# *Trajectoires planétaires et interplanétaires*

## Mesures de poursuite interplanétaire

*Pascal Rosenblatt*

*Observatoire Royal de Belgique*

# Mesures de poursuite interplanétaire

## *Interplanetary tracking data*

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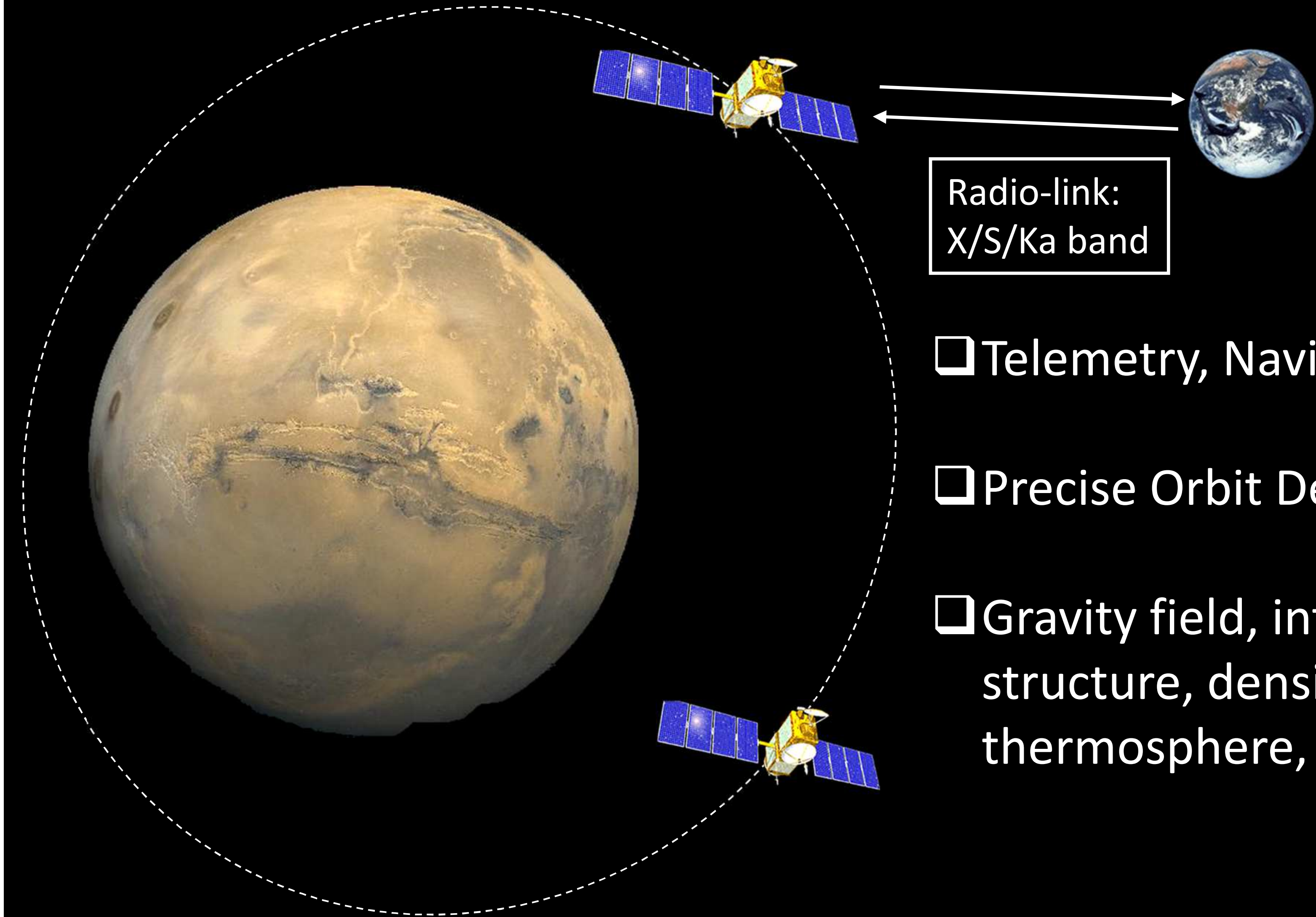
Ecole d'été du GRGS – Trajectoires planétaires et interplanétaires. September 5-9th 2016, Aussois, France.

# Overview

- Deep Space Tracking Stations
  NASA DSN and ESA ESTRACK networks
- Definition and modeling of tracking observables
  Doppler and Ranging
- Propagation media: Plasma and tropospheric effect
- Others techniques: DeltaDoR, SBI, …

# Tracking data for orbiter

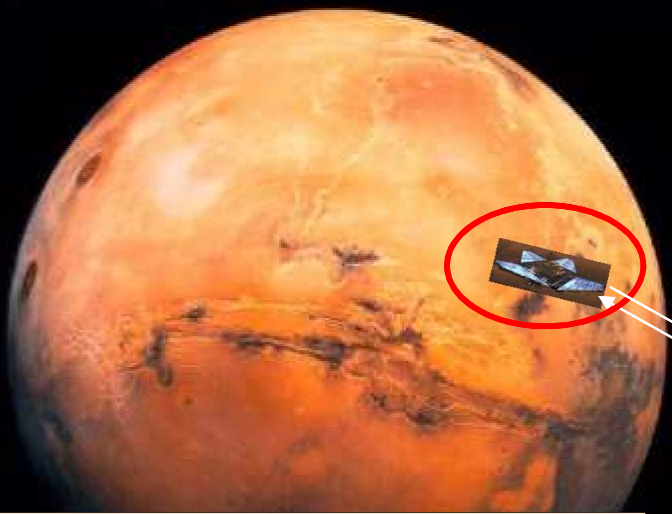



- Telemetry, Navigation
- Precise Orbit Determination
- Gravity field, internal structure, density of the thermosphere, …

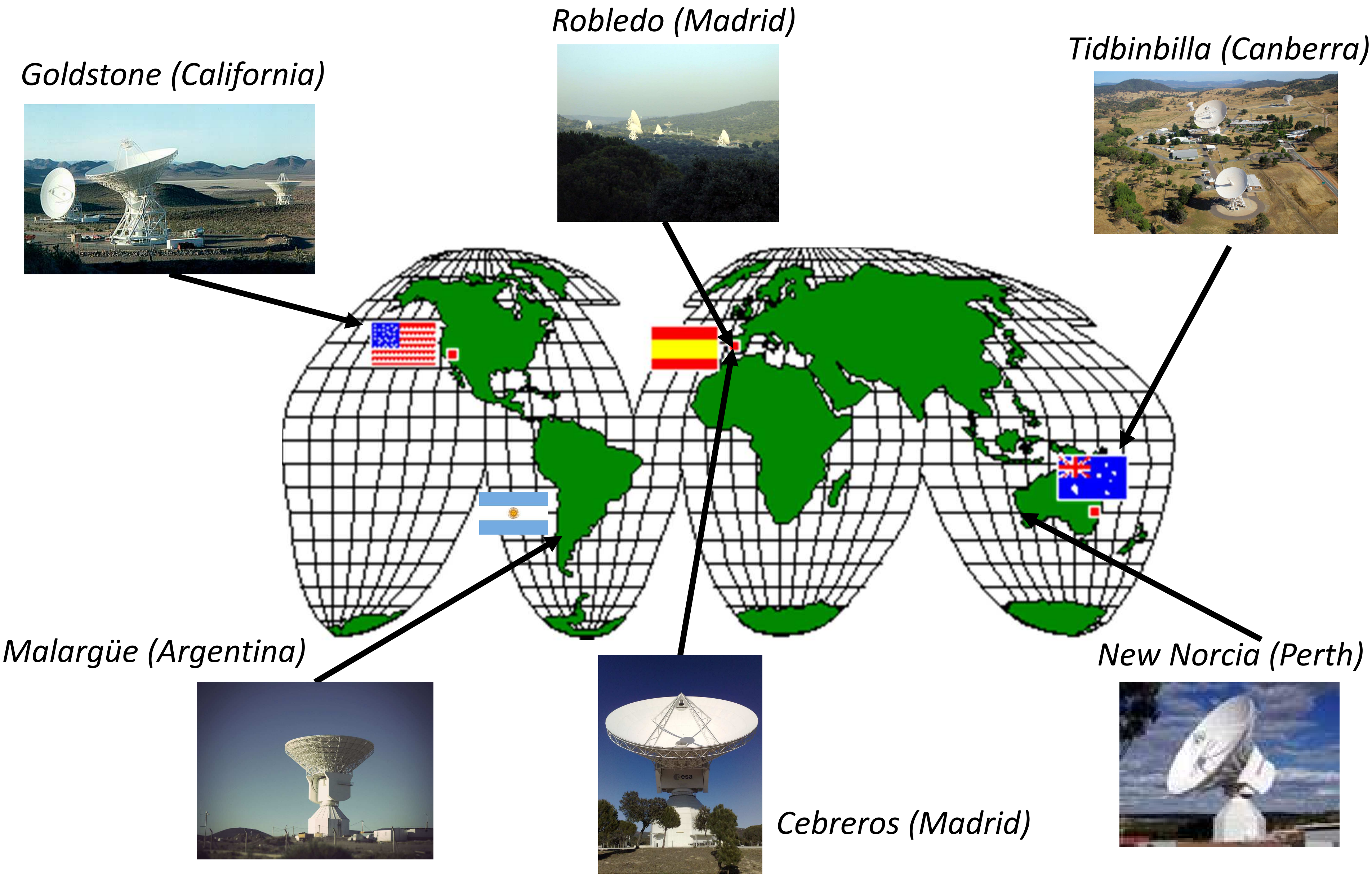
# Tracking data for lander

Direct-To-Earth radio-link

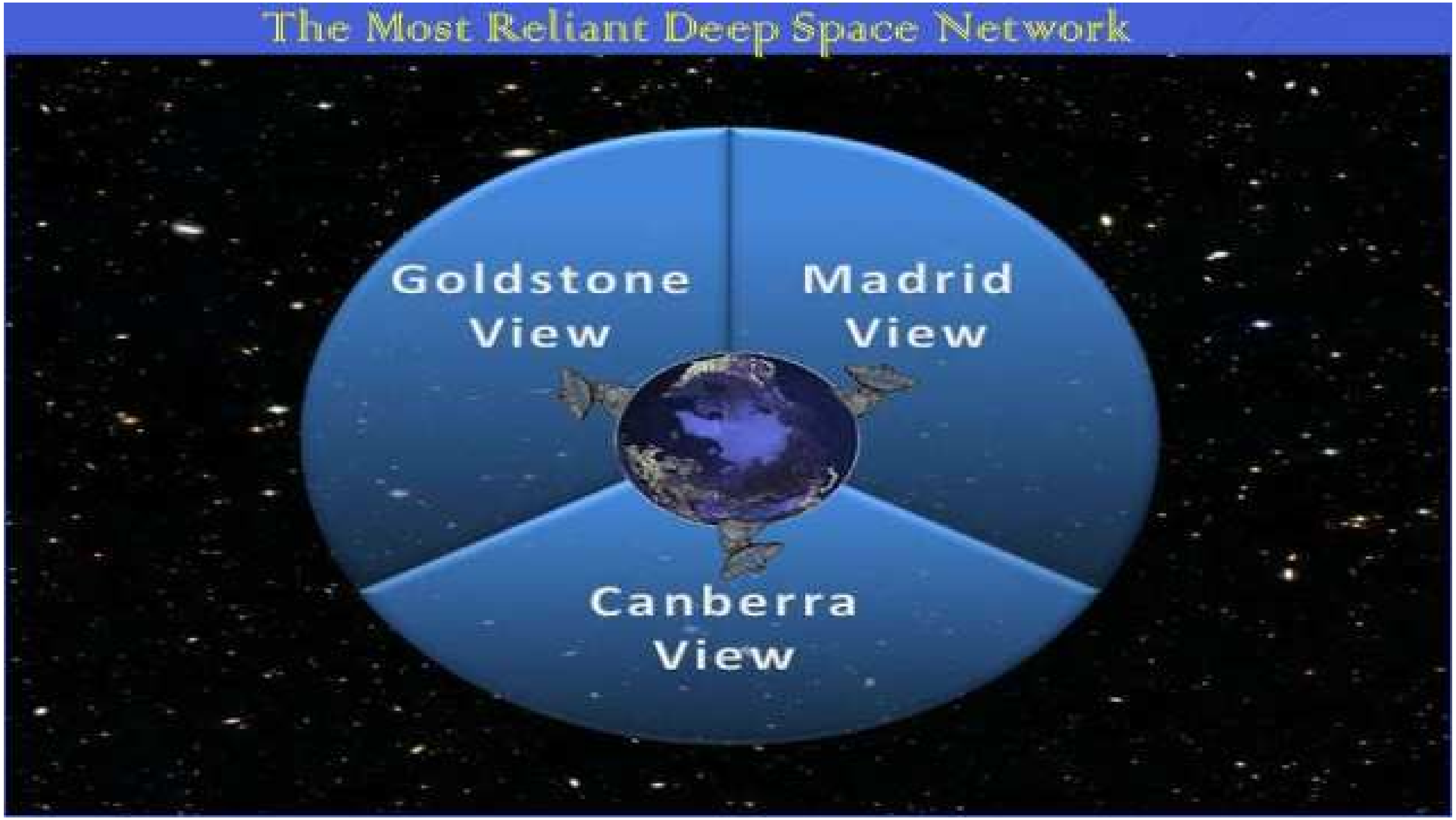
- Telemetry
- Precise positioning
- Rotation & orientation of celestial body
- Deep interior of celestial body



# NASA's DSN and ESA's ESTRACK networks of deep space tracking stations

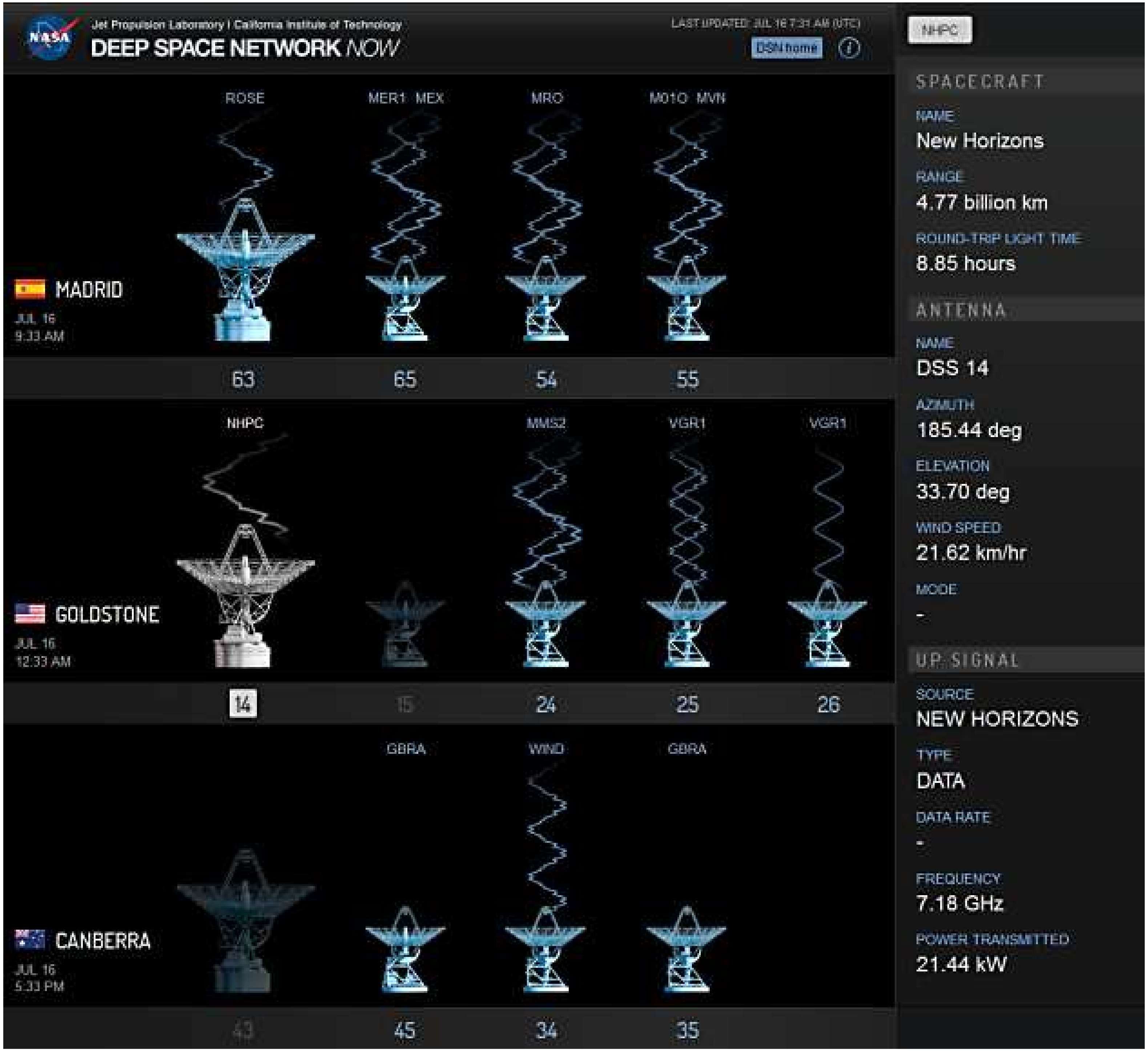


# The NASA Deep Space Network (DSN)




- To track at any time any spacecraft (up to 30) in the Solar system.

https://eyes.nasa.gov/dsn/dsn.html


Jet Propulsion Laboratory | California Institute of Technology
DEEP SPACE NETWORK NOW
LAST UPDATED: JUL 16 7:31 AM (UTC)
DSN home
NHPC
ROSE
MER1 MEX
MRO
M01O MVN
MADRID
JUL 16
9:33 AM
63
65
54
55
NHPC
MMS2
VGR1
VGR1
GOLDSTONE
JUL 16
12:33 AM
14
15
24
25
26
GBRA
WIND
GBRA
CANBERRA
JUL 16
5:33 PM
43
45
34
35
SPACECRAFT
NAME
New Horizons
RANGE
4.77 billion km
ROUND-TRIP LIGHT TIME
8.85 hours
ANTENNA
NAME
DSS 14
AZIMUTH
185.44 deg
ELEVATION
33.70 deg
WIND SPEED
21.62 km/hr
MODE
-
UP SIGNAL
SOURCE
NEW HORIZONS
TYPE
DATA
DATA RATE
-
FREQUENCY
7.18 GHz
POWER TRANSMITTED
21.44 kW

# Goldstone complex (1958) – Madrid complex (1974)
# Canberra complex (1965)

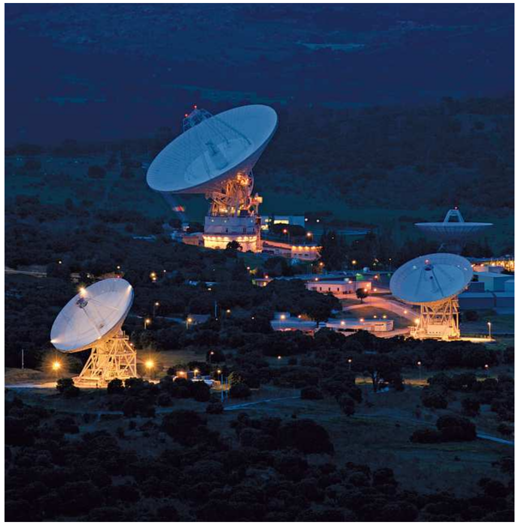
*70m antenna*
*(8000 tons - 3500 tons Parabola dish)*

At each site one single 70m antenna:

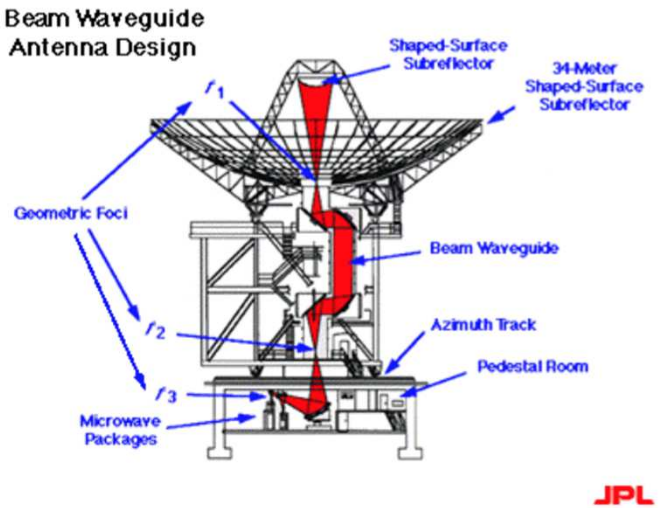
Goldstone (DSS-14), Madrid (DSS-63) & Canberra (DSS-43)

Originally 64m diameter, then enlarged to 70m
in 80's for supporting Voyager missions.

