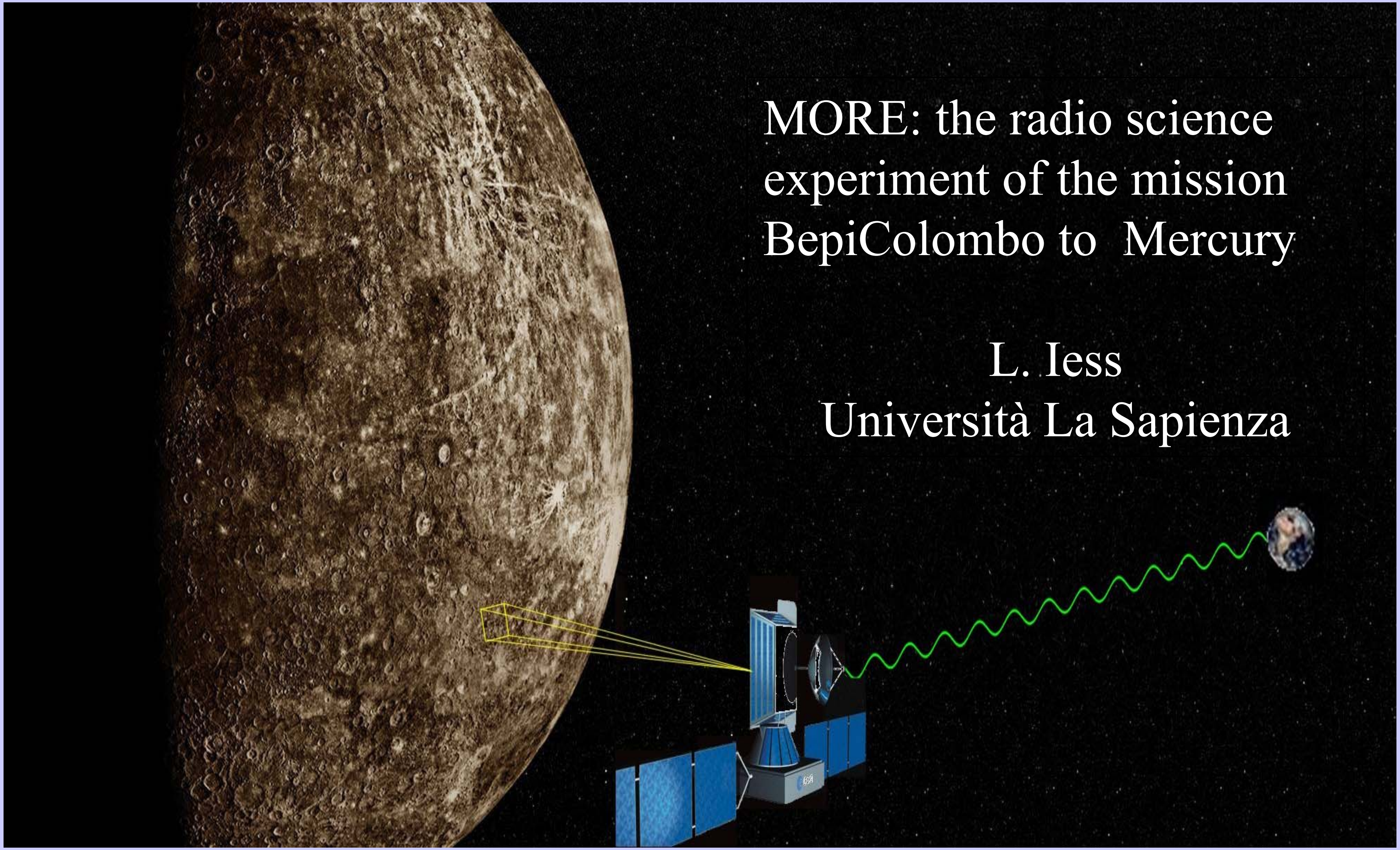
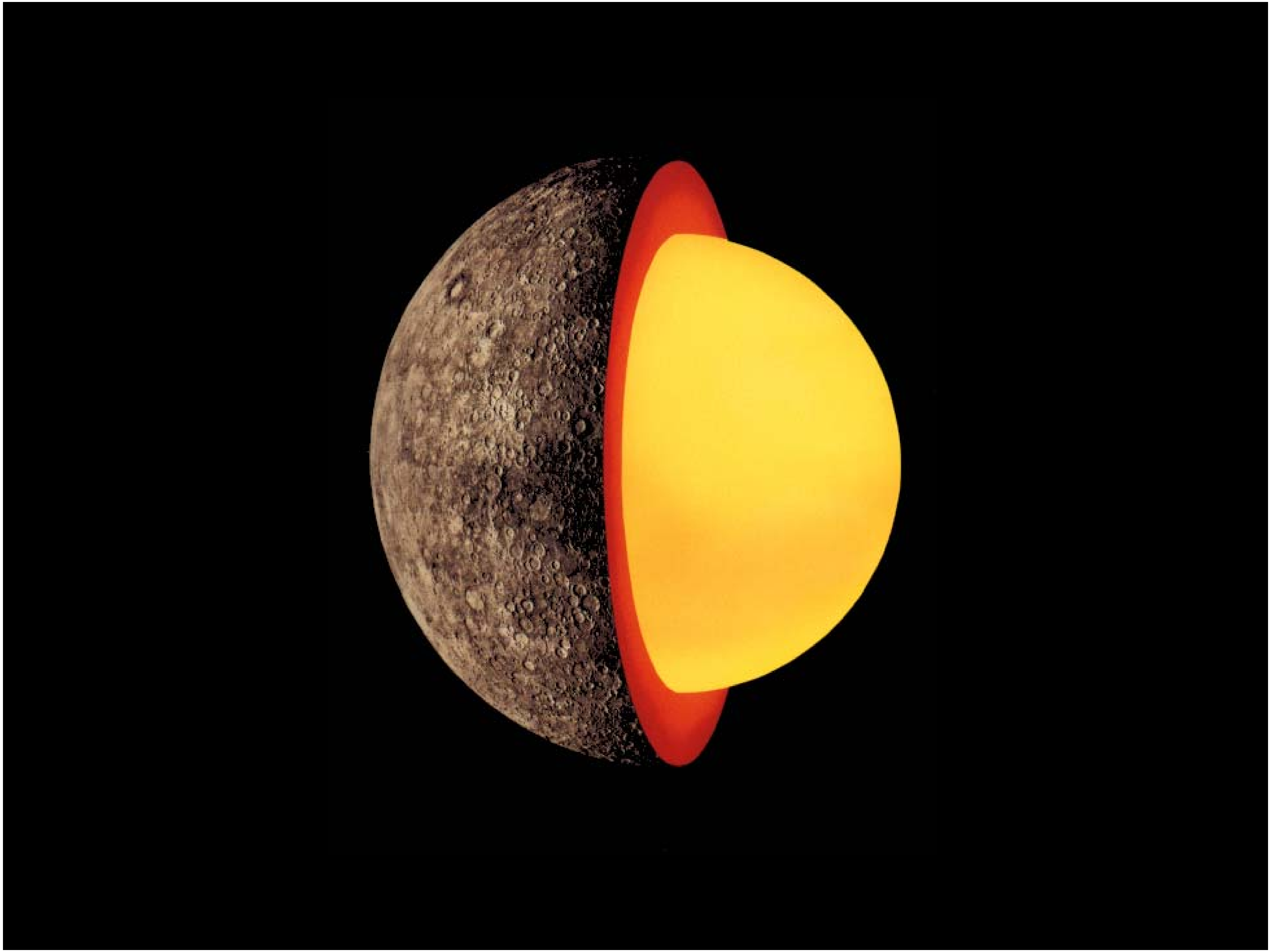
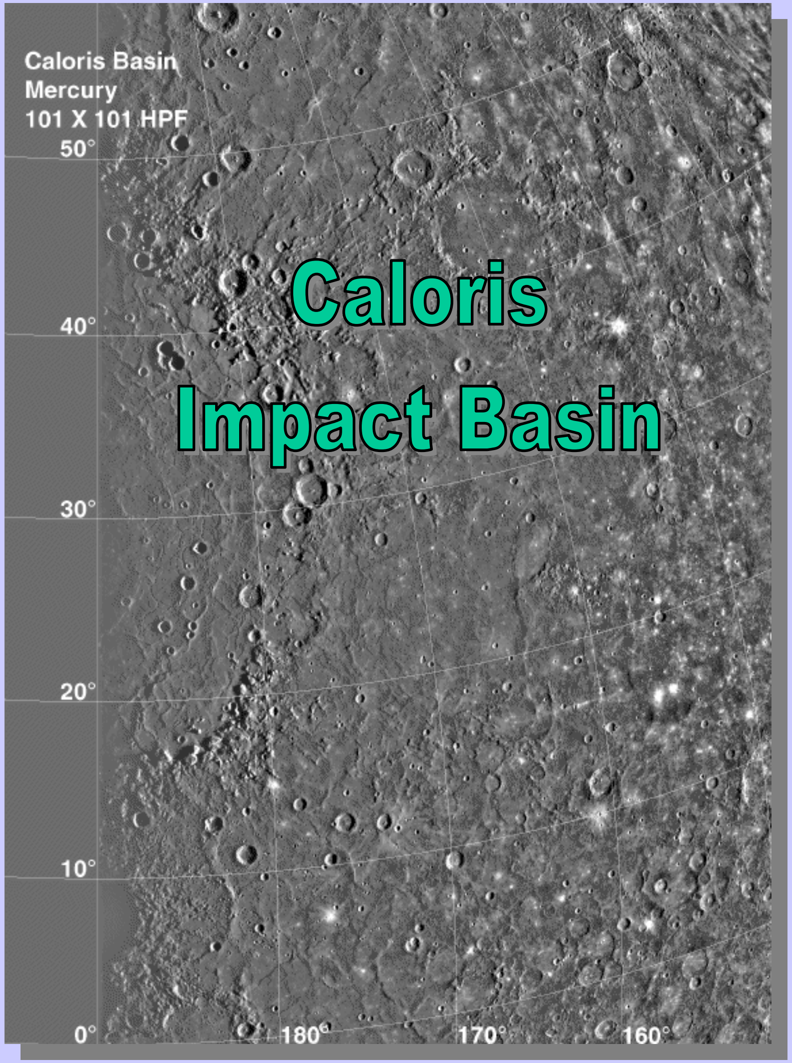
MORE: the radio science experiment of the mission BepiColombo to Mercury

