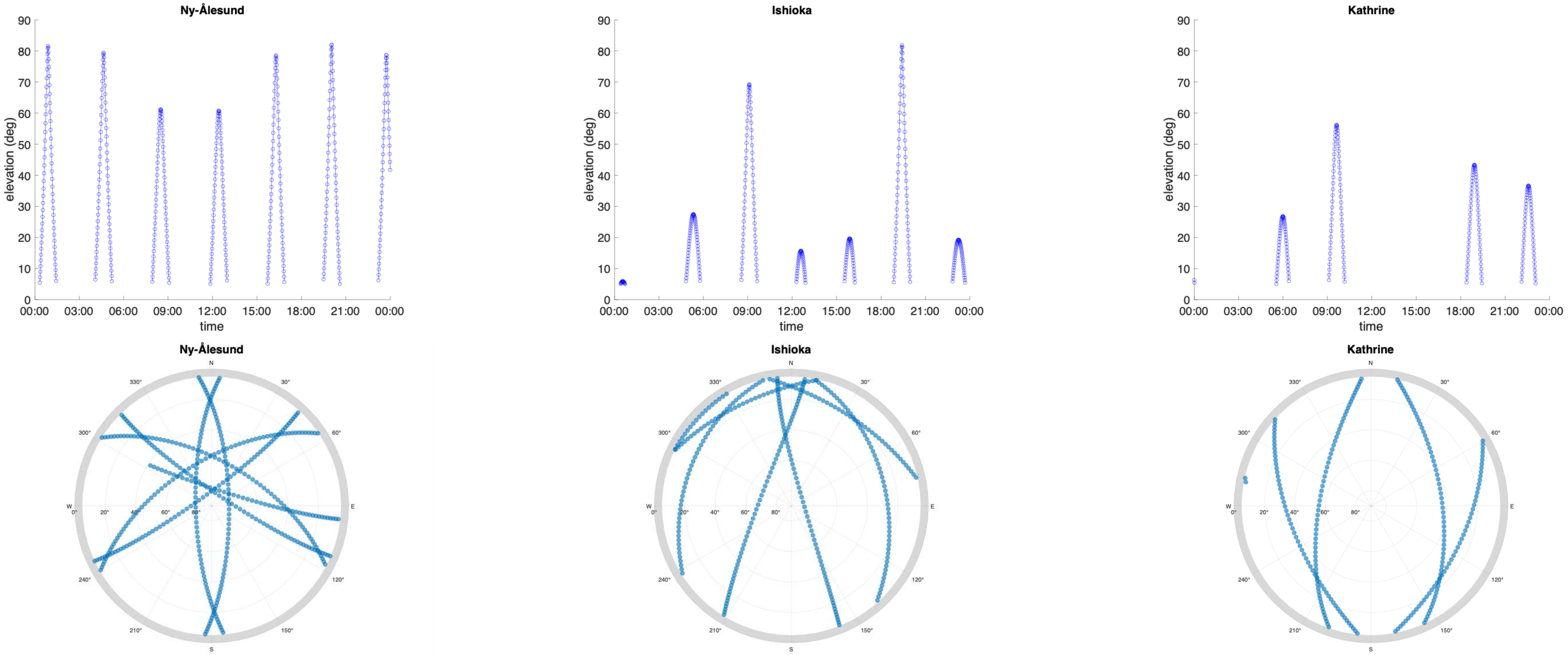
Conclusions from previous work

- "… In the case of LAGEOS-1/-2 satellites, the obtained orbits are characterized by the precision of approximately 2.0 cm for CONT17-type schedules. … "
- " … it was shown that the combination of quasar and satellite observations could allow theoretically for simultaneous estimation of ERP (polar motion and UT1-UTC) along with geocenter offsets, VLBI station positions and satellite orbits. Compared to the reference solution including only quasar observations, ERP and station positions, derived based on the CONT17 network, were degraded only slightly for satellite observation precision levels not better than the precision level of the quasar observations. No negative impact was noticeable, however, in the case of satellite observations and the VGOS-type network. … "