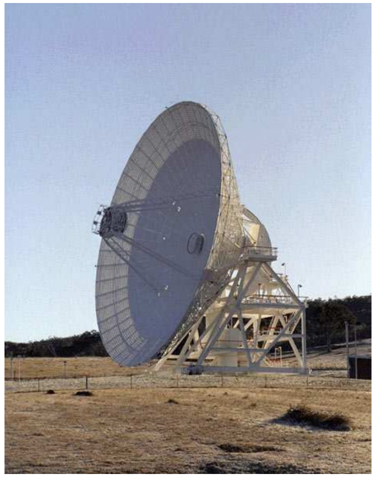
Transmitting/Receiving at X (8.4 GHz) & S-band (2.3 GHz)



# Goldstone complex (1958) – Madrid complex (1974) Canberra complex (1965)




*Transmitter/Receiver devices underground instead of being on the top.*



BWG antenna

HEF antenna

<u>*34m Beam Wave Guide antenna (BWG):*</u>

6 at Goldstone (DSS-13
DSS-24, DSS-25 , DSS-26, DSS-27 & DSS-28)

2 at Madrid (DSS-54 & DSS-55)

1 at Canberra (DSS-34)

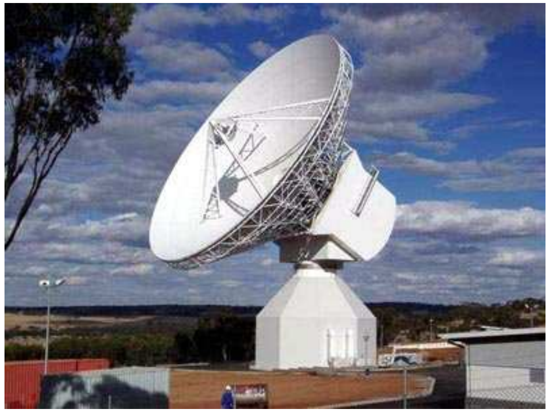
<u>*34m High EFficiency (HEF):*</u>

1 at Goldstone (DSS-15)
1 at Madrid (DSS-65)
3 at Canberra (DSS-35, DSS-36, DSS-45)
(*DSS-36 expected for 2016*)

*Antennas operating at S,X bands.*
*Ka band: for DSS-25 (Transmission/Reception)*
*for others reception only.*

# ESTRACK deep space tracking stations

- New Norcia (NNO) → Australia (Perth)
  Transmission (S/X) – Reception (S/X)



- Cebreros (CEB) → Madrid (Spain)
  Transmission (X) – Reception (S/X)

- Malargüe (MAL) → Argentina
  Transmission (X) – Reception (X/Ka)
  *soon Transmission & Reception (Ka)*
  *(Bepi-colombo, JUICE missions)*

# The Russian deep space network

Eupatoria (70 meters)

- ✓ 3 sites with 3 Parabolic dishes:

  Eupatoria (Crimea) – 70m

  Oussouriisk (Far-East) – 70m

  Bear Lake (near Moscow) – 64m

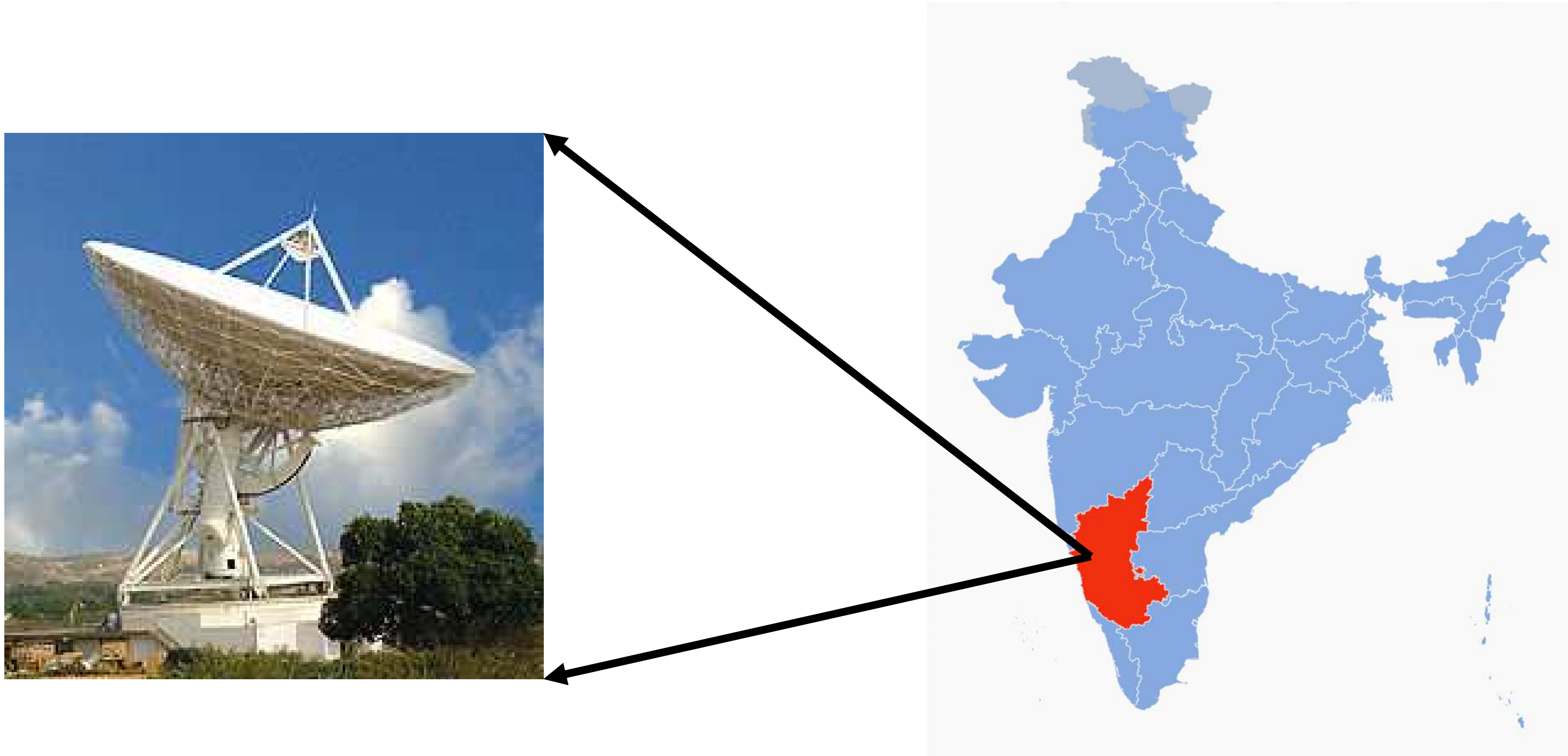
- ✓ Designed for deep space missions
  Ex: Phobos-2 (C-band, 5.3 GHz)

- ✓ Possibly for ExoMars2016 and ExoMars2018 ?

# The Japanese deep space complex


- ✓ Usuda Deep Space Complex
- ✓ Main dish 64m antenna with Beam Wave Guide equipment

# The Indian deep space complex

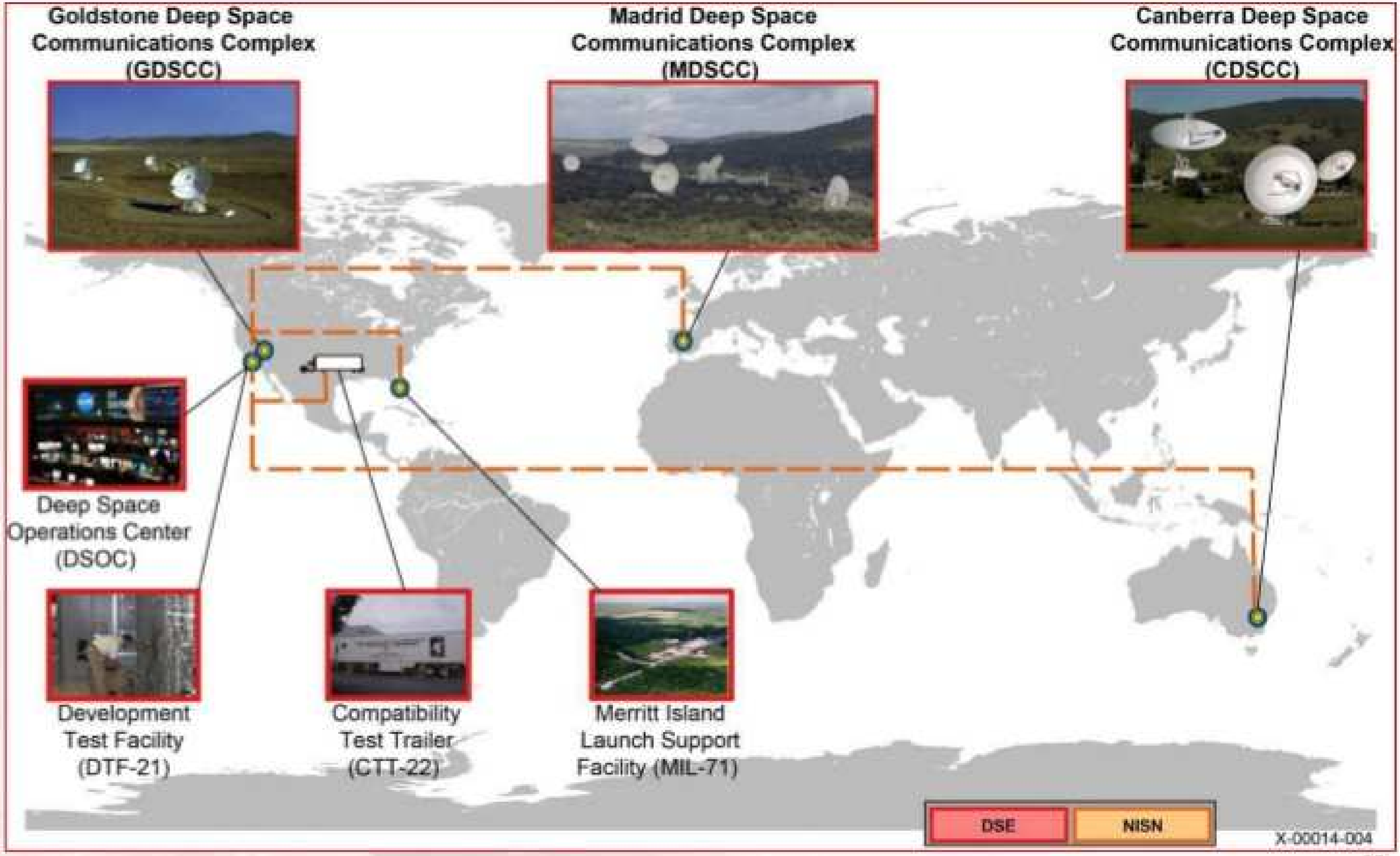


- ✓ Byalalu, Ramanagara district, Karnataka province
- ✓ 3 antennas with diameter of 32m, 18m & 11m (S-band)
  Support to Chandrayaan-1 and Mars Orbiter mission

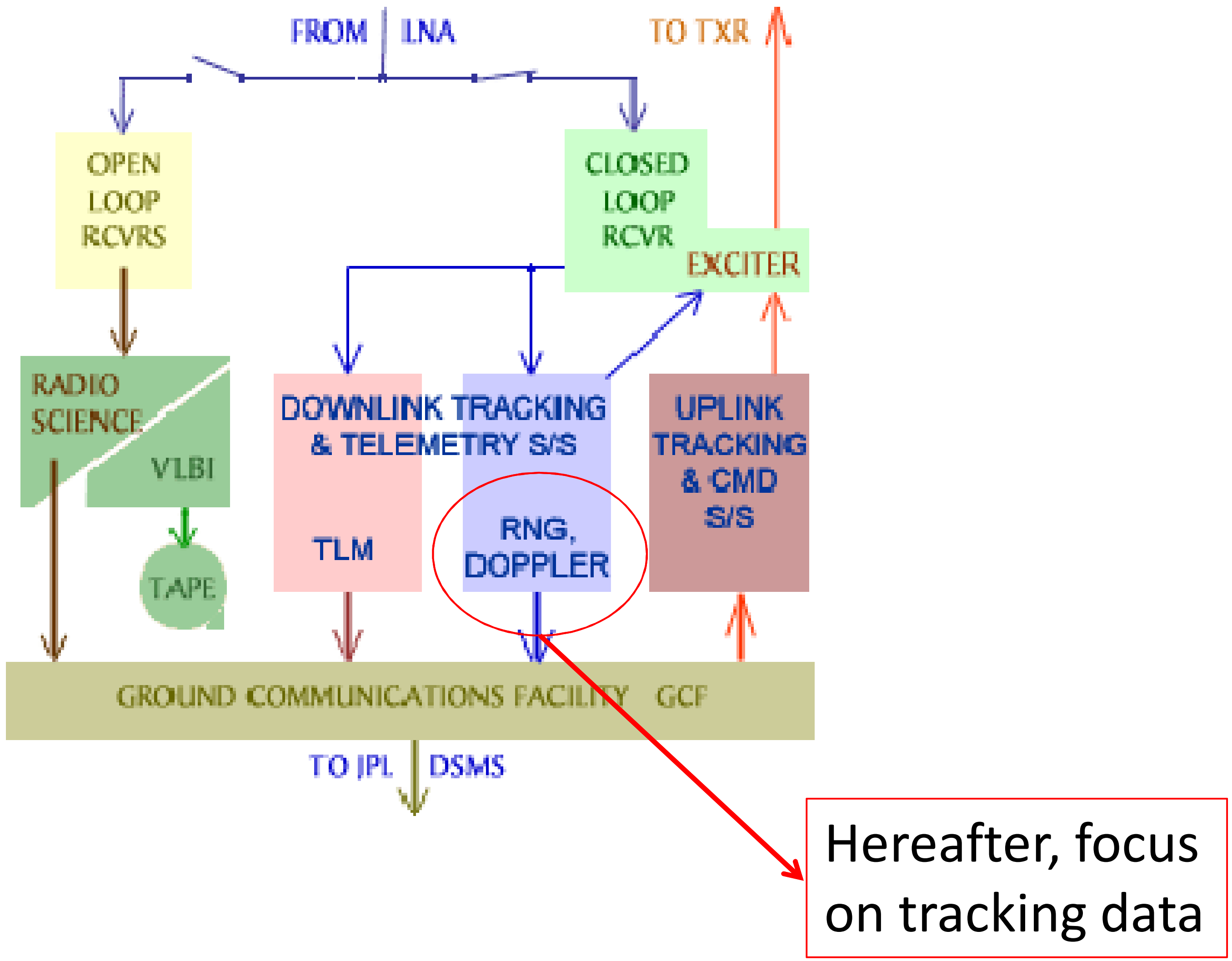
# The Chinese deep space complex

- ✓ 18m antennas at Kashgar & Qingdao - 40m antenna in Yunnan
  50m antenna at Miyun near Beijing - 64m antenna in Jiamusi
  *35m antenna under construction at Kashgar* and *additional ground station in Argentina by 2016*
- ✓ Support to Chang'e -1, -2, -3 missions to the Moon (*next Mars?*).

