Probing space-time in the solar system: Cassini to BepiColombo

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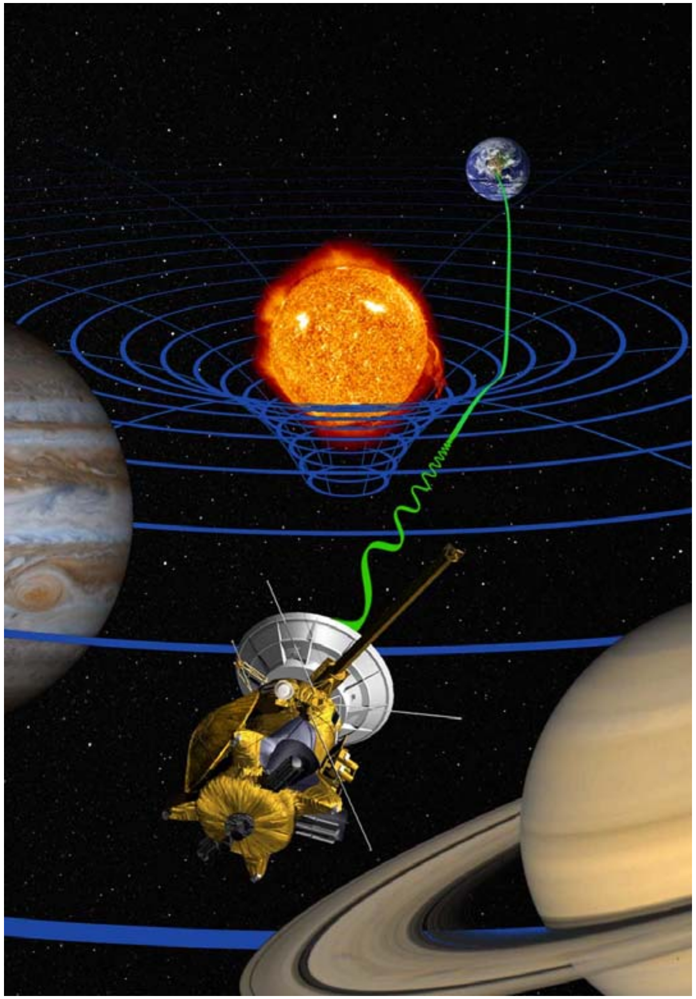
From Quantum to Cosmos: Fundamental Physics Research in Space

Airlie Center, Warrenton, Virginia



Experiment Motivation

- Recent theoretical developments based on inflationary cosmology link the accuracy of GR to the expansion of the universe and indicate that violations may occur at levels as large as 10^{-5}

- The theoretical uncertainties are so large that every experiment able to improve over previous tests is significant

- Violations of GR would have profound consequences in fundamental physics and cosmology