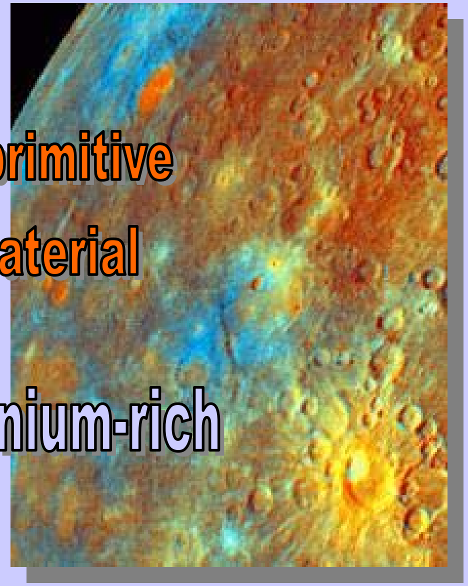
L. Iess
Università La Sapienza

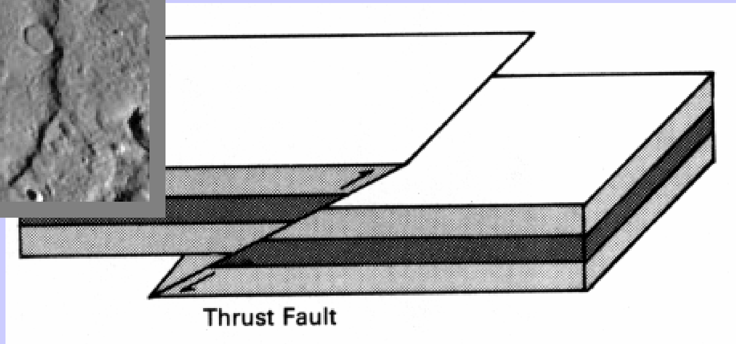




Surface Characteristics

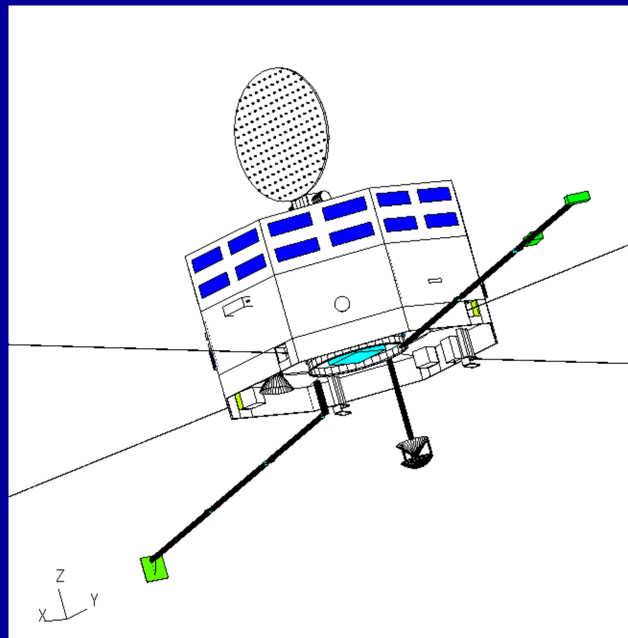






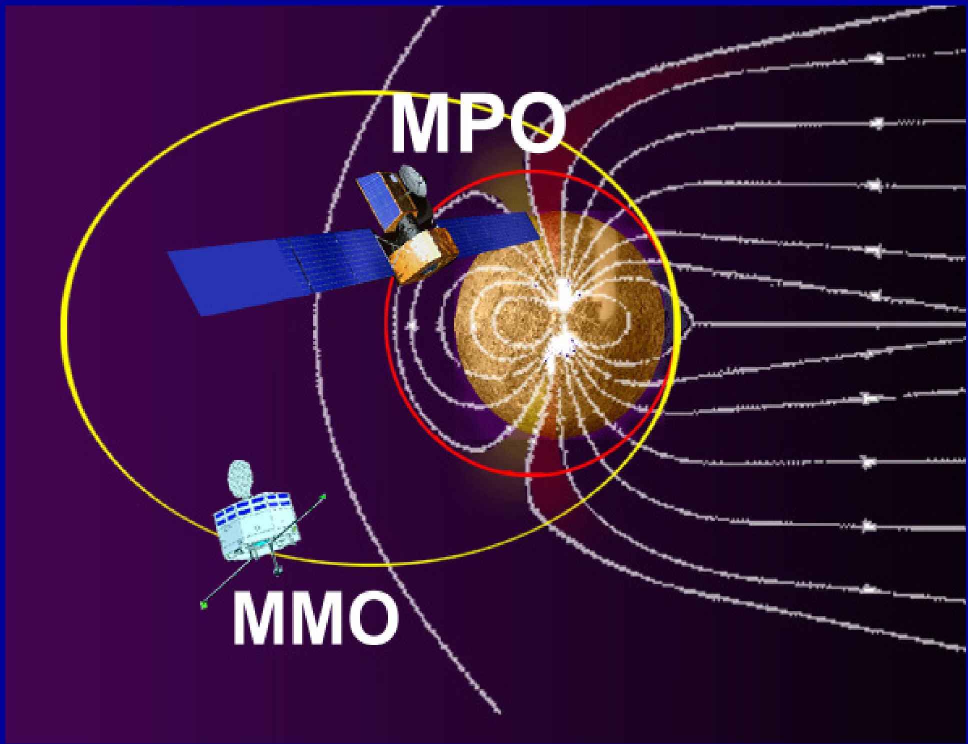
Mercury Planetary Orbiter

Mercury Magnetospheric Orbiter



BepiColombo

MMO & MPO on dedicated orbits



- ✓ MMO orbit optimized for study of magnetosphere
- ✓ MPO orbit optimized for study of planet itself

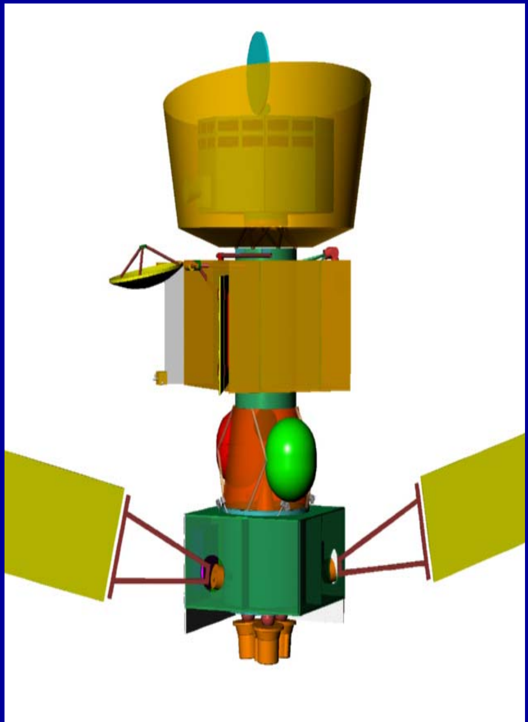
- ➢ High-accuracy measurements of interior structure
- ➢ Full coverage of planet surface at high resolution
- ➢ Optimal coverage of polar area
- ➢ Resolve ambiguities
  - exosphere
  - magnetosphere
  - magnetic field

Launch on Soyuz 2-1B/Fregat-M (**12 August 2013**)

Solar Electric Propulsion

Chemical Propulsion

Arrival: 2017 (?)

