A test of general relativity with radio links with the Cassini spacecraft

B. Bertotti, L. Iess[1] and P. Tortora, Nature 425, 374 (2003)

1. Technology and science in interplanetary telecommunications
2. A new test of general relativity
3. The Cassini experiment
4. Why has it not been done before?
5. A cosmological scenario for gravity

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

No violation. Accuracy improved by a factor 50.

[1]Leader of the experiment

1. Technology and science in interplanetary telecommunications

- A coherent carrier for Doppler effect
- Side bands for data transmission and ranging

PROBLEMS:

- Weak signals (requiring large dishes)
- Large downlink bit rates for planetary imaging

Both show the need for greater frequencies.

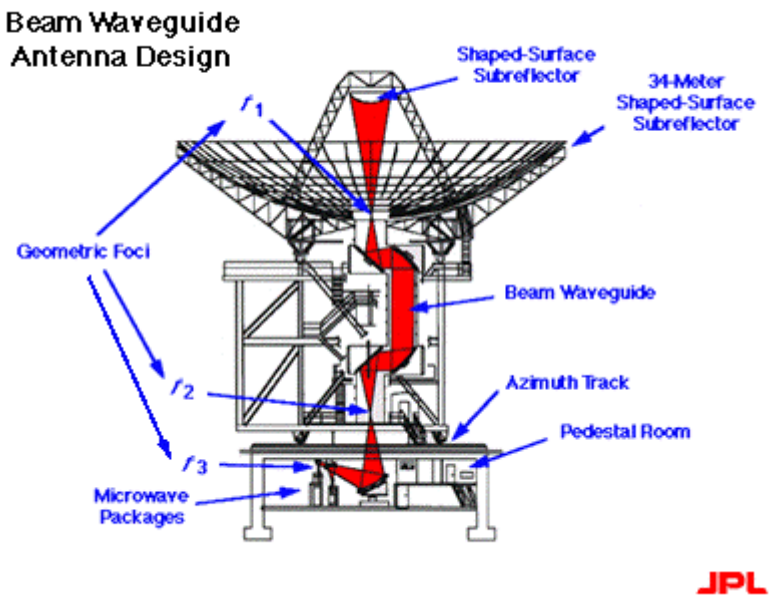
S-band 2-3 GHz

X-band 7-8 GHz

K_a-band 32-34 GHz

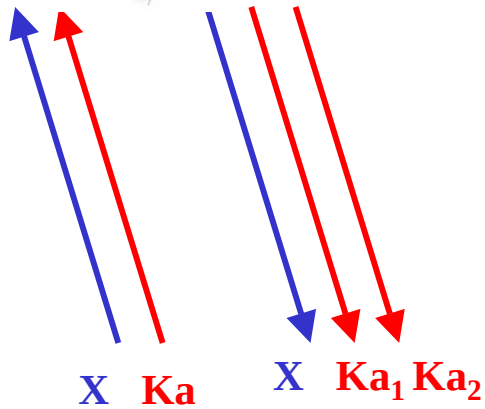
ULYSSES:	S up and down	X down for data
CASSINI:	X up and down (ranging and Doppler)	K_a up and down (Doppler)
MERCURY ORBITER:	X up and down (ranging and Doppler)	Ka up and down (ranging and Doppler)

DSS 25 - Goldstone, California



Multi-frequency radio link

Cassini spacecraft with high-gain antenna (points to the Earth)



$X \rightarrow X$: y_{XX}
$Ka \rightarrow Ka_1$: y_{KK}
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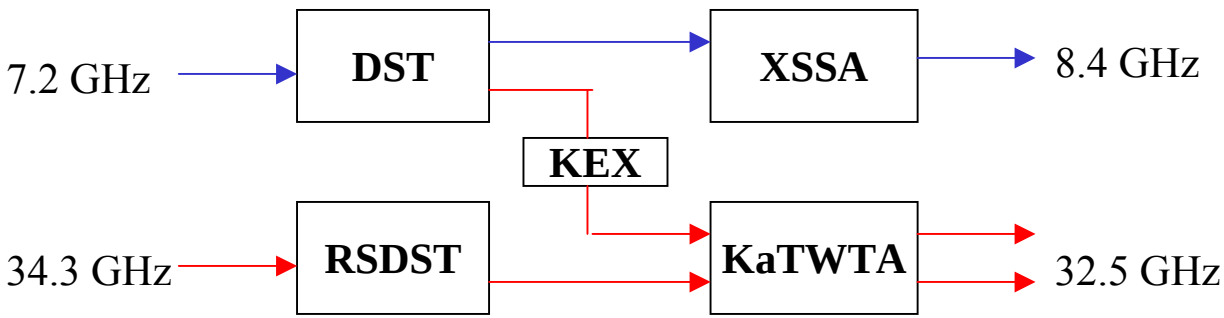
Three independent observables



DSS 25 at Goldstone (CA)

