Tracking Systems for Geodesy

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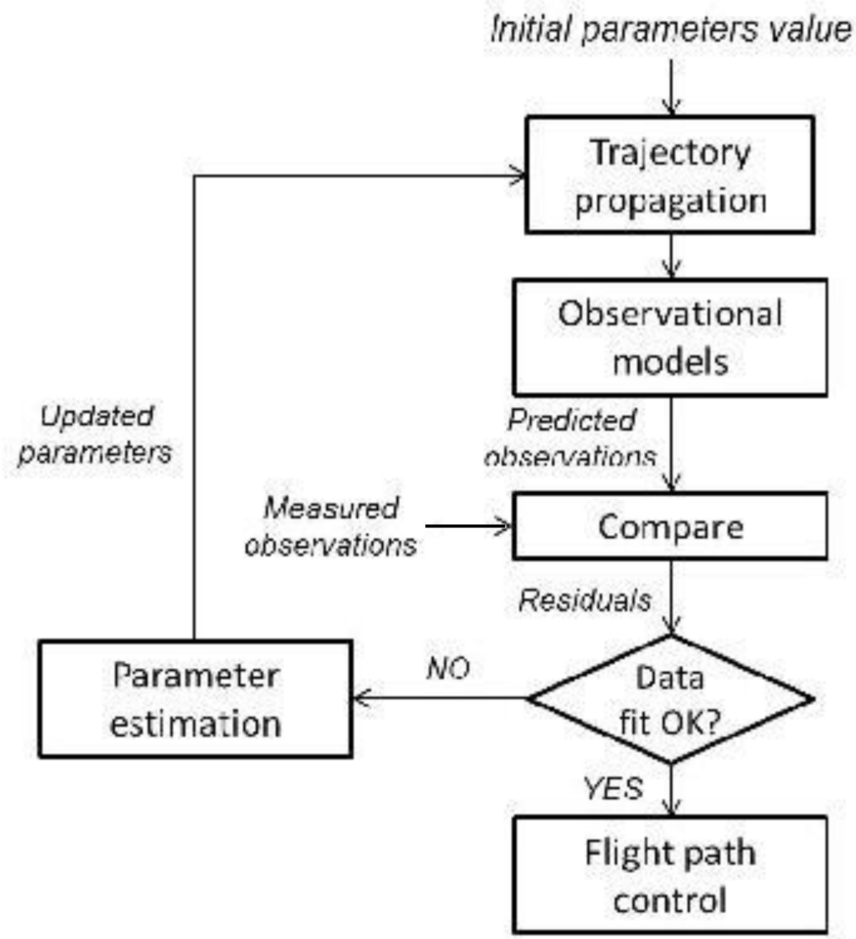
Introduction

- Tracking of vehicles in deep space is accomplished through a variety of radiometric techniques
- Basic radiometric observables (i.e., measurements) are the amplitude and phase of an electromagnetic wave which creates a radio link between the spacecraft and the Earth.
- There exist essentially three fundamental radiometric data types:
  - Range (related to signals' time of travel)
  - Range rate or Doppler (related to line-of-sight velocity)
  - VLBI - Very Long Base Interferometry, which provides differential ranging (related to angular coordinates)

The Navigation Process



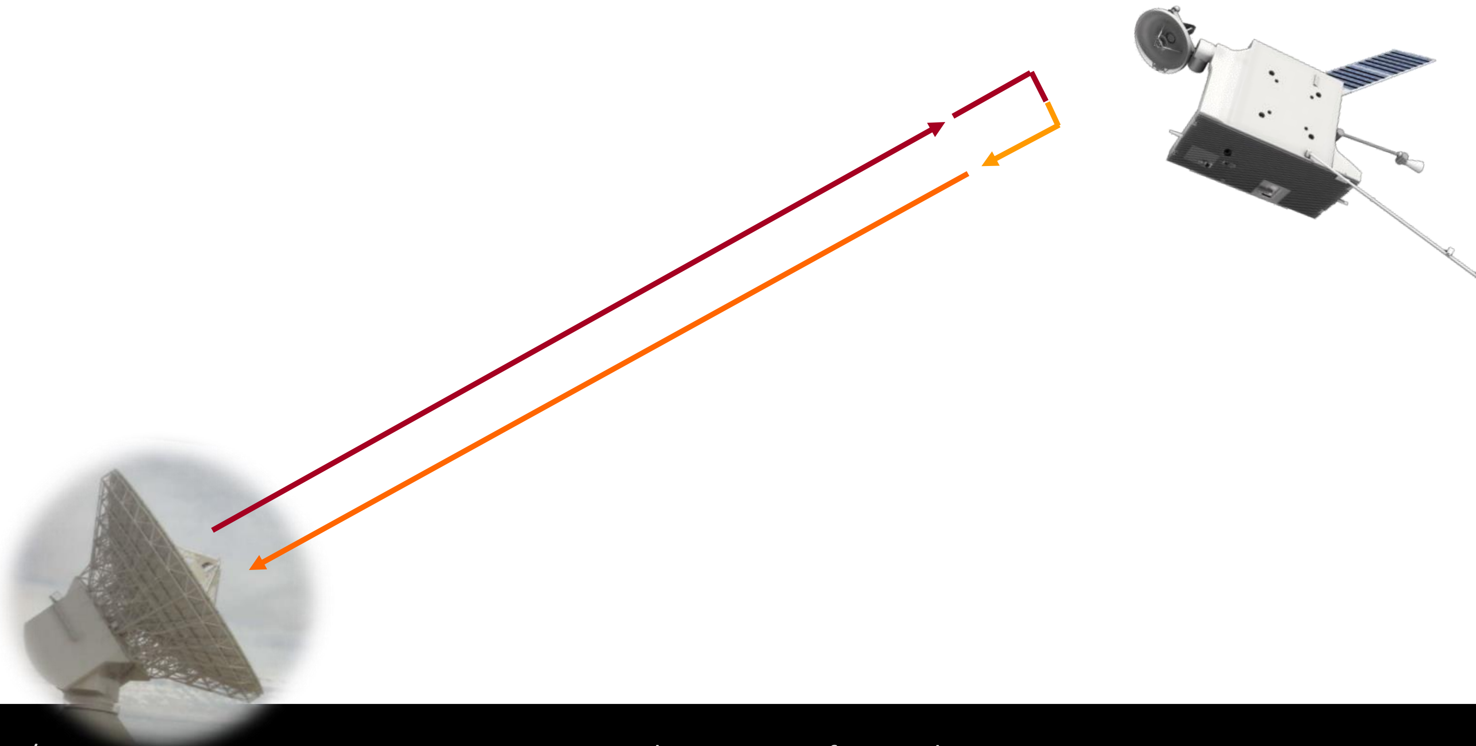
S/C Radio Tracking

A ramp signal is sent to the S/C

The S/C receiver locks on and tracks the uplink carrier via a PLL

The PLL produces a reference signal coherent with the uplink carrier

The reference signal is used to demodulate the downlink signal



Radio Frequencies

Reference frequencies:

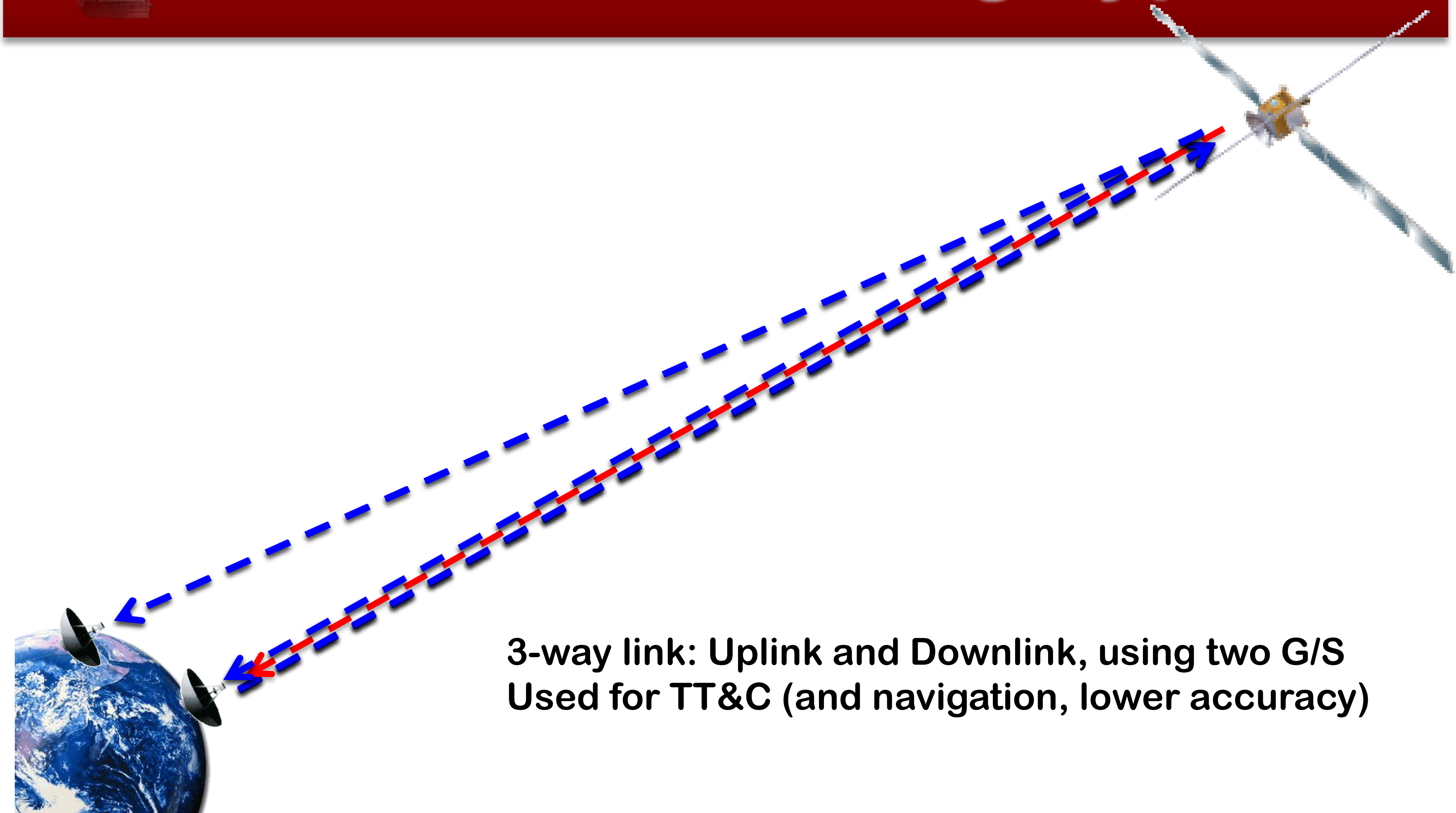
	Uplink	Downlink
S – band	2110 - 2120 MHz	2290 -2300 MHz
X – band	7145 - 7190 MHz	8400 – 8450 MHz
Ka – band	34200 - 34700 MHz	31800 – 32300 MHz

Shorter wavelenght reduce the effects of the charged particels due to ionosphere and solar plasma

Uplink and Downlink frequencies are phase coherent

Uplink	Downlink		
S – band	240/221	880/221	3344/221
X – band	240/749	880/749	3344/749
Ka – band	240/3599	880/3599	3344/3599

Radio Tracking Types



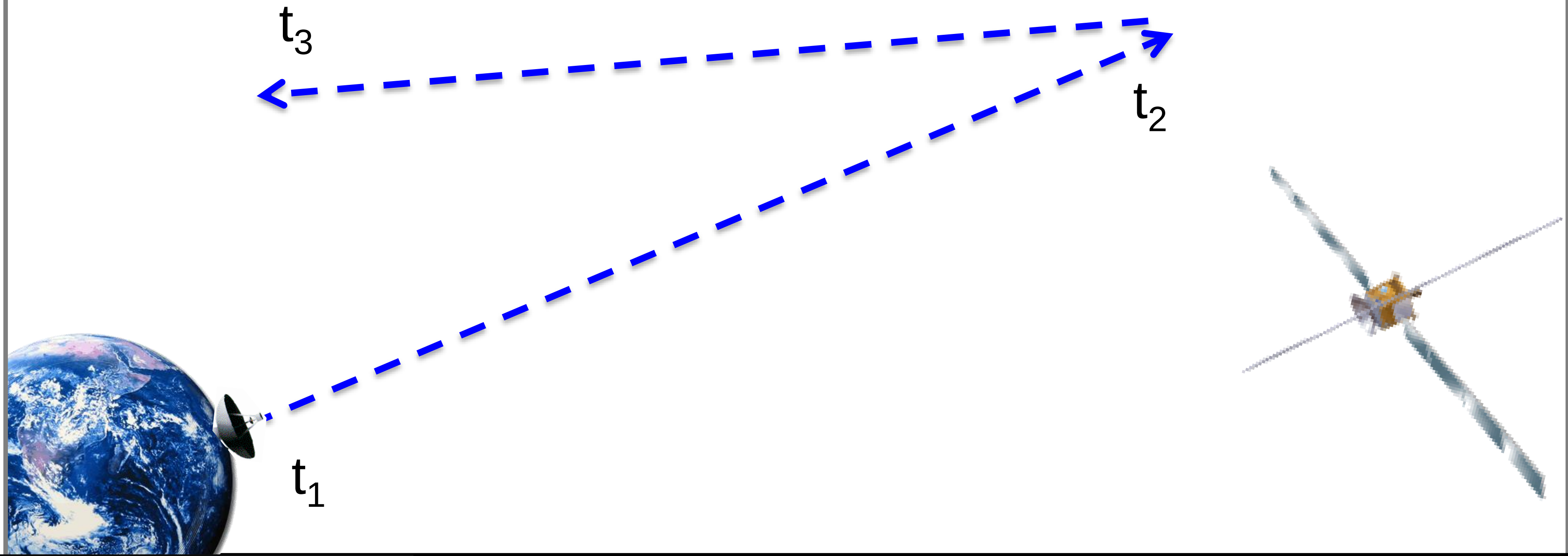
3-way link: Uplink and Downlink, using two G/S
Used for TT&C (and navigation, lower accuracy)