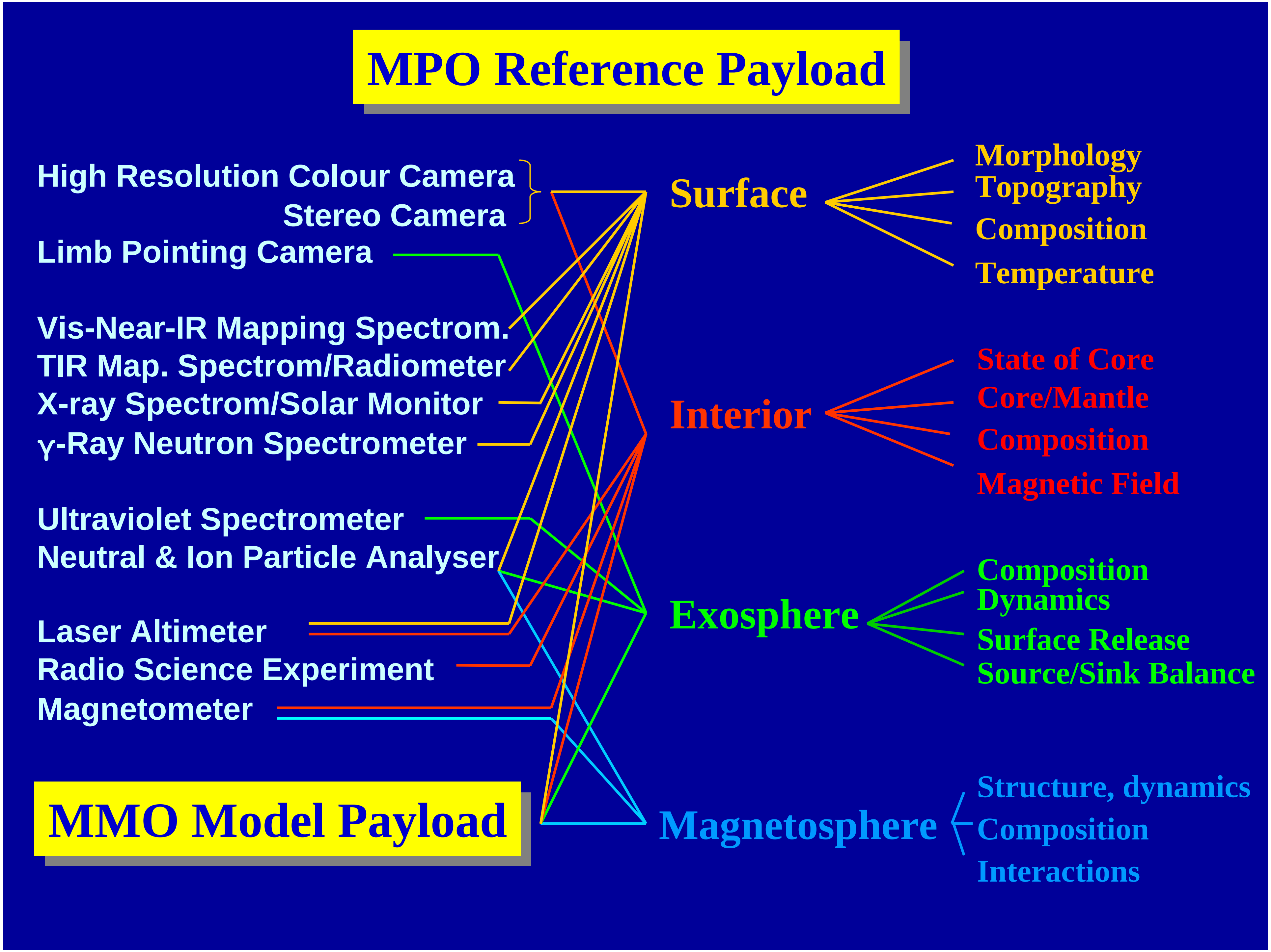


MMO

MPO

CPM

SEPM


MPO Reference Payload
High Resolution Colour Camera
Stereo Camera
Limb Pointing Camera
Vis-Near-IR Mapping Spectrom.
TIR Map. Spectrom/Radiometer
X-ray Spectrom/Solar Monitor
γ-Ray Neutron Spectrometer
Ultraviolet Spectrometer
Neutral & Ion Particle Analyser
Laser Altimeter
Radio Science Experiment
Magnetometer
MMO Model Payload
Surface
Morphology
Topography
Composition
Temperature
Interior
State of Core
Core/Mantle
Composition
Magnetic Field
Exosphere
Composition
Dynamics
Surface Release
Source/Sink Balance
Magnetosphere
Structure, dynamics
Composition
Interactions

MORE: Science Goals

- Spherical harmonic coefficients of the gravity field of the planet up to degree and order 25.
- Degree 2 (C_{20} and C_{22}) with 10^{-9} accuracy (Signal/Noise Ratio ~ 10^4)
- Degree 10 with SNR ~ 300
- Degree 20 with SNR ~ 10
- Love number k_2 with SNR ~ 50.
- Obliquity of the planet to an accuracy of 4 arcsec (40 m on surface – needs also SIMBIO-SYS)
- Amplitude of physical librations in longitude to 4 arcsec (40 m on surface – needs SIMBIO-SYS).
- C_m/C (ratio between mantle and planet moment of inertia) to 0.05 or better
- C/MR^2 to 0.003 or better.

MORE: Science Goals

- Spacecraft position in a Mercury-centric frame to 10 cm – 1m (depending on the tracking geometry)
- Planetary figure, including mean radius, polar radius and equatorial radius to 1 part in 10^7 (by combining MORE and BELA laser altimeter data).
- Geoid surface to 10 cm over spatial scales of 300 km.
- Topography of the planet to the accuracy of the laser altimeter (in combination with BELA).

- Position of Mercury in a solar system barycentric frame to 10-100 cm.
- PN parameter γ, controlling the deflection of light and the time delay of ranging signals to $2.5*10^{-6}$
- PN parameter β, controlling the relativistic advance of Mercury's perihelion, to $5*10^{-6}$
- PN parameter η (controlling the gravitational self-energy contribution to the gravitational mass to $2*10^{-5}$
- The gravitational oblateness of the Sun (J_2) to $2*10^{-9}$
- The time variation of the gravitational constant ($d(\ln G)/dt$) to $3*10^{-13}$ years^{-1}

Why Mercury for Fundamental Science?

- **Mercury lays deeper in the solar gravitational field and moves faster than any other major solar system body.**
- **The relativistic effects are significantly larger on its orbit.**
- **Far from the asteroid belt, Mercury is less affected by unknown gravitational perturbations.**
- **The motion of Mercury's centre of mass can be determined very accurately (1 m) by tracking the Planetary Orbiter from Earth with a novel radio system.**

Measurements used by MORE

- The range and range rate between the ground stations and the spacecraft, having removed the effects of the plasma along the path by means of a multi-frequency link in X and in Ka band.
- The non-gravitational perturbations acting on the spacecraft, by means of the ISA accelerometer.
- The absolute attitude of the spacecraft, in a stellar frame of reference, by means of star trackers.
- The angular displacement, with respect to previous passages, of surface landmarks, by means of pattern matching between SIMBIO-SYS images.