Testing gravitational theories

Deflection of light

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

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

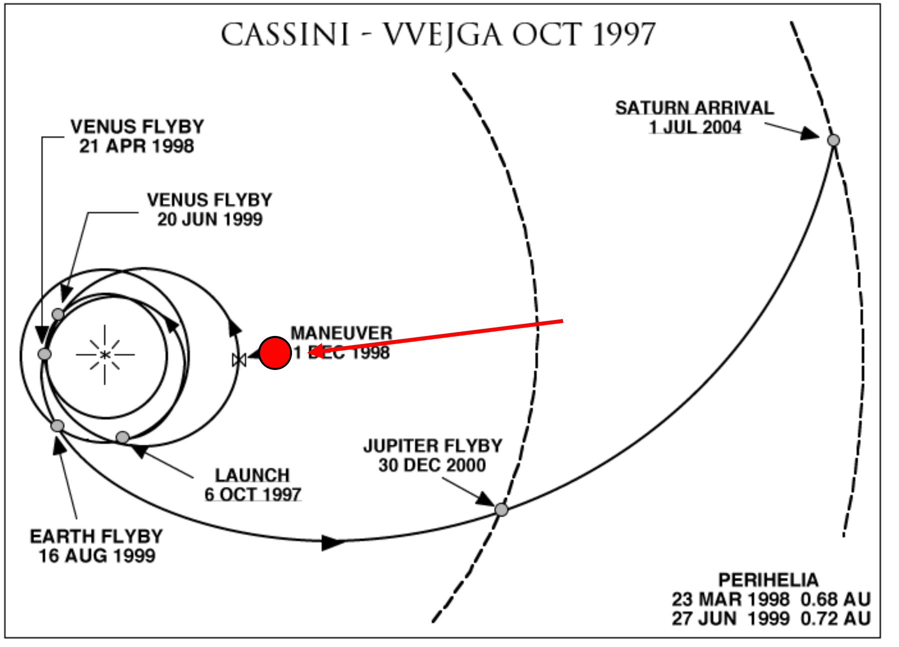
Frequency shift

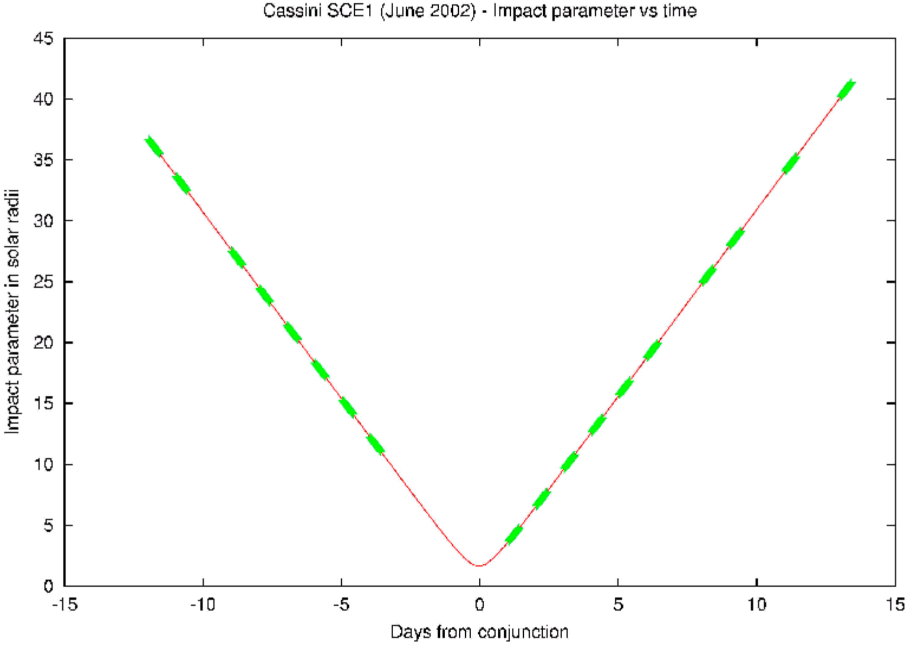
$$\frac{\Delta\nu}{\nu} = 2\frac{\nu_1 l_0 + \nu_0 l_1}{l_0+l_1}\theta \cong 4(1+\gamma)\frac{M_{sun}}{b}\dot{b}$$

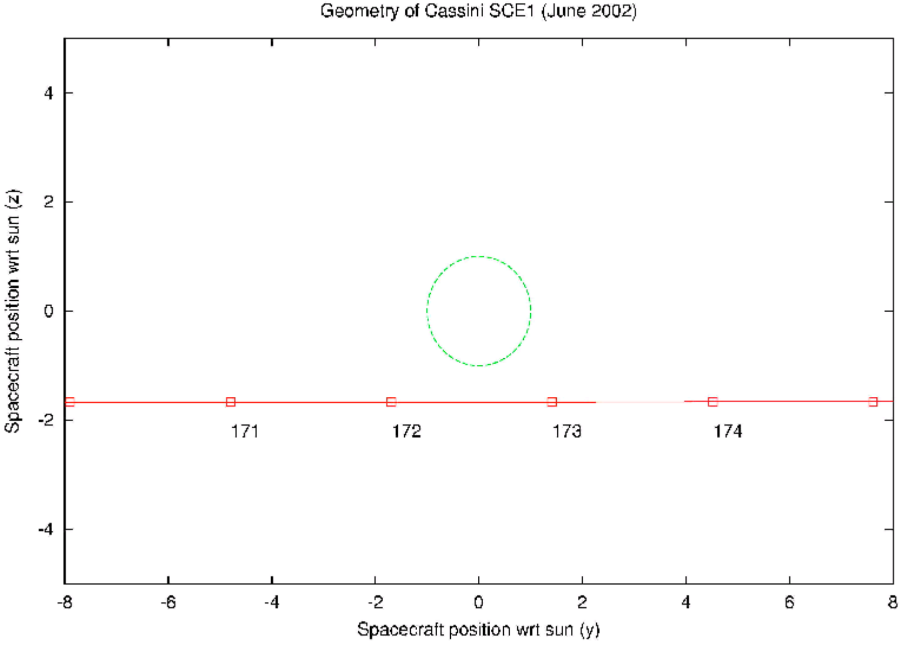
$\approx 8\times 10^{-10}$ for a grazing beam

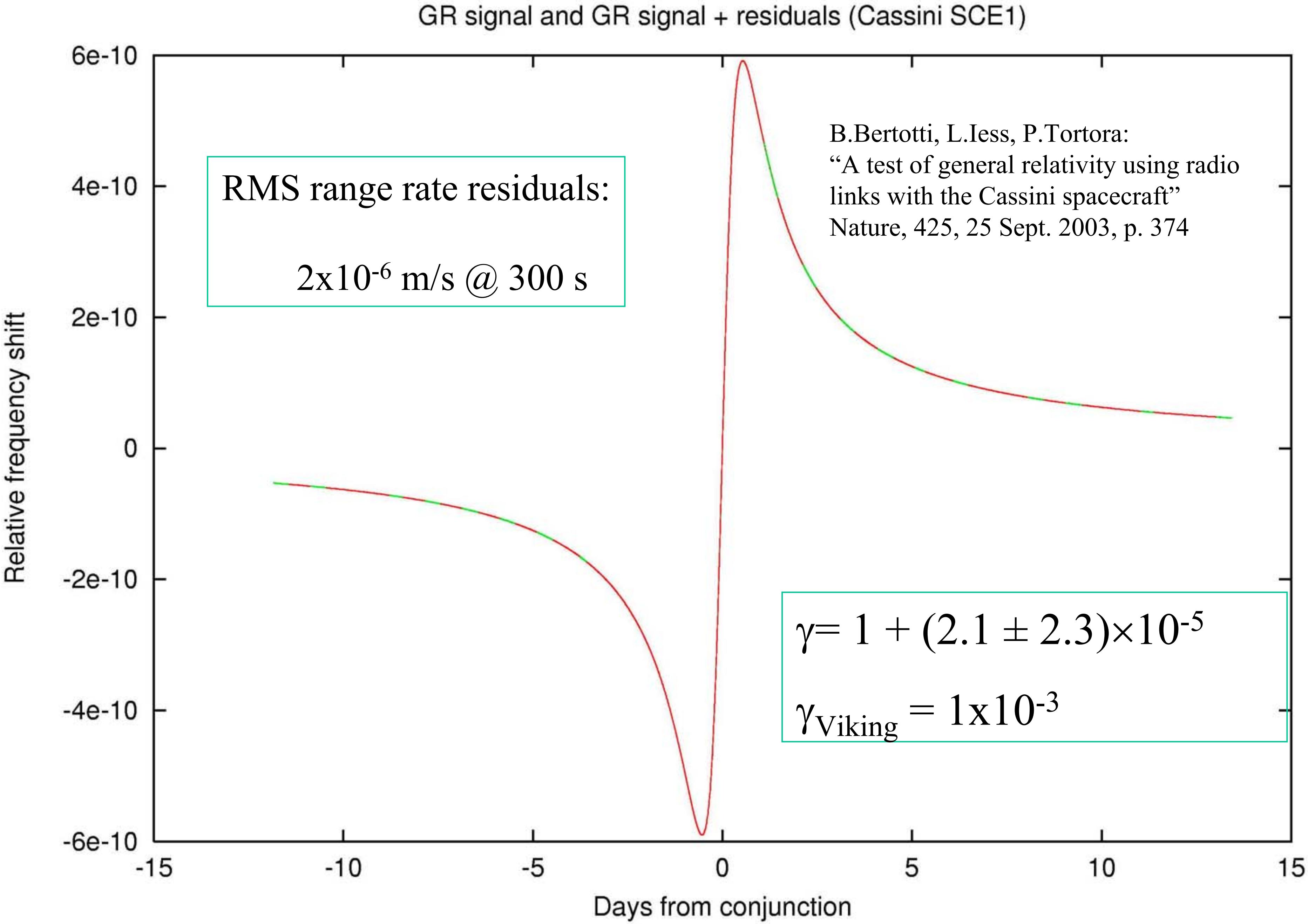
Cassini's First Solar Cojunction Experiment (SCE 1)