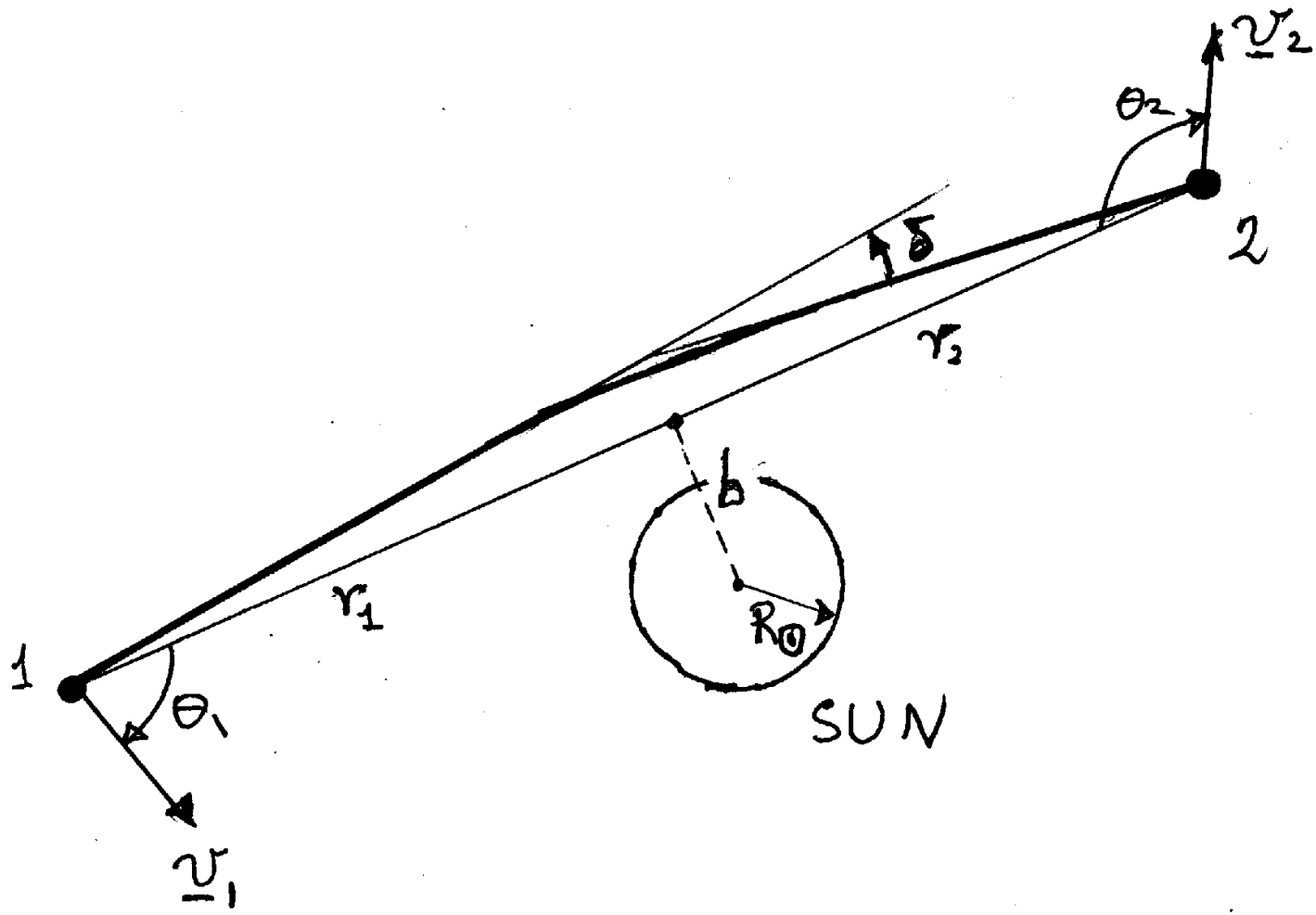
Cassini's target accuracy (in K_a band):

$\Delta\nu/\nu = 10^{-14}$ at 1000 - 10,000 s (conjunctions)
$\Delta\nu/\nu = 3 \times 10^{-15}$ at 1000 - 10,000 s (oppositions)

$\Delta\nu/\nu = 10^{-14}$ corresponds to an accuracy in velocity of 3×10^{-4} cm/s !!

Dynamic range of 10^{10} !!

2. A new test of general relativity



Measuring the space curvature in the solar system.

Deflection of light (Eddington 1919, Lebach 1995)

$$\delta = 2(1+\gamma)\frac{M_\odot}{b} = 4\times10^{-6}(1+\gamma)\frac{R_\odot}{b}\ \text{rad}$$

$M_\odot = 1.5$ km

(gravitational radius)

Solar gravity

Time delay (Reasenberg 1974)

$$\Delta t = 2(1+\gamma)M_\odot \ln\left(\frac{4r_1 r_2}{b^2}\right)$$

Frequency shift (Cassini 2002)

$$y = \frac{\Delta\nu}{\nu} = \frac{d(\Delta t)}{dt} = -4(1+\gamma)\frac{M_\odot}{b}\frac{db}{dt} \le 6\times10^{-10}$$

