Metsähovi geodetic VLBI and SLR

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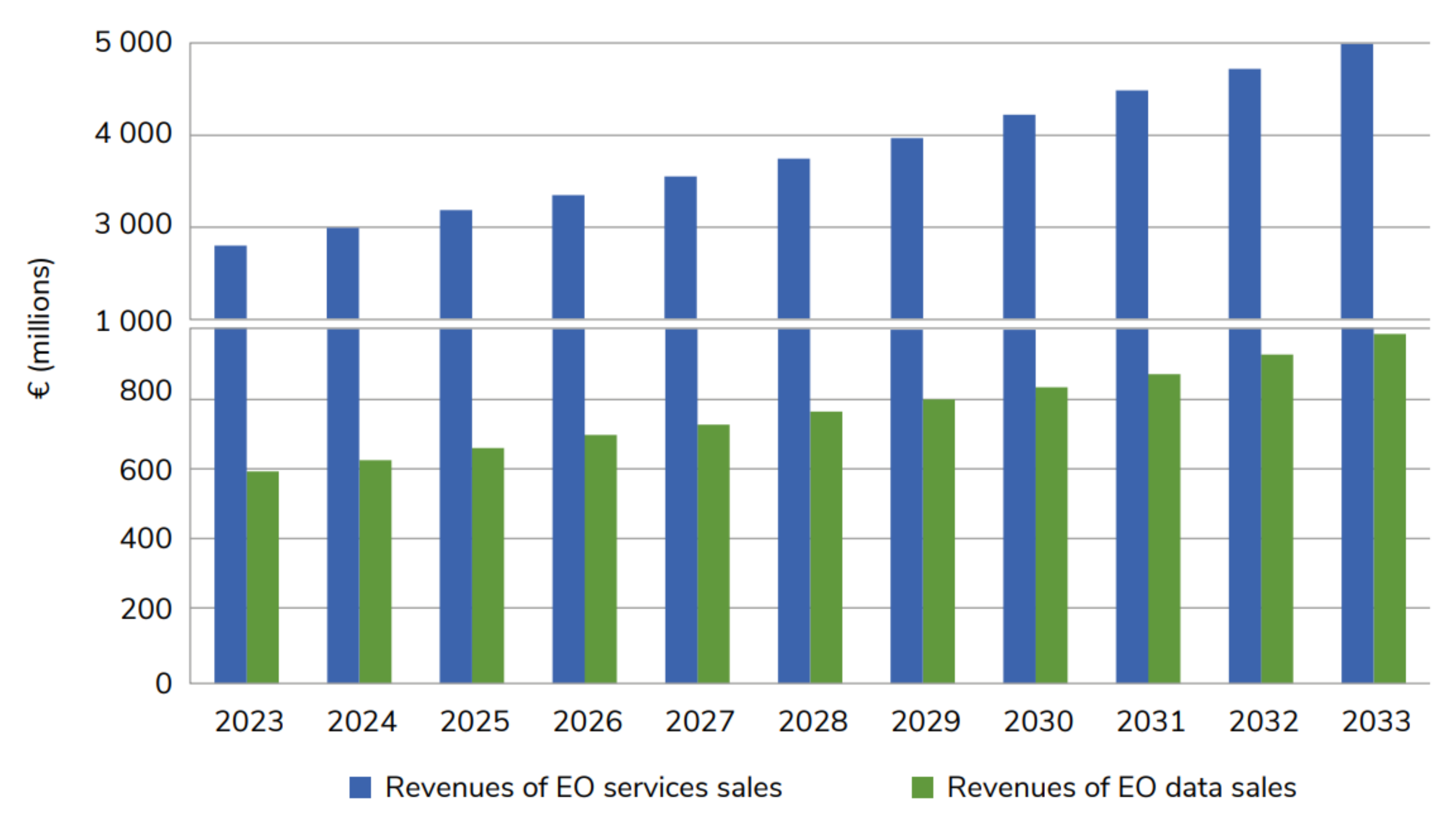
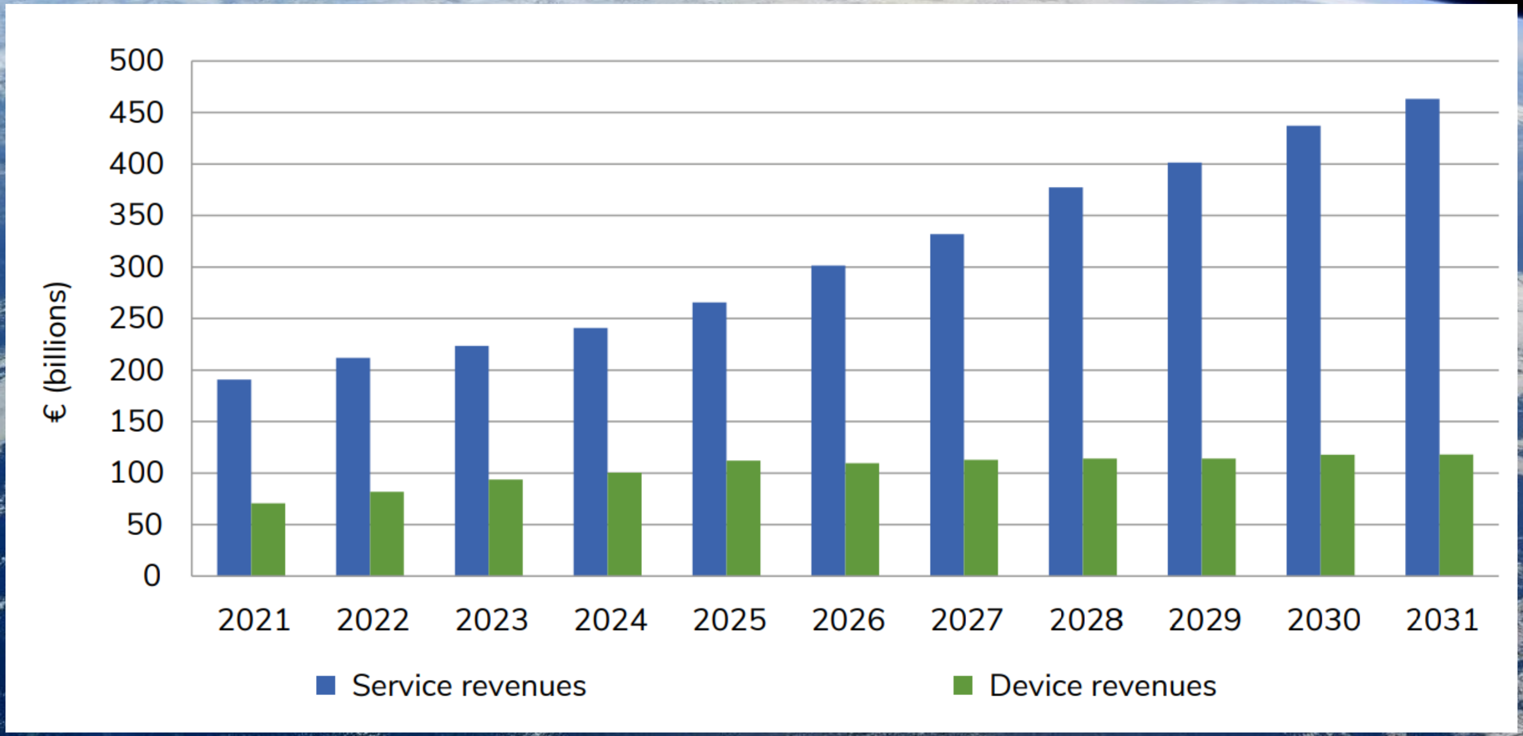
Content

Global Revenue of EO data and services sales



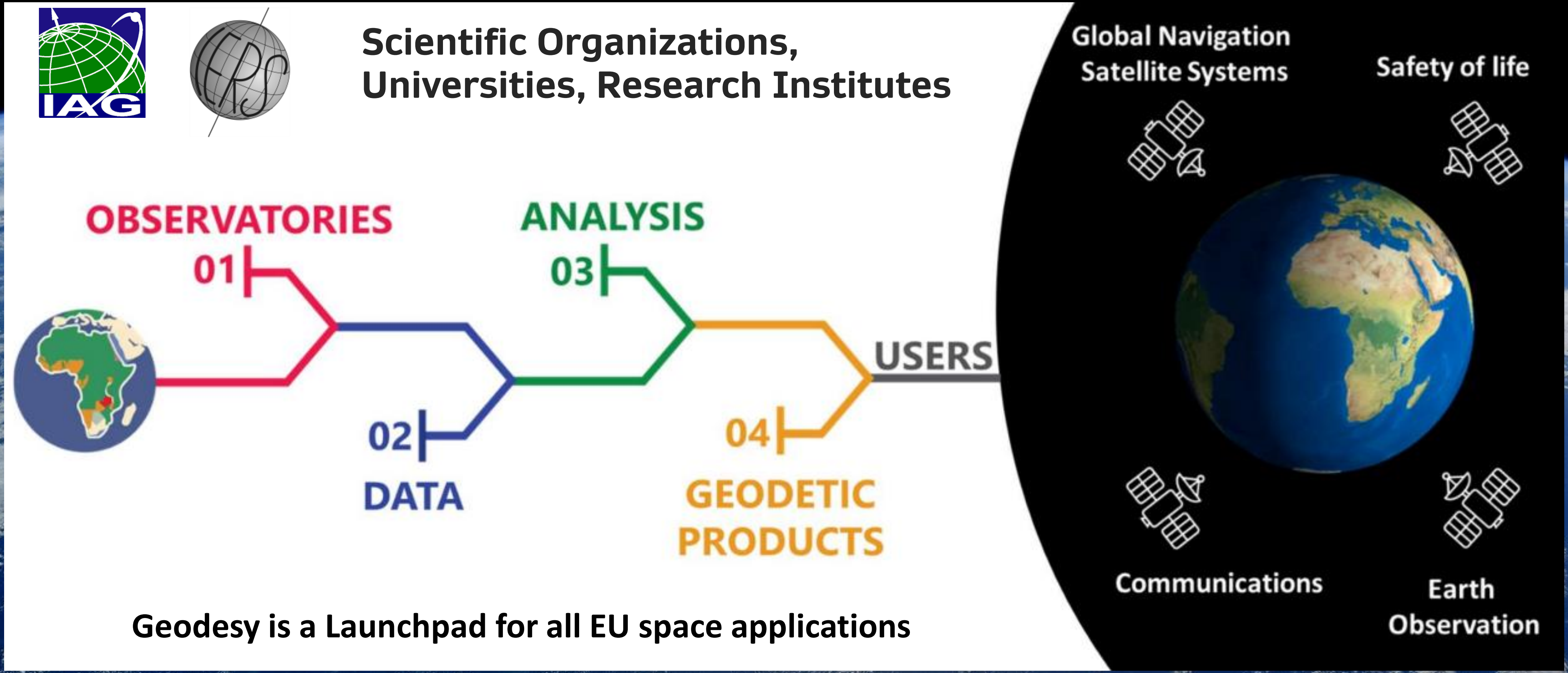
Source: EUSPA EO and GNSS Market Report, 2024

Revenue from GNSS devices sales and services



Source: EUSPA EO and GNSS Market Report, 2024

Global Geodesy Supply Change



Source: Hidden Risk, Policy Brief 001, UN, 2024

Scientific organizations provide crucial information for Space progams

IAG: International Association of Geodesy

International Earth Rotation and Reference System Service IERS

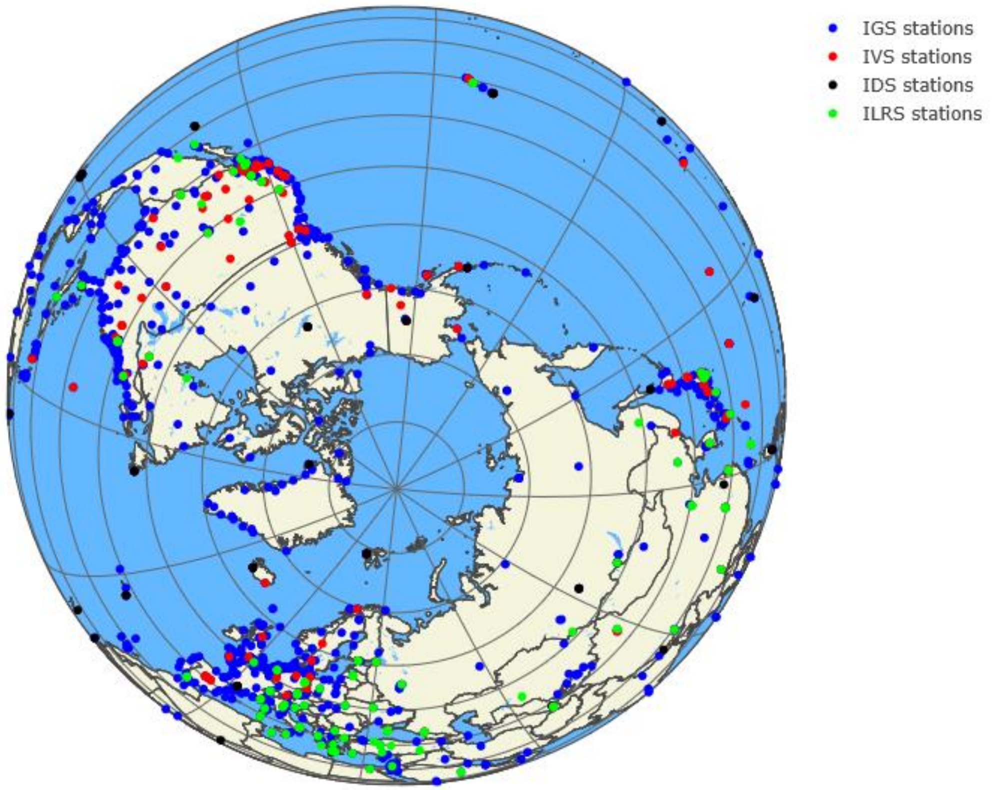
IERS processing and delivering

International GNSS Service IGS GNSS data, analysis and products	→	**ITRS Combination Centres** ITRS realisations
International VLBI Service IVS VLBI data, analysis and products	→	**ITRS Product Centre** ITRF
International Laser Ranging Service ILRS SLR data, analysis and products	→	**EOP Combination Centre** EOP series and forecasts
International Doris Service, IDS Doris data, analysis and products	→	**ICRS Product Center** ICRS