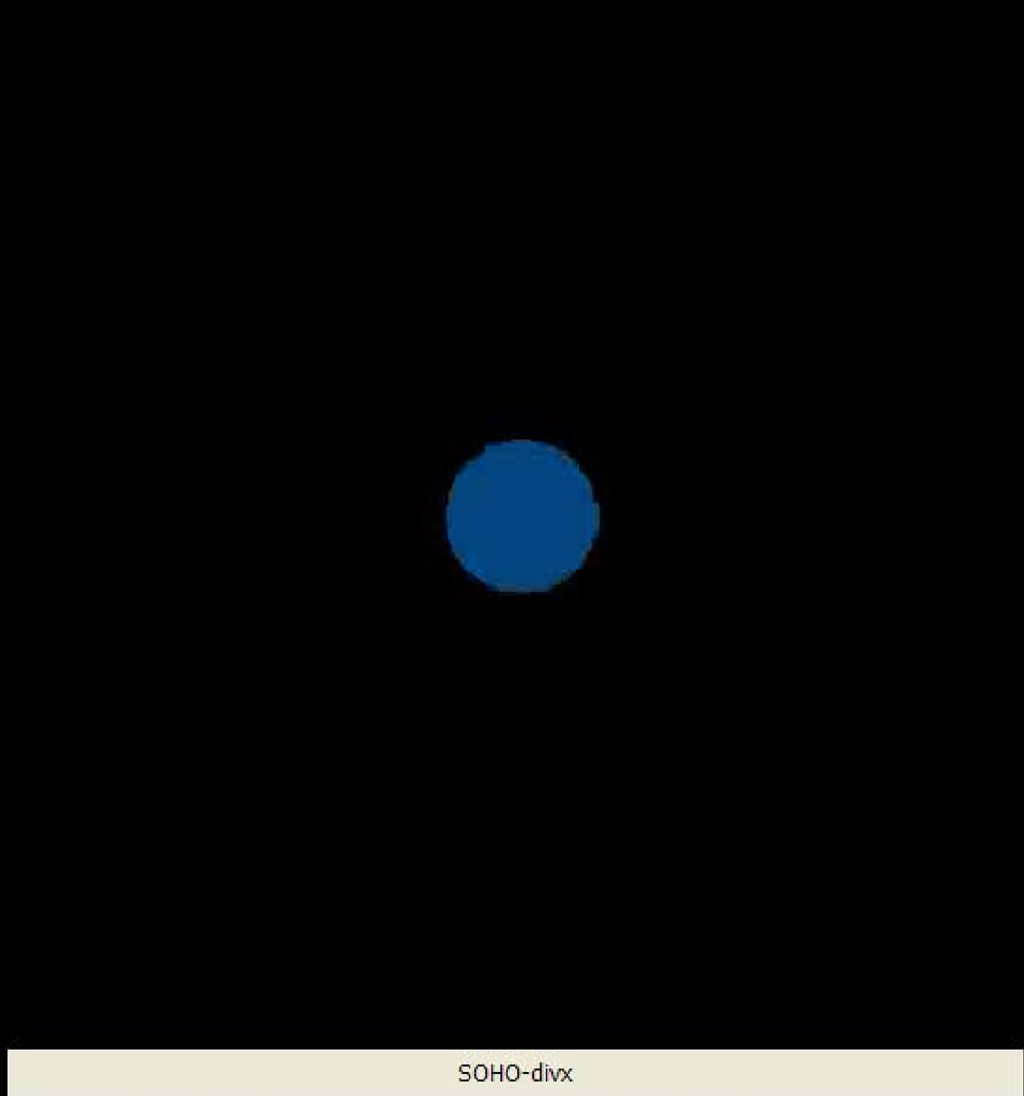
Fighting Noise

- **Dynamical noise and non-gravitational accelerations**
- **Propagation noise (solar corona, interplanetary plasma, troposphere)**
- **Spacecraft and ground instrumentation**

Dynamical noise must be reduced to a level compatible with the accuracy of range-rate measurements:

$$\sigma_a = \frac{c}{\tau}\sigma_y = 3\times10^{-7}\,\mathrm{cm\,s^{-2}}$$ at τ = 1000 s

The trajectory of Cassini in the sky during SCE1



LASCO images - SOHO

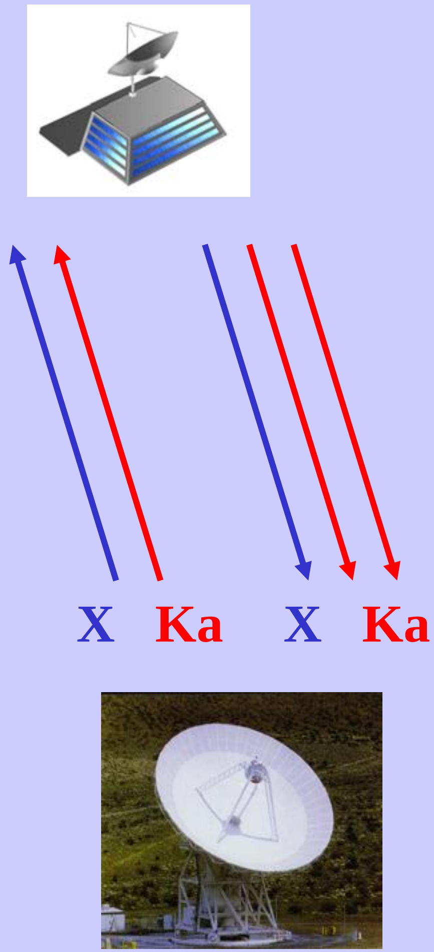
Plasma noise cancellation

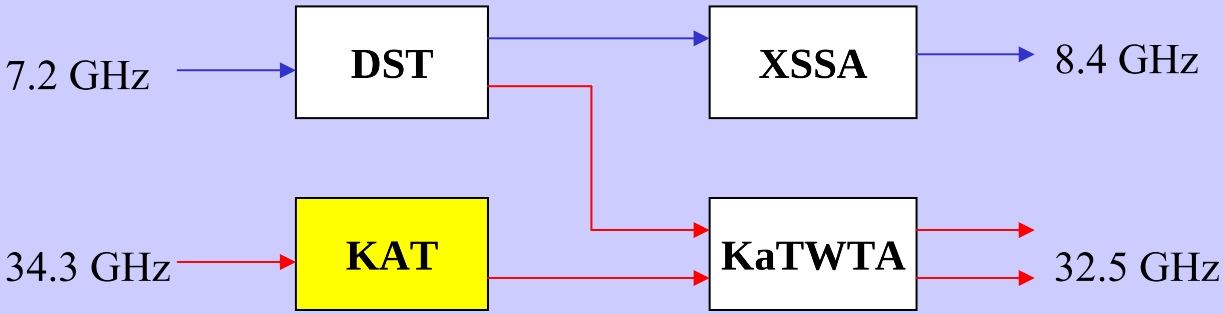
Multifrequency radio link
(two-way)

Target accuracy:

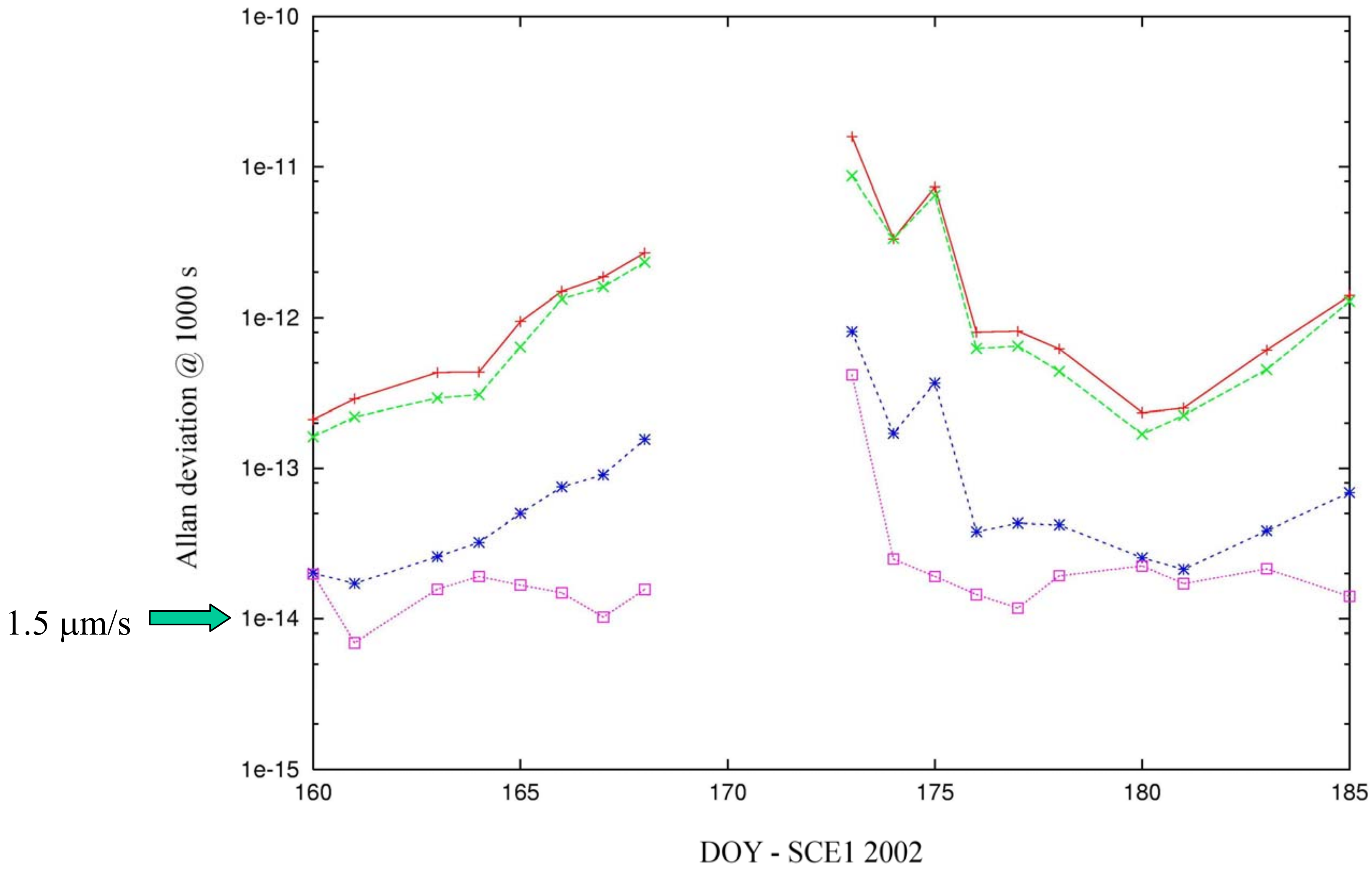
$\Delta f/f = 10^{-14}$ at 10^{3}-10^{4}s
$\Delta\rho$ = 10 cm

