Instrumentation for
Tests of General Relativity
By the BepiColombo Mission

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And the Mercury Orbiter
Radio-science Experiment (MORE) Team

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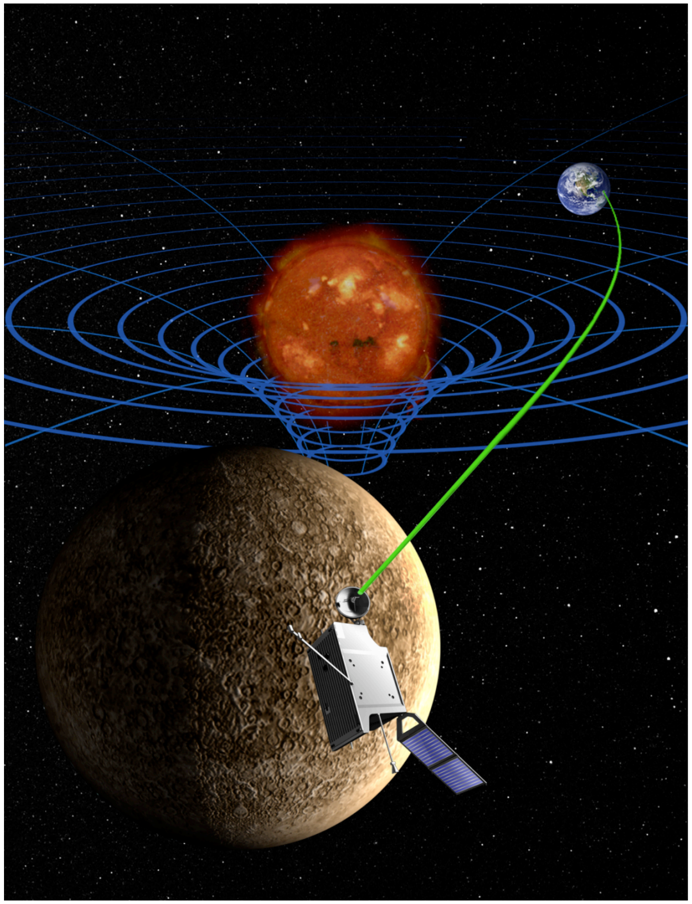
Introduction

- ESA's Mercury Planetary Orbiter (MPO) selected an international Radio Science Team to:
  - Determine the gravitational field of Mercury and investigate the interior structure
  - → Investigate aspects of the theory of general relativity
- Radio Science technique utilize highly stable (low noise) radio links between spacecraft and ground stations



MORE Mercury Orbiter Radio-science Experiment

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Michael Watkins	Jet Propulsion Laboratory
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Testing gravitational theories

Deflection of light

$$\theta_{gr} = 2(1+\gamma)\frac{M_{sun}}{b} = 4\times10^{-6}(1+\gamma)\frac{R_{sun}}{b}\,\text{rad}$$

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

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

≈ 8×10^{-10} for a grazing beam

Simulation Results

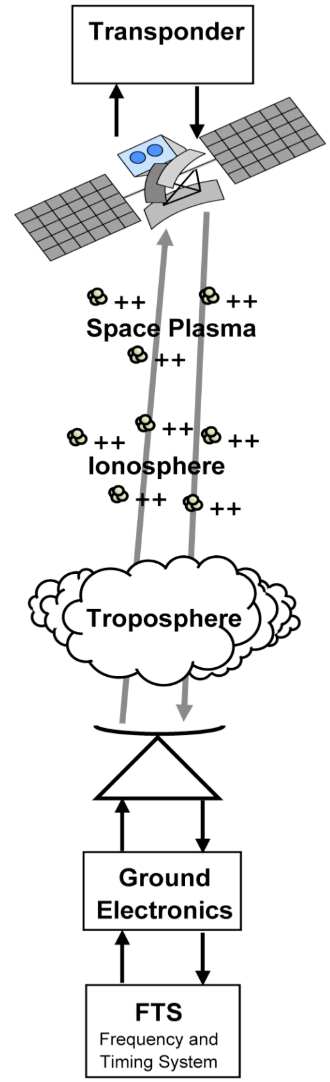
Parameter	*Present Accuracy*	*MORE Accuracy*
γ	2.3×10^{-5}	2×10^{-6}
β	1.2×10^{-4}	7×10^{-6}
η	5×10^{-4}	2×10^{-5}
α_1	1×10^{-4}	7.8×10^{-6}
Solar J_2	4×10^{-8}	4.8×10^{-9}
G dot / G	9×10^{-13} per year	3×10^{-13} per year

Simulations show

- Results are achievable with range and range-rate (Doppler) measurements at X- and Ka-band simultaneously
- Ka-band ranging accuracy to 20 cm
- Range-rate accuracy to ~ 3 microns/s at 1000 s
- Gamma in cruise-phase solar conjunction with quiet spacecraft (no engine pulsing)
- Other parameters in one year of orbital phase