Observables

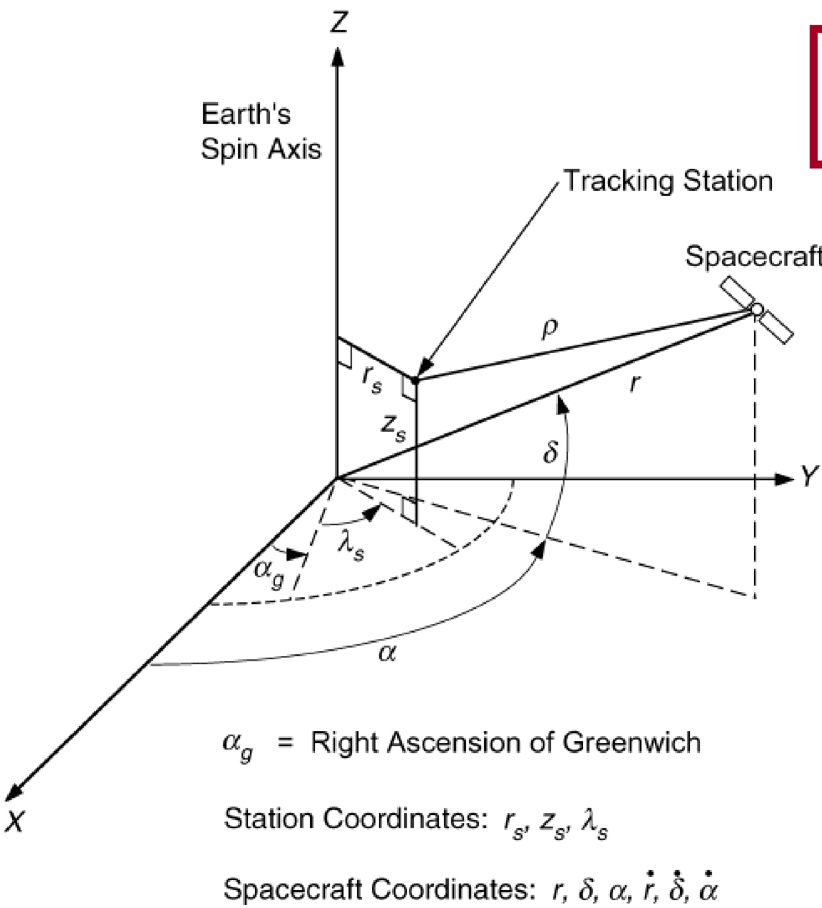
- Ranging (range)
- Doppler (range rate)
- DDOR – VLBI (angular position)

Ranging observables

a dynamical observable, not a static one!



Ranging observables



S/C range data is a measure of the **RTLT** of a ranging signal generated at a ground station

For a one-way signal transmit time t_g

$$\rho = t_g c$$

For a two-way signal

t_1 transmission time

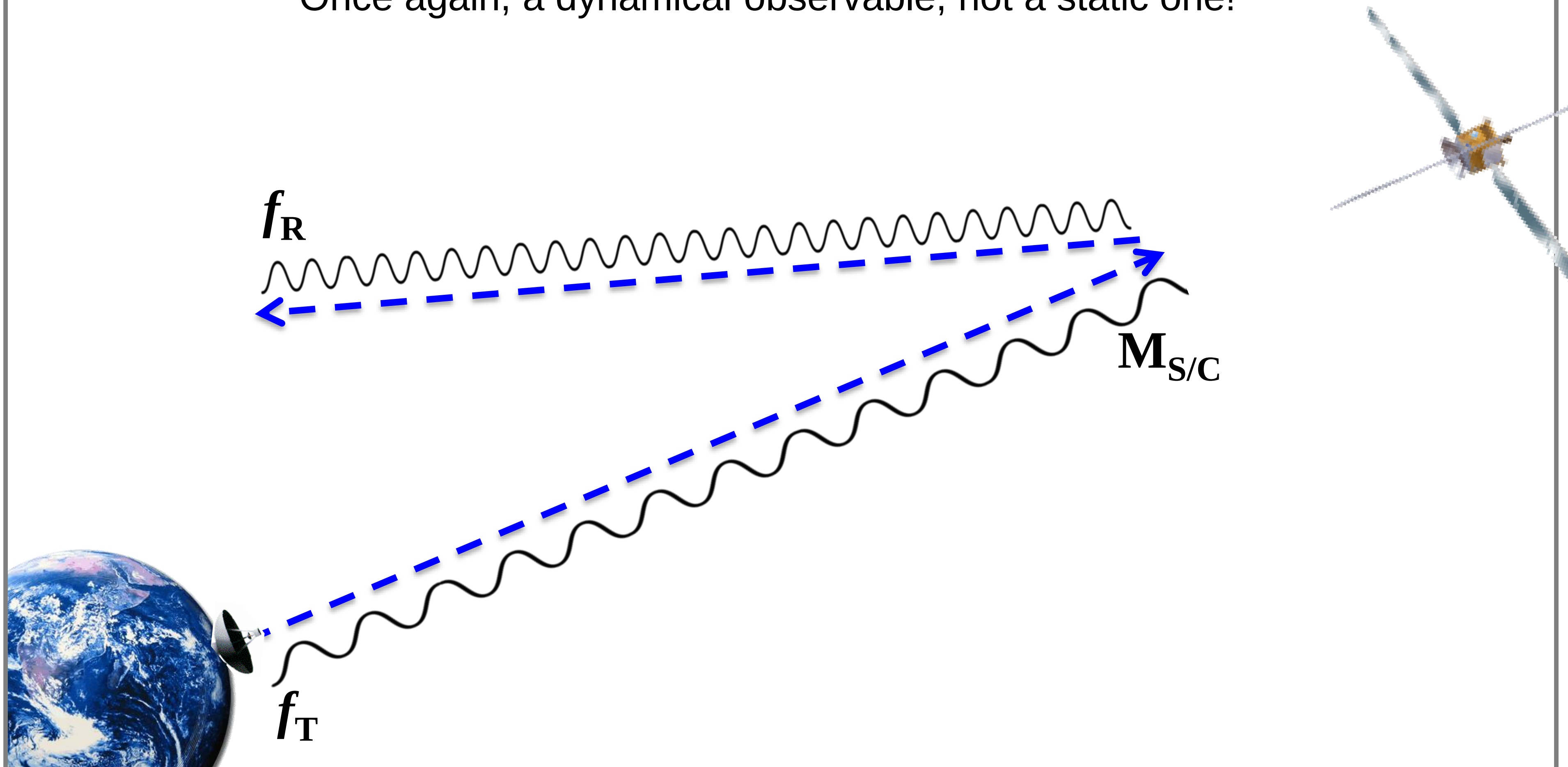
t_2 receiving time at the S/C

t_3 receiving time at the GS

$$\rho = \frac{1}{2}(t_3 - t_1)c$$

Doppler observables

Once again, a dynamical observable, not a static one!



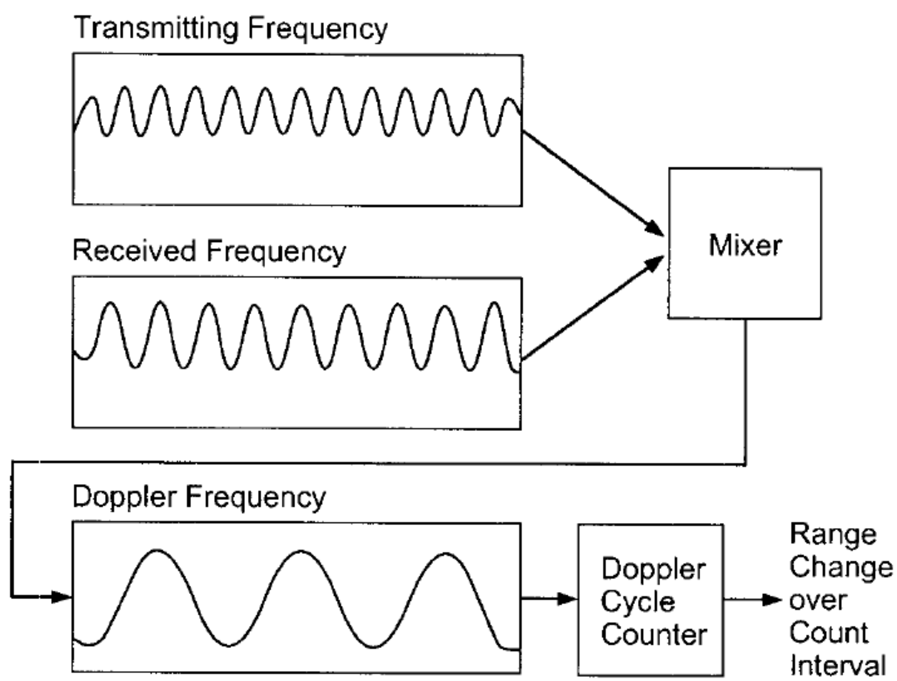
Doppler observables

Doppler data provide information on S/C radial velocity

$$f(t) = f_{REF}(t) - f_R(t) + C$$

$$f_{REF} = M_{S/C} f_T$$

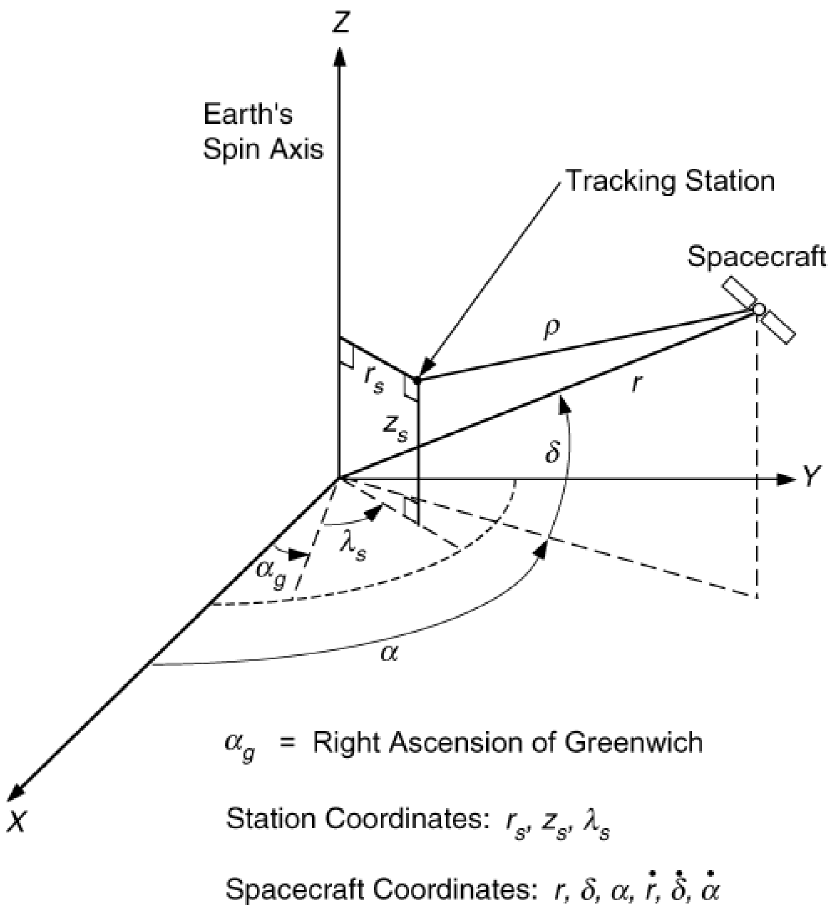
$$f_R = M_{S/C}\left(1 - \frac{\dot{\rho}}{c}\right) f_T$$

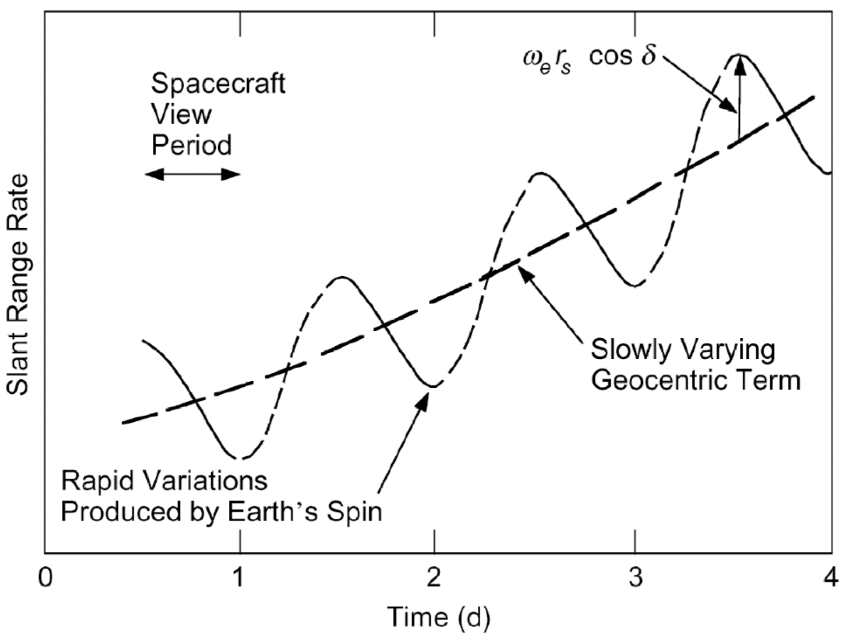


Accuracy (@1000 s int. time):
~ 3µm/s in radial velocity at Ka-band

Doppler observables

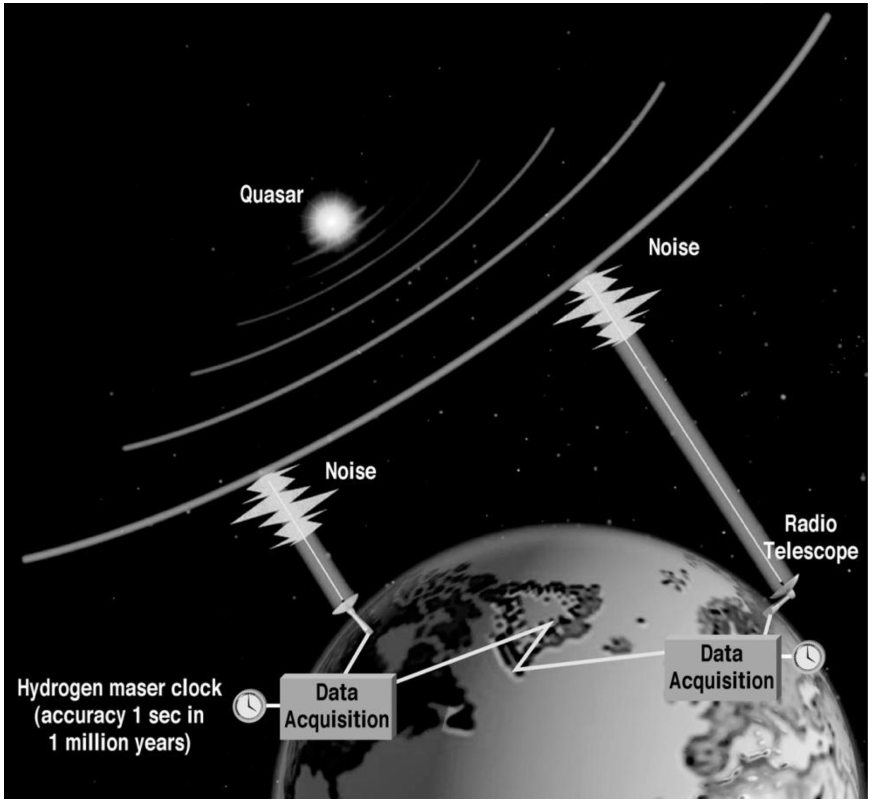
The measurement of Doppler data and the knowledge of the Earth's motion for different passes provides declination δ and right ascension α of the S/C