International Earth Rotation and Reference Systems Service

International Terrestrial Reference Frame

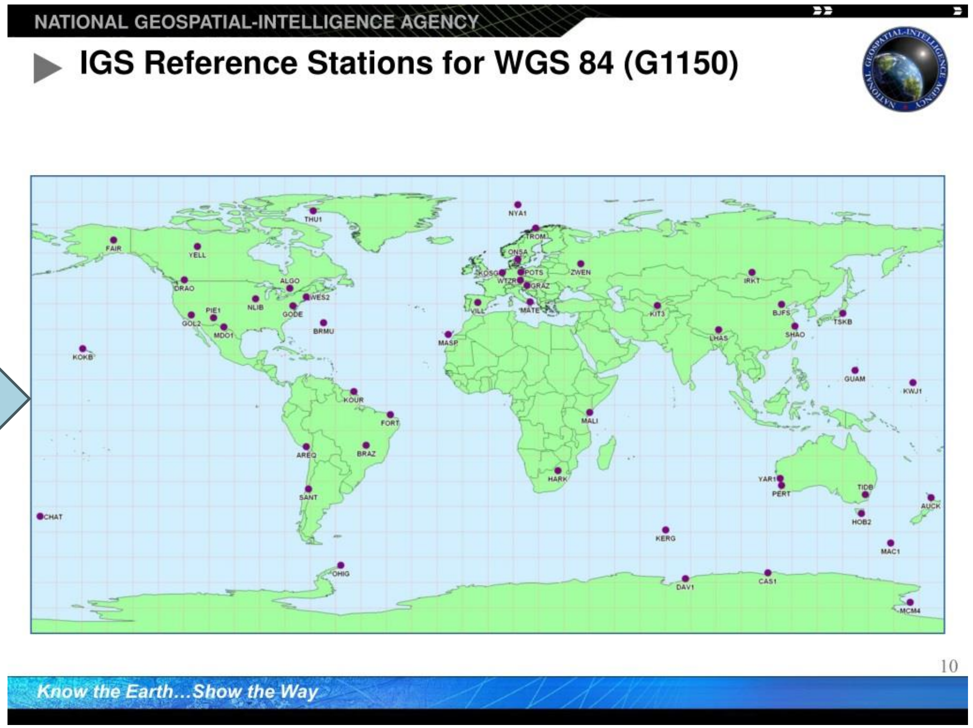
- A set of points with cartesian coordinates X,Y,Z + velocities define the Frame
- Long term stability
- IUGG Resolution, 2019, Montreal:
  - ITRF is standard frame for
    - Positioning
    - Navigation
    - Geosciences
    - Connecting national and regional frames
- All GNSS Frames are adjusted to ITRF



https://earth-info.nga.mil/php/download.php?file=WGS%2084(G2296).pdf

Example: WGS84 updates since 1987

Name/realization	Implementation date		Ref. Epoch	Absolute Accuracy
	GPS Broadcast Orbits	NGA Precise Ephemeris		
WGS 84	1987	1 Jan 1987		1-2 meters
WGS 84 (G730)	29 Jun 1994	2 Jan 1994	1994.0	10 cm/component RMS
WGS 84 (G873)	29 Jan 1997	29 Sep 1996	1997.0	5 cm/component RMS
WGS 84 (G1150)	20 Jan 2002	20 Jan 2002	2001.0	1 cm/component RMS
WGS 84 (G1674)	8 Feb 2012	7 May 2012	2005.0	<1 cm/component RMS
WGS 84 (G1762)	16 Oct 2013	16 Oct 2013	2005.0	<1 cm/component RMS
WGS 84 (G2139)	28 Mar 2021	3 Jan 2021	2016.0	<1 cm/component RMS
WGS 84 (G2296)	7 Jan 2024	7 Jan 2024	2024.0	<1 cm/component RMS



The GPS-week: weeks passed since midnight 5-6 January 1980.

WGS84 is connected to ITRF when the difference is larger than X

EO parameters connect the two systems

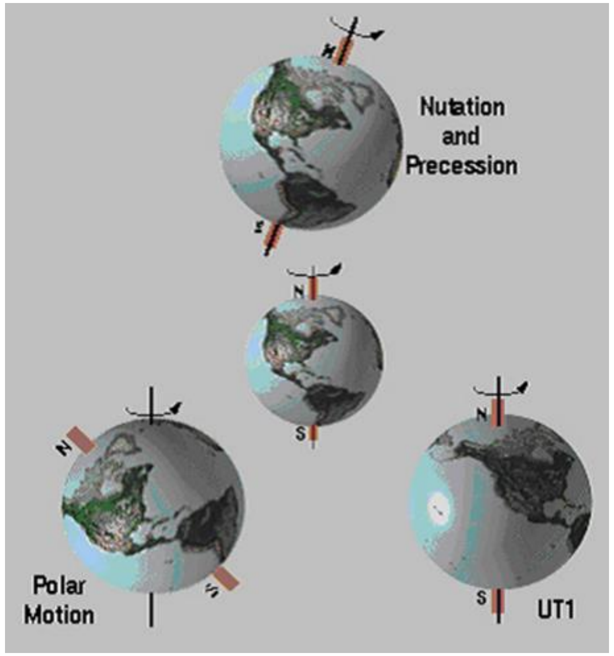
Terrestrial Reference System TRS

ITRS – International TRS

↓realisations

ITRF – International Terrestrial Reference Frame

- ITRF1989, …
- ITRF2000, …
- ITRF2008, ITRF2014
- ITRF2020



Earth Orientation Parameters EOP

- Precession
- Nutation
- Polar motion
- UT1

Celestial Reference System CRS

ICRS – International CRS

↓realisations

ICRF – International Celestial Reference Frame

- ICRF1
- ICRF2
- ICRF3

Space geodetic techniques to observe EOP

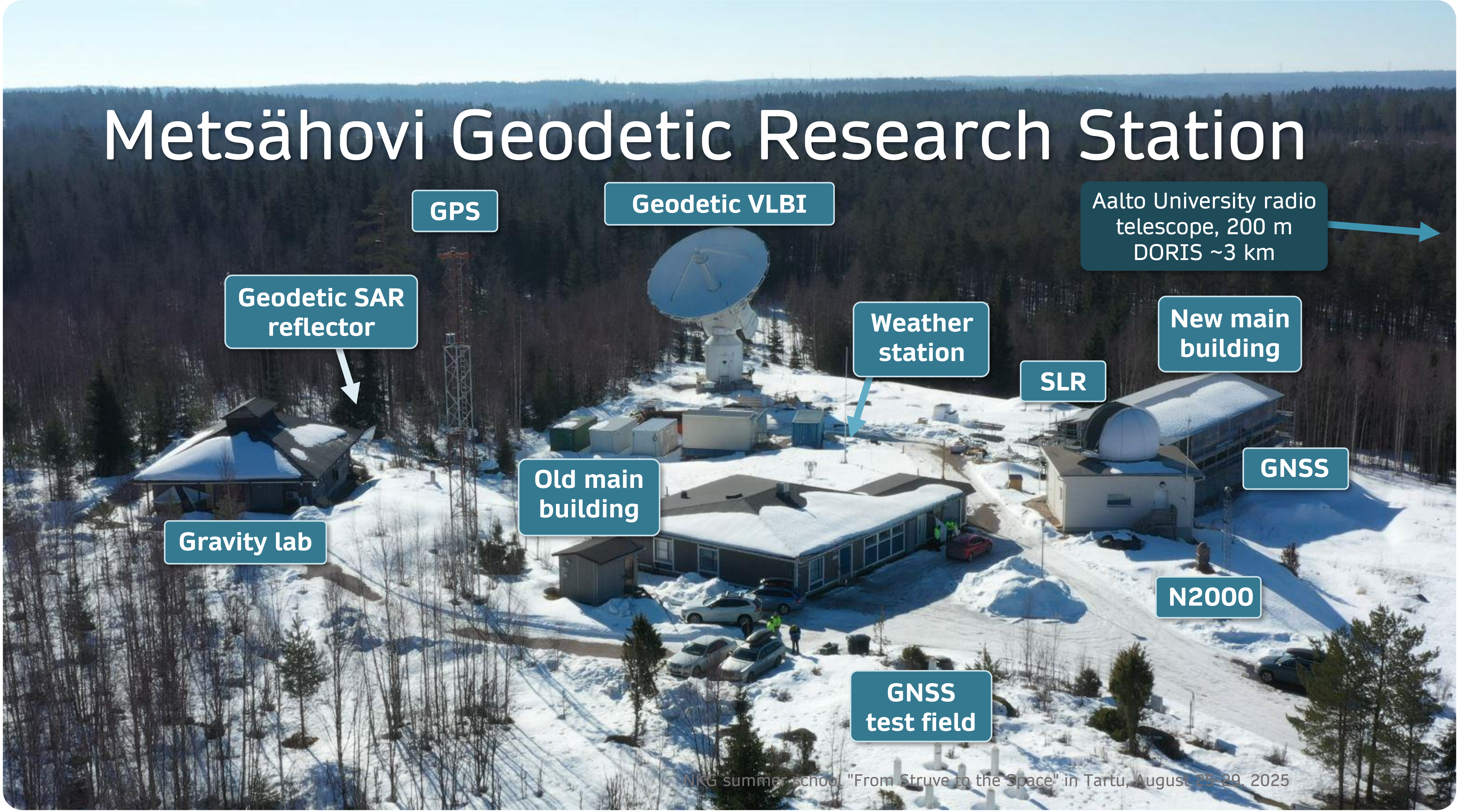
- Global Navigation Satellite Systems (GNSS)
- Satellite Laser Ranging (SLR)
- Lunar Laser Ranging (LLR)
- Very Long Baseline Radio Interferometry (VLBI)
- Doppler Orbit determination and Radiopositioning Integrated on Satellite (DORIS)

Universal time (UT1), polar motion and the celestial motion of the pole (precession/ nutation) are determined by VLBI.