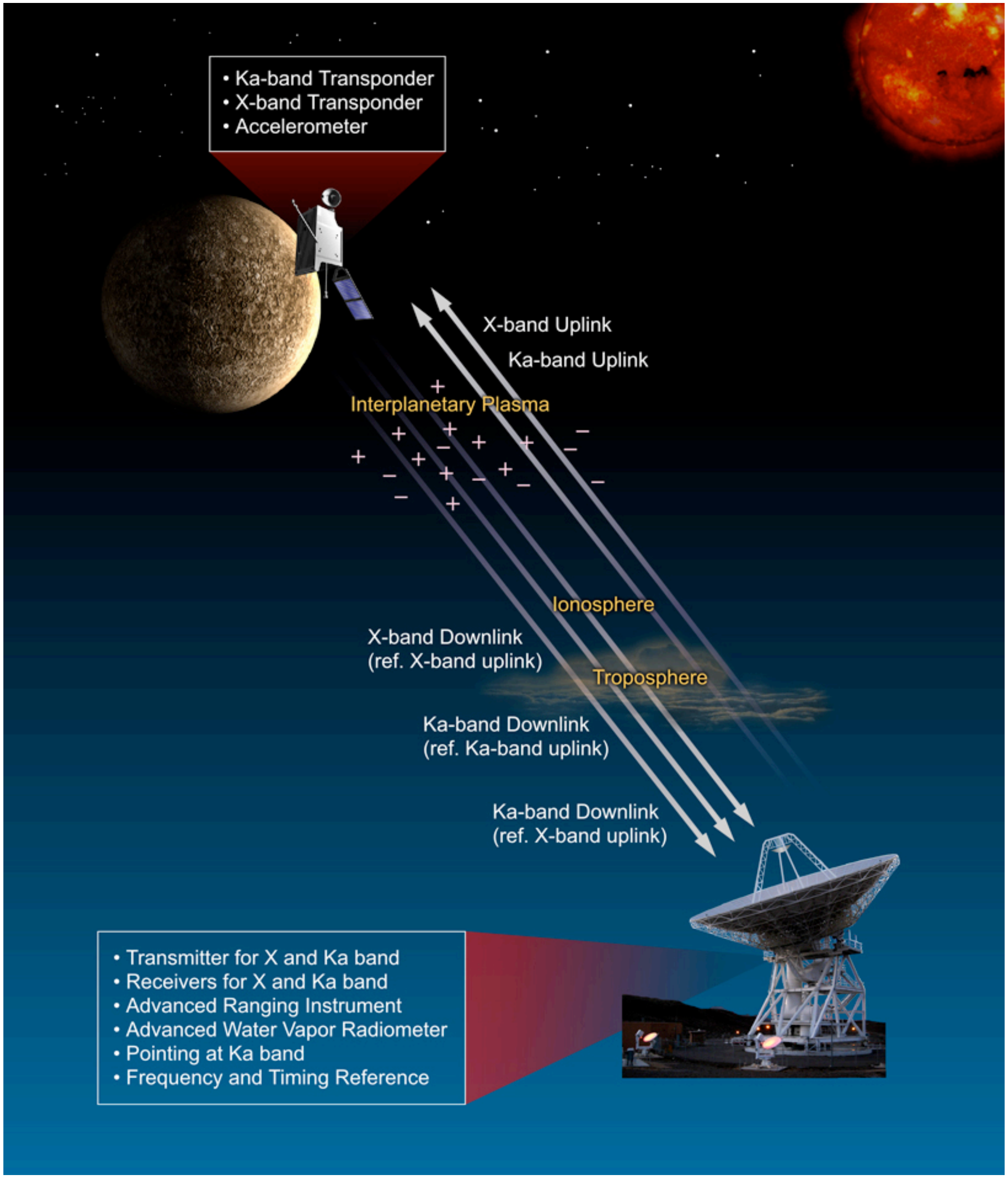
Classification of Noise Sources

1. Instrumental: random errors in hardware systems
   - Phase fluctuations in link
   - Electronic components
   - Noise of frequency standard
   - Antenna mechanical noise
2. Dynamical:
   - Un-modeled bulk motion of spacecraft or ground station
3. Propagation:
   - Solar Wind
   - Ionosphere
   - Troposphere
4. Systematic errors



MORE Measurements!