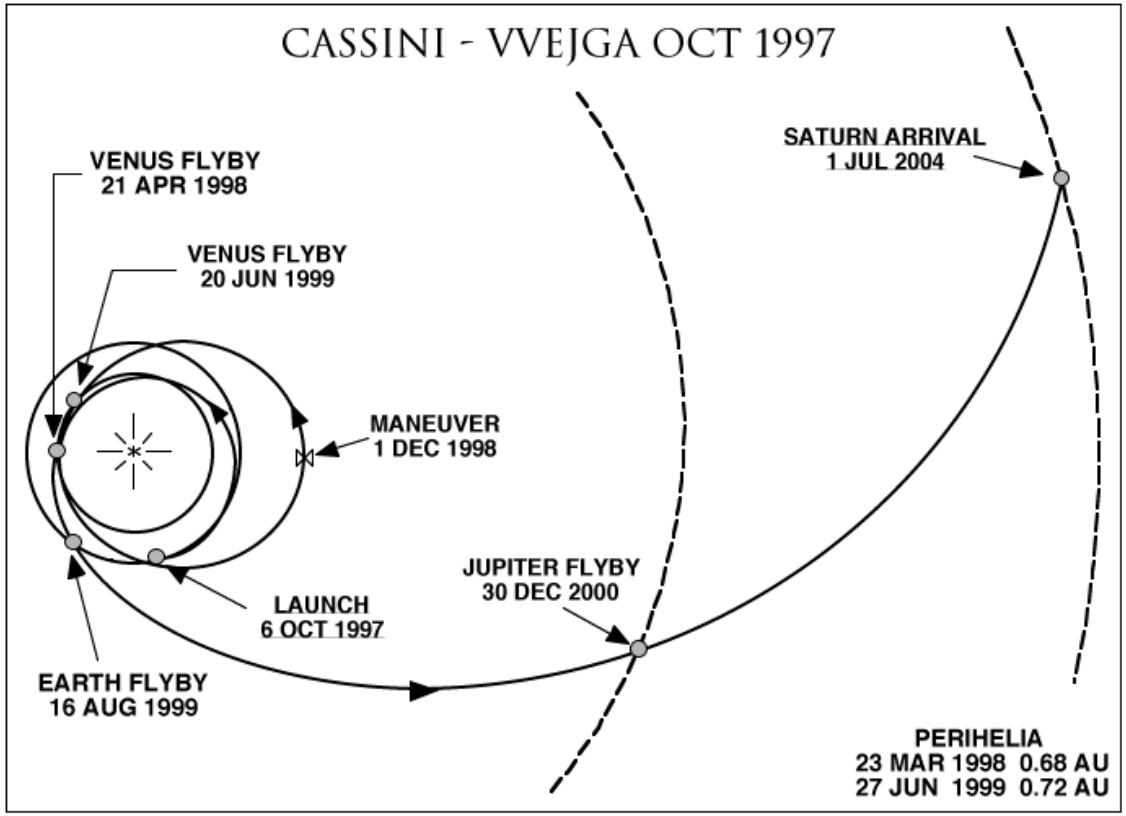
Frequency fluctuations: $\sigma_{\Delta\nu/\nu} = 10^{-14}$

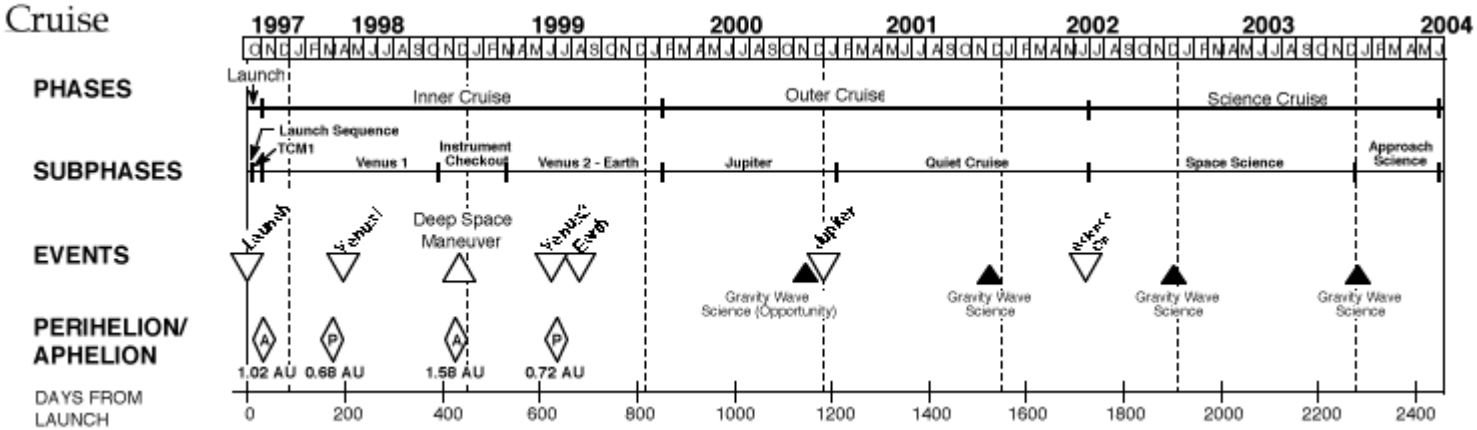
$$\textbf{SNR} = \frac{6\times10^{-10}}{10^{-14}} = 6\times10^{4}$$