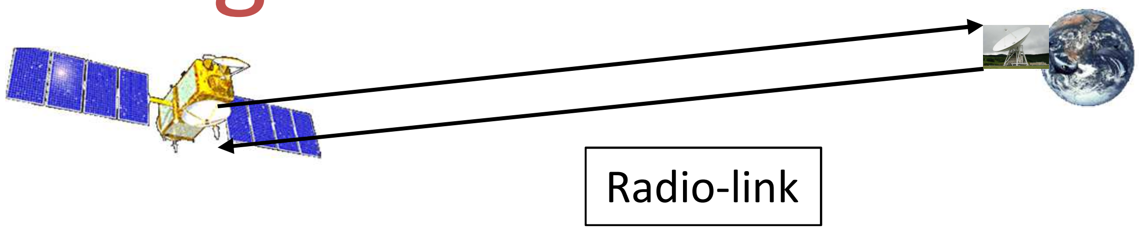
# Deep Space Network → Deep Space Element (DSE)



# General diagram of ground stations data flow



# Basics of tracking measurements: Establishing a radio-link



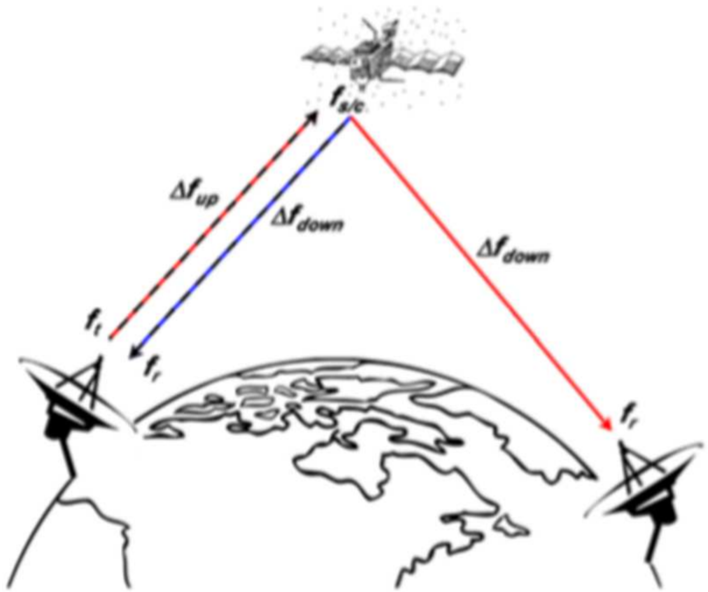

- **Radio-link** between the spacecraft (or lander) and tracking stations:

  Uplink : From Earth to spacecraft
  Downlink: From spacecraft to Earth

- **Carrier frequency bands**

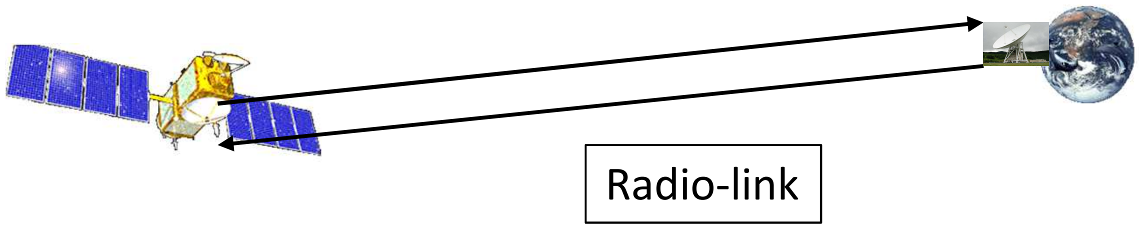
  S-band: ~2.1 GHz in Uplink and ~2.3 GHz in Downlink
  X-band: ~7.2 GHz in Uplink and ~8.4 GHz in Downlink
  Ka band: ~32 GHz in Uplink and ~32.5 GHz in Downlink

# Basics of tracking measurements: Operation modes



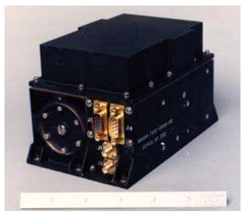
- ✓ **1-way:** Only downlink
- ✓ **2-way:** Uplink and Downlink using the same ground antenna
- ✓ **3-way:** Uplink and Downlink using two different antennas

# Basics of tracking measurements: What do we need?

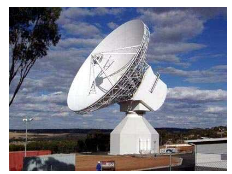



- **Radio-transponder** onboard the spacecraft (or lander) for 2/3-way radio-link that send back to Earth the radio-signal without modifying its phase.

- **or Ultra-stable Oscillator (USO)** onboard the spacecraft for 1-way radio-link to provide a stable reference frequency and precise datation.
  USO stability (at least $5x10^{-12}$ *Allan deviation*)



- **Ground stations** antennas and electronics for transmitting and receiving radio-signals.

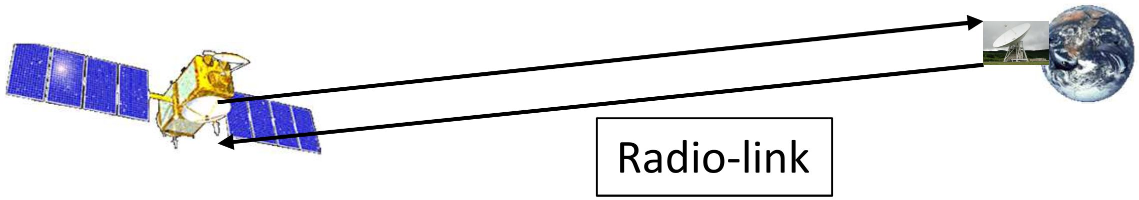


# Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation

**Theodore D. Moyer**

Jet Propulsion Laboratory
California Institute of Technology

# Basics of tracking measurements: DSN Frequency-Phase recording




- What do the antennas measure?

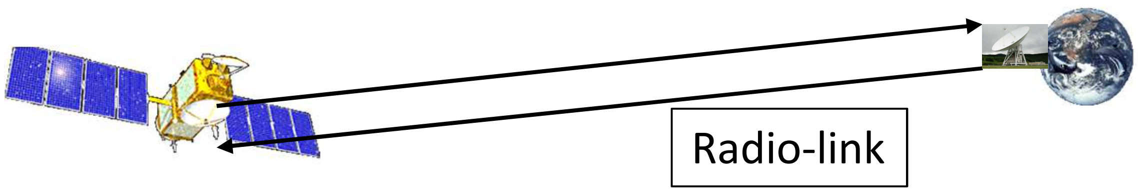
**The frequency and phase of the downlink of the carrier signal at reception time at receiving station.**

- How is it performed? -> Using Closed-loop electronics device

**Down-converting the received frequency and comparing it with the reference frequency of the local oscillator (~22 MHz).**

**Datation using MASER clock: Stability $10^{-15}$ (Allan deviation)**

# DSN tracking observables: Doppler



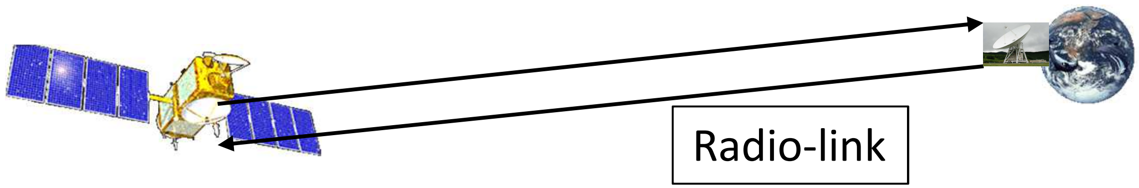

- Doppler cycle count:

  **It measures the number of cycles of the received frequency that accumulates from the beginning of the tracking pass to the current receiving time (given every 0.1 second).**

- Doppler Observable:

  **Change in the Doppler cycle count that accumulate over a given time interval $T_c$ (*Doppler count time*).**
  **Successive $T_c$ intervals over the entire tracking pass.**

# DSN tracking observables: Range




- Range observable:

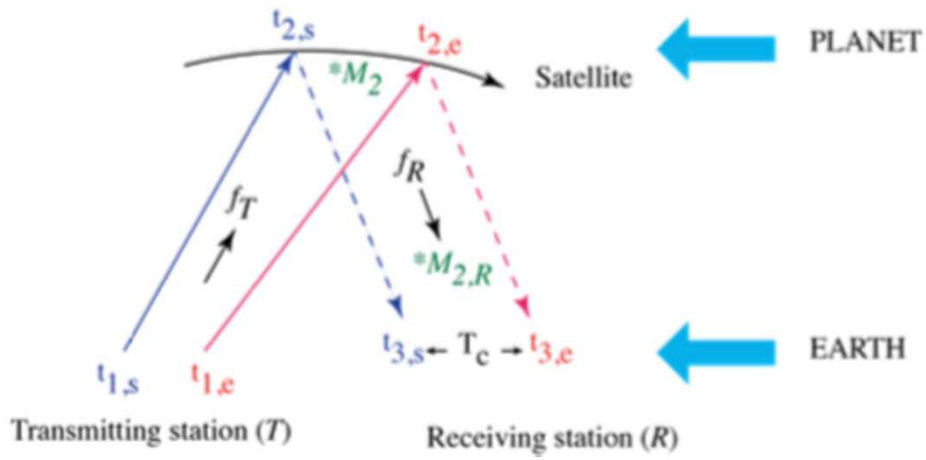
  **The phase difference between received and transmitted times**

- How is it derived?

  **The DIFFERENCE (Modulo *M*) between:**
  **the number of cycles of received frequency accumulated from zero-phase time to current receiving time AND the number of cycles of transmitted frequency from zero-phase time and corresponding transmitting time.**

# Light-time computation (1)

***Moyer's formulation (Section 8)***




- $t_{3,s}$ & $t_{3,e}$ are receiving times at starting and ending of Doppler count time $T_c$
- $t_{2,s}$ & $t_{2,e}$ are spacecraft times at starting and ending of Doppler count time $T_c$
- $t_{1,s}$ & $t_{1,e}$ are transmitting times at starting and ending of Doppler count time $T_c$

- $M_2$ & $M_{2R}$ are transponder ratio (Received over Transmitted frequency ratio)

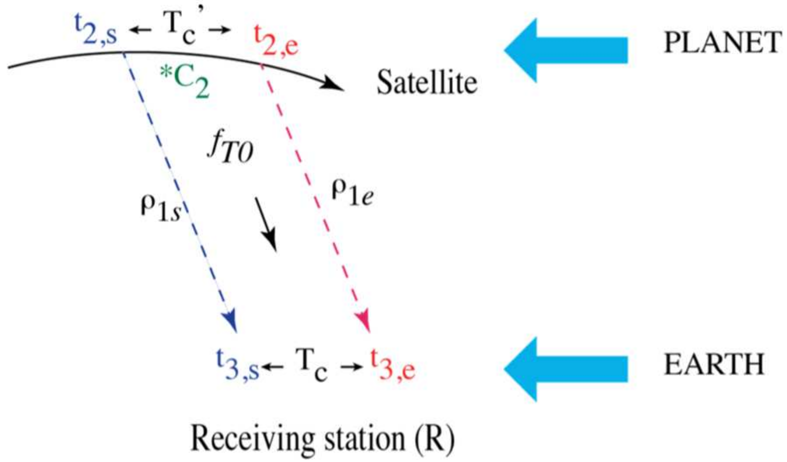
| Uplink Band | Downlink Band S | Downlink Band X | Downlink Band Ka |
|---|---|---|---|
| S | 240/221 | 880/221 | 3344/221 |
| X | 240/749 | 880/749 | 3344/749 |
| Ka | 240/3599 | 880/3599 | 3344/3599 |

# Light-time computation (2)

***Light time solution***
***Section 8***

$$t_2 - t_1 = \frac{r_{12}}{c} + \frac{(1+\gamma)\mu_S}{c^3} \ln\left[\frac{r_1^S + r_2^S + r_{12}^S + \frac{(1+\gamma)\mu_S}{c^2}}{r_1^S + r_2^S - r_{12}^S + \frac{(1+\gamma)\mu_S}{c^2}}\right] + \sum_{B=1}^{10} \frac{(1+\gamma)\mu_B}{c^3} \ln\left[\frac{r_1^B + r_2^B + r_{12}^B}{r_1^B + r_2^B - r_{12}^B}\right]$$

$1 \rightarrow 2$
$2 \rightarrow 3$




- $t_{3,s}$ & $t_{3,e}$ are receiving times at starting and ending of Doppler count time $T_c$
- $t_{2,s}$ & $t_{2,e}$ are spacecraft times at starting and ending of Doppler count time $T_c$

- $C_2$ (Frequency ratio at spacecraft)

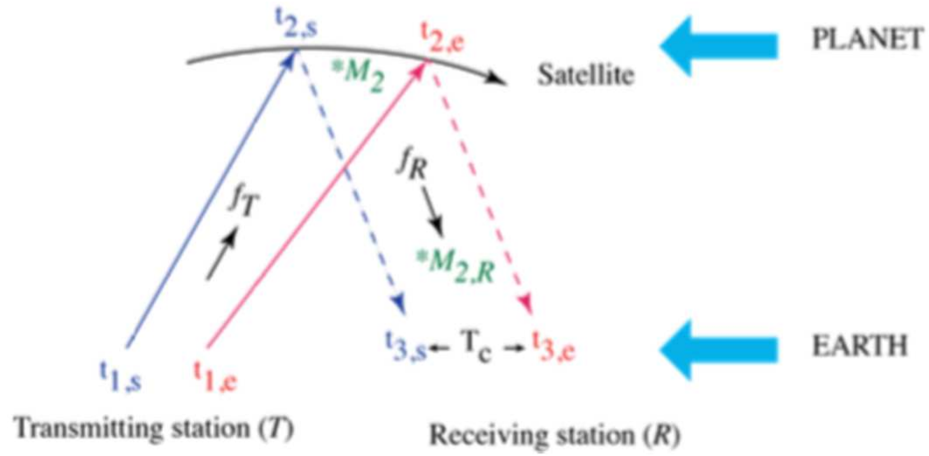
**Downlink Frequency Multiplier $C_2$**

| Downlink Band | Frequency Multiplier |
|---|---|
| S | 1 |
| X | $\frac{880}{240}$ |
| Ka | $\frac{3344}{240}$ |

# Light-time computation (3)

***Light-time solution***

***Moyer's formulation (Section 8)***




- Computing $t_{2,s}$ & $t_{2,e}$ and $t_{1,s}$ & $t_{1,e}$ from $t_{3,s}$ & $t_{3,e}$ :
- $t_{3,s}$ = Time Tag (TT) – $T_c/2$ (in UTC)
  $t_{3,e}$ = Time Tag (TT) + $T_c/2$ (in UTC)
- We take into account the coordinate velocity of light below "c" and the bending of the light path within the solar system.
  (only bending due to the Sun is taken into account).

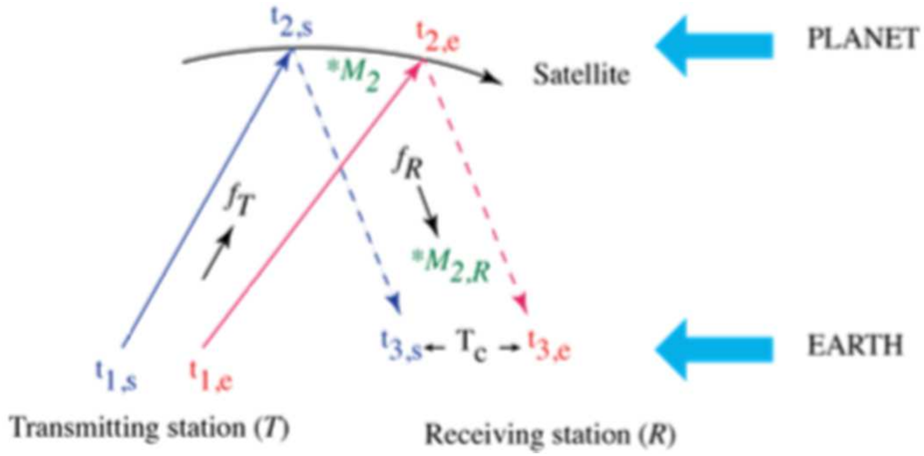
# Light-time computation (4)

***Light time solution***

***(Eq. 8-55 page 8-25 in Moyer)***

$$t_2 - t_1 = \frac{r_{12}}{c} + \frac{(1+\gamma)\mu_S}{c^3} \ln\left[\frac{r_1^S + r_2^S + r_{12}^S + \frac{(1+\gamma)\mu_S}{c^2}}{r_1^S + r_2^S - r_{12}^S + \frac{(1+\gamma)\mu_S}{c^2}}\right] + \sum_{B=1}^{10} \frac{(1+\gamma)\mu_B}{c^3} \ln\left[\frac{r_1^B + r_2^B + r_{12}^B}{r_1^B + r_2^B - r_{12}^B}\right]$$

1 → 2
2 → 3




- 1 → 2 and 2→ 3 means leg from transmitting station to spacecraft and leg from receiving station to spacecraft.
- "S" is for Sun and "B" is for the 9 planets and the Moon.
- "γ" PPN parameter, "c" the speed of light.
- "$r_1$", "$r_2$" the distances between stations (rec. or trans.), the spacecraft and the Sun "S" or the celestial body "B", and "$r_{12}$" is the length of the leg.

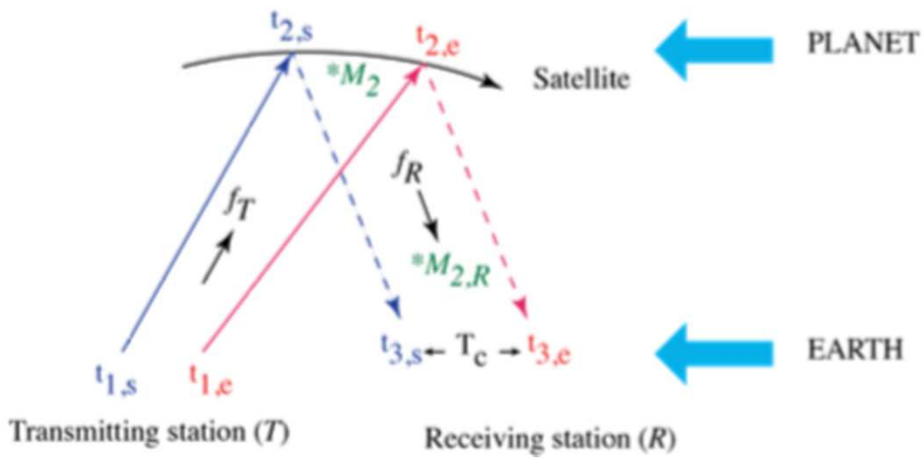
# Light-time computation (5)

***Light time solution***

***Eq. 8-55 page 8-25 in Moyer***

$$t_2 - t_1 = \frac{r_{12}}{c} + \frac{(1+\gamma)\mu_S}{c^3} \ln\left[\frac{r_1^S + r_2^S + r_{12}^S + \frac{(1+\gamma)\mu_S}{c^2}}{r_1^S + r_2^S - r_{12}^S + \frac{(1+\gamma)\mu_S}{c^2}}\right] + \sum_{B=1}^{10} \frac{(1+\gamma)\mu_B}{c^3} \ln\left[\frac{r_1^B + r_2^B + r_{12}^B}{r_1^B + r_2^B - r_{12}^B}\right]$$

$1 \rightarrow 2$
$2 \rightarrow 3$




- This equation is solved by an iterative way for each up-leg and down-leg and for each start and end time of the Doppler count time.
- We obtain a precise round-trip light time between reception and transmission that we'll use for computing the tracking observables.

# Transmitted frequency at DSN (1)

- ✓ We need to know the transmitted frequency to compute Doppler and range observables from DSN tracking files.
- ✓ Transmitted frequency is constant (unramped) or variable (ramped) over the tracking pass.
- ✓ It is provided in the data files or is computed from information contained in the tracking files.

# Transmitted frequency at DSN (2)

***2-way/3-way unramped Doppler: Moyer's formulation (Section 13)***

✓ When the transmitted frequency is computed from DSN tracking files:

The transmitted frequency $f_T(t)$ is built from the reference frequency of the local oscillator: $f_q(t)$ which is given in data files (~ 22 MHz):

X-band $f_T(t) = 32 f_q(t) + 6.5 \times 10^9$ Hz

S-band $f_T(t) = 96\, f_q(t)$

Prior to BVE $f_q'$ is given instead of $f_q(t)$

$$f_q = 4.68125\, f_q' - 81.4125 \times 10^6 \text{ Hz}$$

# Transmitted frequency at DSN (3)

***2-way/3-way ramped Doppler: Moyer's formulation (Section 13)***

✓ When the transmitted frequency is variable (ramped). It is computed from "ramp tables" contained in the DSN tracking files.