30 days of tracking by Deep Space Network








GR signal and GR signal + residuals (Cassini SCE1)
Relative frequency shift
Days from conjunction
6e-10
4e-10
2e-10
0
-2e-10
-4e-10
-6e-10
-15
-10
-5
0
5
10
15
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
$\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$
$\gamma_{Viking} = 1 \times 10^{-3}$

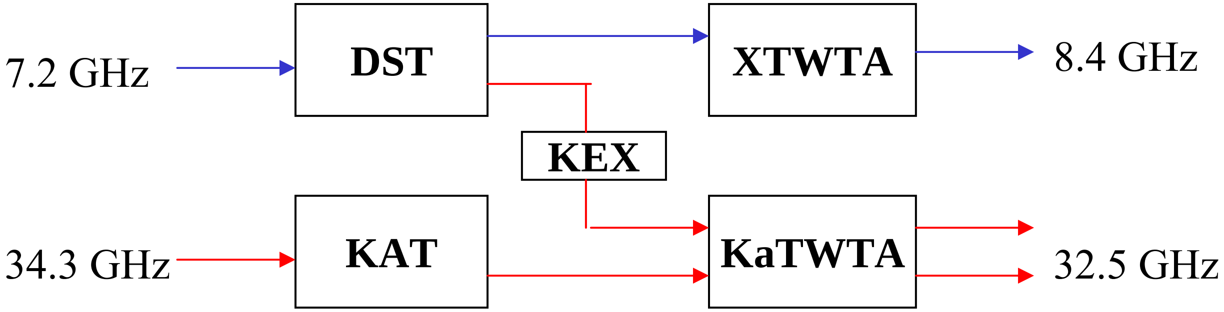
Plasma noise cancellation

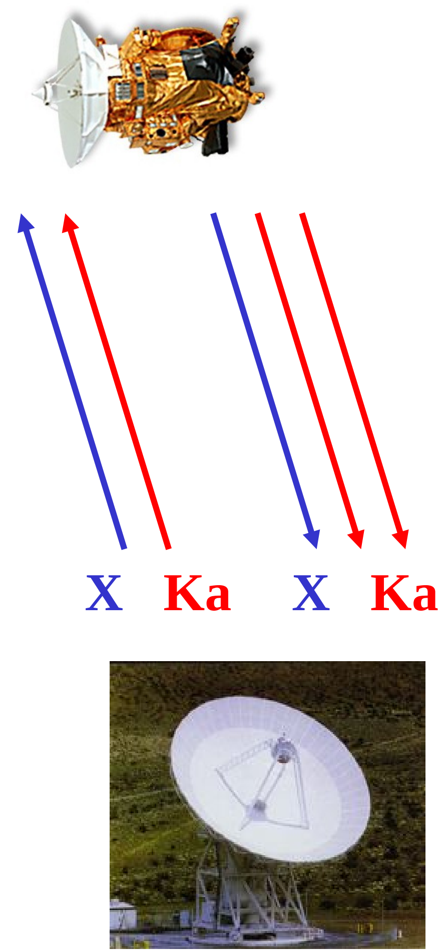
Multi-frequency radio links

(Doppler Only)

Best accuracies:

$\Delta f/f$ = 1x10^{-14} at 1000 s at Conjunctions
$\Delta f/f$ = 3x10^{-15} at 1000 s at Oppositions