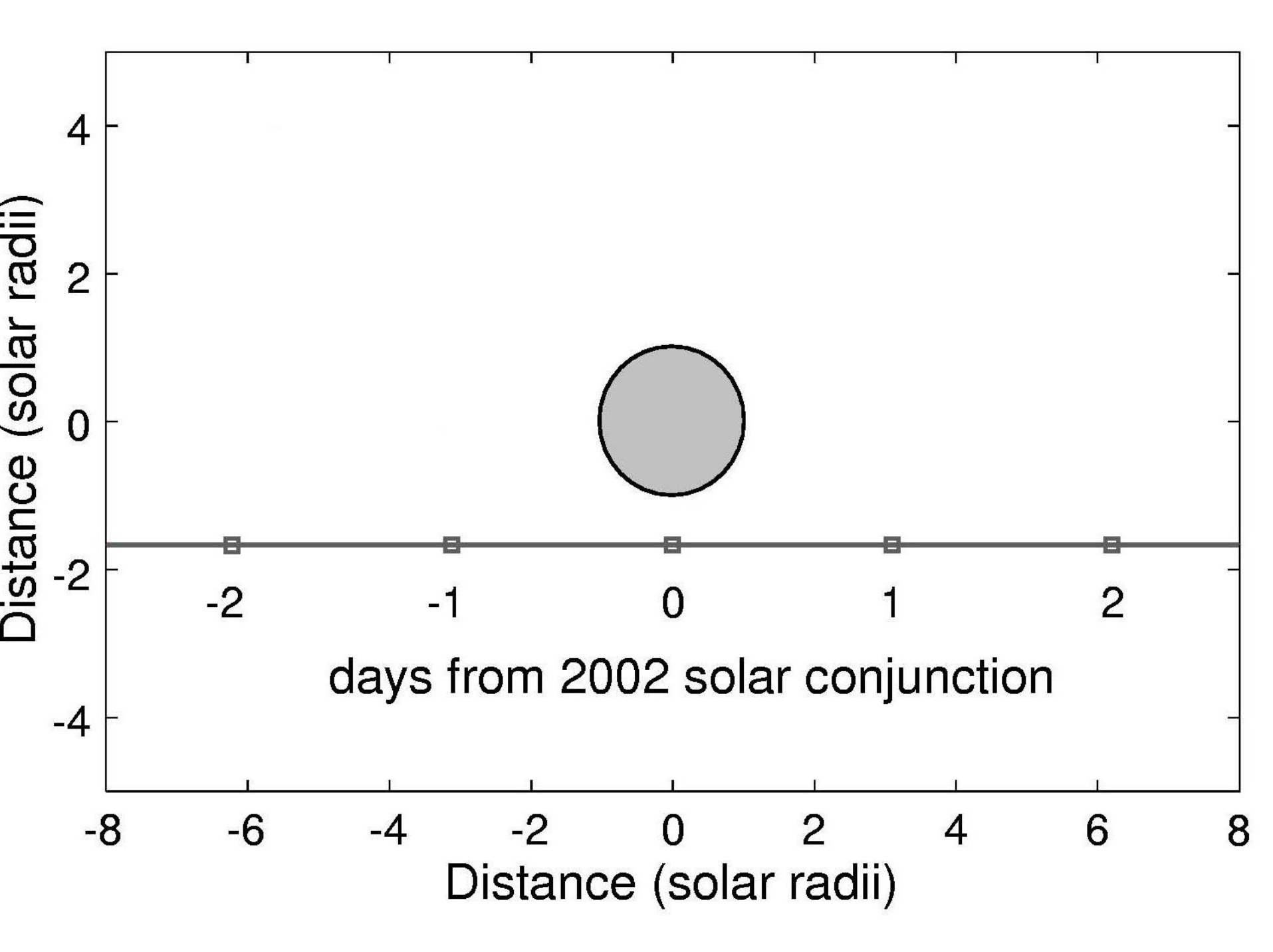
"Expected" error $\sigma_\gamma = 2 \times 10^{-5}$

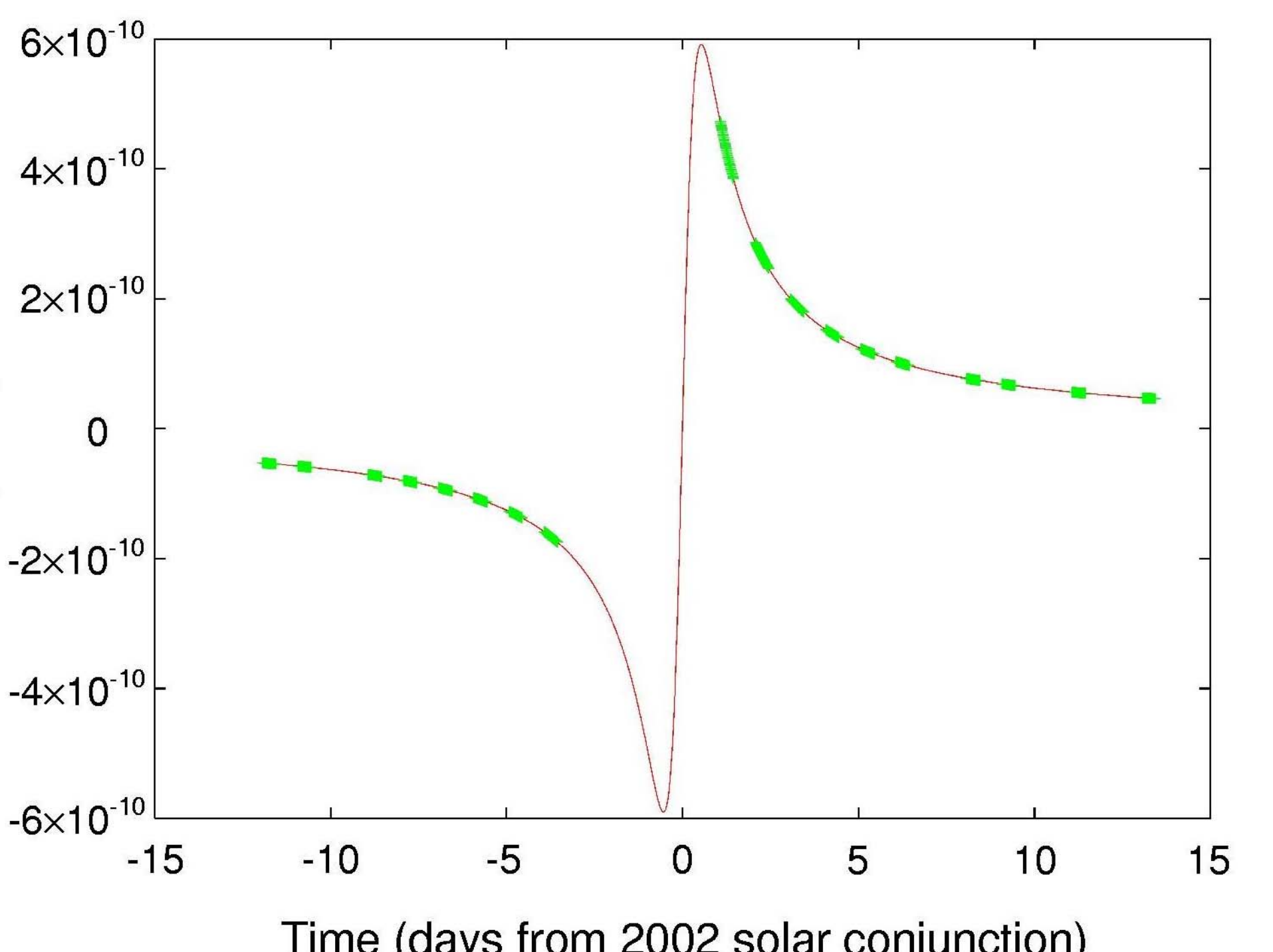
50 times better than earlier measurements !!

