Genesis Science Workshop

3rd -4th April 2025

Matera, Italy

VLBI Session

Working Group 3

ESA GSET WG-3 (VLBI)

general overview

ESA Genesis Science Workshop 2025

3-4 April 2025, Matera, Italy

Rüdiger Haas

Chalmers University of Technology

ESA GSET WG-3 members

- Simone Bernhart – BKG/MPIfR, DEU
- Johannes Böhm – TU Vienna, AUT
- Patrick Charlot – CNRS Bordeaux, FRA
- Thibault Deleu – RoB, BEL
- Pablo de Vicente – IGN, ESP
- Claudia Flohrer – BKG, DEU
- Susana Garcia-Espada – Kartverket, NOR
- Luciano Garramone – ASI, ITA
- Jakob Gruber – BEV Wien, AUT
- Rüdiger Haas – Chalmers, SWE
- Masafumi Ishigaki – GSI, JAP
- Shinobu Kurihara – GSI, JAP
- Lucia McCallum – UTas Hobart, AUS
- Alexander Neidhardt – TU München, DEU
- Axel Nothnagel – TU Vienna, AUT
- Almine Özyildirim – RoB, BEL
- Christian Plötz – BKG, DEU
- Chet Ruszczyk – MIT Haystack, USA
- Matthias Schartner – ETH Zürich, CHE
- Harald Schuh – GFZ Potsdam, DEU
- Gino Tuccari – INAF & MPIfR, ITA/DEU

Ex-officio (ESA GSET coordinator & co-coordinator)

- Özgur Karatekin – RoB, BEL
- Francesco Vespe – ASI, ITA

ESA

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

Today’s WG3 programme

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ESA GSET WG-3 (VLBI) presentations on the ESA Genesis Workshop 2025, Matera

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10:00-10:10 R. Haas (in-person)       ”ESA GSET WG-3 (VLBI) general overview"
10:10-10:15 R. Haas (in-person)       ”WP-1: frequencies, signals, antenna etc.”
10:15-10:20 A. Neidhardt (in-person) ”WP-2: ground station fidelity”
10:20-10:25 J. Gruber (online)        ”WP-3: delay resolution and correlation”
10:25-10:30 M. Schartner (in-person) ”WP-4: scheduling”
10:30-10:35 M. Schartner (in-person) ”WP-5: end-to-end simulations”
10:35-10:40 R. Haas (in-person)       ”WP-6: test observations”
10:40-10:45 A. Özyldirim (in-person) ”WP-7: PRN-option”

10:45-10:59 Questions and discussion
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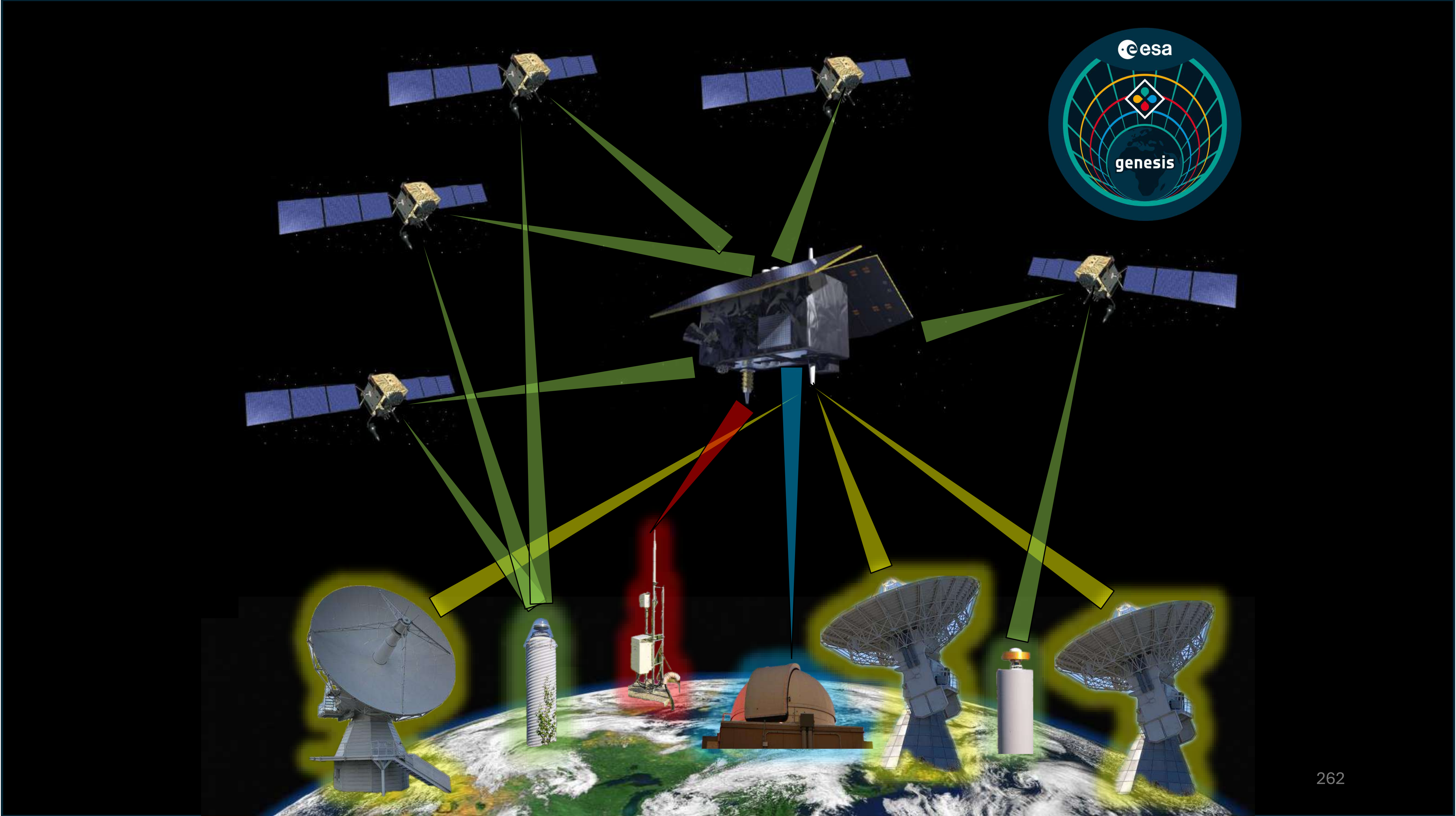
esa
genesis

WP-1: frequencies, signals etc.

- Genesis frequencies
- Signal strength and on/off option
- Genesis antenna gain characteristics
- Genesis antenna phase centre characteristics
- Antenna phase centre and satellite centre of mass

- => Rüdiger's presentation

WP-2: ground station fidelity

- Can the VGOS stations track satellites?
- Can the VLBI backends (DBBC3, R2DBE) observe the Genesis frequencies?
- What is the electromagnetic environment at the stations?
- Can we operate switching back-and-forth between ”standard VGOS” setup and Genesis-setup?
- Are there any issues with data recording?

- => Alexander’s presentation

WP-3: delay resolution and correlation

- Expected delay resolution from Genesis frequency setup?
- Are there any issues with correlation?
- Will a potential PRN signal cause issues?
- Near-field model in the correlation software?
- Can data be post-processed with standard VGOS pipeline?

- => Jakob’s presentation

WP-4: scheduling

- What are suitable observing scenarios?
- Should we include Genesis-observations into standard IVS-sessions or have separate and dedicated Genesis sessions?
- How to create schedules and prepare observation files?
- Advantages/disadvantages of specific satellite inclinations?

- => Matthias’ presentation

WP-5: end-to-end simulations

- Simulation and analysis of simulated data
- What noise levels to expect?
- Estimation of
  - a) “the traditional VLBI parameters”
  - b) additional parameters (e.g. satellite orbits, geocenter, …)
- What will we gain from observing Genesis?
- Important: no harm on geodetic VLBI shall be done!

- => Matthias’ presentation

WP-6: test observations

- Tests of various Genesis frequency setups
- Observations of other, already existing, satellite signals
- Test “switching-schedules”
- Execute the complete chain:
  - scheduling – observation – correlation – fringe-fitting – data analysis
- Important: Gain experience <u>before</u> Genesis will be launched!

- => Rüdiger’s presentation

WP-7: PRN-option

- Why is PRN of interest at all?
- What is the achievable precision for one-way-ranging?
- How can this be integrated into the existing station instrumentation?
- Are there any negative impacts on classical interferometry?
- Is there a need for dedicated software receivers?

- => Alime’s presentation

ESA GSET WG-3 (VLBI)

WP-1: frequencies, signals, antenna etc.

ESA Genesis Science Workshop 2025

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Rüdiger Haas

Chalmers University of Technology

The Genesis VLBI frequencies

- Band-1: 3100–3300 MHz (i.e. B = 200 MHz)
- Band-2: 5250–5570 MHz (i.e. B = 320 MHz)
- Band-3: 8200–8400 MHz (i.e. B = 200 MHz)
- Band-4: 9300–9800 MHz (i.e. B = 500 MHz)

Today’s IVS frequency capability

Legacy S/X

- S-band 2225.99–2365.99 MHz
- X-band 8212.99–8932.99 MHz

(the example above is the frequency setup of a standard ”R1” session)

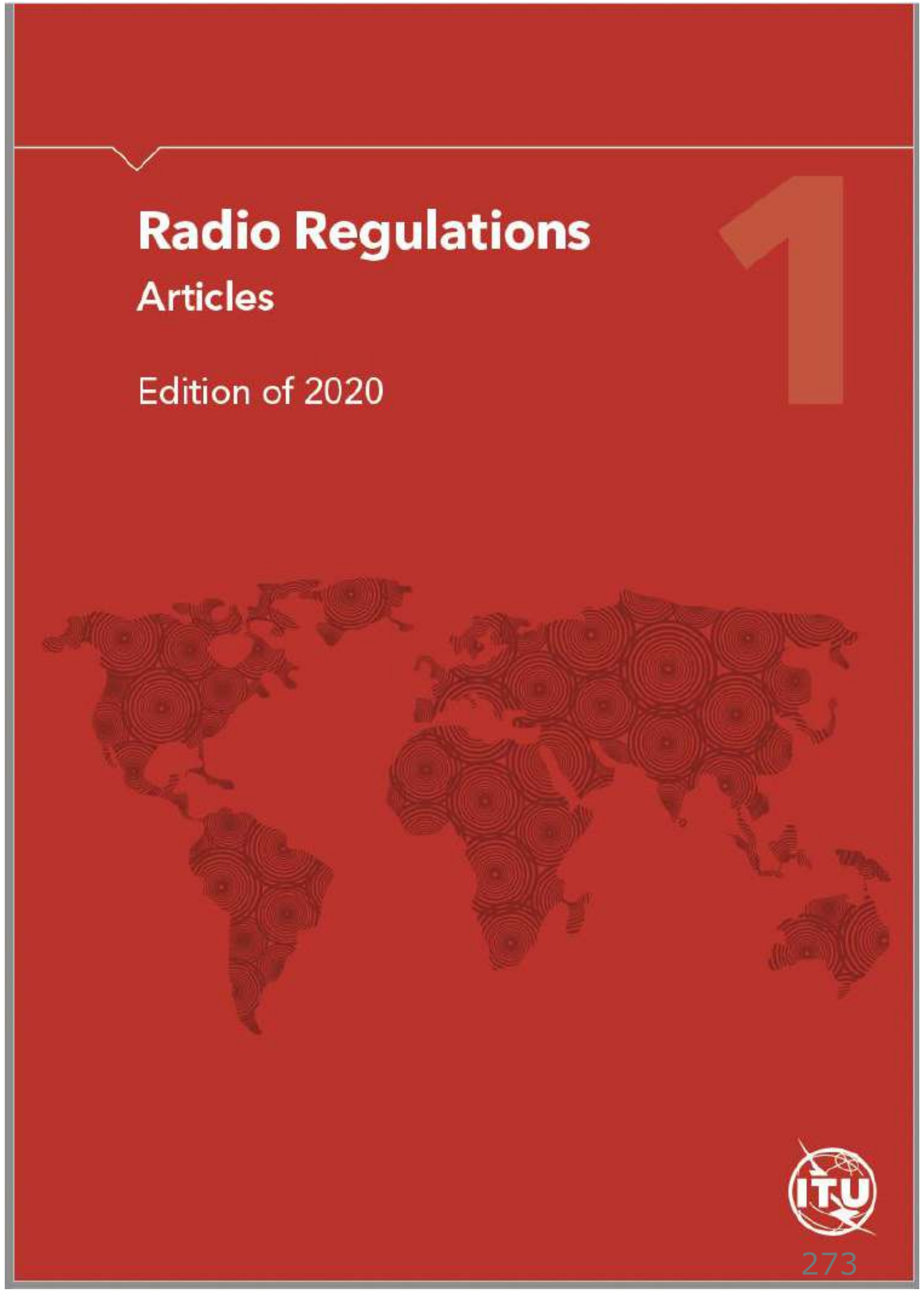
VGOS

- Broadband 3.0–14 GHz
- (4 bands of 1 GHz selectable ”whereever” in this range)

ITU radio regulations

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

➢ Service: “Earth Exploration Satellite”



Possible VGOS channel selection for Genesis

3100-3300 MHz

BAND-1	3132.4	32.0	L
BAND-1	3164.4	32.0	L
BAND-1	3196.4	32.0	L
BAND-1	3228.4	32.0	L
BAND-1	3260.4	32.0	L
BAND-1	3292.4	32.0	L

6 channels

5250–5570 MHz

BAND-2	5276.4	32.0	L
BAND-2	5308.4	32.0	L
BAND-2	5340.4	32.0	L
BAND-2	5372.4	32.0	L
BAND-2	5404.4	32.0	L
BAND-2	5436.4	32.0	L
BAND-2	5468.4	32.0	L
BAND-2	5500.4	32.0	L
BAND-2	5532.4	32.0	L
BAND-2	5564.4	32.0	L

10 channels

8200–8400 MHz

BAND-3	8220.4	32.0	L
BAND-3	8252.4	32.0	L
BAND-3	8284.4	32.0	L
BAND-3	8316.4	32.0	L
BAND-3	8348.4	32.0	L
BAND-3	8380.4	32.0	L

6 channels

9300–9800 MHz

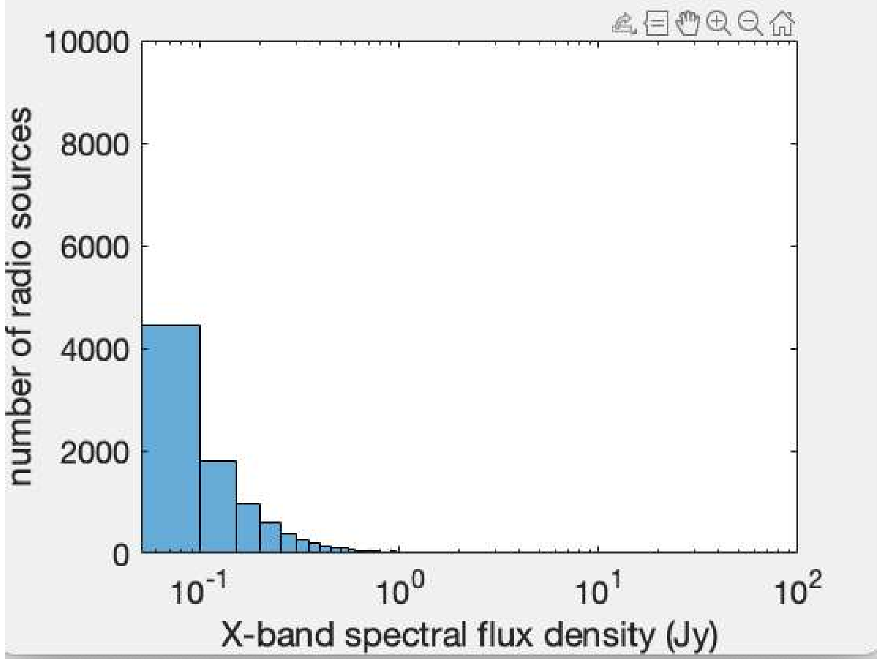
BAND-4	9340.4	32.0	L
BAND-4	9372.4	32.0	L
BAND-4	9404.4	32.0	L
BAND-4	9436.4	32.0	L
BAND-4	9468.4	32.0	L
BAND-4	9500.4	32.0	L
BAND-4	9532.4	32.0	L
BAND-4	9564.4	32.0	L
BAND-4	9596.4	32.0	L
BAND-4	9628.4	32.0	L
BAND-4	9660.4	32.0	L
BAND-4	9692.4	32.0	L
BAND-4	9724.4	32.0	L
BAND-4	9756.4	32.0	L
BAND-4	9788.4	32.0	L

15 channels

=> In total 37 channels, total BW covering 1184 MHz in 4 bands.

Genesis signals strength considerations

- Compromise between
  - Enough signal to get reasonable SNR for reasonable integration time
  - Not disturbing other passive users of the electromagnetic spectrum, in particular radio astronomical observatories
  - => Idea: tuneable signal
  - histogram of spectral flux density of natural radio sources at X-band in Jy, (1 Jy = 10^{-26} W m^{-2} Hz^{-1})



Genesis signal strength ?

- Equation relating signal strength (spectral flux density *F*), station sensitivities (*SEFD*), bandwidth *B*, number of channels *N*, and observation time *t* :
- $SNR = \frac{1}{\eta}\frac{F}{\sqrt{SEFD_1 \cdot SEFD_2}}\sqrt{2 \cdot B \cdot N \cdot t}$
- Assuming SEFD=3000 Jy, t=30 s, B=32 MHz,
  - 6 channels: F= 0.5 / 1 / 5 / 10 Jy will give SNR= 10 / 20 / 100 / 200
  - 15 channels: F= 0.5 / 1 / 5 / 10 Jy will give SNR= 16 / 32 / 160 / 320
- Tuneable signal strength necessary (on/off and tuneable!)

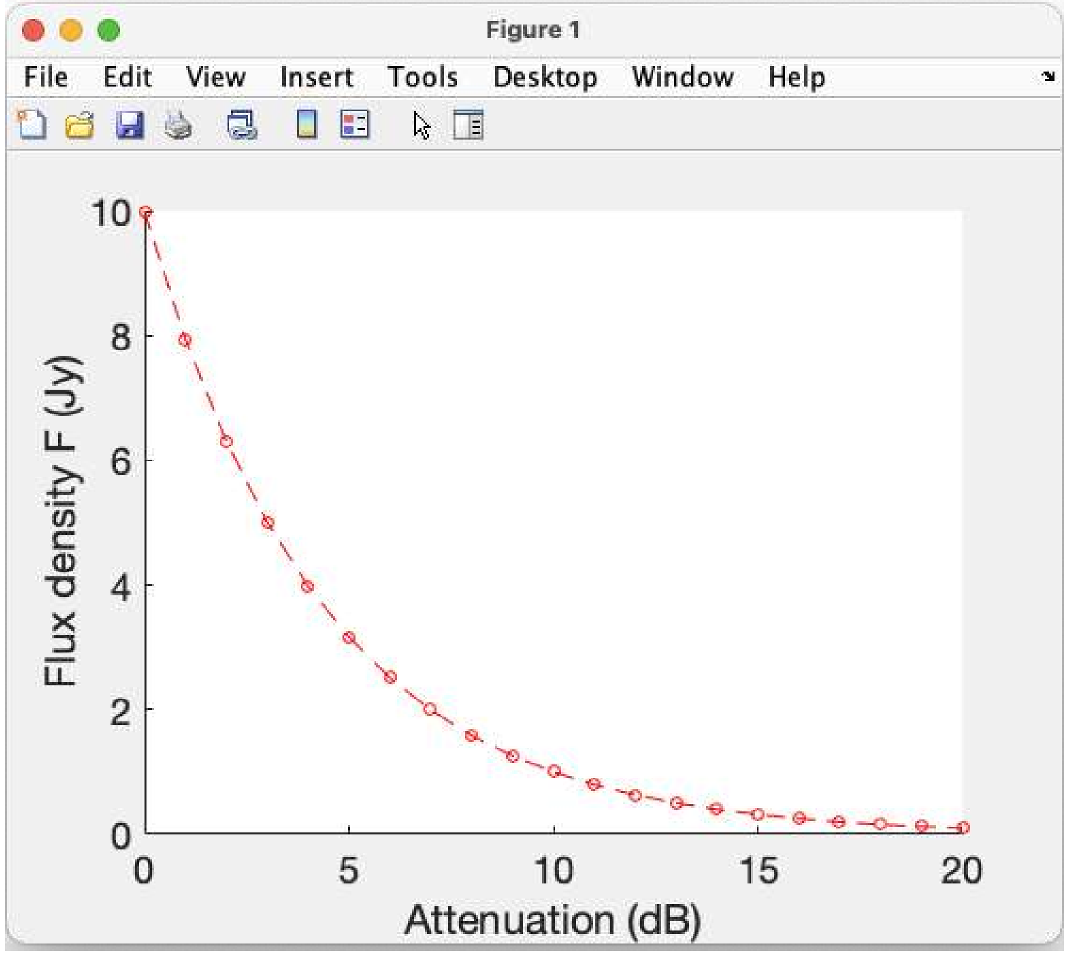
Tuneable signal strength

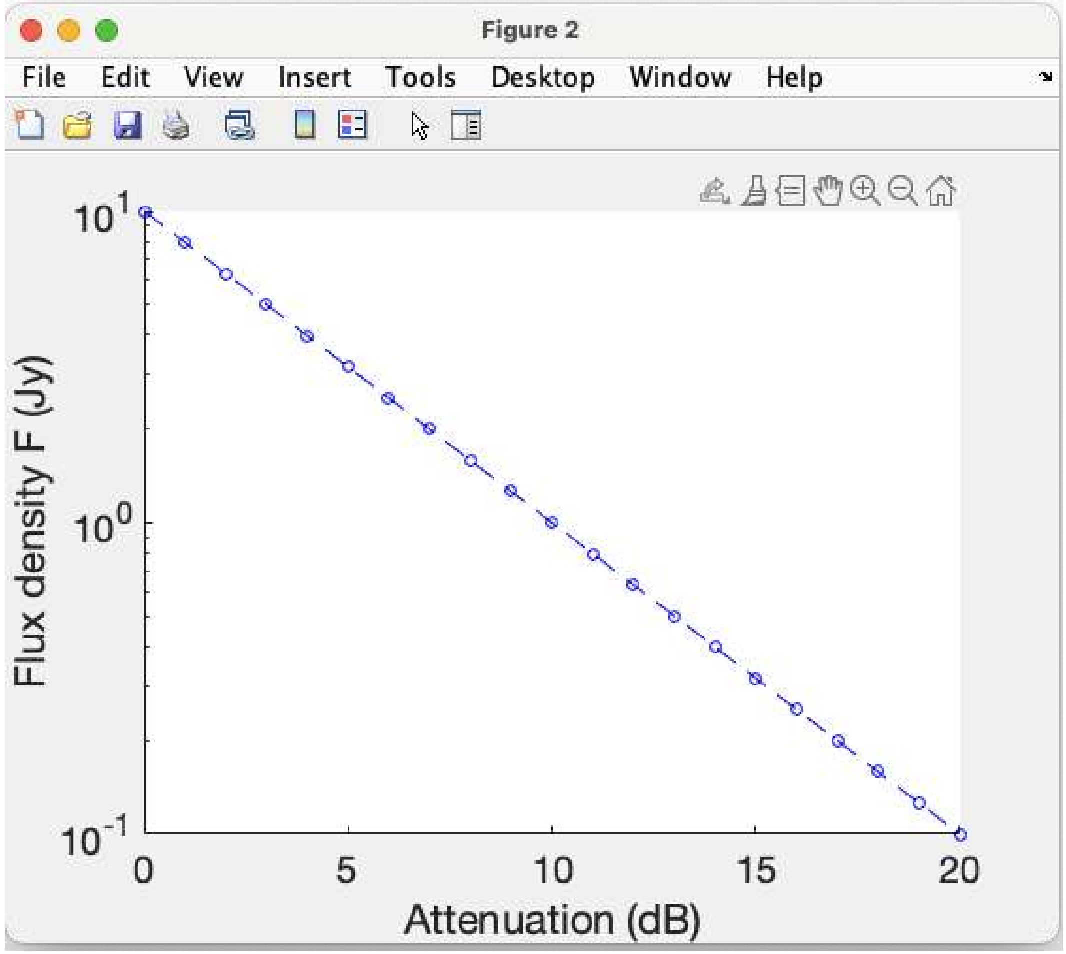
- Logarithmic tuning
- Max. spectral flux density S_{max} = 10 Jy
- Attenuation in 21 steps: A= [0 20] dB

$$S = S_{max} \cdot 10^{\frac{-A}{10}}$$

A (dB)	F (Jy)	A (dB)	S (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	OFF	0

Tuneable signal strength



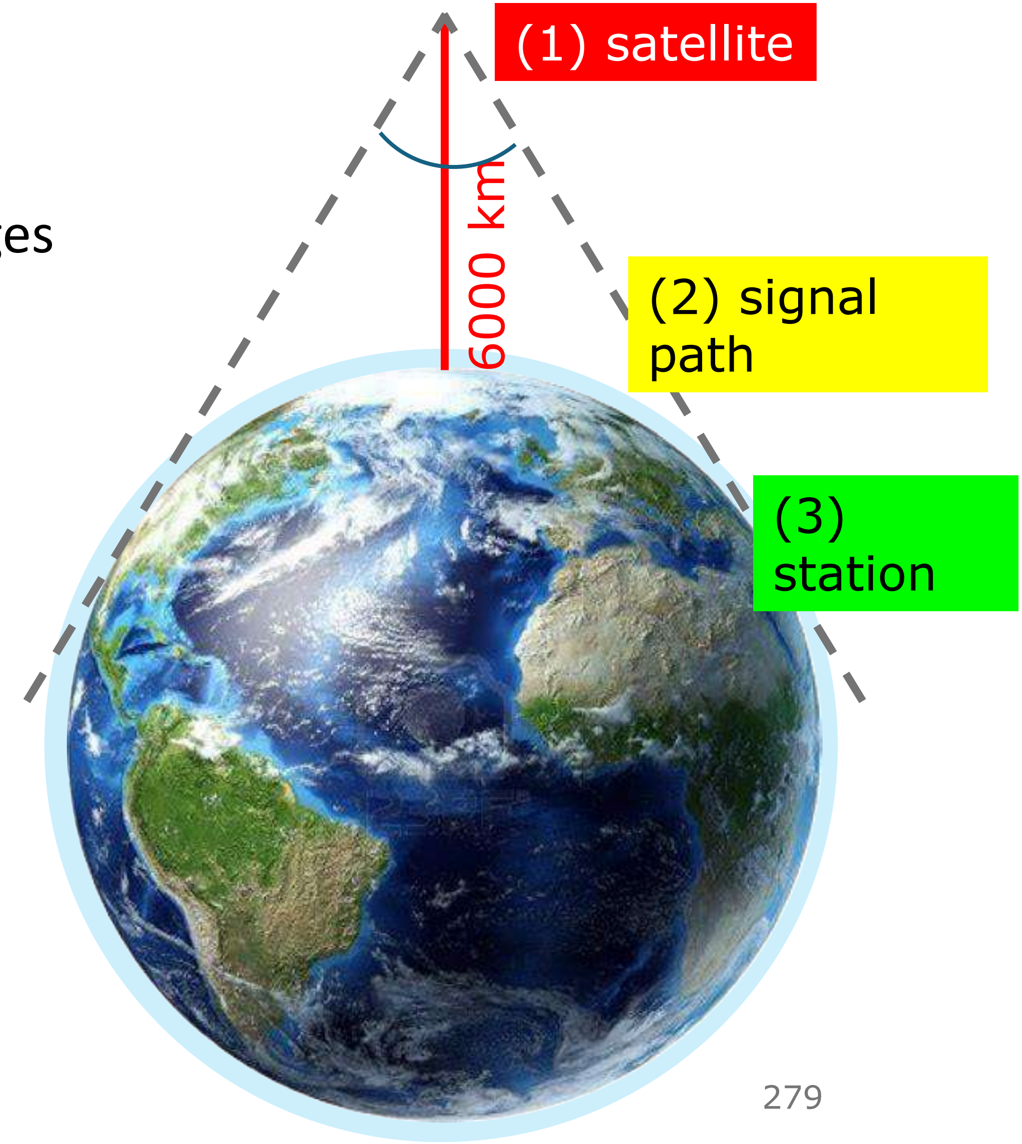


=> Proposal has been forwarded to industry <=

Special situation for VLBI with satellite signals

1) Satellite antenna pattern
   - Gain difference between bore sight and HPBW edges
2) Free space loss
   - Distance and frequency dependent
3) Station sensitivity (incl. atmospheric losses)
   - Frequency and weather dependent
   - Atmospheric gas attenuation
   - Cloud attenuation
   - Scintillation attenuation

   - (Rain attenuation)



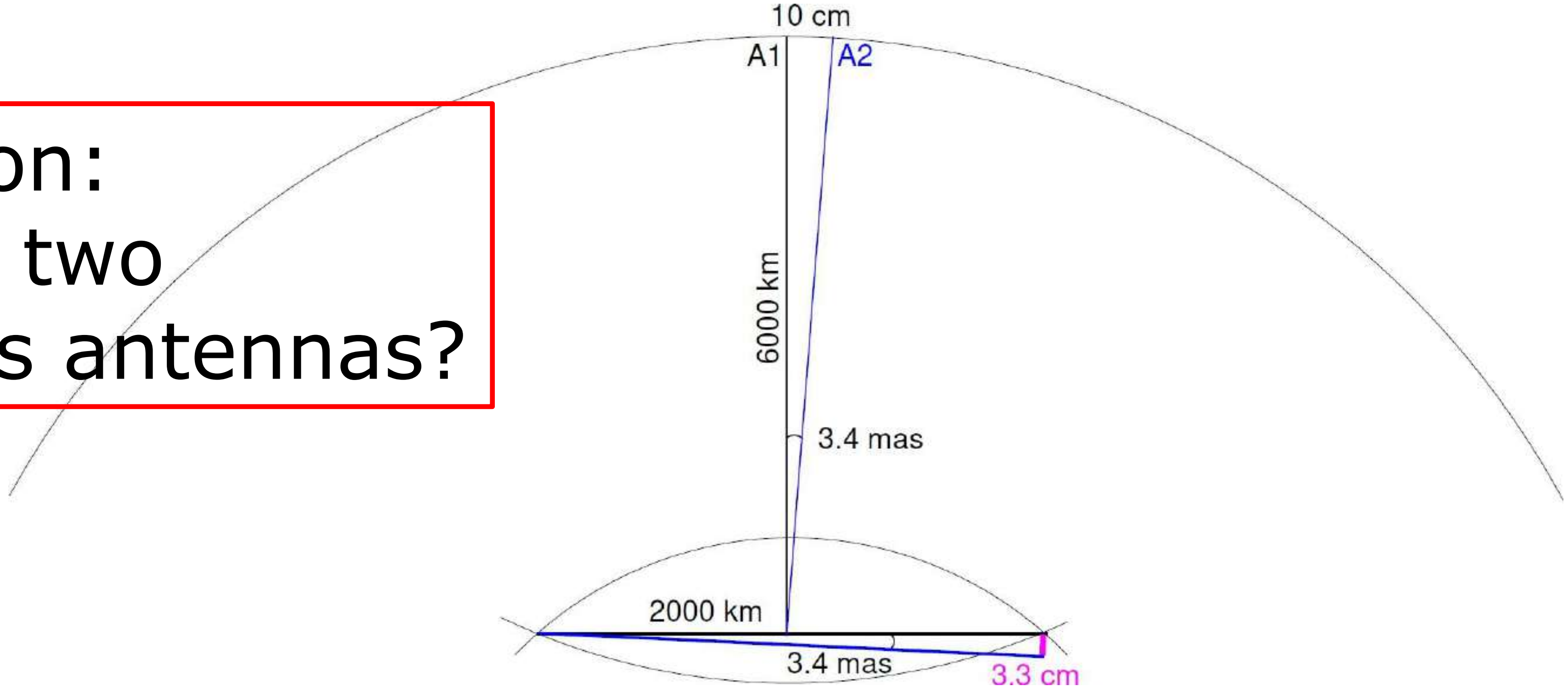
VLBI SNR and satellite signal strength

$$\text{SNR} = \eta \frac{\sqrt{S_1} \cdot \sqrt{S_2}}{\sqrt{SEFD_1} \cdot \sqrt{SEFD_2}} \sqrt{2 \cdot BW \cdot T \cdot bits}$$

- Signal strength S_1, S_2 at two VGOS stations:
  - dependent on Genesis antenna gain
  - dependent on signal path length
- Sensitivity $SEFD_1$, $SEFD_2$ at two VGOS stations:
  - dependent on elevation-dependent system sensitivity

- Problem: $SEFD(\varepsilon)$ not known for all stations (!)