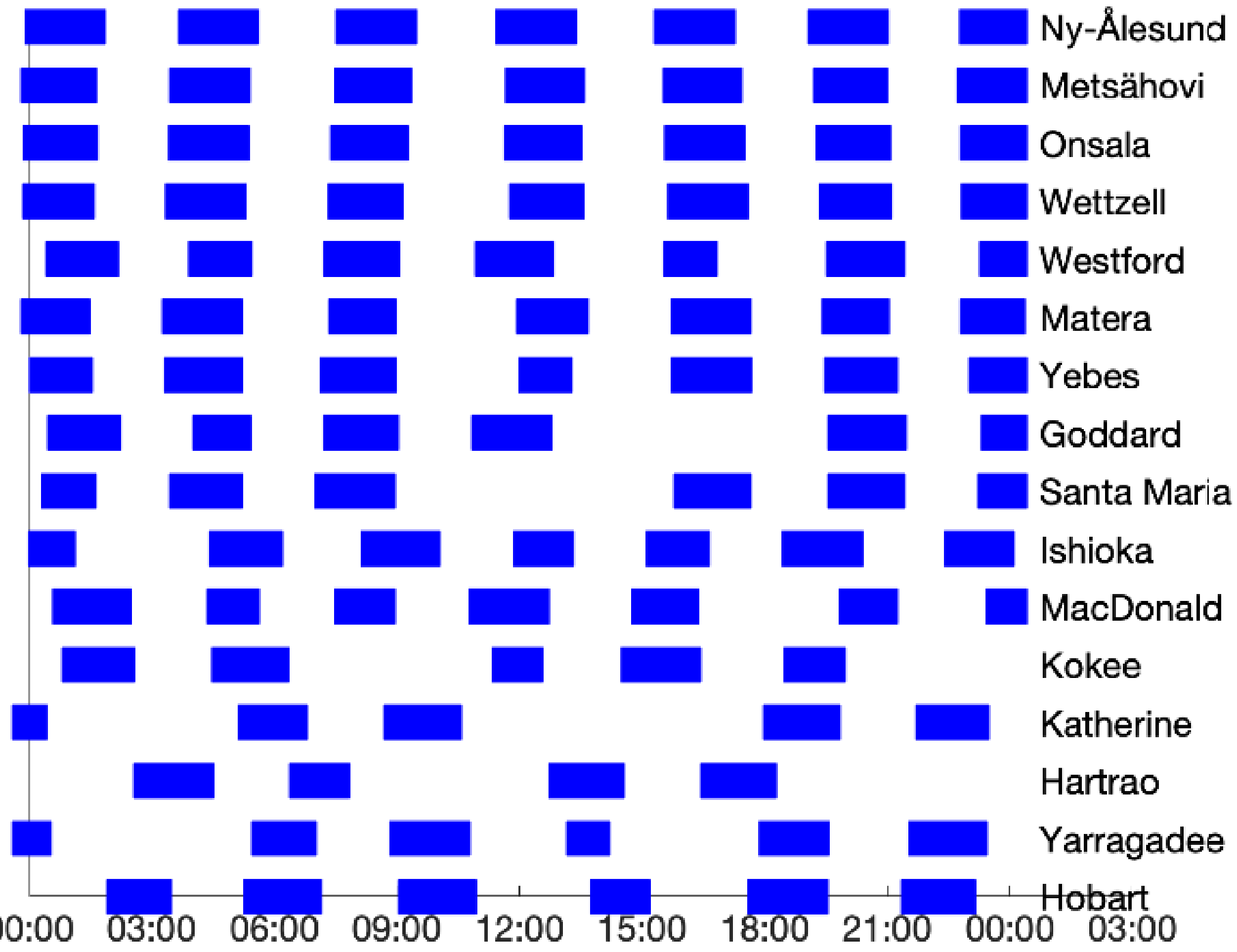
Genesis example



Example: 24 h visibility @ three stations

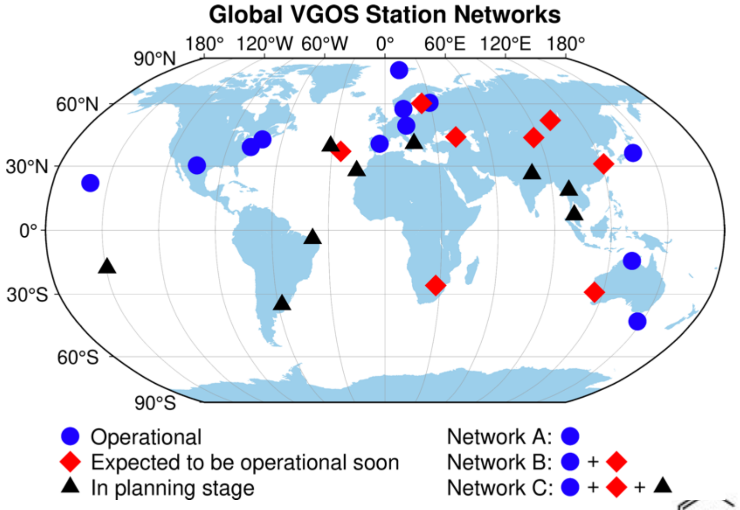


Example: 24 h visibility VGOS network



Recent simulations

- Schunck et al., 2024, *Remote Sensing*, doi 10.3390/rs16173234
- Three different VGOS networks used:
  - VGOS operational network (12 stations)
  - ”VGOS-soon” network (20 stations)
  - VGOS planning network (29 stations)
- Simulated mixed-schedules with scan length
  - 30 s for natural radio sources
  - 10 s for Genesis



remote sensing

MDPI

Article

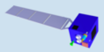
On the Integration of VLBI Observations to GENESIS into Global VGOS Operations