- 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



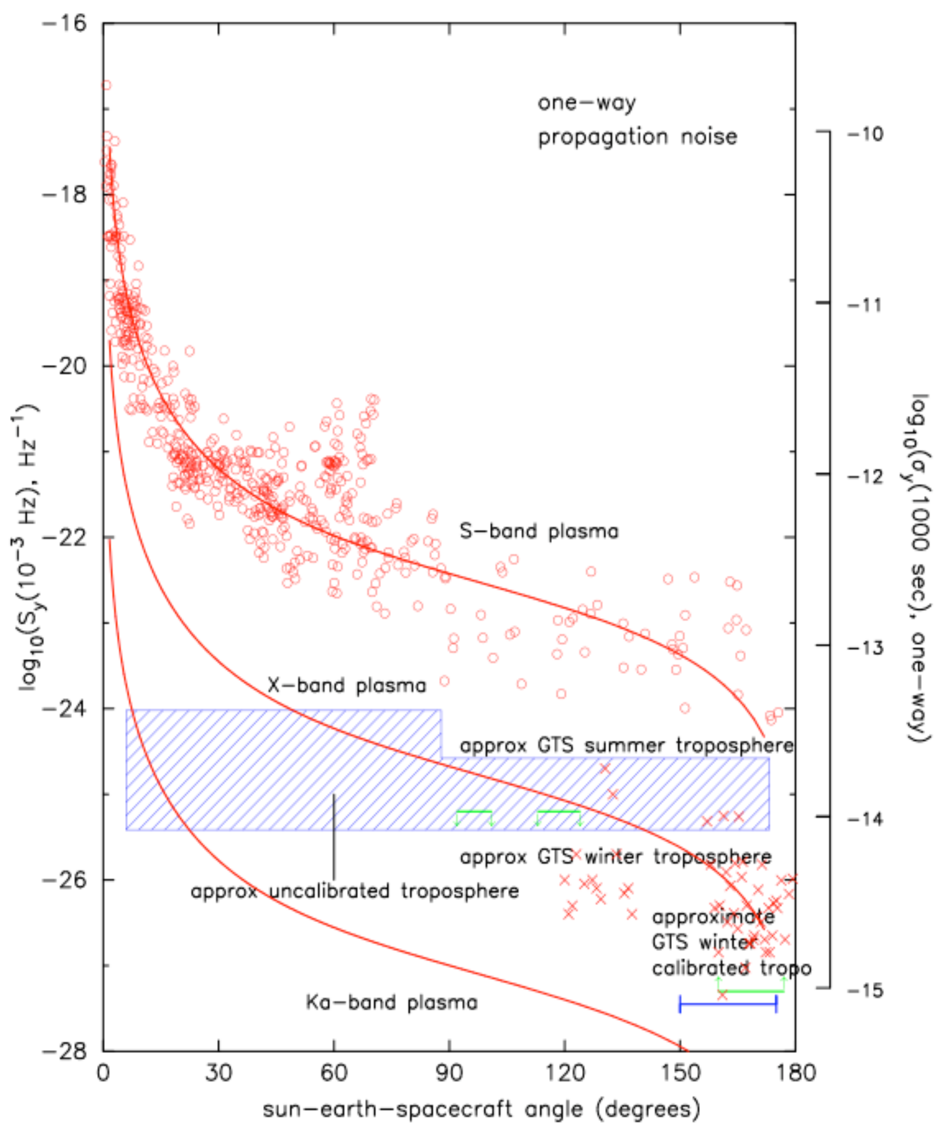
• Ka-band Transponder
• X-band Transponder
• Accelerometer
X-band Uplink
Ka-band Uplink
Interplanetary Plasma
Ionosphere
X-band Downlink
(ref. X-band uplink)
Troposphere
Ka-band Downlink
(ref. Ka-band uplink)
Ka-band Downlink
(ref. X-band uplink)
• Transmitter for X and Ka band
• Receivers for X and Ka band
• Advanced Ranging Instrument
• Advanced Water Vapor Radiometer
• Pointing at Ka band
• Frequency and Timing Reference

Why Ka-band

- One-way propagation noise at
  S-, X-, and Ka-bands as function of angular distance from the Sun (developed by J.W. Armstrong, published in Asmar et al., 2005)