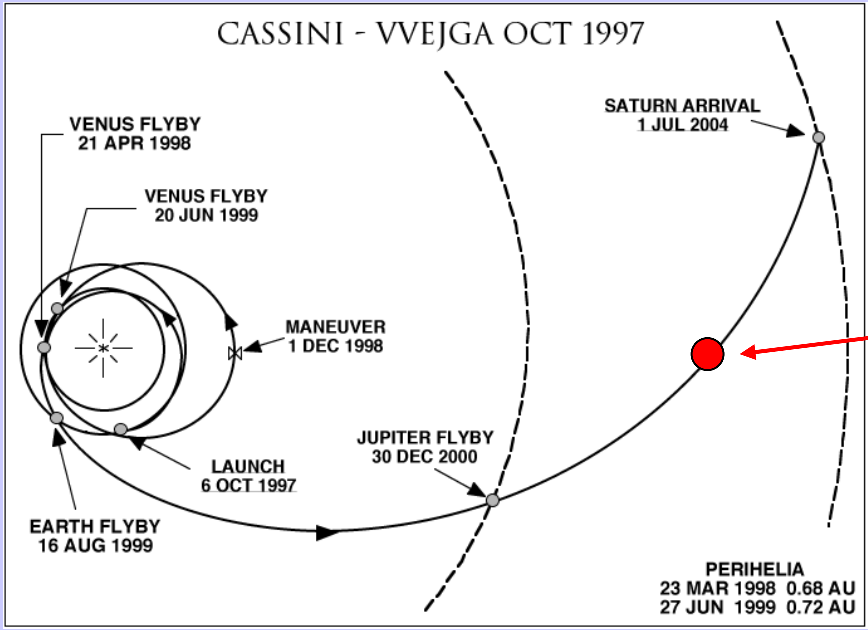
$\sigma_y=10^{-14}$ is equivalent to a one-way range rate of 1.5 micron/s
The corresponding one-way displacement in 1000 s is 1.5 mm



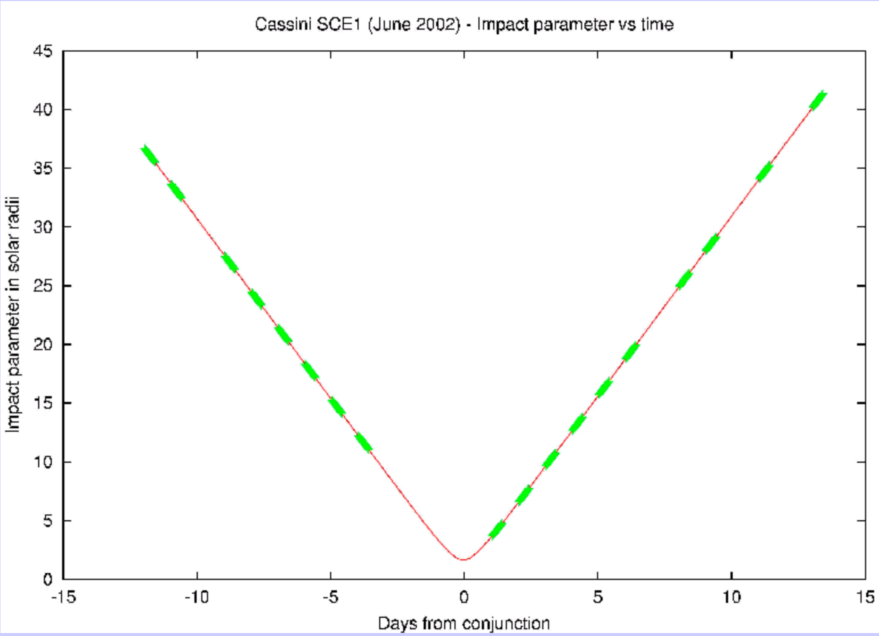


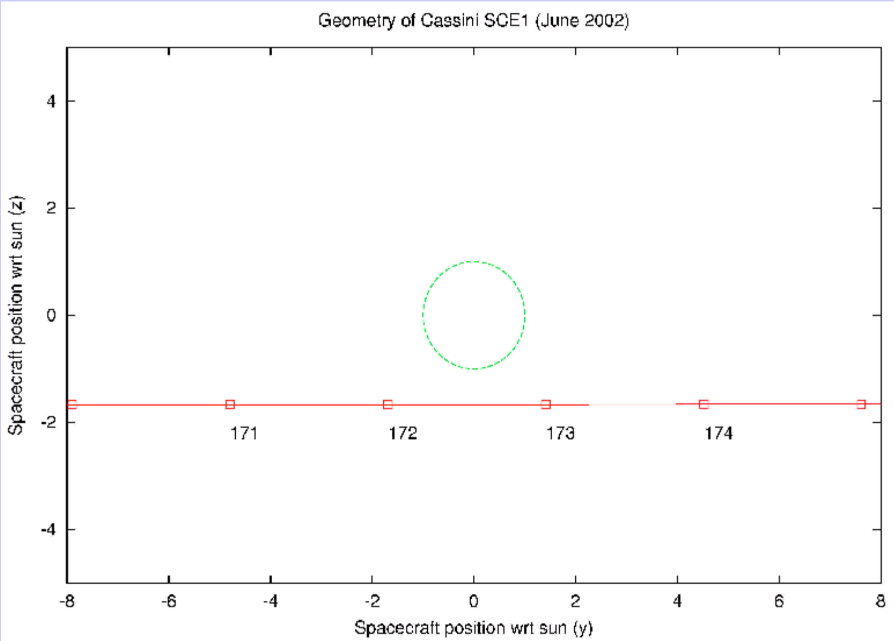
Plasma noise in the X/X, X/Ka, Ka/Ka links and the calibrated Doppler observable (daily Allan dev. @1000s, Cassini SCE1) Minimum impact parameter: 1.6 R_s (DOY 172)





SCE1
30 days
coverage
from DSN





Testing gravitational theories in the solar system.

Deflection of light

$$\theta_{gr} = 2(1+\gamma)\frac{M_{sun}}{b} = 4\times 10^{-6}(1+\gamma)\frac{R_{sun}}{b}\ \text{rad}$$

Solar Gravity

Time delay

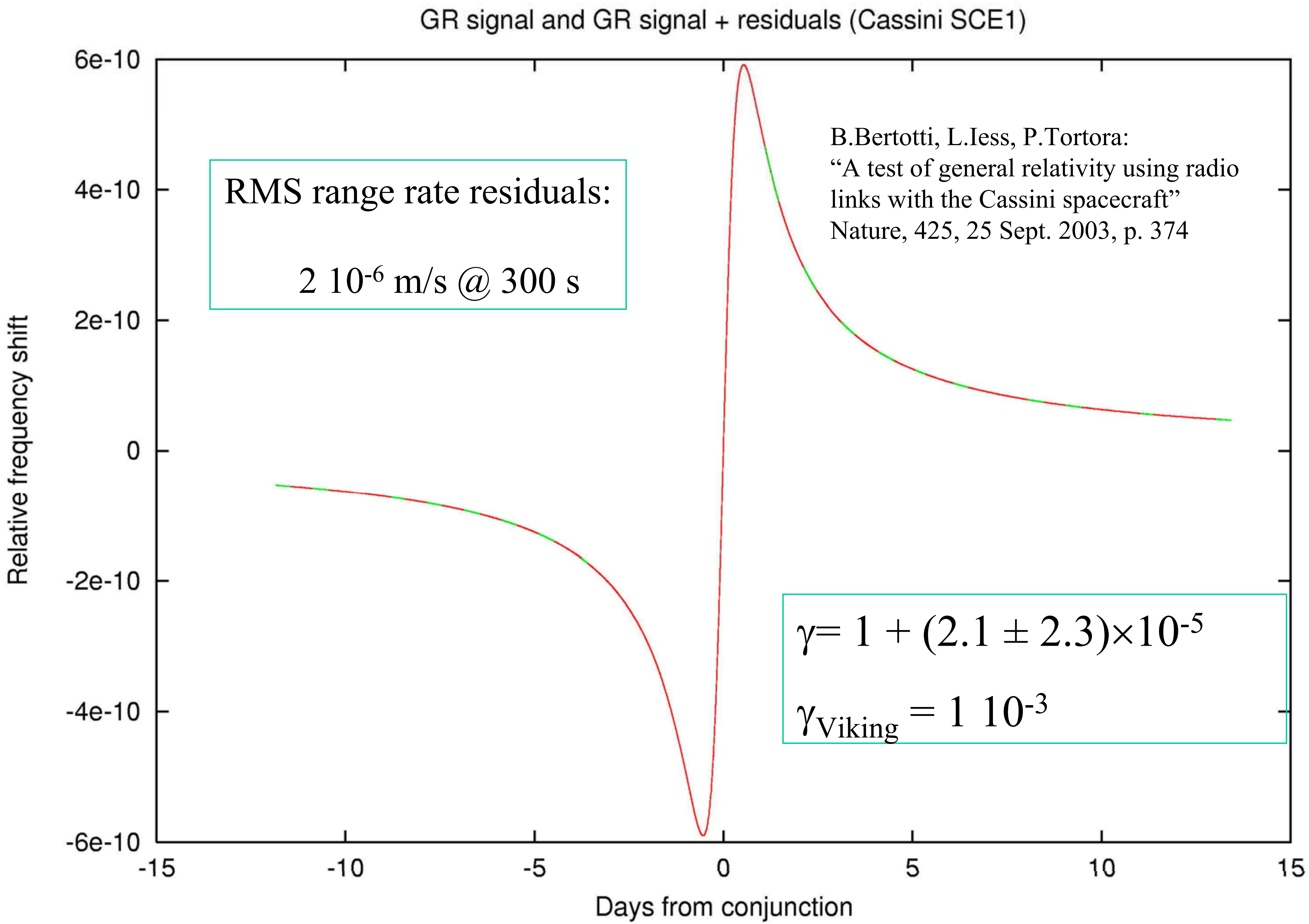
$$\Delta t = (1+\gamma)M_{sun}\ln\frac{l_0+l_1+t}{l_0+l_1-t}$$