VLBI observables

VLBI techniques



2 different station receive broadband microwave radiation emitted by extragalactic radiosources (Quasars)

Geodesy

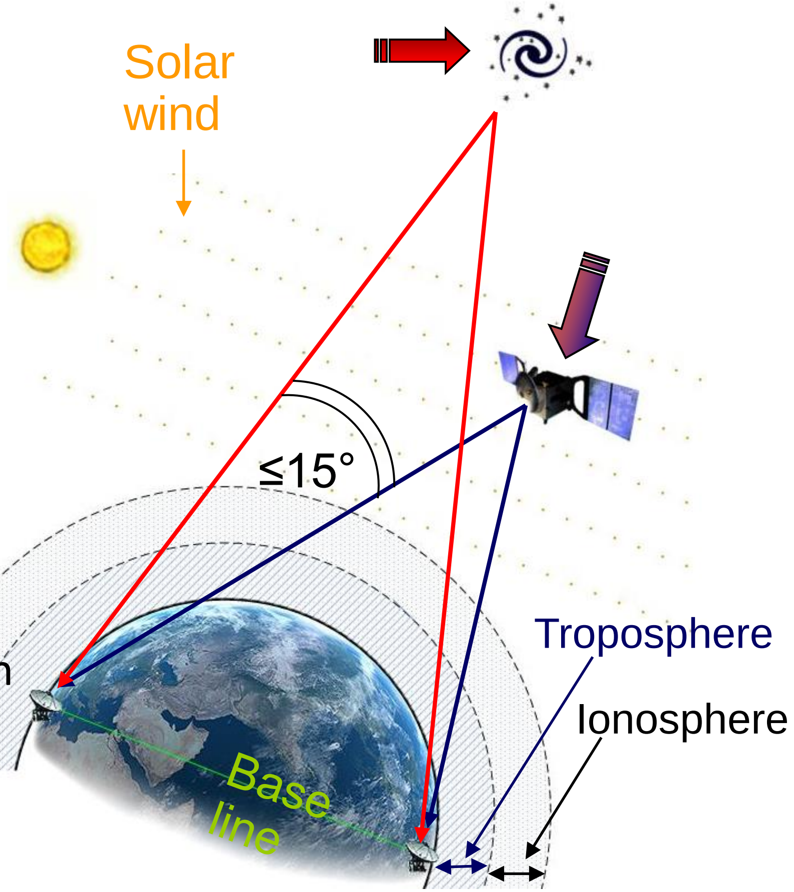
Determines the Baseline and defines the Earth Orientation Parameters (EOP)

Astrometry

Determines declination δ and right ascension α of a celestial body

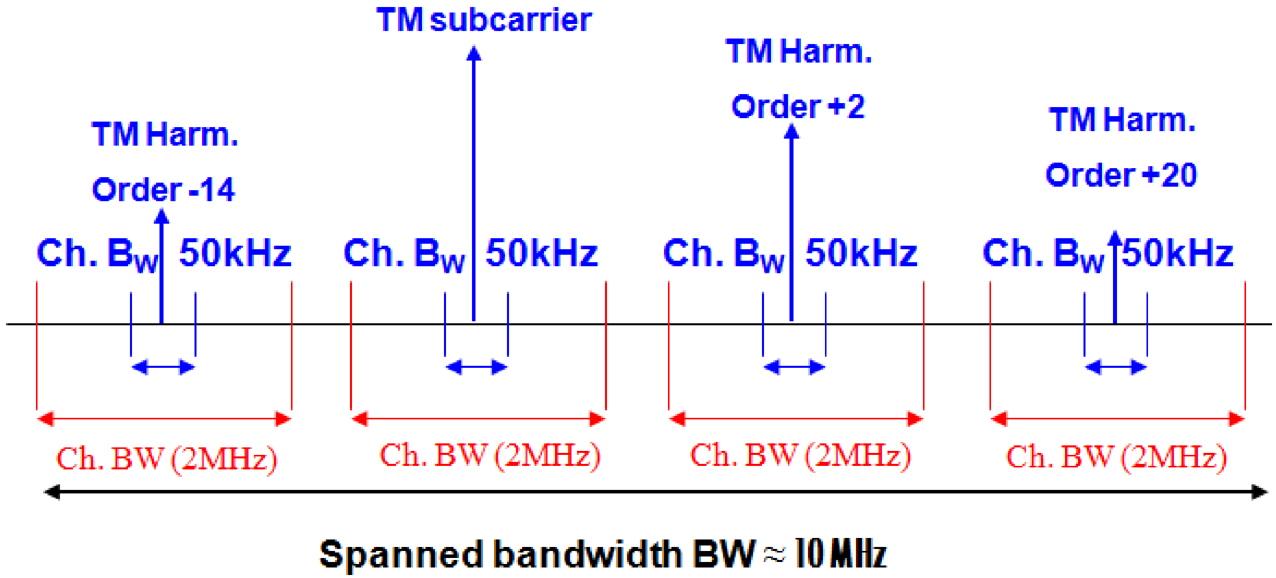
DDOR observables

- **ΔDOR : Delta Differential One-way Ranging**
- **DOR : difference between the times of arrival at two ground stations (max 21 ms)**
  - Calibrated effects: on board oscillator frequency offset, dry troposphere
  - Uncalibrated effects:
    - Clock-offset between the stations (main effect), ESA DSA clock offset max 6 µs
    - Instrumentation noises: phase ripple
    - Residual media effects
- **ΔDOR requires:**
  - Max angular separation: 15°
  - Signals are recorded in the same bandwidth
- **ΔDOR: evaluation of the angular position of a probe in the S/C-baseline plane**



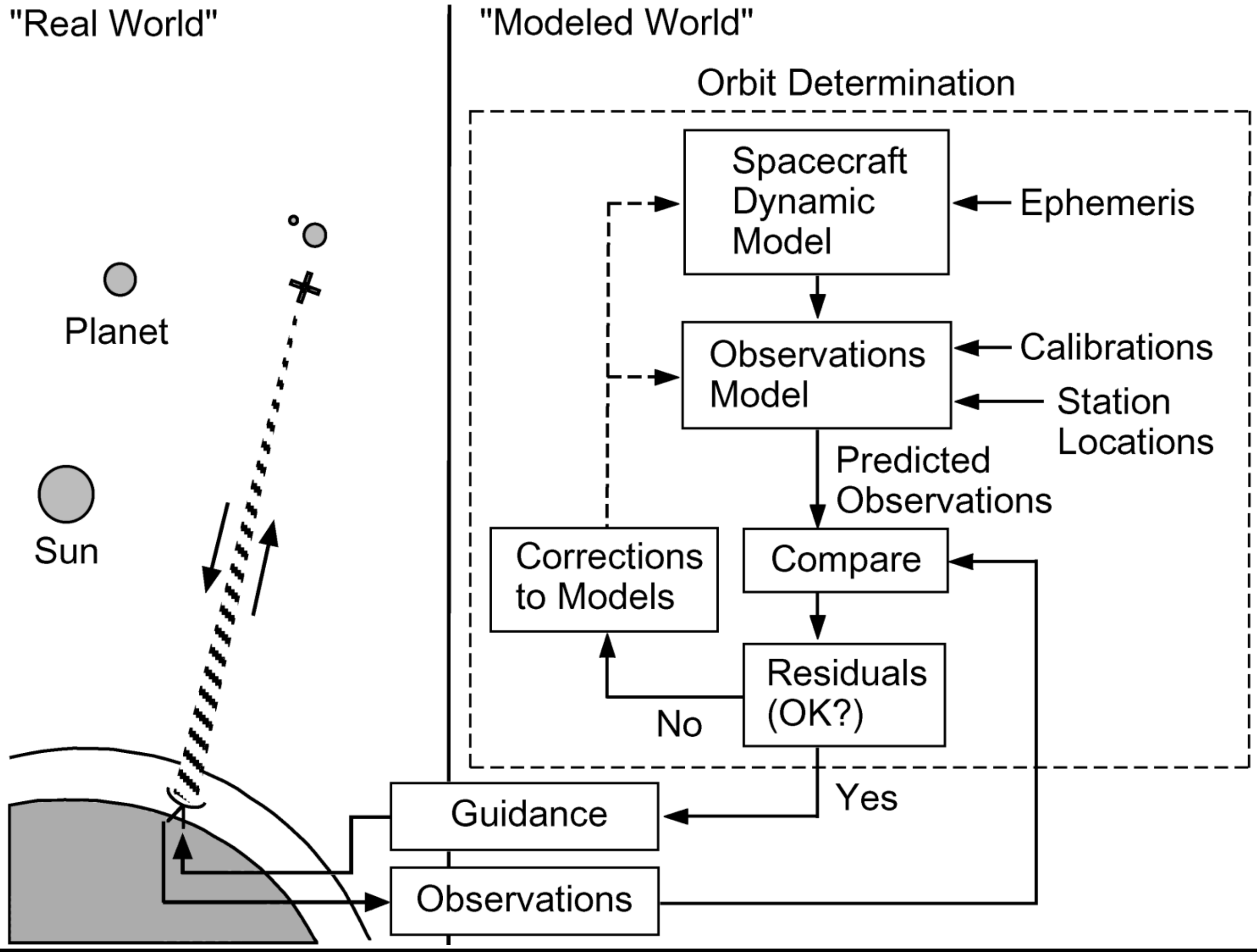
DDOR observables

- **S/C signal**
  - Telemetry harmonics and DOR tones
  - ESA: TM subcarrier harmonics (262 Khz)
  - Fs=50kHz; 8bit
- **QUASAR signal**
  - White noise completely embedded in the receiver noise (0.5 Jy = $0.5 \cdot 10^{-26}$ W/m^2Hz)
  - Fs=2MHz; 2bit
- **Accuracy:**
  - Spanned bandwidth: 10 MHz
  - Signals SNR
  - Integration time



$$\sigma_{\tau_{S/Q}} = \frac{\sqrt{2}}{2\pi B_W \sqrt{(T_{OBS})_{S/Q} \left(S/N_0 \right)_{S/Q}}}$$