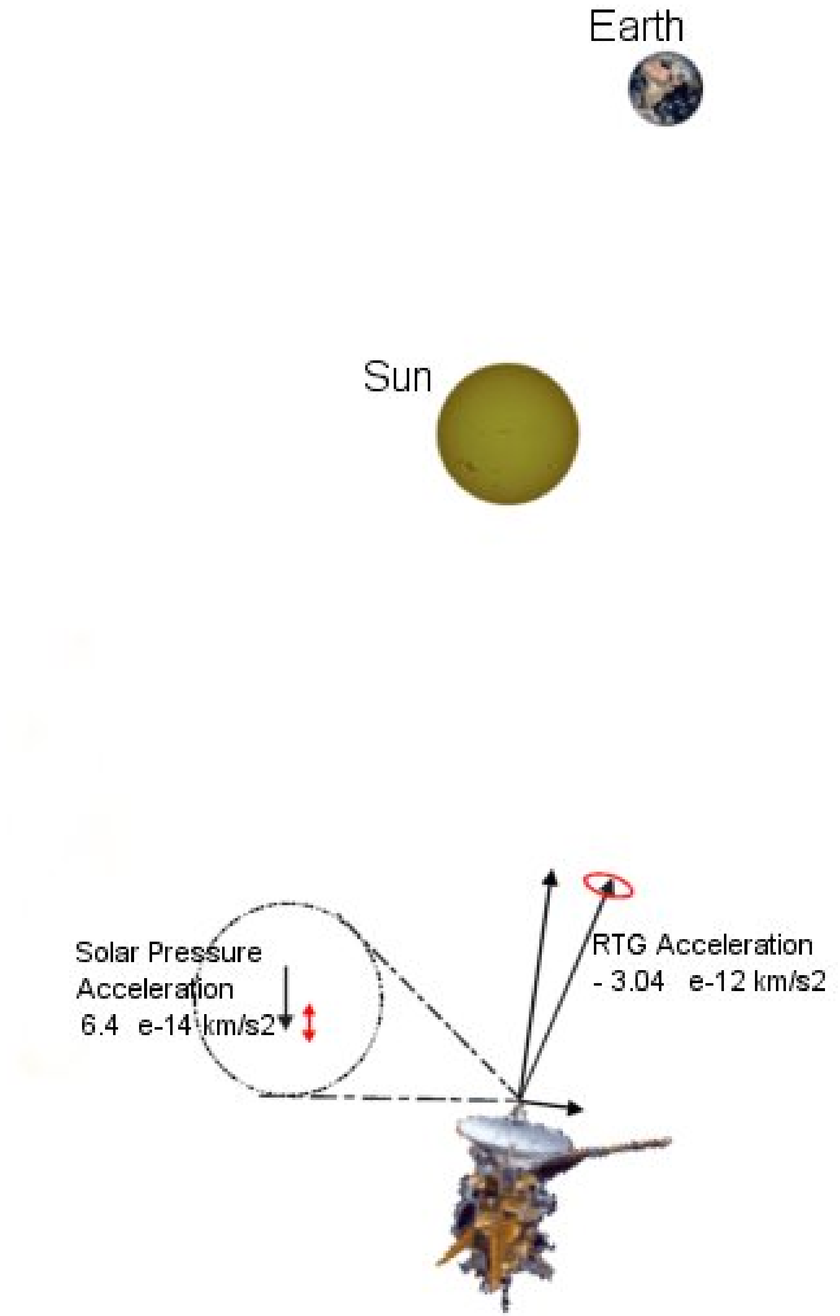


DSS-25
DSN Goldstone

Classification of Noise Sources

- **Dynamical noise, attitude motion and non-gravitational accelerations of the spacecraft**
- **Propagation noise (solar corona, interplanetary plasma, ionosphere, troposphere)**
- **Mechanical noise of ground antenna (wind loading, thermal deformations)**
- **Spacecraft and ground instrumentation**