3. The Cassini experiment


CASSINI - VVEJGA OCT 1997
VENUS FLYBY
21 APR 1998
VENUS FLYBY
20 JUN 1999
MANEUVER
1 DEC 1998
LAUNCH
6 OCT 1997
EARTH FLYBY
16 AUG 1999
JUPITER FLYBY
30 DEC 2000
SATURN ARRIVAL
1 JUL 2004
PERIHELIA
23 MAR 1998 0.68 AU
27 JUN 1999 0.72 AU


Cruise
1997
1998
1999
2000
2001
2002
2003
2004
PHASES
Launch
Inner Cruise
Outer Cruise
Science Cruise
SUBPHASES
Launch Sequence
TCM1
Venus 1
Instrument Checkout
Venus 2 - Earth
Jupiter
Quiet Cruise
Space Science
Approach Science
EVENTS
Deep Space Maneuver
Gravity Wave Science (Opportunity)
Gravity Wave Science
Gravity Wave Science
Gravity Wave Science
PERIHELION/ APHELION
A
P
A
P
1.02 AU
0.68 AU
1.58 AU
0.72 AU
DAYS FROM LAUNCH
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400


Distance (solar radii)
4
2
0
-2
-4
-2
-1
0
1
2
days from 2002 solar conjunction
-8
-6
-4
-2
0
2
4
6
8
Distance (solar radii)


6×10-10
4×10-10
2×10-10
0
-2×10-10
-4×10-10
-6×10-10
-15
-10
-5
0
5
10
15
Time (days from 2002 solar conjunction)

Digging into the signal by 10^{10} :

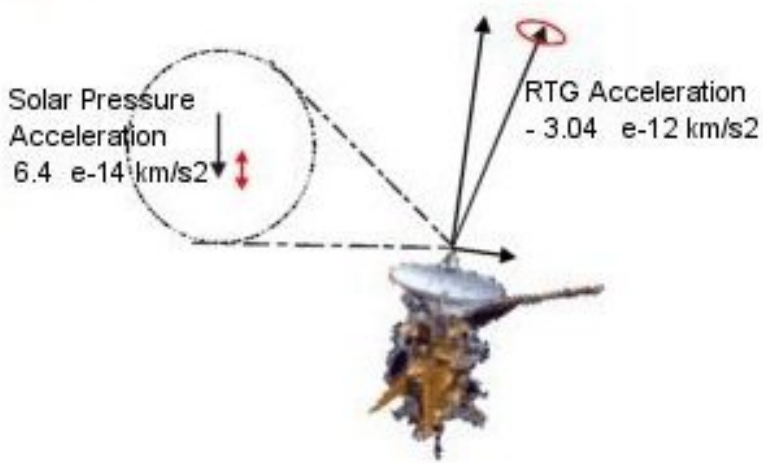
- Position of DSS25 redetermined
- Earth solid tides ("consider" parameters)
- Effect of troposphere: measured at DSS25 with water vapour radiometers
- Non-gravitational forces in part measured, in part fitted:
  - RadioThermoelectric Generators (3)
  - Radiation pressure on antenna dish (2)
- Keplerian parameters of spacecraft (6)
- Etc.

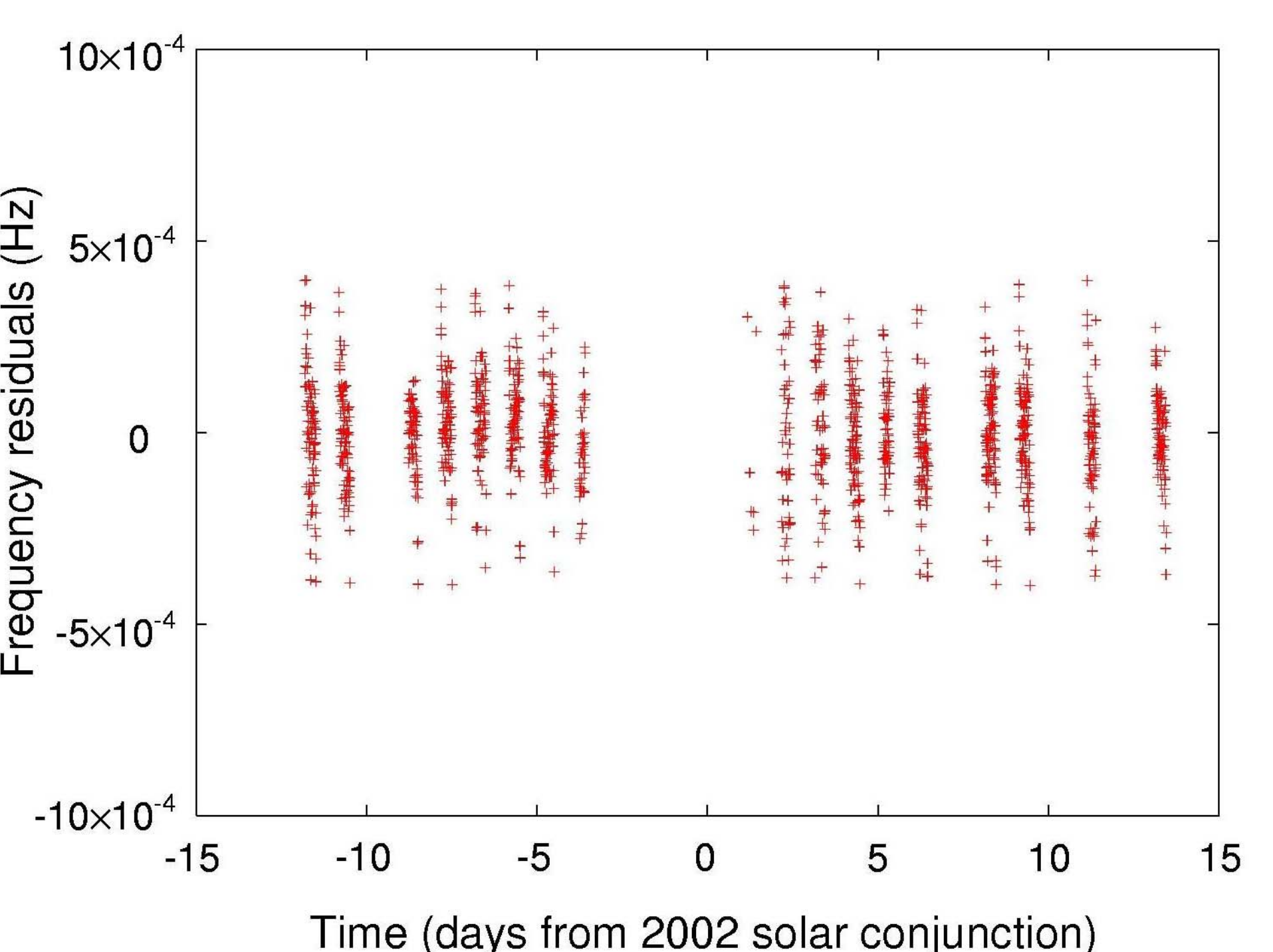
Up to 12 parameters fitted (6 + 3 + 2 + 1)