Orbit Determination Process



Orbit Determination Process

Real | **O_i – Observed observables**

C_i – Computed observables | **Model**

$$J = \sum_{i=1}^{n} \frac{(O_i - C_i)^2}{\sigma_i}$$

n=observations
σ=weigth
k=1,2…n_p

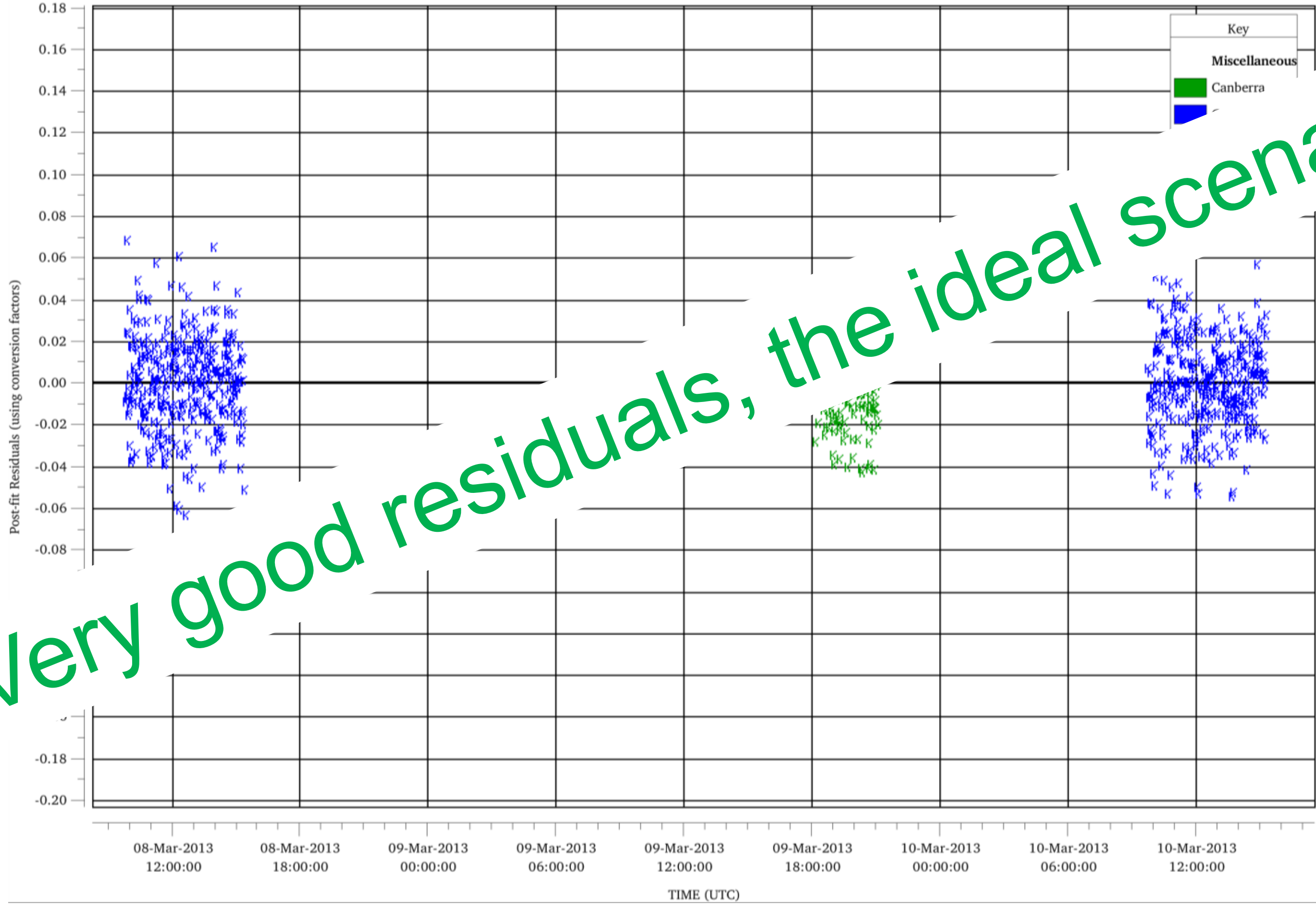
$$\frac{\partial J}{\partial p_k} = 0$$

$$p_k = A^{-1}B \quad \Leftarrow \quad Ap_k = B$$

Initial conditions

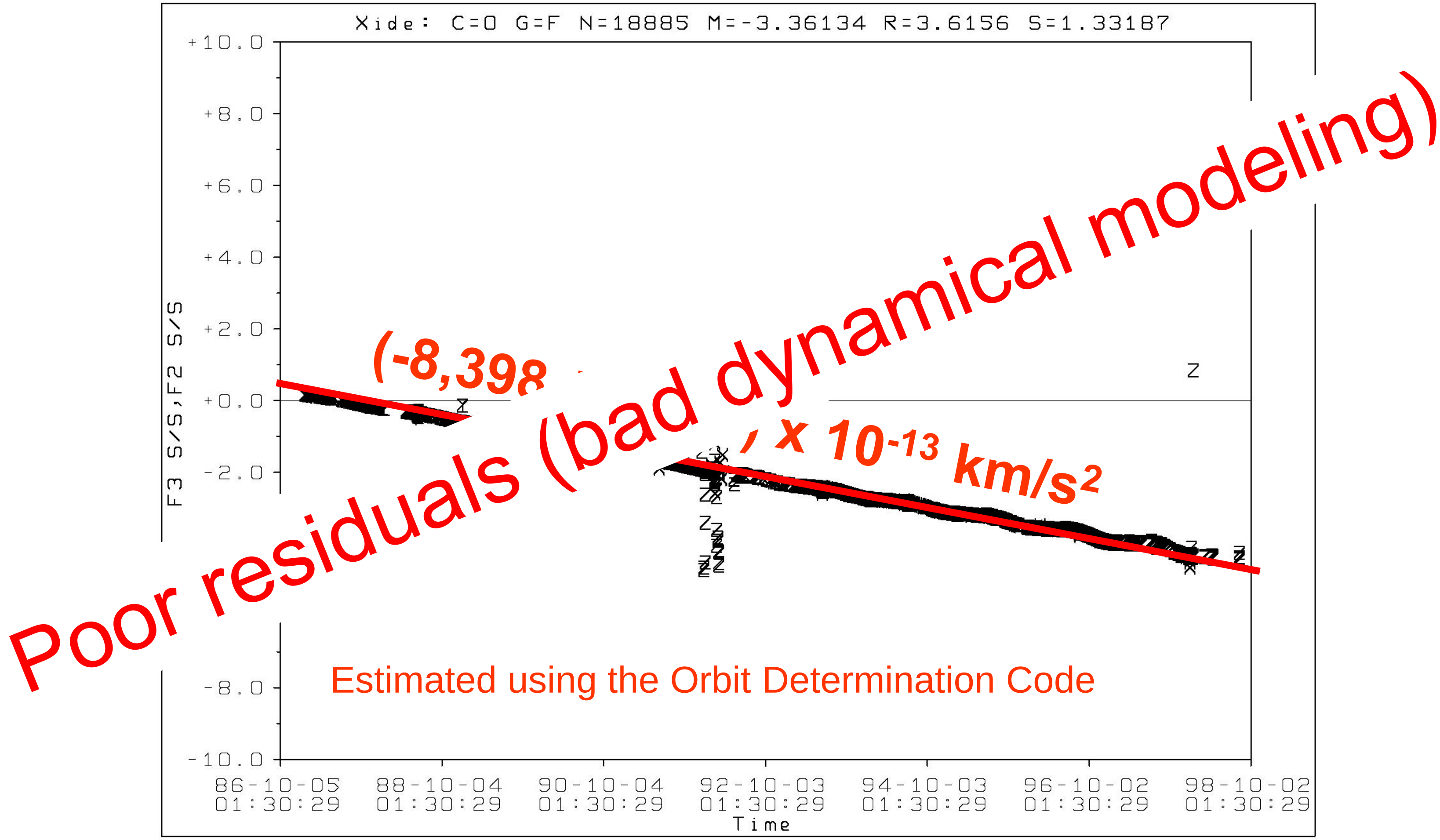
$$C_i = \sum_{k=1}^{n_p} f_k p_k$$

Doppler residuals (1/3)

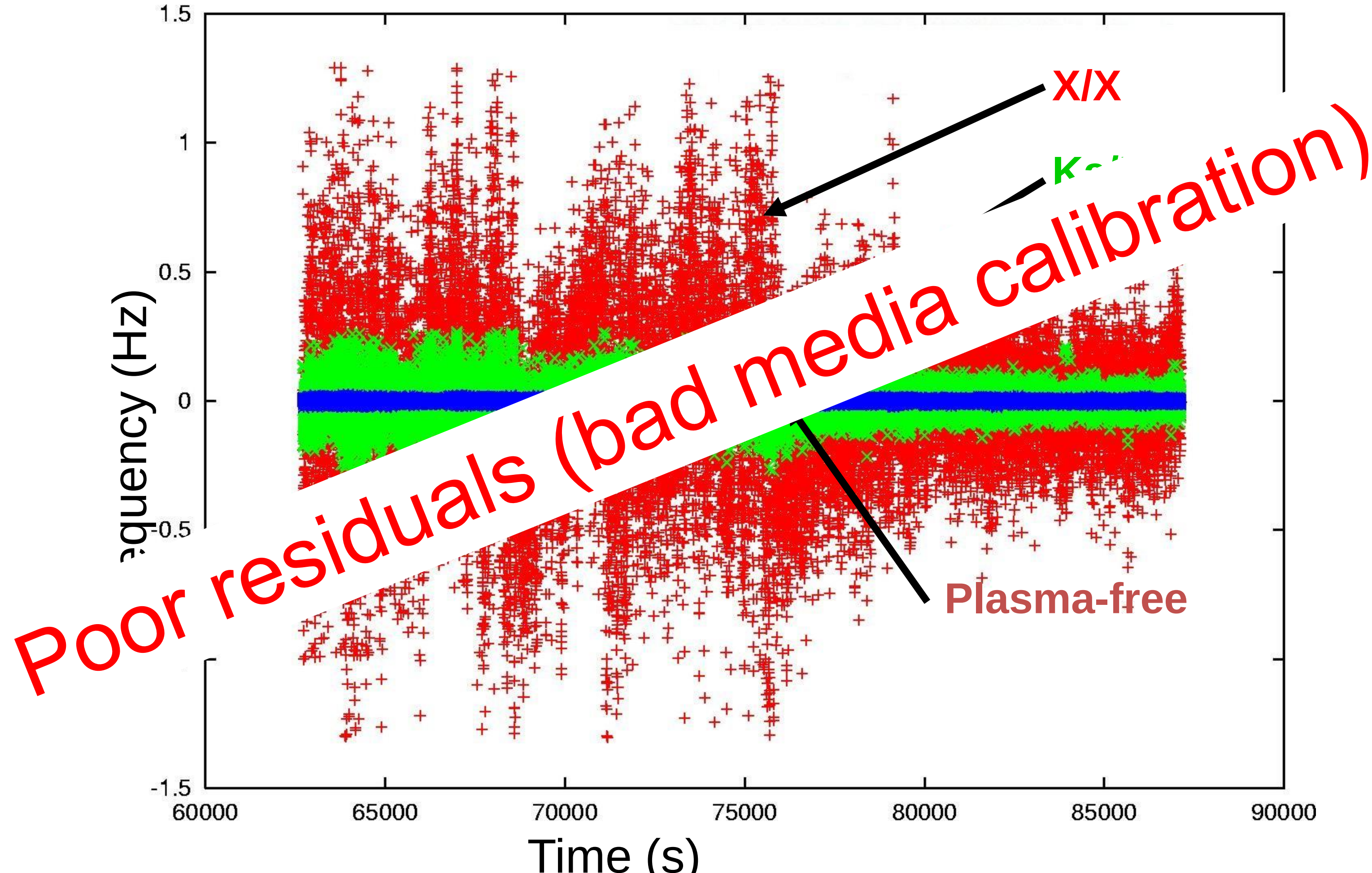


Very good residuals, the ideal scenario

Doppler residuals (2/3)



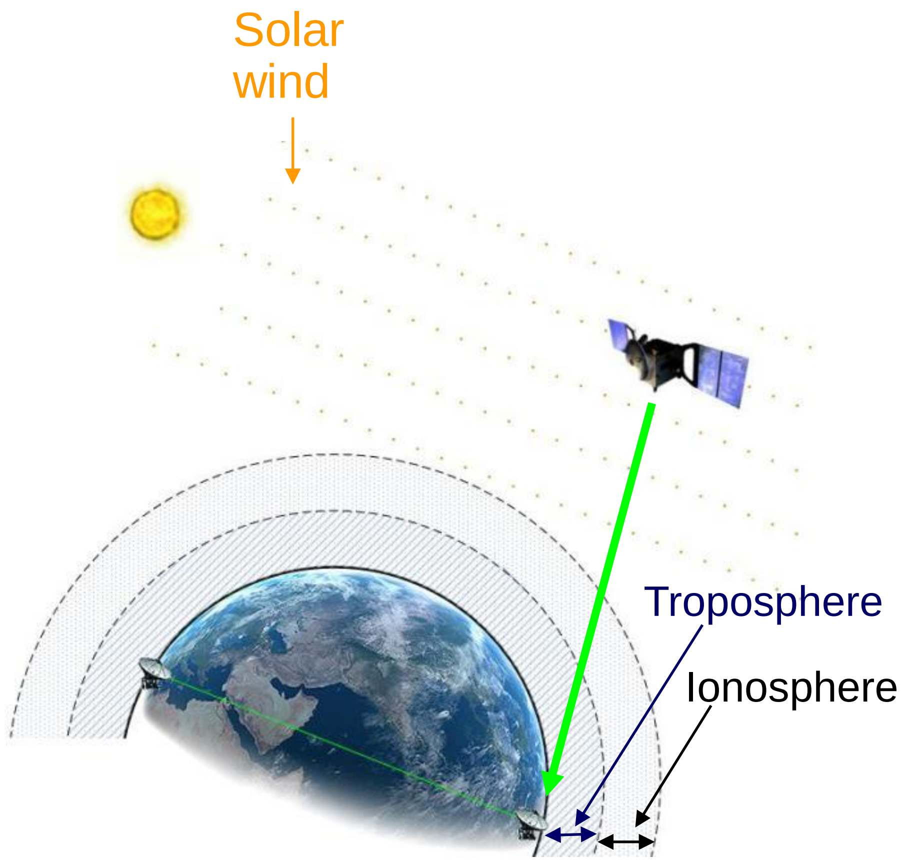
Doppler residuals (3/3)



Transmission Media

Noise sources:

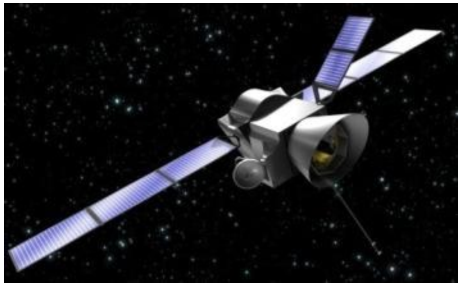
- Solar plasma
- Ionosphere
- Troposphere