1) Satellite antenna pattern



Question:
One or two
Genesis antennas?

- Maximum group delay difference between frequencies is roughly phase center distance times **b**/6000.

Baseline length in km	1000	2000	3000	4000	5000	6000	7000
	1.65 cm	3.3 cm	4.95 cm	6.6 cm	8.25 cm	9.9 cm	11.6 cm
	55 ps	110 ps	165 ps	220 ps	275 ps	330 ps	385 ps

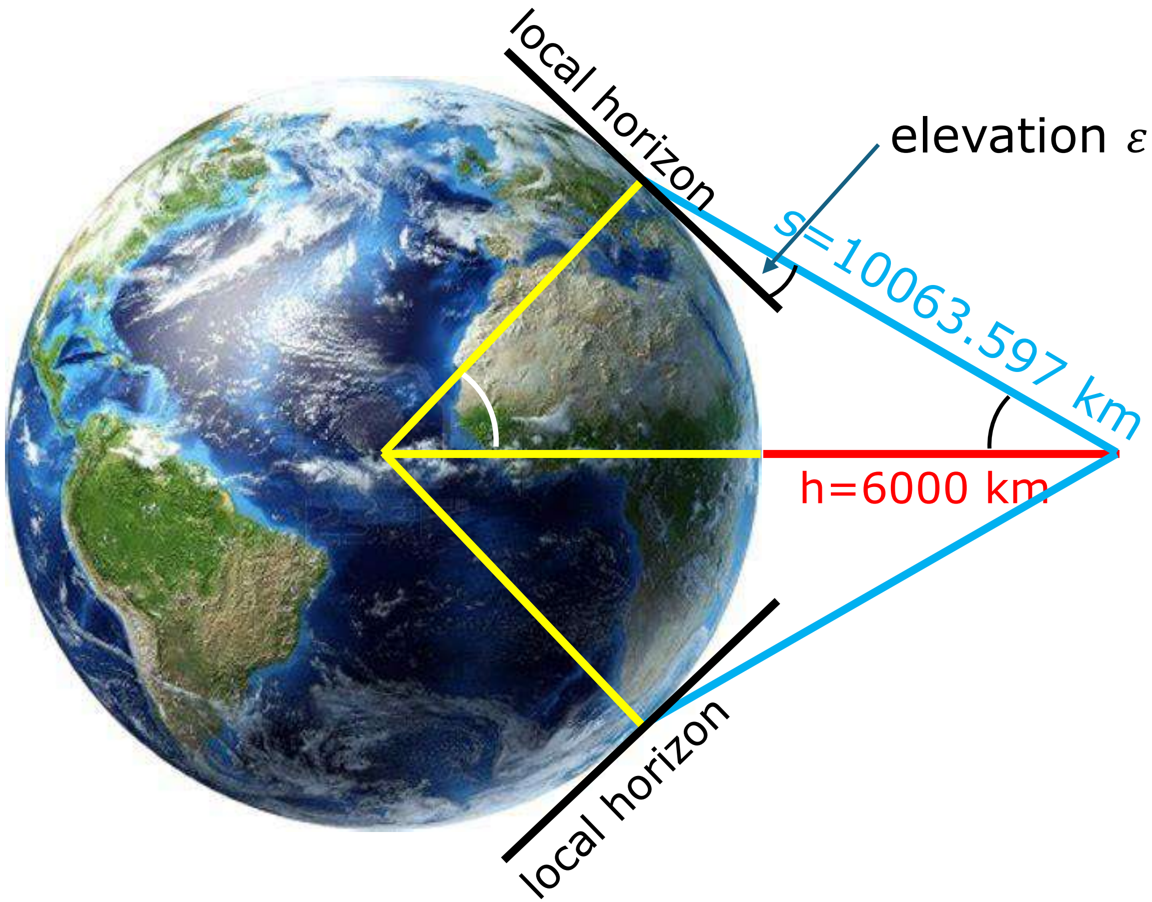
Satellite antenna pattern

- Existing fringe-fitting software for VGOS cannot handle variable geometry-dependent phase vs. frequency effects
- It is thus preferable to have <u>one single broad-band antenna</u>

=> ”One-antenna request” forwarded to industry

- Nevertheless: phase-center variation needs to be calibrated, and potentially the VGOS fringe-fitting software adapted

2) Free space loss effect:



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

Free space loss:

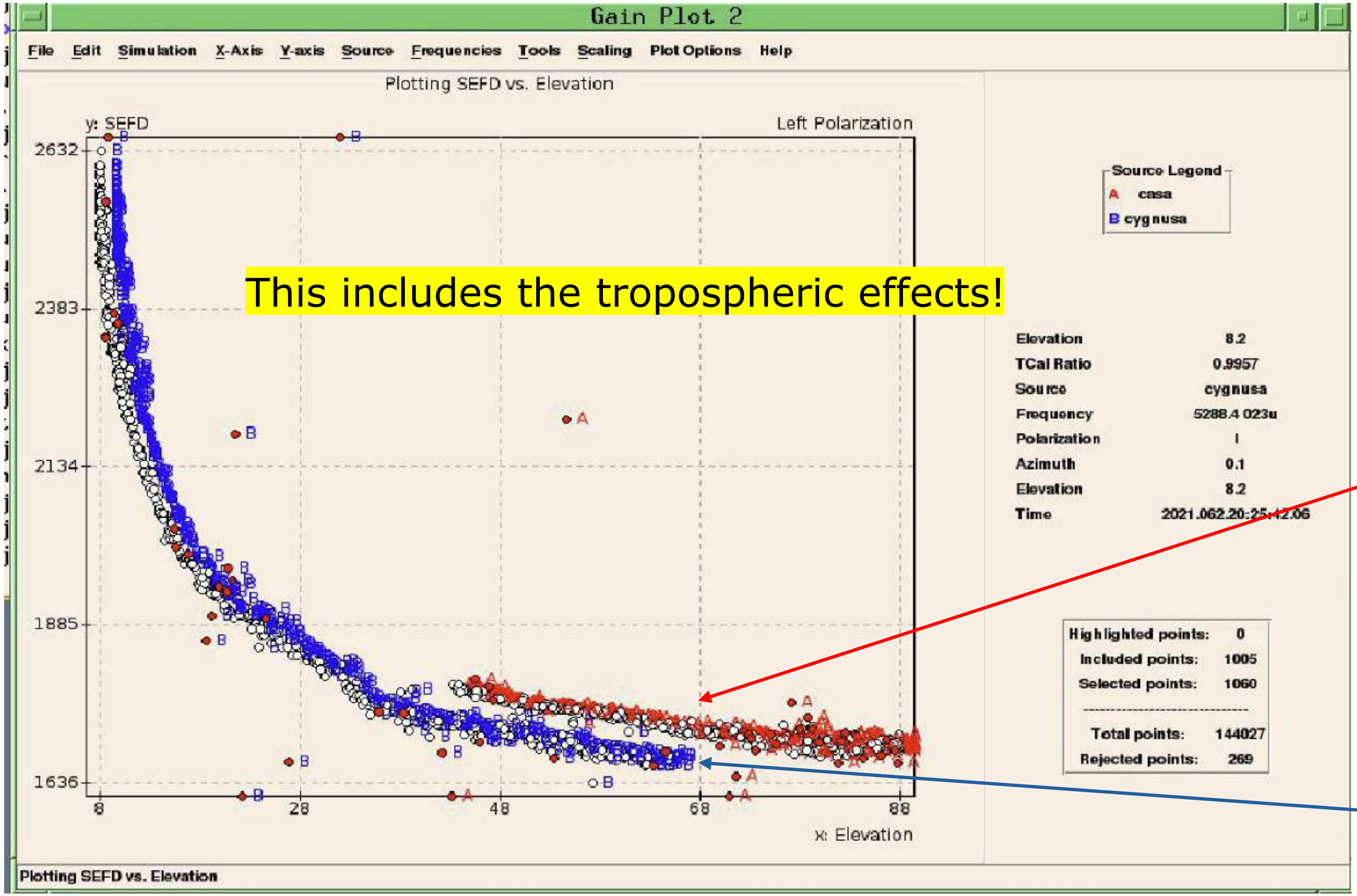
$$L_{FS} = \left(\frac{4 \cdot \pi \cdot R \cdot f}{c}\right)^2$$

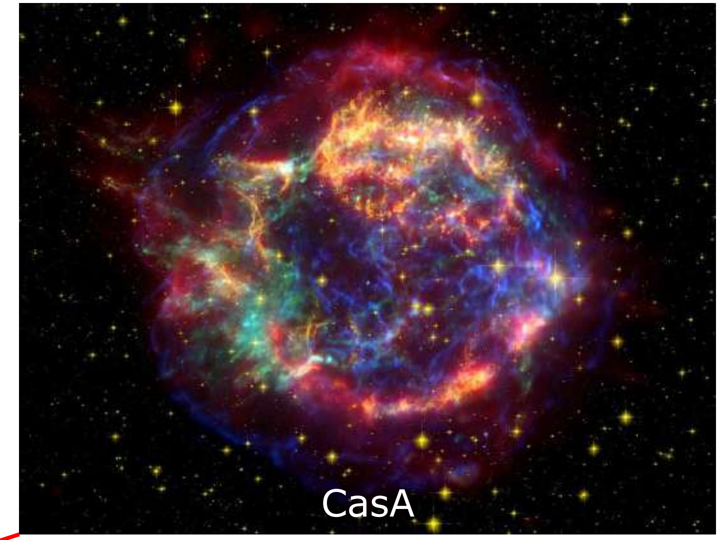
Frequency	3.2 GHz	5.41 GHz	8.3 GHz	9.55 GHz
$L_{FS\_(nadir)}$	178.1 dB	182.7 dB	186.4 dB	187.6 dB
$L_{FS\_(edge)}$	182.6 dB	187.2 dB	190.9 dB	192.1 dB
ΔL_{FS}	4.5 dB	4.5 dB	4.5 dB	4.5 dB

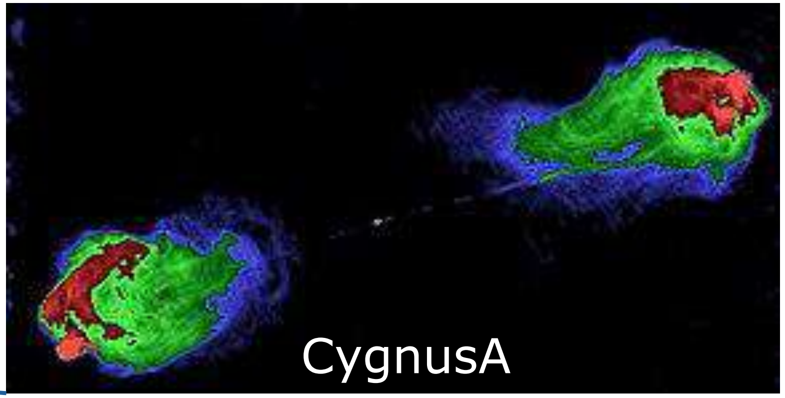
3) Station sensitivity

- Usually expressed as SEFD (System Equivalent Flux Density)
- Meaning: flux density (in jansky) of a fictitious source that gives the same power as the complete system itself
  - Assume we have a system (i.e. antenna, signal chain, backend) with SEFD=1000 Jy, then observing a radio source with flux density of 1000 Jy will result in that the RF power doubles (i.e. +3 dB)
- Needs to be measured/calibrated at the stations
- Includes atmospheric effects and is elevation-dependent
- So-called gain-curves not necessarily known for all VGOS stations

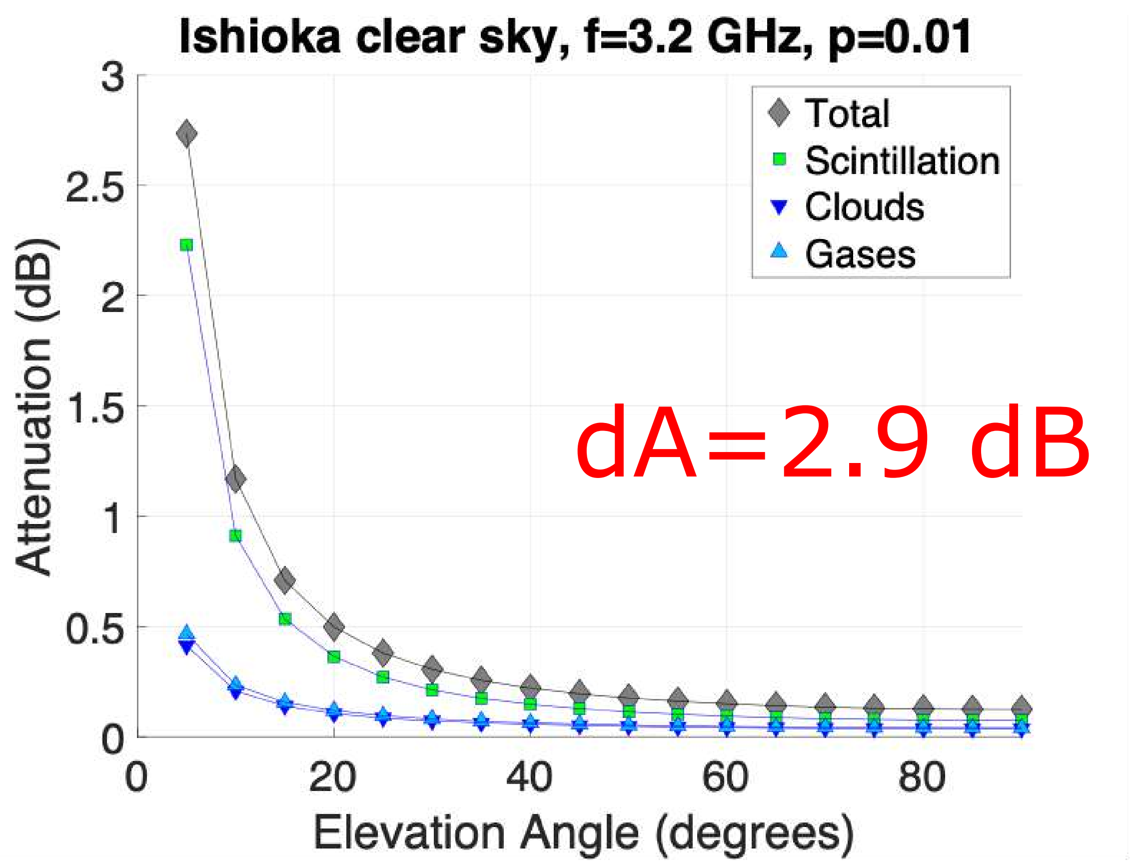
Example: ONSA13NE, H-pol at f=5.3 GHz

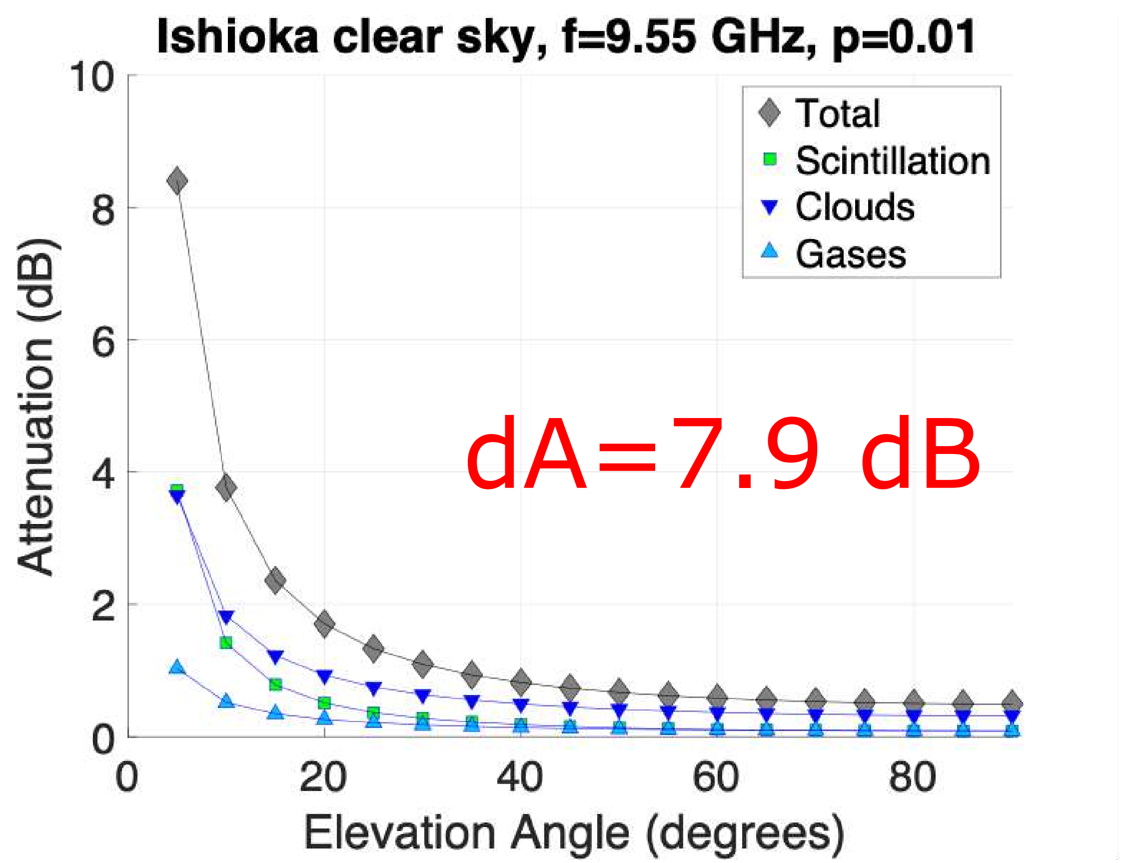




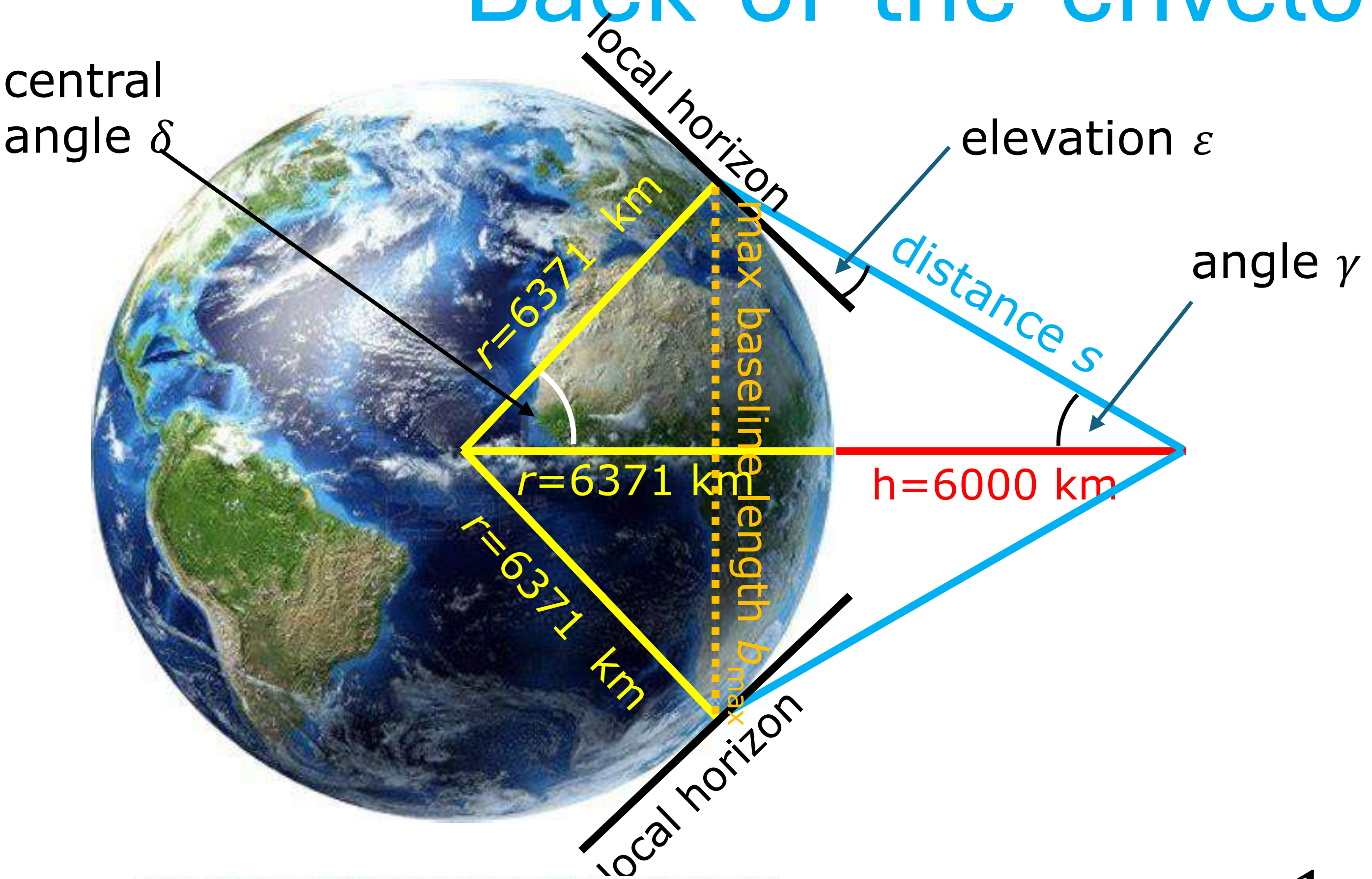


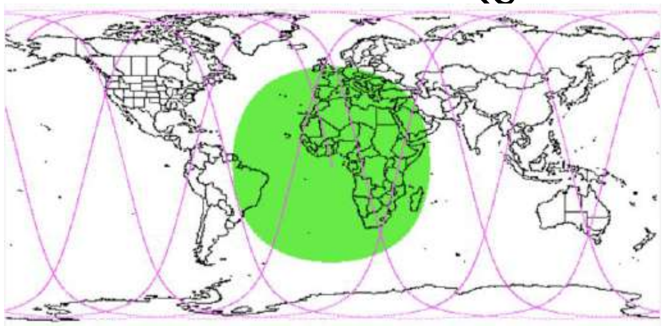
Example atmospheric losses: Ishioka (JAP)





Back-of-the-envelope calculation





Kind of ”worst case”

What is the observation time T that is needed to achieve a specific *SNR*:

$$T = \frac{1}{2 \cdot BW \cdot bits} \cdot \left(\frac{SNR}{\eta} \cdot \frac{\sqrt{SEFD_1}}{\sqrt{S_1}} \cdot \frac{\sqrt{SEFD_2}}{\sqrt{S_2}} \right)^2$$

Back-of-the-envelope calculation

- Assumptions:
  - Genesis signal at boresight: 10 Jy
    - Antenna gain variation 10 dB between boresight and edges
    - Additional free-space loss contribution 4.5 dB
  - Two stations observing at 5° elevation (baseline ca. 10000 km)
    - Station SEFD @ zenith: 2000 Jy
    - Elevation-dependent SEFD variation (SEFD @ 5°: ca. 3300 Jy)
  - Bandwidth BW=200 MHz
  - SNR goal 25
  - Correlation efficiency: η=0.75

=> observation time required: T=120 s

Conclusions so far from WP-1

- One broad-band Genesis VLBI antenna is preferred
- Antenna phase centre variation needs to be calibrated
  - Potential adjustments in VLBI processing software are necessary
- Signal strength should be tuneable
  - possibility to switch off desirable
- Station sensitivity needs to be measured and monitored

ESA GSET WG-3 (VLBI)

WP-2: ground station fidelity

Alexander Neidhardt (TUM, Wettzell)

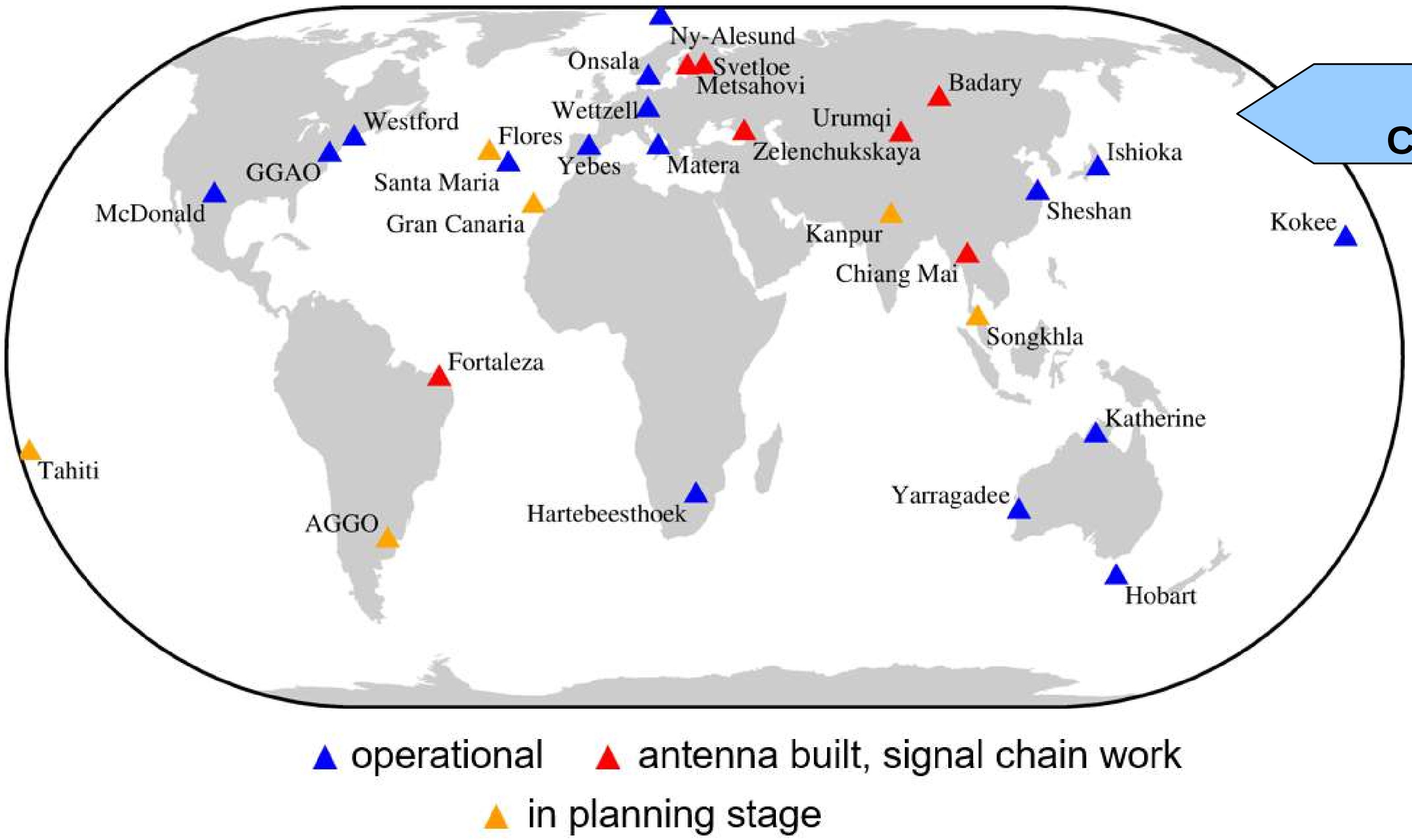
Rüdiger Haas (Chalmers University of Technology),
ESA GSET WG-3 members, stations

ESA GSET WG-3 (VLBI)

WP-2:
ground station fidelity

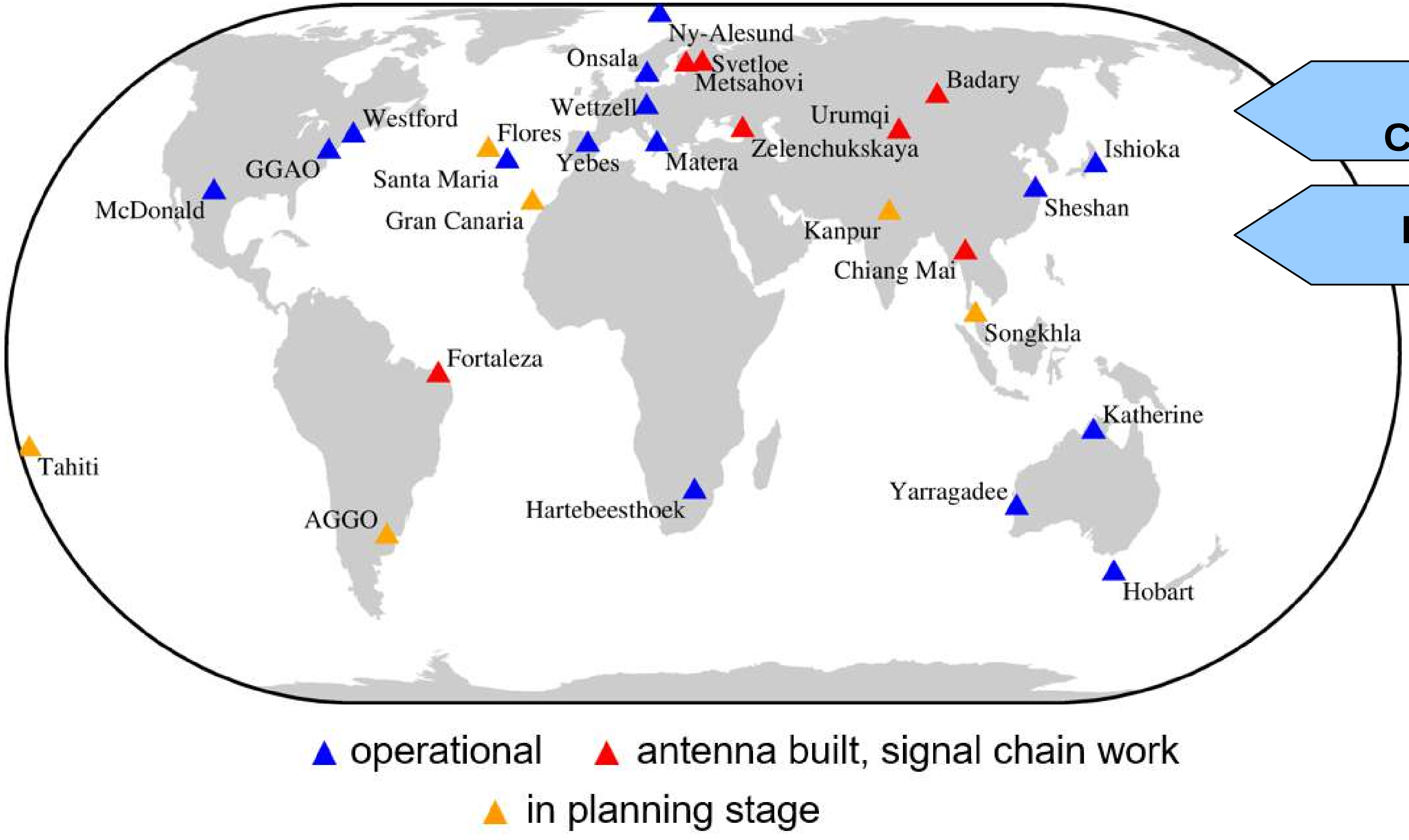
- **VGOS Network**
- Antenna capabilities
- Equipment
- RFI Situation
- Quality