= 72 km for a grazing beam

Frequency shift

$$\frac{\Delta\nu}{\nu} = 2\frac{v_1 l_0 + v_0 l_1}{l_0+l_1}\theta \cong 4(1+\gamma)\frac{M_{sun}}{b}\dot{b}$$

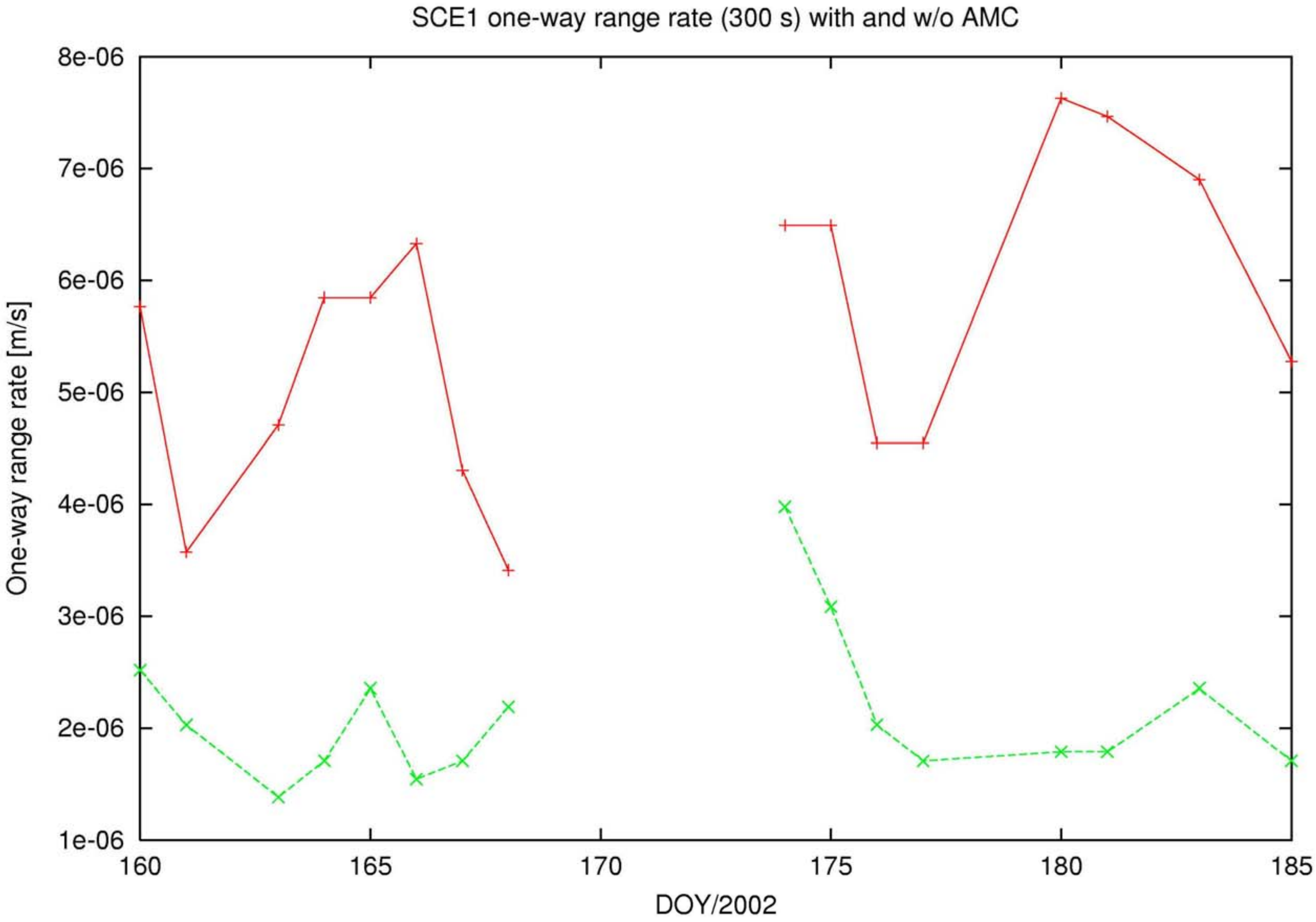
≈ 8×10^{-10} for a grazing beam



GR signal and GR signal + residuals (Cassini SCE1)
6e-10
4e-10
2e-10
0
-2e-10
-4e-10
-6e-10
Relative frequency shift
-15
-10
-5
0
5
10
15
Days from conjunction
RMS range rate residuals:
$2\ 10^{-6}$ m/s @ 300 s
B.Bertotti, L.Iess, P.Tortora:
"A test of general relativity using radio links with the Cassini spacecraft"
Nature, 425, 25 Sept. 2003, p. 374
$\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$
$\gamma_{Viking} = 1\ 10^{-3}$

The 34m beam waveguide tracking station DSS 25, NASA's Deep Space Network, Goldstone, California

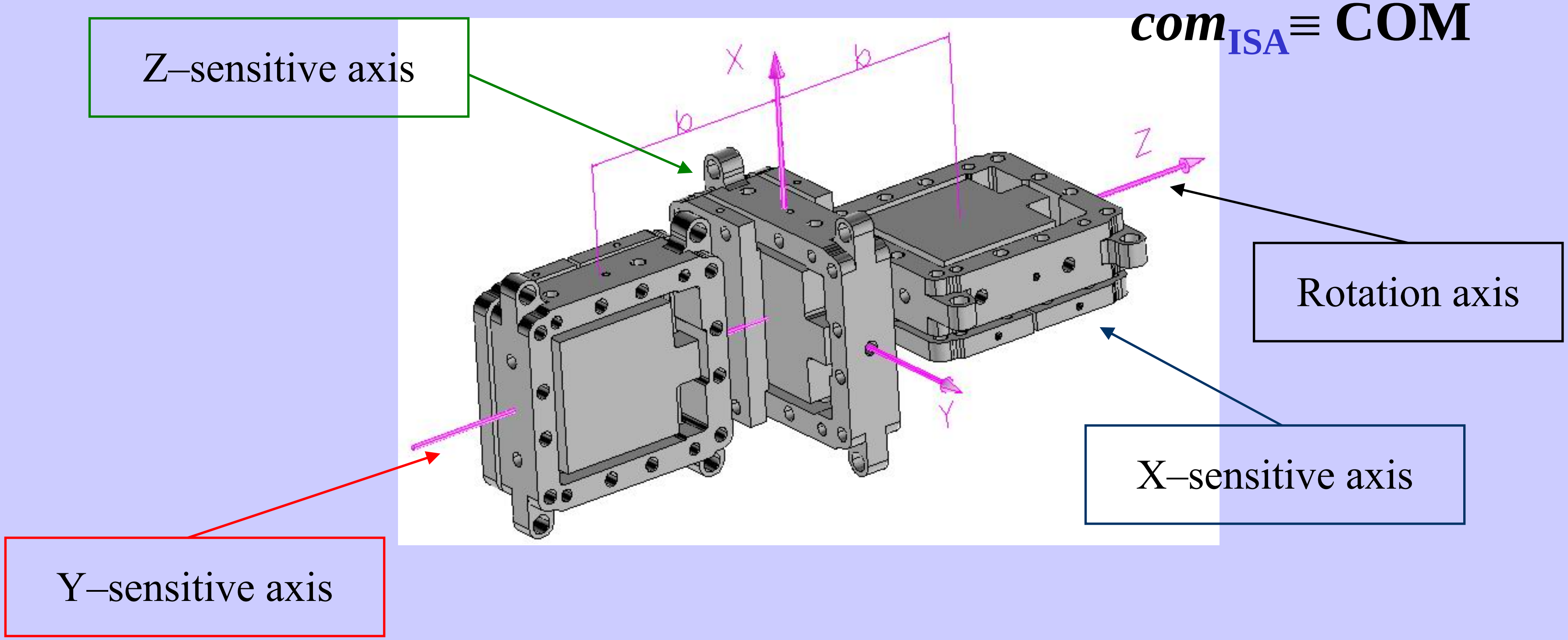
The Advanced Media Calibration System for tropospheric dry and wet path delay corrections.