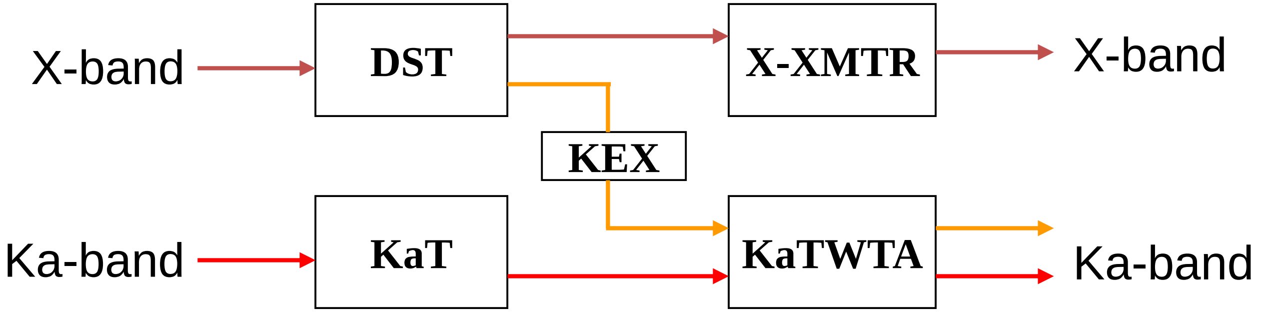


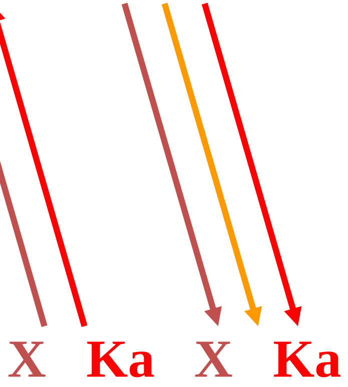
Transmission Media

- Solar plasma
- Ionosphere

Tracking errors resolved with the triple link

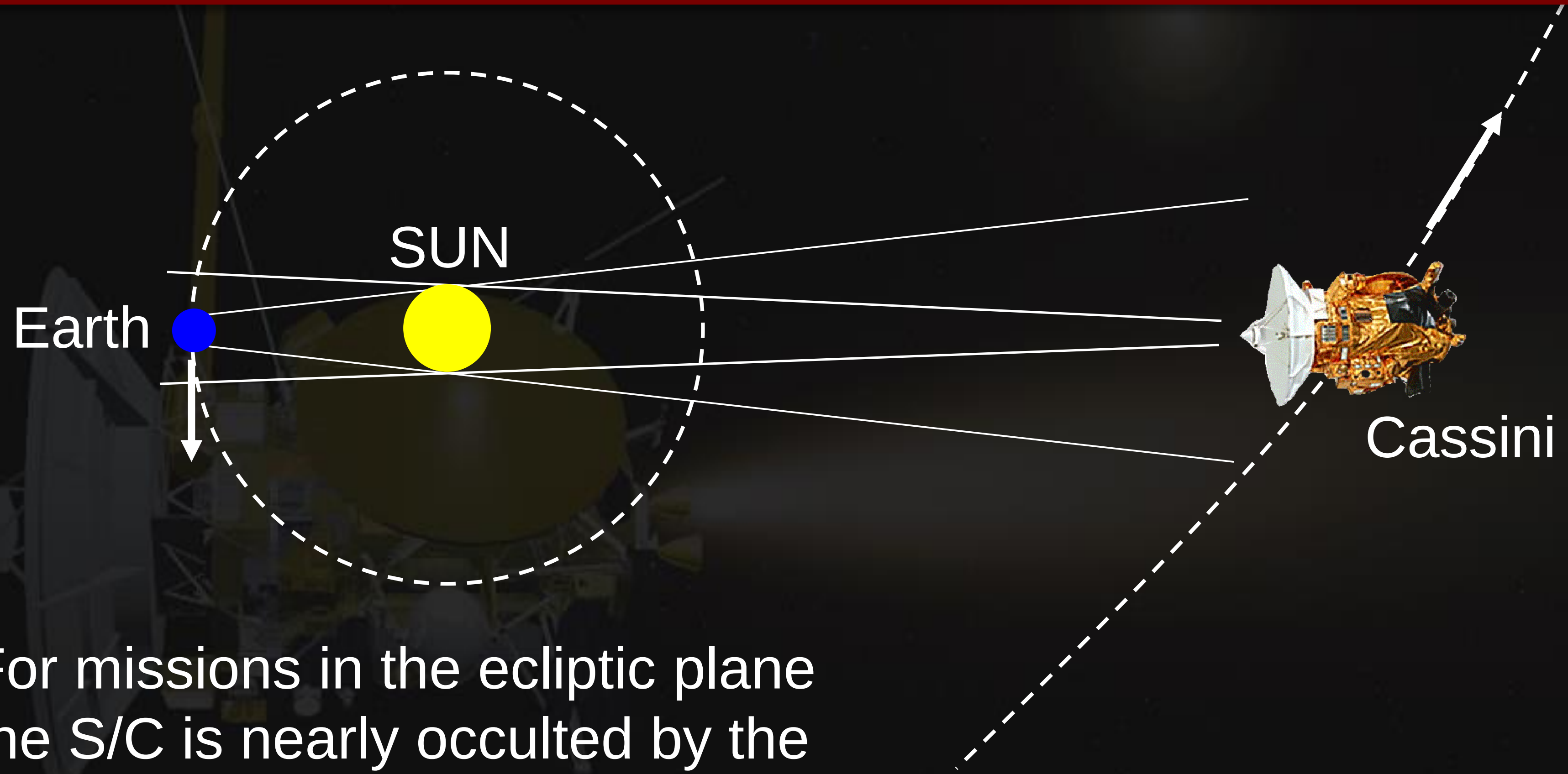






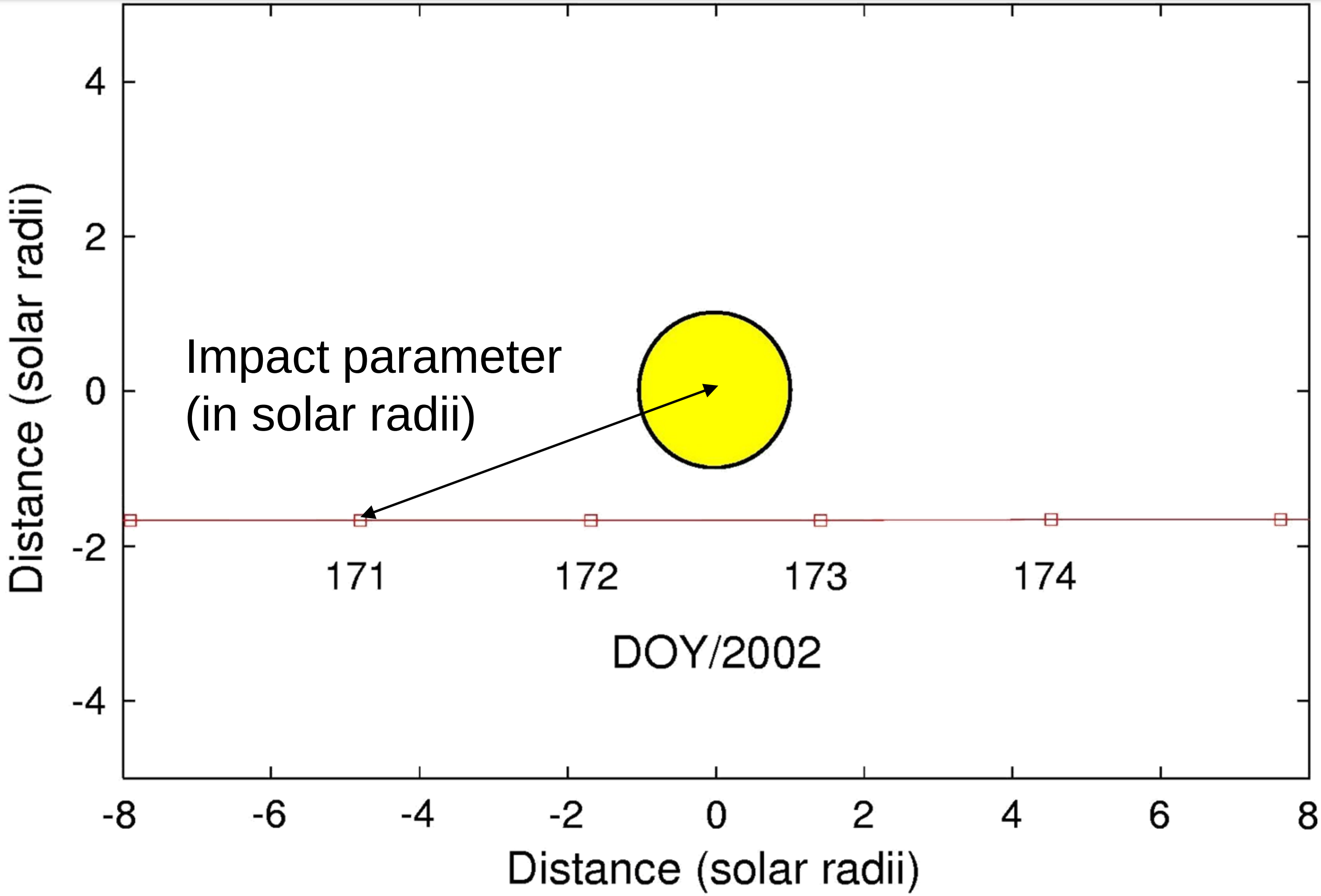
Non standard Ka turnaround ratio 14/15
Ka-band ranging channel

What is a Solar Conjunction?

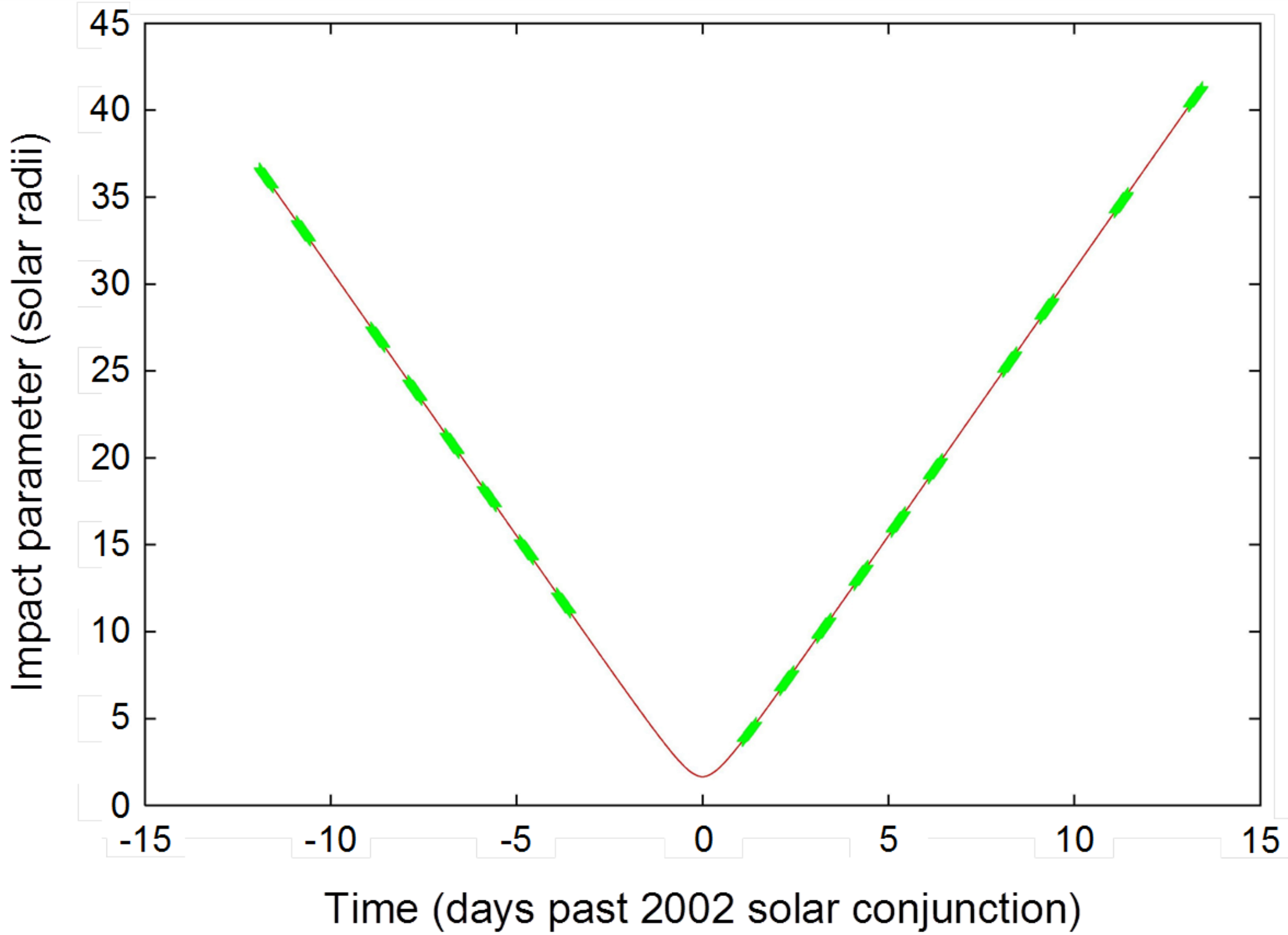


For missions in the ecliptic plane the S/C is nearly occulted by the Sun (as seen from the Earth)

Cassini trajectory wrt the Sun (SCE1)