David Schunck *, Lucia McCallum and Guifré Molera Calvés

Analysis approaches

- Analysis of pure radio astronomical schedules => reference
- Analysis of mixed schedules
  - Only using radio astronomical observations
  - Using both observations to natural radio source and Genesis
- No orbit estimation
- EOPs and radio sources fixed for combined analysis

Ref. Schunck et al., 2024

VGOS Processing		GENESIS Processing	
	**Source type**		
	Simulation		
✓	Troposphere	✓	✓
✓	Station clocks	✓	✓
✓	Noise	✓	✓
	Orbit errors		✓
	Constraints		
✓	No-Net-Translation	**unconstrained**	
✓	No-Net-Rotation	**unconstrained**	
	Estimation		
✓	Troposphere	✓	✓
✓	Station clocks	✓	✓
✓	Station positions	✗	✓
✓	EOPs	**fixed**	
✓	Source positions	**fixed**	

Some results from Schunck et al., 2024

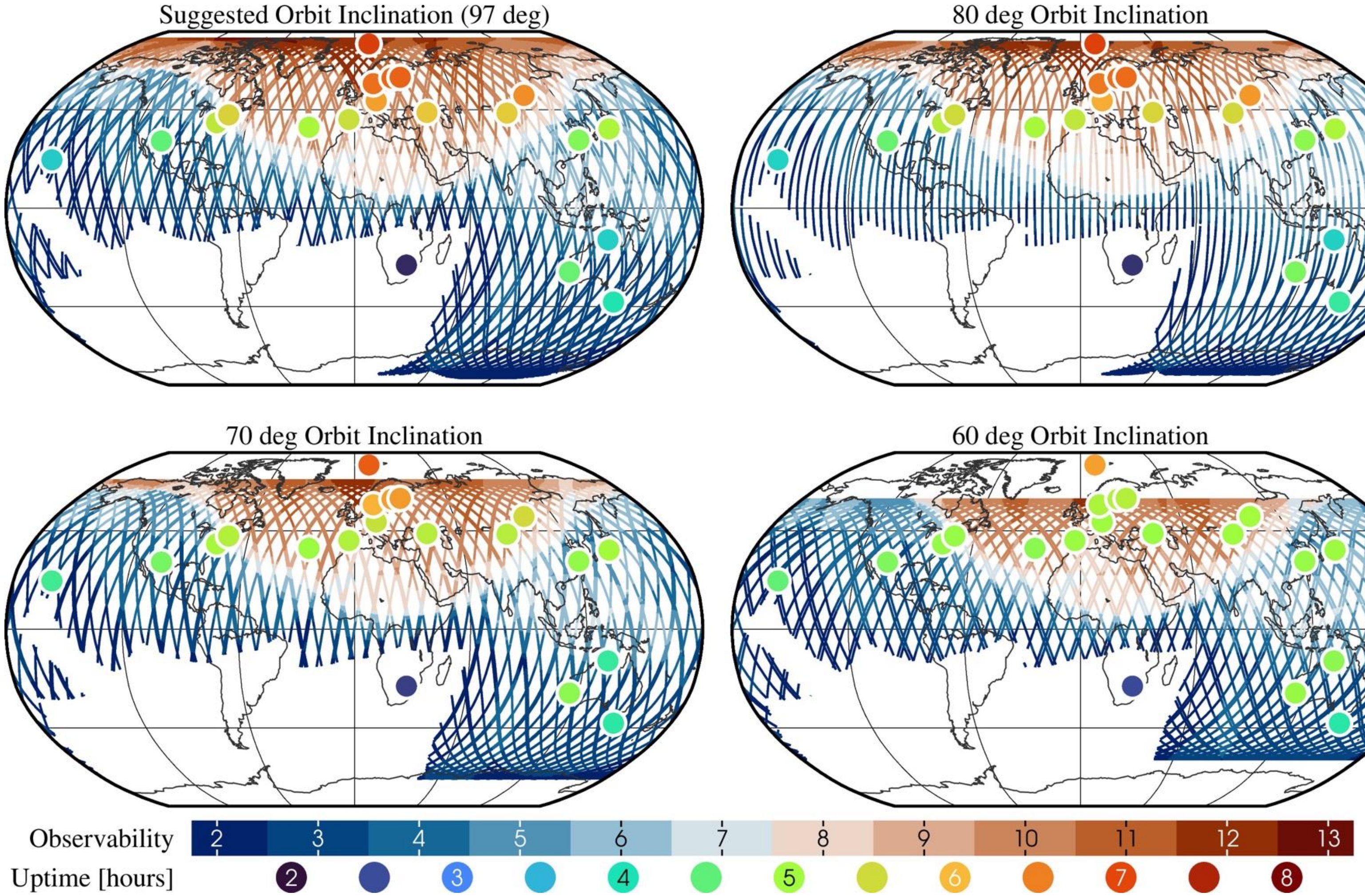
- Impact of Genesis on VGOS is quasi-negligible
  - With 5 min repeat time on Genesis => no negativ impact on VGOS products
- Frame tie after one year 2-4 mm, assuming
  - 3 mixed sessions per week
  - Assuming orbit errors of 5 cm