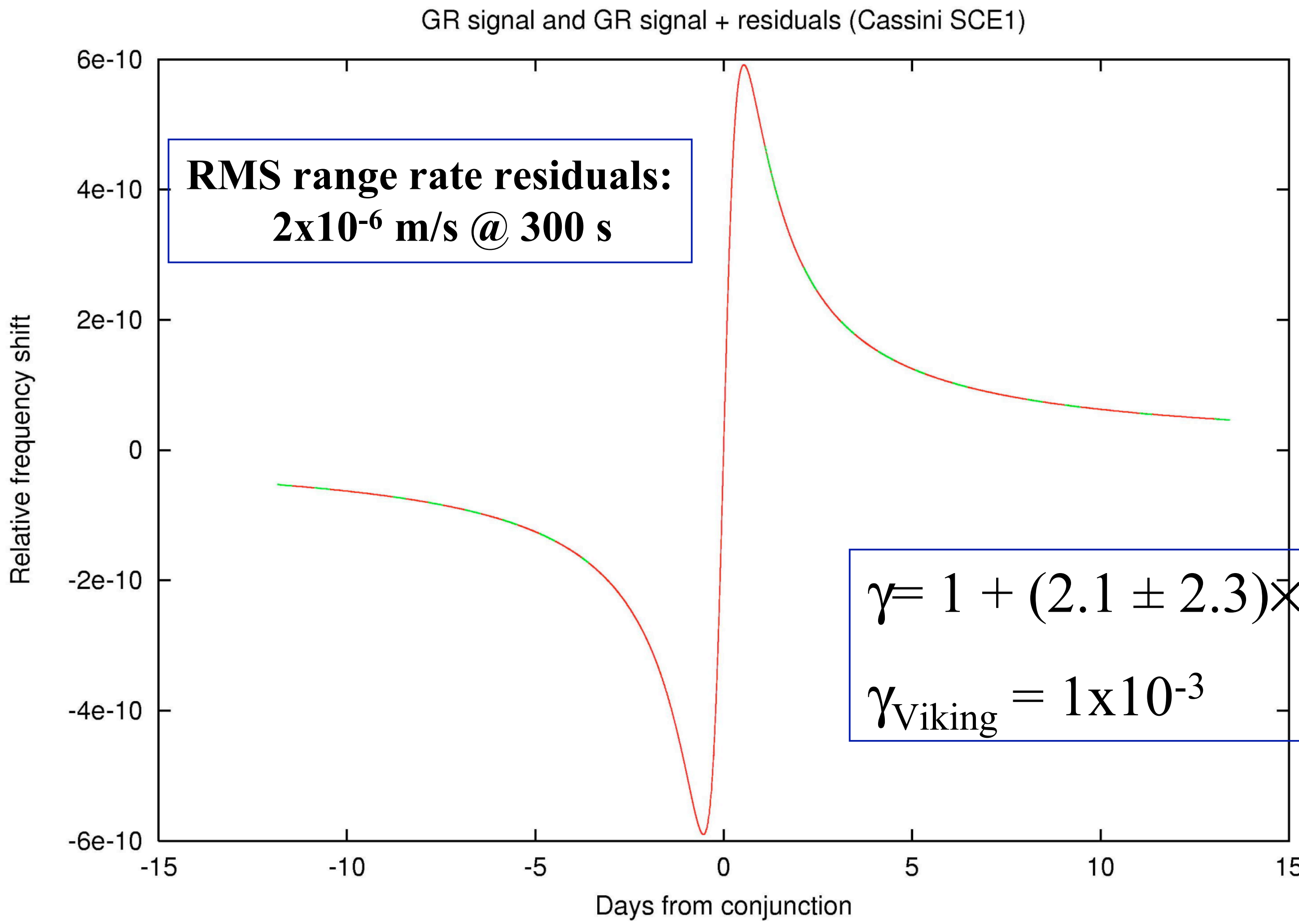
- $F_{Ka}/F_X = \sim 4$

- Improvement by factor $\sim 4^2$



Method Successfully Demonstrated by Cassini

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



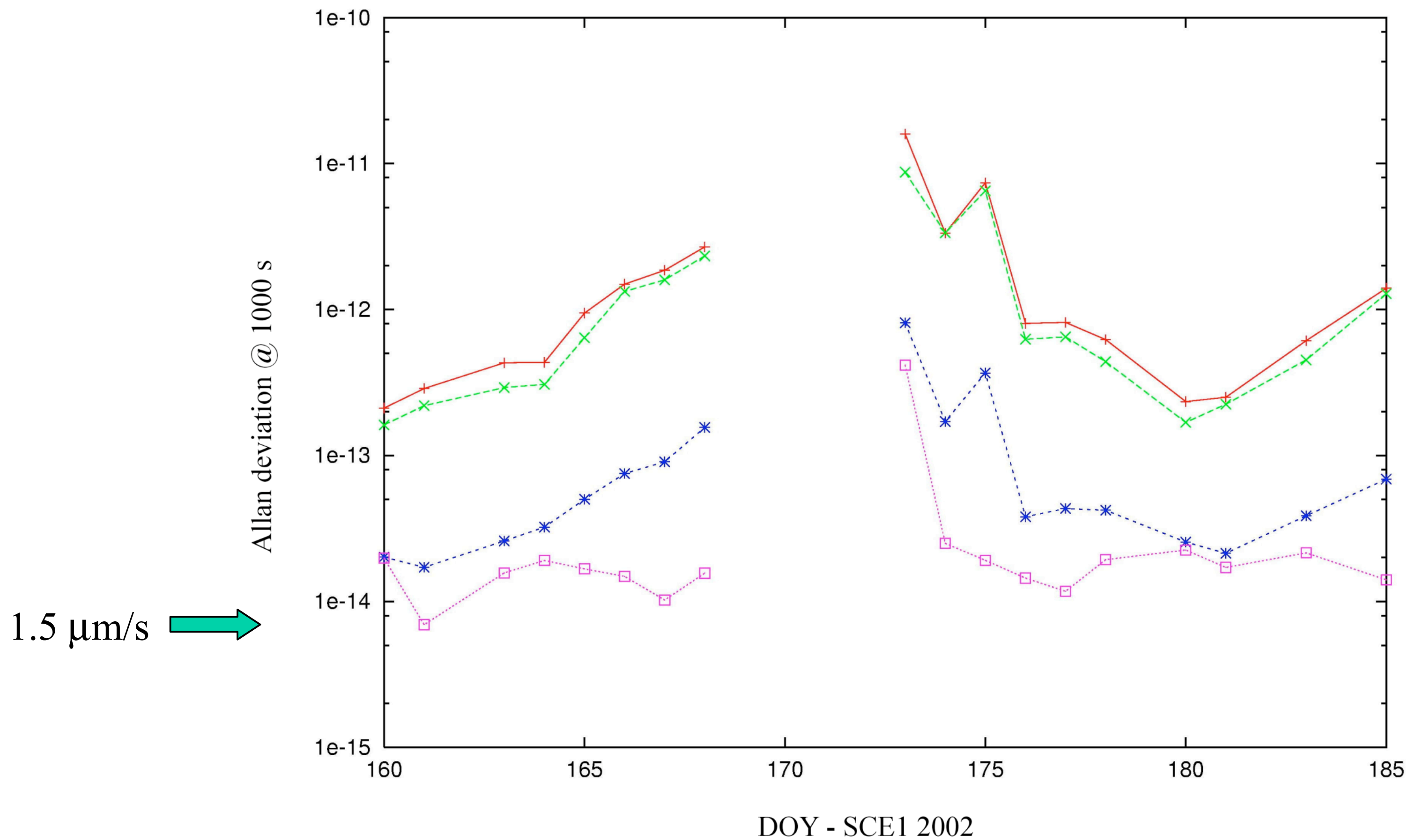
RMS range rate residuals:
$2x10^{-6}$ m/s @ 300 s