Dynamical model

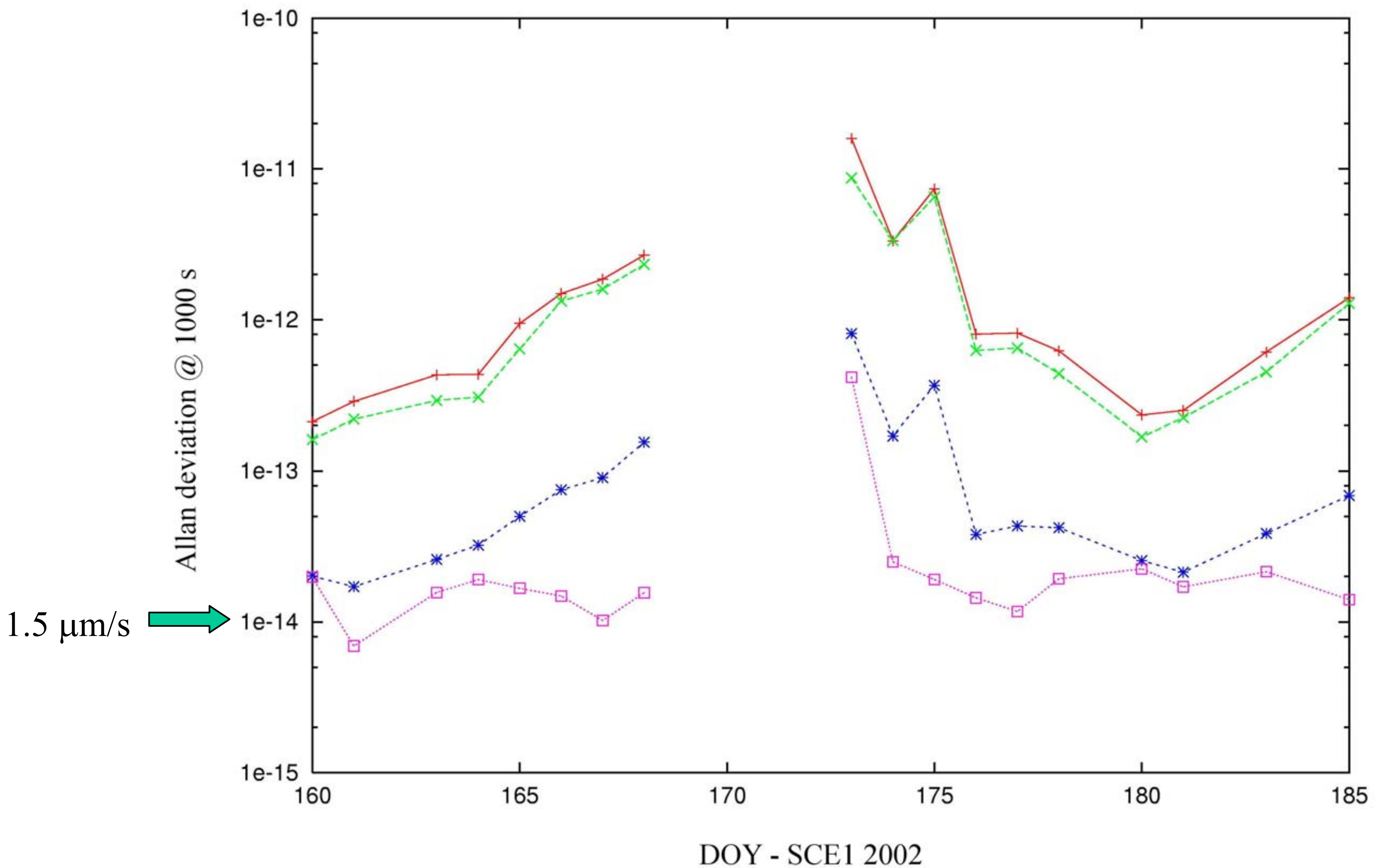


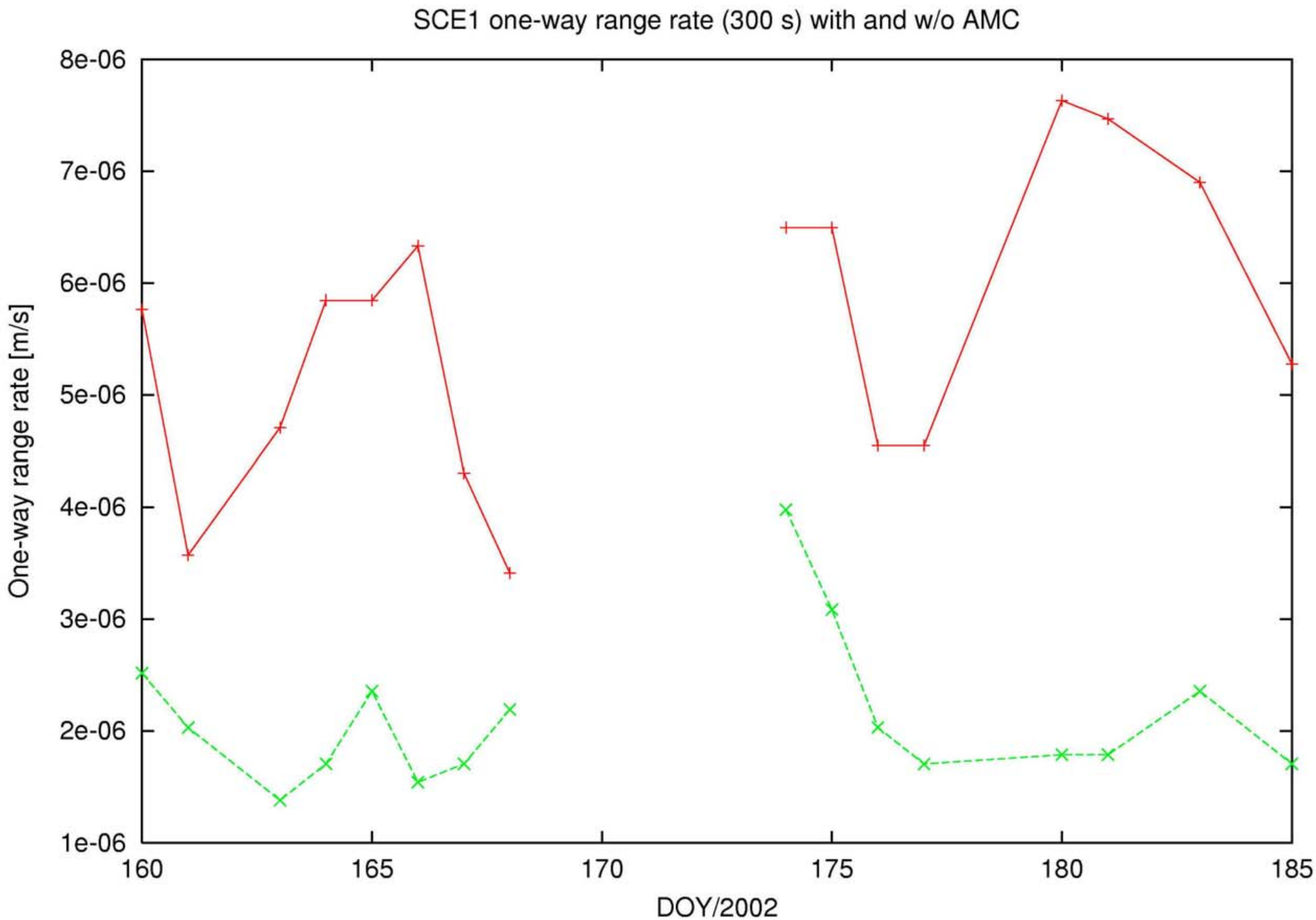
Solve-for parameters:

- Spacecraft state vector
- Specular and diffuse reflectivity of the spacecraft antenna (4 m diameter for Cassini)
- Acceleration from anisotropic thermal emission from the three RTG
- γ

No indication of anomalous acceleration; “Pioneer Anomaly” does not affect Cassini