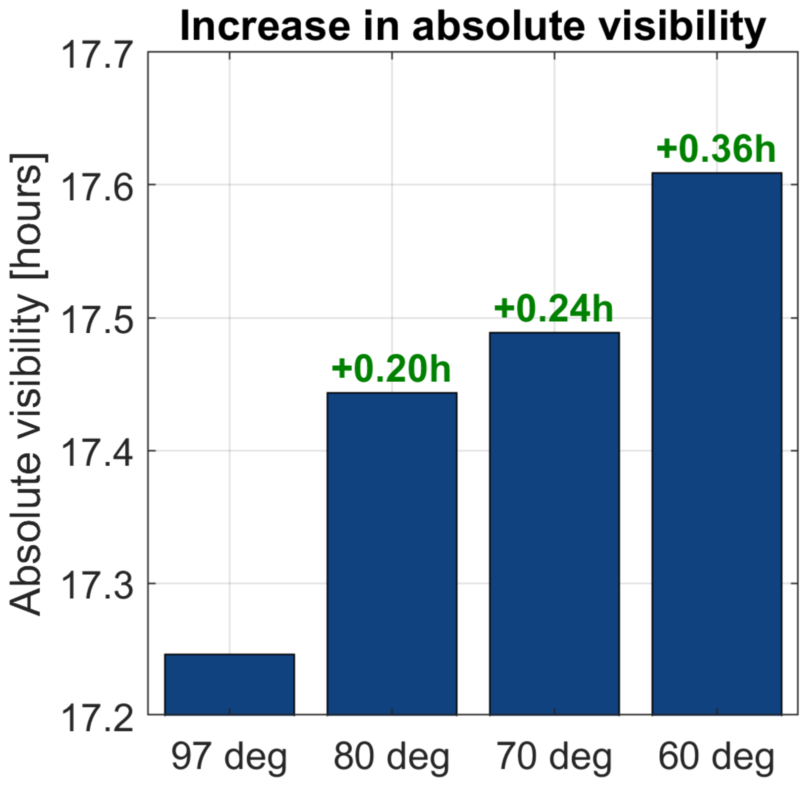
The inclination question

- The other space geodetic techniques, primarily SLR and DORIS, are in favour of a lower inclination, e.g. 60 degree
- Reasons are estimating geocenter z-component and seperating draconitic and annual orbit variations

- Some simulations on impact of inclination on VGOS visibility
  - Schunck et al., IAG symposia, doi 10.1007/1345_2024_245
  - Schartner