✓ Each ramp table contains:

1) The start and end time $T_0$ and $T_f$ of the ramp interval at the transmitting station
2) The ramp rate applied for the ramp interval
3) The frequency value at $T_0$ is $f_0$

$$f_T(t) = f_o + \dot{f}(t - t_o)$$

*N.B.: Ramp tables can provide* $f_q(t)$ *instead of* $f_T(t)$. *Use previous relationship with:*

S-band: $\dot{f}_T = 96\,\dot{f}_q$

X-band: $\dot{f}_T = 32\,\dot{f}_q$

# Transmitted frequency at spacecraft

*1-way Doppler:*
*Moyer's formulation*
*(Section 13)*

✓ When the frequency is generated onboard the spacecraft: **USO !**

$$f_T(t) = C_2\, f_{S/C}$$

$$f_{S/C} = f_{T_0} + \Delta f_{T_0} + f_{T_1}(t - t_0) + f_{T_2}(t - t_0)^2$$

$f_{S/C}$ ≈ 2.3 GHz (9192631770 cycles of an imaginary Cesium atomic clock)

**Downlink Frequency Multiplier $C_2$**

| Downlink Band | Frequency Multiplier |
|---|---|
| S | 1 |
| X | $\frac{880}{240}$ |
| Ka | $\frac{3344}{240}$ |

- The nominal frequency $f_{T_0}$ and $\Delta f_{T_0}, f_{T_1}, f_{T_2}$ the quadratic terms for USO frequency drift are given at time $T_0$ in the DSN tracking files.

# Doppler observables at DSN (1)

- ✓ 3 types of Doppler observables are available.
  Each is derived from Doppler cycle count of either:

1) Frequency shift between received and reference frequencies
2) Received frequency (*sky frequency*)
3) Received phase

- ✓ Each type depends on electronics or software implementation at the receiving tracking station:

1) Before Block V Receivers (BVR): 2-3 way *unramped and ramped*
2) After Block V Receiver (BVR): 2-3 way *only ramped*
3) After Network Simplification Program (NSP) implementation
   2/3 way *only ramped*

# Doppler observables at DSN (2)

- ✓ Cycles count accumulated from the beginning of the tracking pass (obtained after the closed-loop):

$$N(t_3) = \int_{t_{3_0}}^{t_3} f(t_3)\, dt_3 \qquad \text{cycles}$$

- ✓ The changes in the cycles count is:

$$\Delta N = N\left(t_{3_e}\right) - N\left(t_{3_s}\right) \qquad \text{cycles}$$

- ✓ The Doppler Observable is:

$$F = \frac{\Delta N}{T_c} - f_{\text{bias}} \qquad \text{Hz}$$

$f_{\text{bias}}$ *depends on Doppler observable types*

# Doppler observables at DSN (3)

Type 1: Before BVR - from cycle count of frequency shift $f(t_3)$

$$f(t_3) = f_{\mathrm{REF}}(t_3) - f_{\mathrm{R}}(t_3) + C_4 \qquad \mathrm{Hz}$$

Where $f_{\mathrm{REF}}(t_3) = M_{2_{\mathrm{R}}} f_{\mathrm{T}}(t_3)$

$M_{2_{\mathrm{R}}}$ : Spacecraft turn around ratio built at reception station from band index of uplink at reception station (given in the DSN tracking files).

$C_4$ : + or – 1 MHz, generated at transmitting station (given in the DSN tracking files).

$f_{\mathrm{R}}(t_3)$ : Frequency at receiving station (Sky frequency).

# Doppler observables at DSN (4)

Type 1: Before BVR - from cycle count of frequency shift $f(t_3)$

$$F = \frac{\Delta N}{T_c} - f_{\text{bias}}$$ Hz , becomes:

for 1-way Doppler observable: $$F_1 = \frac{1}{T_c} \int_{t_{3_s}(\text{ST})_R}^{t_{3_e}(\text{ST})_R} \left[ C_2 f_{T_0} - f_R(t_3) \right] dt_3$$

given : $f_{\text{bias}} = f_{\text{REF}}(t_3) - C_2 f_{T_0} + C_4$

# Doppler observables at DSN (5)

Type 1: Before BVR - from cycle count of frequency shift $f(t_3)$

$$F = \frac{\Delta N}{T_c} - f_{\text{bias}}$$ Hz , becomes:

for 2/3-way unramped
Doppler observable: $$\text{unramped } F_{2,3} = \frac{1}{T_c} \int_{t_{3_s}(\text{ST})_R}^{t_{3_e}(\text{ST})_R} \left[ M_2 f_T(t_1) - f_R(t_3) \right] dt_3$$

given: $f_{\text{bias}} = f_{\text{REF}}(t_3) - M_2 f_T(t_1) + C_4$

# Doppler observables at DSN (6)

Type 1 : Before BVR - from cycle count of frequency shift $f(t_3)$

$$F = \frac{\Delta N}{T_c} - f_{\text{bias}}$$

Hz , becomes:

for 2/3-way ramped
Doppler observable:

$$\text{ramped } F_{2,3} = \frac{1}{T_c} \int_{t_{3_s}(\text{ST})_R}^{t_{3_e}(\text{ST})_R} \left[ f_{\text{REF}}(t_3) - f_R(t_3) \right] dt_3$$

given:

$$f_{\text{bias}} = C_4$$

# Doppler observables at DSN (7)

Type 2: After BVR – received frequency $f_R(t_3)$

$$N(t_3) = f_{REF}(t_3)\left(t_3 - t_{3_0}\right) - \phi(t_3) + C_4\left(t_3 - t_{3_0}\right) \qquad \text{cycles}$$

With: $$\phi(t_3) = \int_{t_{3_0}}^{t_3} f_R(t_3)\, dt_3 \qquad \text{cycles}$$

Where: $f_{REF}(t_3) = M_{2_R}\, f_T(t_3)$

$C_4$ : + or – 1 MHz, generated at transmitting station (given in the DSN tracking files).

$\phi(t_3)$: given in the DSN tracking files.

# Doppler observables at DSN (8)

Type 2: After BVR – received frequency $f_R(t_3)$

$$F = \frac{\Delta N}{T_c} - f_{bias} \qquad \text{Hz}$$

becomes as 1-way and ramped 2/3 ways Doppler observables for "before BVR" data type .

*N.B. No unramped 2/3 ways in that data types.*

# Doppler observables at DSN (9)

Type 3: Received phase $\phi(t_3)$

$$N(t_3) = -\phi(t_3) \qquad \text{cycles}$$

$\phi(t_3)$ : given in the DSN tracking files.

# Doppler observables at DSN (10)

Type 3: Received phase $\phi(t_3)$

$$F = \frac{\Delta N}{T_c} - f_{\text{bias}}$$ Hz , becomes:

$$F = -\frac{\left[\phi\left(t_{3_e}\right) - \phi\left(t_{3_s}\right)\right]}{T_c}$$ Hz , *with* $f_{\text{bias}} = 0$

finally: $$F_1, \text{ ramped } F_{2,3} = -\frac{1}{T_c}\int_{t_{3_s}(\text{ST})_R}^{t_{3_e}(\text{ST})_R} f_R(t_3)\,dt_3$$ Hz

which is similar to previous definitions with

$f_{\text{REF}}(t_3)$ & $C_2 f_{T_0}$ set to zero.

# Computing Doppler observables at DSN (1)

✓ One needs to compute tracking observables in order to fit model of spacecraft motion to the tracking data (least-square fit procedure)

- Number of cycles of frequency at transmission is equal to number of cycles of frequency at reception $\frac{f_R}{f_T} = \frac{M_2\, dn}{dt_3}\frac{dt_1}{dn} = M_2 \frac{dt_1}{dt_3}$

$$\text{unramped } F_{2,3} = \frac{1}{T_c}\int_{t_{3_s}(ST)_R}^{t_{3_e}(ST)_R} \left[ M_2 f_T(t_1) - f_R(t_3) \right] dt_3$$

becomes

$$\text{unramped } F_{2,3} = \frac{M_2 f_T(t_1)}{T_c}\left[\int_{t_{3_s}(ST)_R}^{t_{3_e}(ST)_R} dt_3 - \int_{t_{1_s}(ST)_T}^{t_{1_e}(ST)_T} dt_1\right]$$

# Computing Doppler observables at DSN (2)

- As the transmitted frequency $f_T(t_1)$ is constant:

$$\text{unramped } F_{2,3} = \frac{M_2 f_T(t_1)}{T_c} \left\{ \left[ t_{3_e}(ST)_R - t_{1_e}(ST)_T \right] - \left[ t_{3_s}(ST)_R - t_{1_s}(ST)_T \right] \right\}$$

→ 2/3 way unramped Doppler are difference of round-trip light time at the start and end of Doppler count time.

→ We can replace round-trip light time *t* by the distance *ρ* (i.e. *t=ρ/c, c* speed of light) between stations and spacecraft at each leg of the uplink and downlink at the start and end of Doppler count time.

→ *The unramped Doppler observable can be computed as a range-rate measurement.*

*N.B. Viking Landers and Phobos-2 data were given as range-rate*

# Computing Doppler observables at DSN (3)

- For ramped 2/3-way Doppler, still given: $\frac{f_R}{f_T} = \frac{M_2\, dn}{dt_3}\frac{dt_1}{dn} = M_2 \frac{dt_1}{dt_3}$

$$\text{ramped } F_{2,3} = \frac{1}{T_c}\int_{t_{3_s}(\mathrm{ST})_R}^{t_{3_e}(\mathrm{ST})_R} \left[ f_{\mathrm{REF}}(t_3) - f_R(t_3) \right] dt_3$$ becomes

$$\text{ramped } F_{2,3} = \frac{M_{2_R}}{T_c}\int_{t_{3_s}(\mathrm{ST})_R}^{t_{3_e}(\mathrm{ST})_R} f_T(t_3)\, dt_3 - \frac{M_2}{T_c}\int_{t_{1_s}(\mathrm{ST})_T}^{t_{1_e}(\mathrm{ST})_T} f_T(t_1)\, dt_1$$

since $f_{\mathrm{REF}}(t_3) = M_{2_R}\, f_T(t_3)$

# Computing Doppler observables at DSN (4)

- If $f_{\mathrm{REF}}(t_3)$ at the receiving station is constant (which is generally the case) then:

$$\text{ramped } F_{2,3} = f_{\mathrm{REF}}(t_3) - \frac{M_2}{T_c} \int_{t_{1_s}(\mathrm{ST})_T}^{t_{1_e}(\mathrm{ST})_T} f_T(t_1)\, dt_1$$

- The start and end time $t_{1s}$ & $t_{1e}$ are computed from the light-time solution from reception time (i.e. $t_{3e}$ and $t_{3s}$)

- The ramped 2/3 way Doppler observable is then computed by integrating the transmitted frequency over the Doppler count interval at the transmitting station, i.e. ($t_{1s}$ - $t_{1e}$).

# Computing Doppler observables at DSN (5)

- The transmitted frequency is computed from the ramp tables.
- The integral over the Doppler count time ($t_{1s}$ - $t_{1e}$) is computed as the average of the ramped frequency over the Doppler count time:

$$\int_{t_s}^{t_e} f_T(t)\,dt = \sum_{i=1}^{n} f_i W_i$$

$W_i = t_f - t_o$ is the $i^{th}$ ramp interval

$f_i = f_o + \frac{1}{2}\dot{f}\,W_i$ is the average transmitter frequency for the $i^{th}$ ramp interval

# Computing Doppler observables at DSN (6)

- For ramped 1-way Doppler, given: $\frac{f_R}{f_T} = \frac{dn}{dt_3(\mathrm{ST})_R}\frac{dt_2(\mathrm{TAI})}{dn} = \frac{dt_2(\mathrm{TAI})}{dt_3(\mathrm{ST})_R}$

- For data type 3, i.e. $C_2 f_{T_0}$ = 0 (after NSP):

$$F_1,\ \text{ramped}\ F_{2,3} = -\frac{1}{T_c}\int_{t_{3_s}(\mathrm{ST})_R}^{t_{3_e}(\mathrm{ST})_R} f_R(t_3)\, dt_3$$

becomes

$$F_1(\text{after NSP}) = -\frac{C_2}{T_c}\int_{t_{2_s}(\mathrm{TAI})}^{t_{2_e}(\mathrm{TAI})}\left[f_{T_0} + \Delta f_{T_0} + f_{T_1}(t_2 - t_0) + f_{T_2}(t_2 - t_0)^2\right] dt_2(\mathrm{TAI})$$

# Computing Doppler observables at DSN (7)

- It can be expressed as:

$$F_1\,(\text{after NSP}) = -\,C_2\left\{f_{T_0} + \Delta f_{T_0} + f_{T_1}\left(t_{2_m} - t_0\right) + f_{T_2}\left[\left(t_{2_m} - t_0\right)^2 + \frac{1}{12}\left(T_c{}'\right)^2\right]\right\}\frac{T_c{}'}{T_c}$$

with: $t_{2_m} = \dfrac{t_{2_e}(\text{ET}) + t_{2_s}(\text{ET})}{2}$ and $\dfrac{T_c{}'}{T_c} = 1 - \dfrac{\hat{\rho}_{1_e} - \hat{\rho}_{1_s}}{T_c}$

$\dfrac{T_c{}'}{T_c}$ is the ratio of the Doppler count time interval expressed at spacecraft (in TAI) to the Doppler count time at receiving station.

with $\hat{\rho}_{1_e} - \hat{\rho}_{1_s} = \rho_{1_e} - \rho_{1_s} + \Delta$ and $\Delta = (\text{ET} - \text{TAI})_{t_{2_e}} - (\text{ET} - \text{TAI})_{t_{2_s}}$

$\rho_{1_e} - \rho_{1_s}$ is the spacecraft to station light-time difference (in ET) between the start and end of the Doppler count time

# Computing Doppler observables at DSN (8)

- For data type 2, i.e. $C_2 f_{T_0} \neq 0$ (before NSP):

$$F_1\,(\text{before NSP}) = C_2 f_{T_0} \frac{\left(\hat{\rho}_{1_e} - \hat{\rho}_{1_s}\right)}{T_c}$$

$$- C_2 \left\{ \Delta f_{T_0} + f_{T_1}\left(t_{2_m} - t_0\right) + f_{T_2}\left[\left(t_{2_m} - t_0\right)^2 + \frac{1}{12}\left(T_c{}'\right)^2\right] \right\} \frac{T_c{}'}{T_c}$$

# Range observable at DSN (1)

- 3 types of range observables:

  - Planetary Ranging Assembly (PRA)
  - Sequential Ranging Assembly (SRA)
  - Next-Generation Ranging Assembly (RANG) (i.e. after NSP)

- Ranging is either 2-way or 3-way (not 1-way)

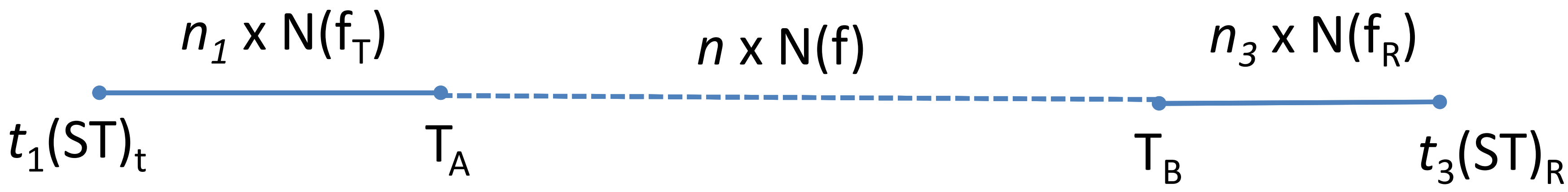
- For SRA and PRA, 2-way range can be ramped or unramped while 3-way is ramped.

- For RANG, all range is ramped.

- Only at S and X-band, not Ka band so far (PRA only in S-band).

# Range observable at DSN (2)

- Principle of range observable:




- Range observable (number of cycles) of frequency

$$= n_1 \times N(f_T) + n \times N(f) + n_3 \times N(f_R)$$

- Only $n_1$ and $n_3$ are measurements. The phase ambiguity $n$ can only be solved from modeling.

- $T_A$ & $T_B$ zero-phase times at the transmitting and receiving stations (normally given in tracking data files).

# Range observable at DSN (3)

- Measured number of cycles are not exactly cycles of the carrier frequency: *Definition of the Range Unit (RU)*

S-band: $F = \frac{1}{2} f_T(S)$ range units/second 1 RU = 2 cycles of the S-band freq.

X-band: at HEF station before Block V Exciter (BVE)

$F = \frac{11}{75} f_T(X, HEF)$ range units/second 1 RU = 75/11 cycles of the X-band freq.

X-band: at HEF station after BVE

$F = \frac{221}{749 \times 2} f_T(X, BVE)$ range units/second 1 RU = (749x2)/221 cycles of the X-band freq.

# Computing range observable at DSN (4)

- For 3-way ranging observable (PRA, SRA):

$$\rho_3(\text{ramped}) = \left[\int_{T_B}^{t_3(\text{ST})_R} F(t_3)\,dt_3 - \int_{T_A}^{t_1(\text{ST})_T} F(t_1)\,dt_1\right], \text{ modulo } M \quad \text{range units}$$

- For 2-way ranging observable (PRA, SRA) $T_A = T_B$ , hence:

$$\rho_2(\text{ramped}) = \int_{t_1(\text{ST})_T}^{t_3(\text{ST})_R} F(t)\,dt, \text{ modulo } M \qquad \text{range units}$$

# Computing range observable at DSN (5)

$t_3(\mathrm{ST})_\mathrm{R} = TT$ given by the time tag of measurement

$t_1(\mathrm{ST})_\mathrm{T} = t_3(\mathrm{ST})_\mathrm{R} - \rho$ with $\rho$ from light-time solution

- The modulo M is computed as:

$M = 2^{n+6}$ range units SRA, RANG

$M = 2^{9 + \mathrm{minimum}(1, HICOMP) + LOWCOMP}$ range units PRA

*n* as well as *HICOMP* and *LOWCOMP* are given in the tracking data files for each range measurement.

→ *N.B. range observables are corrected from delays at stations but not from delay at the spacecraft transponder. It is typically of 1 to 2 micro-seconds (hundreds of meters)*

# Access to DSN data tracking

- The tracking data files are *binary* data files that are archived on the Planetary Data system (PDS): https://pds.nasa.gov, but not for all missions. Missions before Mars Global Surveyor (MGS) are rarely on the PDS.