SCE1 one-way range rate (300 s) with and w/o AMC
One-way range rate [m/s]
8e-06
7e-06
6e-06
5e-06
4e-06
3e-06
2e-06
1e-06
160
165
170
175
180
185
DOY/2002

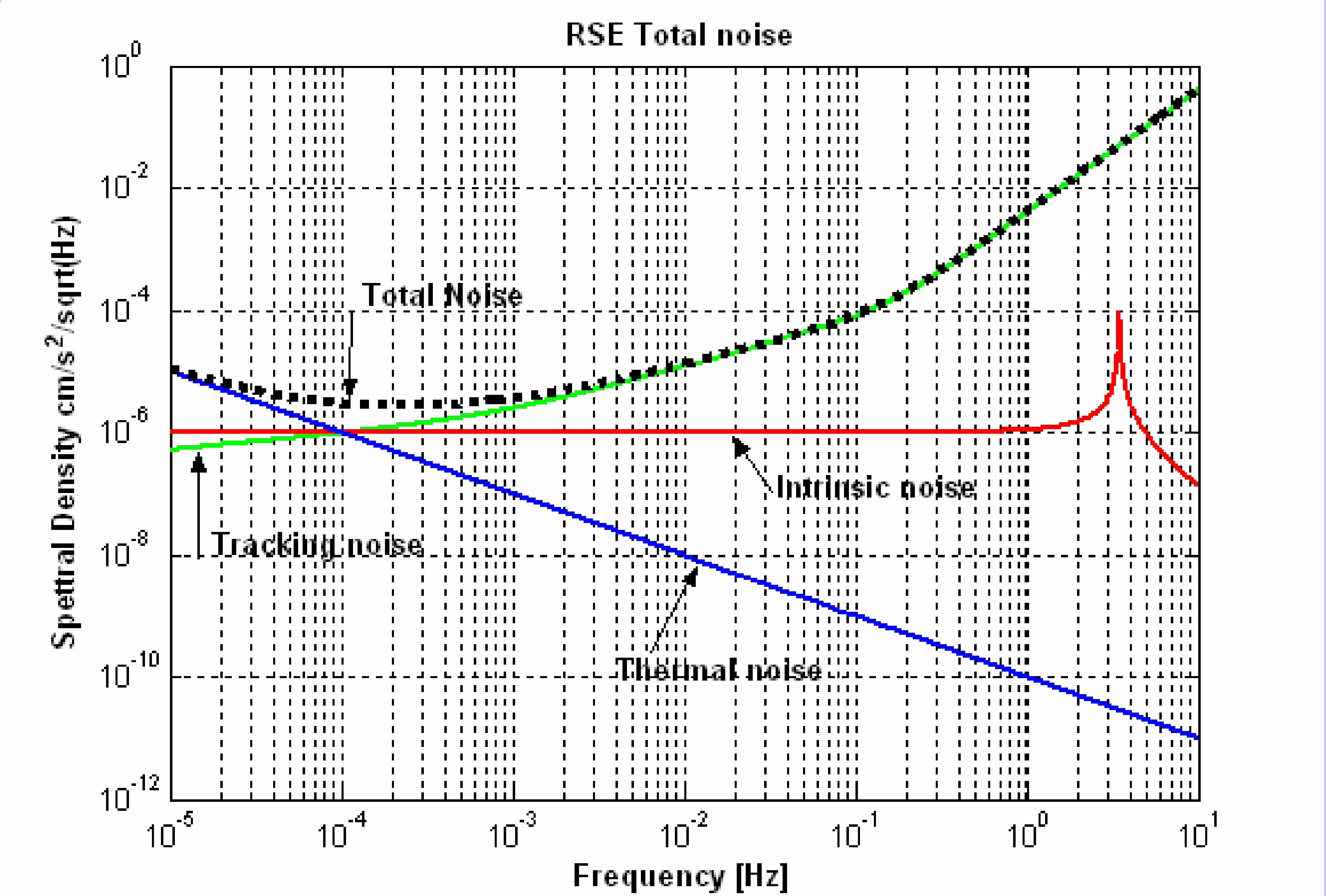
ISA Positioning

This result suggest for the best configuration of the accelerometer a location with the three sensitive masses aligned along the rotation axis of the **MPO**, and with the ***com*** of the mass with sensitive axis along the rotation axis coincident with the ***com*** of the accelerometer as well as with the **MPO** one:

$$com_{ISA} \equiv \mathbf{COM}$$



ISA Microvibration noise



Numerical simulations

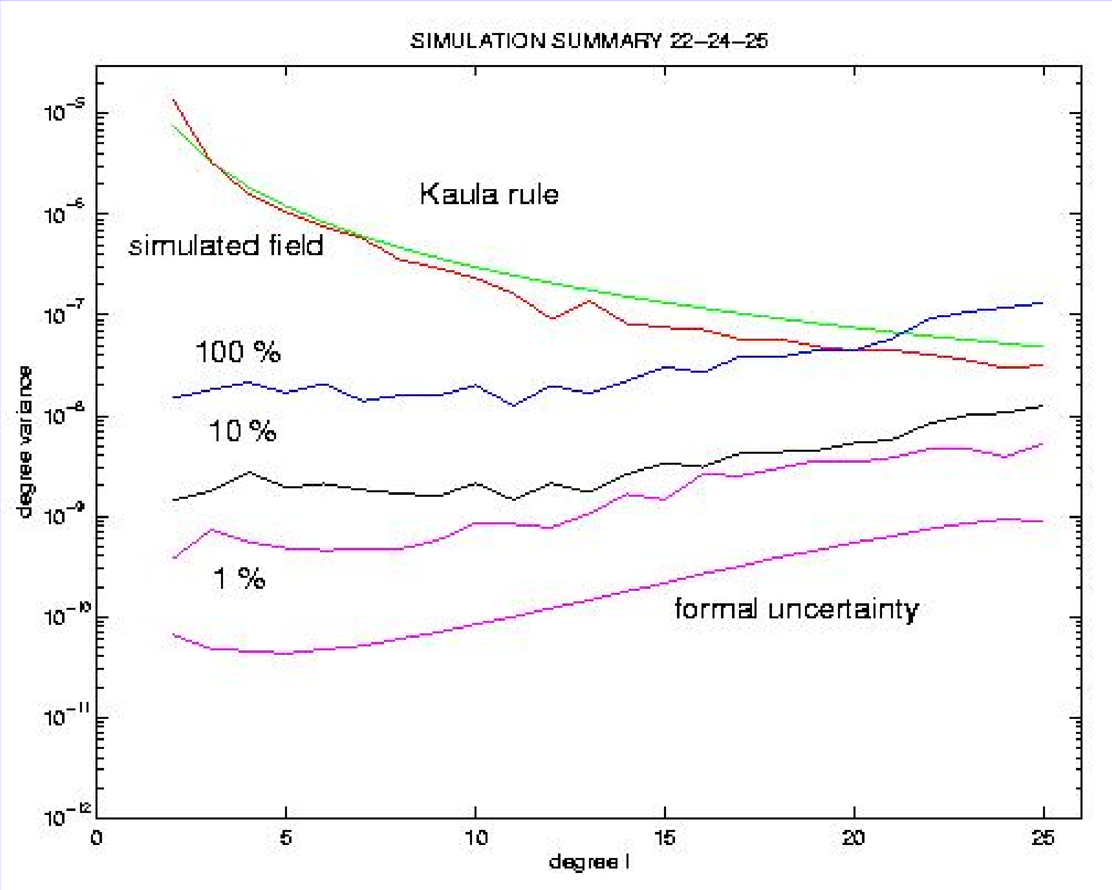
Noise models

- Colored Doppler noise — $\Delta f/f = 10^{-14}$ at 10^3-10^4s

- Gaussian range noise with systematic measurement errors (aging) — $\Delta\rho = 20$ cm