VGOS observing network



Antenna Capabilities

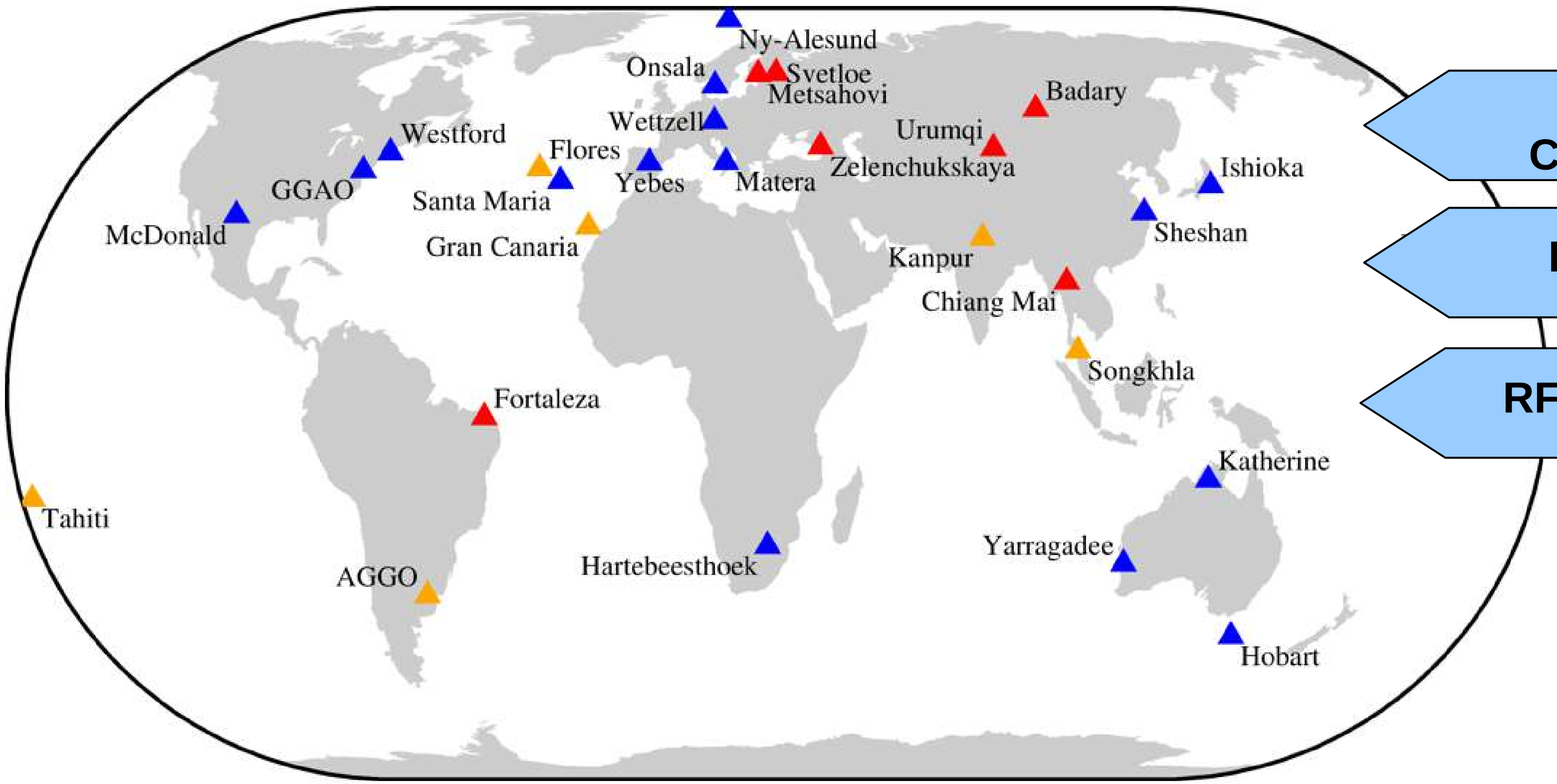
VGOS observing network



Antenna Capabilities

Equipment

VGOS observing network



▲ operational ▲ antenna built, signal chain work

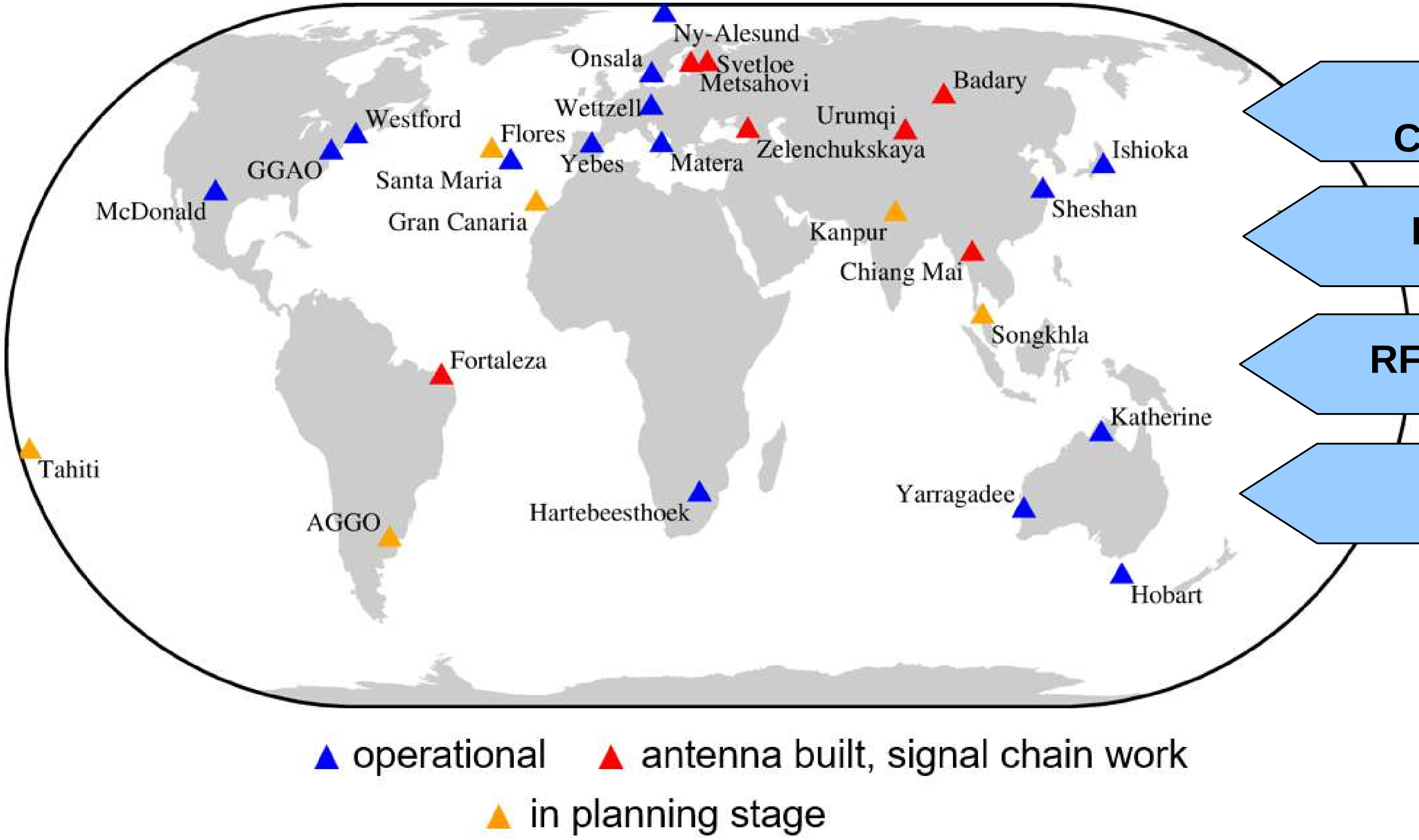
▲ in planning stage

Antenna Capabilities

Equipment

RFI Situation

VGOS observing network



- Antenna Capabilities
- Equipment
- RFI Situation
- Quality

VGOS observing network

Betreff: [IVSGENESIS] Is your VGOS-site ready for GENESIS => we need your feedback and help
Von: Alexander Neidhardt <alexander.neidhardt@tum.de>
Datum: 30.03.2025, 22:38
An: ivs-stations@lists.nasa.gov, ivs-vgos-tech@lists.nasa.gov

Dear responsible staff at VGOS stations,

I would like to draw your attention to an important future support mission for VGOS. The European Space Agency (ESA) has approved the GENESIS mission, which can be described as follows (see also https://www.esa.int/Applications/Satellite_navigation/Genesis): *"The Genesis satellite will combine the main geodetic techniques (very-long-baseline interferometry, satellite laser ranging, global navigation satellite systems and possibly DORIS), synchronising and cross-calibrating the instruments to determine biases inherent to each technic, allowing to correct them for superior precision."* ESA GSET WG-3 (VLBI) has commenced work on the preparation and coordination of IVS tasks together with ESA staff. For a more detailed planning, we request your help in gathering information for your site.

GENESIS is planned to be launched in 2028 and has a mass of 300 kg. It will orbit Earth at a height of 6000 km (inclination 95 deg) and can be observed on the following frequencies:
- Band-1: 3100–3300 MHz (i.e., B = 200 MHz)
- Band-2: 5250–5570 MHz (i.e., B = 320 MHz)
- Band-3: 8200–8400 MHz (i.e., B = 200 MHz)
- Band-4: 9300–9800 MHz (i.e., B = 500 MHz)

For the simulation of the scheduling, we would like to have the following information:

1) Antenna capabilities

- Is your antenna able to track satellites?
- Does your antenna support continuous or step-wise RaDec-tracking?
- If not, can it be extended to track satellites until 2028?
- What do you need for the tracking (e.g.,TLEs)?

2) Current equipment

- What is you current equipment? We want to update the info on https://www.ivs-technology-coordinator.info/ivs-station-data/. Please check, what is written there and update it or inform me to update it.
- Can your frontend, converters, and backend be adapted to the listed frequencies (LOs if used, etc.)?
- Can your digital baseband converter / digitizers handle the smaller bands of 200 MHz or 320 MHz?

3) Spectrum

- Do you have spectrum information, e.g., spectra plots, for the above bands?
- Do you have any restrictions for these bands (e.g., directional dependencies, known elevation masks)?

4) Antenna quality

- Can you send the latest SEFD or system temperature values?
- Do you have SEFDs for different elevation positions?
- Do you have graphs from fivept, onoff, acquire for a gain calibration, or the log files of a longer observation or something similar, which we can use to get a 24-hour data set for different sources (e.g., cygnusa, casa, etc.)? See: https://www.haystack.mit.edu/wp-content/uploads/2023/05/Calibration-TOW-2023.pdf and https://www.haystack.mit.edu/wp-content/uploads/2023/05/TOW_MW_FSOperations_Neidhardt.pdf (starting on page 56)

If you have all (or part) of this information, I would appreciate it very much if you just insert it into this text above and if you sent it to me via email. Please use the special tag [IVSGENESIS] so that it arrives in the right folder. In any case, we can discuss further details at the EVGA (provided you attend the meeting) or in a Zoom call at your convenience.

Thank you all for your efforts and looking forward to your feedback.

Best regards, Alexander

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Department of Aerospace and Geodesy

Waiting for feedback

ESA GSET WG-3 (VLBI)

WP-2:
ground station fidelity

- VGOS Network
- **Antenna capabilities**
- Equipment
- RFI Situation
- Quality

Antenna capabilities

Questions are:

- Is your antenna able to track satellites?
- Does your antenna support continuous or step-wise RaDec-tracking?
- If not, can it be extended to track satellites until 2028?
- What do you need for the tracking (e.g.,TLEs)?

Because:

- We have „slow“ VGOS antennas and fast VGOS antennas (12 deg/s in azimuth and 6 deg/s in elevation)
- Not all antenna control systems are yet ready for satellite tracking tables.
- Not all locations have the possibilities to upgrade existing software (maybe new VLBI Field System versions)
- The input type to send orbit positions to the antenna control might be different (VLBI Field System supports TLEs, but currently no way to get schedules with TLEs => additional „workaround“ programs, VEX2?)

Antenna capabilities

Idea from Yebes (Pablo de Vicente)

VGOS satellite tracking proof of concept

Implementing the TLE in the FS (Field System)

1. Create a new FS command called “satellite”:
   satellite=sat%20name (spaces are replaced by %20)

   The command just stores the name in a FS local variable (satname) readable from antcn.c

2. Use FS command to start the tracking:
   source =satellite,00000,00000

   The source name “satellite” is treated in a different way in antcn.c, than natural sources:

   This looks for the TLE in https://celestrak.org/NORAD/elements/gp.php?NAME=" + satname + "&FORMAT=tle"
   Downloads the 2 lines and parses them sending them to an algorithm.

3. Use an algorithm to create a: Time, Az, El table from the TLE for the next 20 minutes.

4. Load the table in the VGOS telescope control system and start the real tracking.

Similar sample from Wettzell (A. Neidhardt)

2025.090.21:18:14.26#antcn#* antenna=tle,,: follow a passage of a sattelite orbit *
2025.090.21:18:14.26#antcn#* for seconds given as Two Line *
2025.090.21:18:14.26#antcn#* Element (TLE) in the folder /usr2/tle_files *

Antenna capabilities

Idea from Yebes (Pablo de Vicente)

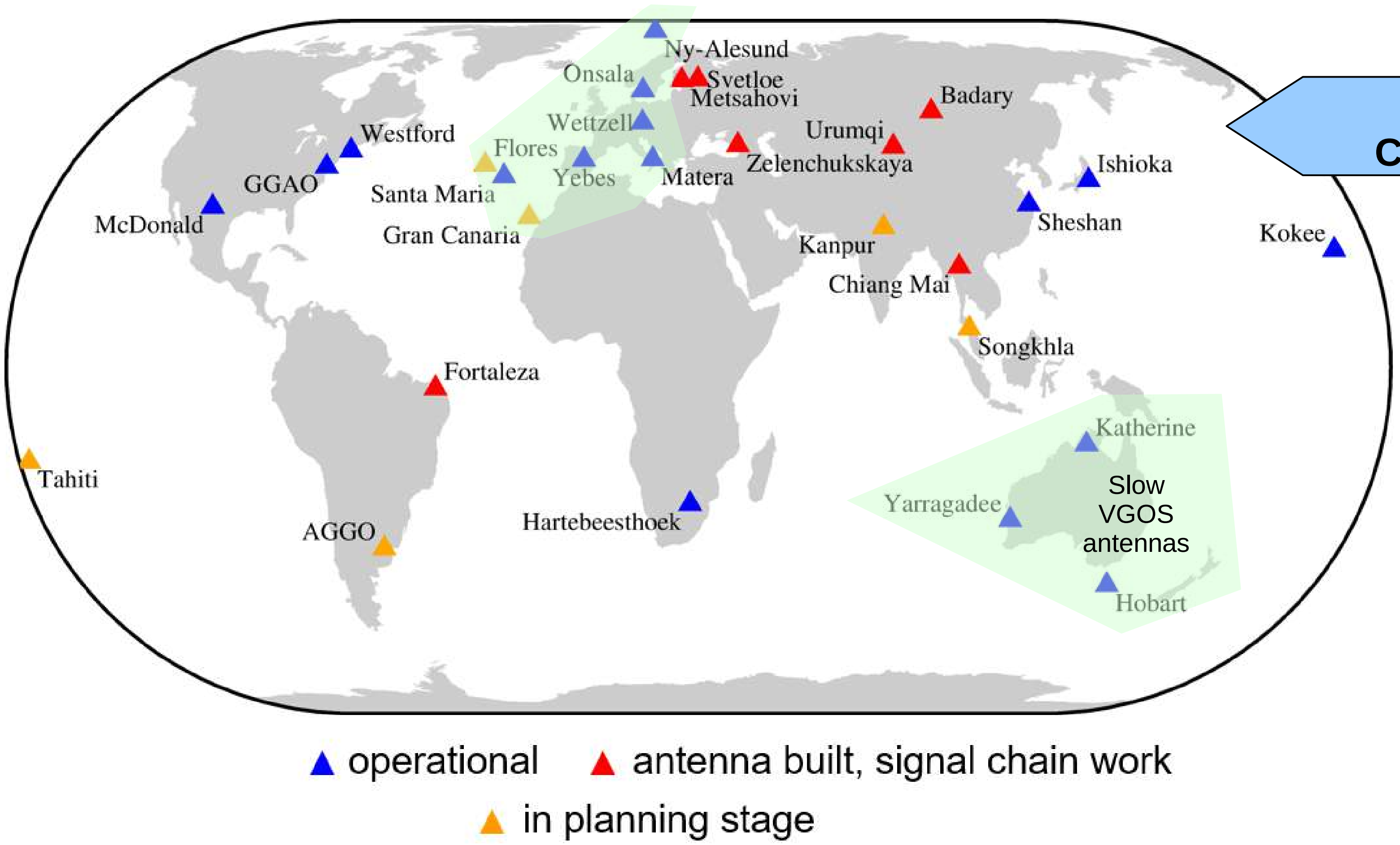
VGOS satellite tracking proof of concept

Satellites with a beacon in X band:

COSMO	8.120 GHz & 8.250 GHz
SENTINEL-2C	8.2 GHz.

Within the VGOS subbands.
Heliosyncronous orbit
Fast movement: 100 minute period orbits
Already tracked from Matera VGOS RT (during commissioning)

Antenna capabilities



Antenna Capabilities

ESA GSET WG-3 (VLBI)

WP-2:
ground station fidelity

- VGOS Network
- Antenna capabilities
- **Equipment**
- RFI Situation
- Quality

Equipment

Questions are:

- What is your current equipment? We want to update the info on https://www.ivs-technology-coordinator.info/ivs-station-data/. Please check, what is written there and update it or inform me to update it.
- Can your frontend, converters, and backend be adapted to the listed
  - Band-1: 3100–3300 MHz (i.e., B = 200 MHz)
  - Band-2: 5250–5570 MHz (i.e., B = 320 MHz)
  - Band-3: 8200–8400 MHz (i.e., B = 200 MHz)
  - Band-4: 9300–9800 MHz (i.e., B = 500 MHz)
- Can your digital baseband converter / digitizers handle the smaller bands of 200 MHz or 320 MHz?

Because:

- We have different frontends (up-down-converter, down-converter, RFoverFiber-connection and DBBC3s).
- We have different backends, mainly DBBC3s and RDBEs (and follow-on models).
- We have different recorder, which is not a problem.

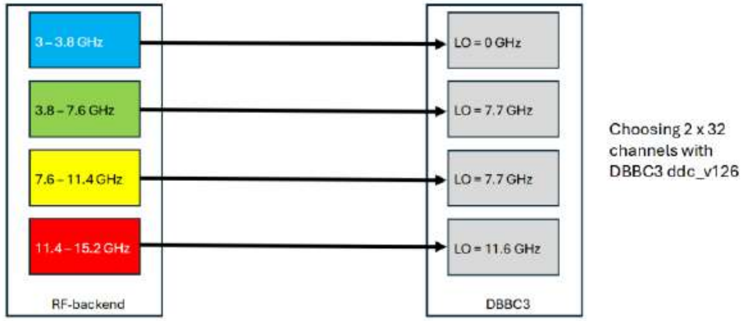
Equipment

Feedback from AuScope

- **A & B into 3-7 BPF, 16 channels available → okay**
- **C: into 6-10 BPF → okay**
- **D: into 9.5-13.5 (16 channels) → on the edge of the bandpass (for 9.3 Genesis frequency); looks okay, may need to adjust LO**

Feedback from Onsala

Genesis @ OSO, using DBBC3 ddc_v126 firmware



Feedback from Yebes and Santa Maria

Pablo de Vicente (2024-09-03):

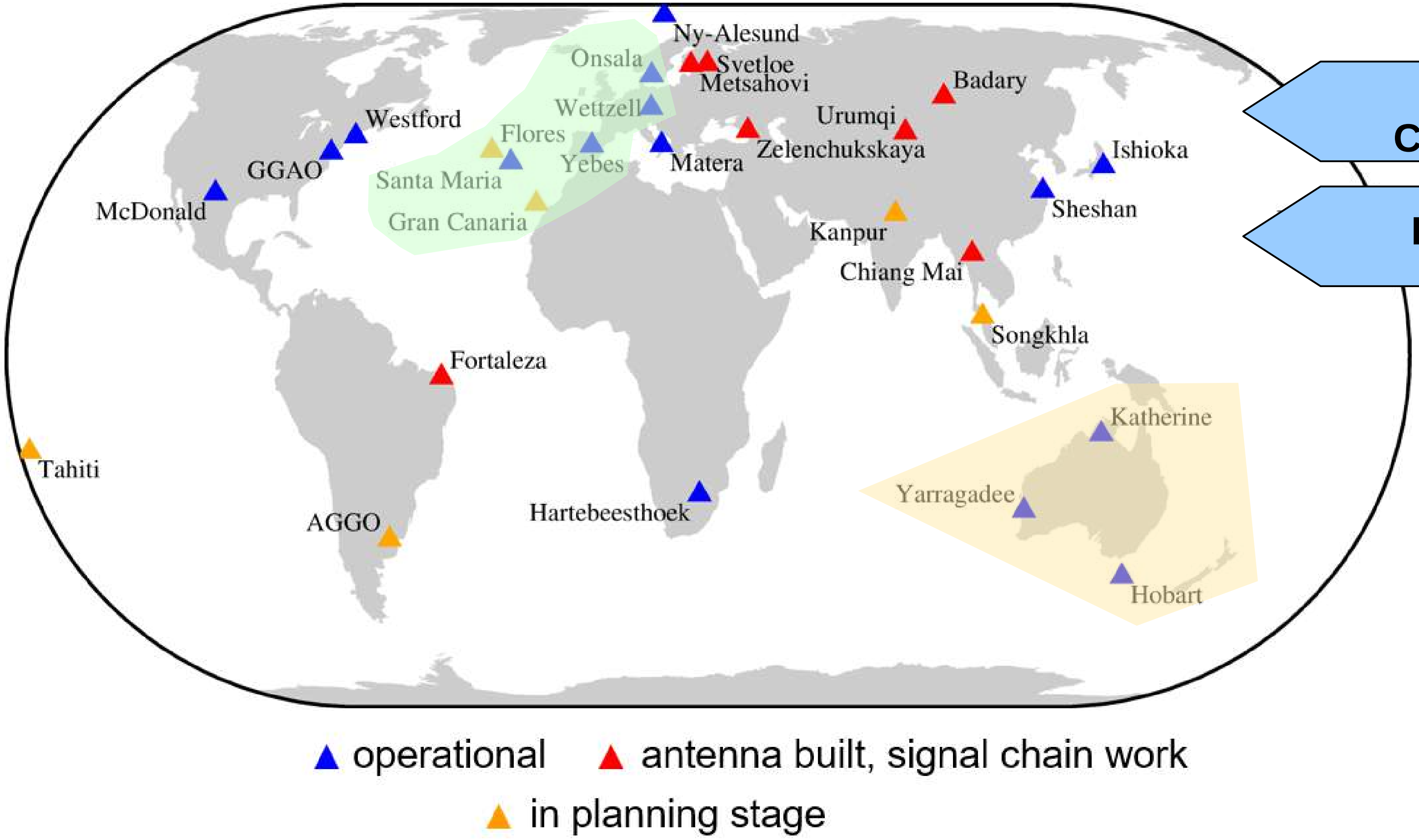
"We can observe the 4 GENESIS bands using an extra output we have at our filtering modules before the VLBI backends. That also applies to Santa Maria."

Feedback from Wettzell

Ws: Elevenfeed, down-converter with fixed frequencies, up-down-converter with variable frequency settings as optional second receiver path, 2xDBBC2/FILA10G and Mark6 as recorder (DBBC3 and Flexbuff as recorder is tested locally and equivalent, so that a switching to the new system will be soon in November/December 2024)
=> Antenna can participate in GENESIS observations, but it requires a re-cabling from the pure down-converter to the up-down-converter and a correct setting of the Holzworth synthesizer; additionally, DBBC3/Flexbuff is the solution to avoid special setups with the PFB mode in DBBC2s

Wn: QRFH-Callisto-feed, down-converter with fixed frequencies, DBBC3 and Flexbuff as recorder
=> Antenna cannot participate in GENSIS observations if we don't do some changes

Equipment



Antenna Capabilities

Equipment

ESA GSET WG-3 (VLBI)

WP-2:
ground station fidelity

- VGOS Network
- Antenna capabilities
- Equipment
- **RFI Situation**
- Quality

RFI Situation

Questions are:

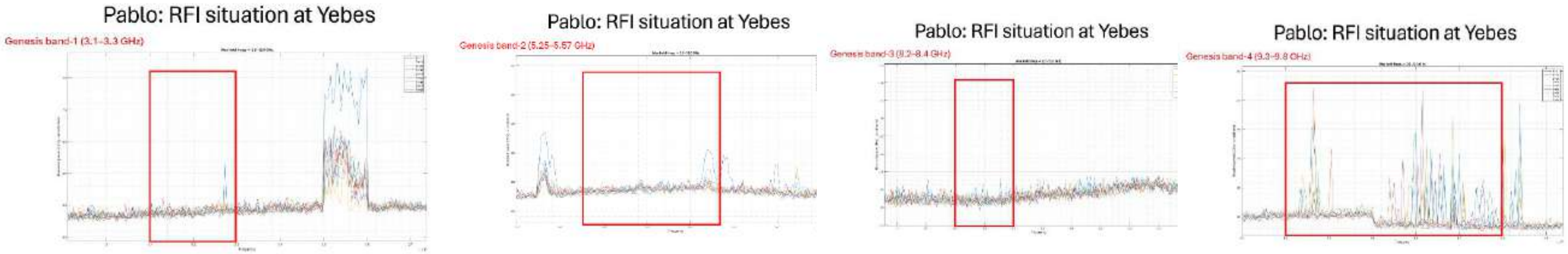
- Do you have spectrum information, e.g., spectra plots, for the above bands?
- Do you have any restrictions for these bands (e.g., directional dependencies, known elevation masks)?

Because:

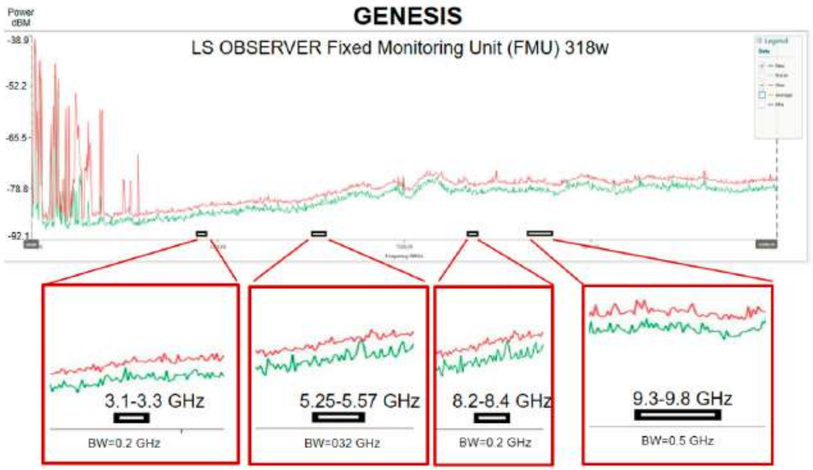
- Many areas are polluted by RFI (5G, 4G/LTE, Star Link, WLAN, etc.)
- There is almost no protection.
- Sites are sometimes just polluted from directions of urban installation.

RFI Situation

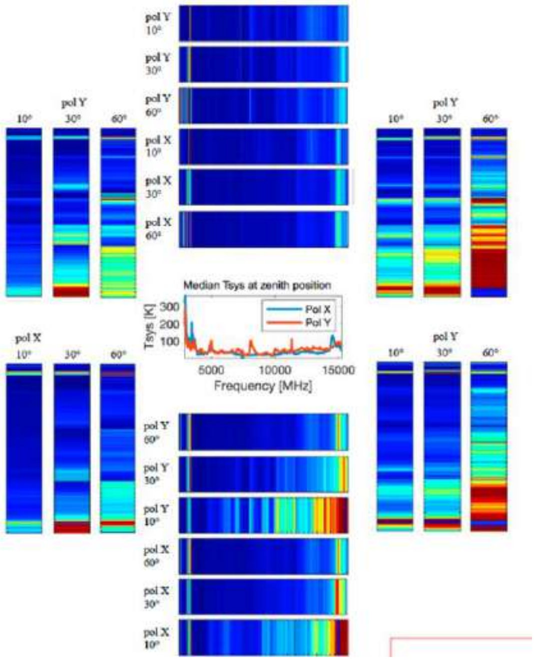
Feedback from Yebes



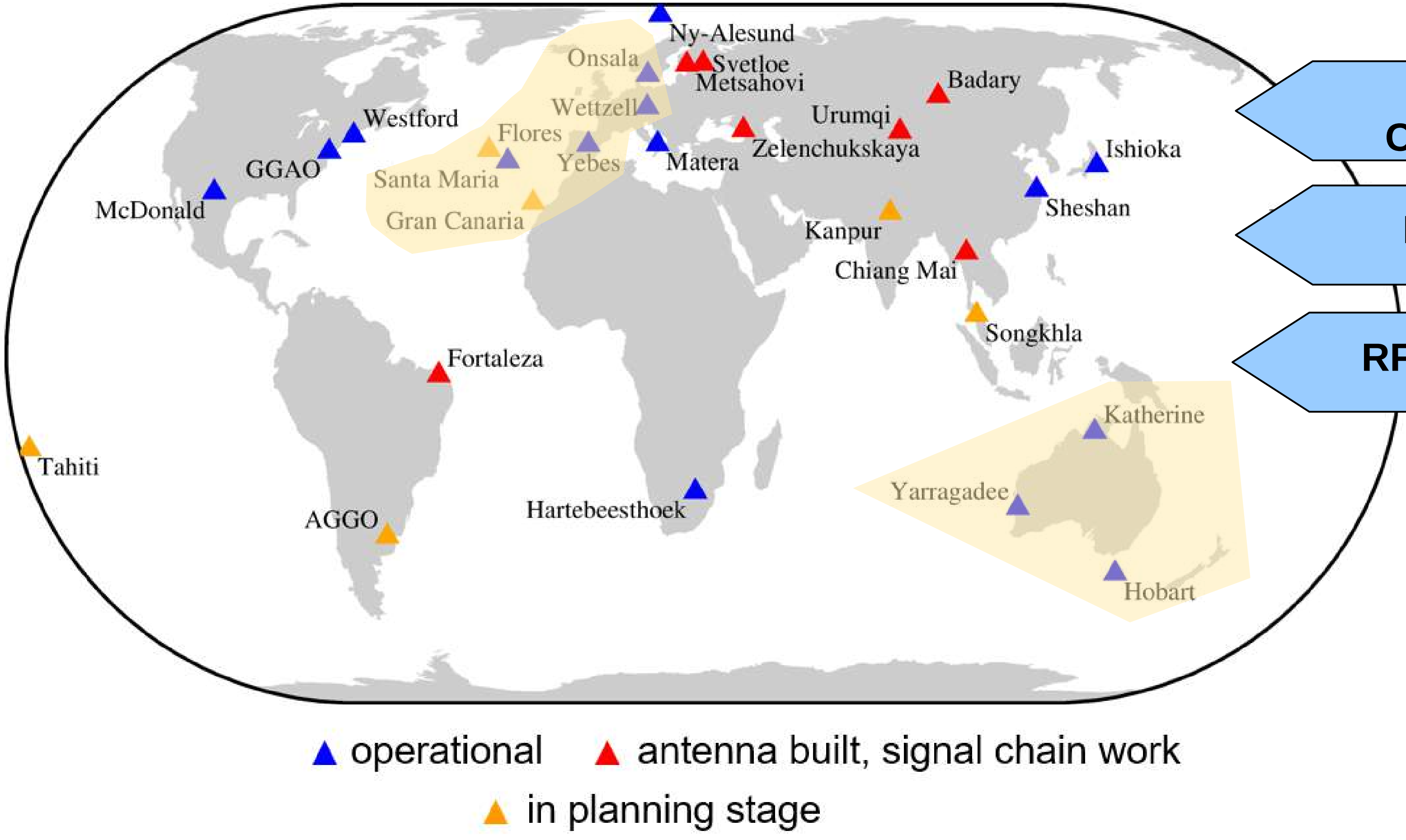
Feedback from Wettzell



Feedback from Onsala



RFI Situation



- Antenna Capabilities
- Equipment
- RFI Situation

ESA GSET WG-3 (VLBI)

WP-2:
ground station fidelity

- VGOS Network
- Antenna capabilities
- Equipment
- RFI Situation
- **Quality**

Quality

Questions are:

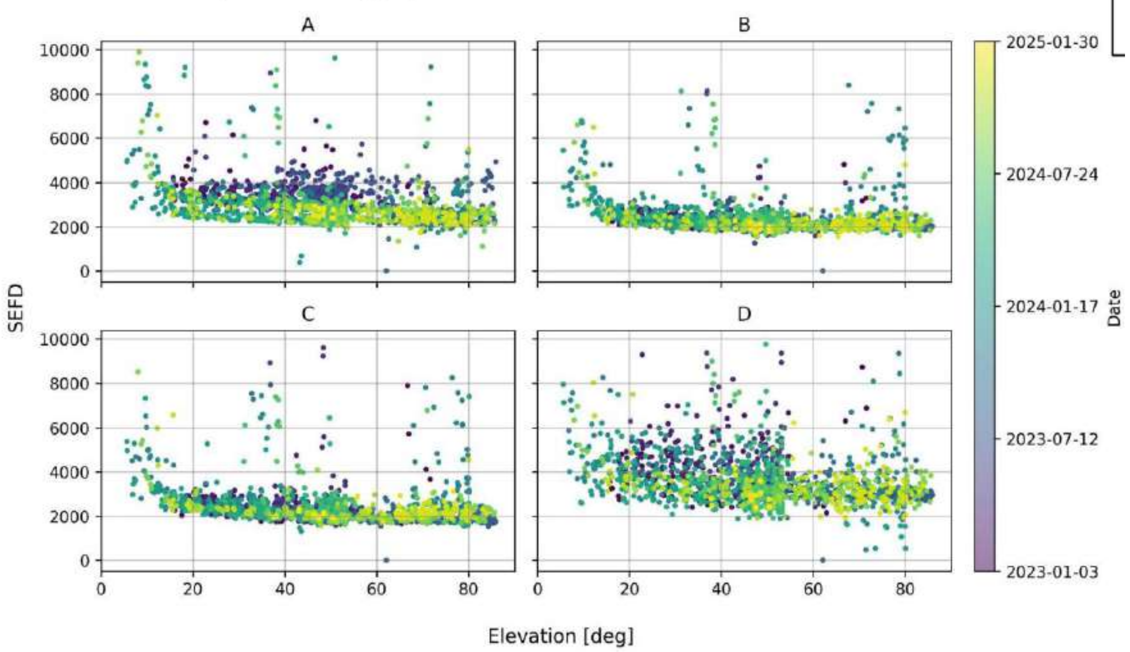
- Can you send the latest SEFD or system temperature values?
- Do you have SEFDs for different elevation positions?
- Do you have graphs from fivept, onoff, acquire for a gain calibration, or the log files of a longer observation or something similar, which we can use to get a 24-hour data set for different sources (e.g., cygnusa, casa, etc.)? See: https://www.haystack.mit.edu/wp-content/uploads/2023/05/Calibration-TOW-2023.pdf and https://www.haystack.mit.edu/wp-content/uploads/2023/05/TOW_MW_FSOperations_Neidhardt.pdf (starting on page 56)

Because:

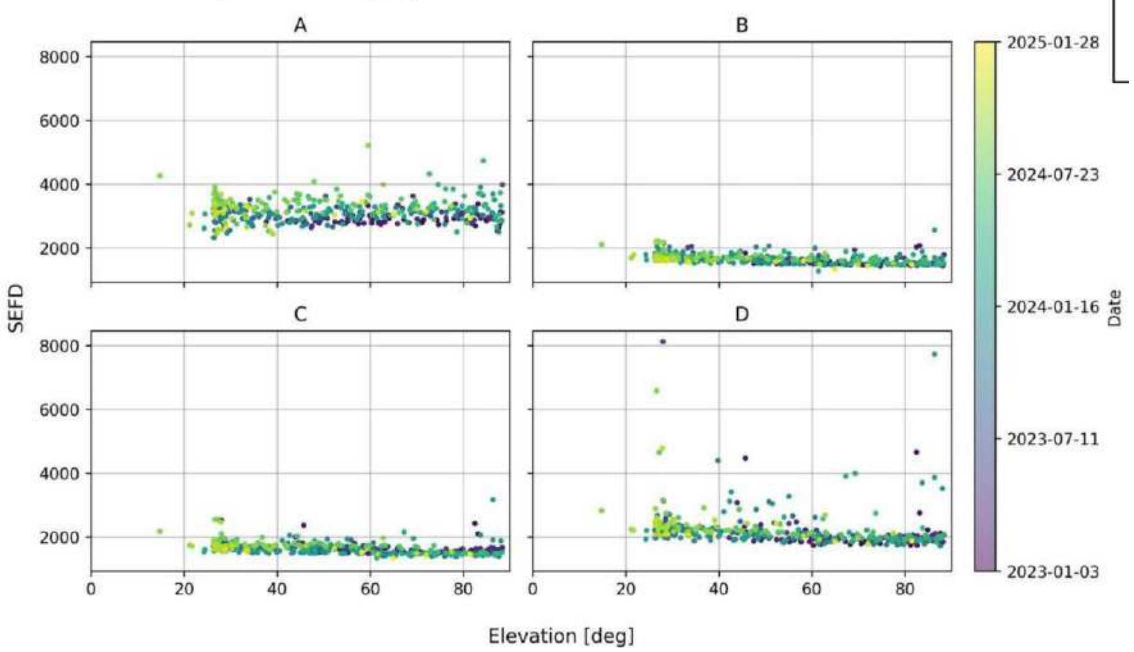
- Gain calibration is often just available for astronomical antennas.
- SEFD, Tsys, etc. values change over time.
- Quality changes over time in VGOS sessions (Pcal, etc.)

Quality

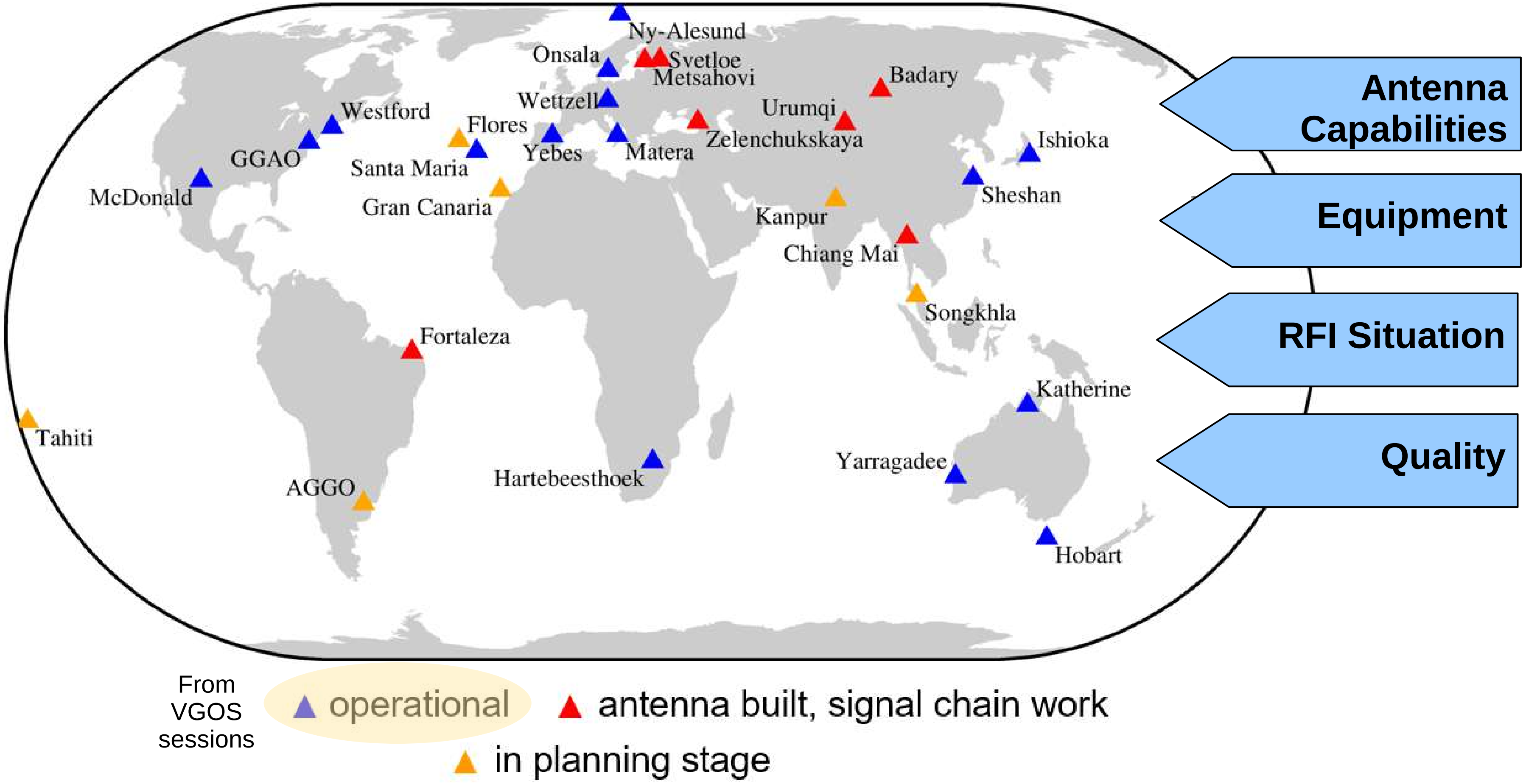
Topic 1: SEFD (from logs)



Topic 1: SEFD (from logs)



Quality


Ny-Alesund
Onsala
Svetloe
Metsahovi
Badary
Wettzell
Urumqi
Westford
Flores
Zelenchukskaya
Ishioka
GGAO
Yebes
Matera
Santa Maria
McDonald
Sheshan
Gran Canaria
Kanpur
Chiang Mai
Songkhla
Fortaleza
Katherine
Tahiti
Yarragadee
Hartebeesthoek
AGGO
Hobart
Antenna Capabilities
Equipment
RFI Situation
Quality
From VGOS sessions
operational
antenna built, signal chain work
in planning stage

ESA GSET WG-3 (VLBI)

Thank you …

ESA GSET WG-3

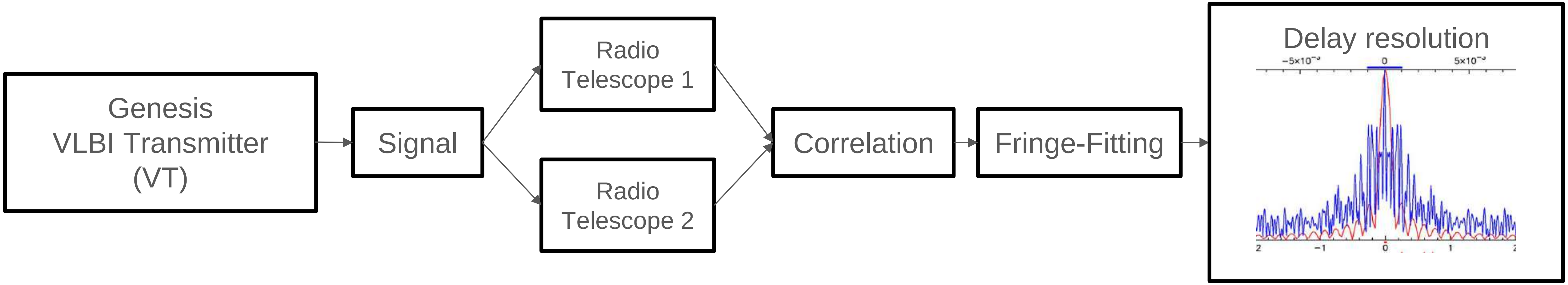
WP-3: Delay Resolution and Correlation

Jakob Gruber (BEV), on behalf of Working Group 3

ESA Genesis Science Workshop, Matera – April 4, 2025

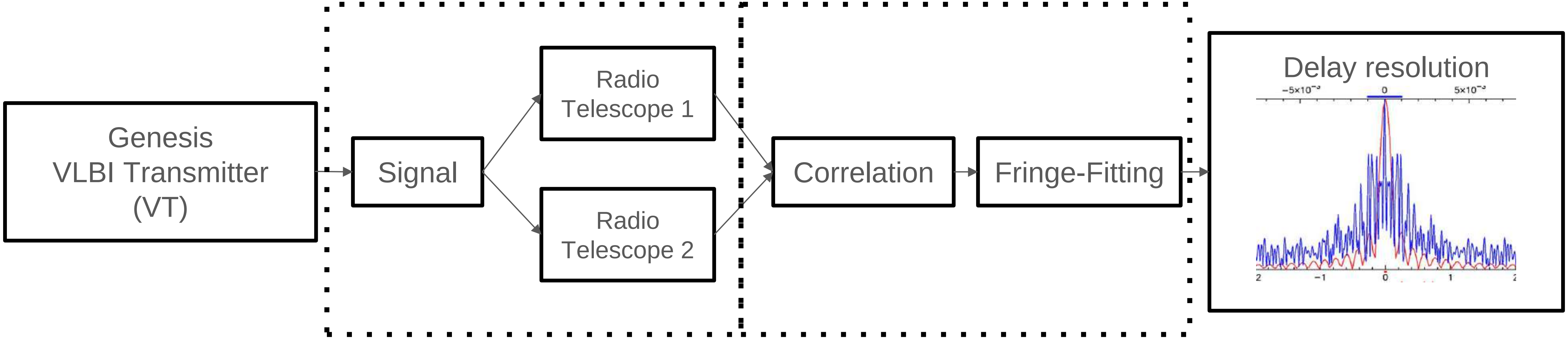
Key questions of WP-3

- What is the expected delay resolution from VLBI to Genesis?
- Are there any issues with Genesis signal correlation or post-processing (e.g., fringe fitting)?



Key questions of WP-3

- What is the expected delay resolution from VLBI to Genesis?
- Are there any issues with Genesis signal correlation or post-processing (e.g., fringe fitting)?



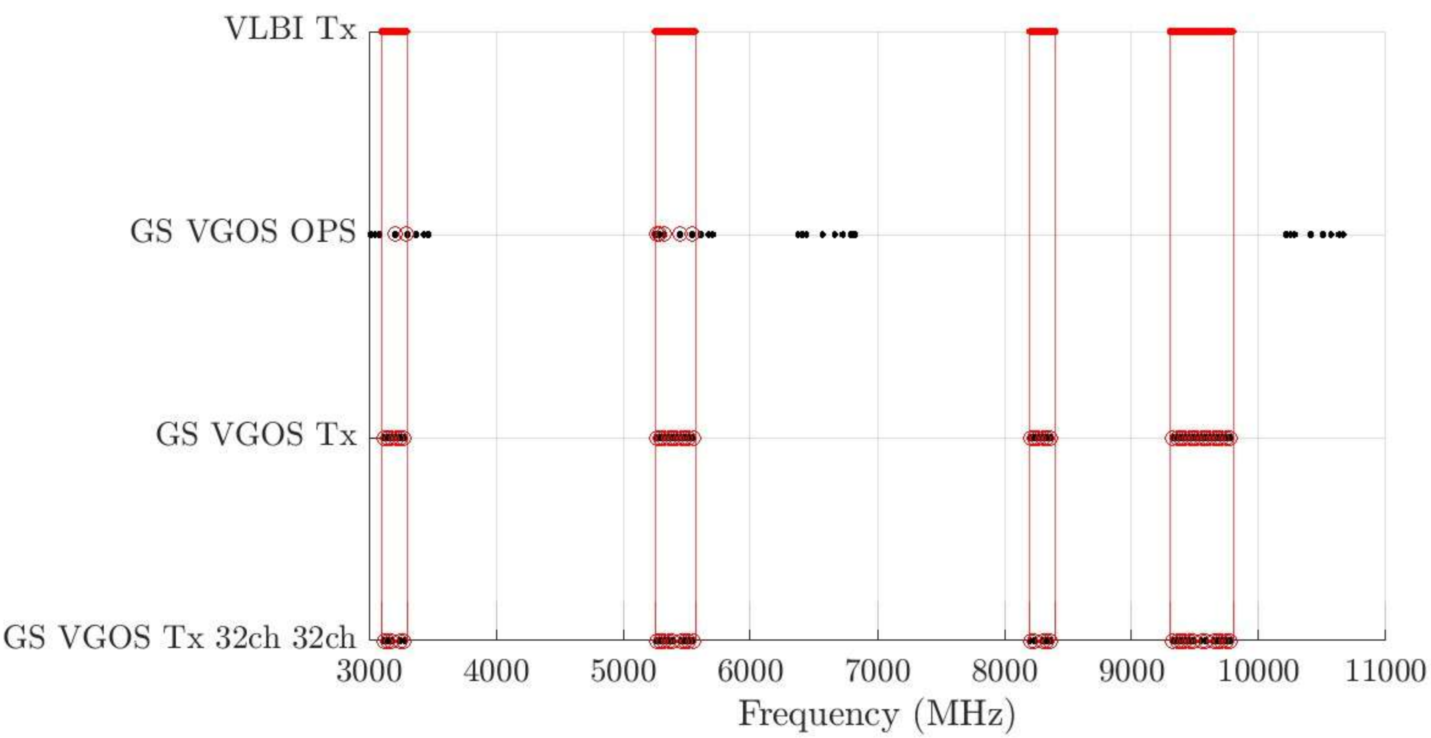
Software simulation

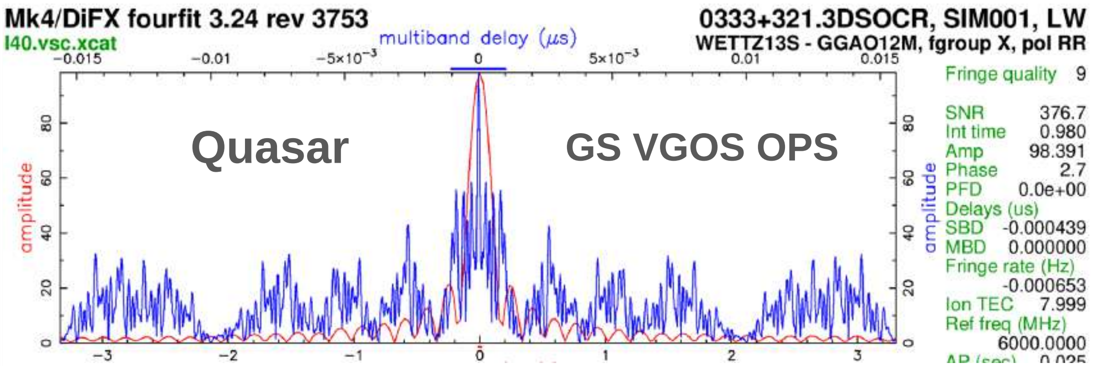
Established signal correlator
and fringe-fitter
(DiFX+HOPS)

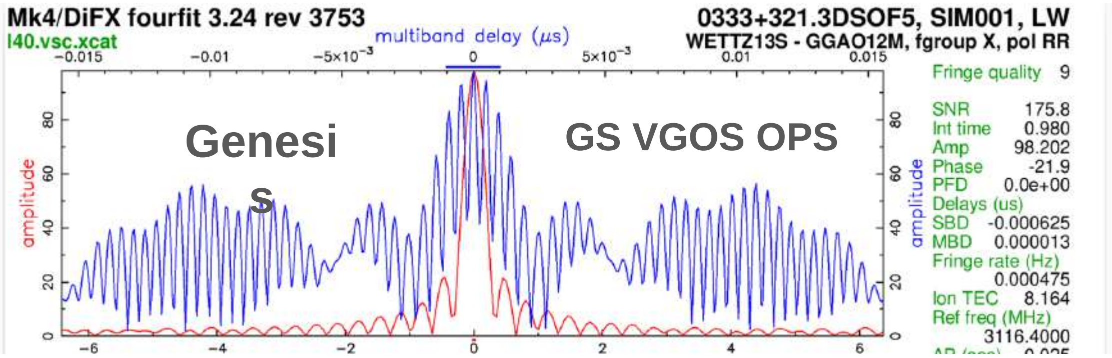
Overview of progress

1. **June 2024**: Investigation of delay resolution achieved by VLBI (VGOS) to Genesis.
2. **August 2024**: Testing of a new frequency setup to align with Genesis emission bands.
3. **October 2024**: Comparison of Gaussian and binary random signals from Genesis within the VLBI processing chain.
4. **October 2024**: Simulation of single-dish observations of signals with 256/512 MHz bandwidth.

(1) Investigation of delay resolution obtained by VLBI (VGOS) to Genesis VT

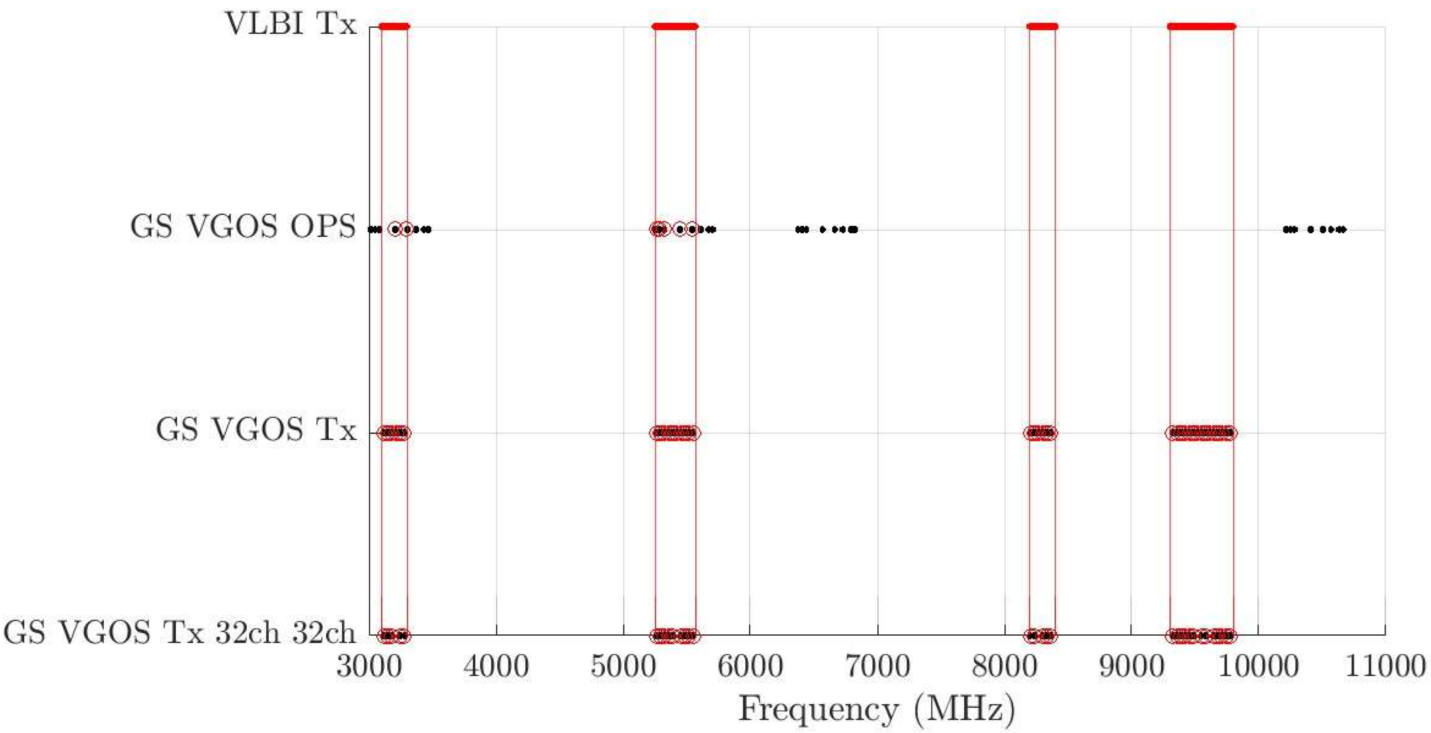


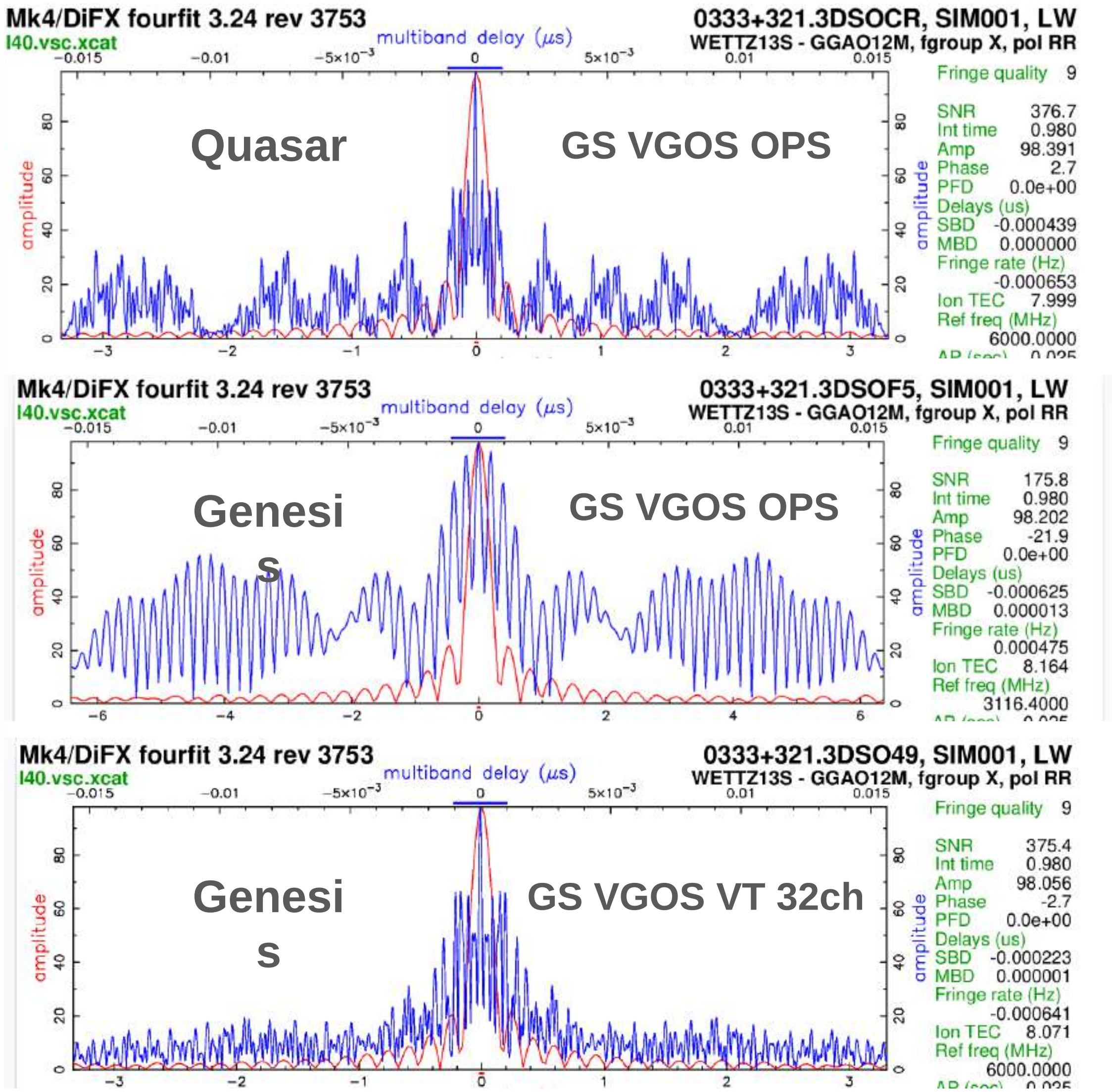




Delay accuracy loss due to limited signal bandwidth (mm to cm).

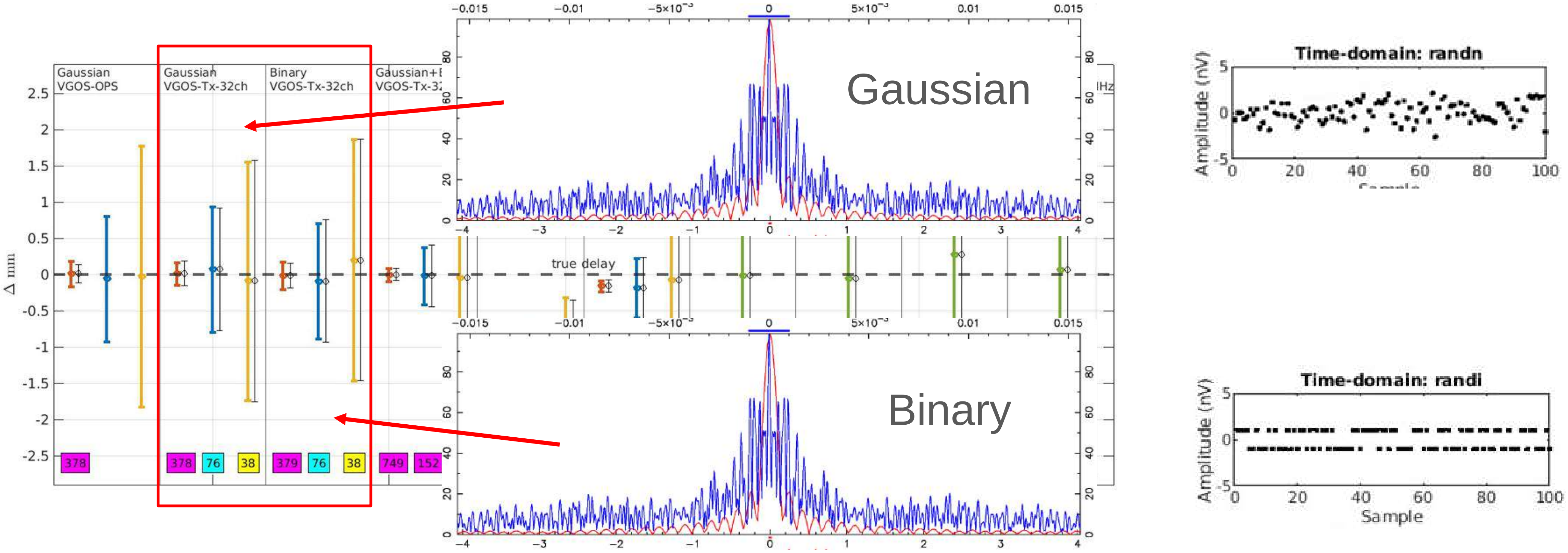
(2) Testing of a new frequency setup to align with Genesis emission bands





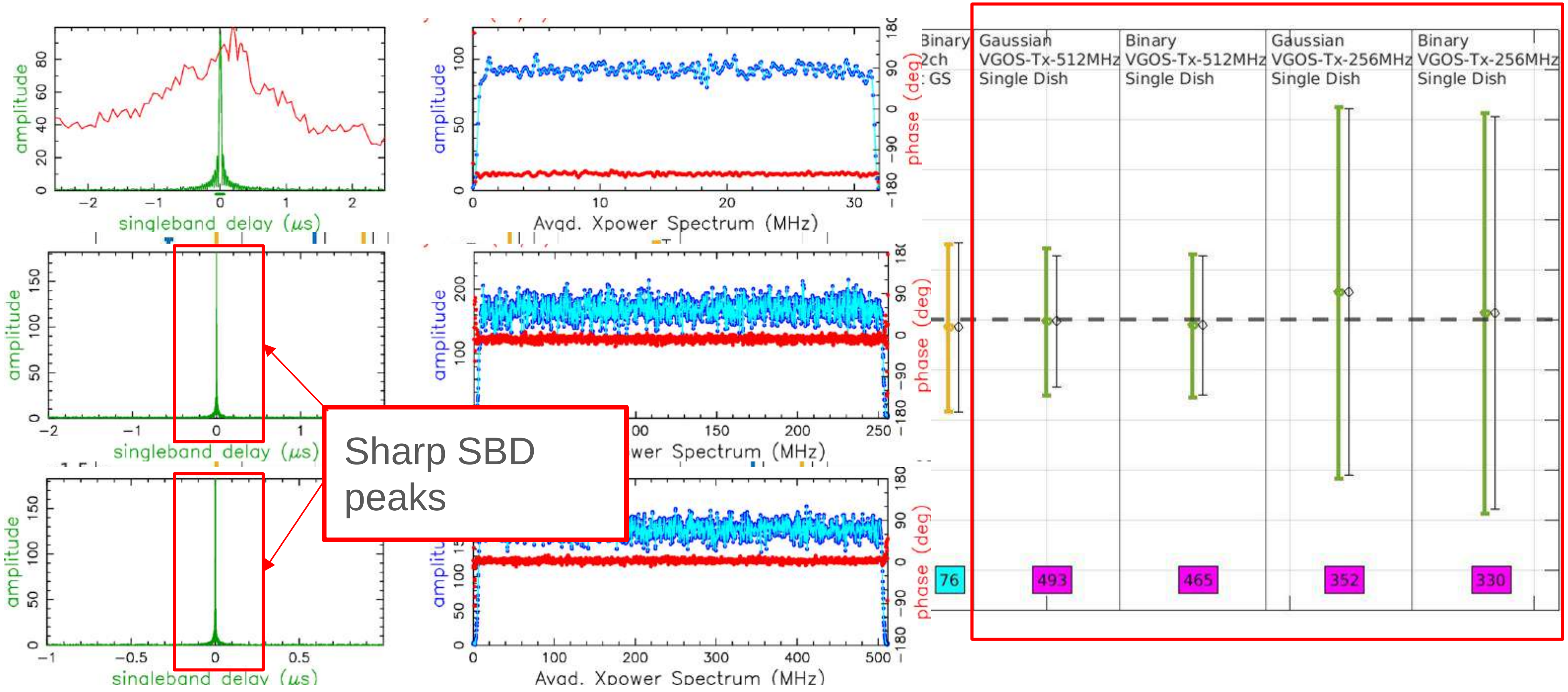
The VGOS VT 32-channel setup for Genesis achieves a precision level comparable to VGOS-OPS.