GNSS, SLR and DORIS, determine polar motion and the rapid variations of universal time

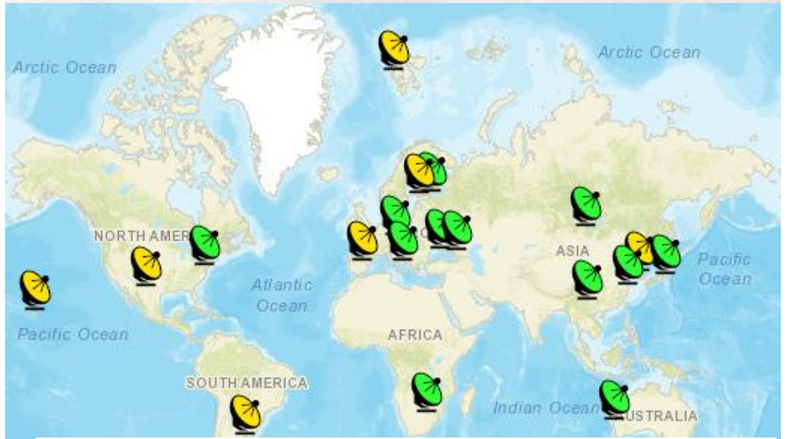
	VLBI	GNSS	DORIS	SLR	AG/SG
Celestial Reference frame	X				
Nutation	X	(X)		(X)	
Polar variation	X	X	X	X	X
Earth rotation (UT1)	X				
Length of Day (LOD)	(X)	X	X	X	
Global reference frames	X	X	X	X	X
Earth Center of Mass		X	X	X	X
Earth Gravity Field		X	X	X	X
Geoid					X
Satellite orbits (GPS, Galileo,...)		X	X	X	
Orbits of environmental satellites		X	X	X	
Ionosphere and troposphere	X	X	X		
National reference frames		X			

Metsähovi Geodetic Research Station



Metsähovi Geodetic Research Station

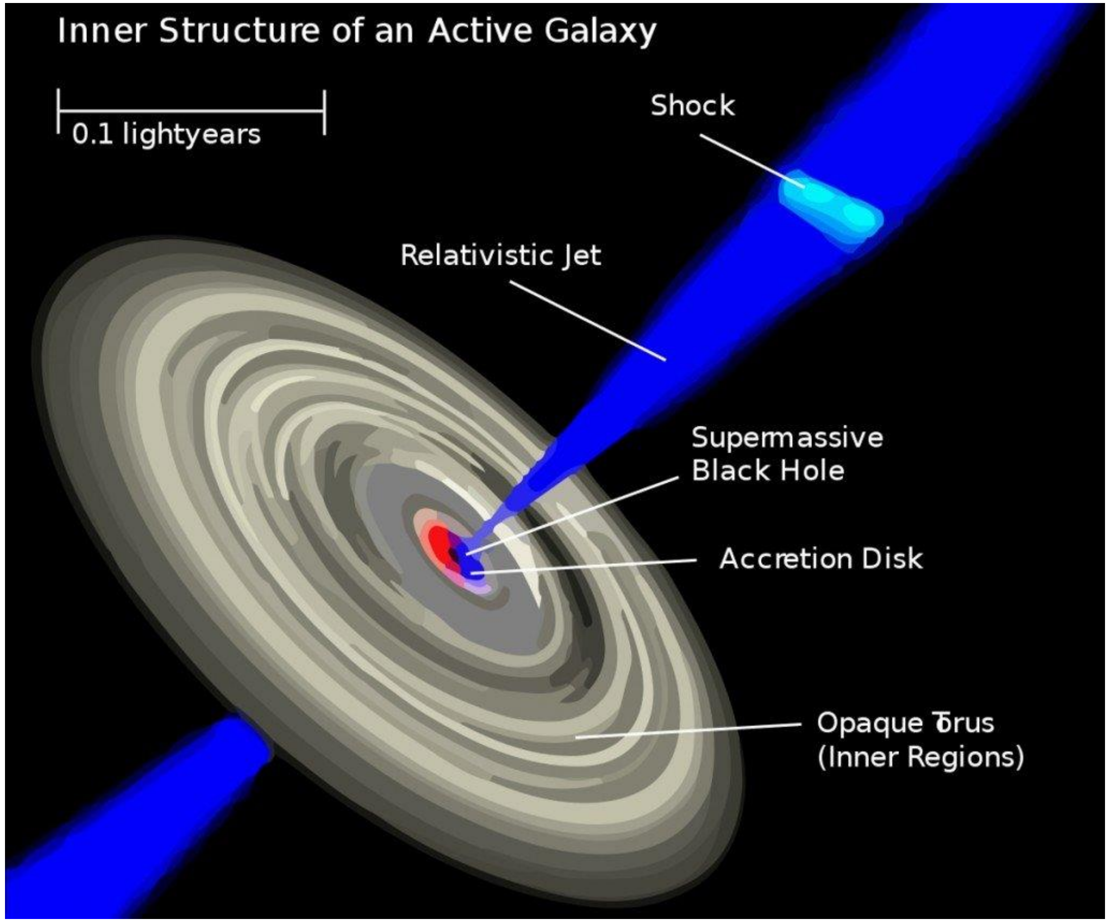
- 60.21N, 24.39E
- The easternmost and northernmost geodetic core site within the EU
- Located in rural area near Helsinki, 45 min drive from city center
- Have all relevant new geodetic instruments
- All instrumentation founded on bedrock
- Metsähovi is the Finnish contribution to the UN 2015 GA resolution on Global Geodetic Reference Frame for Sustainable Development



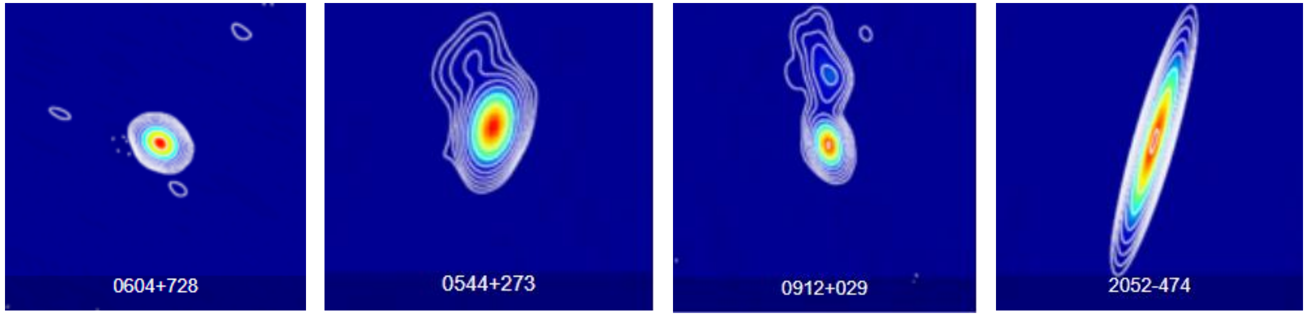
Map: GGOS Core Stations / https://ggos.org/

Very Long Baseline Interferometry (VLBI)

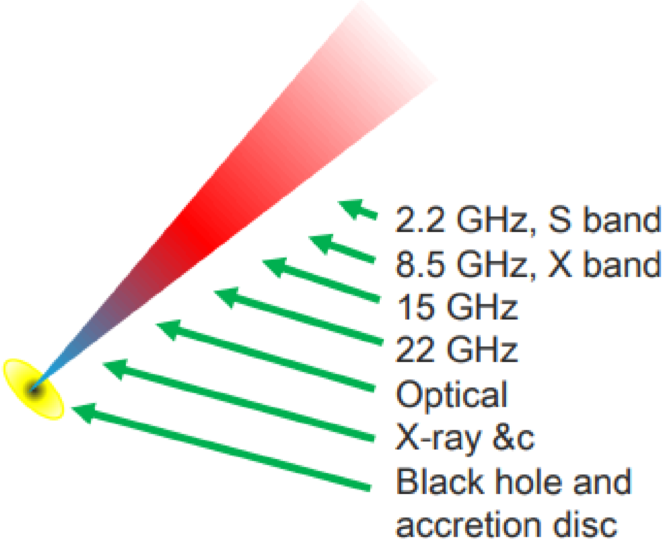
Quasars



Wikimedia commons



[https://bvid.astrophy.u-bordeaux.fr/]



Quasars are assumed in geodetic VLBI as point-like sources. In reality, they have internal structure. The radio frequencies observed in VLBI are produced in different places of the relativistic jet. There is a frequency dependency on the shape and exact position of the quasar.

VLBI in Astronomy

Originally developed in the 1960's for astronomical purposes to increase the resolution R of observations of radio sources: $R \propto \frac{\lambda}{D}$

λ = wavelength of signal, D = diameter of radio telescope

When D is increased, R gets smaller → smaller details of objects can be resolved

The maximum size of the telescope gives the limit. But by combining telescopes, the resolution grows to be the distance between the radio telescopes. The telescopes can even be on opposite sites of the Earth!

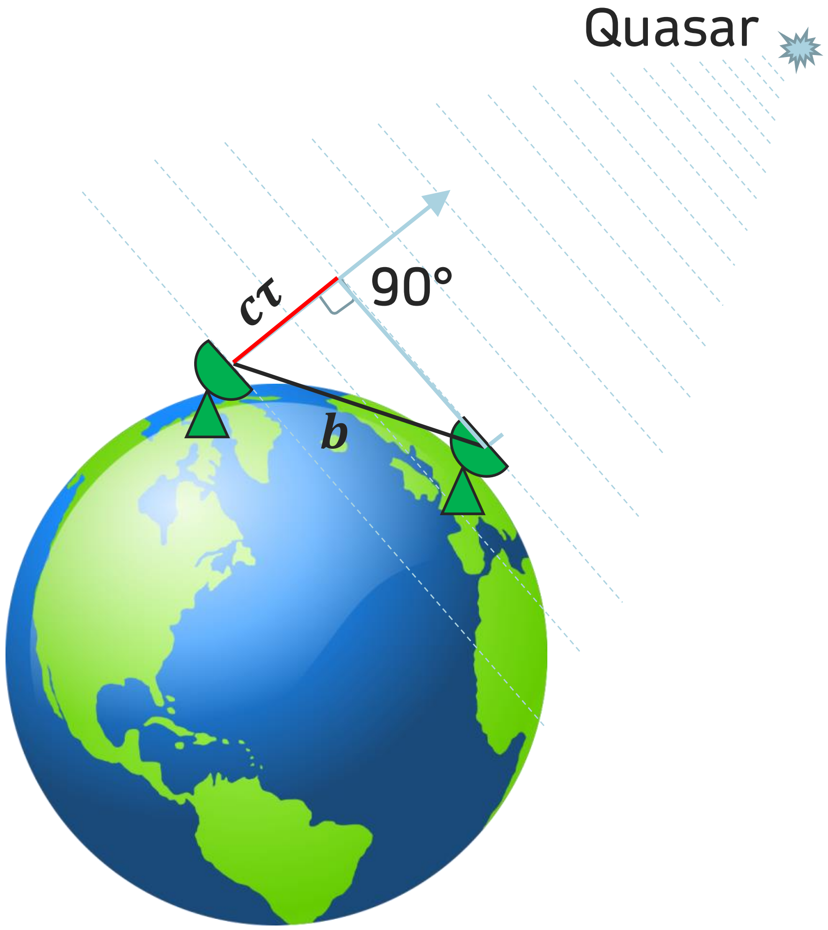
Geodetic VLBI

In geodesy the resolution increase is used to:

- Improve accuracy of vector $\vec{b}$ between telescopes
- Improve coordinates of celestial objects (quasars in case of geoVLBI)
- Improve determination of Earth Orientation parameters

Measurement of the ***time difference*** between the arrival of a ***radio wave front*** emitted by a radio source (***quasar***) at two ***antenna's*** on Earth.

Traditionally, geodetic VLBI observations are made on two different wavelength bands, S and X.
S = 2.19∼2.3 GHz,
X = 8.2∼9.0 GHz



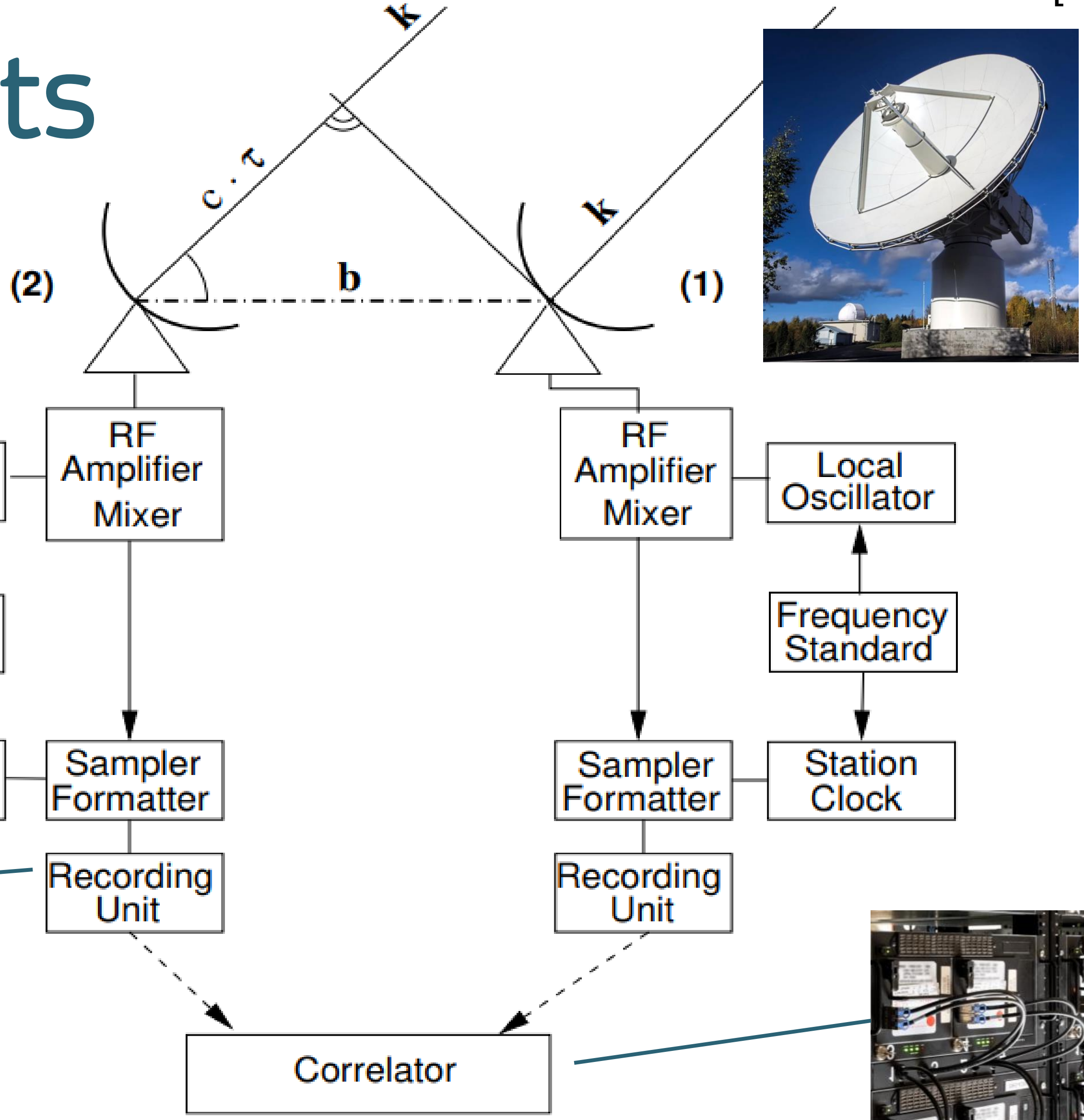
[Nothnagel, 2021]