- Each data type corresponds to a given binary data format:
  *TRK-2-25* for Doppler data type 1 (priori to BVR/BVE) and PRA range. (Ex. Galileo, Magellan)
  *TRK-2-18* for Doppler data type 2 (after BVR/BE and before NSP) and SRA range. (Ex. MGS, ODY, MRO, Cassini, MEX, …)
  *TRK-2-34* for Doppler data type 3 (after NSP) and RANG range.
  *N.B. From MAVEN mission (2014) TRK-2-34 is THE archive data format (TDM) "better because ASCII" would be available in a close future.*

- You must use the computing formulae given in Moyer (see above) to correctly extract the tracking observable from the tracking data files and to accurately compute the observable in your orbitography software.

# Tracking observables at ESA ESTRACK network

- The phase accumulated from the beginning of a tracking pass is recorded in doppler data files, i.e. $N(t_3)$.
- The round-trip delay (modulo $\tau$) is also given in range data files (the phase ambiguity must also be modeled).
- Doppler is computed from the phase difference between two different time tag separated by the Doppler count time that can be chosen by the user. The time tag is the middle of the Doppler count time $T_c$.
- It corresponds to the DSN definition of Doppler observable:

$$F = \frac{\Delta N}{T_c} - f_{\text{bias}} \quad \text{with } f_{\text{bias}} = 0 \quad \text{and} \quad \Delta N = N\left(t_{3_e}\right) - N\left(t_{3_s}\right)$$

# Computing tracking observables at ESA ESTRACK network (1)

- The ESTRACK doppler observable is not ramped. The unramped DSN formulation can be used to compute ESTRACK doppler observable:

$$\text{unramped } F_{2,3} = \frac{M_2 f_T(t_1)}{T_c}\left\{\left[t_{3_e}(ST)_R - t_{1_e}(ST)_T\right] - \left[t_{3_s}(ST)_R - t_{1_s}(ST)_T\right]\right\}$$

- And the transmitted frequency $f_T(t_1)$ is read from the header of the ESTRACK tracking file.

- It is valid for Mars Express and Venus Express mission.

- However for future missions like JUICE, ramping might be applied at ESTRACK stations too.

# Computing tracking observables at ESA ESTRACK network (2)

- The data type 2 *received frequency* (after BVR and before NSP) can be applied to handle ESTRACK Doppler observable.

$$\text{ramped } F_{2,3} = f_{\mathrm{REF}}(t_3) - \frac{M_2}{T_c} \int_{t_{1_s}(\mathrm{ST})_\mathrm{T}}^{t_{1_e}(\mathrm{ST})_\mathrm{T}} f_\mathrm{T}(t_1)\, dt_1$$

- The reference frequency is computed as: $f_{\mathrm{REF}}(t_3) = M_{2_R}\, f_\mathrm{T}(t_3)$

- The transmitted frequency $f_\mathrm{T}(t_1)$ is now obtained from a ramp table provided with the tracking data files.

- Note that the reference frequency must be added to the observable $\Delta N = N(t_{3_e}) - N(t_{3_s})$ to apply this data type 2 formulation.

# Computing tracking observables at ESA ESTRACK network (3)

- Alternatively the data type 3 (after NSP) of the DSN doppler observable can be applied:

$$F_1,\ \text{ramped } F_{2,3} = -\frac{1}{T_c}\int_{t_{3_s}(ST)_R}^{t_{3_e}(ST)_R} f_R(t_3)\,dt_3 \qquad \text{Hz}$$

- It yields:

$$\text{ramped } F_{2,3} = f_{REF}(t_3) - \frac{M_2}{T_c}\int_{t_{1_s}(ST)_T}^{t_{1_e}(ST)_T} f_T(t_1)\,dt_1$$

with $f_{REF}(t_3) = 0$

$f_T(t_1)$ from ramp tables

- In that case the observable $\Delta N = N\left(t_{3_e}\right) - N\left(t_{3_s}\right)$ must be used.

# Computing tracking observables at ESA ESTRACK network (4)

- The data type 2 *received frequency* (after BVR and before NSP) can also be applied to handle unramped ESTRACK Doppler observable.

$$\text{ramped } F_{2,3} = f_{\mathrm{REF}}(t_3) - \frac{M_2}{T_c}\int_{t_{1_s}(\mathrm{ST})_\mathrm{T}}^{t_{1_e}(\mathrm{ST})_\mathrm{T}} f_\mathrm{T}(t_1)\,dt_1$$

- We then set the ramp-rate to zero:

$f_\mathrm{T}(t) = f_\mathrm{o} + \dot{f}(t - t_\mathrm{o})$ with $\dot{f}$ = 0 and $f_\mathrm{o}$ = the transmitted frequency computed from the header of the tracking data files

- And $f_{\mathrm{REF}}(t_3)$ = $M_2$ x $f_\mathrm{o}$

# Access to ESA ESTRACK tracking files

- Each doppler and ranging files are ASCII files (yahoo !!!) with a header allowing for computation of transmitted frequency.

- The raw level of data is the Level1a and can be downloaded from the Planetary Science Archive (PSA): http://www.cosmos.esa.int

  → But only for radio-science experiment. Tracking data used for navigation are only available upon request to ESA.

- The tracking file are recorded at three different channels IFMS-1, IFMS-2 and IFMS-3.

- The IFMS-1 channel contains the X-band tracking data and the IFMS-3 the S-band data when available. Each channel is redundant (D1 & D2).

# Source of noise on the tracking observables

- Different sources of noise:

  - Instrumental noise (electronics, antenna mechanics, frequency standard noise).
    Low level: $6x10^{-4}$ mm/s in X-band at 60sec Doppler count time.

  - Thermal noise (sky, antenna).
    Low level: 0.01 mm/s in X-band at 60sec Doppler count time.

  - Spacecraft transponder: ~0.02 mm/s in 2-way X-band at 60sec Doppler count time

  - Propagation: Charged particles and neutral media.
    Interplanetary plasma and Earth troposphere drives the propagation noise at larger level than the others sources of noise.

# Propagation noise: Interplanetary or plasma noise

- The charged particles of the interplanetary plasma form a dispersive medium with a refractive index $n_p$ depending on the plasma frequency $f_p$

$$n_p = \sqrt{1 - \left(\frac{f_p}{f_c}\right)^2}, \quad \text{with} \quad f_p = \sqrt{\frac{N_e e^2}{4\pi^2 \epsilon_0 m_e}} \simeq 8.9779\sqrt{N_e}.$$

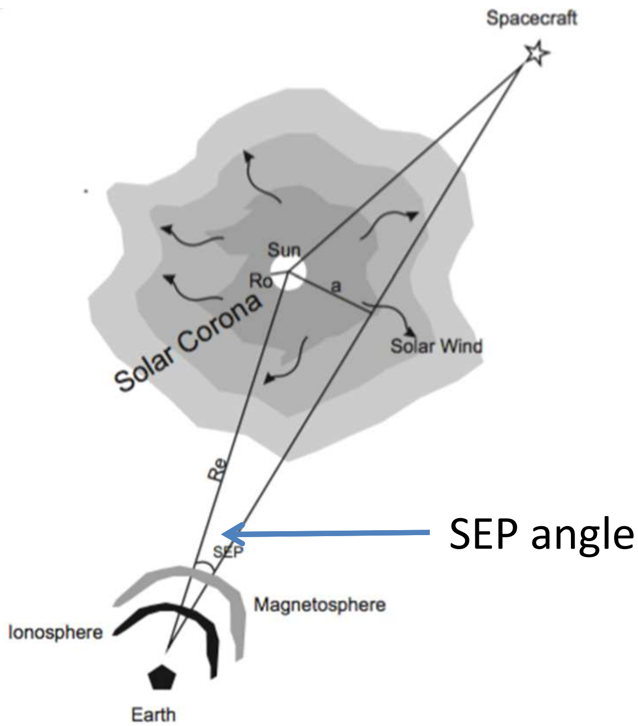
$N_e$ the density number of charged particles (electrons)

- At radio-tracking frequency $f_c$ we can write: $f_p^2 << f_c^2$, hence:

$$n_p = 1 - 40.3\frac{N_e}{f_c^2}.$$

- We immediately see the interest of Ka band (32 GHz) wrt X-band (8.4 GHz) and especially S-band (2.3 GHz) to minimize the *plasma noise*.

# Propagation noise: Solar corona plasma




*From Ho et al., 2008*

- In conjunction the radio-wave propagates in the solar corona where the electron density is the highest.
- This area of high plasma noise is characterized by the Solar Elongation Probe (SEP) angle. Low SEP high noise !
- Model of electron density are required to correct tracking observables

# Effect on range observable

- In plasma, the radio-wave propagates slightly slowler.

- In turn, it is received slightly later than without propagation in plasma.

- This time-delay is the time group delay $t_g$ depends on the total electron number (TEC) along the propagation path:

$$t_g = \int_{s/c}^{Earth} \frac{dy}{v_g} = \frac{40.3}{cf_c^2} \int_{s/c}^{Earth} N_e dy = \frac{40.3}{cf_c^2} I$$

- The TEC depends on the electron number density $N_e$ along the propagation wave. It can be computed from 'empirical' models.

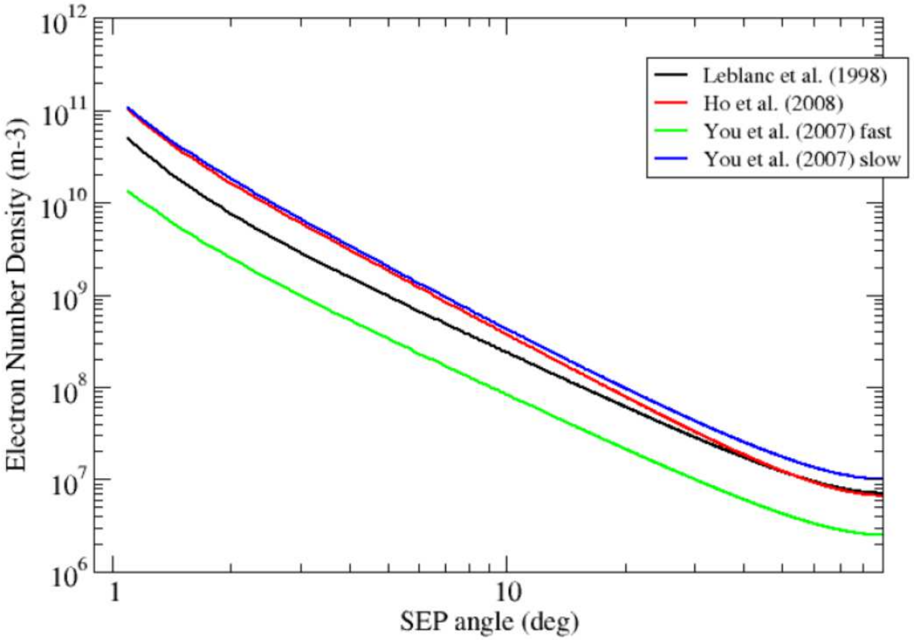
# Electron Number Density (END)

- Different models:

$$END = 3.3\,10^{11}\left(\frac{r}{r_0}\right)^{-2} + 4.1\,10^{12}\left(\frac{r}{r_0}\right)^{-4} + 8.0\,10^{13}\left(\frac{r}{r_0}\right)^{-6}\; m^{-3}$$

$$END = 1.155\,10^{11}\left(\frac{r}{r_0}\right)^{-2} + 32.3\,10^{11}\left(\frac{r}{r_0}\right)^{-4.39} + 3257\,10^{11}\left(\frac{r}{r_0}\right)^{-16.25}\; m^{-3}$$

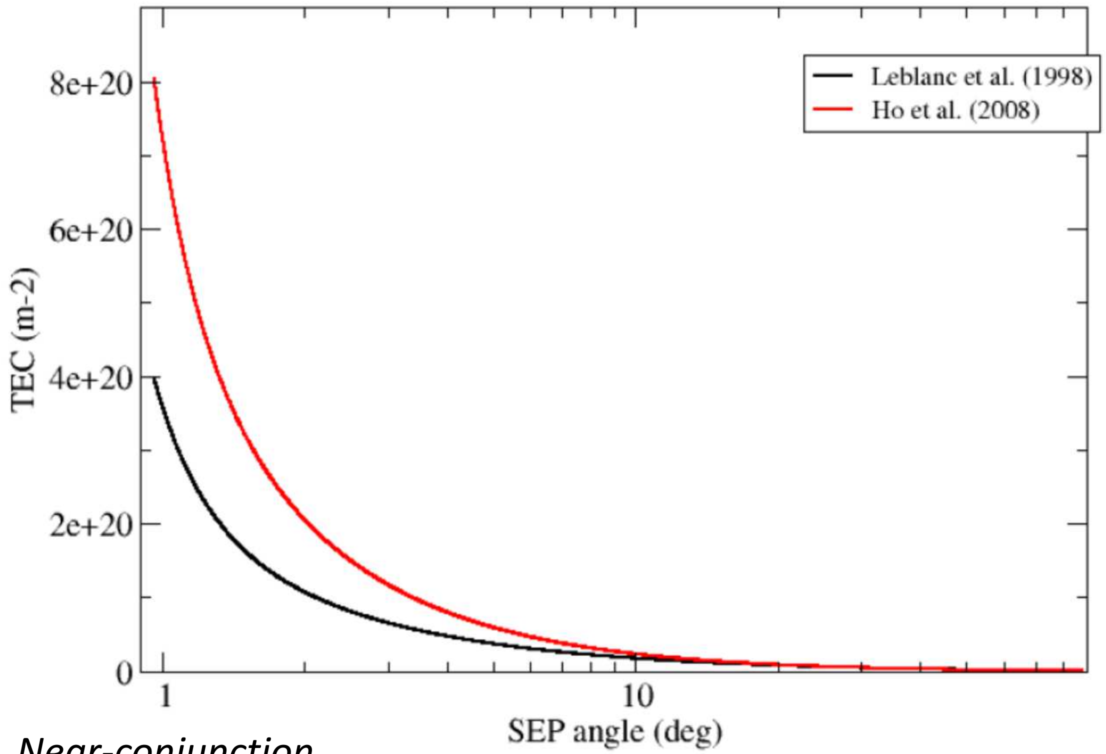
$$END = 1.155\,10^{11}\left(\frac{r}{r_0}\right)^{-2} + 32.3\,10^{11}\left(\frac{r}{r_0}\right)^{-4.39} + 3257\,10^{11}\left(\frac{r}{r_0}\right)^{-16.25}\; m^{-3}$$




- All model assume an isotropic distribution of electron density, i.e. only radial variations.

- These profiles differ by a factor of up to 2.

# Total Electron Content (TEC): Martian s/c to Earth propagation path




*Near-conjunction*

Total Electron Content (TEC):

Total amount of electron (columnar density) along the entire 's/c to Earth' path (expressed in $m^{-2}$)

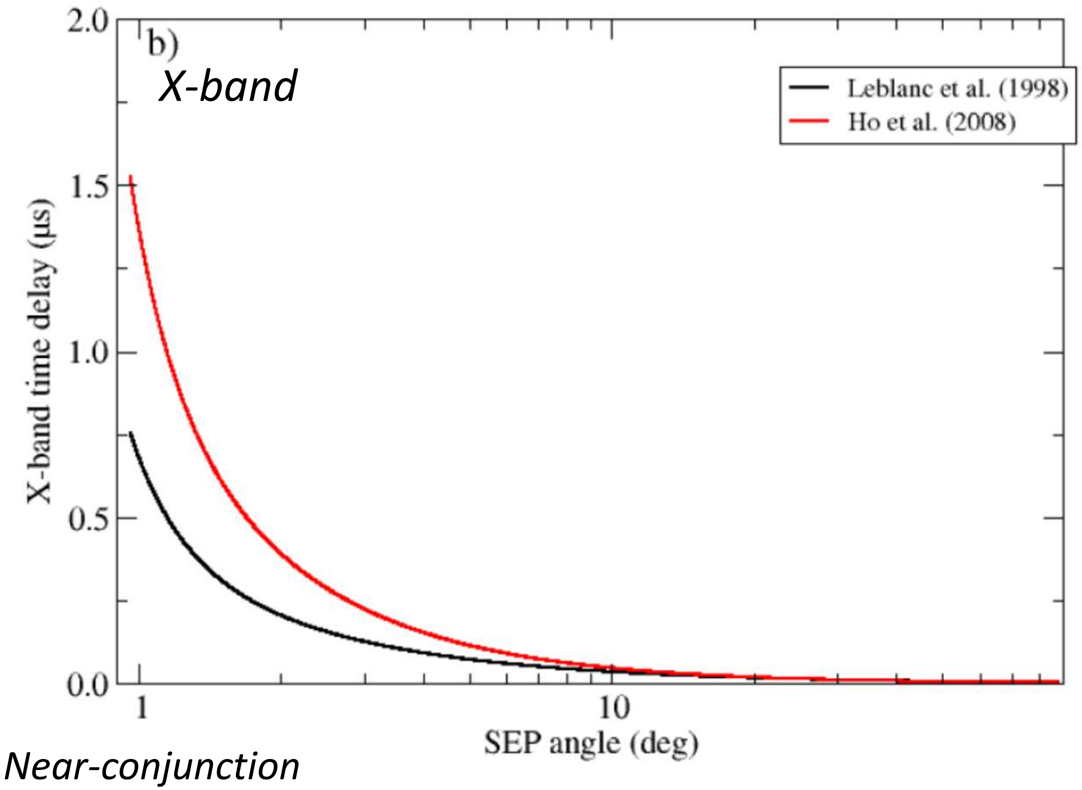
$$TEC = \int_{s/c}^{Earth} END\, dl$$

- Inaccuracy of a factor of up to 2 at small SEP angles, coming from the discrepancy among the electron density models.