(3) Comparison of Gaussian and binary random signals from Genesis within the VLBI processing chain



Simulations show equivalent results for Gaussian and binary random signals.

(4) Simulation of single dish observations of signals with 256/512 MHz bandwidth



Delay observations can be obtained with a single radio telescope for 256/512 MHz bandwidth signals using signal replication.

Future work

- Implementation of realistic BOC signals in VieRDS, including magnitude shape and code length.
- Investigation of BOC signal behavior in the VLBI processing chain.
- Analysis of the effects of superimposing BOC and Gaussian noise signals within the VLBI processing chain.

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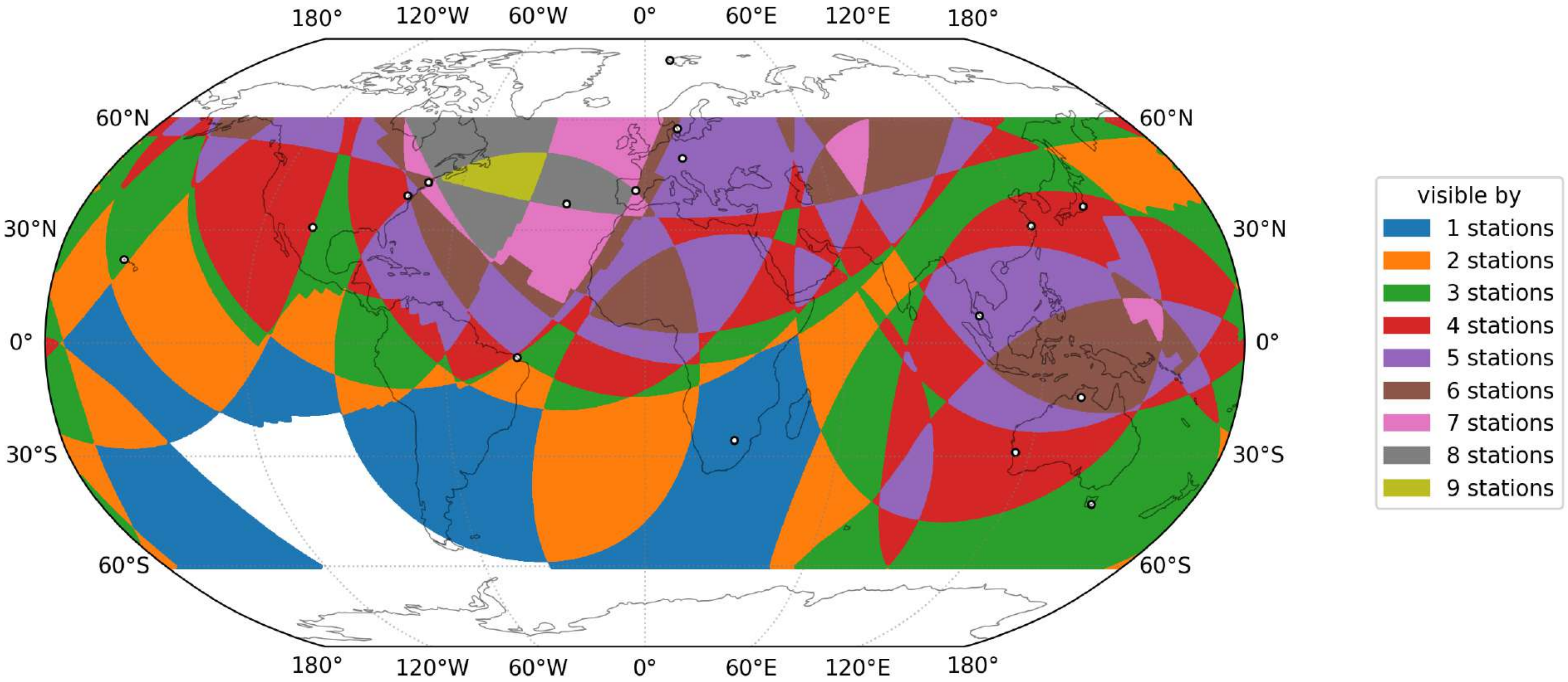
GSET WG-3 (VLBI)
WP-4: Scheduling

Matthias Schartner
ESA Genesis Science Workshop 2025
03-04 April 2025, Matera

Previously: Visibility w.r.t. Orbit

Studied various orbits
- Altitude: 6000 km
- Inclination: 60 deg



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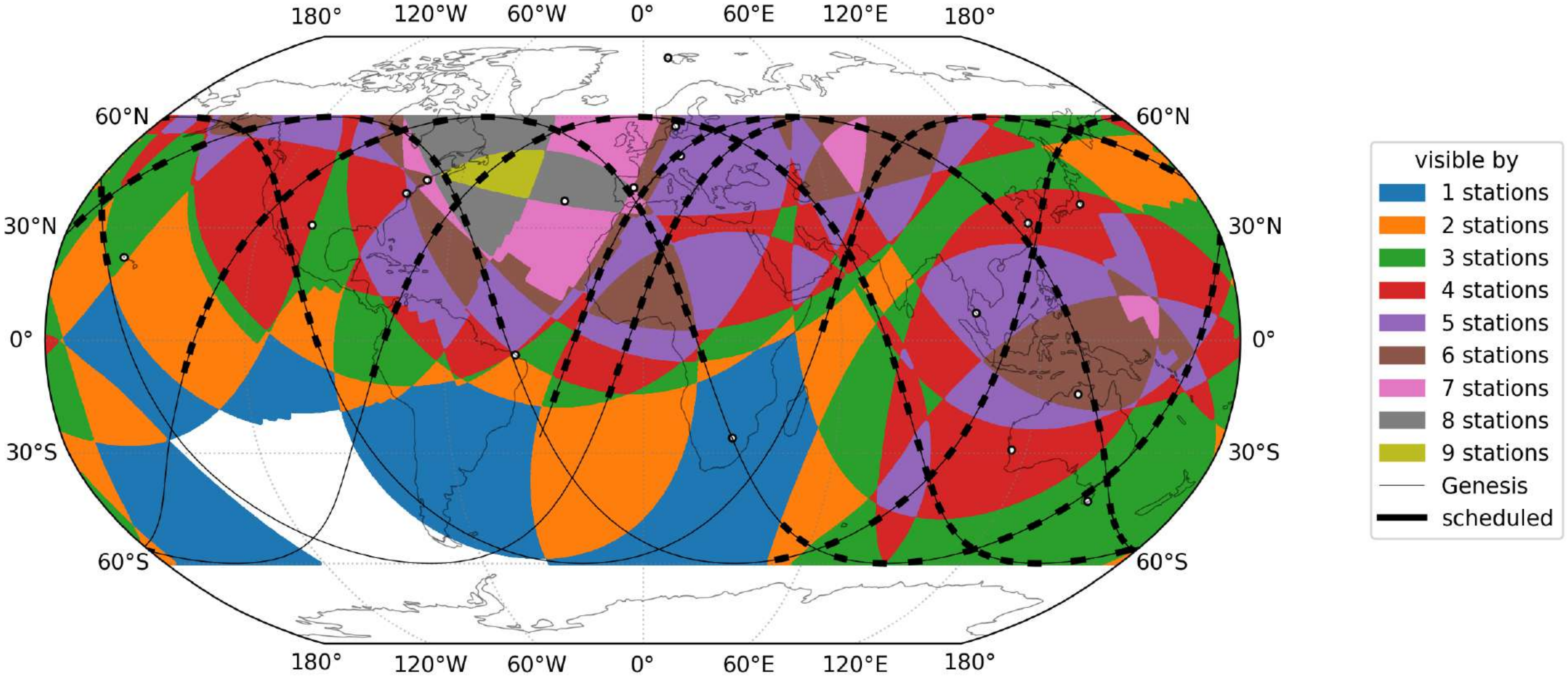
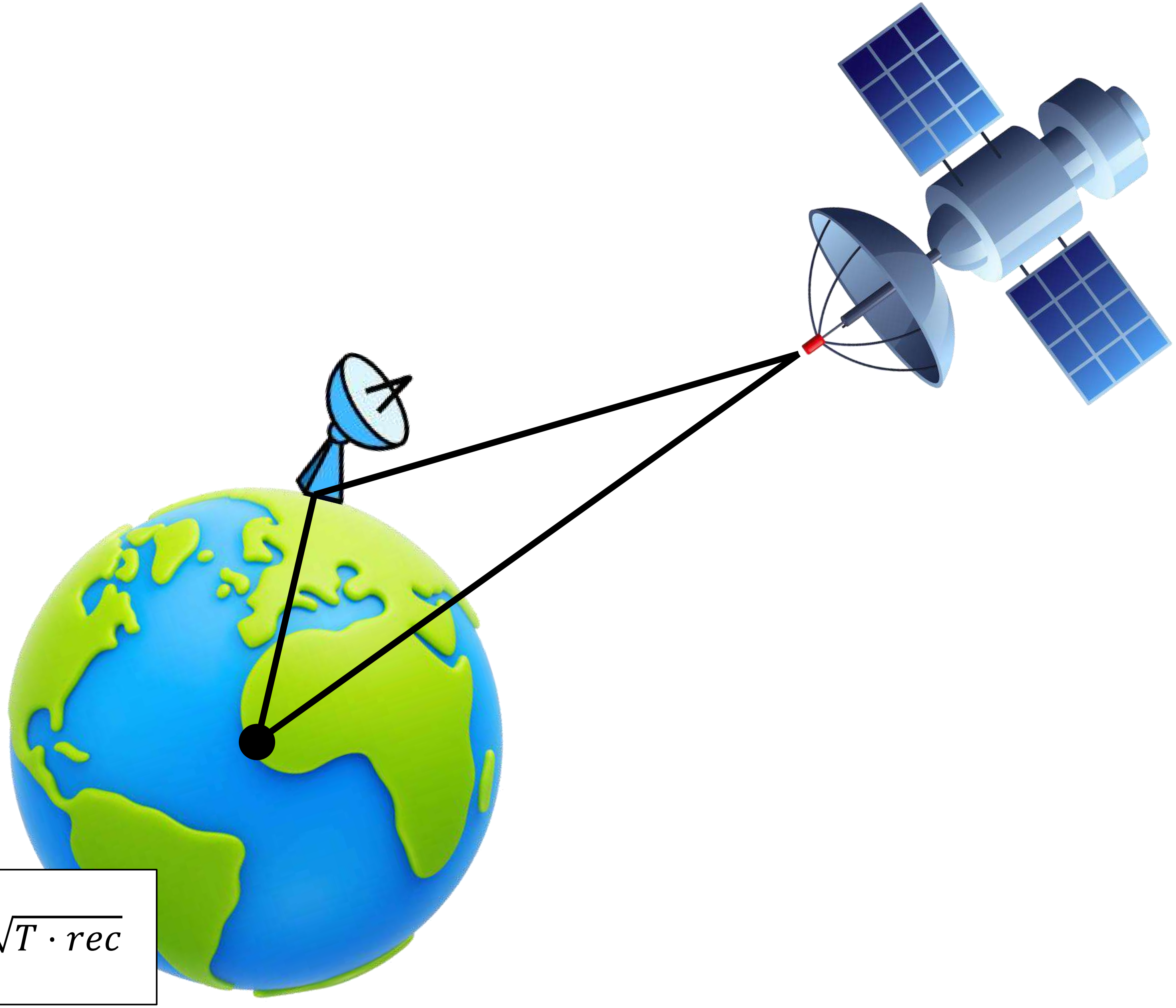


Signal Strength



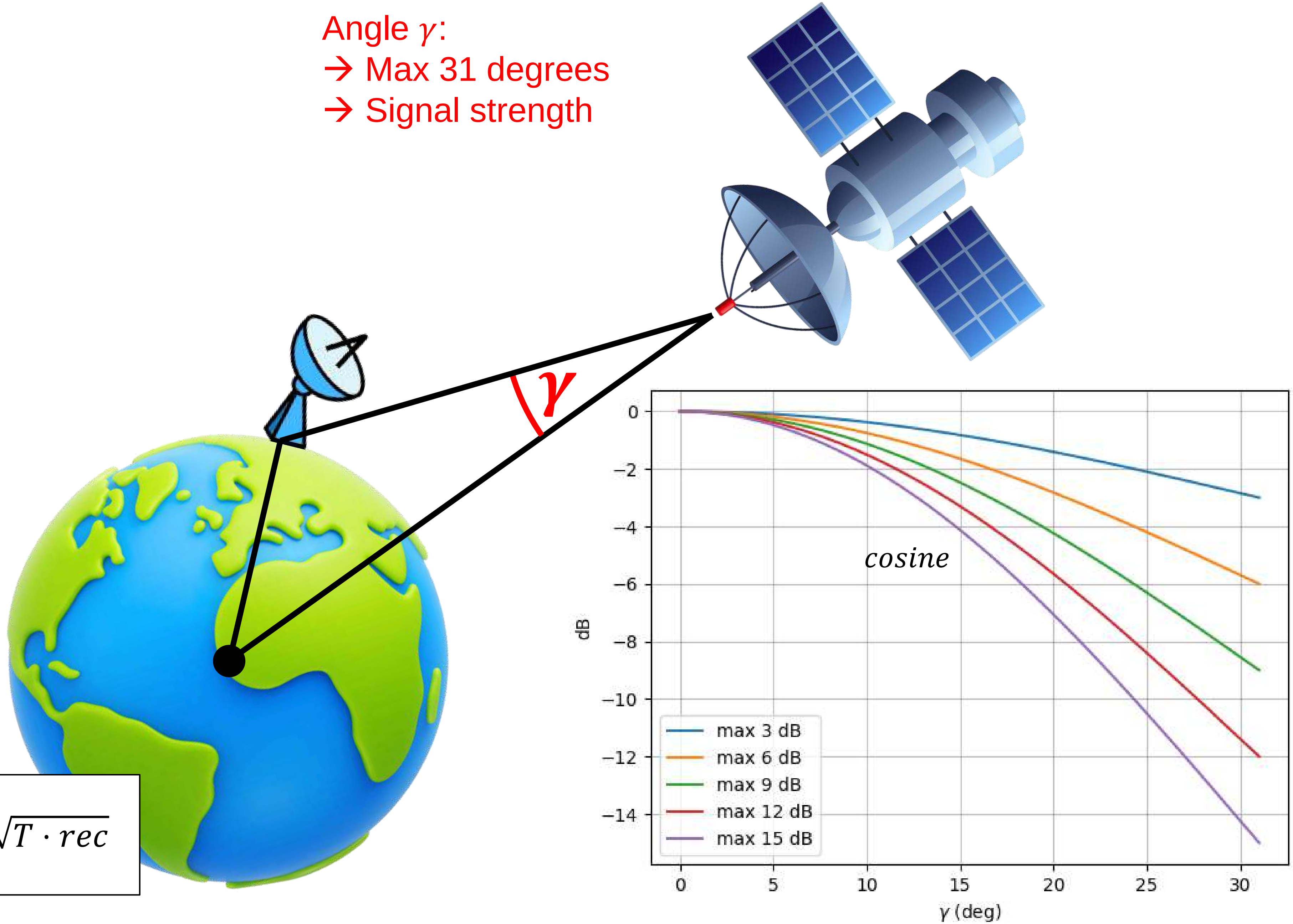
$$SNR = \eta \frac{\sqrt{S_1 \cdot S_2}}{\sqrt{SEFD_1 \cdot SEFD_2}} \sqrt{T \cdot rec}$$

Signal Strength

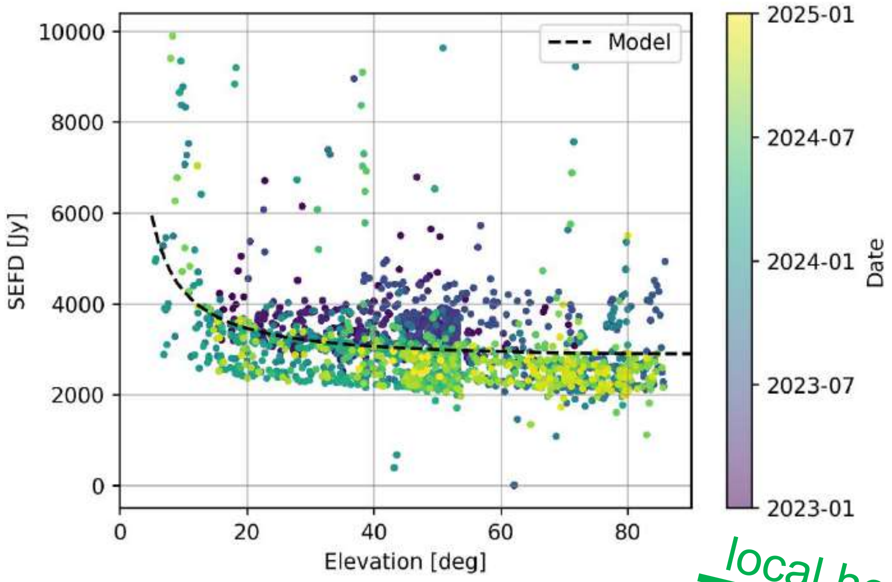
Angle γ:

→ Max 31 degrees

→ Signal strength

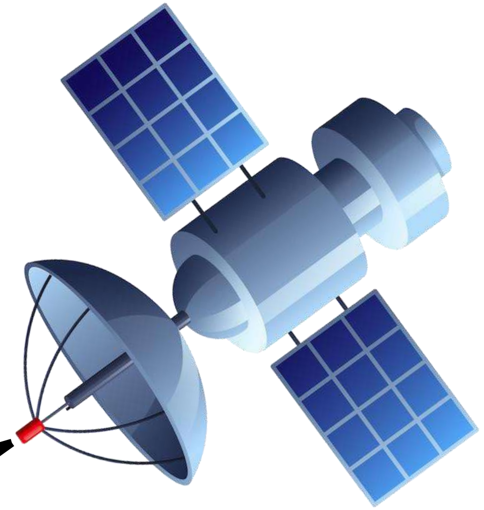


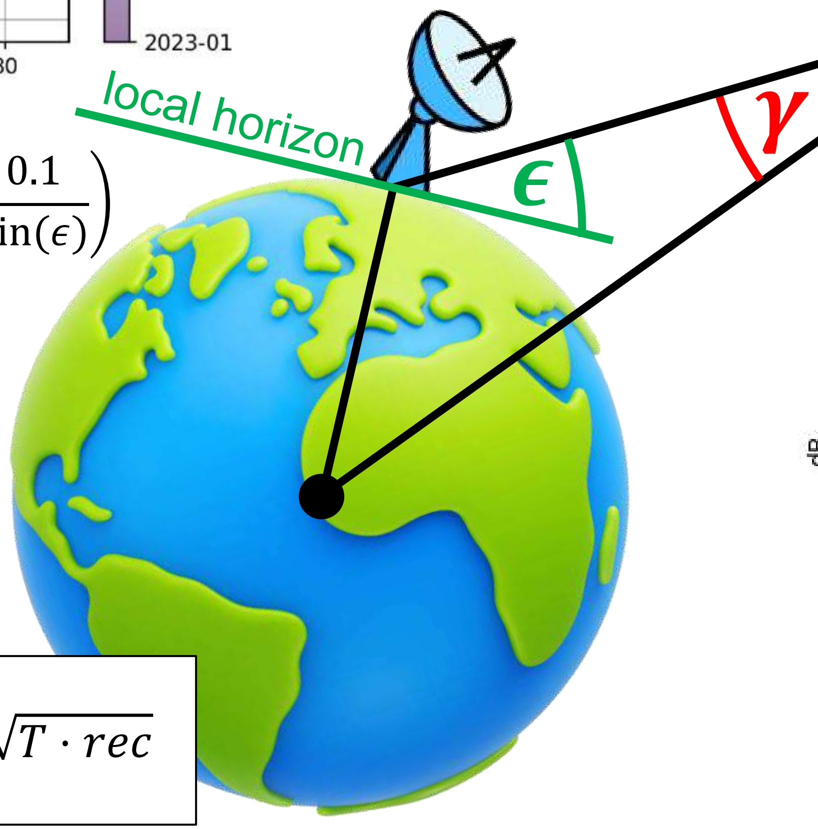
$$SNR = \eta \frac{\boxed{\sqrt{S_1 \cdot S_2}}}{\sqrt{SEFD_1 \cdot SEFD_2}} \sqrt{T \cdot rec}$$



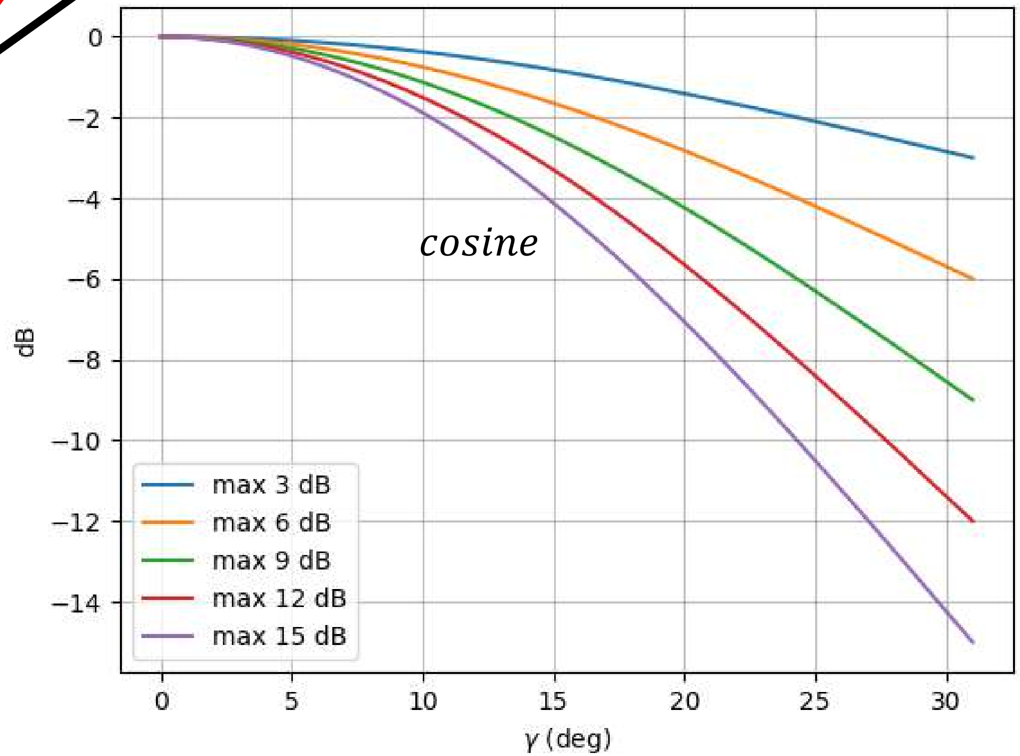
Angle γ:
→ Max 31 degrees
→ Signal strength

Elevation ϵ:
→ Sensitivity





$$SEFD(\epsilon) = SEFD_{zenith} \cdot \left(0.9 + \frac{0.1}{\sin(\epsilon)}\right)$$



$$SNR = \eta \frac{\boxed{\sqrt{S_1 \cdot S_2}}}{\boxed{\sqrt{SEFD_1 \cdot SEFD_2}}} \sqrt{T \cdot rec}$$

Many degrees of freedom for scheduling

Variable:

- **Signals strength in nadir (x-axis)**
- **Signal loss at γ = 31 degrees (y-axis)**

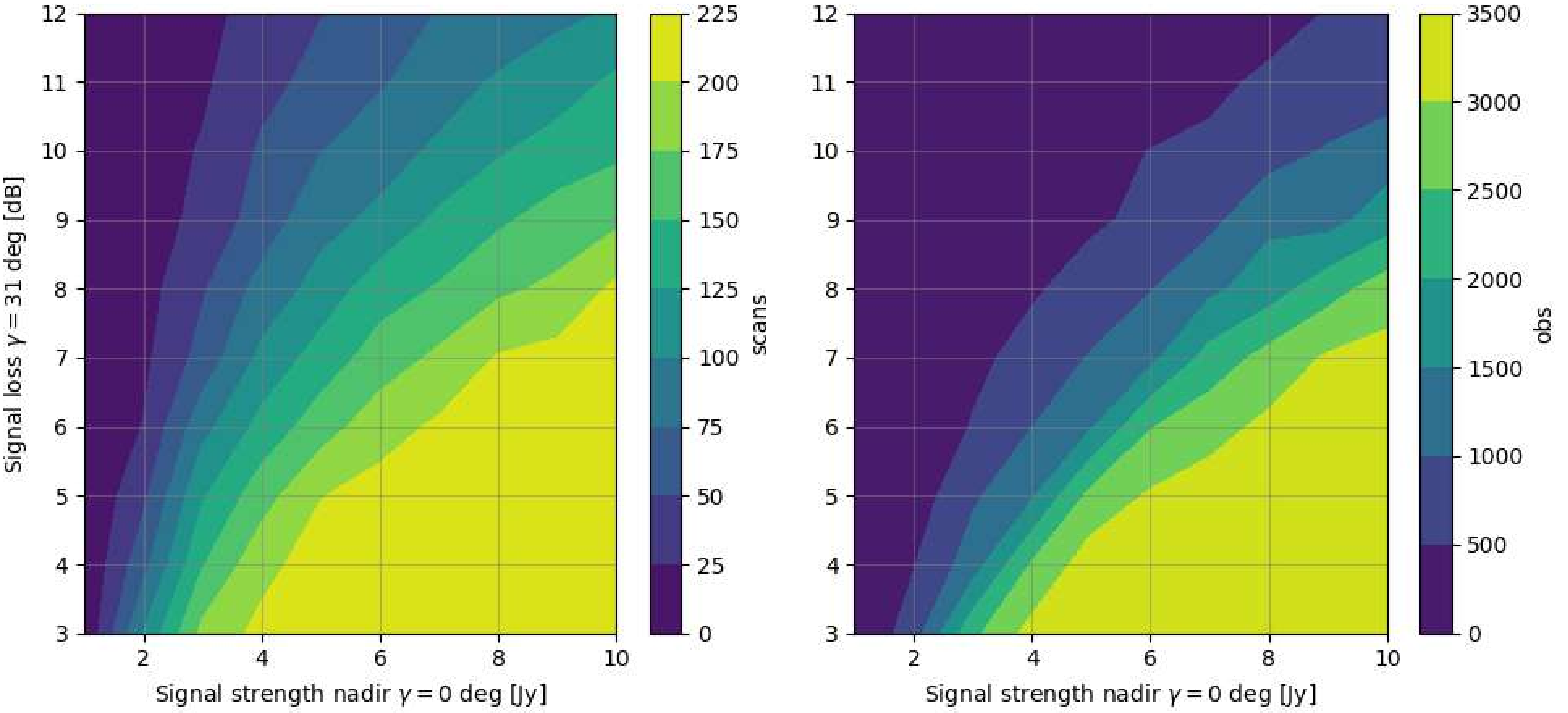
Question:

- **What signal strength do we need**
- **Tuneable signal strength 0.1-10 Jy (logarithmic scale)? :-/**

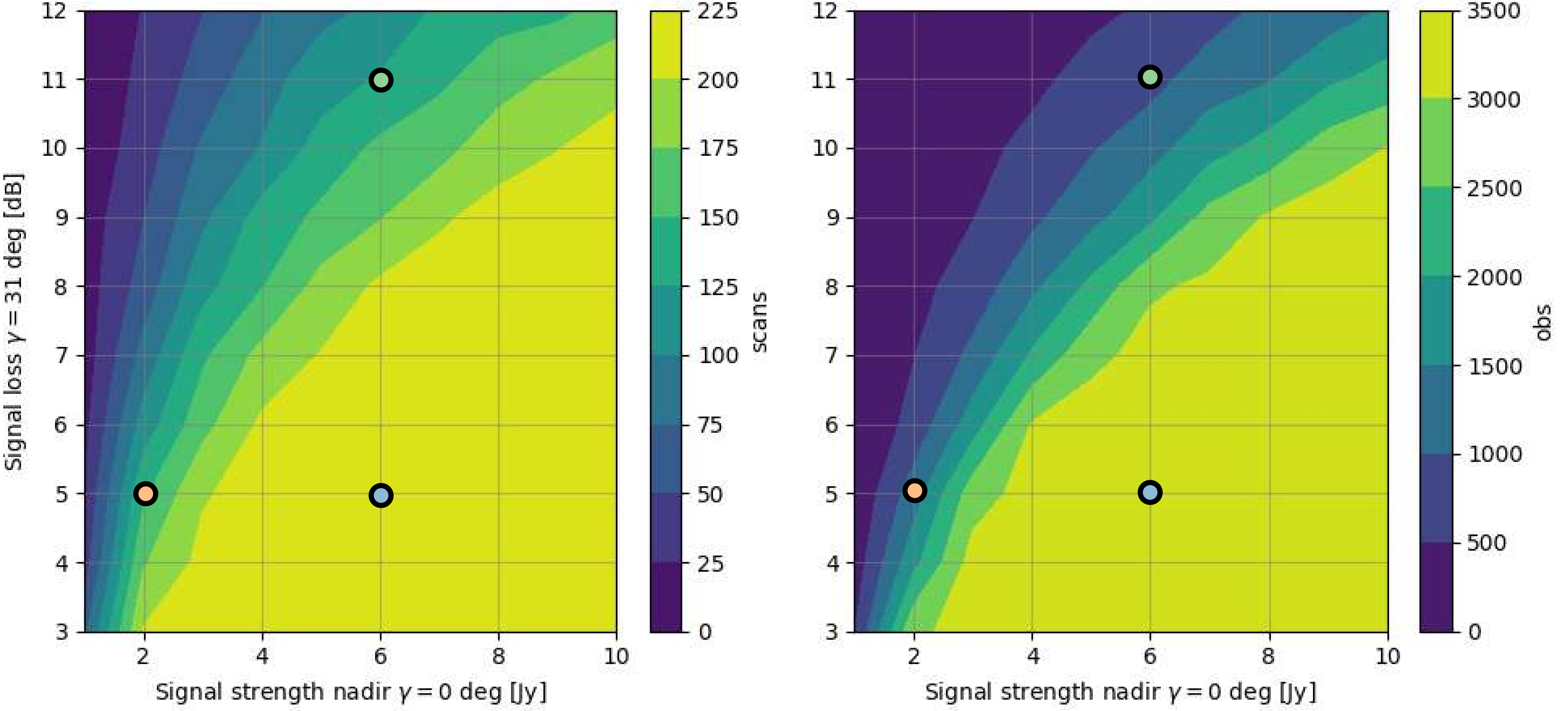
Fixed:

- Observation duration
- Genesis antenna gain curve:
  - Cosine
- SEFD:
  - Elevation-dependent models
- Required SNR:
  - 20 per band
- Recording rate:
  - A, C: 640 Mbps
  - B, D: 1024 Mbps
- Satellite min repeat time:
  - 3 minutes

observation duration: 10 sec

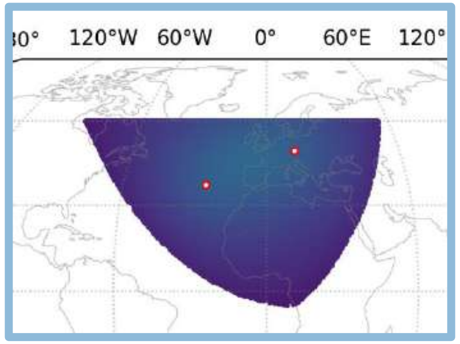


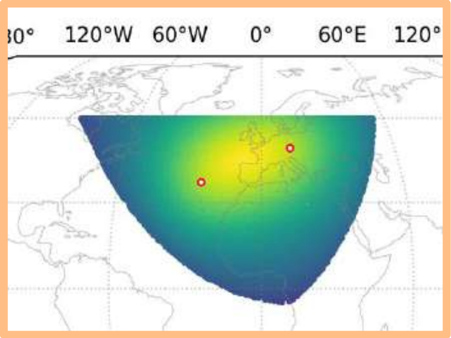
observation duration: 30 sec

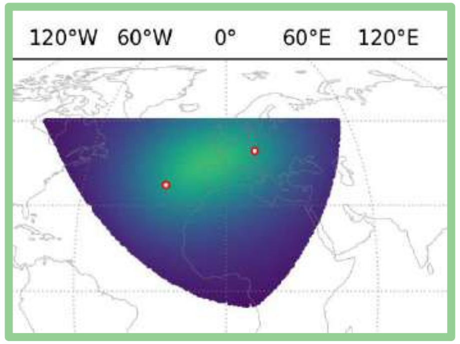


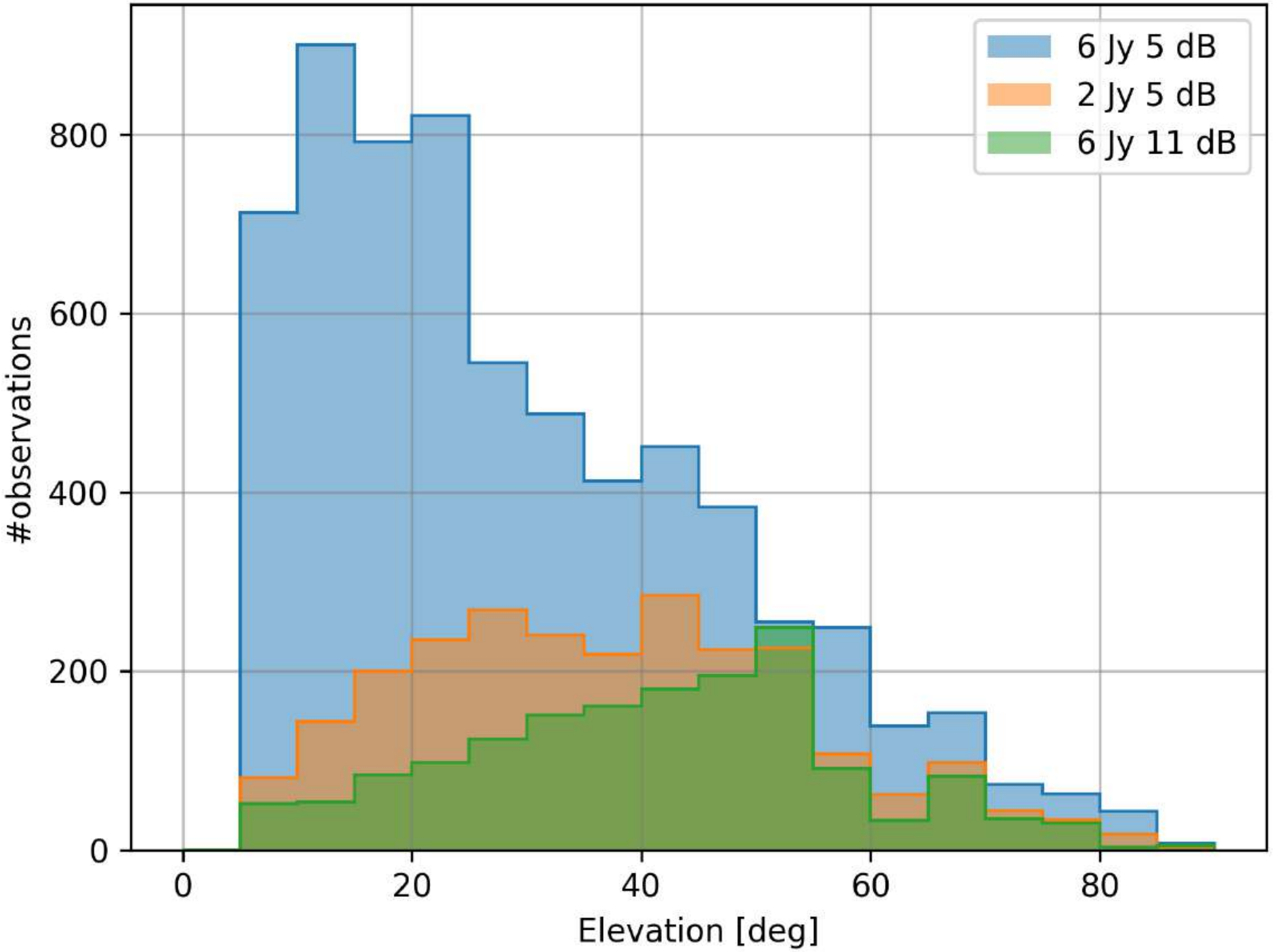
What observations do we loose?

Mostly low elevation scans

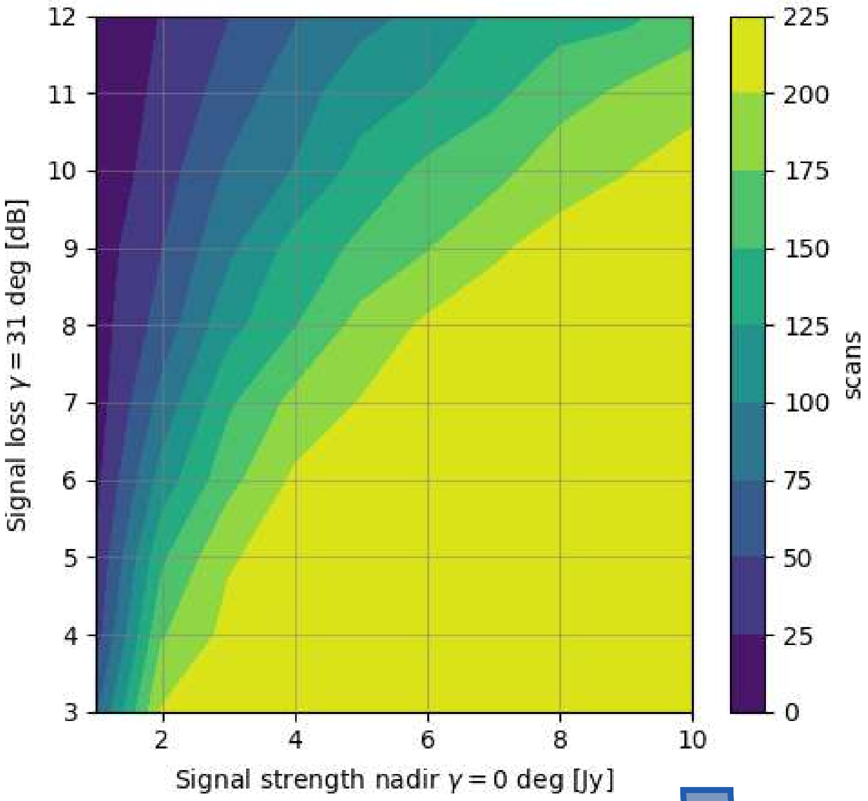


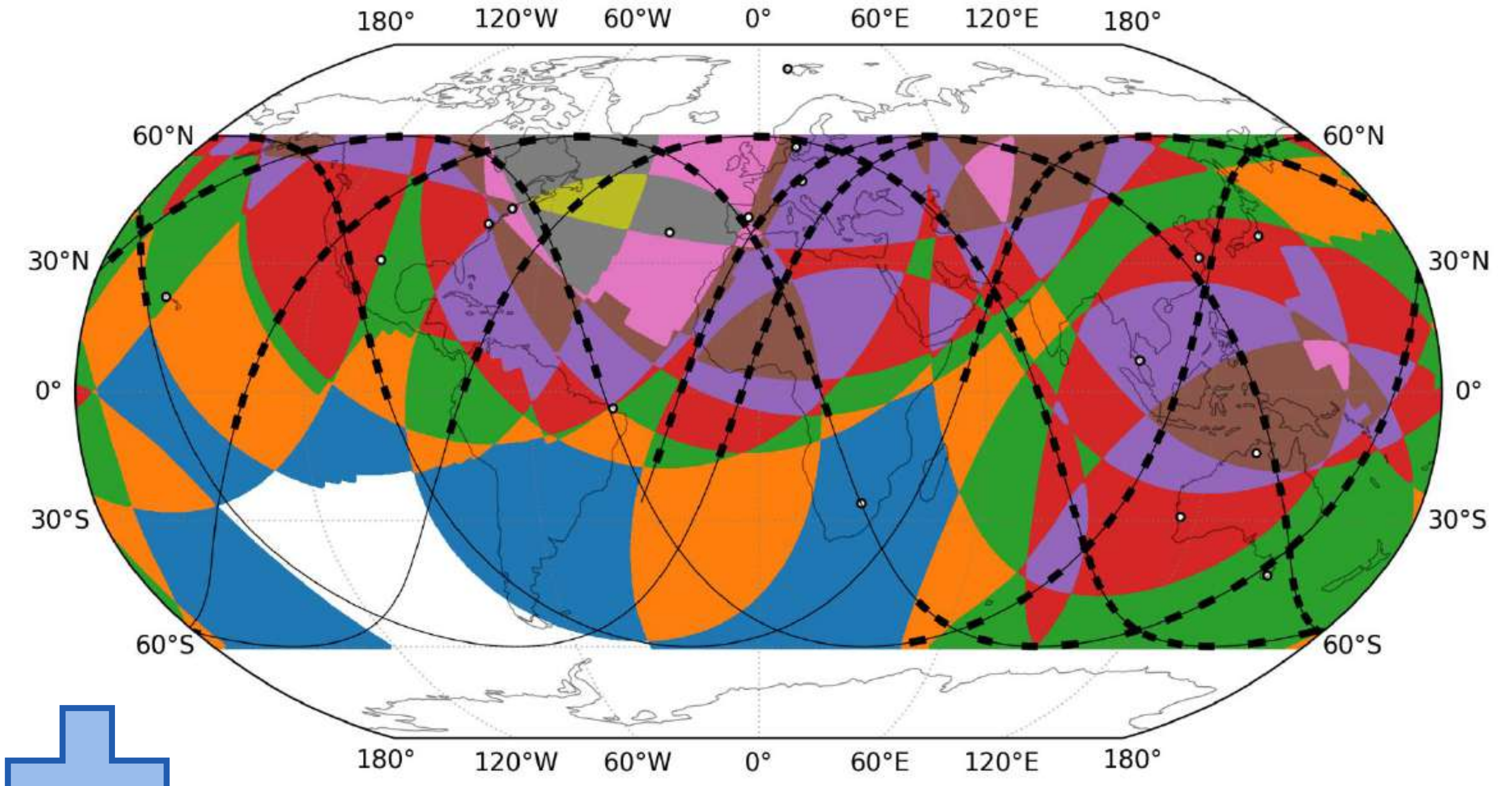






Next Step: Generalize Investigations

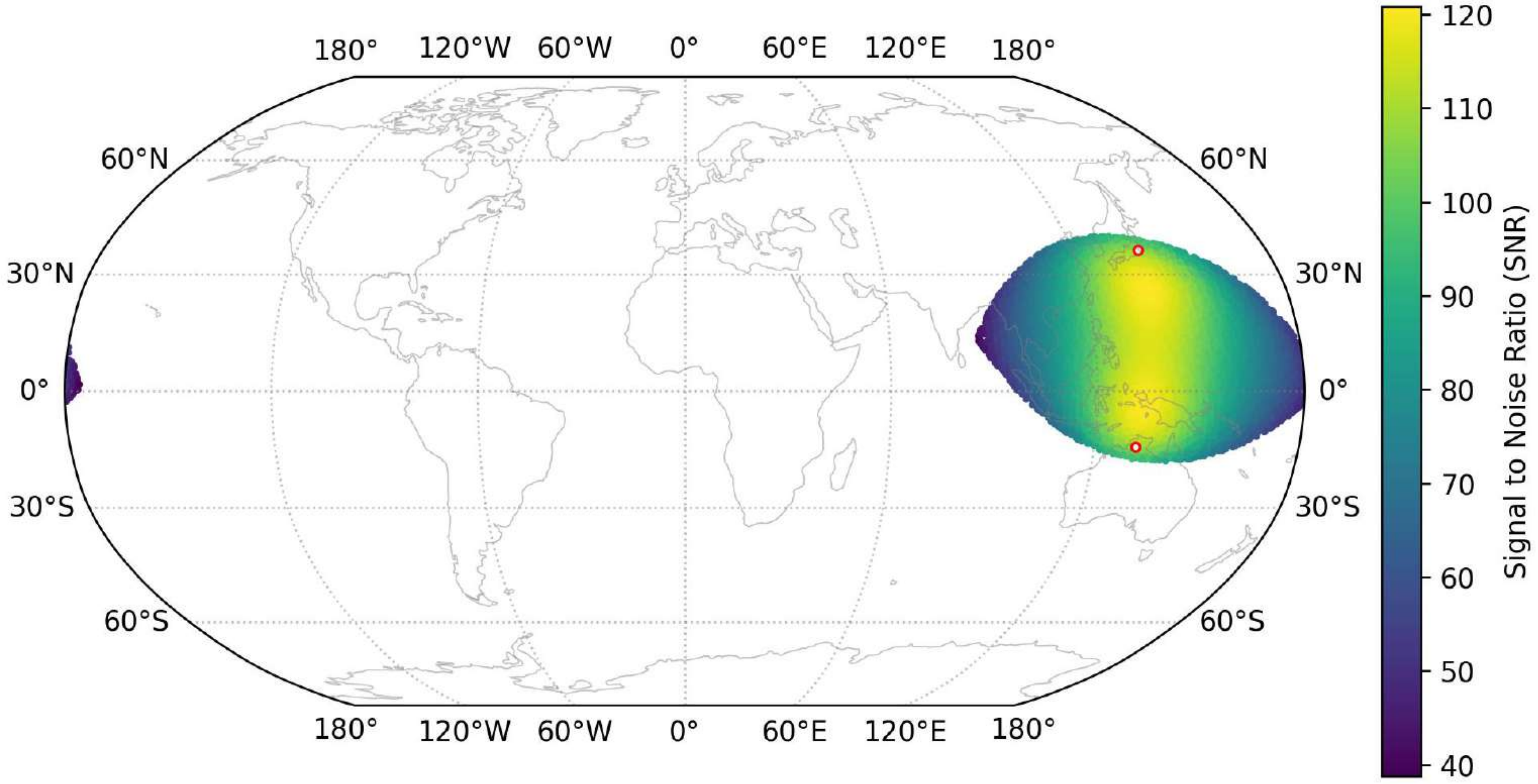




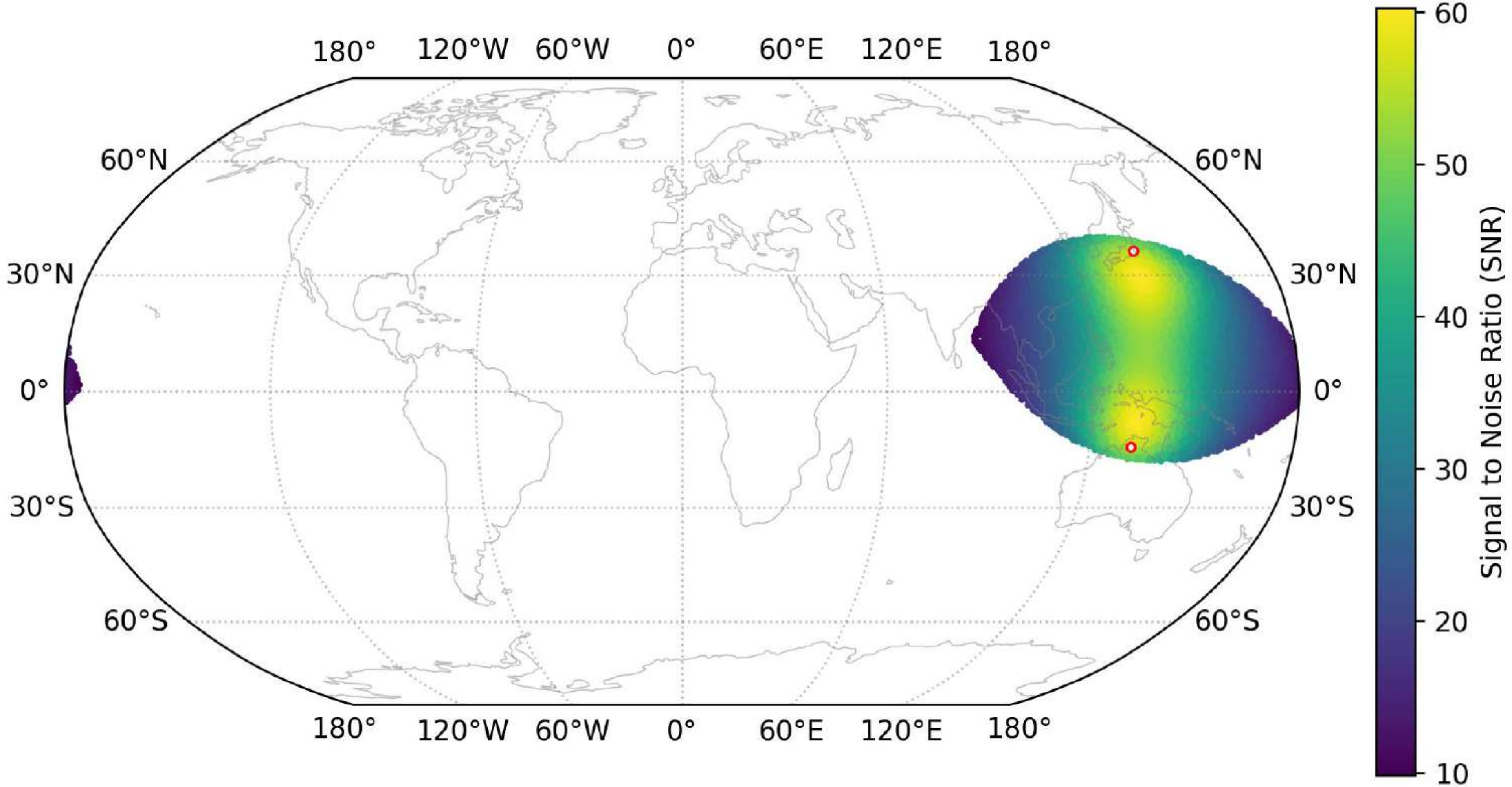
end-to-end simulations

Appendix

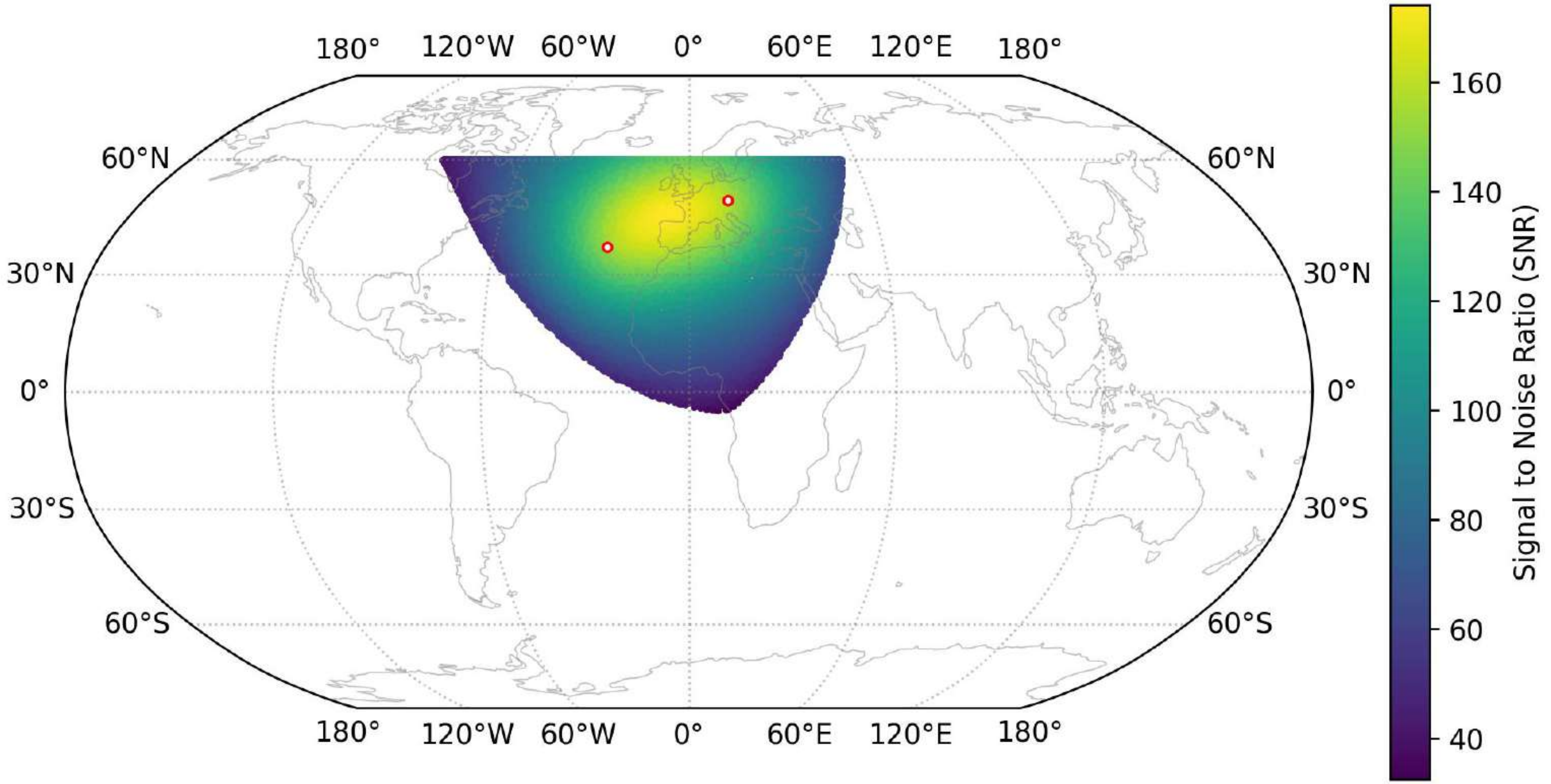
6 Jy with 5 dB at γ=31 deg



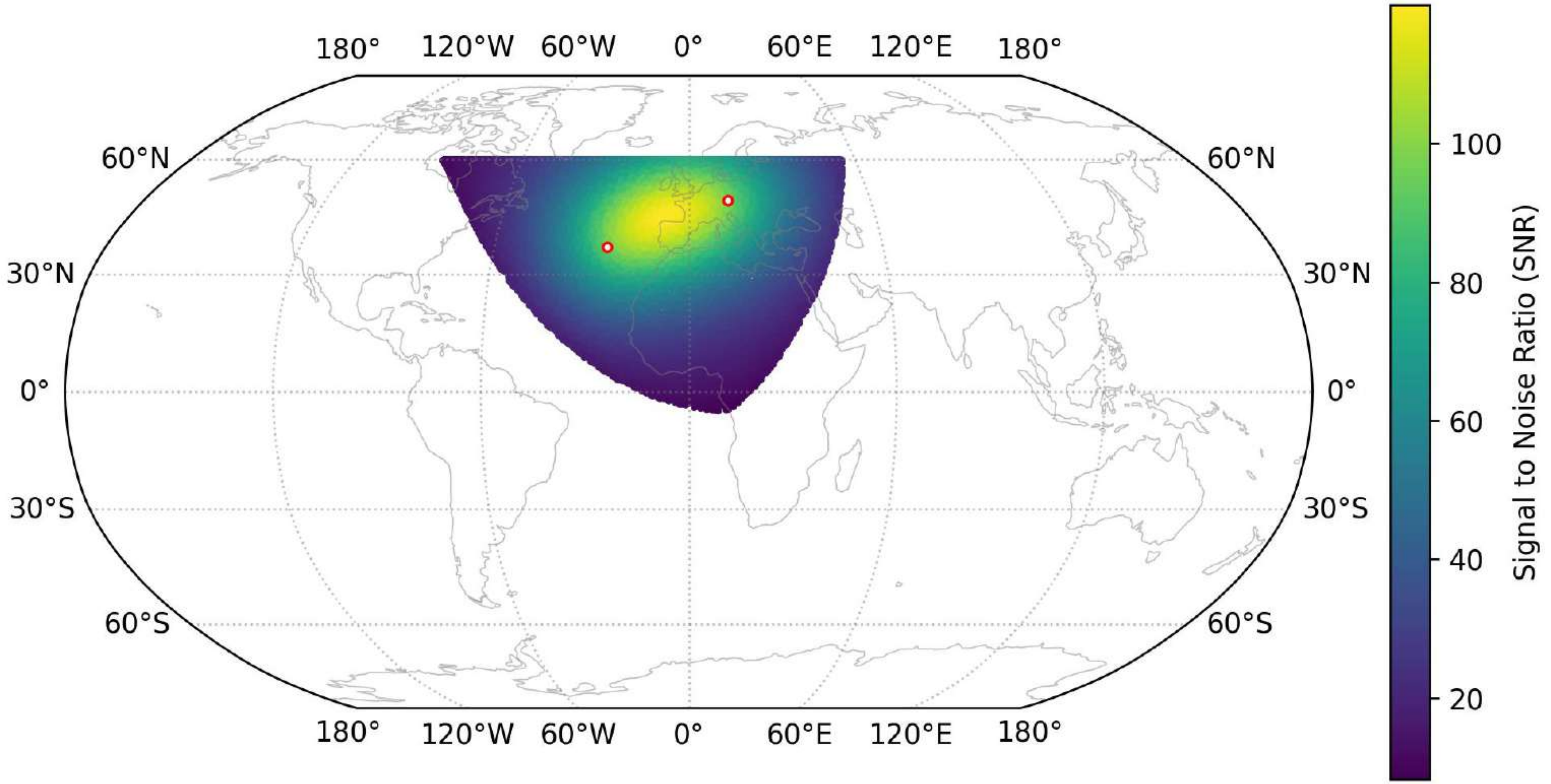
6 Jy with 11 dB at γ=31 deg



6 Jy with 5 dB at γ=31 deg



6 Jy with 11 dB at γ=31 deg



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GSET WG-3 (VLBI) WP-5: Simulations

Matthias Schartner

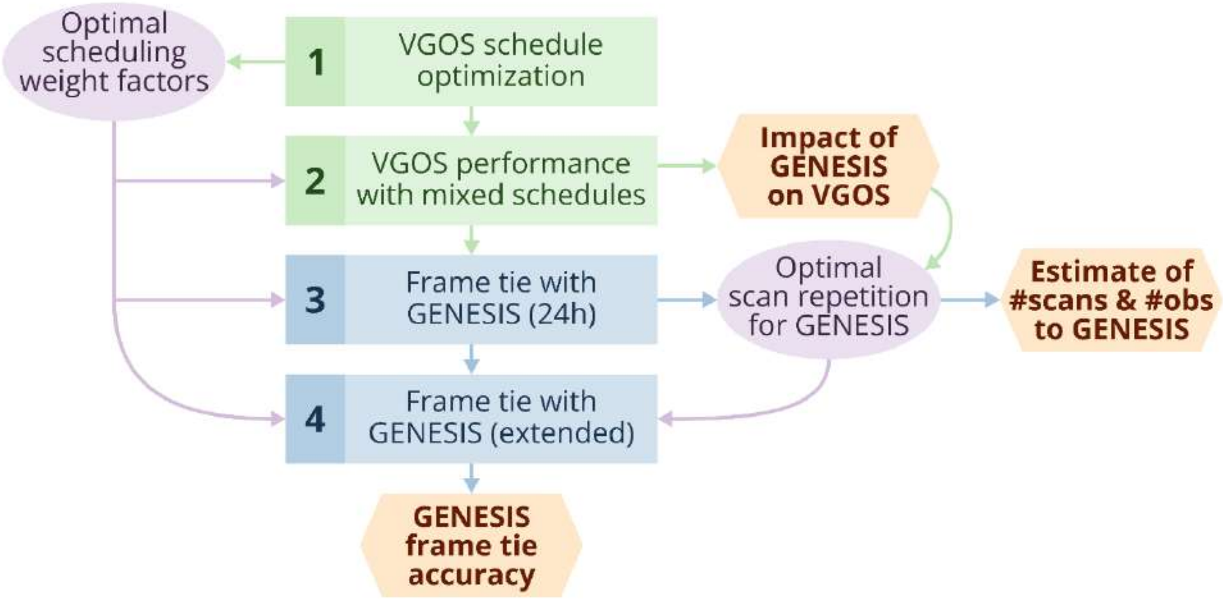
ESA Genesis Science Workshop 2025

03-04 April 2025, Matera

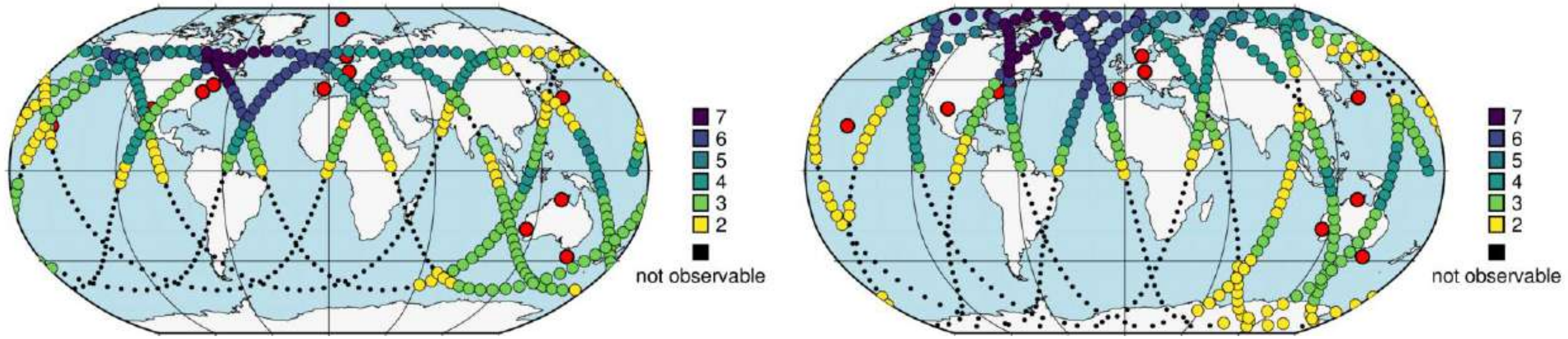
Simulation Studies

Schunck, D., McCallum, L., & Molera Calvés, G. (2024).
On the Integration of VLBI Observations to GENESIS into Global VGOS Operations.
In Remote Sensing (Vol. 16, Issue 17, p. 3234). MDPI AG. https://doi.org/10.3390/rs16173234

- Scheduling:
  - 10 sec (every 5 minutes)
  - 3 networks (12, 20, 29 VGOS stations)
- Simulations:
  - Additional error source (orbital errors)
- Results:
  - 150 – 200 scans (good agreement with prev. findings)
  - Impact on traditional geodetic products negligible → ☺



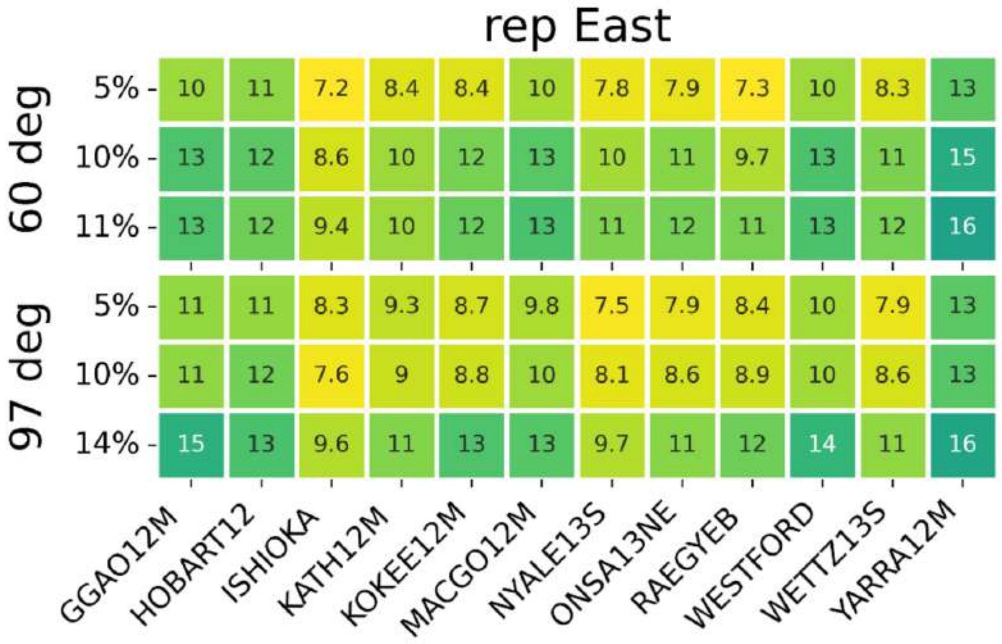
Simulation Studies



Wolf, H., Böhm, J. (2025)
How accurate can the VLBI station coordinates be derived from VLBI observations to the Genesis satellite?