VLBI components

Cryogenic receiver, cooled down to ~14K

H-maser

Mark V recording Unit



Observations

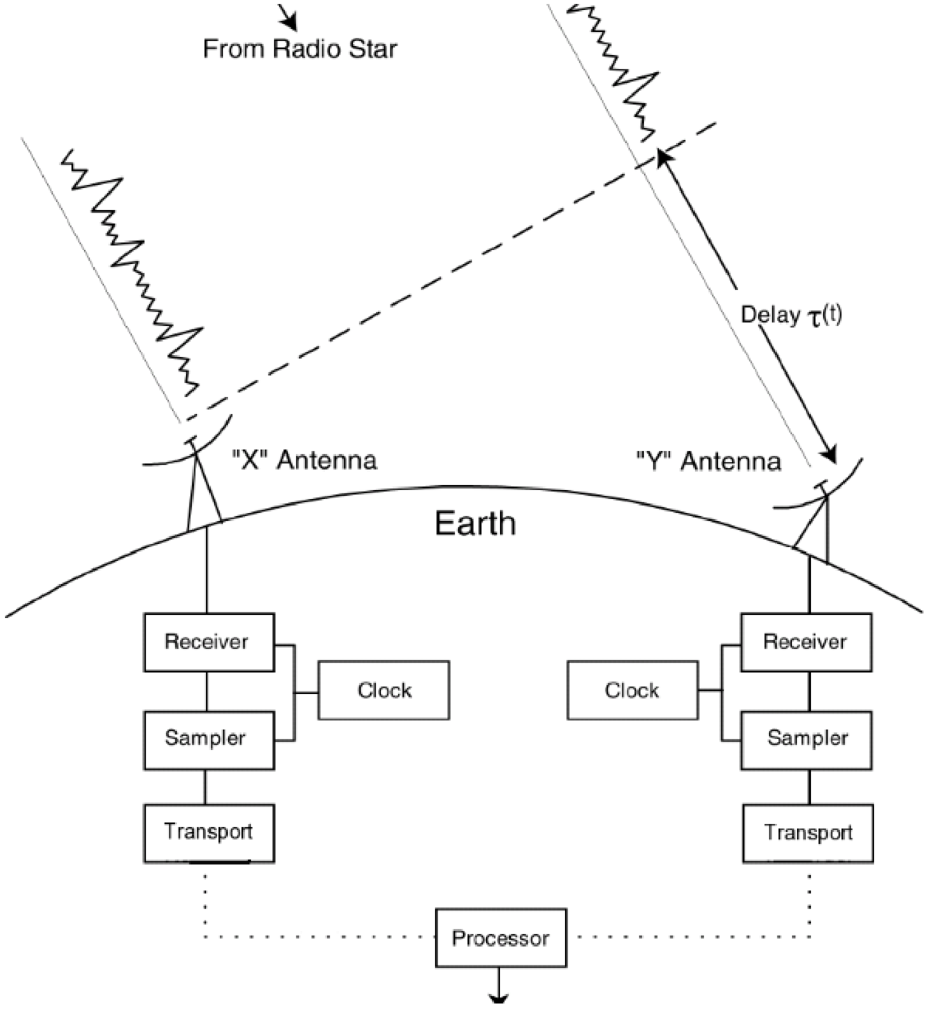
The wavefront coming from a quasar is reaching the telescopes at different times.

Timing is made by precise on-site clocks, the most common is the hydrogen maser.

Observations (“random noise”) are recorded on hard disks.

Data from telescopes are transferred to the correlators either by sending the discs or (nowadays already more common) via internet.

Typical amount of data > 1TB per 24 h session



VLBI Correlation

The phase difference ϕ between the two signals is related to the time delay, $\tau(t) = T_2 - T_1$, between the signal arrival time to the two telescopes:

$$\phi(t) = 2\pi\nu\tau(t)$$

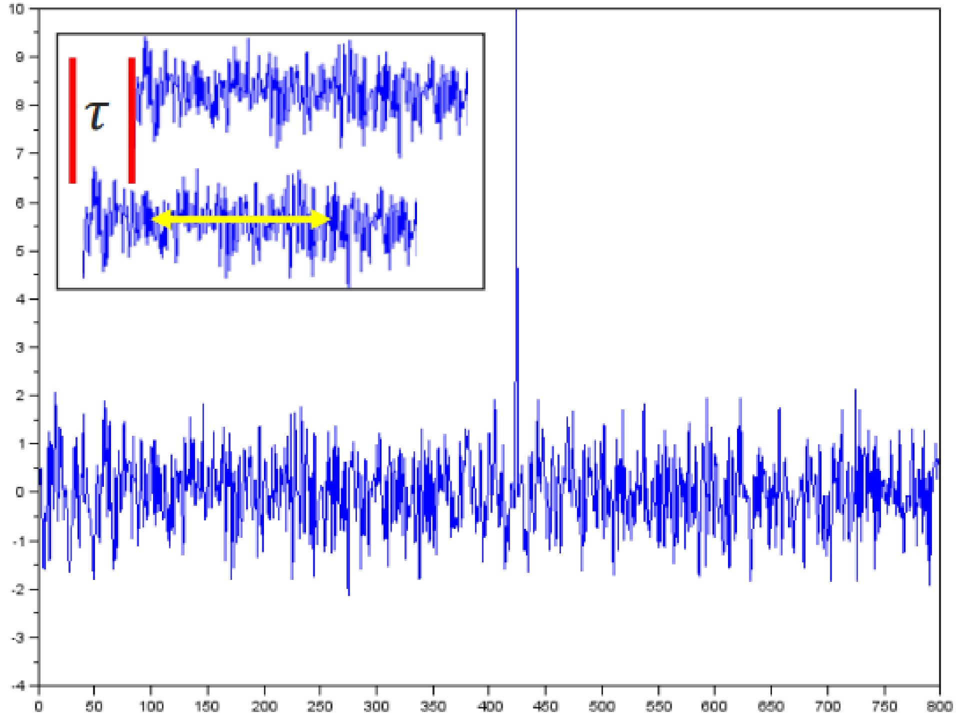
ν = frequency of the signal

One can find the time difference between two telescopes by correlating the signals. Maximum of the correlation function gives the delay at the epoch t.

If the observed signals are $V_1(t)$ and $V_{\mathbf{2}}(t)$, maximum of the correlation function R can be found:

T = time interval over which integration is made

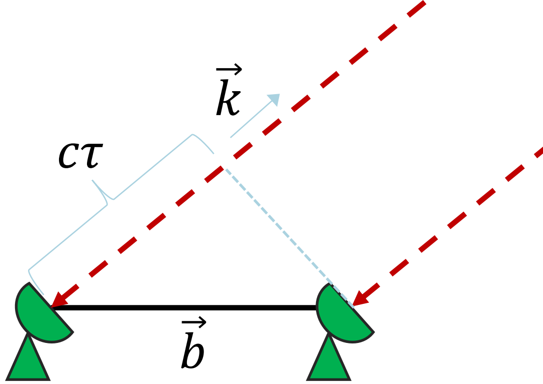
τ = delay between the signals at epoch t



A simplified example of correlation:
Autocorrelation of random noise

$$R(t) = \frac{1}{T}\int_0^T V_1(t)V_2(t-\tau)dt$$

VLBI – Observation equation



- Vector $\mathbf{b}$ contains Cartesian coordinates of telescopes 1 and 2 in the terrestrial reference frame ITRF
- Vector $\mathbf{k}$ contains the position of the quasars in the celestial reference frame ICRF

To express them in the same reference frame we need the rotation matrices for precession and nutation, $\boldsymbol{Q}(X(t), Y(t))$, daily spin $\boldsymbol{S}(\theta(t))$, and polar motion $\boldsymbol{W}\left(x_p(t), y_p(t)\right)$. Then the time delay, τ, can be given as:

$$\tau(t) = T_2 - T_1 = -\frac{1}{c}\mathbf{b} \cdot \boldsymbol{W}(t) \cdot \boldsymbol{S}(t) \cdot \boldsymbol{Q}(t) \cdot \mathbf{k}$$

$$\mathbf{b} = \begin{pmatrix} x_2 - x_1 \\ y_2 - y_1 \\ z_2 - z_1 \end{pmatrix}, \mathbf{k} = \begin{pmatrix} \cos\delta_c \cdot \cos\alpha_c \\ \cos\delta_c \cdot \sin\alpha_c \\ \sin\delta_c \end{pmatrix}$$

δ = declination
α = ascension

VLBI – Corrections

Corrections to the observed delay:

$$\tau_{obs^{corr}}(t) = \tau_{obs} - \Delta\tau_{atm^h}(t) - \Delta\tau_{ion}(t) - \Delta\tau_i$$

$\Delta\tau_i$ instrument related delays (i.e. thermal expansion, telescope's gravitational deformations, telescopes cable delays)

$\Delta\tau_{atm^h}(t)$ atmosphere related delays, includes troposphere

$\Delta\tau_{ion}(t)$ ionosphere related delays

Corrections applied to the apriori delay, $\boldsymbol{\tau_{vac}}$, give the theoretical delay:

$$\tau_{theoretical} = \tau_{vac} + \Delta\tau_{abb}(t) + \Delta\tau_{E.T.}(t) + \Delta\tau_{P.T.}(t) + \Delta\tau_{O.L.}(t) + \Delta\tau_{A.I.}(t)$$

$\Delta\tau_{abb}(t)$ daily aberration due to the rotation of the Earth and finite speed of the light in the direction of the quasar

$E.T.$ = Earth Tides, $P.T.$ = Pole Tide, $O.L.$ = Ocean Loading, $A.I.$ = Atmospheric Loading

VLBI – Estimated parameters

Single session solution:

- Clock parameters
- Telescope coordinates
- Earth Orientation parameters: Polar motion, UT1-UTC, precession/nutation
- Atmosphere parameters