# Plasma noise on range observable (1)

✓ Time group delay

$$\Delta T_g = \frac{40.31}{c f_0^{\,2}} TEC$$




✓ Bias on range observable corrected using TEC estimates

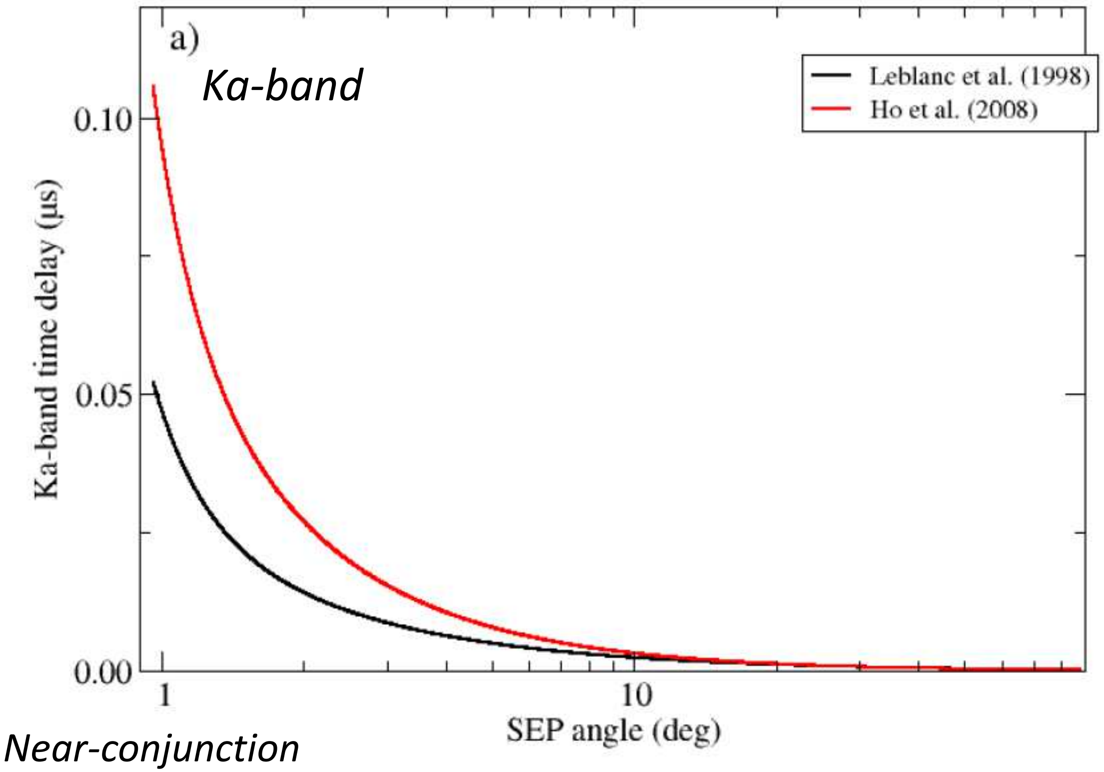
- Up to 1.5 μs (or 450 meters) at SEP=1°.
- Discrepancy of a factor of up to 2 at small SEP angles.
- At SEP > 10°, all model predicts less than 0.1 micro-seconds (< 30 meters)

# Plasma noise on range observable (2)

✓ Time group delay

$$\Delta T_g = \frac{40.31}{c f_0^{\,2}} TEC$$

✓ Bias on range observable corrected using TEC estimates




- Less effect at Ka-band than at X-band (‘only’ 0.1 µs or 30 meters at SEP=1°).
- At SEP > 10°, only a few meters for all models.

# Plasma noise on Doppler observable (1)

- The plasma generates noise on Doppler due to the time variability of the TEC:

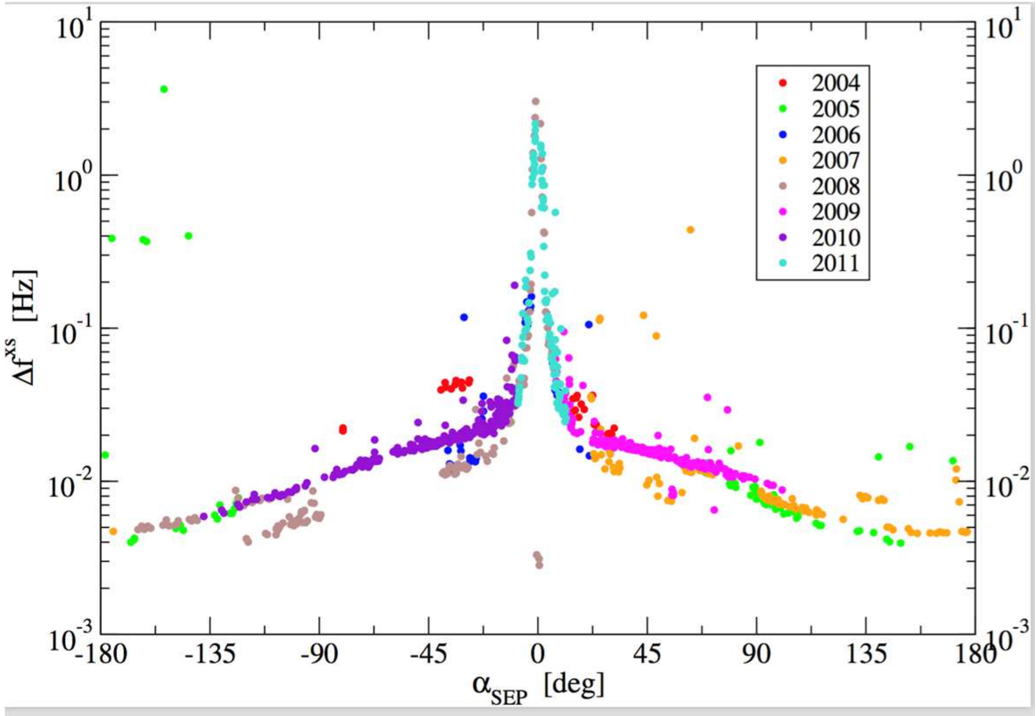
$$\Delta f_{ion} = \frac{40.3}{c f_c} \dot{I}$$

- TEC models do not include fluctuations in the solar corona.

- Dual-frequency method can be applied (plasma-free correction) thanks to different frequency at X-band, S-band or even Ka-band. One can show for 2-way Doppler in X/S bands:

$$\Delta f_{ion}^{2w} = \frac{40.3}{c} \left( \frac{1}{f_u} + \frac{1}{f_d} \right) \dot{I}.$$

# Plasma noise on Doppler observable (2)




✓ Interplanetary plasma (+ Earth ionosphere) Doppler effect from dual-frequency X/S band on Mars Express.

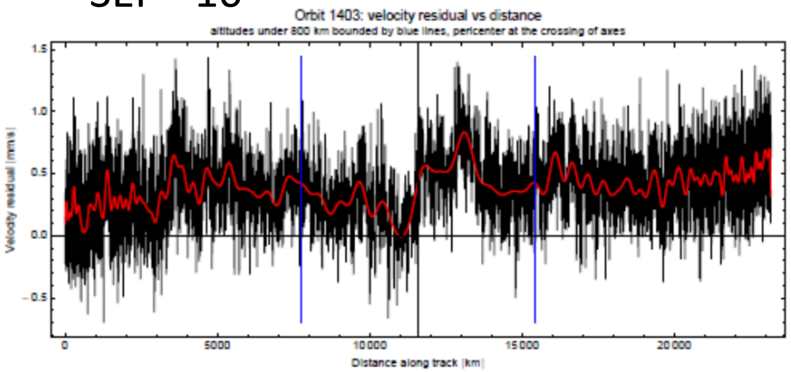
*N.B. Earth ionosphere TEC fluctuations are lower than plasma (< 0.5 mHz in X-band).*

- At SEP < 10° the effect on Doppler dramatically increases from ~ 10 mHz to 1 Hz (~ 0.35 mm/s to 35 mm/s in X-band).
- Dual-frequency is not systematics and those estimates cannot be used to accurately correct the Doppler observable.

- ***In practice, we avoid using Doppler data at SEP angle < 10°-15°***

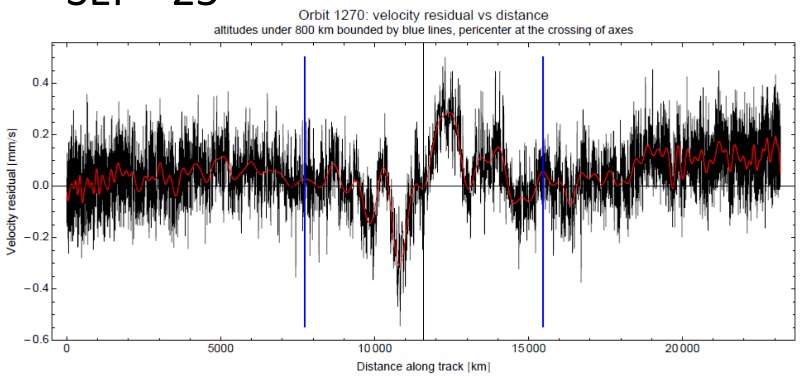
# Example of Solar Corona Plasma noise: Venus Express drag campaign

SEP ~10°




Campaign#3

SEP ~25°




Campaign#2

- Venus Express tracking at pericenter pass in X-band at 1sec Doppler count time :

  - at SEP angle ~ 10° , Doppler residuals noise at ~ 0.5 mm/s
  - at SEP angle ~ 25° , Doppler residuals noise at ~ 0.1 mm/s

# Propagation noise: Neutral troposphere (1)

- The Earth troposphere is non-dispersive (propagation delay does not depend on frequency).
- Let's set *D* the propagation delay due to the refraction index *n* of the troposphere along the propagation path, we have

$$D = r_{tropo} \simeq 10^{-6} \int_{s/c}^{Earth} N ds, \qquad N \simeq 10^{6}(n-1),$$

- There is two components: Dry ($N_d$) and Wet ($N_w$) troposphere, which depends on Pressure, temperature and humidity.

$$N_d = k_1 \frac{P_d}{T},$$
$$N_w = k_2 \frac{P_w}{T} + k_3 \frac{P_w}{T^2}.$$

- ✓ $N_d$ is 90% of the delay and can be precisely computed
- ✓ $N_w$ is less known because of water vapor fluctuations

# Propagation noise: Neutral troposphere (2)

- The tropospheric delay $D(\alpha_e)$ is computed at zenith angle for dry $D_d^z$ and wet $D_w^z$ component.

- Then, a mapping function for dry and wet component $m_d(\alpha_e)$ and $m_w(\alpha_e)$ is applied to account for the slant propagation path in the sky of the station (so, it depends on the elevation angle $\alpha_e$):

$$D(\alpha_e) = D_d(\alpha_e) + D_w(\alpha_e) = D_d^z m_d(\alpha_e) + D_w^z m_w(\alpha_e)$$

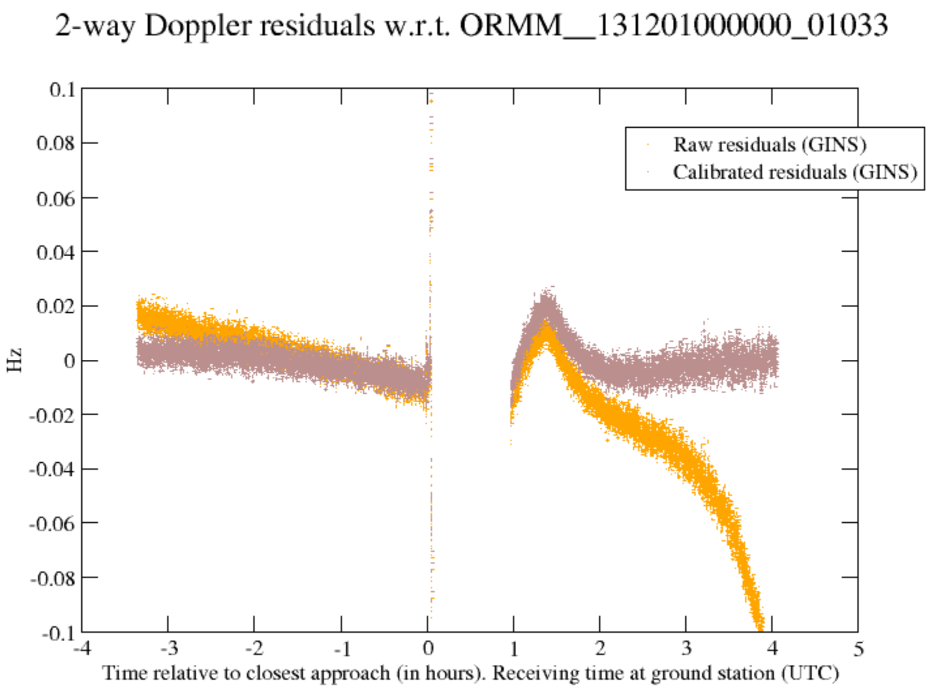
- Several mapping functions exist. They only depart from each other for elevation angle lower than ~5°. A typical example of mapping funtcion is the one of Marini:

$$m(\alpha_e) = \frac{1}{\sin\alpha_e + \frac{a}{\sin\alpha_e + \frac{b}{\sin\alpha_e + \frac{c}{\cdots}}}}.$$

# Propagation noise: Neutral troposphere (3)

- The correction the range observable is $D(\alpha_e)$
- The correction on the Doppler is: $\Delta f^c_{tropo}(t) = \frac{f^c\left(r_{tropo}(t + t_c/2) - r_{tropo}(t - t_c/2)\right)}{c t_c}.$
  where $t_c$ is the Doppler count time and $c$ the speed of light.

*Example of tropospheric correction (MEX Phobos flyby Dec. 29th 2013)*

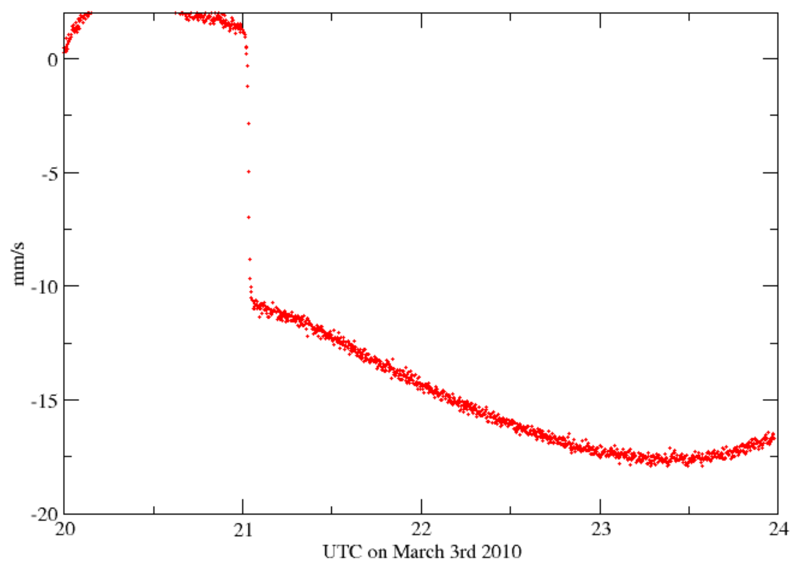


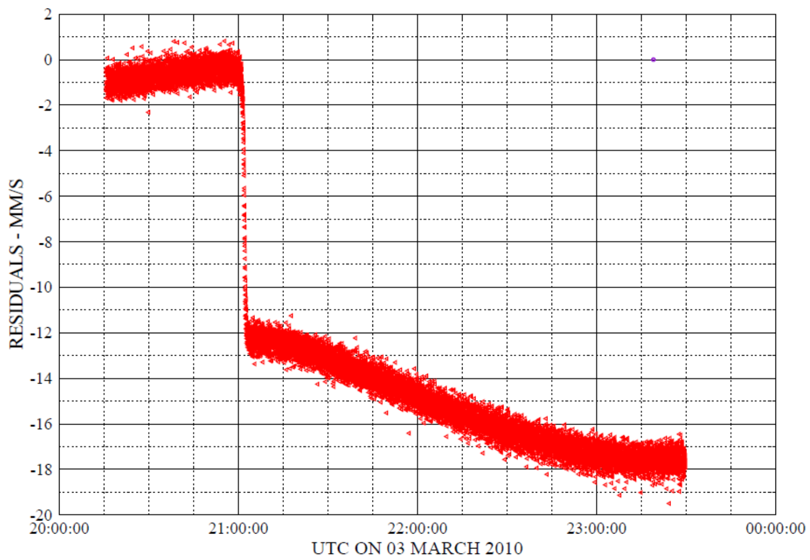
# Propagation noise: Neutral troposphere (4)

- Another effect of the troposphere is a significant attenuation of the radio-signal, especially the wet component at Ka band.

- It requires a water-vapor radiometer at the ground station to correct this effect in order to get all the gain of the Ka band on plasma effect.

# Simulation of Doppler tracking observable (1)




Simulation

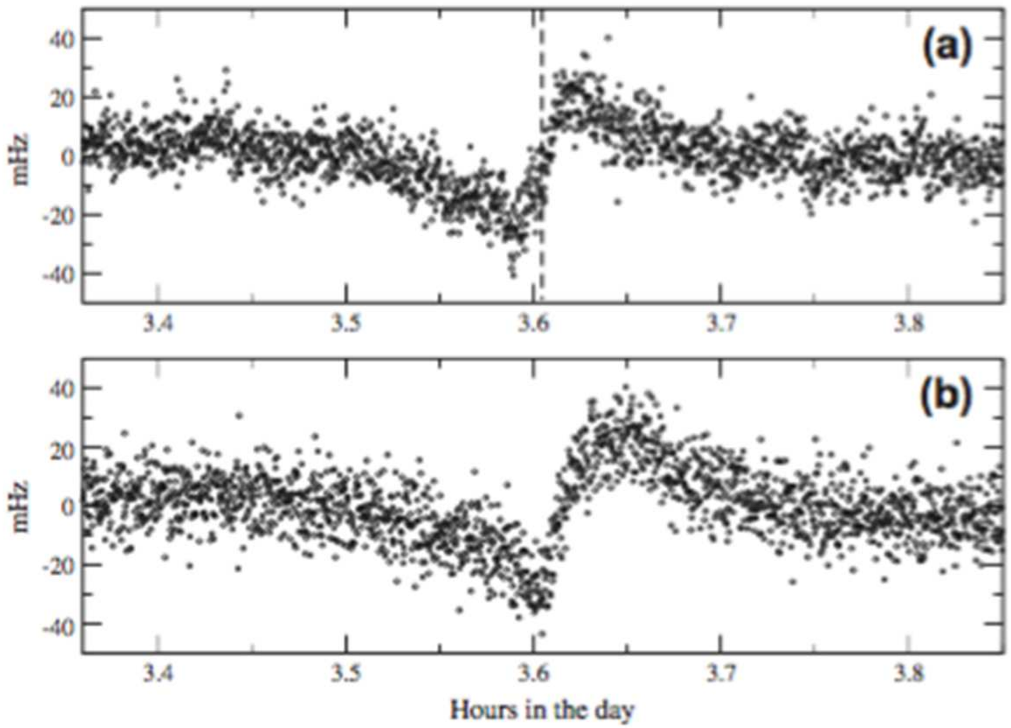
Real data

- Effect of the mass of Phobos on MEX Doppler residuals around a close flyby

# Simulation of Doppler tracking observable (2)

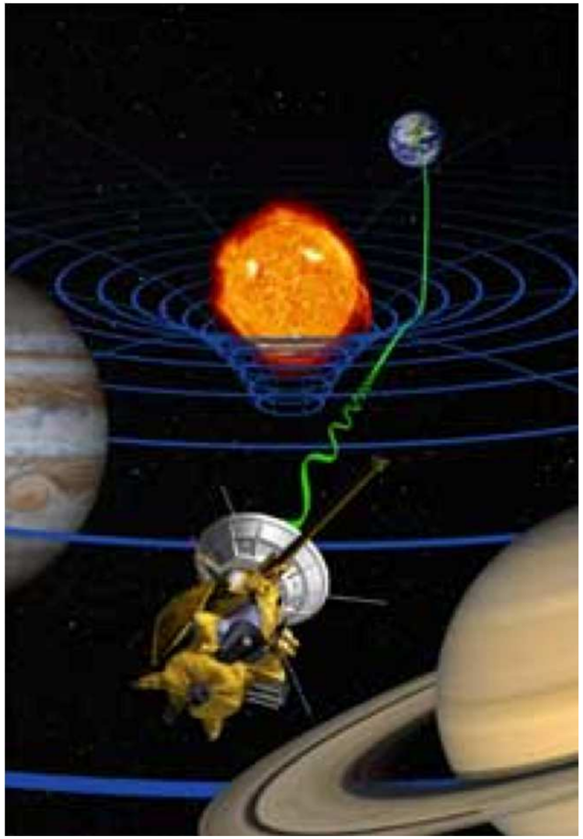
True data

Simulation



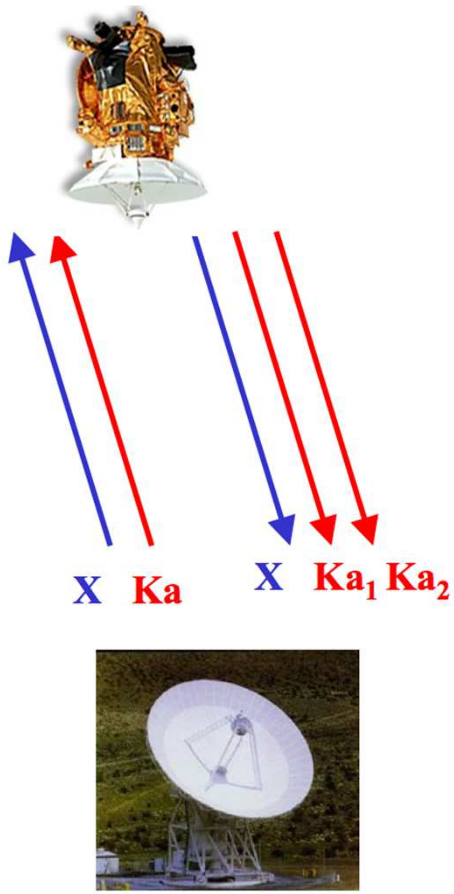

- Venus Express tracking pass at pericenter at about 165 km altitude
- Processing and simulation with GINS software