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

$\gamma_{Viking} = 1x10^{-3}$

Plasma noise in the X/X, X/Ka, Ka/Ka links and the calibrated Doppler observable

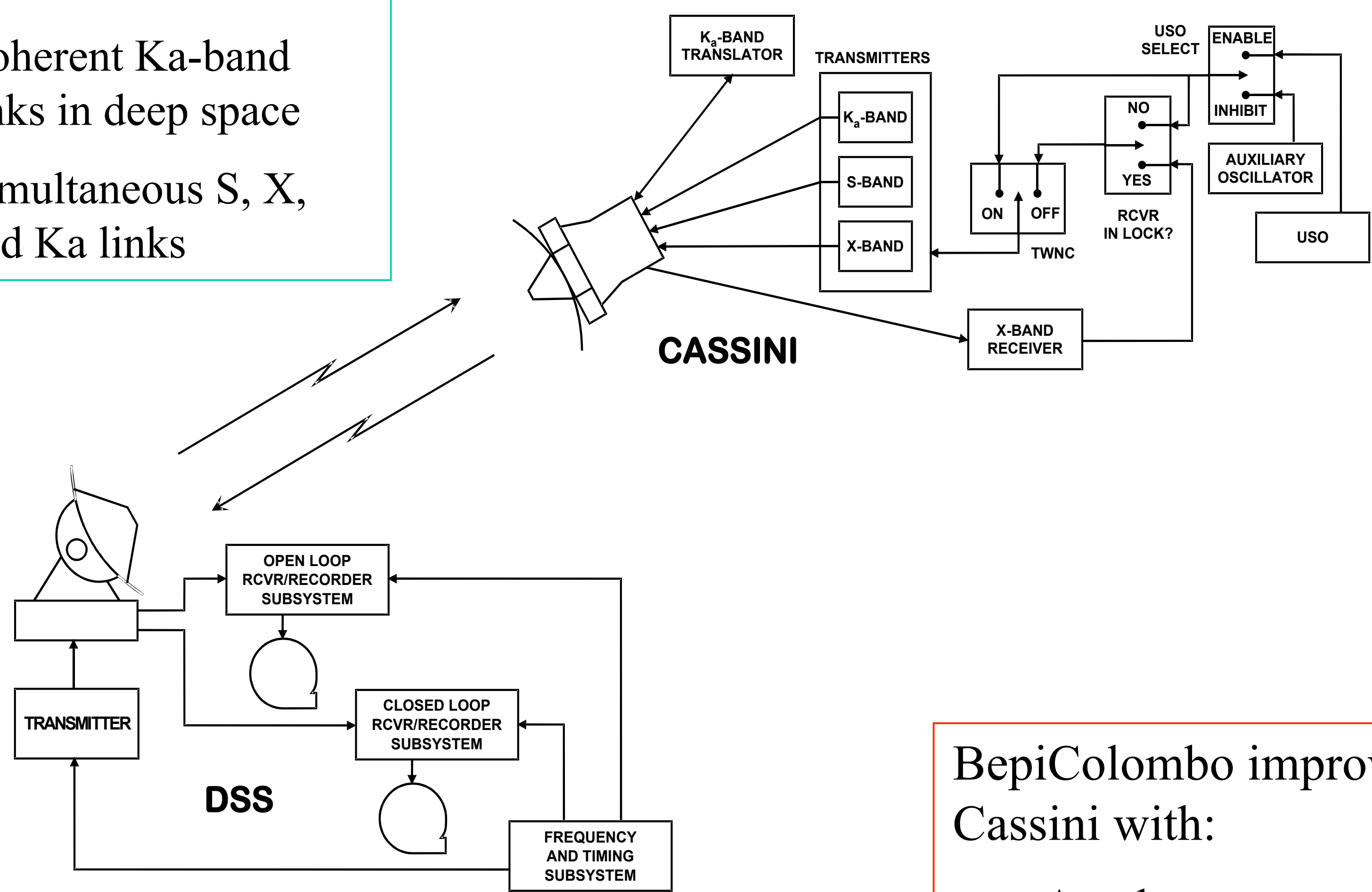
Daily Allan deviation @1000s, Cassini SCE1
Minimum impact parameter: 1.6 R_s (DOY 172)



Cassini Meets Marconi

Cassini Firsts:

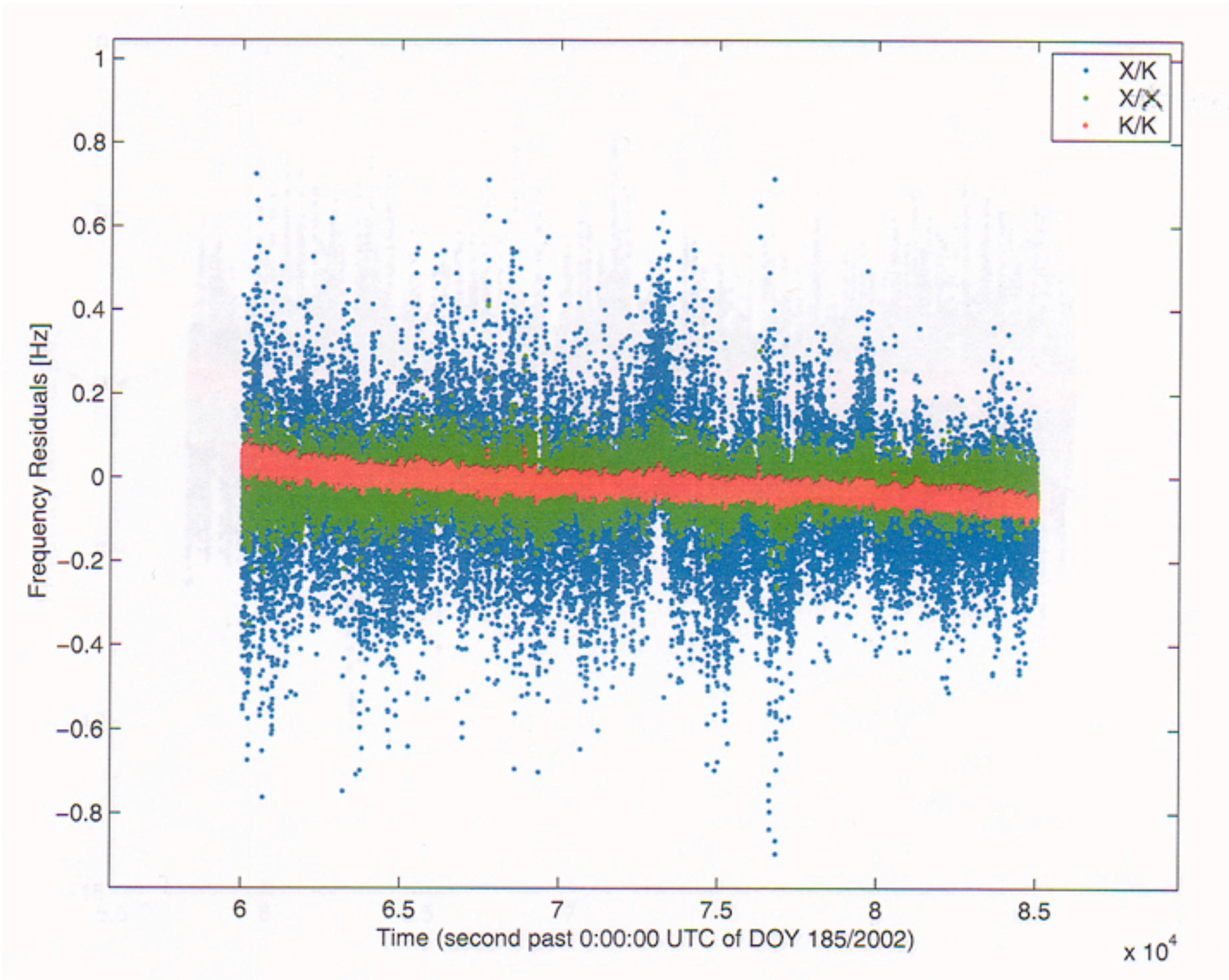
- Coherent Ka-band links in deep space
- Simultaneous S, X, and Ka links



BepiColombo improves on Cassini with:

- Accelerometer
- Ka-band ranging

Example: Cassini Data Calibration



Doppler Quality from three links from Cassini Radio Science

For illustration only

Improvements over X/X

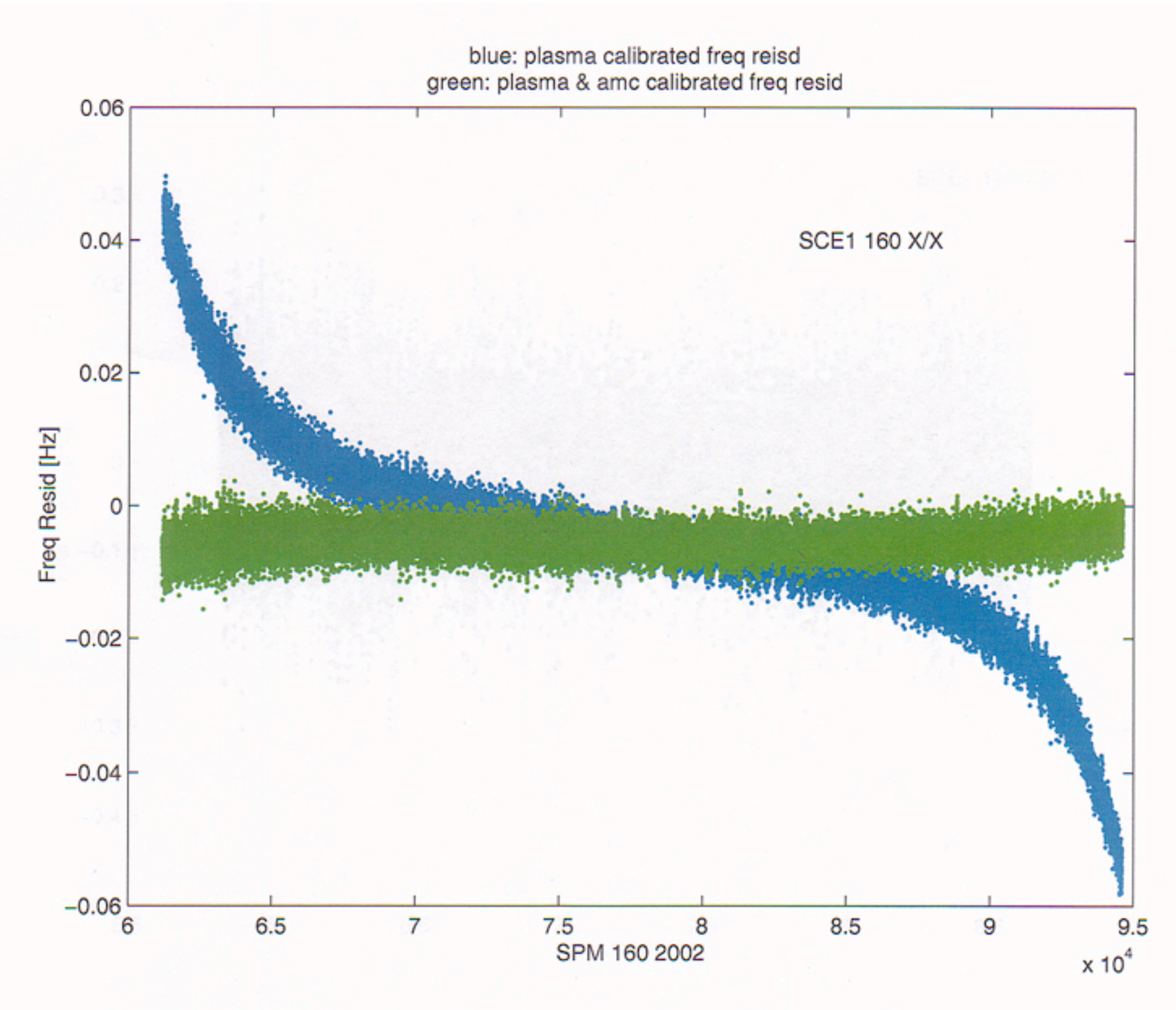
- X/K 40% (this link only back-up)
- K/K factor of 16
- K/K calibrated using X/X not shown