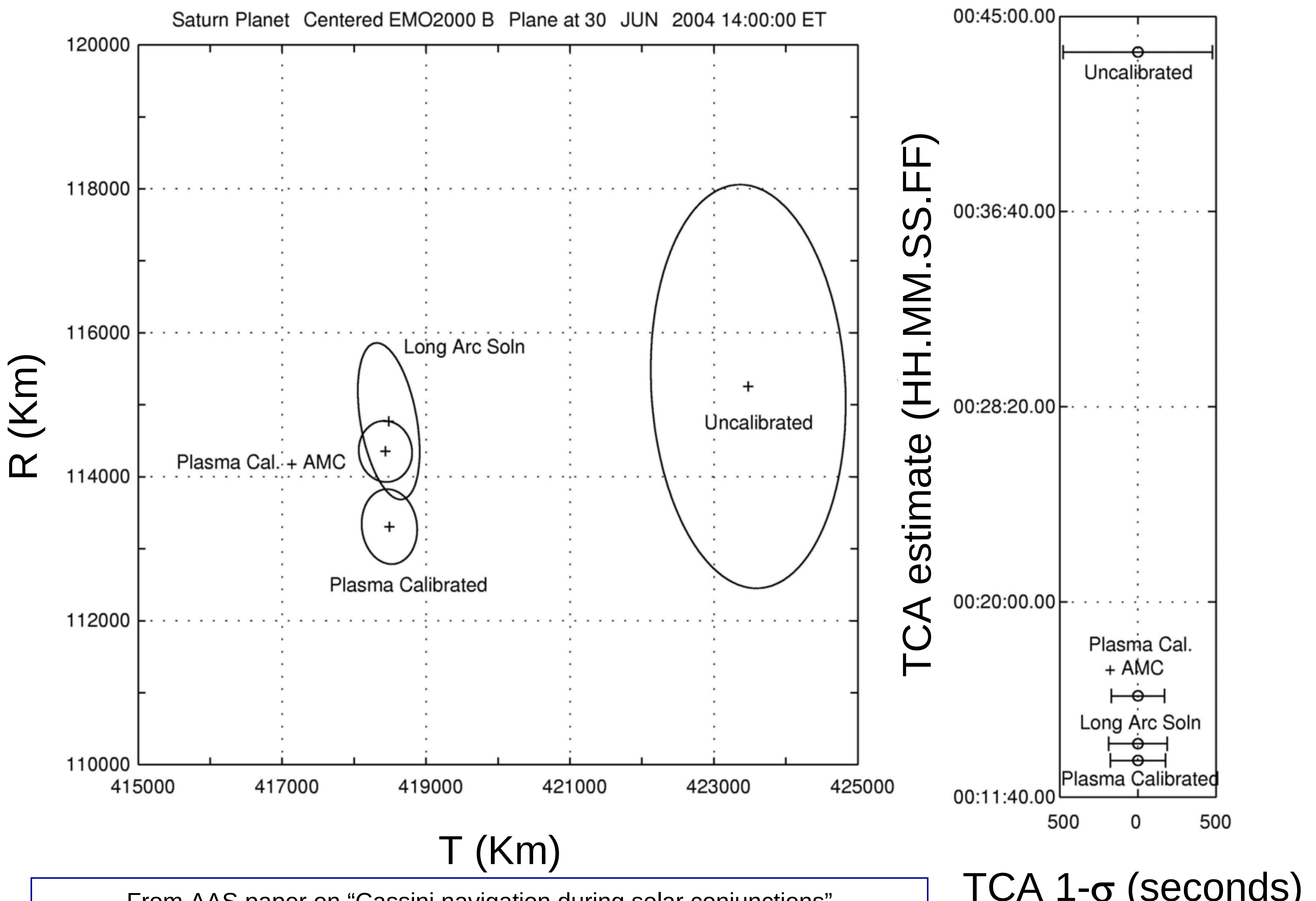
Plasma noise in the X/X, X/Ka, Ka/Ka links and the calibrated Doppler observable (daily Allan dev. @1000s, Cassini SCE1)
Minimum impact parameter: 1.6 R_s (DOY 172)





SCE1 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

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



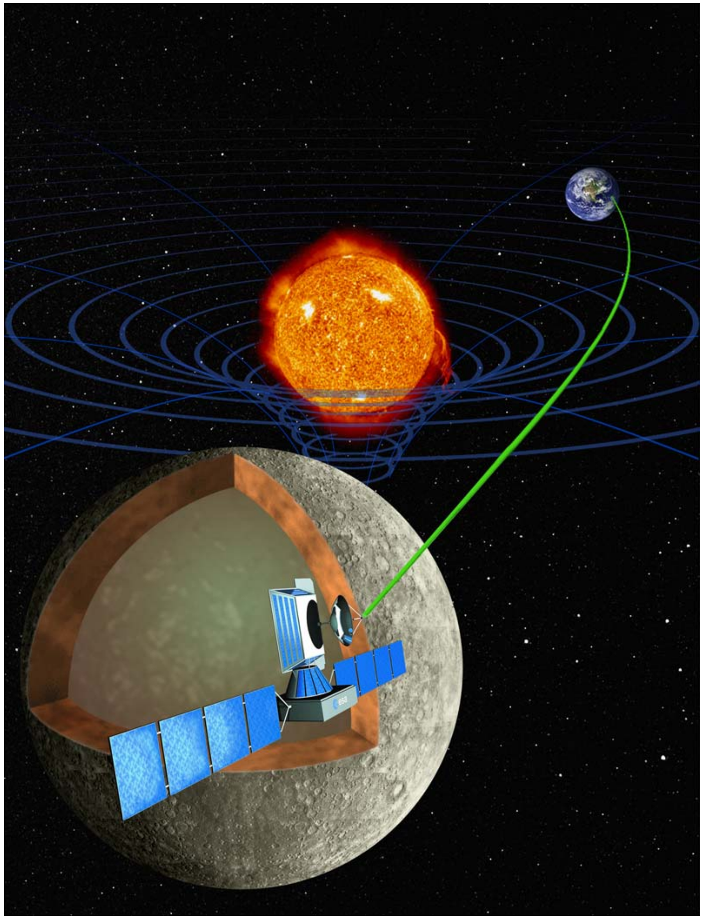
From AAS paper on "Cassini navigation during solar conjunctions"
P.Tortora, L.Iess, J.J. Bordi, J.E. Ekelund, D. Roth

DSS-25, 34 m diamter station at NASA's Deep Space Network, Goldstone, California

Advanced Media Calibration System for tropospheric dry and wet path delay calibrations, Goldstone, California

BepiColombo
Mecruty Orbiter Radioscience Experiment (MORE)
Science Goals

- Determine the gravity field of Mercury
- Determine the size and physical state of its core
- Provide crucial experimental constraints to models of Mercury's internal structure
- Test theories of gravity
- Measure the gravitational oblateness of the Sun
- Test and characterize the most advanced interplanetary tracking system ever built
- Assess the performances of the novel tracking system in precise orbit determination and space navigation.