# Test of relativity with Cassini spacecraft



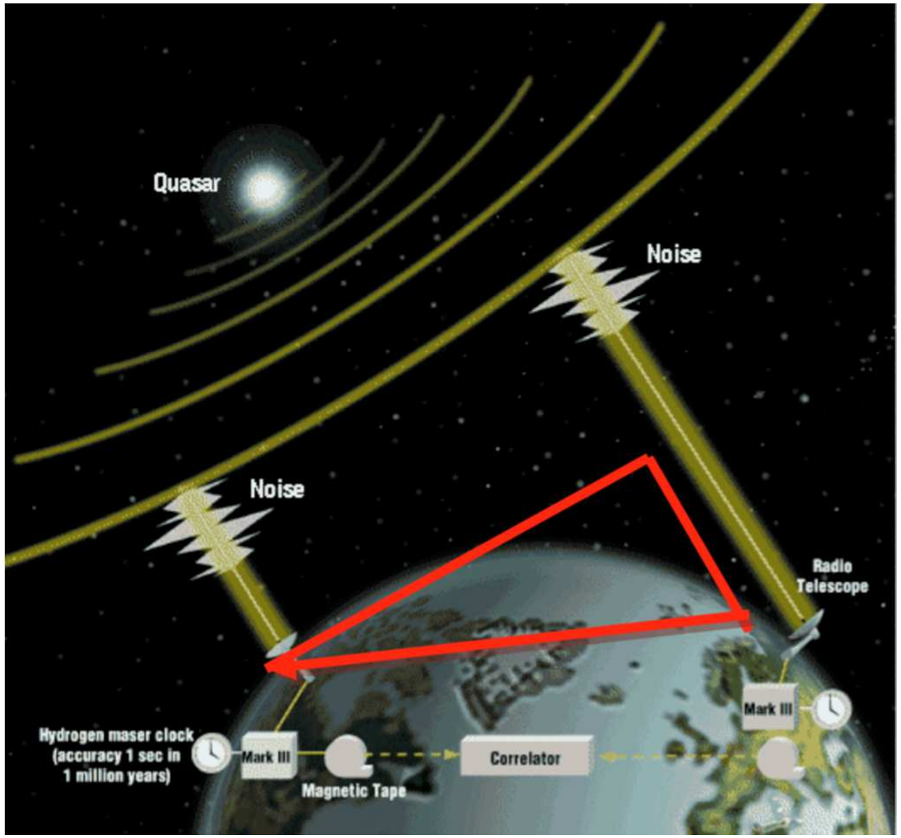
Experiment of light deflection
with Cassini en route to Saturn
*Bertotti, et al., Nature (2003)*

$$\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5} (1\sigma)$$




- X-Ka bands radio-links to perform plasma-free corrections
- Radiometer water-vapor used.

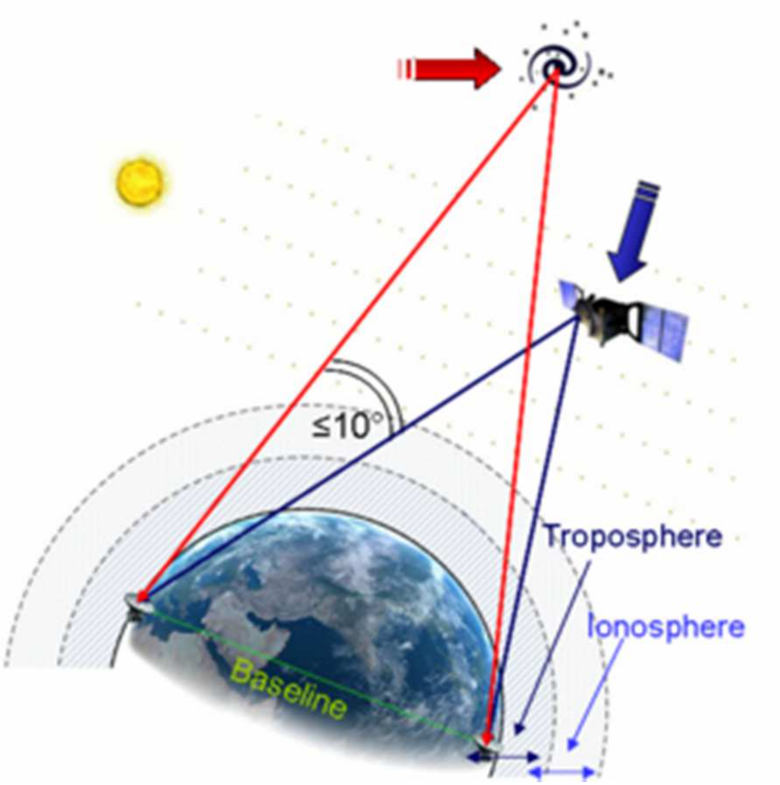
# Very Large Base Interferometry (VLBI)




- Measurement of arrival time difference at two different stations by cross-correlation of phase signal.

- Earth orientation wrt inertial frame (ICRF).

# DeltaDoR observable




- Measurement of arrival time difference at different ground stations
- Alternatively, measuring quasar and spacecraft
- Position of spacecraft on the celestial sphere

# DeltaDoR observable

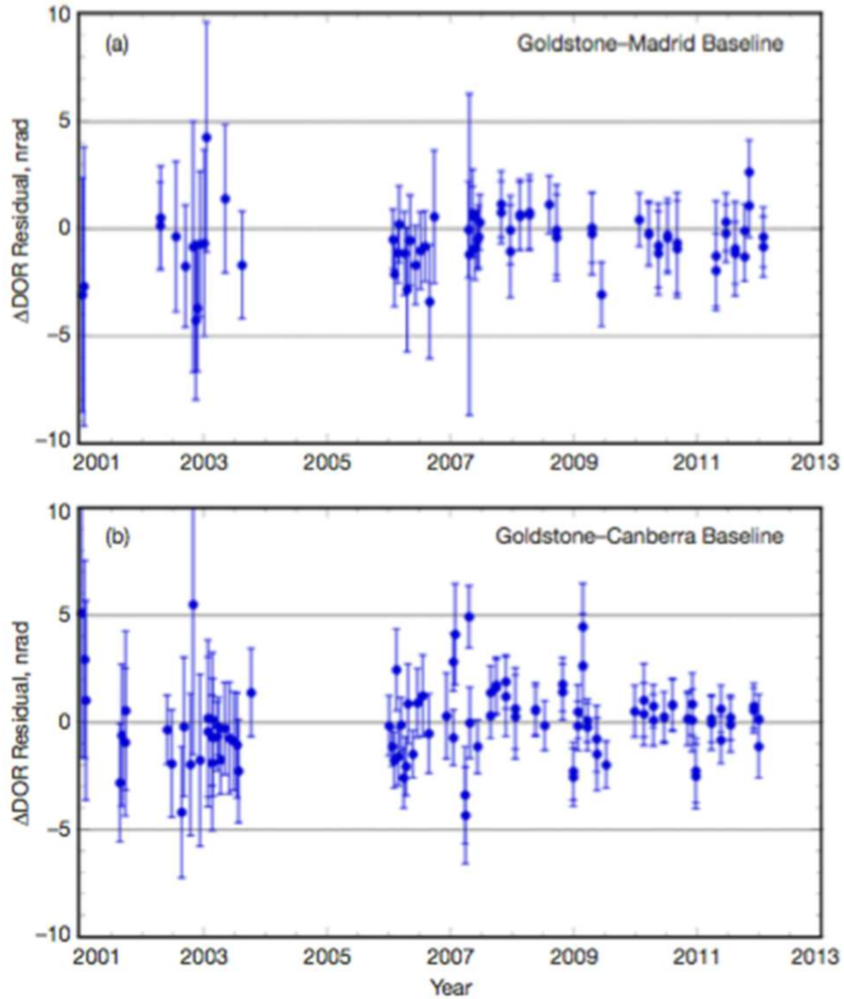
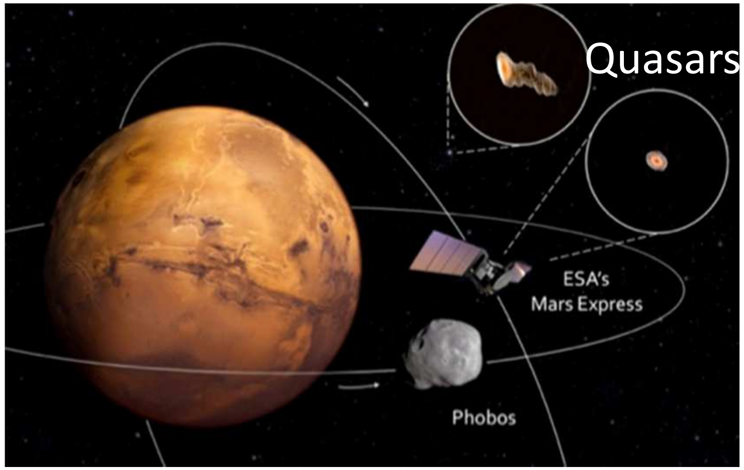
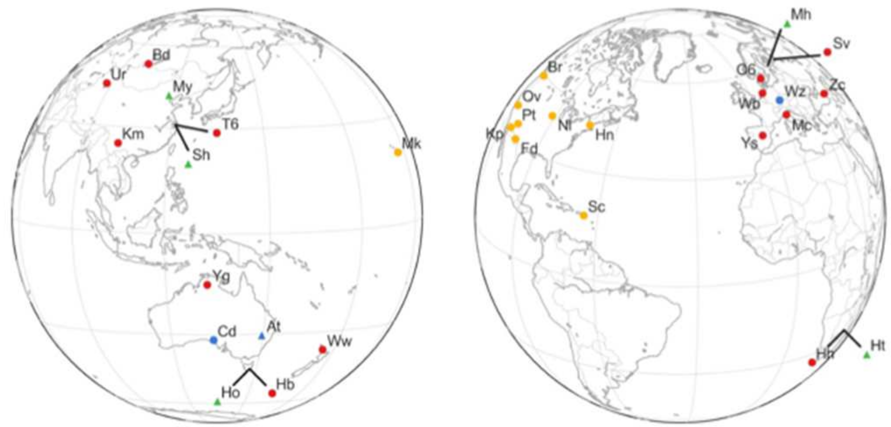


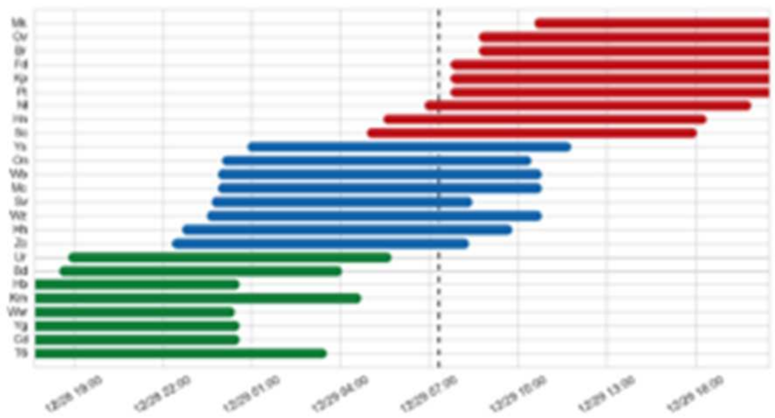

**Figure 16. Residuals of ΔDOR observations of Mars-orbiting spacecraft.**

- Nano-radians precision (150 meters at 1 UA)

# PRIDE (Planetary Radio Interferometry and Doppler Experiment)

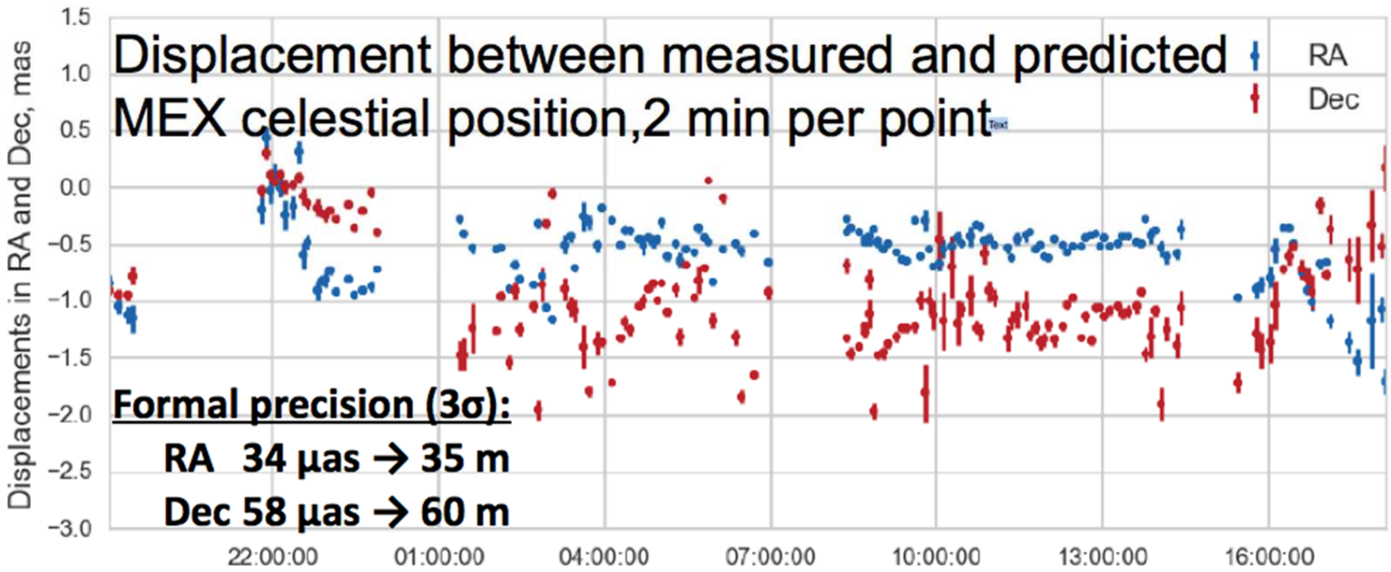


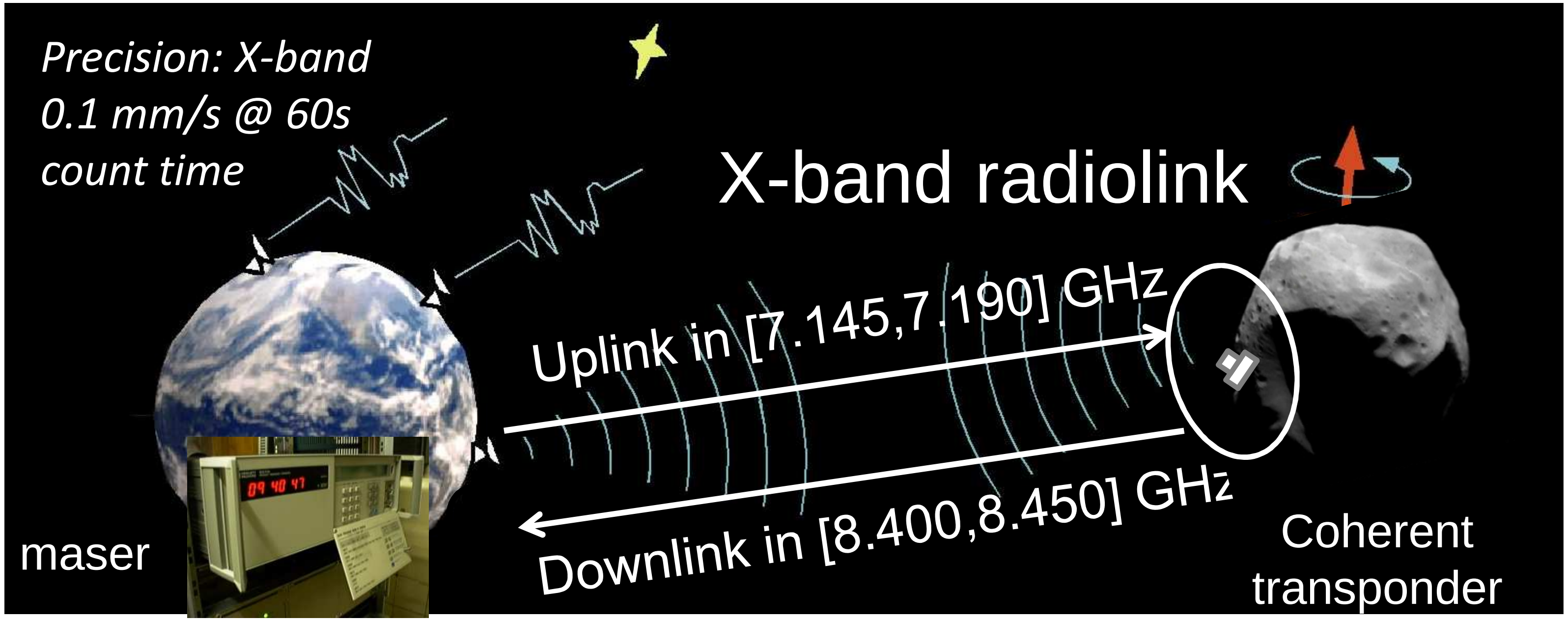
Almost 24 hours of PRIDE tracking during Phobos flyby by MEX performed in Dec. 29th 2013

# PRIDE (Planetary Radio Interferometry and Doppler Experiment)

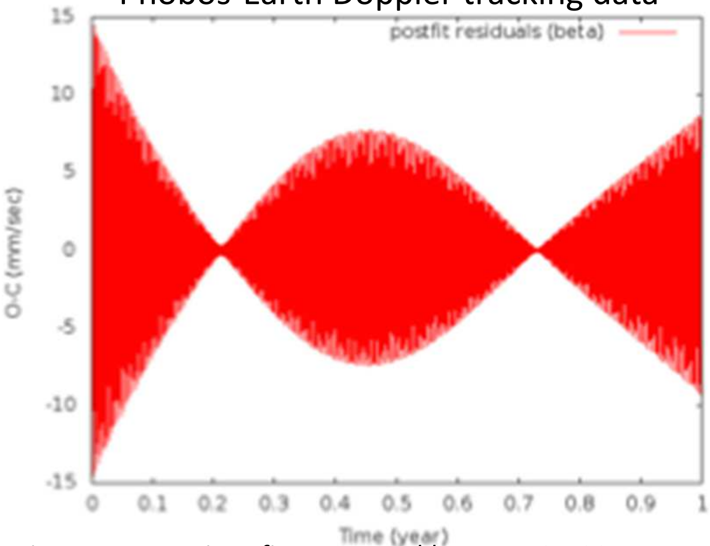



- Spacecraft positioning precision: 34 meters in RA & 60 meters in DEC.
- Spacecraft positioning accuracy: ~ - 500 meters in RA and ~ - 1286 meters in DEC.