Tropospheric Calibration

The 34-meter diameter tracking Station at NASA's Deep Space Network at Goldstone, California, With advanced Radio Science Instrumentation to support Juno

The Advanced Water-Vapor Radiometer, part of the a calibration System for tropospheric path delay

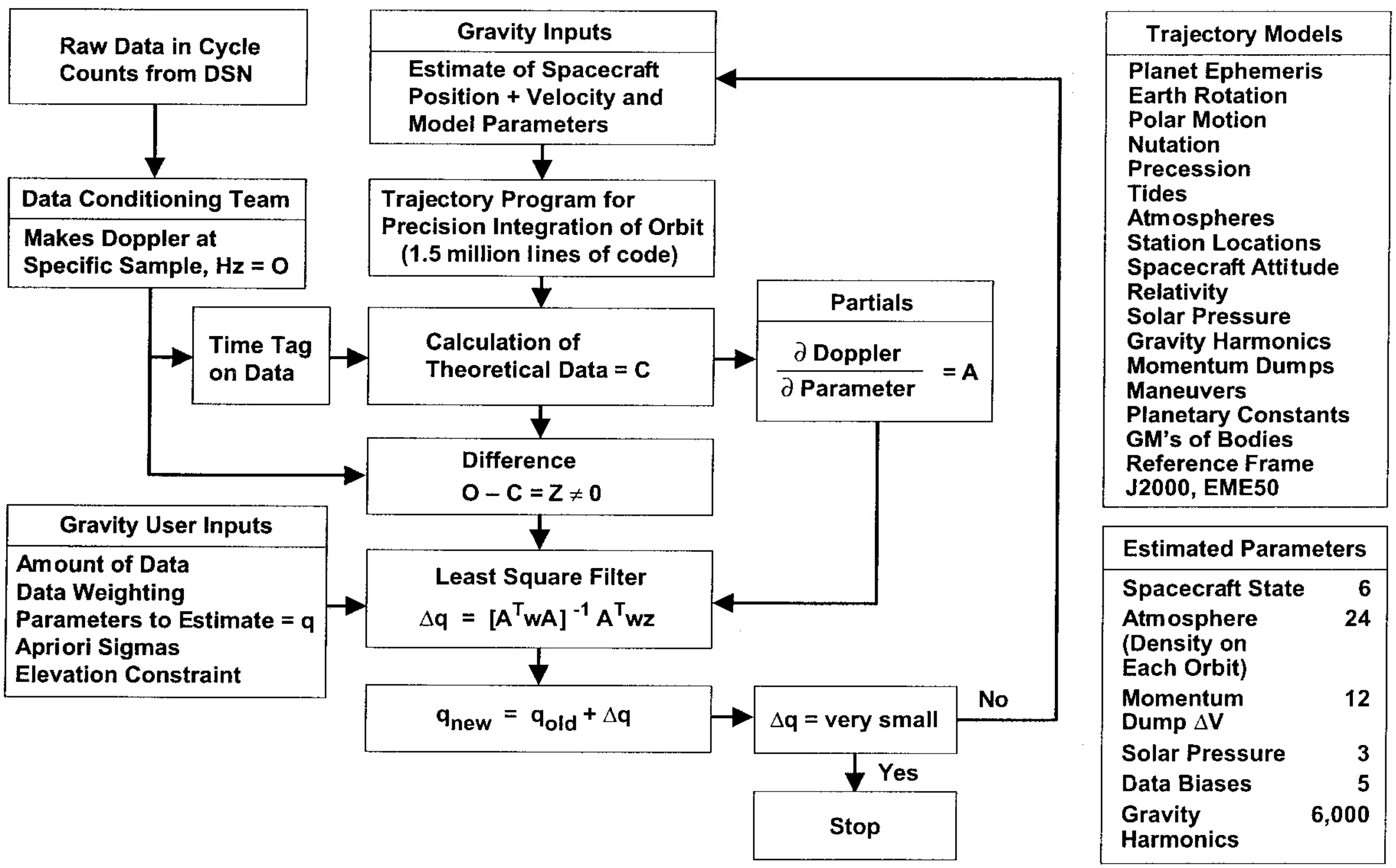
Tropospheric Calibration Example



- Doppler Quality from Cassini Radio Science
- Blue curve illustrates increased water-vapor contribution at low elevation angles
- Green curve illustrates the same Doppler residuals after applying the water-vapor radiometer calibration