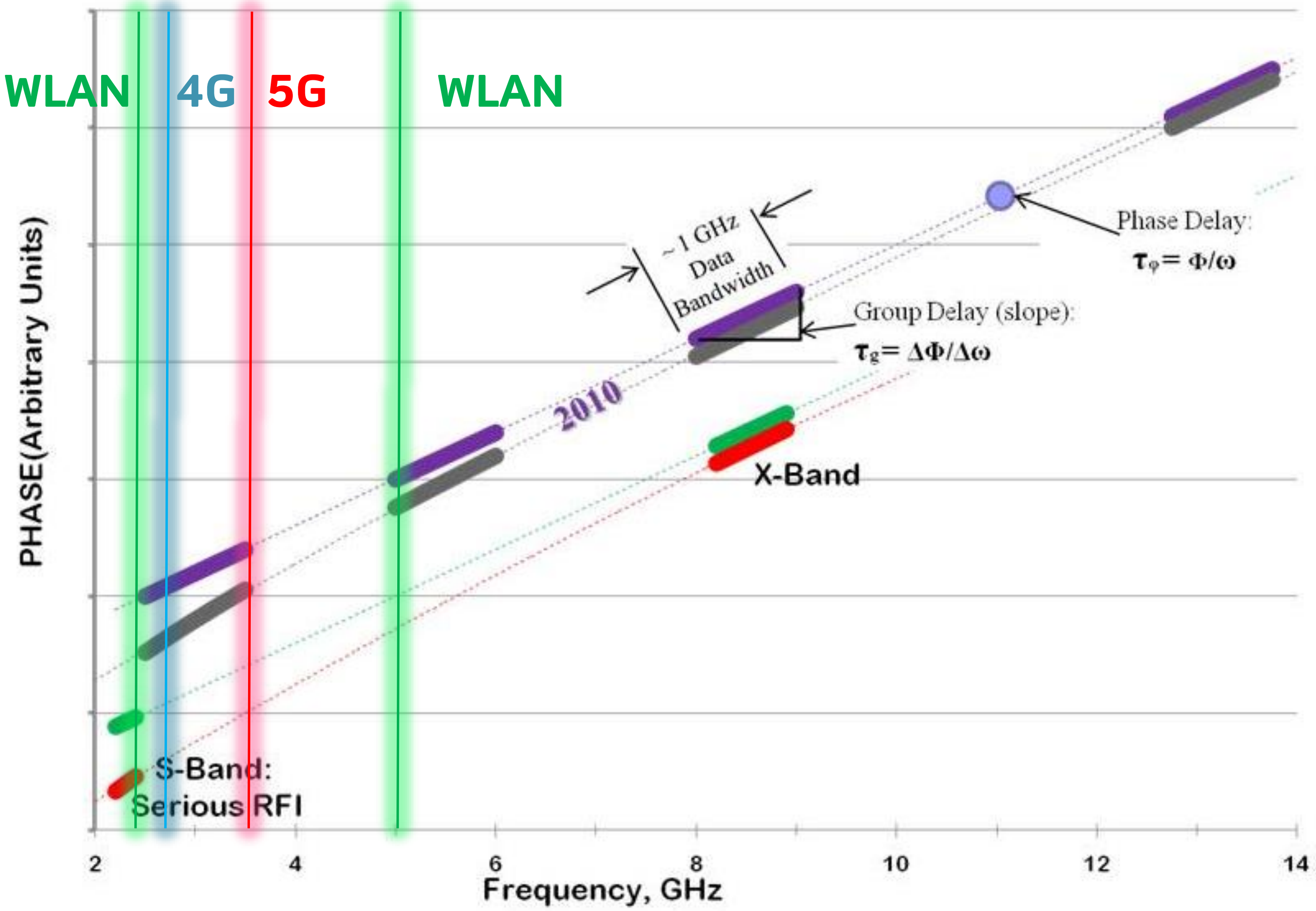
Multi-session or global solution:

- Radio source positions
- Telescope coordinates at reference epoch
- Linear or higher order velocities of the radio telescopes due to geodynamic effects

New VGOS system, frequencies

The VGOS system is based on the broadband delay which uses four or more frequency bands in the range from 2.5 GHz to 14 GHz. The observations are to be taken by fast-slewing, 12-m class antennas at a high data rate of 8 Gbps and above. The implied higher sampling of the sky, as compared to the legacy system, will allow beating down the impact of error components. Together with a reduction of systematic errors, this will result in an anticipated overall accuracy of 1 mm.

(IVS)



New VGOS system, frequencies

Improve geodetic VLBI

- Better SNR/sensitivity by increased bit rate (legacy 512-1000 Mbps to 4 – 8 Gbps, VGOS)
- Multiple broad-band frequencies
- Improved digital back ends and filters
- Better calibration of the signal chain, improved troposphere models
- Better modeling of quasar structure and frequency dependency
- Increasing observations / quasars at the Southern hemisphere
- **Towards near-real time data processing and products (especially the EOP parameters**

VGOS goals

IVS products and goals for the coming years in terms of accuracy, frequency of solutions, resolution and timeliness

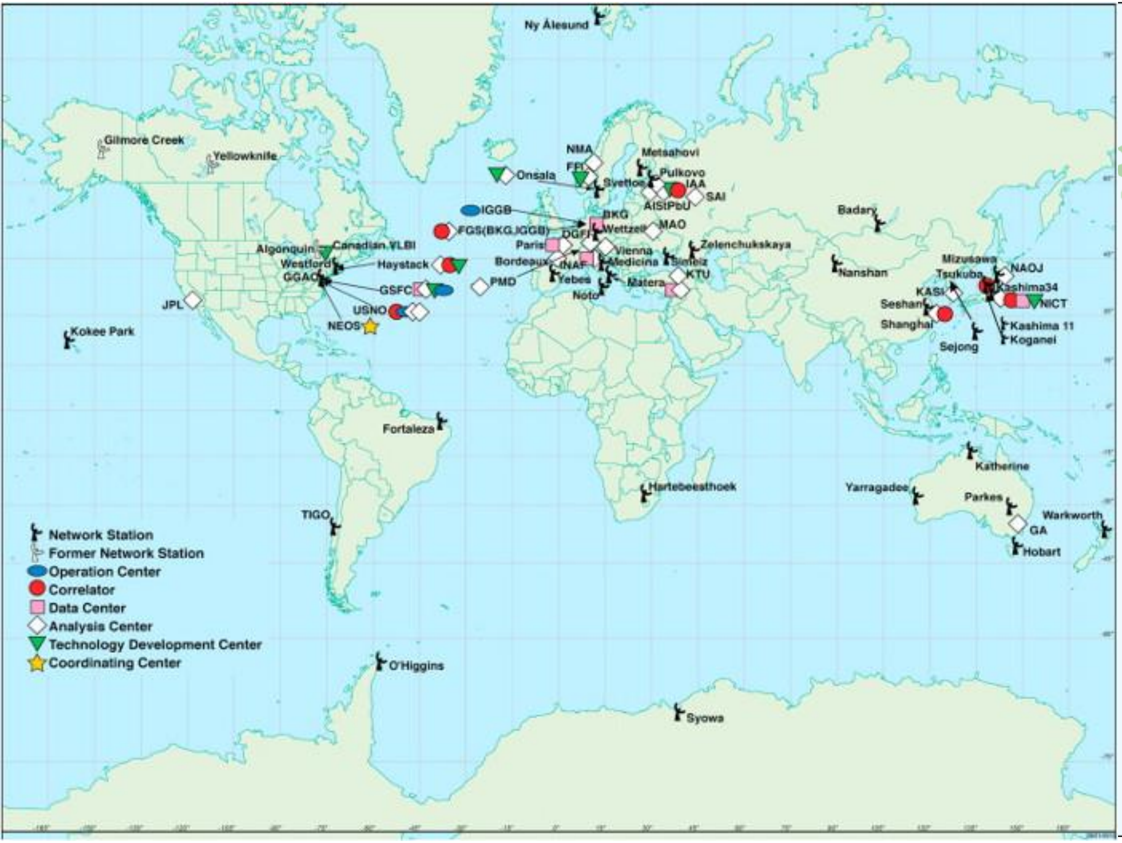
- https://ivscc.gsfc.nasa.gov/about/wg/wg3/IVS_WG3_report_050916.pdf
- https://ivscc.gsfc.nasa.gov/publications/misc/TM-2009-214180.pdf
- https://www.iag-aig.org/doc/5cdac368ce909.pdf

Category	Products	Accuracy	Frequency of solutions	Resolution	Timeliness
CRF	α,δ	0.25 mas for as many sources	yearly		1 month
	α,δ time series	0.5 mas	monthly	1 month	1 month
	source structure		monthly	1 month	3 months
	flux density		7 days/week	1 hour	near real time
TRF	x,y,z time series (1 solution/session)	2…5 mm	7 days/week	1 day	1 day
	episodic events	2…5 mm	7 days/week	< 1 day	near real time
	annual solution coordinates velocities	 1…2 mm 0.1…0.3 mm/y	yearly	-	1 month
EOP	DUT1	5 µs	7 days/week continuous	10 min	near real time
	$D\varphi, d\varepsilon$	25…50 µas	7 days/week	1 day	near real time
	x_P, y_p	25…50 µas	7 days/week	10 min	near real time
	$dx_P/dt, y_p/dt$	8…10 µas/day	7 days/week	10 min	-
Geodynamic parameters	solid Earth tides h,l	0.1%	1 year	1 year	1 month
	ccean loading A, φ	1%	1 year	1 year	1 month
	Atmoshere loading	10%	1 year	1 year	1 month
Physical parameters	tropospheric parameters zenith delay gradients	 1…2 mm 0.3…0.5 mm	 7 days/week 7 days/week	 10 min 2 hours	near real time
	ionospheric mapping	0.5 TEC units	7 days/week	1 hour	near real time
	light deflection parameter	0.1%	1 year	all sessions used	1 month

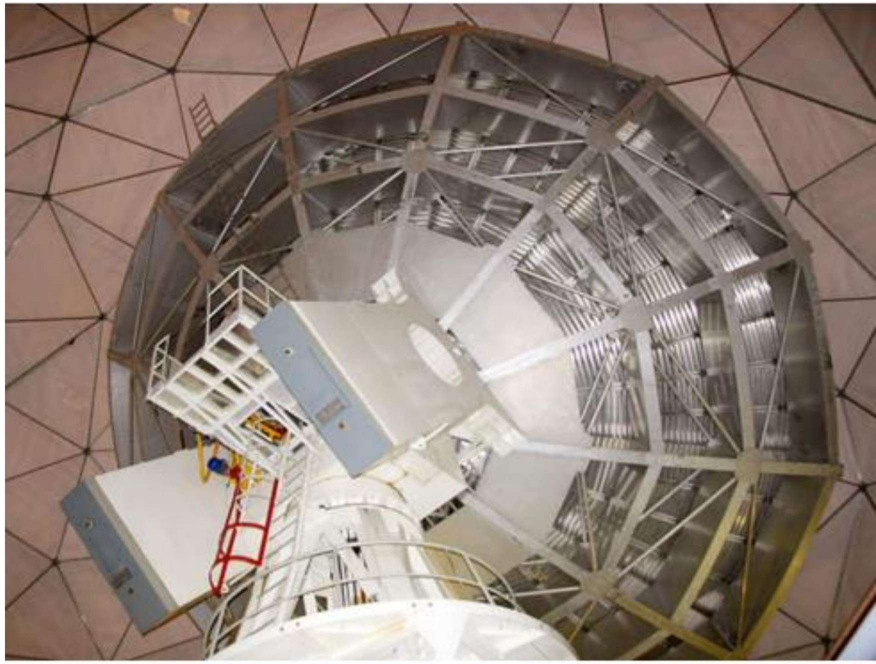
Current and future IVS / VGOS sites

IVS = International VLBI Service for Geodesy and Astrometry (IVS) is an international collaboration of organizations that operate or support VLBI instruments and activities.

Current IVS network



Legacy VLBI at Metsähovi



- Radio telescope (14 m dish) owned by Aalto University. Telescope built 1974
- 2-8 geo-VLBI campaigns/year
- Current telescope is slow
- Telescope-time limited
- Geodetic VLBI observations since 2004 as a co-operation of FGI and Aalto. Was discontinued.