The result (1σ):

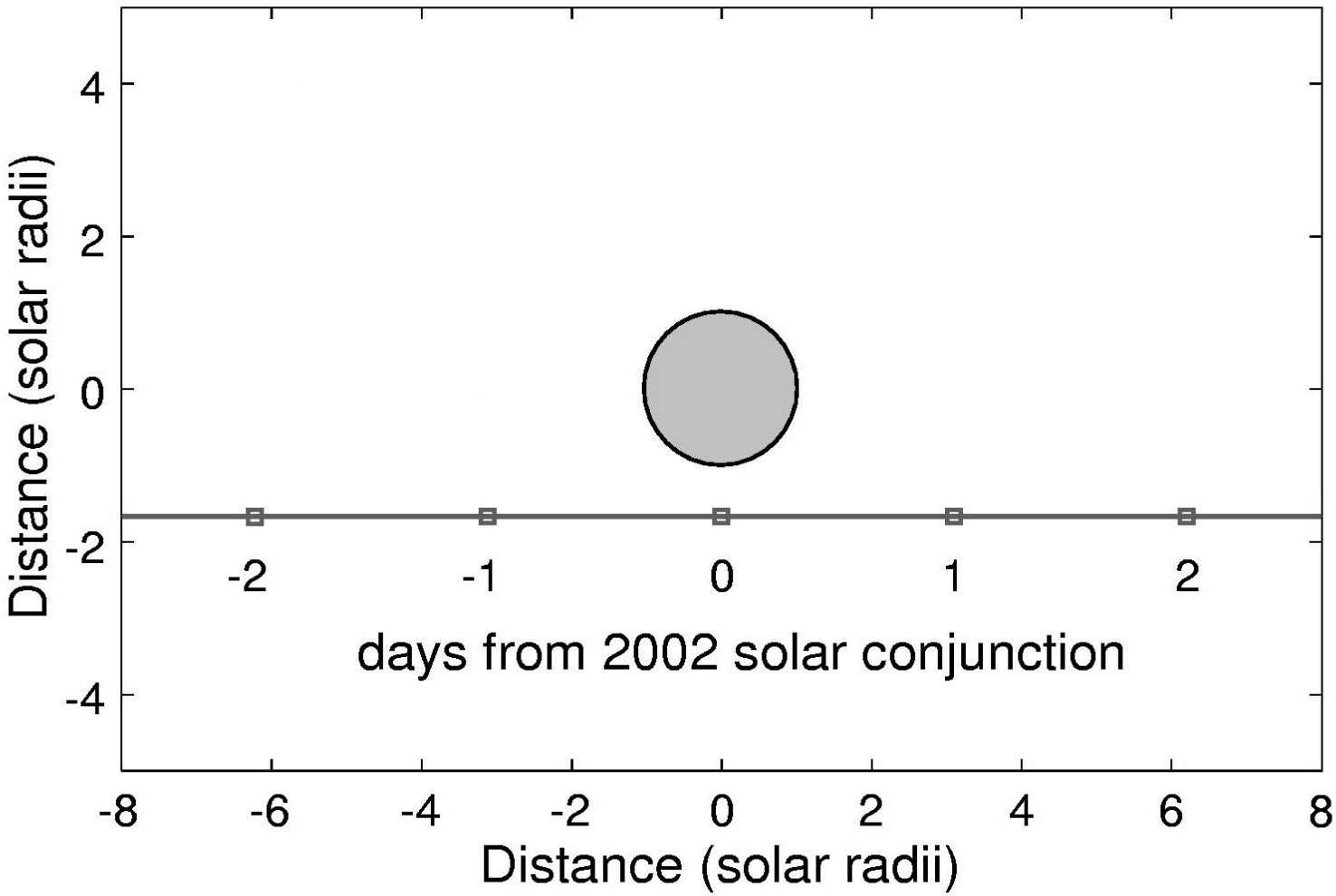
$$\gamma = 1 + (2.1 \pm 3.2) \times 10^{-5}$$