Other Calibrations: Planet's Gravity

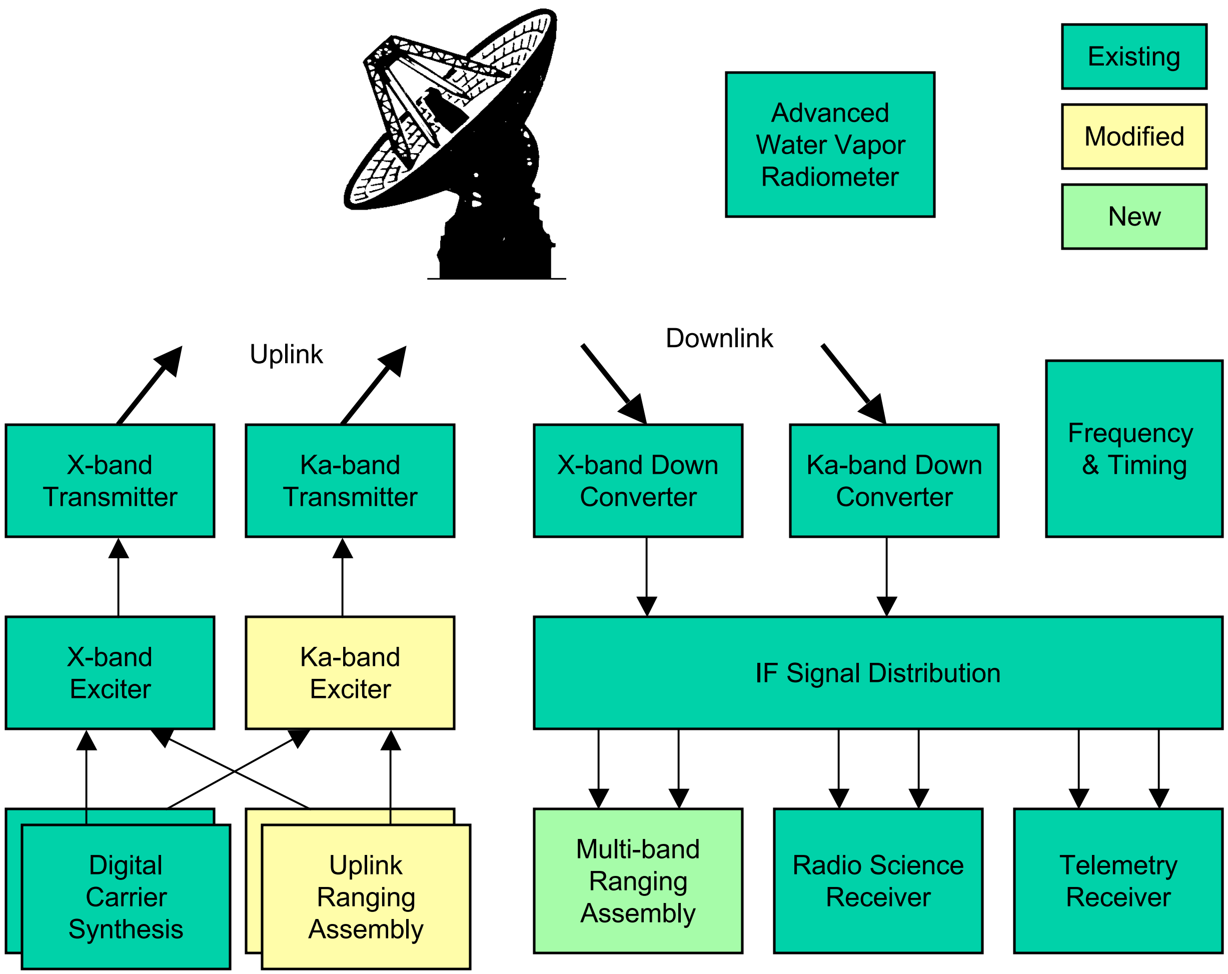
FLOW DIAGRAM FOR GRAVITY DATA REDUCTION



The challenge:
An Advanced Ranging Instrument

- Deep space range measurements are typically based on sequential procedure
- Ranging signal phase modulates the uplink carrier; spacecraft transponder demodulates and recovers and retransmits to ground by phase modulating the downlink carrier
  - The tone/code at highest frequency defines the accuracy while the others are sequentially applied for ambiguity resolution
- A new design utilizes Ka-band uplink and downlink to minimize the largest error source due to interplanetary plasma
  - PN ranging; 24 MHz bandwidth for station exciter system; utilizes an open-loop receiver
  - More precise and frequent **calibration** of delay in electronics
  - Etc.

Overview of Proposed Advanced Ranging Instrument



Conclusion

- BepiColombo will provide excellent 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
- **Team “invented“ a system a decade ago for improved Range-rate**
  - **~ 3microns/s at 1000 s; demonstrated by Cassini**
- **Now “invented“ a system for improved Ranging**
  - **~ 20 cm; yet to be demonstrated**
- **Pushing limits of technology in tracking and Radio Science benefits all future deep space missions**