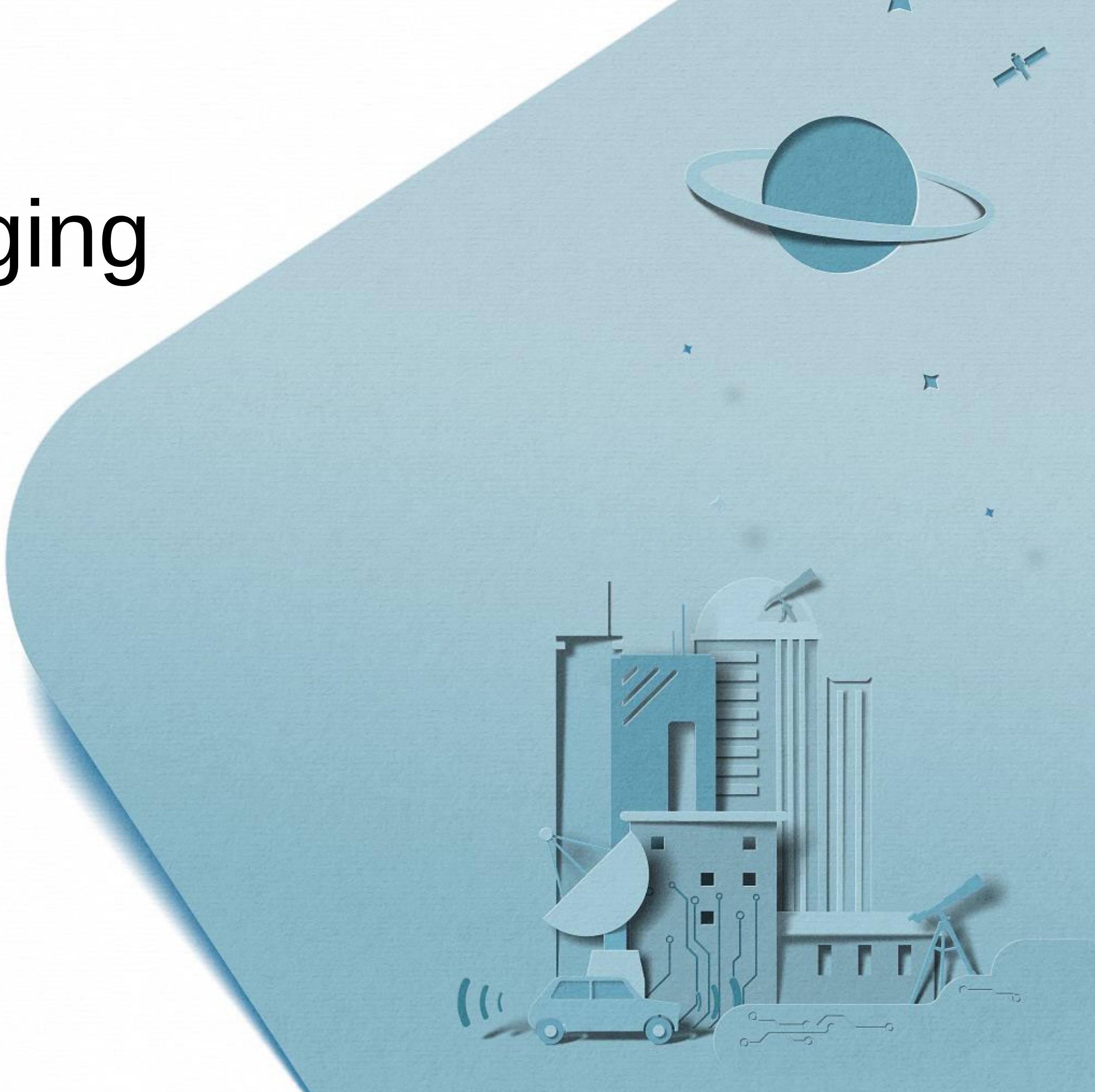
VGOS system at Metsähovi

- VGOS-compatible telescope installed 2018-2019, commissioning 2020-25, operational 2025-2026
- Manufactured by MT Mechatronics
- New multi-band receiver 2-14 GHz (Yebes)
- Hydrogen Maser, 2024

Table 1 Telescope technical characteristics.

Title	Description
Antenna mount	Standard azimuth-elevation type
Reflector optics	Cassegrain, ring focus
Diameter of the main reflector	13.2 m
Surf. accuracy of the main refl.	< 0.3 mm rms
Surf. accuracy of the subrefl.	< 0.1 mm rms
Antenna motion	
Velocity in azimuth	12 deg/s
Velocity in elevation	6 deg/s
Acceleration in azimuth	2.5 deg/s^2
Acceleration in elevation	2.5 deg/s^2

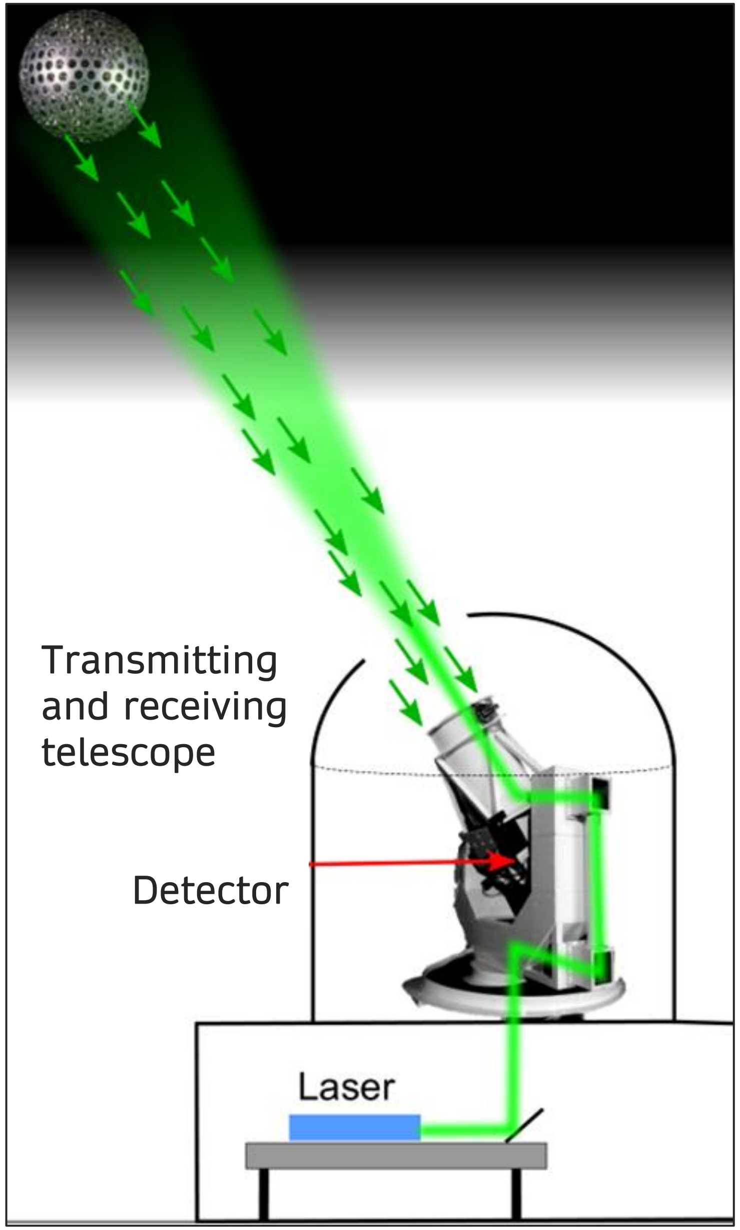
Satellite Laser Ranging (SLR)



Satellite Laser Ranging

A technique to measure distances to satellites using the flight time of ultrashort laser pulses.

- A transmitting system is attached to a telescope. It sends out the laser pulses.
- The telescope detects the return pulses.
- Satellites are equipped with retroreflectors which reflect the pulses back into the direction the were coming from.



Lageos 1 & 2

Laser GEOdynamics Satellite-1 (LAGEOS)

- Designed by NASA, launched 1976
- First satellite dedicated to high-precision Satellite Laser Ranging
- Possibility to get laser ranging data not degraded by errors due to satellite obits or the satellite array

LAGEOS-2

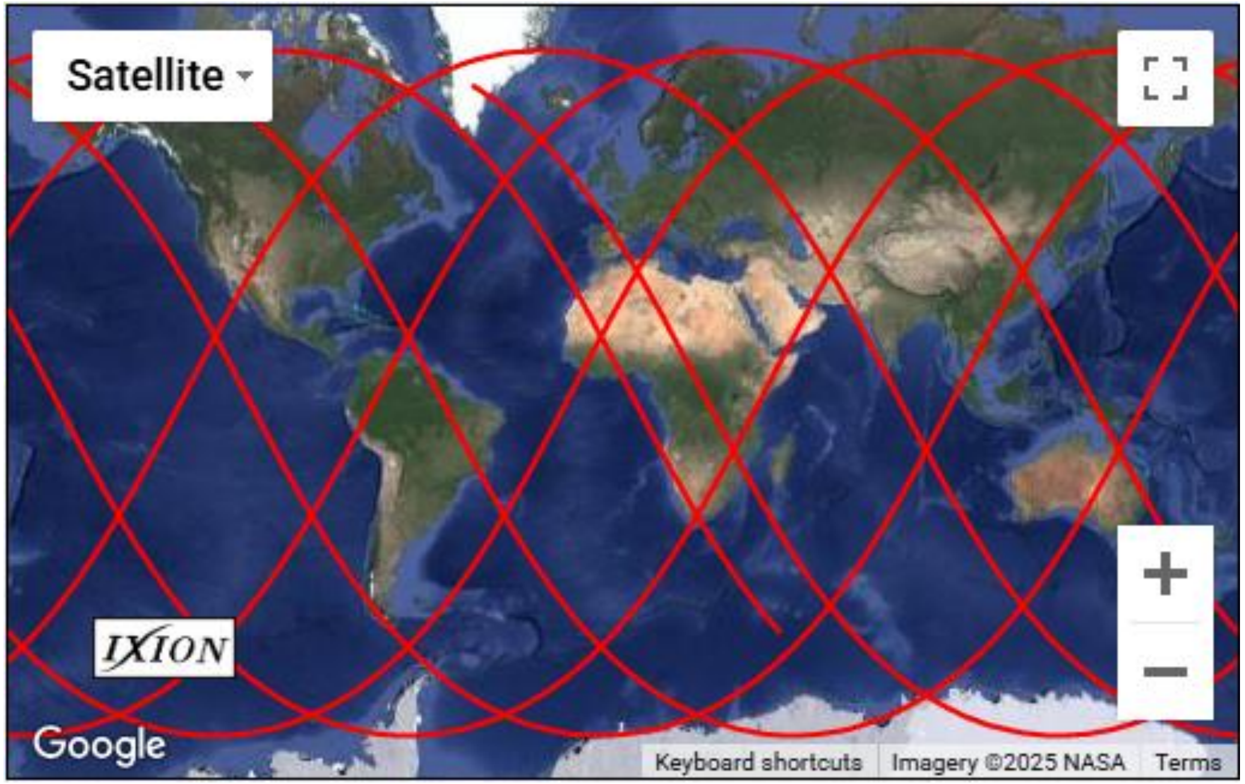
- Designed as LAGEOS-1 by Italian Space Agency, launch in 1992

Plans for LAGEOS-3

	LAGEOS	**LAGEOS-2**
Launch Date:	May 4, 1976	October 22, 1992
Diameter:	60 cm	60 cm
Shape:	sphere	sphere
Reflectors:	426 corner cubes	426 corner cubes
Orbit:	circular	circular
Inclination:	109.84 degrees	52.64 degrees
Eccentricity:	0.0045	0.0135
Perigee:	5.860 km	5,620 km
Period:	225 minutes	223 minutes
Weight:	406.965 kg	405.38 kg