MORE Mercury Orbiter Radio-science Experiment

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David Vokroulicky	Charles University, Prague
Michael Watkins	Jet Propulsion Laboratory
Xiaoping Wu	Jet Propulsion Laboratory

BepiColombo

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 SYMBIO-SYS)
- Amplitude of physical librations in longitude to 4 arcsec (40 m on surface – needs SYMBIO-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.

BepiColombo
MORE Science Goals II

- 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}

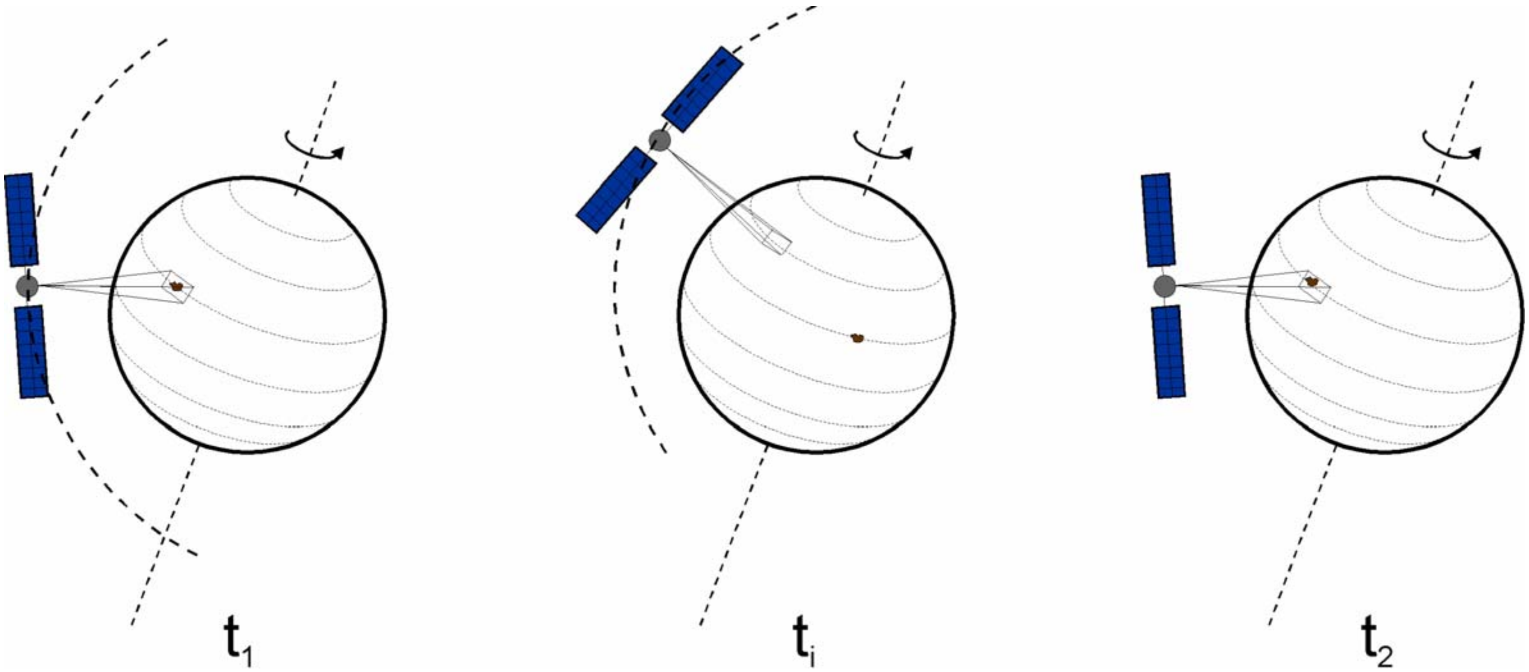
Expected Accuracies

PN Parameter	Present Accuracy	BepiColombo Accuracy
γ	2.3×10^{-5}	2.5×10^{-6}
β	7×10^{-4}	5×10^{-6}
η	5×10^{-4}	2×10^{-4}
Solar J_2	4×10^{-8}	2×10^{-9}
$d(\ln G)/dt$	1×10^{-12} /yr	3×10^{-13} /yr

Measurements used by MORE

- The range & range rate between spacecraft and ground stations
  - Removing the effects of the plasma along the path by means of a multi-frequency (X- and in Ka-bands) links
- The non-gravitational perturbations acting on the spacecraft, by means of the 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 tracking passes, of surface landmarks, by means of pattern matching between images

C_m/C: Landmark Tracking from Orbit



$$\phi_0 \approx \frac{B-A}{C_m} \qquad C_{20} = \frac{C-A}{MR^2} + \frac{1}{2}\frac{B-A}{MR^2} \qquad C_{22} = \frac{1}{4}\frac{B-A}{MR^2}$$