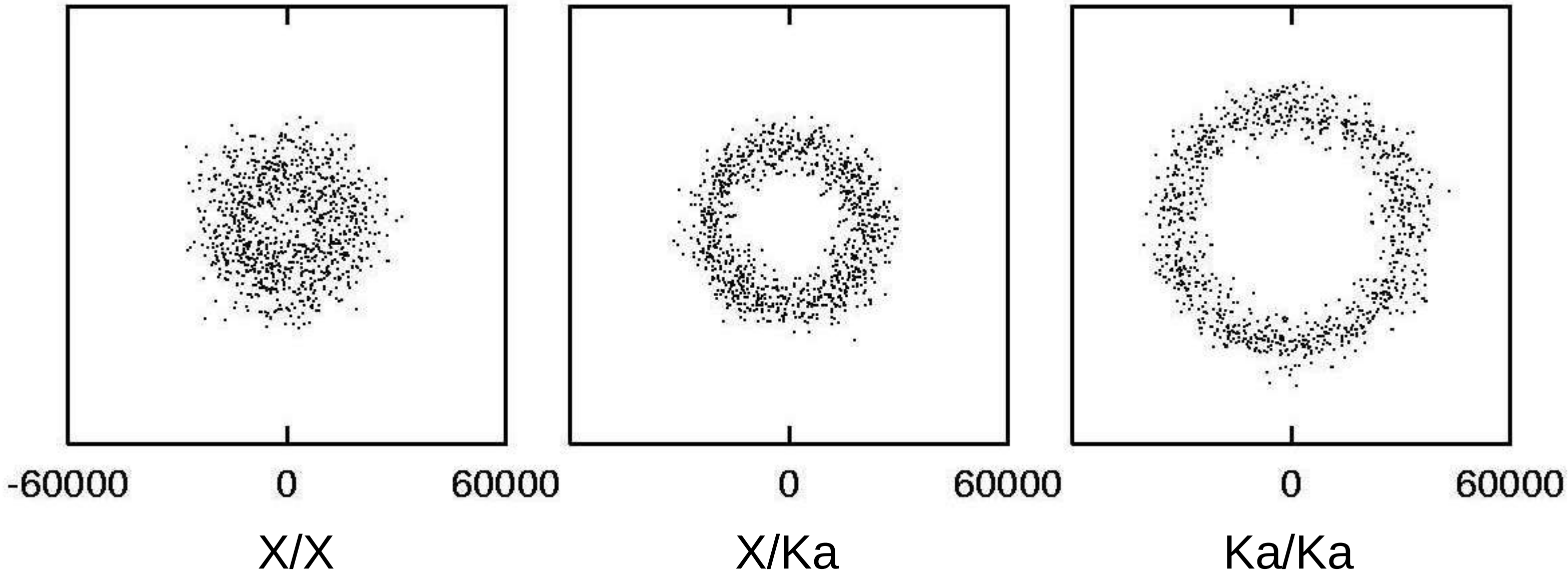


Impact Parameter



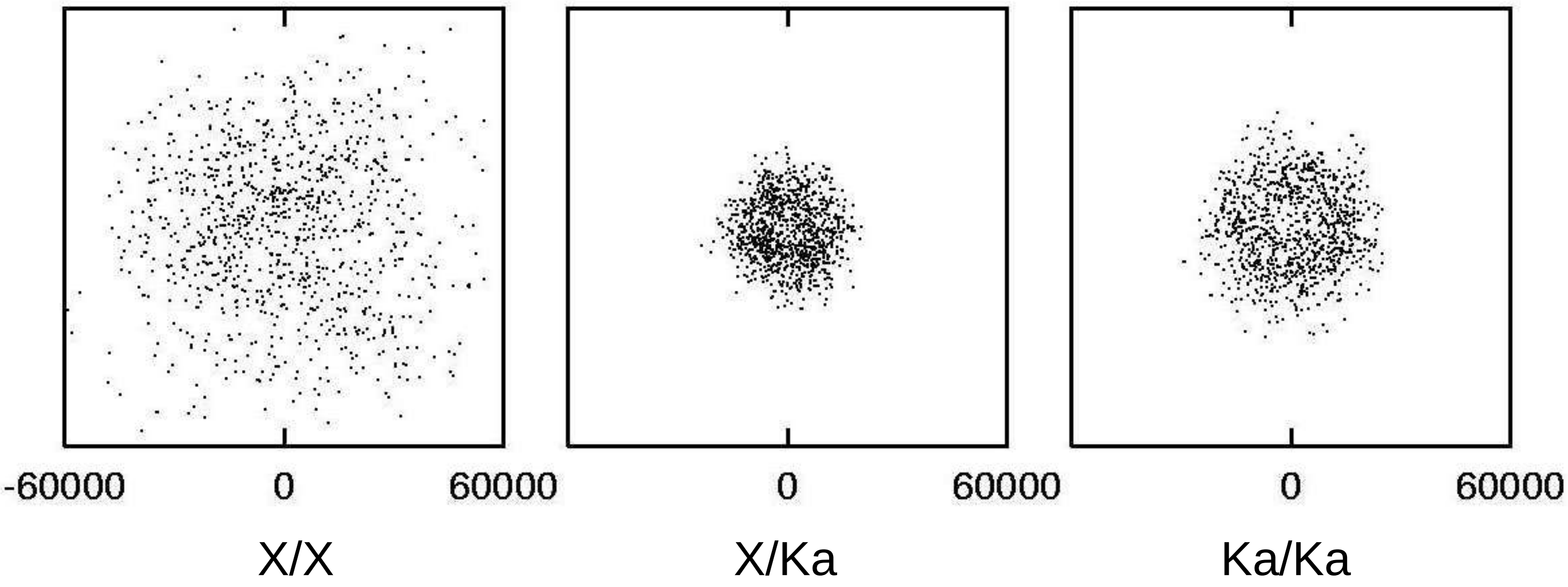
What does the signal look like?

DOY 165, 2002



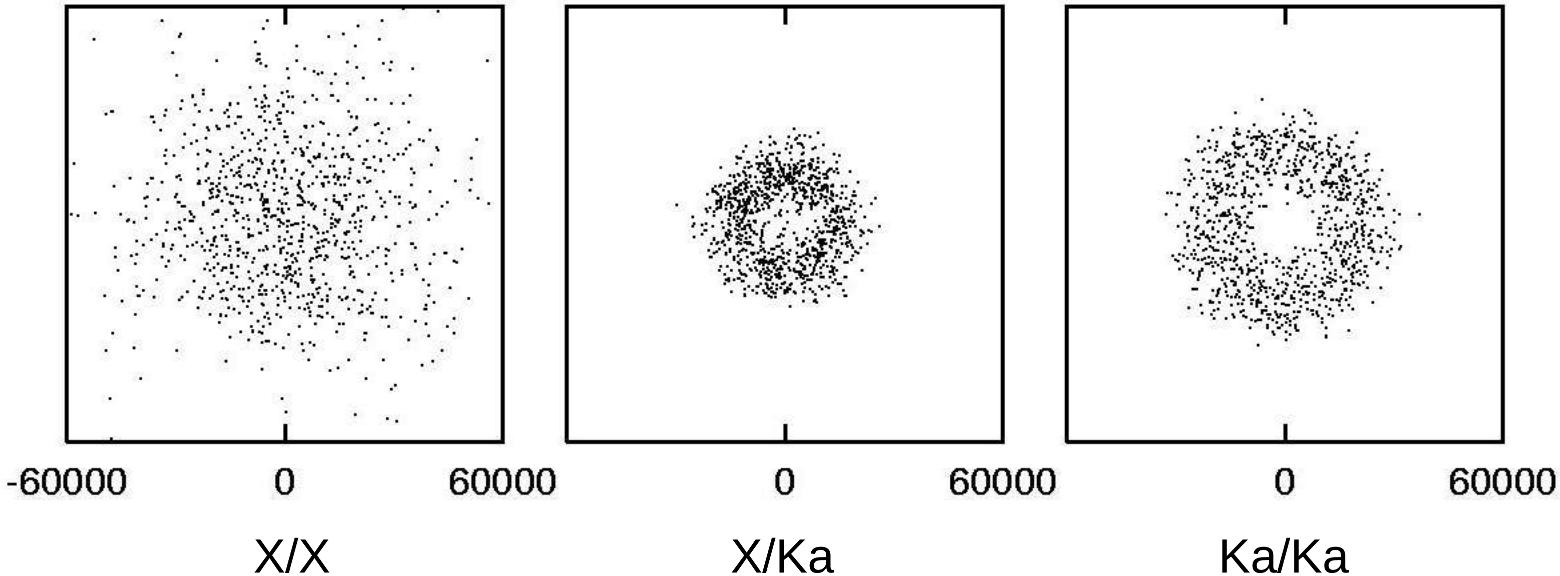
What does the signal look like?

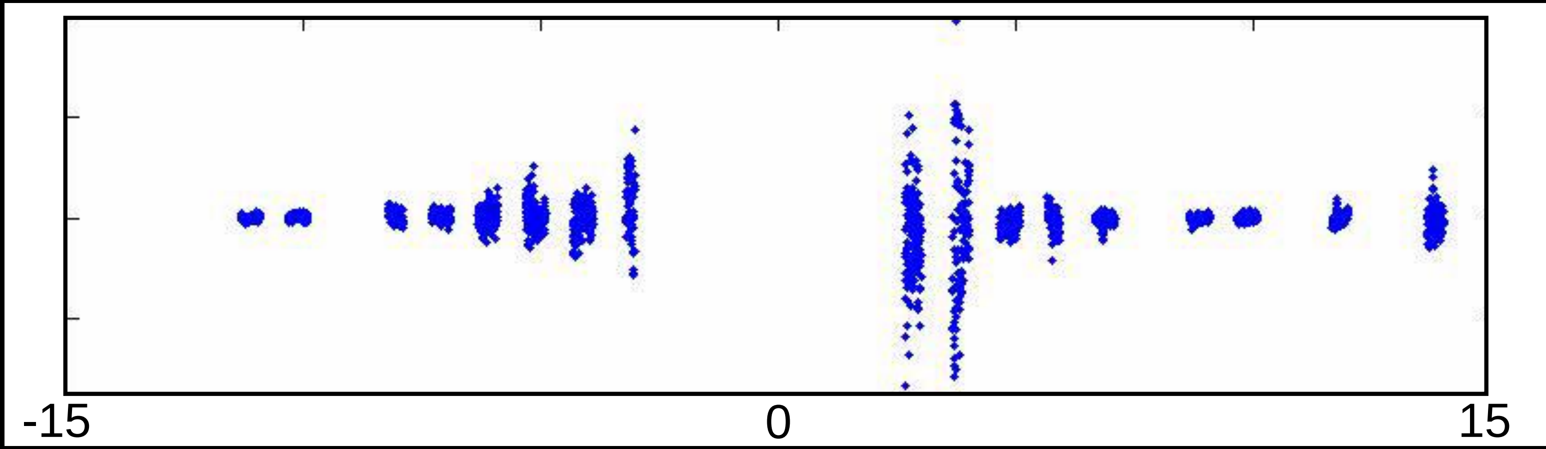
DOY 172, 2002

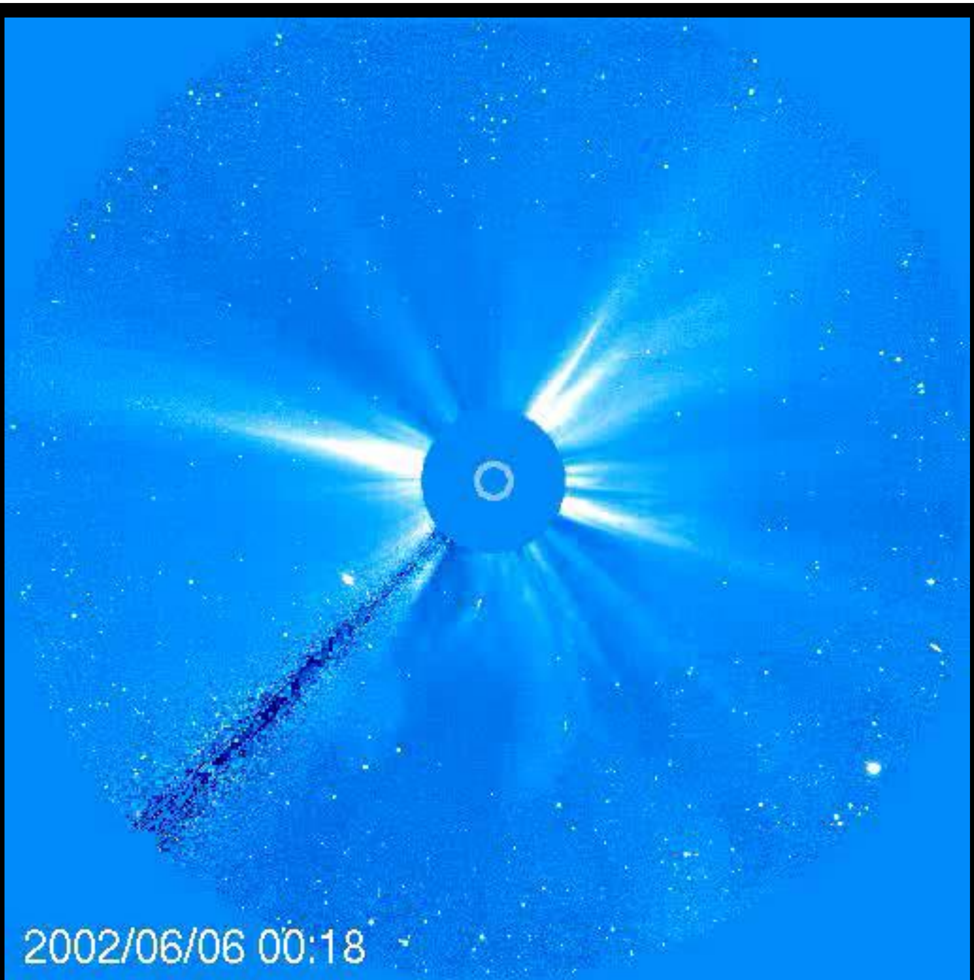


What does the signal look like?

DOY 172, 2002 (ten seconds later)



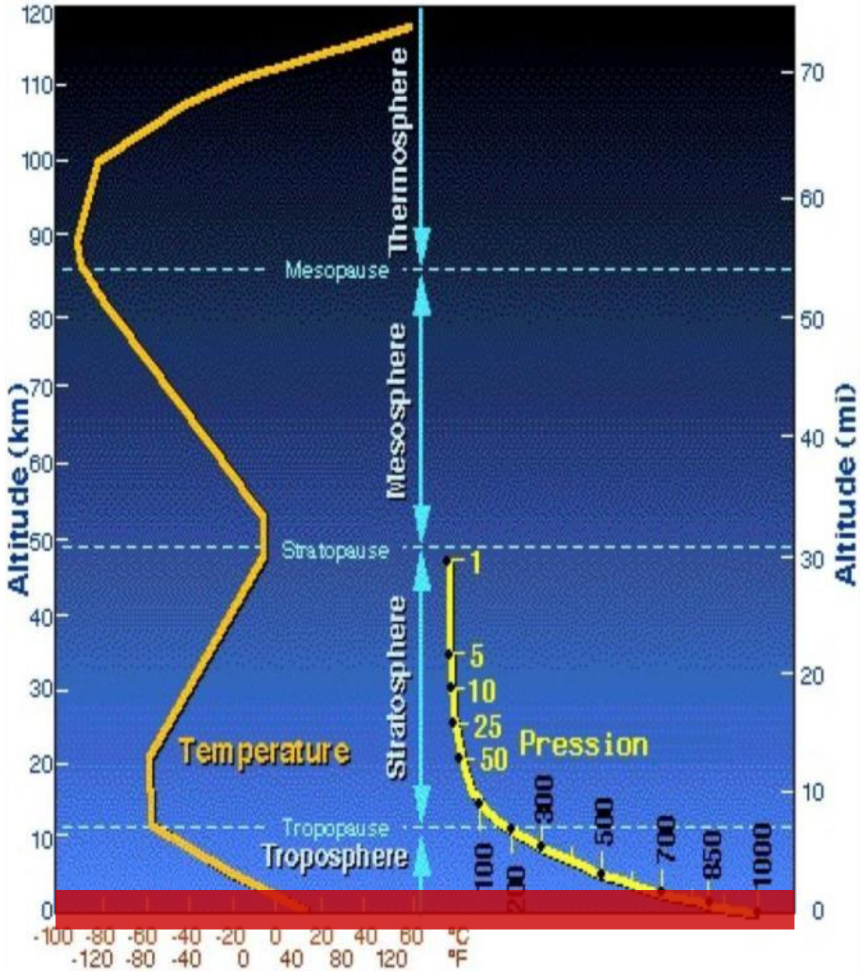

-15
0
15


2002/06/06 00:18

Transmission Media

- Solar plasma
- Ionosphere
- Troposphere

Non - dispersive effect
Depends upon P, T and RH



Tropospheric Path Delay Calibration

- Two components:
  - DRY (2.2 m, molecules in hydrostatic equilibrium)
  - WET (20 cm, water vapor)