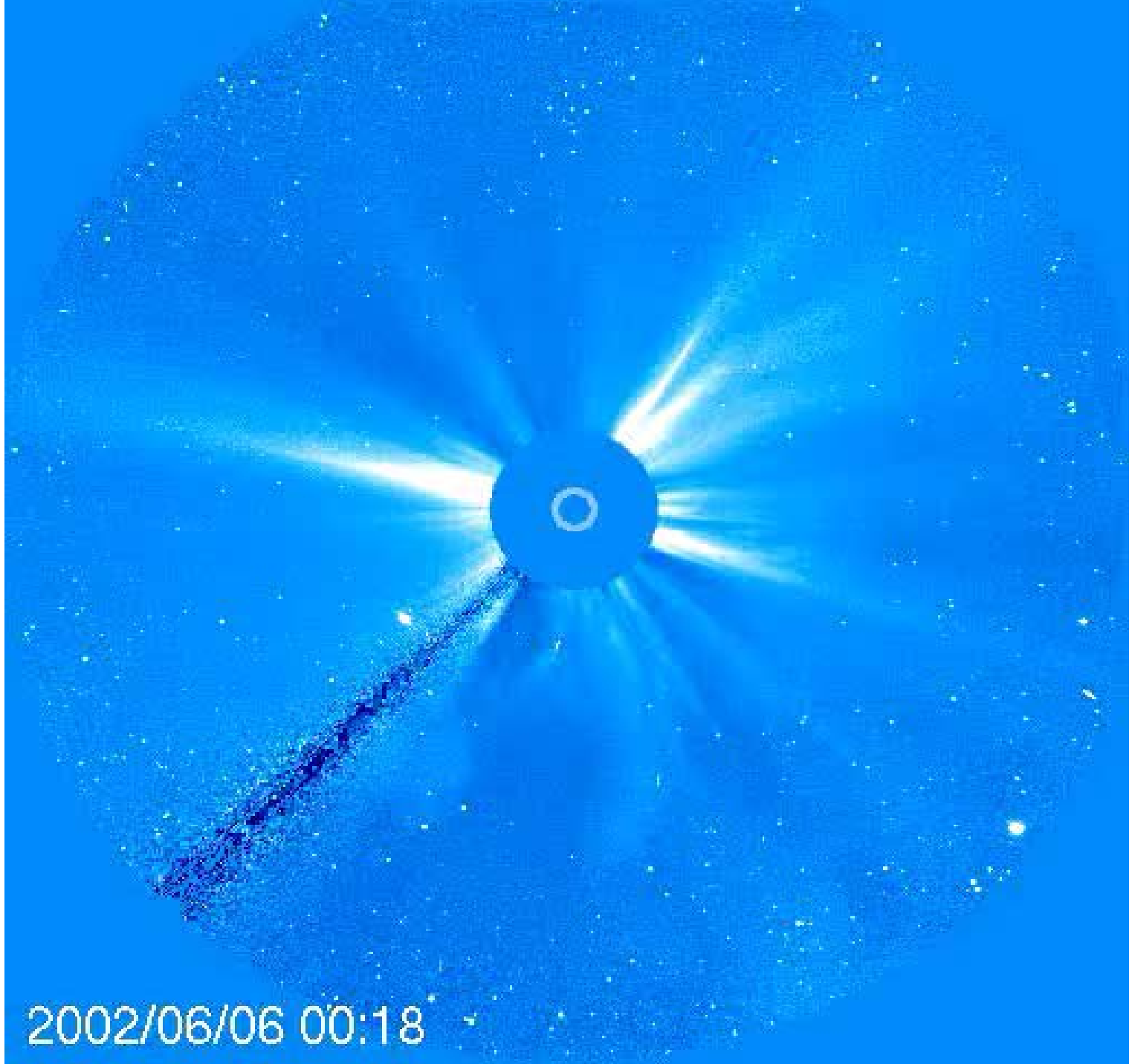
Non-gravitational acceleration in the orbitral plane




10×10-4
5×10-4
0
-5×10-4
-10×10-4
Frequency residuals (Hz)
-15
-10
-5
0
5
10
15
Time (days from 2002 solar conjunction)

4. Why has it not been done before?

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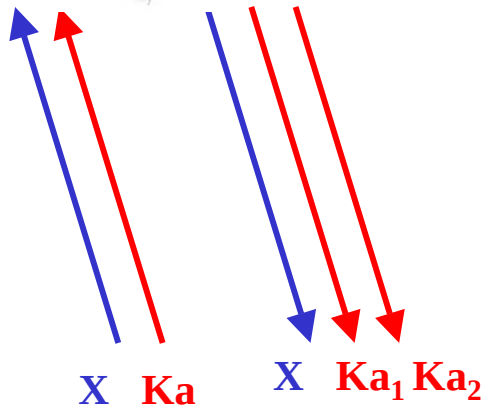

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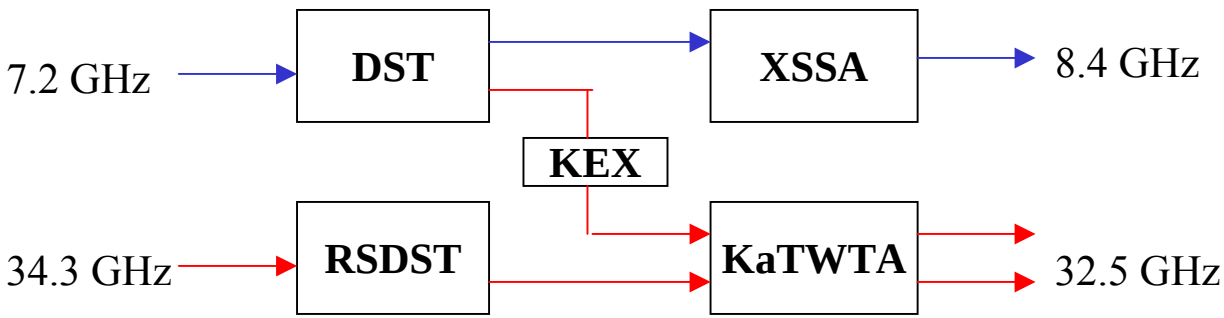