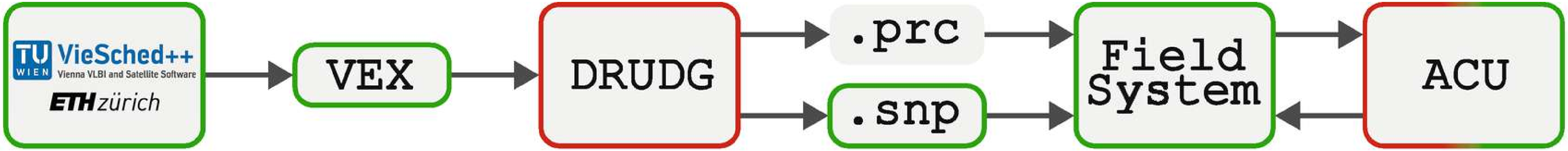
- Scheduling:
  - 30 sec
  - Two inclinations **(60° and 97°)**

- Simulations
- Analysis:
  - EOP (quasar only)
  - Station coordinates (sat + quasar)
- Conclusions:
  - For that specific task, 97° slightly better than 60°
  - Larger networks have less impact w.r.t. inclination



Simulation Studies

Schunck, D., McCallum, L., & Molera Calvés, G. (2024).
Practical Considerations of VLBI Observations to the GENESIS Mission.
In International Association of Geodesy Symposia.
Springer Berlin Heidelberg. https://doi.org/10.1007/1345_2024_245

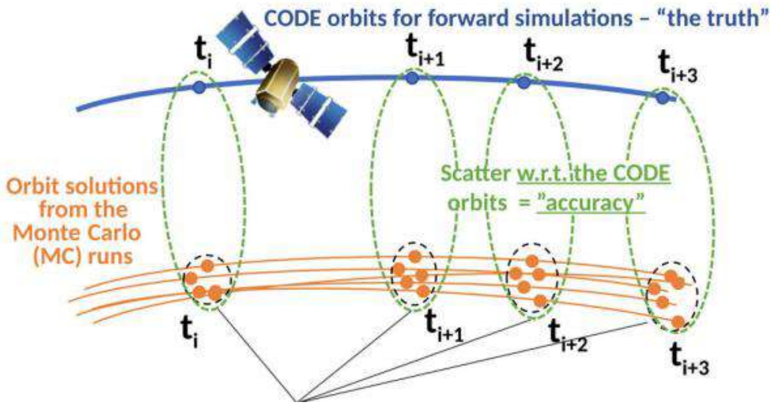


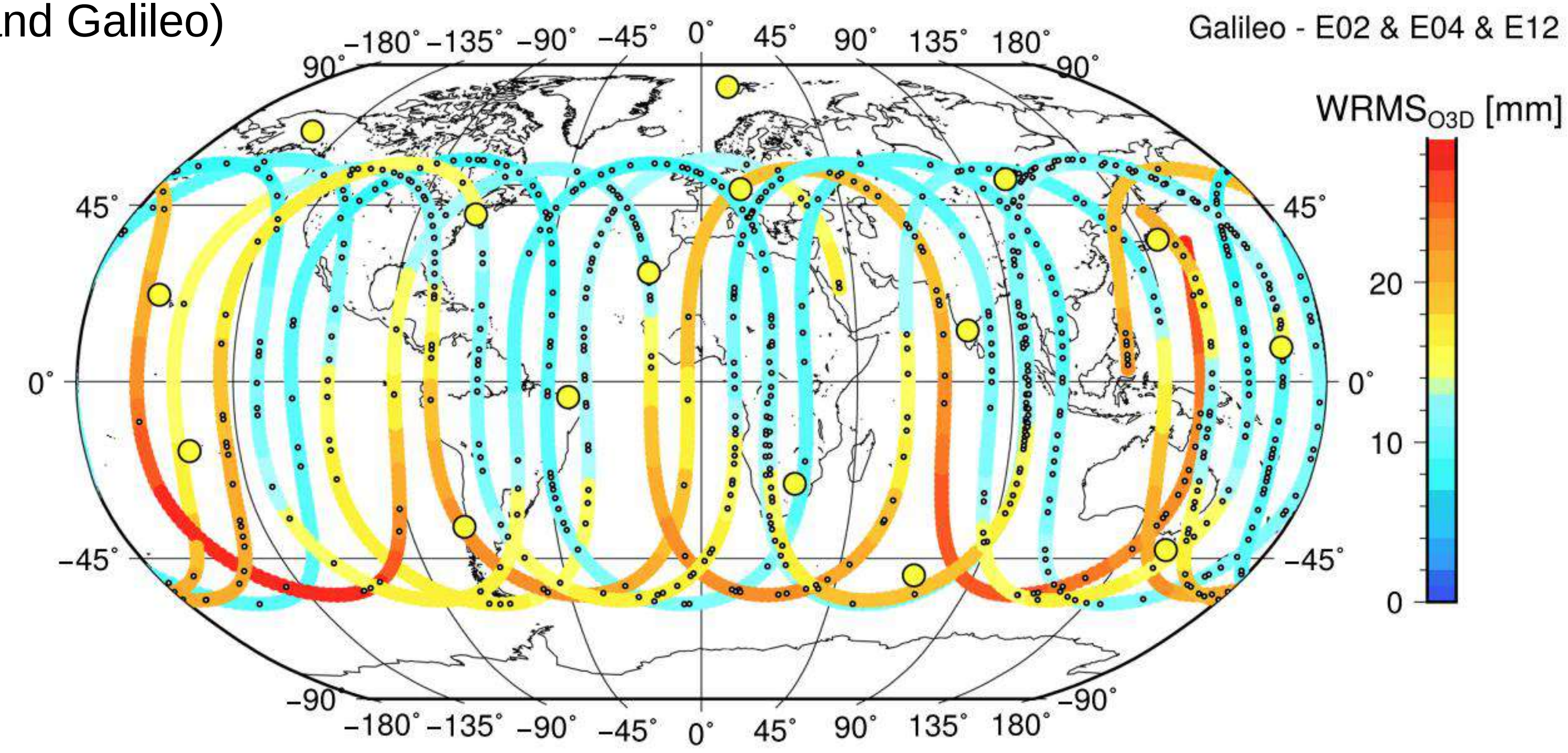
- Genesis visibility (→ good agreement with prev. findings)
- Identify missing software components
- How many VGOS sessions will observe Genesis?
  - Dedicated sessions needed (frequency setup differs)
  - Regular one session per week: VGOS already at maximum capacity
  - Additional resources need to be allocated for Genesis sessions

Prev. Simulation Studies

Klopotek, G., Hobiger, T., Haas, R., & Otsubo, T. (2020).
Geodetic VLBI for precise orbit determination of Earth satellites: a simulation study.
In Journal of Geodesy (Vol. 94, Issue 6). https://doi.org/10.1007/s00190-020-01381-9

- Precise Orbit Determination (POD) C5++
- MEO Satellites (LAGEOS-1/-2 and Galileo)
- Monte-Carlo simulations
  - 3D orbit precision of few cm
  - Geocenter offset…





Next steps

- Coordinate efforts
- **Bring all topics together:**
  - Underlying models
  - Genesis observing duration
  - Simulated error sources
  - Analysis steps
- **Diversity:**
  - Additional software packages
  - Others can also be used
- **Focus on key topics:**
  - Orbit parameters?
  - Signal strength?
  - Precision of orbit determination / geodetic parameters?
  - Combination with other techniques?

TU WIEN VieSched++ Vienna VLBI and Satellite Software

ETH zürich

TU WIEN VieVS Vienna VLBI and Satellite Software

CHALMERS UNIVERSITY OF TECHNOLOGY

Bernese

\+ Many more ☺

ESA GSET WG-3 (VLBI)

WP-6: test observations

ESA Genesis Science Workshop 2025

3-4 April 2025, Matera, Italy

Rüdiger Haas

Chalmers University of Technology

Possible VGOS channel selection for Genesis

3100-3300 MHz

BAND-1	3132.4	32.0	L
BAND-1	3164.4	32.0	L
BAND-1	3196.4	32.0	L
BAND-1	3228.4	32.0	L
BAND-1	3260.4	32.0	L
BAND-1	3292.4	32.0	L

6 channels

5250–5570 MHz

BAND-2	5276.4	32.0	L
BAND-2	5308.4	32.0	L
BAND-2	5340.4	32.0	L
BAND-2	5372.4	32.0	L
BAND-2	5404.4	32.0	L
BAND-2	5436.4	32.0	L
BAND-2	5468.4	32.0	L
BAND-2	5500.4	32.0	L
BAND-2	5532.4	32.0	L
BAND-2	5564.4	32.0	L

10 channels

8200–8400 MHz

BAND-3	8220.4	32.0	L
BAND-3	8252.4	32.0	L
BAND-3	8284.4	32.0	L
BAND-3	8316.4	32.0	L
BAND-3	8348.4	32.0	L
BAND-3	8380.4	32.0	L

6 channels

9300–9800 MHz

BAND-4	9340.4	32.0	L
BAND-4	9372.4	32.0	L
BAND-4	9404.4	32.0	L
BAND-4	9436.4	32.0	L
BAND-4	9468.4	32.0	L
BAND-4	9500.4	32.0	L
BAND-4	9532.4	32.0	L
BAND-4	9564.4	32.0	L
BAND-4	9596.4	32.0	L
BAND-4	9628.4	32.0	L
BAND-4	9660.4	32.0	L
BAND-4	9692.4	32.0	L
BAND-4	9724.4	32.0	L
BAND-4	9756.4	32.0	L
BAND-4	9788.4	32.0	L

15 channels

=> In total 37 channels, total BW covering 1184 MHz in 4 bands.

Some VLBI restrictions

- VLBI Data Interchange Format (VDIF):

9.3 Multi-channel real-data Data Array format

For simplicity, and in accordance with historical VLBI practice, the VDIF specification for multi-channel Data Arrays supports only 2^n channels with 2^k bits/sample; maximum #channels is 2^{31}=2,147,483,648 and maximum bits/sample is 2^5=32. Extension of these formats to include an arbitrary number of bits/sample is not contemplated. In such cases, users are strongly encouraged to use single-channel Data Threads, which do not impose this constraint.

=> 37 channels impossible, but 32 work fine

G1 frequency setup (5-9-5-13)

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~~	~~3228.4~~	~~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~~	~~5436.4~~	~~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~~	~~8284.4~~	~~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~~	~~9532.4~~	~~32.0~~	~~L~~
BAND	D	9564.4	32.0	L
BAND	D	9596.4	32.0	L
~~BAND~~	~~D~~	~~9628.4~~	~~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.

Further restrictions

- Backends:
  - Perferable to have 8 channels per IF

$\Rightarrow$ modified Genesis frequency setup developed at Onsala

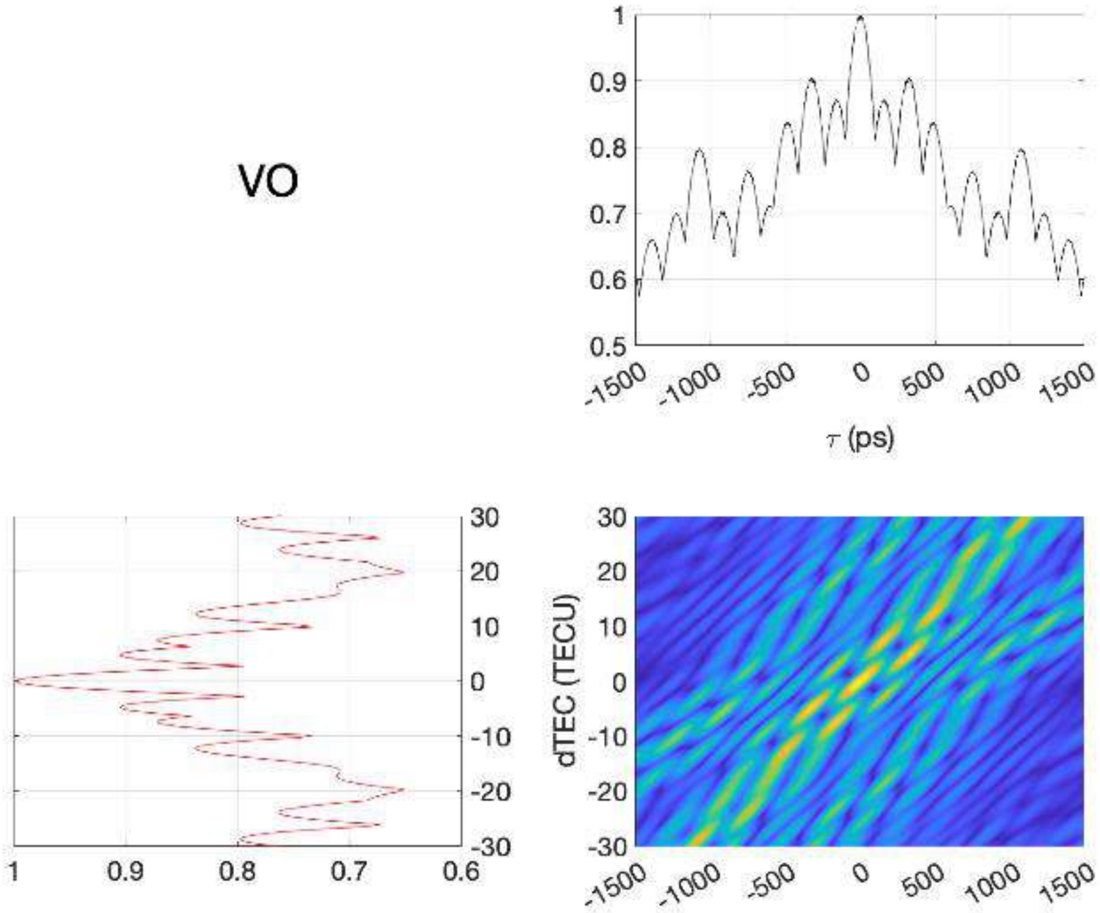
Table 2: Modified Genesis frequency setup with 8 BBC per IF. Frequencies are given in unit MHz. Shown are the upper edges of 32 MHz wide channels. The channels shown in gray and in brackets are outside the Genesis frequency bands. They have been recorded but were not used for further correlation and fringe-fitting. The channels shown in red are part of the current VGOS operational (VO) setup.

Channel	Band-1	Band-2	Band-3	Band-4
1	(3608.4)	5560.4	8376.4	9784.4
2	(3480.4)	5528.4	8344.4	9752.4
3	(3384.4)	5496.4	8312.4	9688.4
4	3288.4	5464.4	8280.4	9624.4
5	3256.4	5432.4	8248.4	9560.4
6	3224.4	5400.4	(8216.4)	9432.4
7	3192.4	5368.4	(8152.4)	9368.4
8	3160.4	5336.4	(7928.4)	9336.4

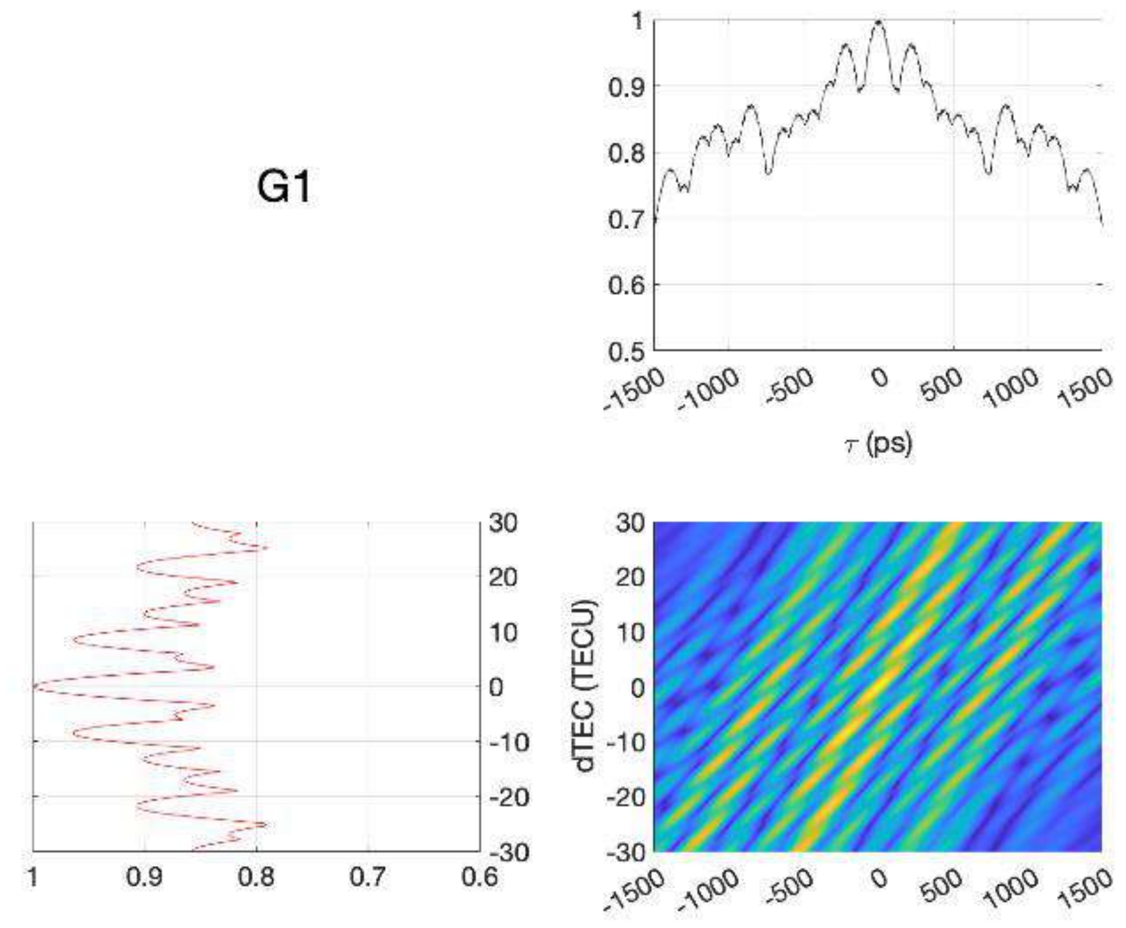
Test observations at OSO

- G1-test: with 5-9-5-13 channels
  - Requires special DBBC3 DDC_v126 firmware
  - Has problems with HOPS/Fourfit post-processing
- G2-test: with modified Genesis frequency setup 5-8-5-8
  - Simplification to keep 8 BBC per IF
  - Allows to use DBBC3 DDC_v125 firmware that is standardly used for VGOS observations
- Observations Oe-Ow, correlation with DiFX and fringe fitting with HOPS/Fourfit

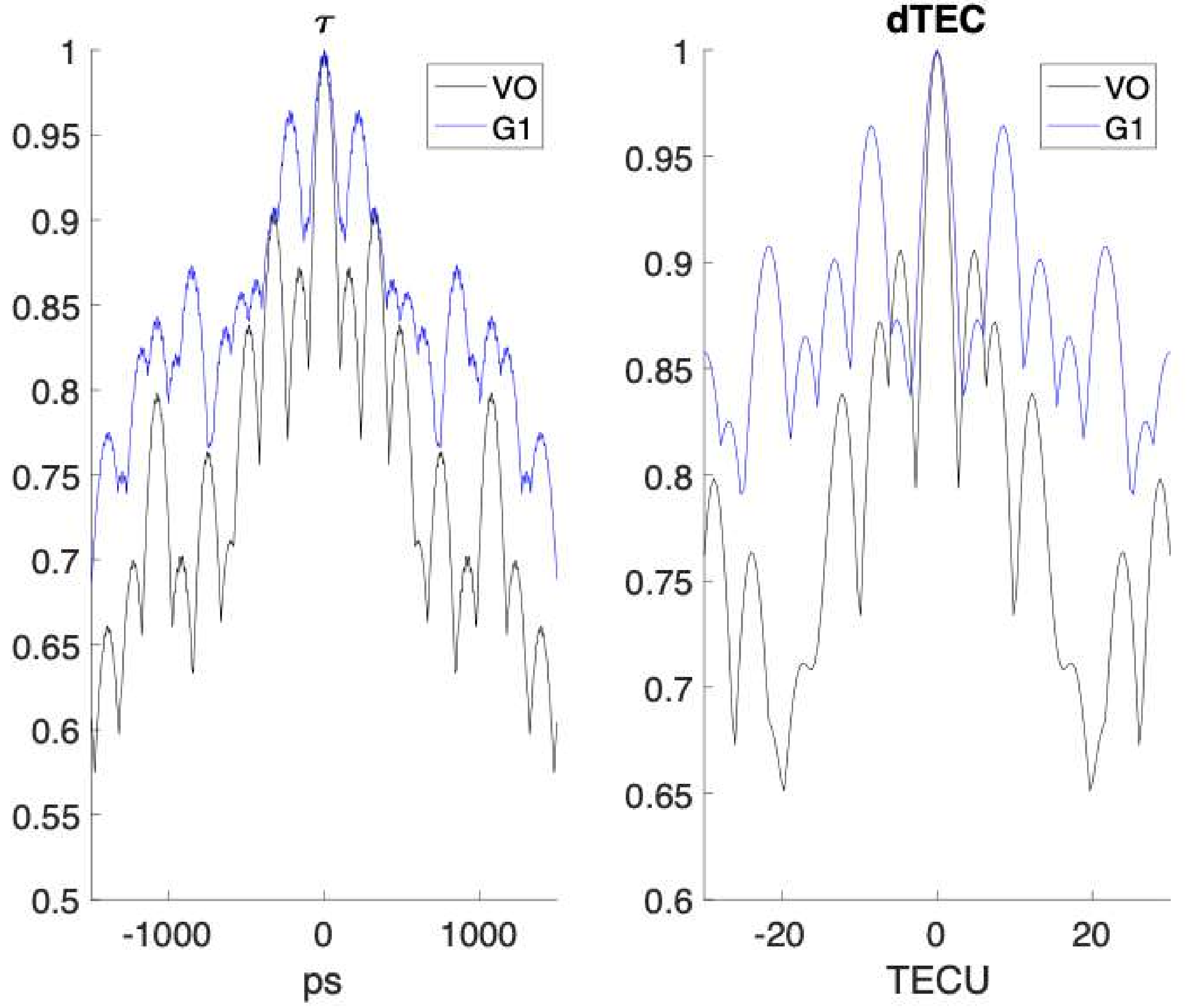
Delay resolution function VO



Delay resolution function G1



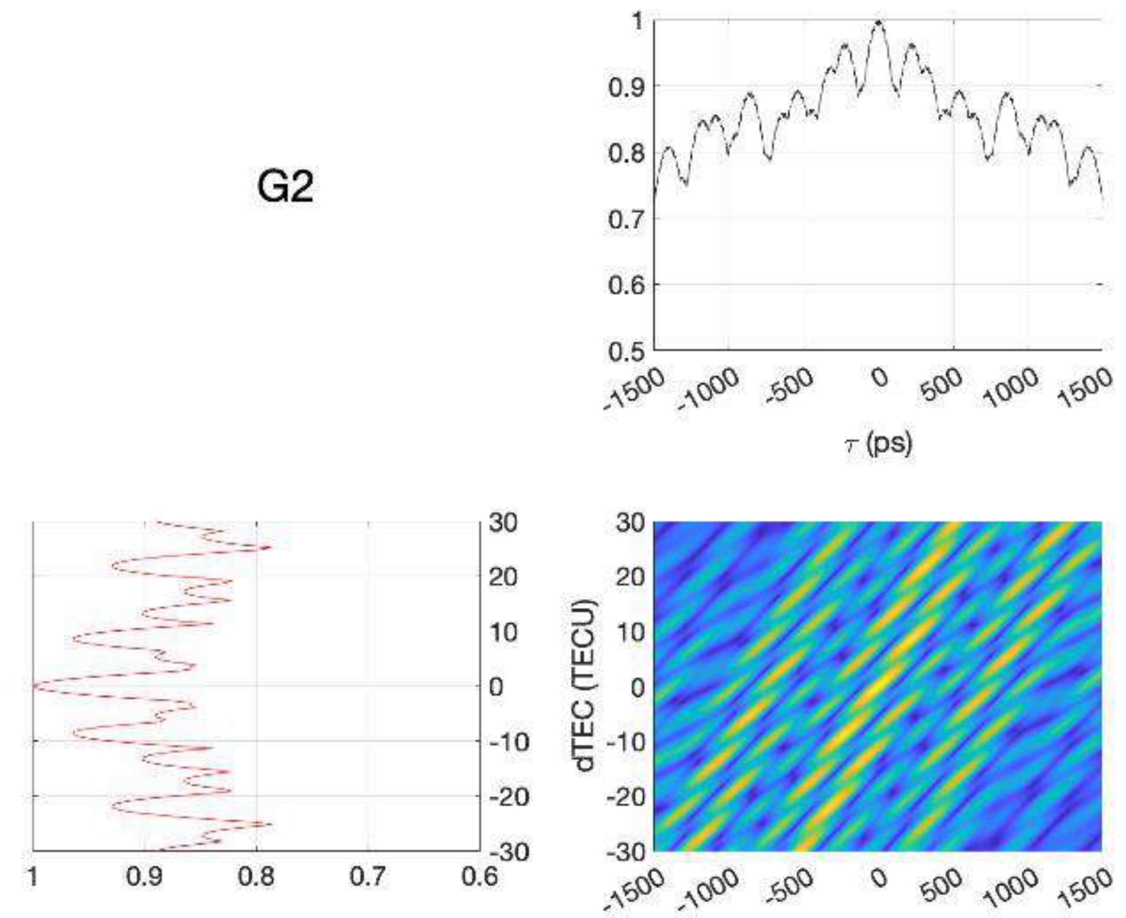
Comparsion G1 vs. VO setup



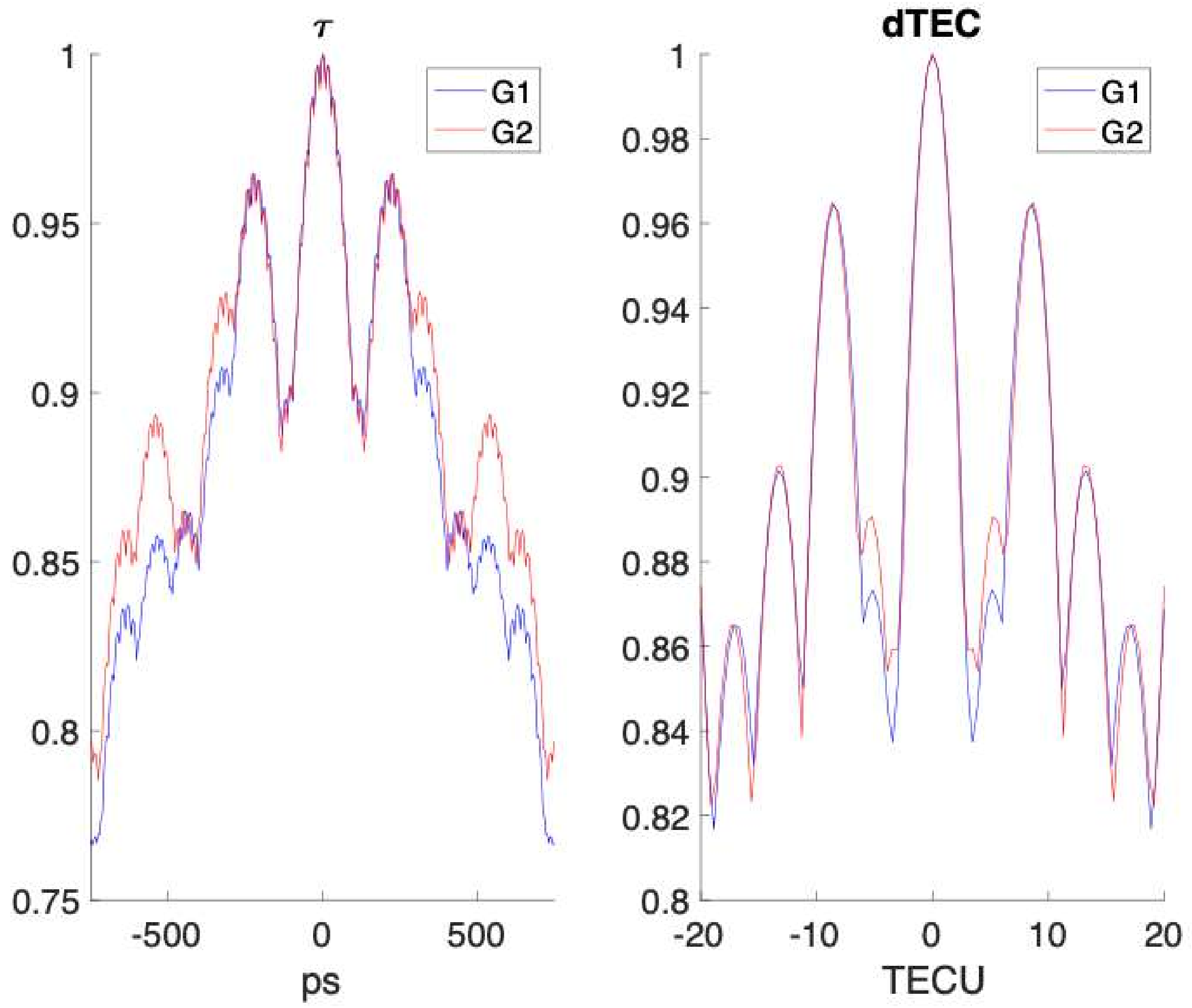
G1 setup has higher level of sidelobes than VO setup

Nothing we can do about due to the Genesis allocated frequencies

Delay resolution function G2



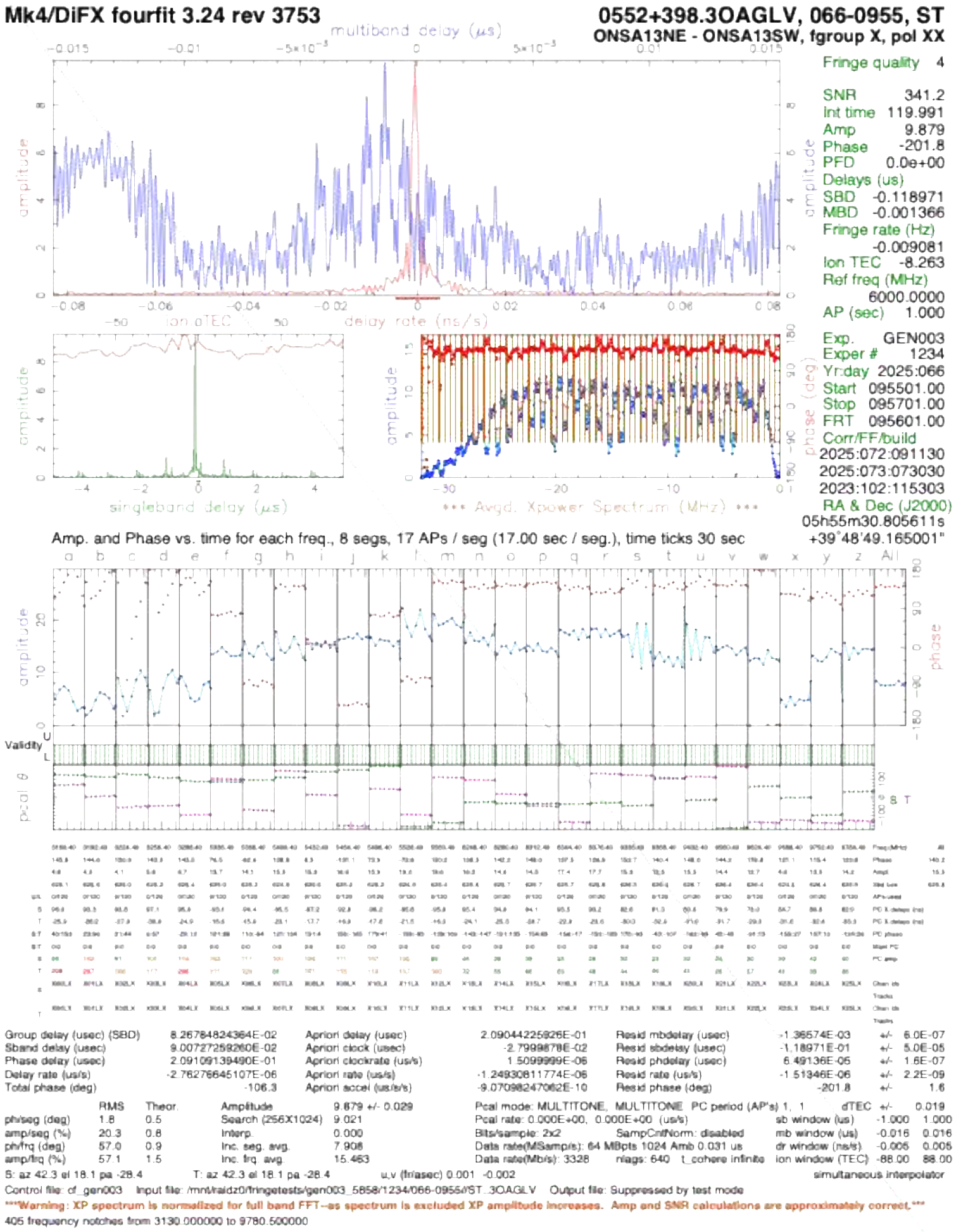
Comparison G2 vs. G1 setup



No big differences between G2 and G1 setups!