$$K_1(\theta)\frac{C-A}{C} + K_2(\theta)\frac{B-A}{C} = K_3(\theta)$$

$$\frac{C_m}{C} = \frac{C_m}{B-A}\frac{B-A}{MR^2}\frac{MR^2}{C}$$

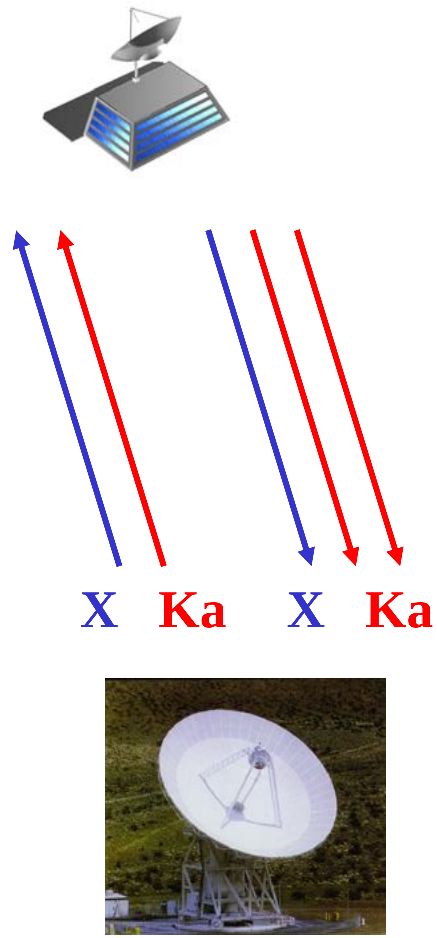
BepiColombo Radio Configuration

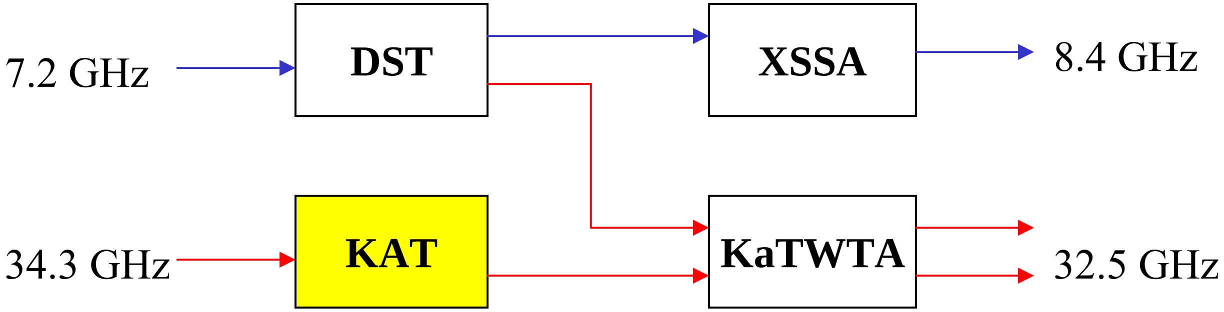
Multi-frequency radio link (Doppler and Range)

Target accuracy:

$\Delta f/f = 10^{-14}$ at 1000 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





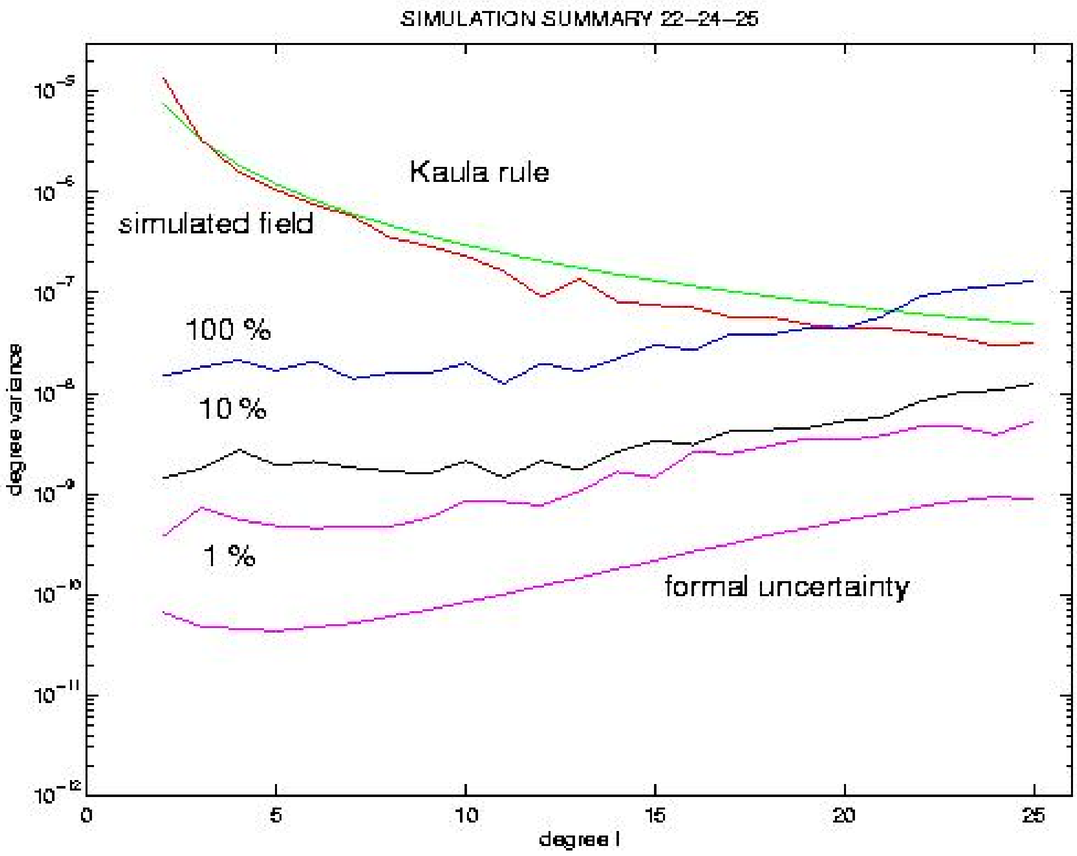
Numerical Simulations
Noise Models

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

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

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

Detailed numerical simulations at the Univ. of Pisa Mercury's Gravitational Field



Example: requirements on accelerometer calibration from gravimetry experiment

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

Conclusion

- BepiColombo will provide good science with relatively inexpensive instrumentation
- Same instrumentation used for geodesy/geophysics and GR
- Results available after its first year of nominal mission
- BC-MORE will reach the limits of the microwave instrumentation for interplanetary radio links
- Better gravitational measurements will require dedicated missions and novel instrumentation