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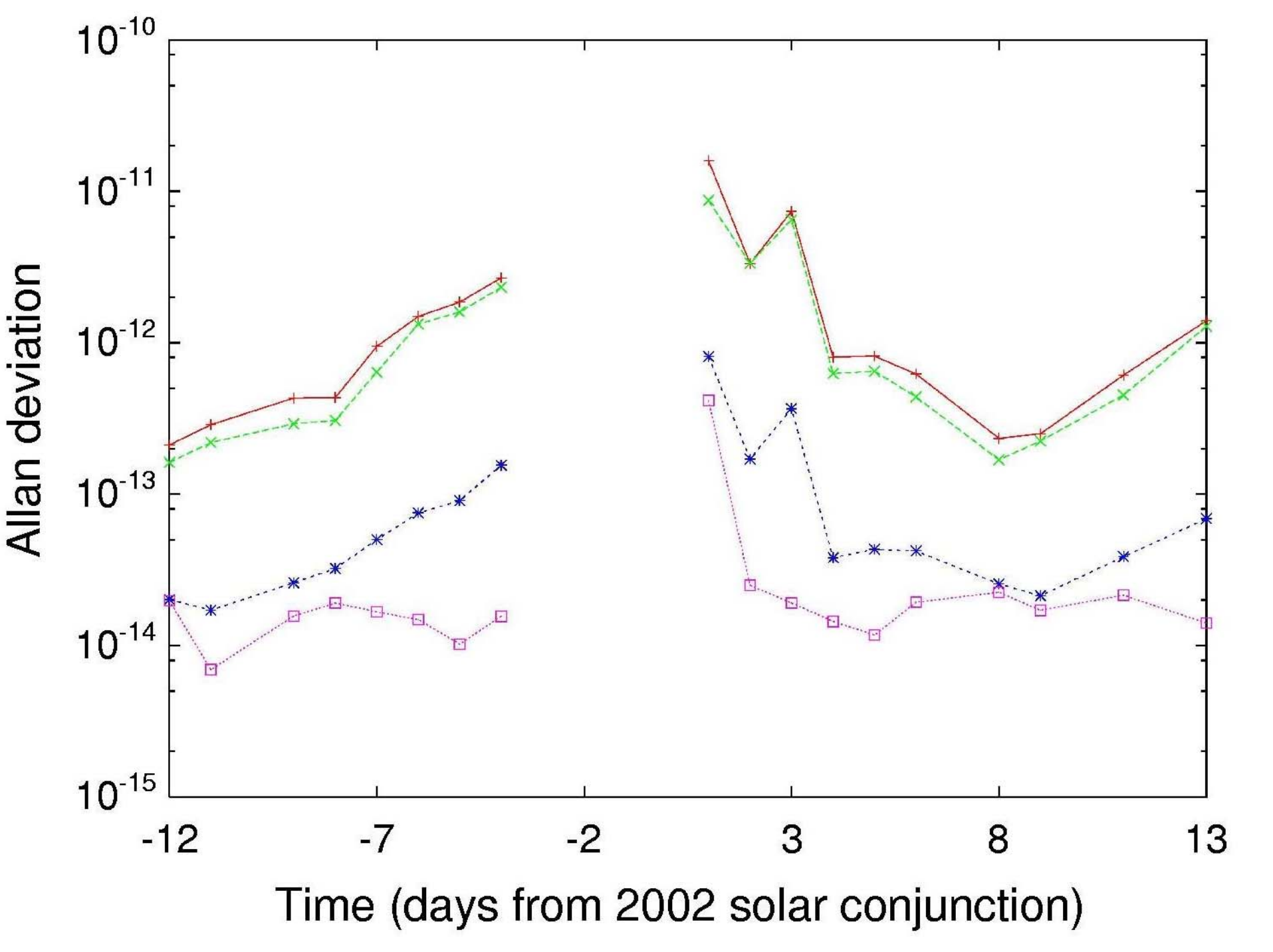
Allan deviation
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
-12
-7
-2
3
8
13
Time (days from 2002 solar conjunction)

5. A cosmological scenario for gravity

Let δ_N be the Newtonian deflection. In General Relativity $\delta_{GR} = 2\delta_N$

Set:

$$\delta = (\gamma + 1)\delta_N$$

Newtonian model: $\gamma = 0$; General Relativity: $\gamma = 1$.

If a scalar field, in addition to the metric, contributes to gravity, we expect $\gamma < 0$.

---|----------|---> γ

0 1

Scalar gravity Tensor gravity

In string theory a scalar ϕ, partner to the graviton, is needed; if massless, it produces long-range forces between neutral bodies (Damour, Polyakov, etc.) and contributes to gravity. ϕ is essential in primordial cosmology. In this view gravity is not purely geometrical and couples to other fields in (unknown) ways dependent on ϕ. As the Universe expands, its effects get weaker, but a present-day remnant will **generically and jointly** violate all tests (γ, β, $\eta_{Nortvedt}$, dG/dt, free-fall laboratory experiments, etc.). A firm prediction:

$$\gamma < 1$$

Murray et al claim violation of SEP:

$$\alpha^{em} = \alpha^{em}_{now} \, [1 - (0.72 \pm 0.18) \times 10^{-5}]$$

Expected value of $1-\gamma$ smaller than 10^{-5}.

Investigating early cosmology from solar system experiments?