# Test of relativity with Phobos orbit




Signature of coefficient β on Phobos-Earth Doppler tracking data



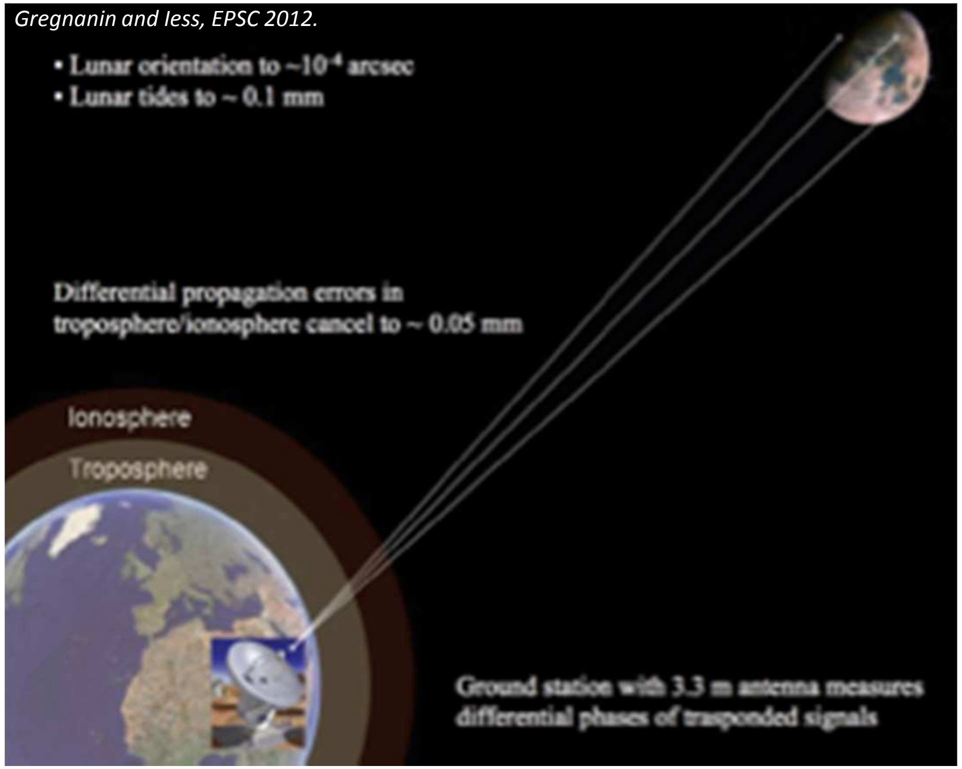

*Lainey V., Le Poncin-Lafitte C., Rosenblatt P., EPSC, 2011*

Precision expected after one year of Doppler tracking

| Physical effect | 1-sigma | Today accuracy |
|---|---|---|
| Annual $J_2$ | $1.0 \times 10^{-11}$ | few $10^{-9}$ |
| Semi-annual $J_2$ | $4.2 \times 10^{-12}$ | few $10^{-9}$ |
| $\beta$ | $3.9 \times 10^{-5}$ | $10^{-4}$ |

Opportunity of mission with a Lander at Phobos surface at JAXA (2022, but Lander not yet decided)

# Same Beam Interferometry (SBI)




- Network of Landers at Lunar surface observed by a same antenna at the same time.
- Measurements of arrival time of each Lander radio-signal at the Earth-station.
- Accurate measurements of relative positioning between each Lander of the network:

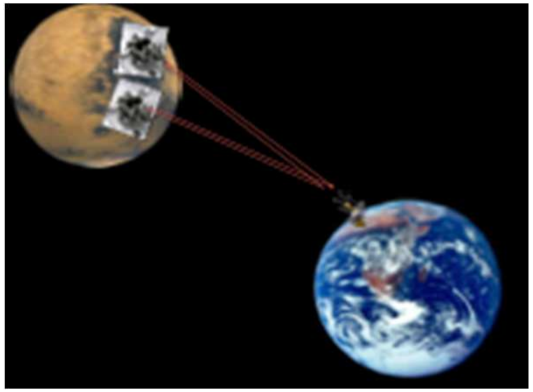
  ***→0.1 mm (at Ka band)   (1 mm with LLR)***

- Needs digital architecture of Lander radio-transponder

- Open a new era in Lunar geophysical studies (Libration, Tides, …)

# Same Beam Interferometry (SBI)

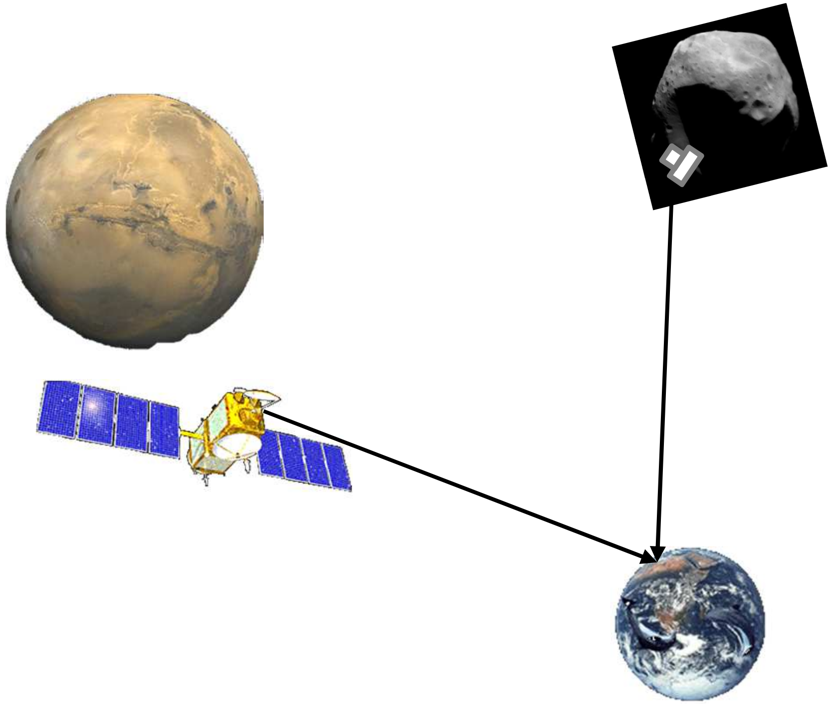
- Network of Landers at Mars' surface:
  1 mm (at X-band) - Nutations, tides, …



*Yseboodt et al., EPSC 2012.*

Opportunity: INSIGHT+ExoMars2018

Improving Mars precession, nutations …



- Monitoring orbiter to Phobos-surface distance
  **with a precision of 1 mm**
  Phobos orbital and proper motion, test of General Relativity …

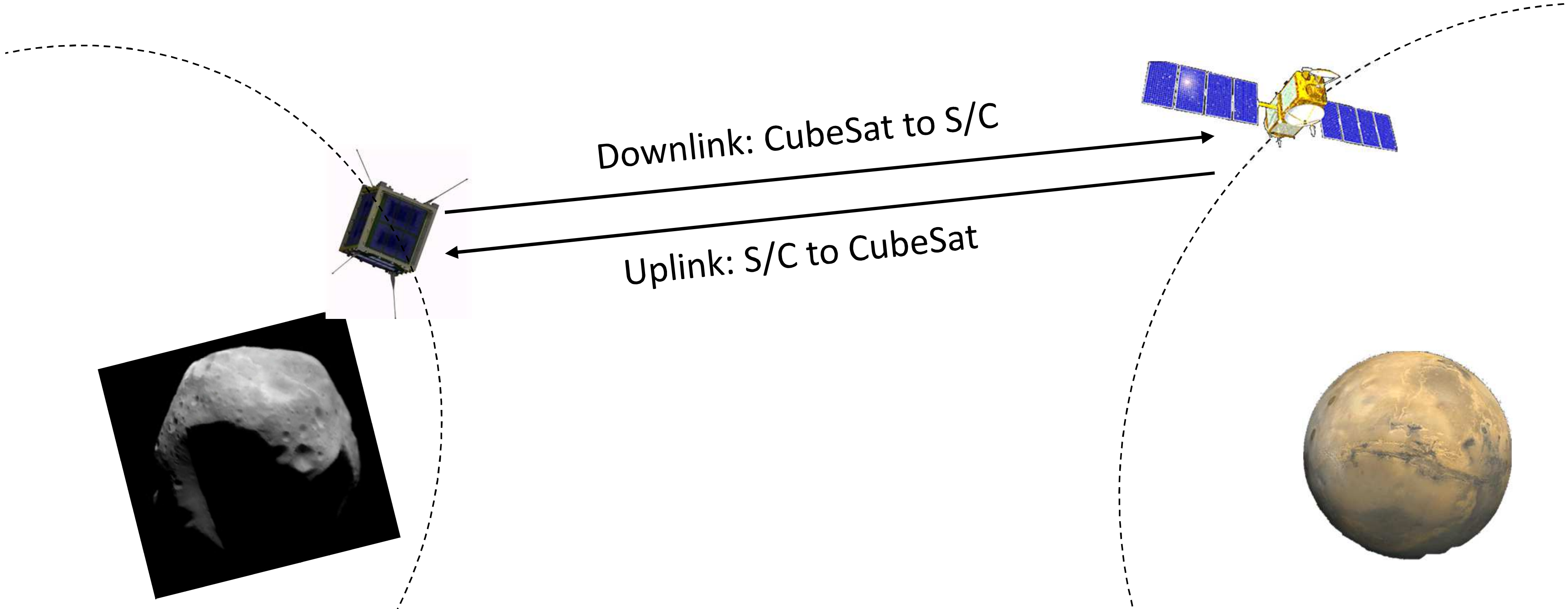
  Opportunity: Missions ot Phobos (JAXA, ESA)

# Current Spacecraft GNC constraints on Phobos flyby

| Type of Constraint | Numbers<br>(MAVEN Navigation) | Correction<br>(Released constraints) |
|---|---|---|
| Phobos size<br>Phobos ephemeris<br><br>S/C-Phobos Velocity<br>2.2 km/s | ~15 km in radius<br>~15 km (3-sigma)<br>~**30 km** keep-out-zone<br><br>~**15 seconds** | ~15 km in radius<br>~3 km in radius (3-sigma)<br>~**20 km** keep-out-zone<br><br>~**10 seconds** |
| S/C Maneuver timing<br>S/C Orbit precision | 3-5 days required<br>~**20 seconds** | < 1 day Special Request<br>~**5 seconds (10-15)** |
| Timing offset<br>to avoid collision<br><br>**Safety flyby distance from Phobos center** | 15 + 20 = 35 seconds<br><br>2.2*35 ~ 70 km<br>**Altitude: ~ 60 km**<br>*(MeX: 45 km)* | 10 + 5 = 15 seconds<br><br>2.2*15 ~ 30 km<br>**Altitude: ~ 20 km** |

- **Navigation constraints make difficult very close flyby (2-5 km)**

# Spacecraft-to-CubeSat radio-link:
# *Links of proximity*

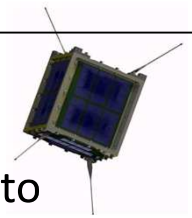



- CubeSat performing very close flybys
- Spacecraft tracking CubeSat

- Entering into the Hill sphere of Phobos (within 5 km of altitude) to probe its gravity field
- Constraints on the internal mass distribution of a small body

# Radio-Science with CubeSat.

CubeSat:



Radio-transponder to
- send back radio-signal to S/C without modifying the phase stability: ~$10^{-13}$ (Allan Deviation)
 (CNES R&D)
- Auto-Navigation system To perform several flybys (QBDIM/Birdy, IMCCE)

Spacecraft:

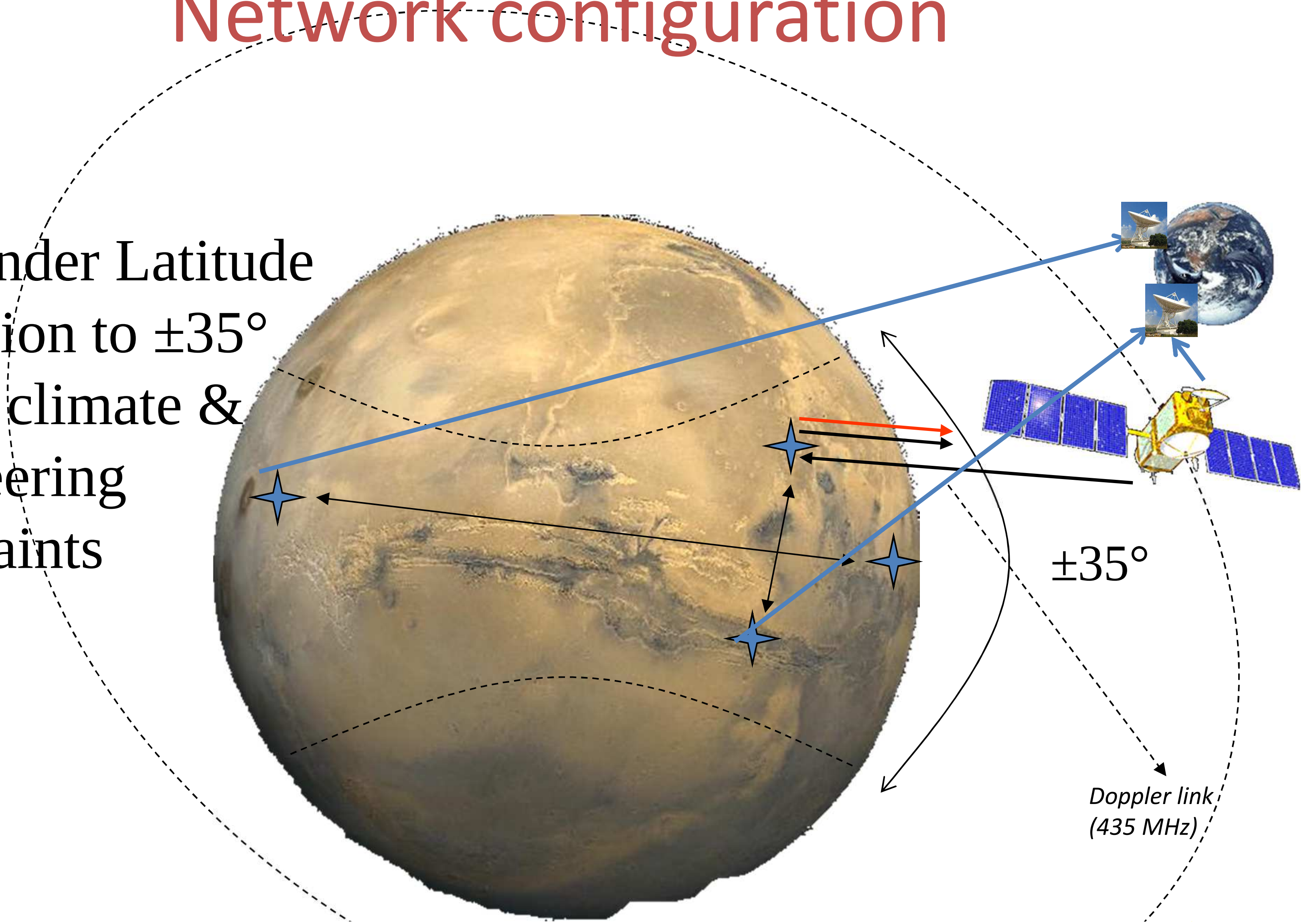
Stable reference frequency for:
- Uplink frequency
- Datation of Downlink signal sent back by CubeSat

USO: Onboard Ultra Stable Oscillator ~ $10^{-13}$ (Allan Deviation)

- Precise Doppler measurements of relative velocity between S/C and CubeSat (0.02 mm/s @ 60 sec)
- Very short distance links (w.r.t. Mars-Earth distance): Excellent budget link Very limited power consumption
- No needs to use high frequency (X or Ka band or even S band) since no propagation effect (charged particles, neutral atmosphere)

# Network configuration

NetLander Latitude limitation to ±35° due to climate & engineering constraints




- Improvement of Mars rotation and orientation through large baseline between Landers and higher sensitivity of orbiter-Doppler link to Lander motion (i.e. Mars motion).
- But one needs to take into account errors on the orbit of the spacecraft like those due to desaturation of inertial wheels.

# Partial derivatives for orbit reconstruction

- Partial derivatives can be computed from computing formulae of tracking observable (see Moyer).
  Example with unramped Doppler:

$$\frac{\partial\left(\text{unramped } F_{2,3}\right)}{\partial \mathbf{q}} = \frac{M_2 f_T(t_1)}{T_c}\left(\frac{\partial \rho_e}{\partial \mathbf{q}} - \frac{\partial \rho_s}{\partial \mathbf{q}}\right)$$

where **q** are parameters of the spacecraft (Lander) position $\rho$

- It allows to perform a least-squares fit of spacecraft motion to the tracking data in order to precisely reconstruct its orbit and determine geophysical parameters (nutations, gravity field, …)

**→ See next lesson**