Lageos 1 & 2

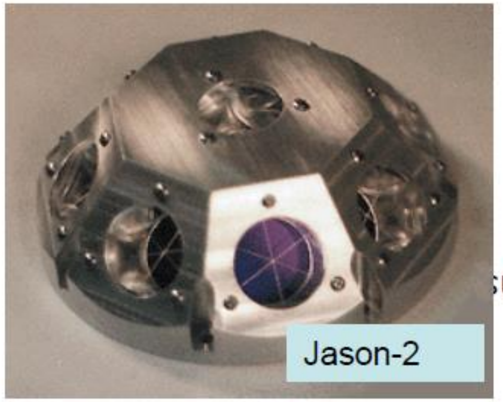
e: 0.004417 i: 109.86° T = 225.49mn

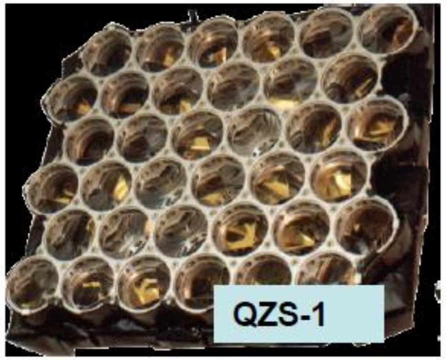


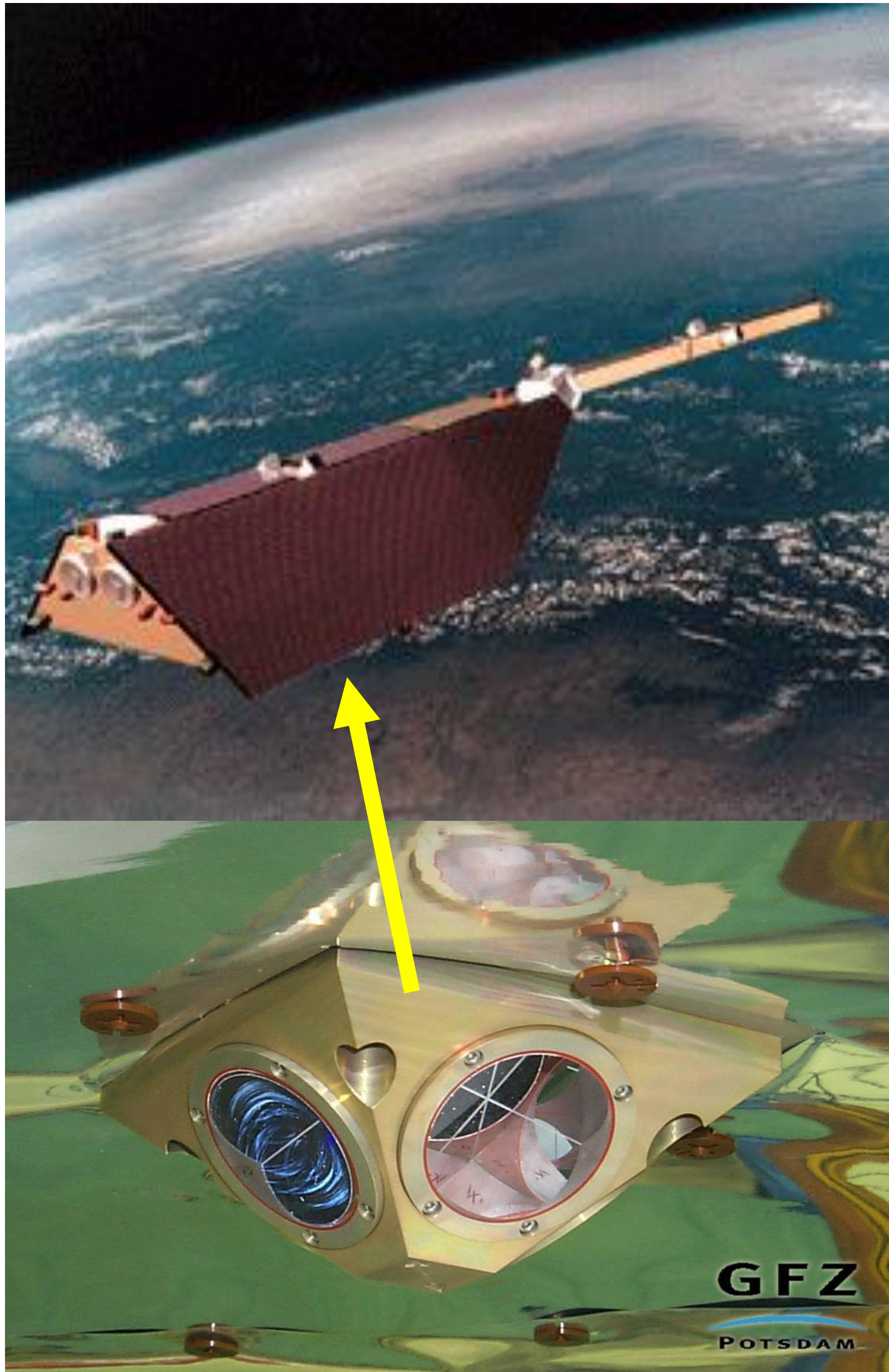
e: 0.013712 i: 52.64° T = 222.42mn

Retroreflectors

International Laser Ranging Service



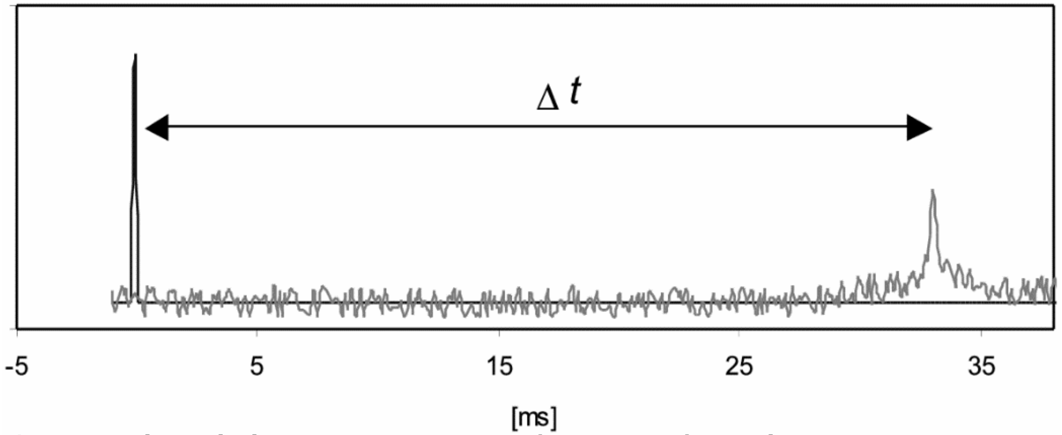




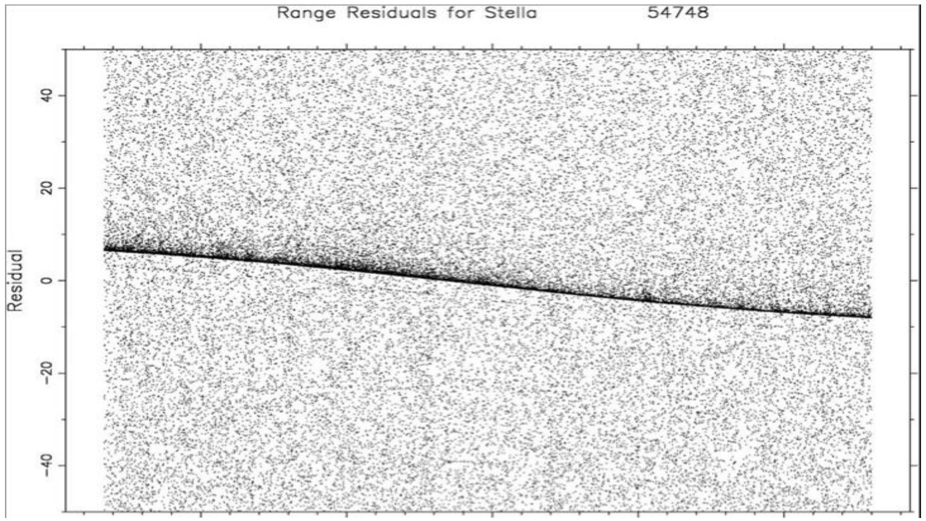
Principle

Pulse laser transmits short pulses

- Modern lasers, typically Nd:YAG @532 nm
- Pulse length few tens of ps (= some mm)
- Pulse energy some tenths of mJ to a few mJ
- Single Photon Avalanche Diode (SPAD) detector



Laser is giving a start pulse to the time counter at the moment 1 when the laser pulse is sent. When the detector observes the return signal at time 2, it sends the stop pulse to the counter.



A typical observation with a SPAD detector. Reflections from the satellite forms the black line. Other dots are random noise.

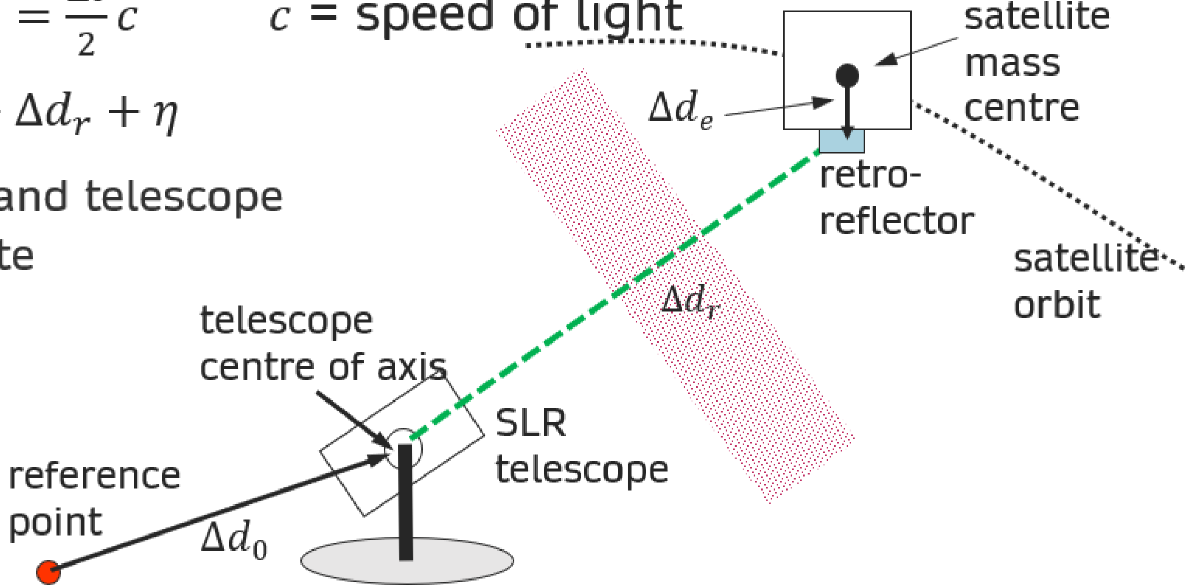
Formulas

Time of pulse transmission and receiving is recorded. $\Delta t = t_{pulse\ arrival} - t_{pulse\ transmission}$

Then distance d to the satellite: $d = \frac{\Delta t}{2} c$ c = speed of light

In reality $d = \frac{\Delta t}{2} c + \Delta d_0 + \Delta d_e + \Delta d_d + \Delta d_r + \eta$

Δd_0 correction due to orientation of laser and telescope
Δd_e prism eccentricity correction in satellite
Δd_d delays in ground system (electronics)
Δd_r atmospheric refraction correction
η other systematic or random errors



Telescope:

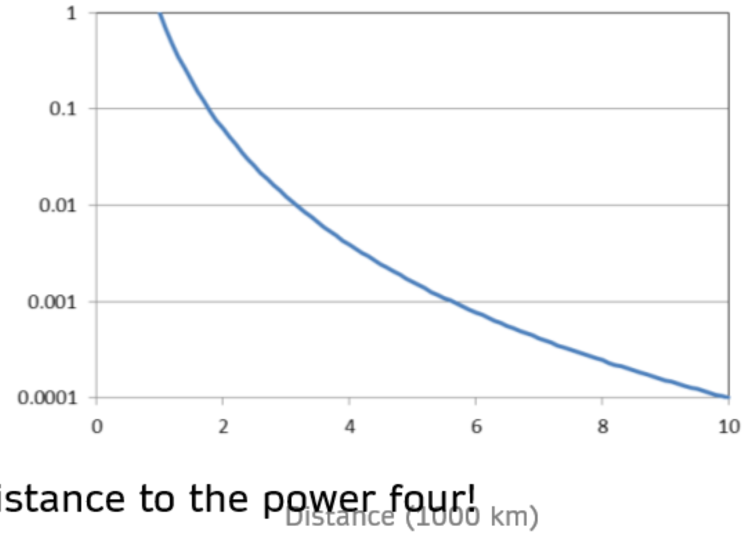
- Monostatic: Outgoing signal is using the same telescope as the incoming signal
- Bi-static: Transmitting telescope is separate. Fast kHz systems use bi-static structure.

Signal strength N of the returning signal

$$N = \frac{E_t}{h\nu} G_t A_r G_s A_s \frac{1}{D^4} T_a^2 T_r$$

E_t	Transmission energy
$h\nu$	Photon energy
G_t	Transmission gain
A_r, A_s	Effective area of the receiver and satellite prism
G_s	Gain of signal at satellite
D^4	Satellite distance
T_a	Atmospheric transmission
T_r	Telescope optics transmission coefficient

Effect of distance on the strength of the return signal



Note: Signal decreases fast: related to the inverse of the distance to the power four!

For a target without a reflector, the returning signal is only a fraction of the signal from a retroreflector.

When only single photons coming back, the signal strength can be increased by:

1. stronger laser to increase pulse energy E_t.
2. more sensitive detector to improve optical quality of the telescope.