Gensis visibility as function of inclination

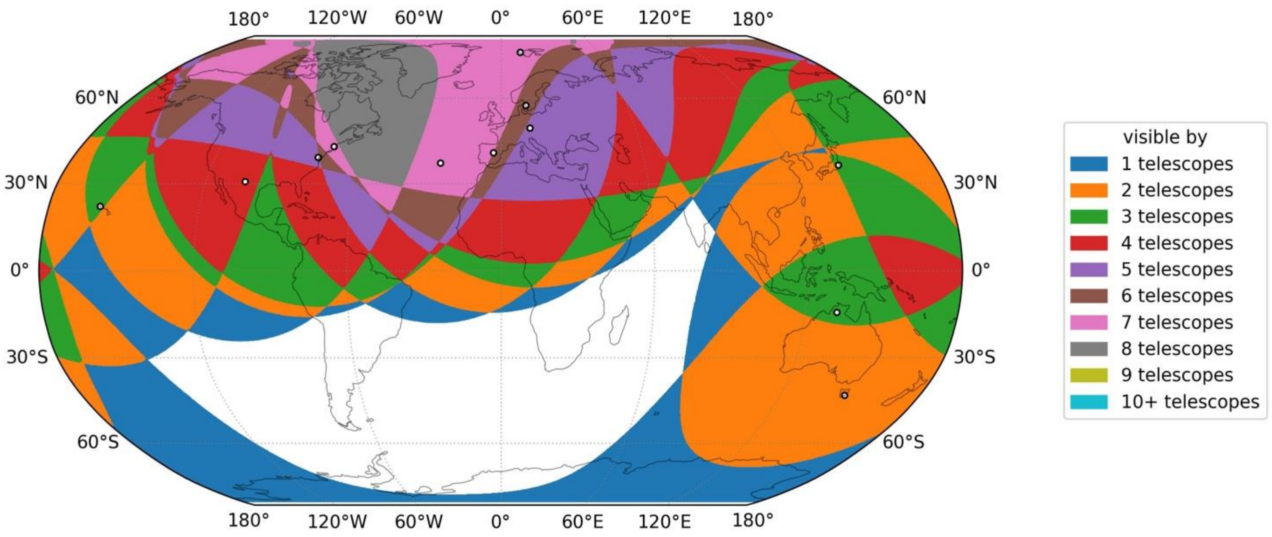




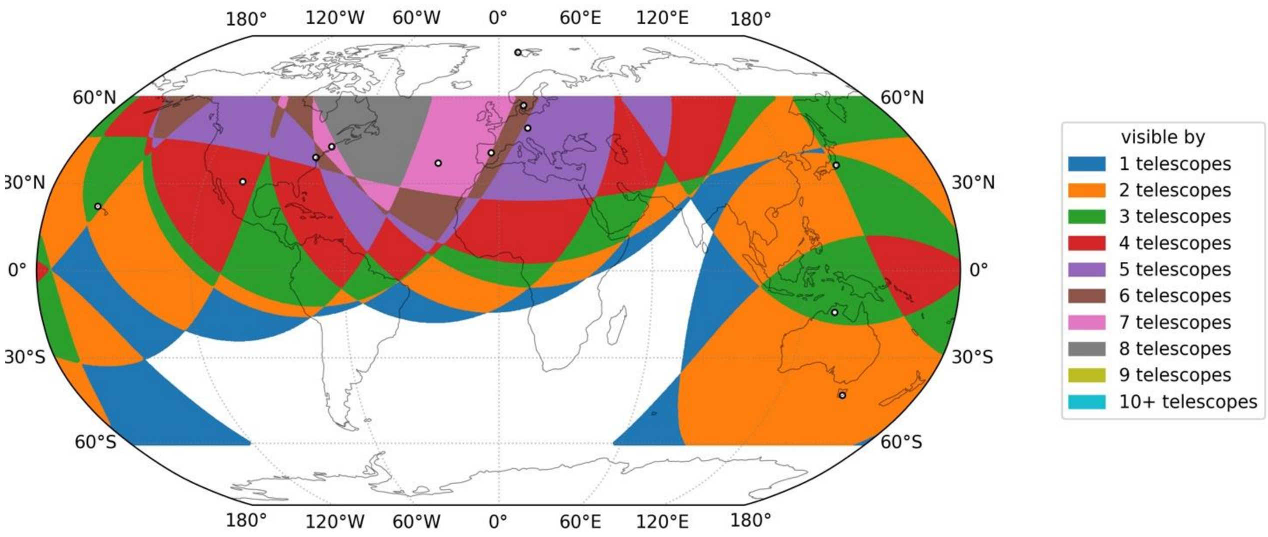
From Schunck et al., IAG symposia

Visibility of Genesis for today's VGOS

h=6000 km, i=95°



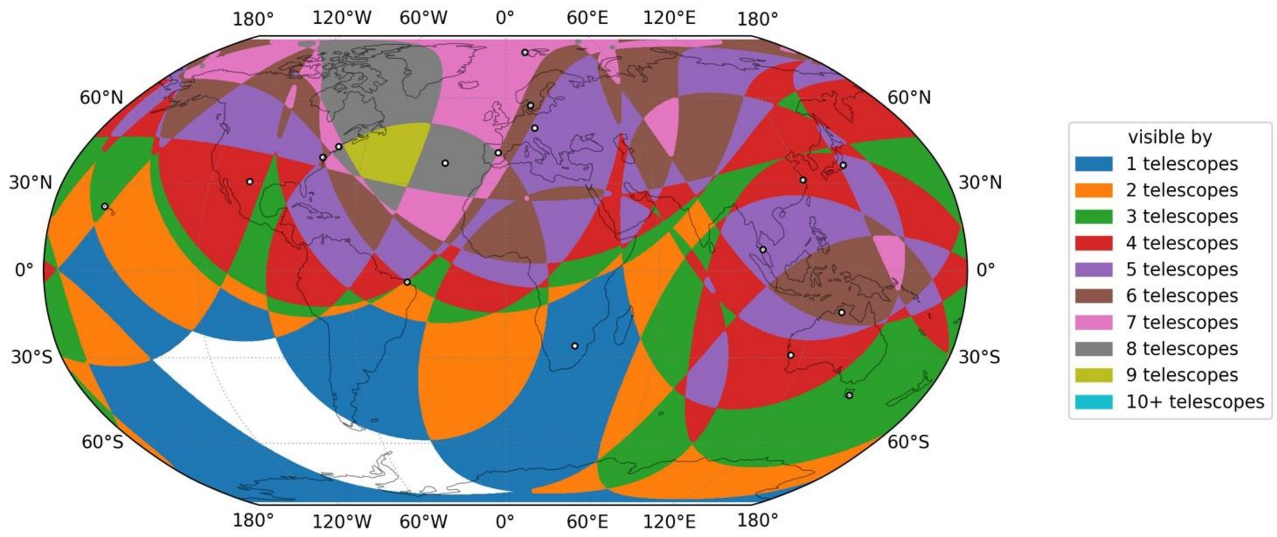
h=6000 km, i=60°



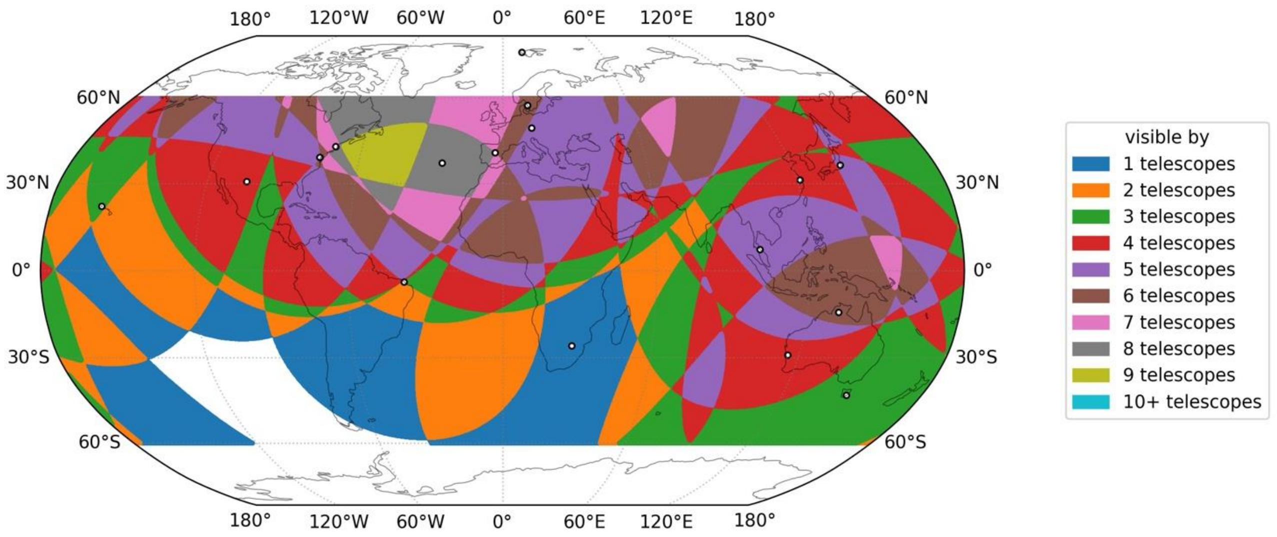
Ref. Matthias Schartner, ETH Zürich

Visibility of Genesis for future VGOS

h=6000 km, i=95°



h=6000 km, i=60°



Ref. Matthias Schartner, ETH

Importance of Genesis inclination

- No big difference in terms of visibility
- About ± 10–15 % in visibility time
- Larger variations due to scheduling possible
- Orbit altitude has larger impact