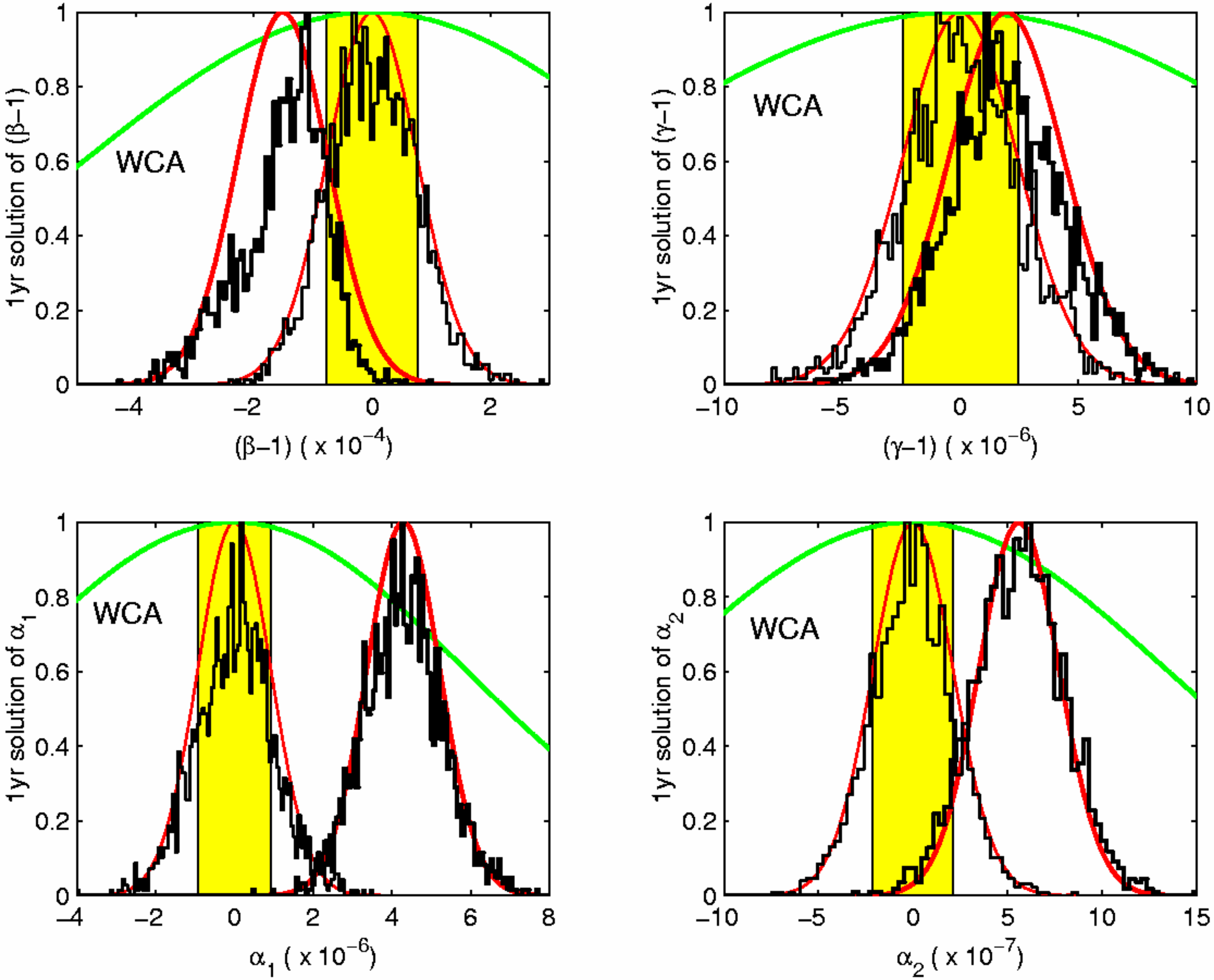
- Colored acceleration noise with 1/*f* component — $\sigma_a = 10^{-7}$ cm/s^2 at 10^3 s

RSE concept was tested by detailed numerical simulations at the Univ. of Pisa, for a scientifically consistent definition of the mission and RSE-related payload.



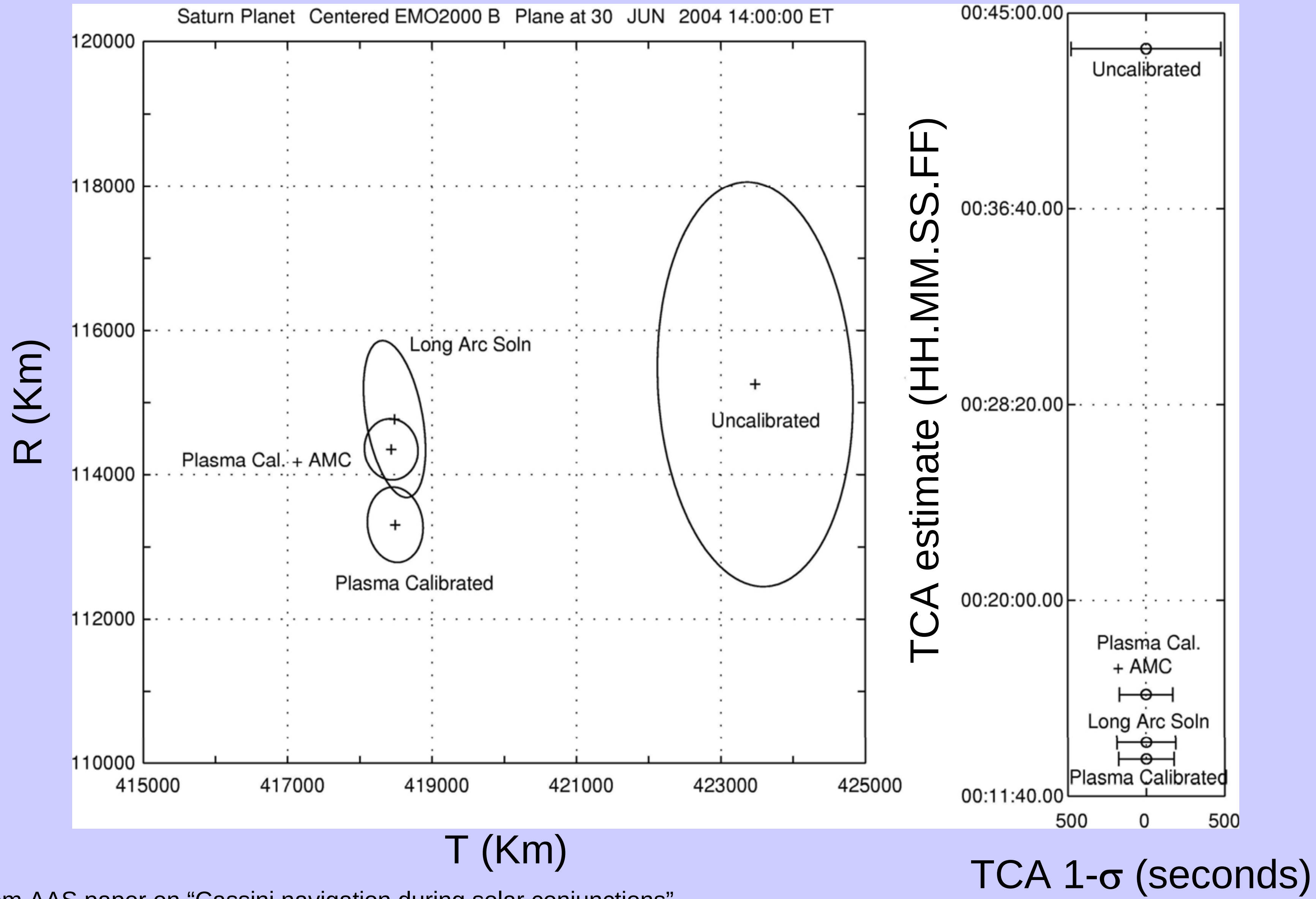
Example: requirements on accelerometer calibration from gravimetry exp.

Software used is a prototype for the operational MORE data processing.



WCA
1yr solution of (β–1)
(β–1) (x 10^−4)
WCA
1yr solution of (γ–1)
(γ–1) (x 10^−6)
WCA
1yr solution of α1
α1 (x 10^−6)
WCA
1yr solution of α2
α2 (x 10^−7)

Saturn-centered B-plane plot of the Cassini orbital solutions



From AAS paper on "Cassini navigation during solar conjunctions"
P.Tortora, L.Iess, J.J. Bordi, J.E. Ekelund, D. Roth

MORE

Mercury Orbiter Radio-science Experiment

Luciano Iess	Università di Roma La Sapienza
Sami Asmar	Jet Propulsion Laboratory
John W. Armstrong	Jet Propulsion Laboratory
Neil Ashby	University of Colorado
Jean Pierre Barriot	CNES
Peter Bender	University of Colorado
Bruno Bertotti	Università di Pavia
Thibault Damour	Institut des Hautes Etudes Scientifiques
Veronique Dehant	Observatoire de Bruxelles
Peter W. Kinman	Case Western Reserve University
Alex Konopliv	Jet Propulsion Laboratory
Anne Lemaitre	University of Namur
Andrea Milani Comparetti	Università di Pisa
Tilman Spohn	Westfälische Wilhelms-Universität
Paolo Tortora	Università di Bologna
David Vokroulicky	Charles University, Prague
Michael Watkins	Jet Propulsion Laboratory
Xiaoping Wu	Jet Propulsion Laboratory

Good results start from good data