Data Processing

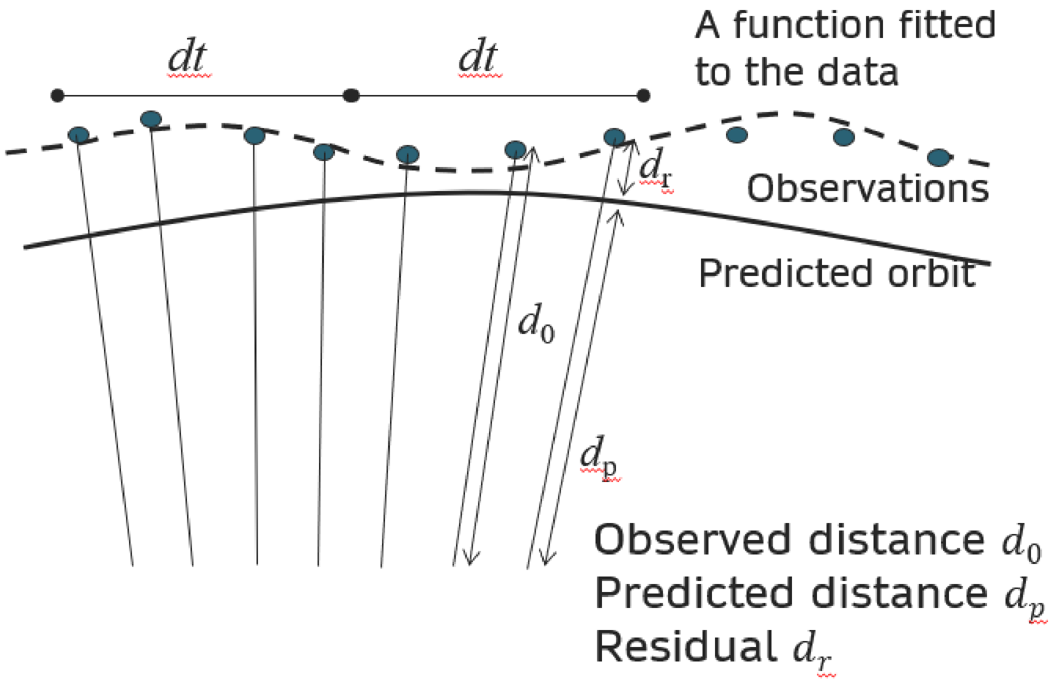
Control of raw data in filtering and compression process to:

- Detect and eliminate gross errors
- Evaluate the accuracy of the observations
- Reduce amount of data for processing

Multi-step process:

Step 1: Compare observed ranges d_0 with predicted ranges d_p: $d_r = d_0 - d_p$

→ Eliminate gross errors



High precision needed
Refraction delay must be included

Step 2: Fit a trend function $f(p)$ to the residuals d_r: orbital parameters or (Chebyshev) polynomial. Then look in the deviations after the fit for outliers (3σ): $f_r = d_r - f(p)$

This step can be iterated

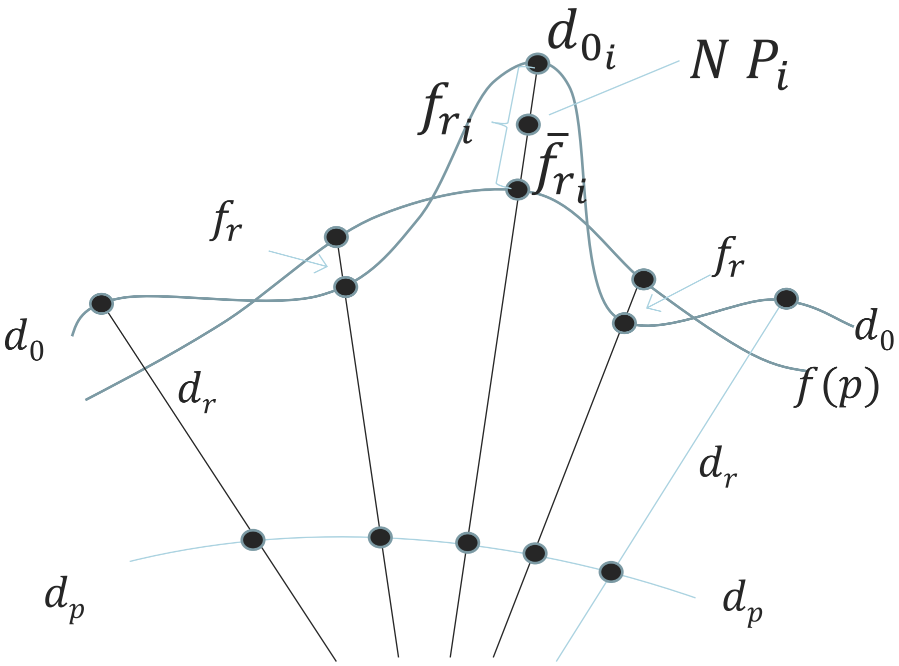
Data processing

Step 3:

- Divide the trajectory into fixed intervals “bins”, start from 0:00 UTC
- Calculate the mean $\bar{f}_{r_i}$ of all deviations f_r in each interval.
- Add the mean $\bar{f}_{r_i}$ to the trend function at the center of the interval. This creates the normal point $N\,P_i$.
- The normal point range is then: $d_{N\,P_i} = d_{0_i} - (f_{r_i} - \bar{f}_{r_i})$
- The noise or “normal point precision” of $d_{N\,P_i}$ is calculated from the differences of the single residuals f_r with the mean $\bar{f}_r$: $f_r - \bar{f}_r$

  Normal point precision for third generation SLR: ±1 - 2 cm, and better than 3mm for modern systems

Example bins:	
GPS, GLONASS	300 seconds
LAGEOS-1,2	120 seconds
STARLETTE, STELLA	30 seconds
ERS-1/2	15 second
GRACE	5 seconds



Parameter estimation

Combining all available tracking data from the global SLR network to estimate:

- Geocentric station coordinates
- Gravity field coefficients
- Pole components
- Earth rotation and universal time (UT1) – Earth Orientation Parameters
- Model parameters of Solid Earth and Ocean Tides
- Additional parameters for the description of the satellite orbit

Not all parameters can be estimated together.

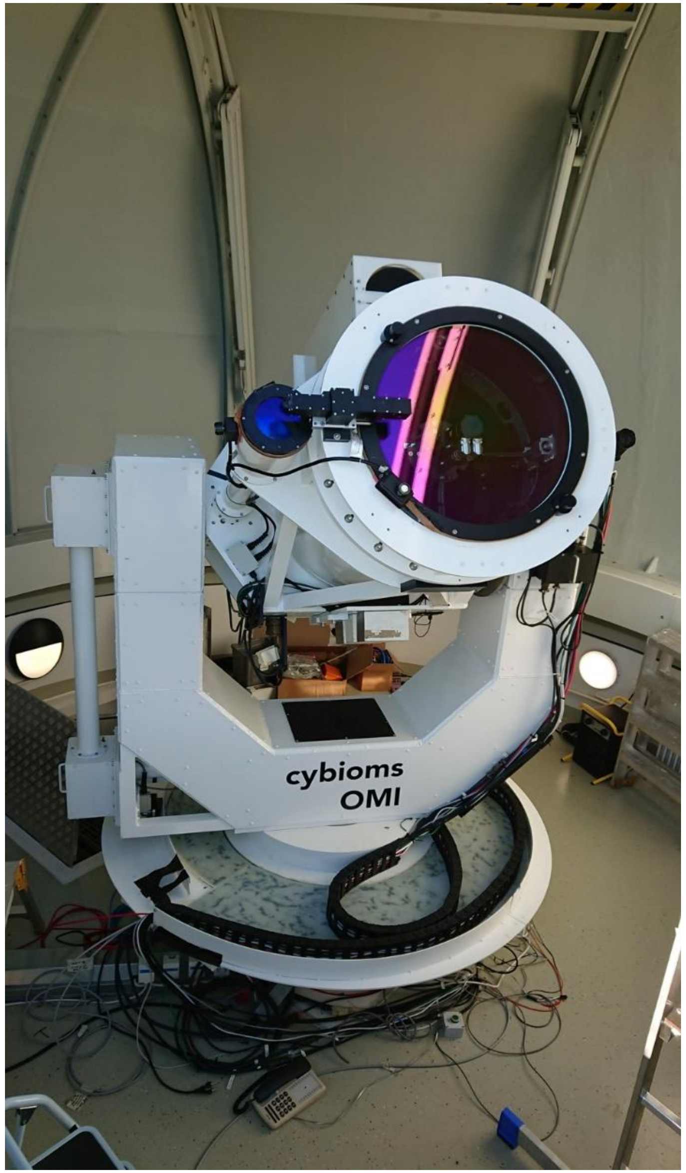
Other applications: Precise Time Transfer, Fundamental Physics, Precision tracking

Future challenges and possibilities

- Accuracy requirements of the new reference frames
- Automatization of the stations
- Targets that detect the laser pulse and can conduct time transfer across continents.
- Targets that also simultaneously perform laser communications.
- Distant targets in the solar system that are carrying detector or transponder
  technology.

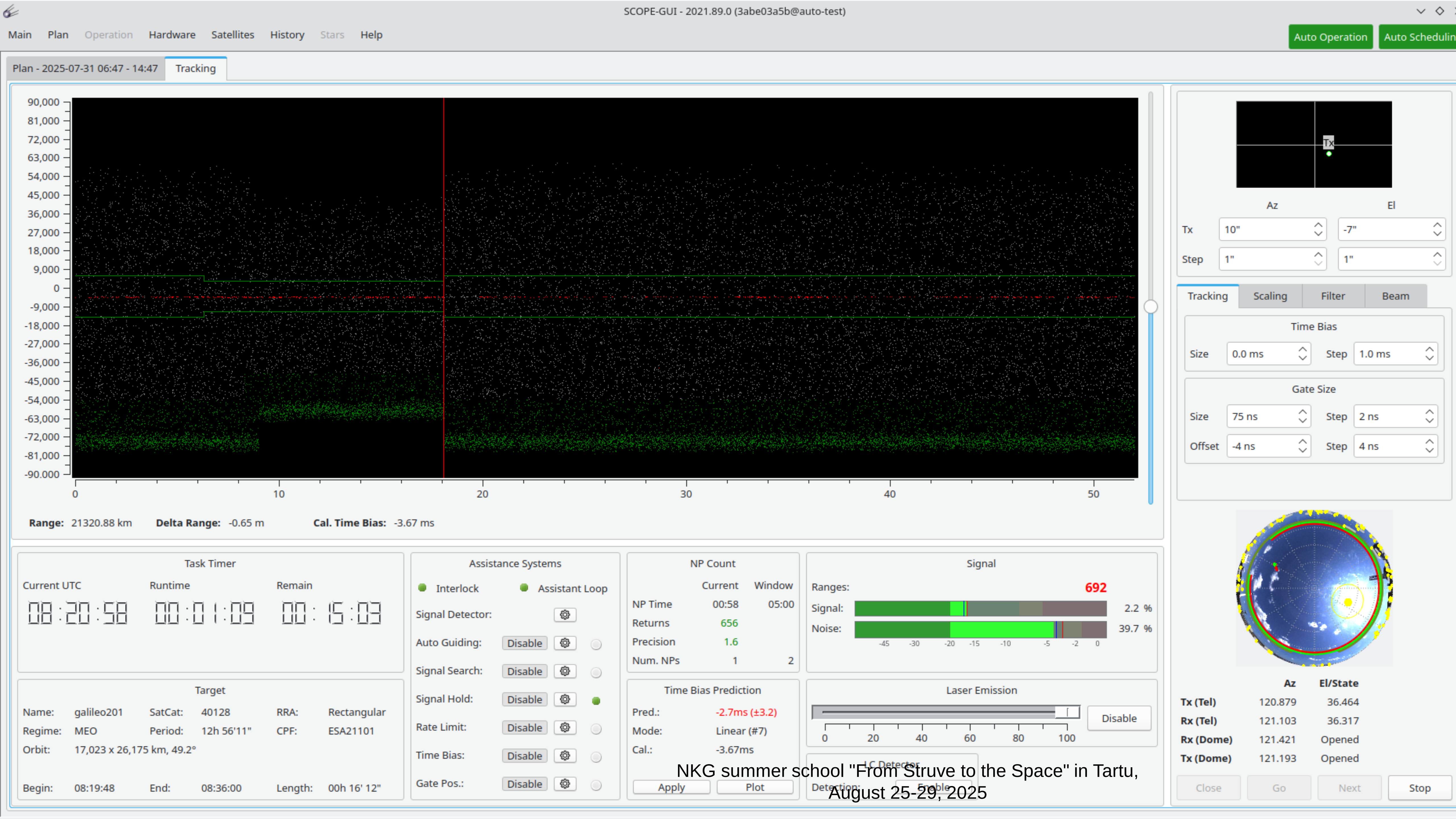
Metsähovi SLR

- First telescope (60 cm) built in 1975, second one (100 cm) 1992; In-house made lasers
- New modern telescope 2025
  - Laser downstairs on optical table, in temperature controlled laboratory room
  - Guided via Coudé path to a 10-cm transmitting telescope
  - Receiving telescope mirror 50-cm
  - Single photon detector (SPAD) in Cassegrain focus



Metsähovi SLR

- Current HighQ (2 kHz) laser:
  - Wavelength 532nm
  - Power: 0.85W @ 532nm @2kHz repetition
  - Pulse energy: 0.4mJ @ 532nm @2kHz
  - Pulse length: ~12 ps
- Passat laser: replacing the HighQ laser
  - Wavelenght: 532 & 1064 nm
  - rep rate 1kHz
  - pulse energy ~1mJ @532nm
  - pulse energy ~2mJ @1064nm
  - Otherwise similar to above
- Space Debris Laser 2027



NKG summer school "From Struve to the Space" in Tartu, August 25-29, 2025

Summary

Geodetic core stations are used for

- A stable reference frame
- Earth Orientation Parameters

Metsähovi Geodetic Reserach Station

- Has all major geodetic instruments
- SLR will be operational 2025
- VGOS will be operational 2026
- Space debris SLR will be operational 2027

Extra links to UN Geodesy

Document by the UN Global Geodetic Centre of Excellence

- Policy Brief: Hidden Risk
- Policy Brief: Geodesy is Critical to Climate Science
- Policy Brief: Safeguarding VLBI Radio-Frequencies

Global Geodesy Needs Assessment (2024)

1st Joint Development Plan for Global Geodesy

We know the Earth
– we secure the future

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