- However, impact on orbit determination with VLBI has not been quantified yet

WP-7

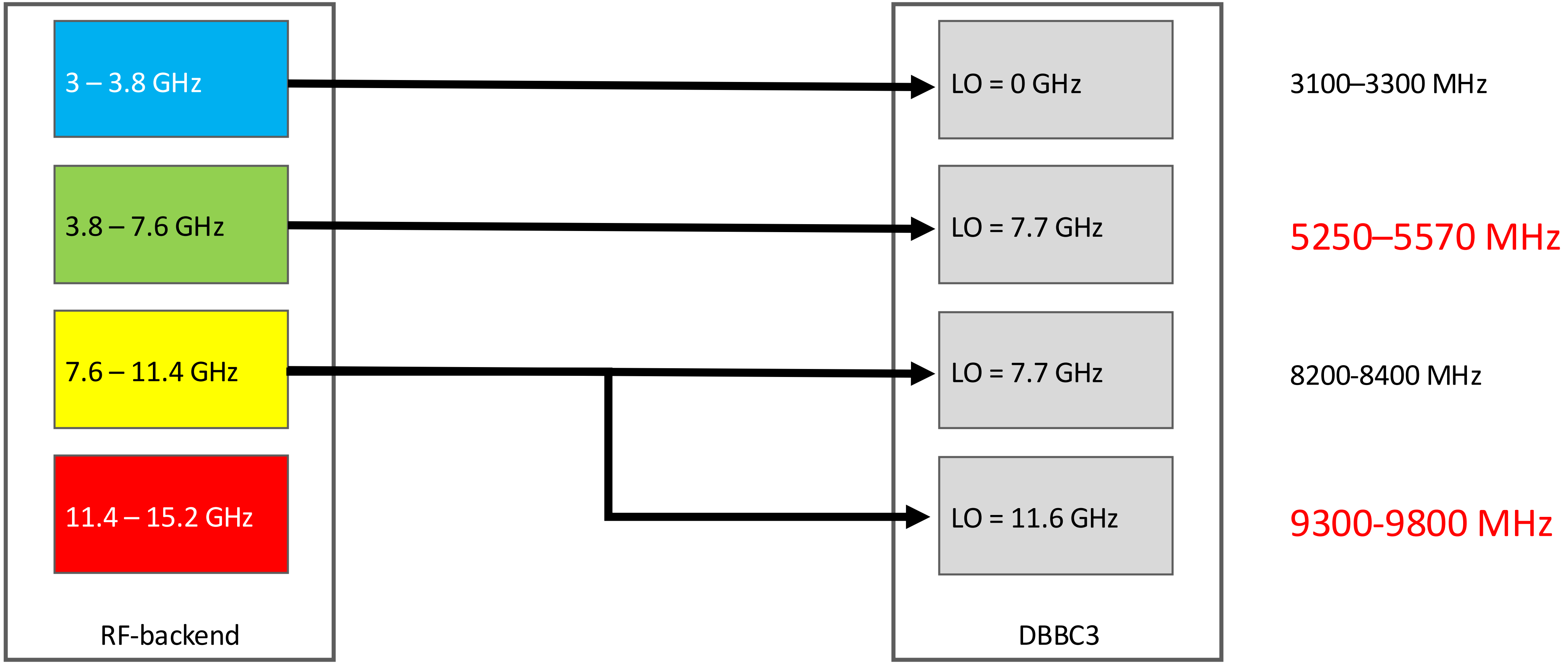
PRN option

Idea: One-way-ranging, time transfer

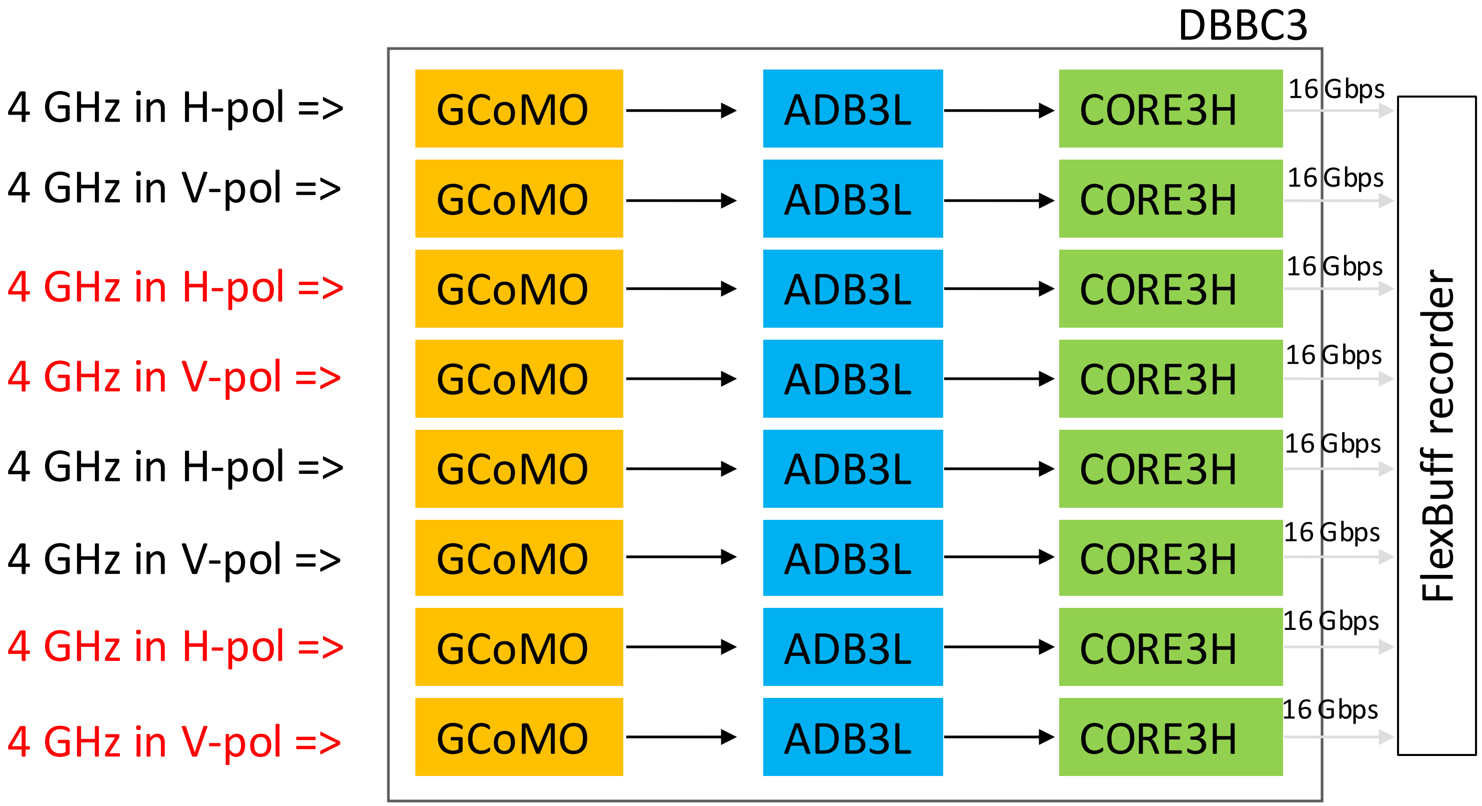
- Chip-rate of 160 Mchip/s needs 320 MHz and can be accommodated in Genesis band-2 and band-4
- 160 Mchip/s => 19 mm (62.5 ps) measurement accuracy, assuming 1 % of the chip length can be resolved
- Would be > 15 times better than GPS P-code measurements