- The **DRY** component fluctuates slowly through the day and can be calibrated to sub-mm level by models based on surface weather data (Saastamoinen)

- The **WET** component has a negligible Range contribution but is **relevant in the Range-Rate error budget** (turbulence e inhomogeneous), not possible to model precisely

The Path Delay (PD) scales with satellite's elevation upon the tracking site: the Zenithal value (ZWD, ZHD, ZTD) is scaled to the *slant* direction with a **mapping function** *F = f(elev) (*effect magnification up to 4-5 times*)*

Tropo Delay Calibration Techniques

- **Statistical (Seasonal) models**
  - Weather data is guessed using regressions on statistical weather datasets
  - Calibration effectiveness not adequate to modern radio science requirements
- **Surface weather measurements models**
  - Path delay is retrieved by a mathematical relation to surface pressure, temperature and water vapor pressure
  - DRY component calibrated completely, wet component up to 5-6 cm precision
  - Weather station required at tracking site
- **GNSS-based delay estimation:**
  - Exploits non-dispersive nature: deep-space X- and Ka-bands are affected as GNSS L-band carriers
  - Precise GPS satellites orbits and receivers positions provided by IGS
  - Tropospheric path delay is estimated using traditional point position algorithms used for satellite navigation
  - Geodetic GNSS receiver required at tracking site
- **Microwave Radiometers (MWR)**
  - They measure the brightness temperature of the sky and reconstruct the absorption spectra of substances in the sky (O_2, H_2, N, H_2O)
  - Wet path delay is retrieved from the absorption spectrum by an inverse mathematical approach
  - Wet delay and Doppler shift removal >90%MWR instrument required at tracking site, simultaneous operation with deep-space antenna

Microwave Radiometers

A MWR/WVR measures the atmosphere brightness temperature, collected in the probe tracking direction using its pointing system.

Thanks to dedicated retrieval algorithms, the atmosphere attenuation and the **ZWD** (Zenith Wet Delay), due to the water vapor content of the atmosphere, can be measured.

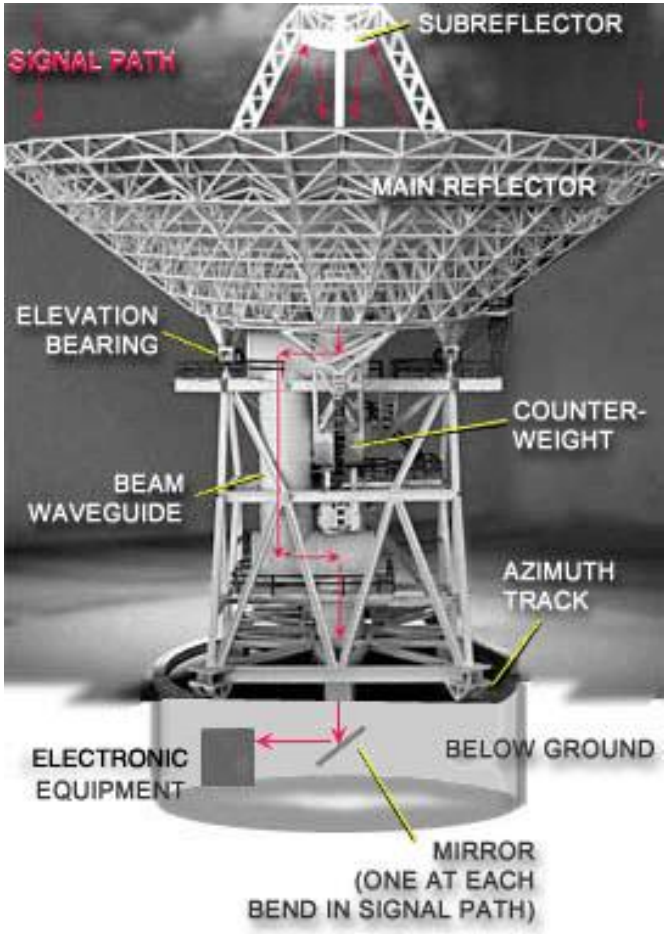
Ground Segments

- NASA – Deep Space Network
- ESA – ESTRACK
- EVN – European VLBI Network
- Jaxa – Usuda Deep Space Center
- ISRO – Deep Space Network

Ground Segments

Beam WaveGuide antenna

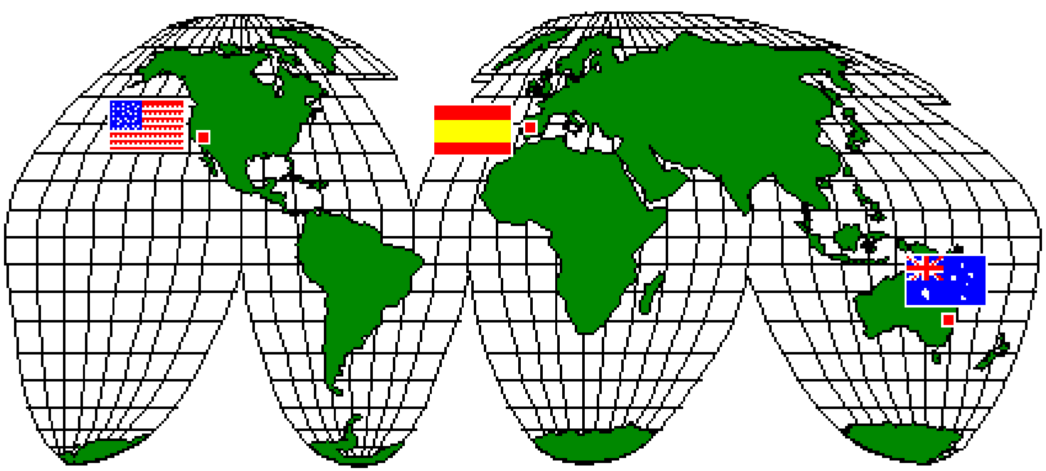
- All the front-end equipment are placed in a large basement under the structure
- The signal is guided via a system of flat and curved reflector
- Multiple feed system, without performance degradation
- Small additional loss caused by the spillover of the beam



NASA DSN

Three complex

- C10 – Goldstone, CA (USA)
- C40 – Canberra (AUS)
- C60 – Madrid (E)



Each complex consists of ultrasensitive receiving systems and large parabolic dish antennas:
26 m antenna
70 m antenna
34 m High Efficiency antenna
34 m Beam Waveguide antenna

Remotely operated from a Signal Processing Center at each complex

About 120° longitude

NASA DSN

Functions and activities

- Telemetry
- S/C commands
- Radiometric tracking
- VLBI
- Radio science
- Monitor and control
- Science

NASA DSN - Goldstone

C10 – Goldstone complex

Antennas:

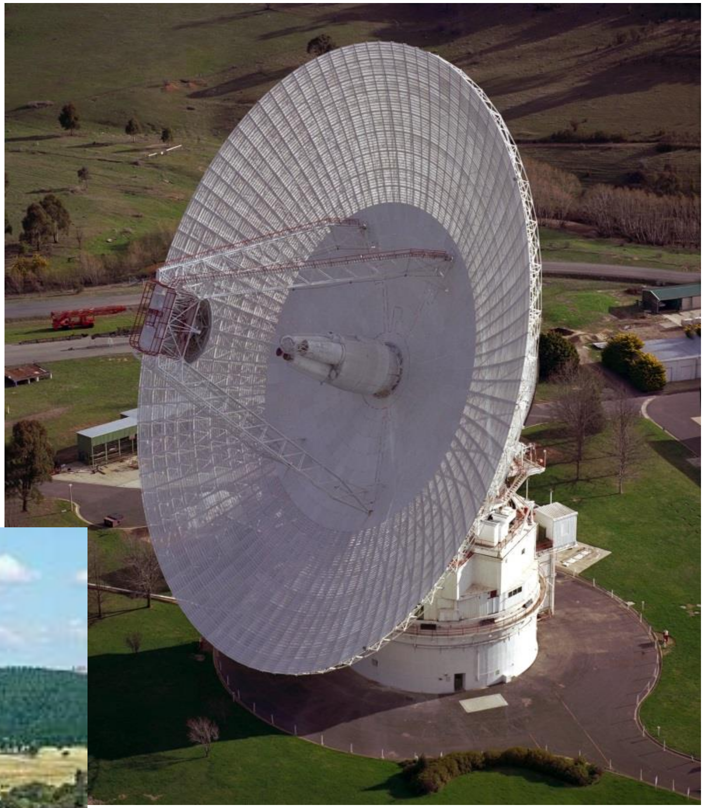
- One 70 m
- One 34 m HEF
- Three 34 m BWG
- One 34 m HSB
- One 26 m

NASA DSN - Canberra

C40 – Canberra complex

Antennas:

- One 70 m
- One 34 m HEF
- One 34 m BWG
- One 26 m

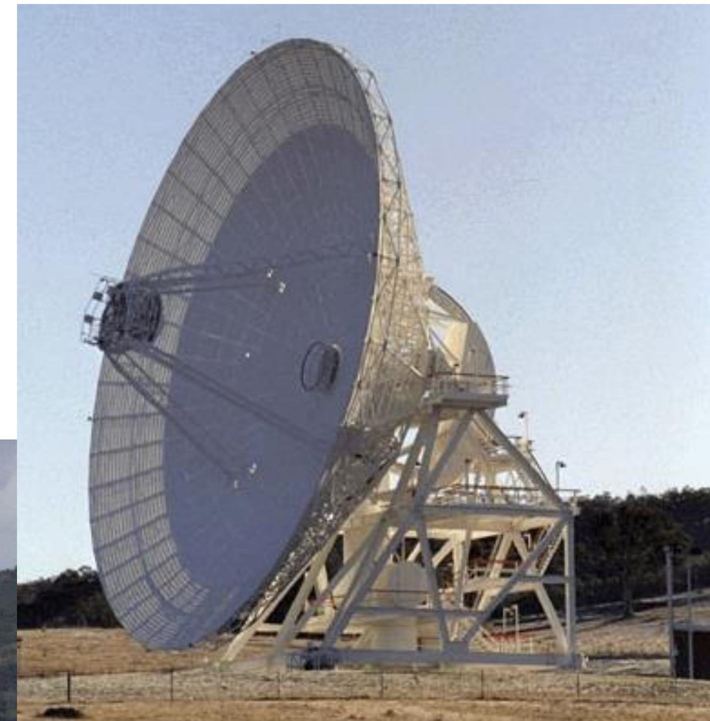


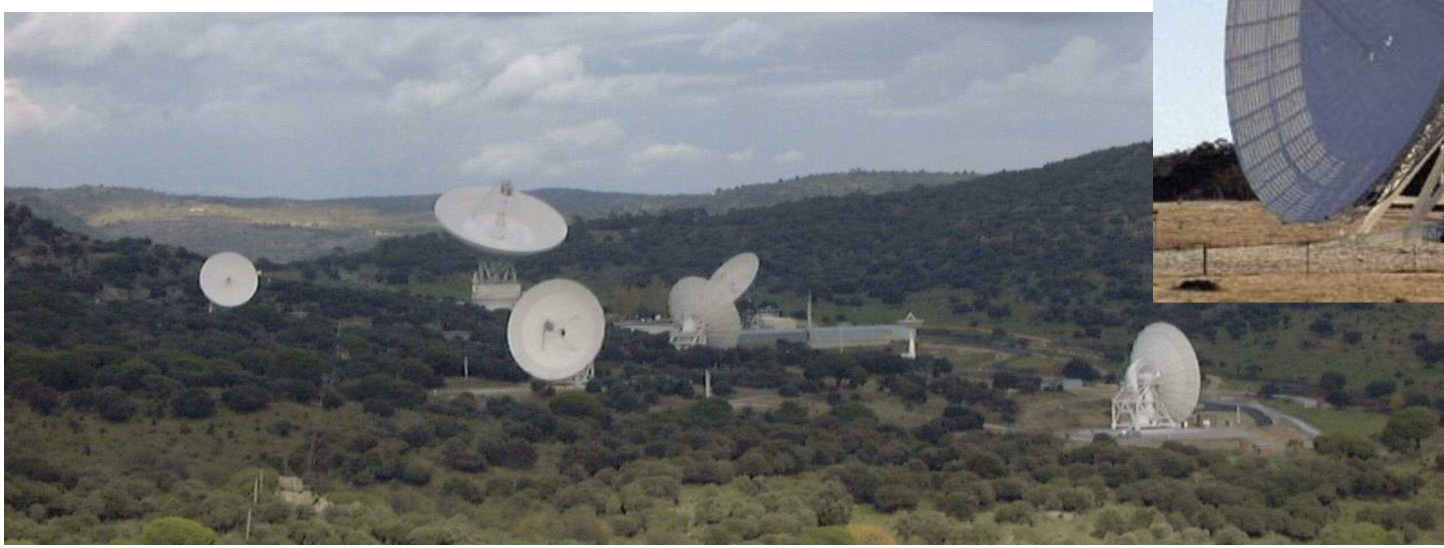
NASA DSN - Madrid

C60 – Madrid complex

Antennas:

- One 70 m
- One 34 m HEF
- Two 34 m BWG
- One 26 m





ESTRACK


Kiruna
Redu
Cebreros
Villafranca
Santa Maria
Maspalomas
Kourou
Malargüe
Perth
New Norcia
COOPERATIVE NETWORK
1 Poker Flat
2 Goldstone
3 Madrid
4 Weilheim
5 ESRANGE
6 HBK
7 Malindi
8 Kerguelen
9 Usuda
10 Masuda
11 Canberra
CORE ESA NETWORK
1 Kourou
2 Kiruna
3 Redu
4 Cebreros
5 Villafranca
6 Maspalomas
7 Perth
8 New Norica
9 Santa Maria
10 Malargüe
AUGMENTED NETWORK
1 South Point
2 Santiago
3 Troll
4 Svalbard
5 Dongara