G2 test observations

Successful! ☺



Outlook

- VGOS R&D Genesis session has been proposed and granted
  - Complete IVS VGOS network
  - G2 frequency setup
  - 24 h observations and complete data analysis

- Tests with ”real satellite signals”
  - (but different frequency setups)
  - Example: AuScope VGOS observations of GNSS L-band (McCallum et al., 2025)

Single Station Delay Measurements (PRN-Option)

Alime OZYILDIRIM

On the behalf of WG-3 / WP-7

April 2025

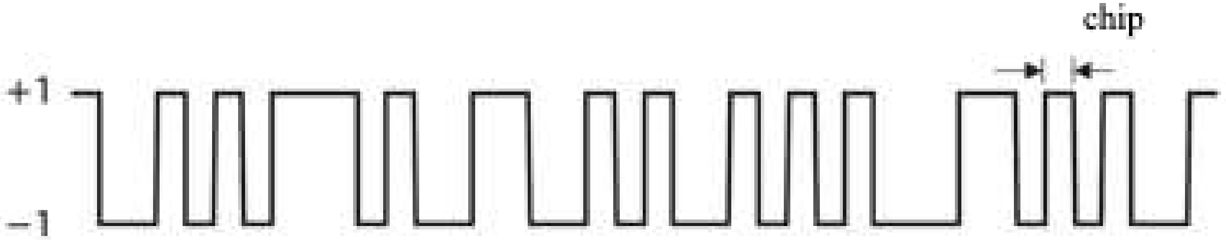
Royal Observatory of Belgium

VLBI Transmitter

- VLBI transmitter will broadcast
  - White noise signals mimicking quasars
  - Pseudo Random Noise (PRN) codes enabling single station delay measurements at VLBI ground stations.

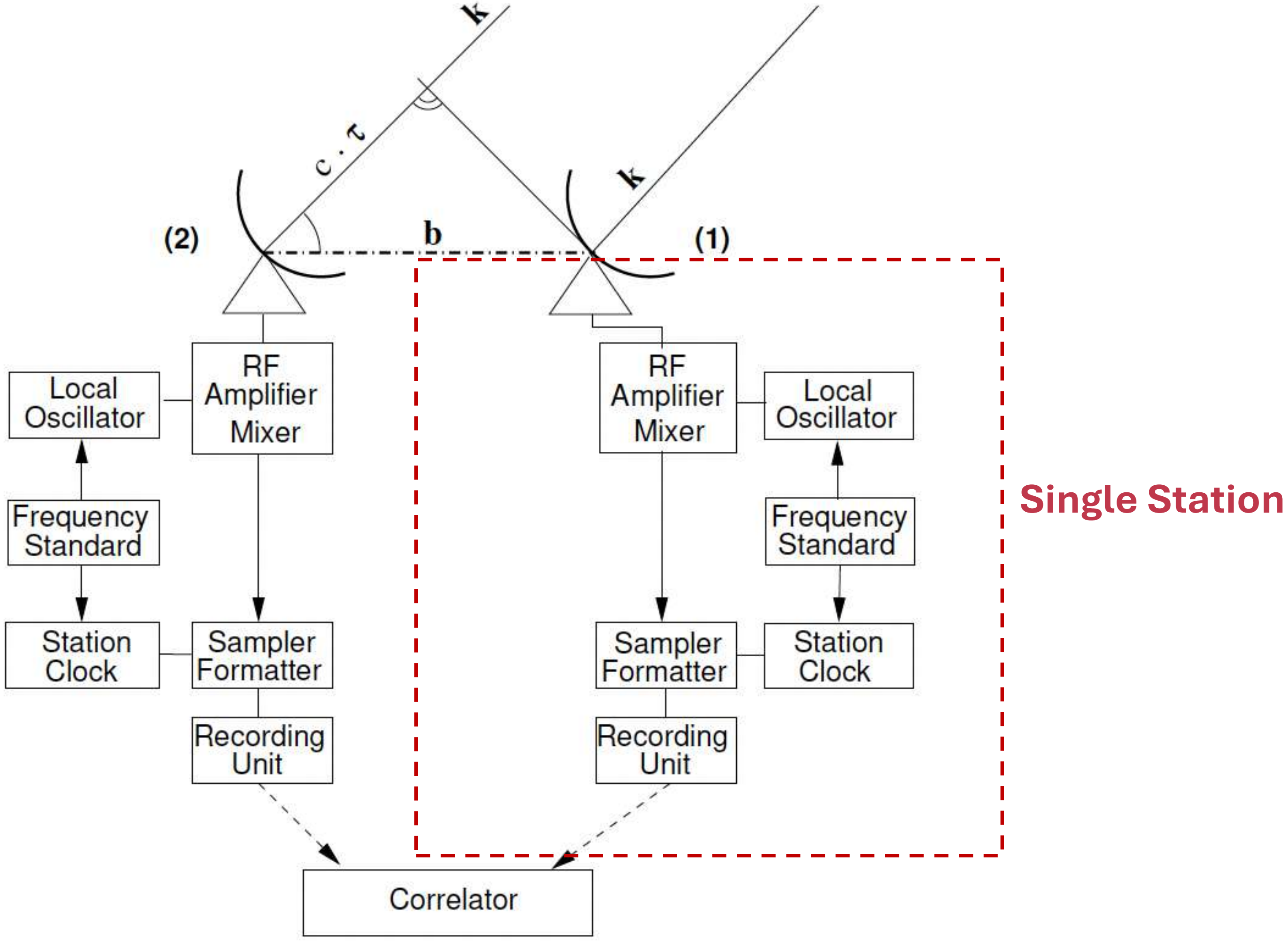
https://h2020nav.esa.int/project/h2020-038-01

- **PLD-VLB-130**: **Single Station Delay Measurements**
  - The signals transmitted shall enable single station delay measurements at the VLBI ground stations.



https://ggos.org/item/ivs/

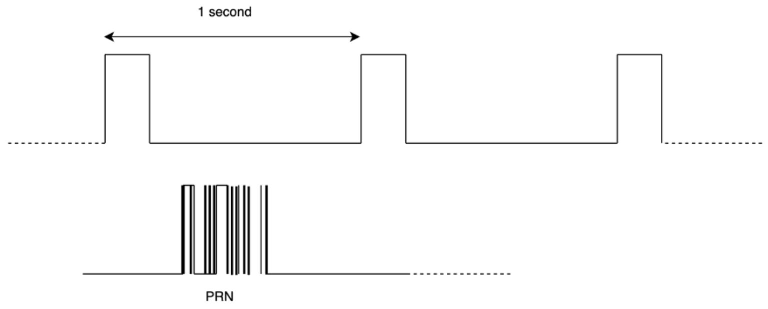
Principle of VLBI Observation



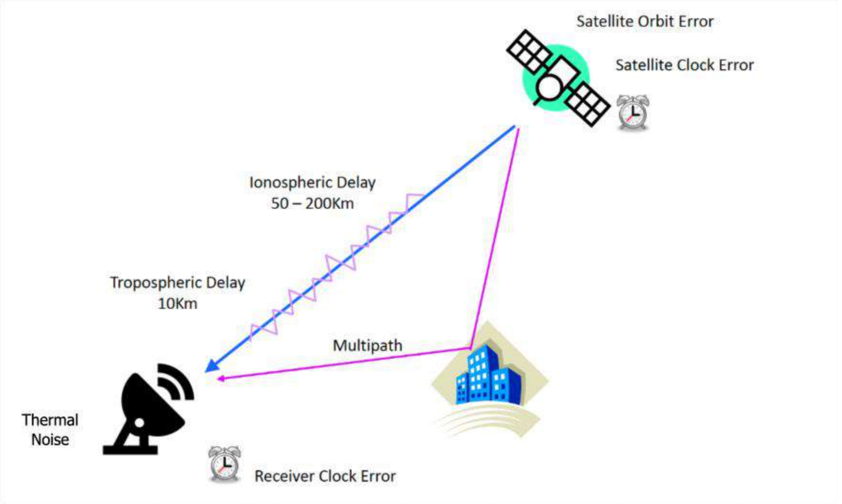
(Nothnagel A., *Elements of Geodetic and Astrometric Very Long Baseline Interferometry, April 2024*)

Single Station Delay Measurement

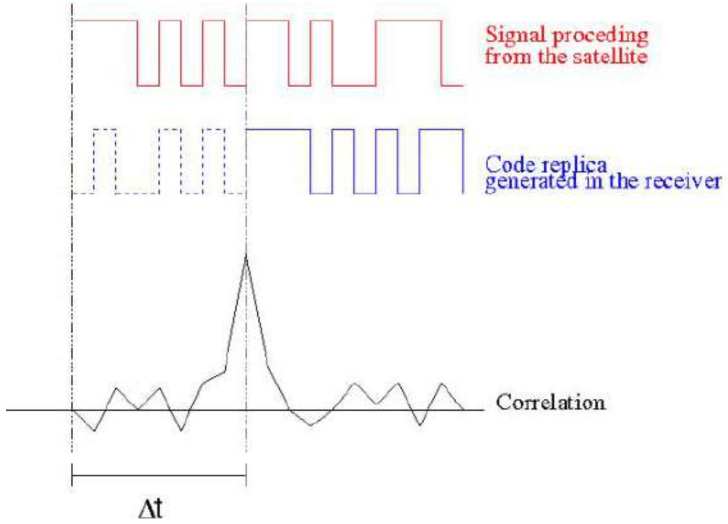
- **Ranging Process!**



1 PPS Signal and PRN Code



Errors in Pseuodorange Measurements
(Manandar D., GNSS Introduction, Jan. 2023)



Travelling time of the transmitted signal from the satellite
(ESA Navipedia, GNSS_Basic_Observables)

Ideal Case (True Range): $\rho_0 = c(t_r - t_s)$

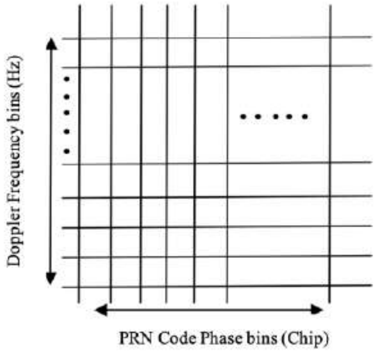
$$\rho = \rho_0 + c(\delta_r - \delta_s) + I_\rho + T_\rho + Ins_r - Ins_s + MP_\rho + \xi$$

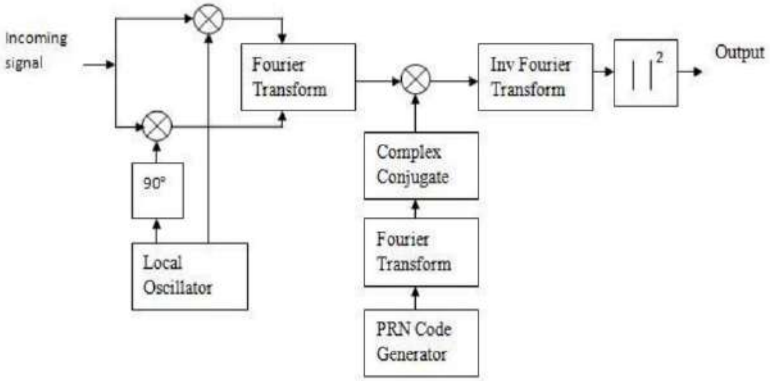
where

- δ_r and δ_s represent receiver clock error and satellite clock error
- I_ρ and T_ρ denote frequency dependent ionosphere and tropospheric errors (in m)
- Ins_r and Ins_s are the receiver and satellite instrumental delays
- MP_ρ and ξ refer to multipath error and receiver thermal noise

Steps for Ranging Process (Implementation)

1. Acquisition
   - Doppler frequency shift of carrier frequency
   - Code phase (delay) of PRN code (correlation)
2. Model and calculate tropospheric delay
3. Calculate ionosphere delay
4. Consider other delay errors (clock errors, instrumental delays, etc.)





→ **Identify requirements for the appropriate platform (HW and SW) for implementation!**

❖ **Similar to GNSS Receiver Ranging Process for a single Satellite!**

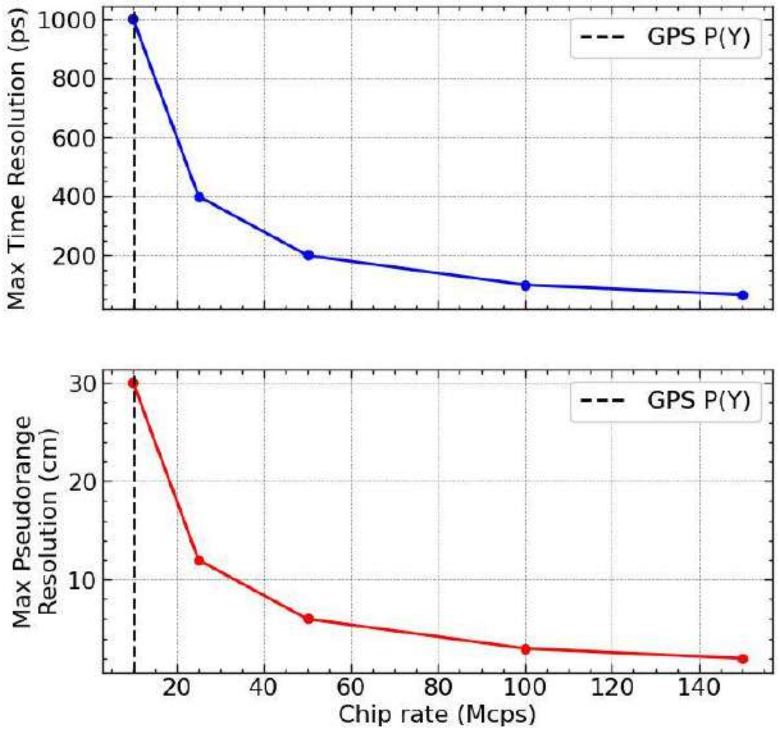
Pseudorange Resolution

Frequency Band	Frequency range (MHz)	Carrier Frequency (MHz)	Occupied Bandwidth (MHz)
S	3100-3300	3200	200
C	5250-5570	5410	320
X (low)	8200-8400	8300	200
X (high)	9300-9800	9550	500

Chip rate (Mcps)	Time resolution (psec)	Pseudorange Resolution (cm)
150	66.67	2.00
100	100.00	3.00
50	200.00	6.00
25	400.00	12.00
10.23	977.52	29.33
1.023	9775.17	293.26

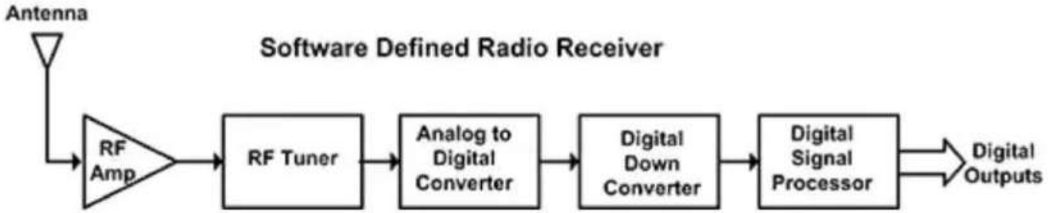
- If C & X_{high} → 300 MHz Bandwidth → 150 Mcps
  - **66.7 ps time resolution** (%1 rule of thumb used in GPS systems)
    20 mm measurement resolution
- Some factors can affect the correlation such as
  - analog-to-digital conversion
  - receiver antenna characteristics, etc.

leading to distortion → a reduction in time resolution!



SDR Implementation

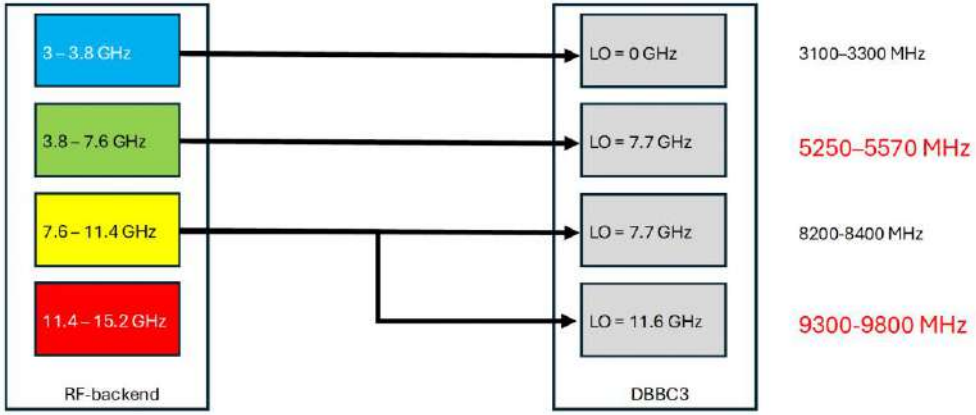
- Software Defined Radio (SDR) receiver approach may be employed to avoid additional hardware modifications in ground stations
- Ranging will be carried out in SDR based receiver
- Several questions arise
  - Can the recorded data be used as it is?
  - Is it possible to record data with wider BW and higher bits at VGOS stations?
  - What are instrumental delays at VGOS stations?
  - How do VGOS stations differ from each other?
    - Frontend & Backend
    - AGC
    - Instrumental delays
    - Sampling rates and number of bits
    - …

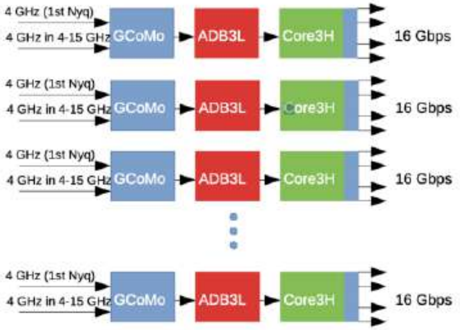


https://www.digikey.com/en/articles/learn-the-fundamentals-of-software-defined-radio

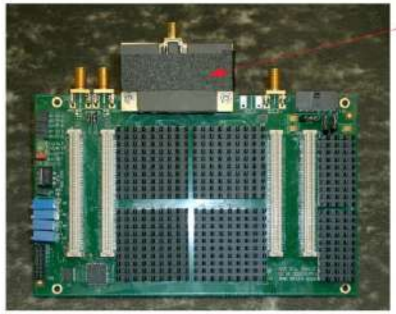
Aim: Perform Pseudorange calculation on a SDR based Receiver!

VGOS DBBC3 (Current, Later?)

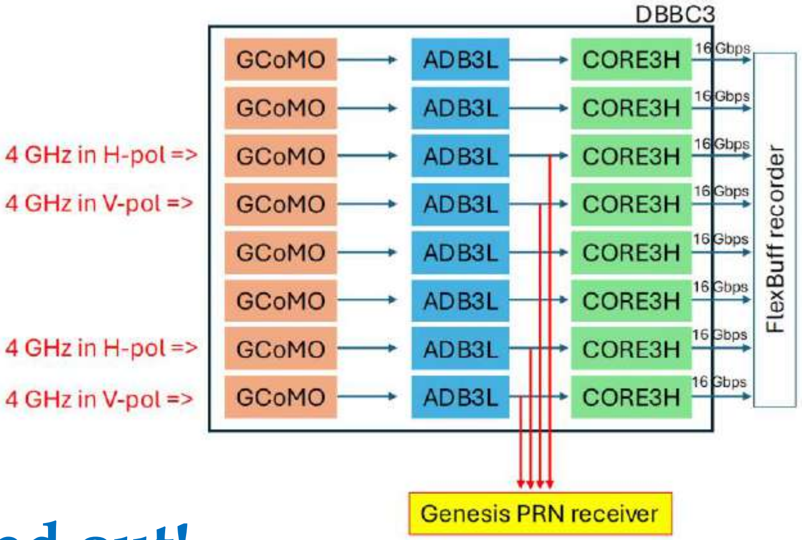




- GCoMo: Analog signal processing
  automatic gain control
  power level monitoring
  optional downconversion (4-15 GHz → 0-4 GHz)
- ADB3L: Analog Digital Converter
  4-way interleaved sampling @ 2048 MHz
  → 4096 MHz bandwidth
  output: 8Gsps @ 10 Bit
- Core3H: Digital Postprocessing
  digital filtering, depending on observation mode
  time and 1PPS synchronization
  monitoring of sampler statistics
  creation of VDIF packets and data transmission to recorders (up to 16 Gbps/IF)



- Sampling method: 4-way interleaved sampling using four ADC devices each running at 2048 MHz
- Phase Adapter required to distribute the analog signal to all four samplers
- Requires careful calibration of each samplers offset, gain and phase delay to prevent artifacts in the reinterleaved datastream.
- Possible Input Bandwidths: 1x4 GHz, 2x2 GHz, 4x1 GHz
- Output Bandwidth: 8 Gsps @ 10 Bit → 80 GBit/s

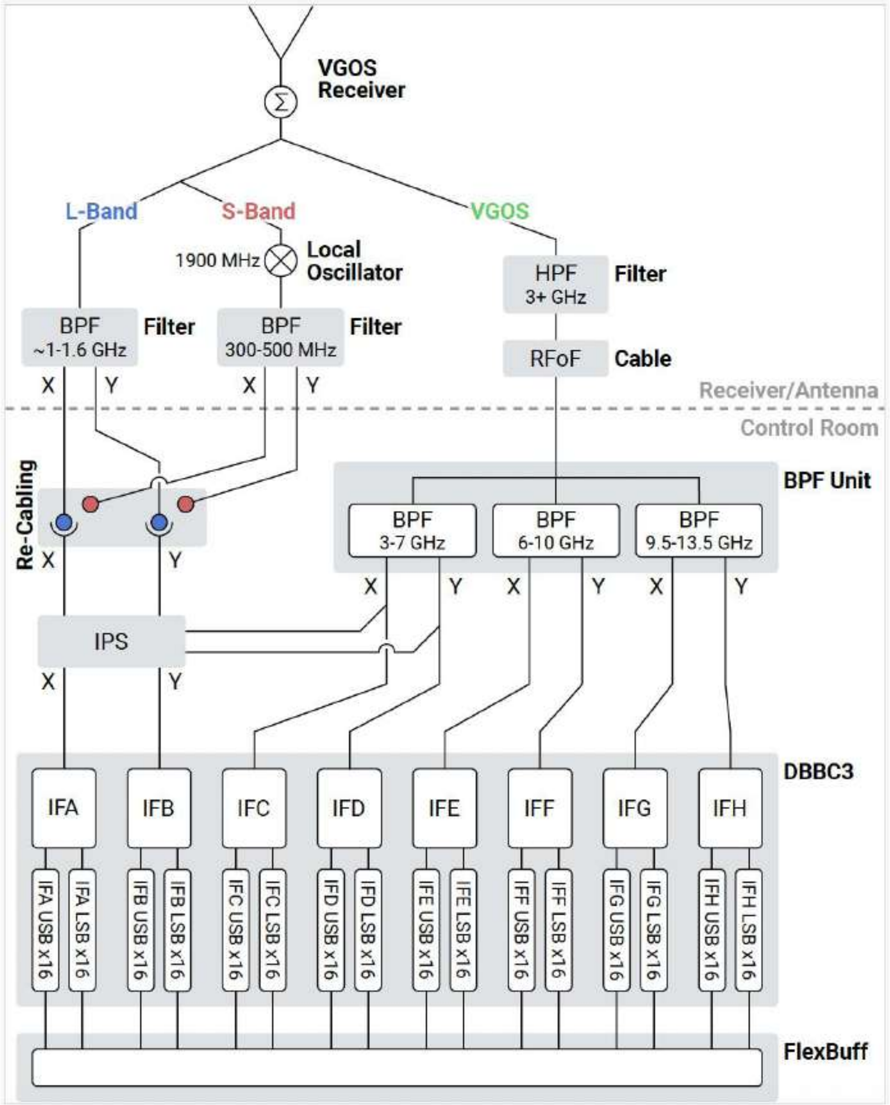


😊 **VGOS Survey will be carried out!**

Exercise (?)

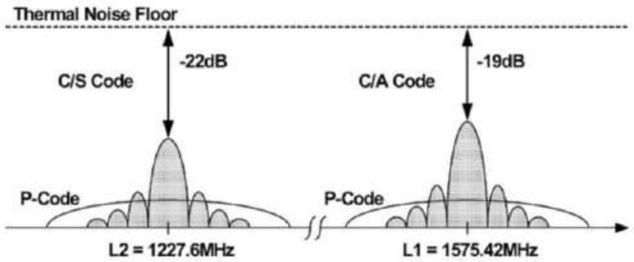
1. Start with GNSS data recorded at L-Band VLBI stations
   - Australia VLBI Ground Station
   - Sweden VLBI Station (Onsala)
2. Learn VDIF format to parse data
3. Understand GNSS (GPS or Galileo) transmitted data (at 2 carrier frequencies)
4. Understand GNSS receiver processes
5. Generate a replica of PRN codes for acquisition process (correlation)
   - Analyze Doppler frequency shift of carrier frequency
   - Analyze code phase (delay) of PRN Code
6. Research particularly tropospheric and ionosphere delays for GNSS signals
7. Consider other delay errors (clock errors, instrumental delays, etc.)

Yarragadee Station (Yg)

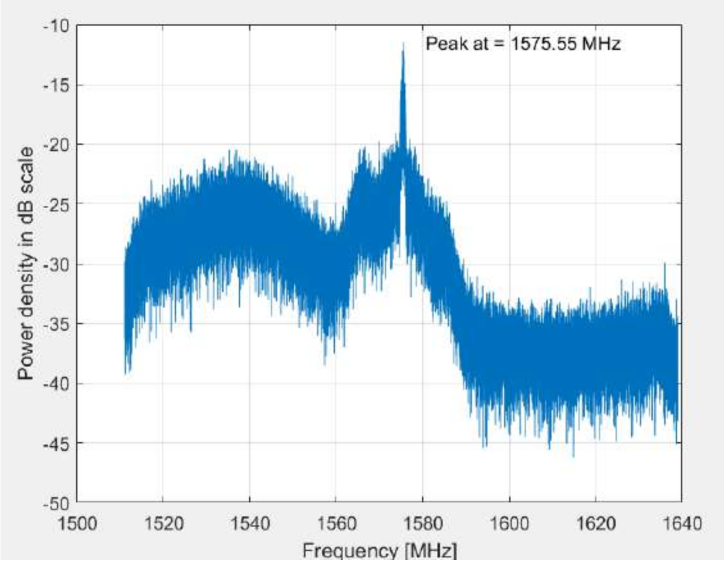


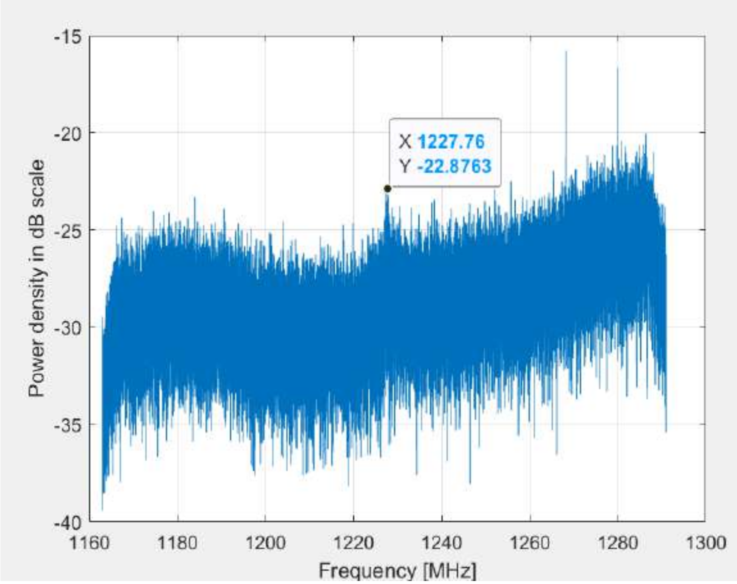
UNIVERSITY of TASMANIA

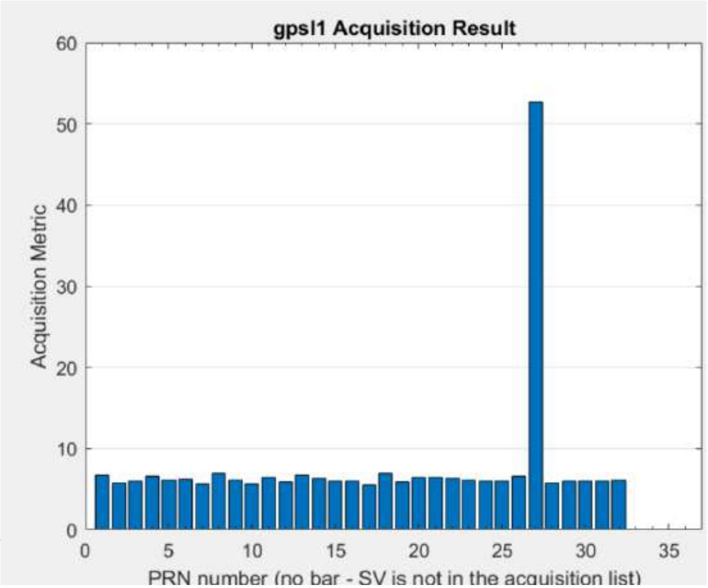
✓ L Band recorded data (20 GB) has been arrived!
  - **GPS Block IIF-4** (PRN 27)
  - 12-m antenna in Yarragadee station
  - 20 second scan
  - 2 linear polarization
  - 2 channels, 128 MHz BW and 8 bits
  - 20 GB of data



Early Results







Topics for Consideration

- How many bands will be used (2 or all)?
- What chip-rate is feasible?
- Which type of PRN-code is suitable?
- What type of modulation (e.g., BPSK, BOC) is feasible?
- Operational scenario
  - Transmission of PRN signals
    - Mix PRN signal with white noise signal
    - Separate transmission