- Seems to be attractive for e.g. time transfer, i.e. distribute same time from the ultra-stable oscillator onboard Genesis to several ground stations worldwide

”Genesis-VGOS” @ OSO



DBBC3L-8H8H architecture



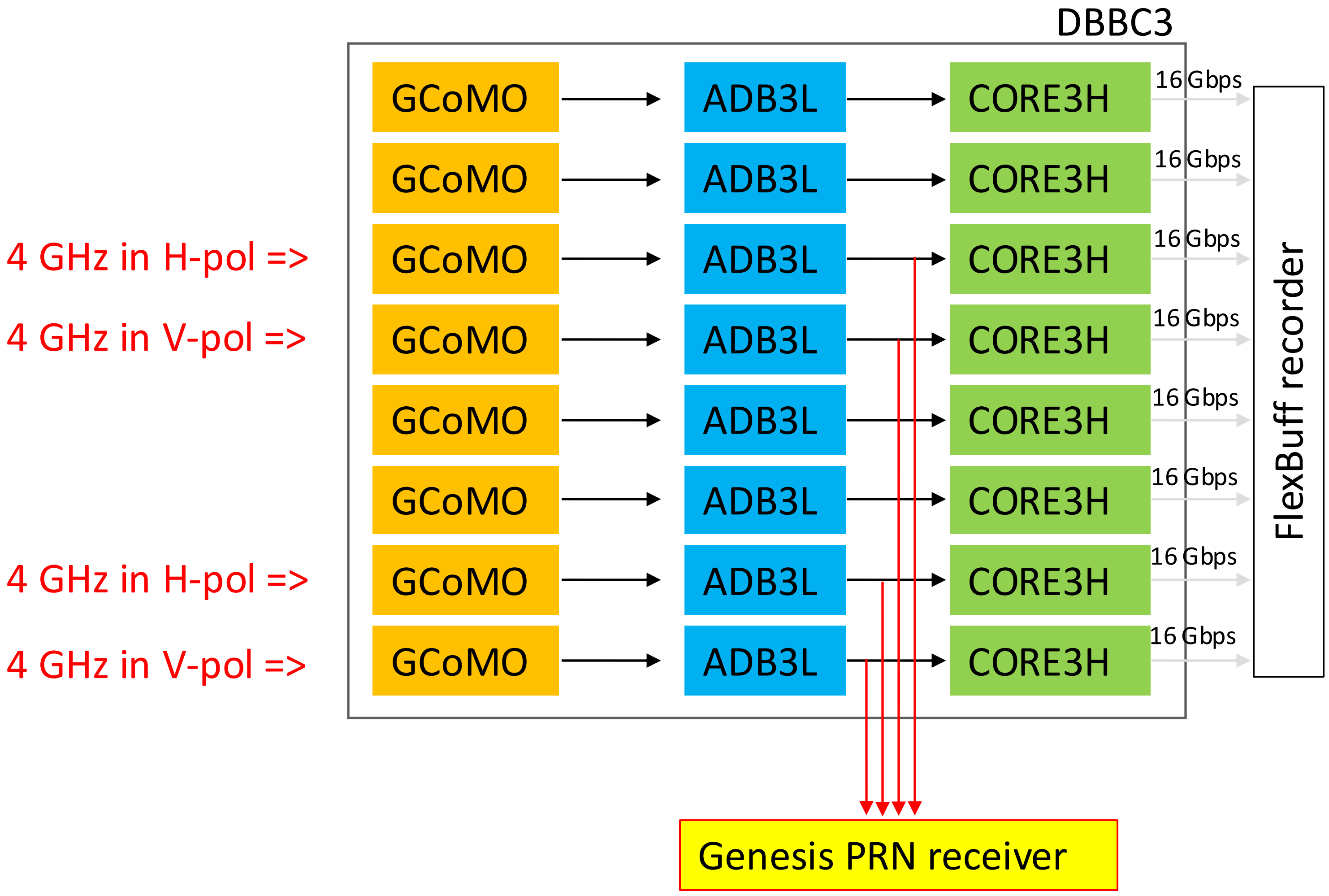
GCoMo :
downconvert 4 GHz bandwidth

ADBL3:
sampler board
sampling representation 10 bit
Equivalent sample rate 2-4-8 GSps

CORE3H:
FPGA processing board

=> Question: Where to tap the Genesis PRN signals?

Tapping Genesis PRN?



- After the ADB3L sampler?
- Possibilities need to be checked, also with RDBE/R2DBE

Open questions

- What to do with Genesis band-1 and band-3 (B=200 MHz)?
- How to embed PRN signal in white noise signal for ”classical VLBI”?
- Any negative effects on ”classical VLBI”?

Questions?