ESTRACK - Perth

New Norcia, Perth (AUS)

Inaugurated in Apr 2003

First DSS of ESA

35 m diameter parabolic antenna

ESTRACK - Cebreros

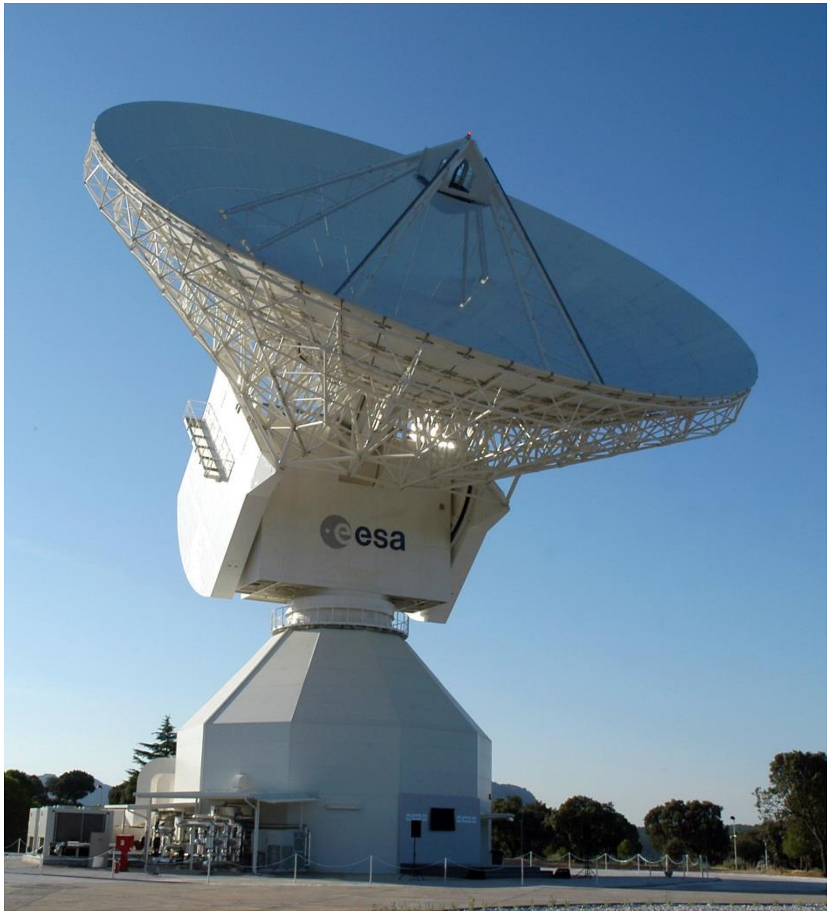
Cebreros, Avila (E)

Inaugurated in Sep 2005

35 m diameter parabolic antenna

Ka band receiver

Maximum pointing error 6 mdeg



ESTRACK - Malargue

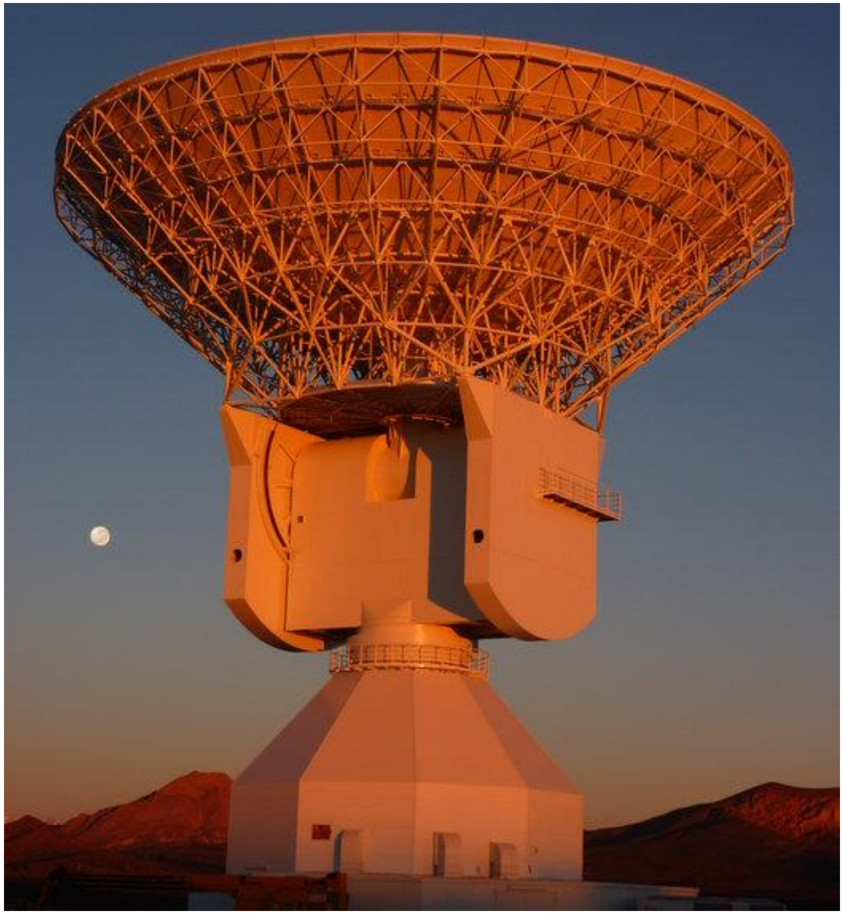
Malargue (Ar)

Inaugurated in Dec 2012

35 m diameter parabolic antenna

Ka band transmitter and receiver

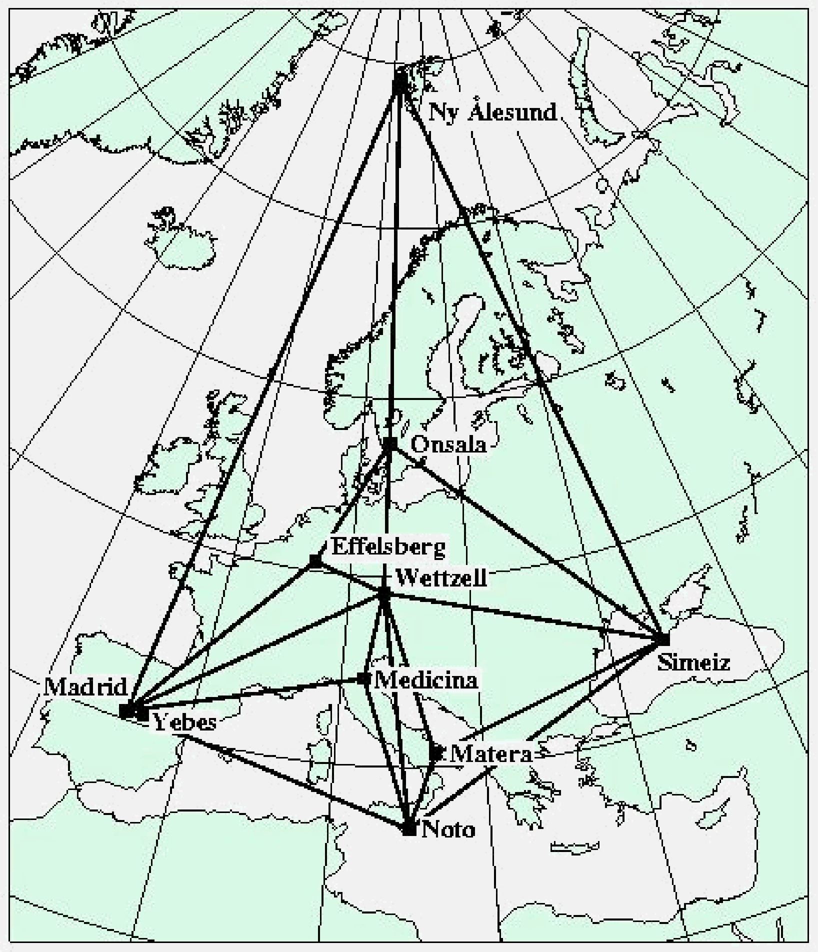
Maximum pointing error 6 mdeg



European VLBI Network

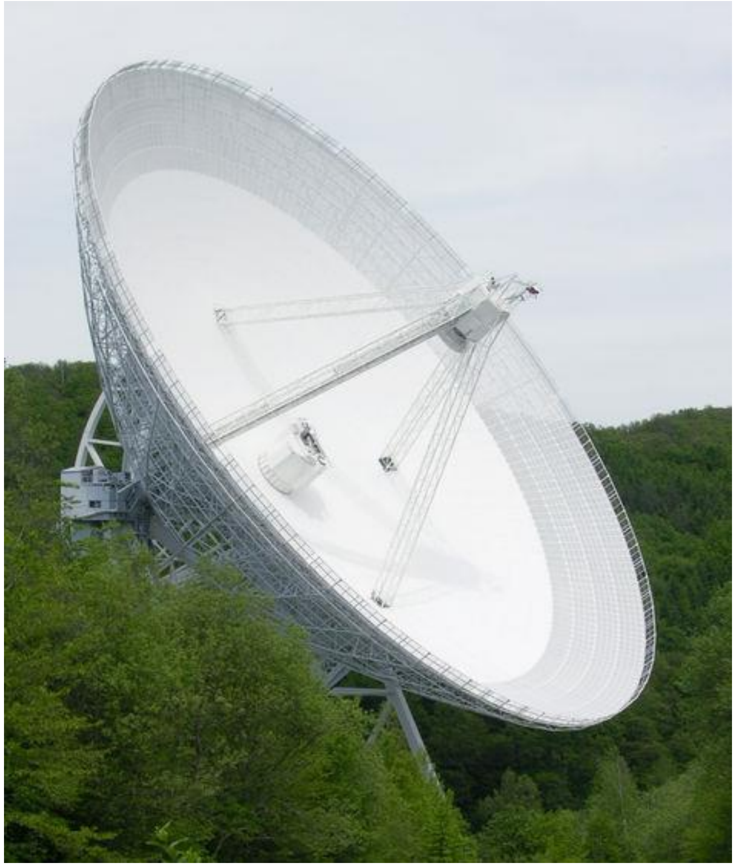
The European VLBI Network (EVN) is an interferometric array of radio telescopes spread throughout Europe and beyond which conduct unique, high resolution, radio astronomical observations of cosmic radio sources

European VLBI Network



European VLBI Network

Effelsberg (D)

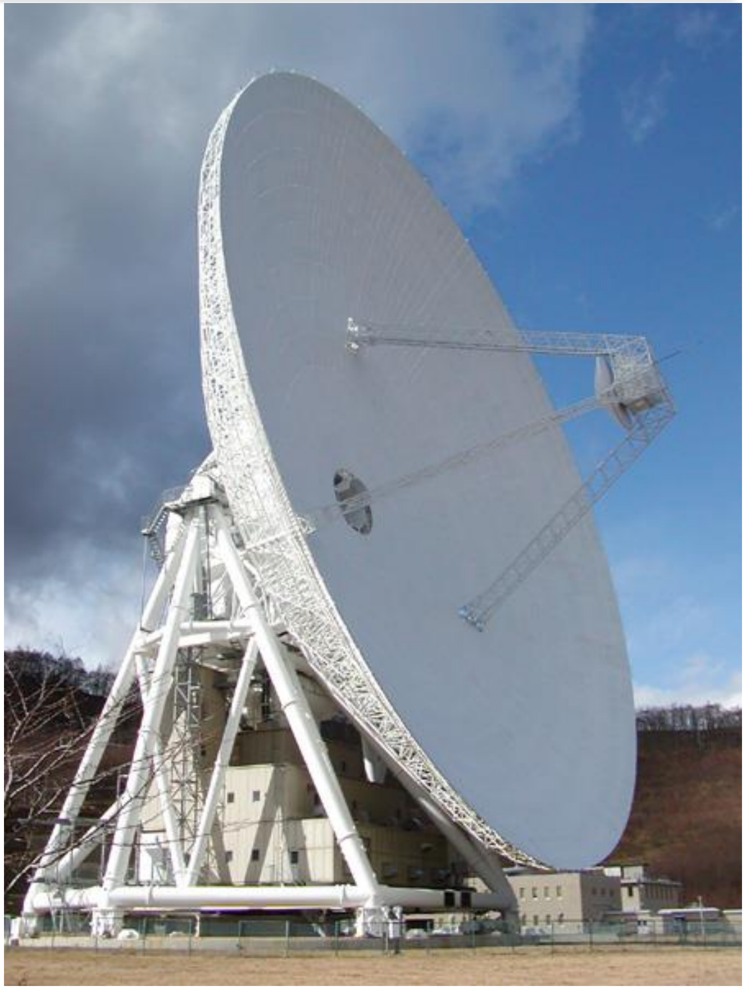


100 m radiotelescope

Operative frequencies: 0.800 to 96 GHz

Usuda Deep Space Center

- 64 m diameter parabolic antenna
- S-band and X-band system
- Tracking, command and telemetry
- Located about 1450 m AGL



ISRO DSN

Placed at Byalalu village, about 40 km from Bangalore

One 18 m antenna operative

One 32 m antenna

One 11 m antenna

S-band and X band system to control Indian probe to the moon and to mars

The System is augmented with a station in Bearslake, Russia and APL/JPL, USA

Conclusions

- Gravity field measurements are powerful tools to constrain the **radial interior structure of the planets** and satellites, providing information on the internal dynamics and evolution;
- The observable quantities used by **gravity science experiments** are obtained by means of spacecraft tracking at microwave frequencies from a ground antenna;
- The main observable for gravity, the **range-rate** is obtained by measuring the Doppler shift of a radio carrier sent by a ground antenna to the spacecraft and coherently retransmitted back to Earth, with uncertainties as low as **~3μm/s @1000s int. time**;
- The availability of state-of-the-art **Orbit Determination Codes**, and space and ground instrumentation to **calibrate for media noises** proves crucial to achieve challenging gravity science objectives.