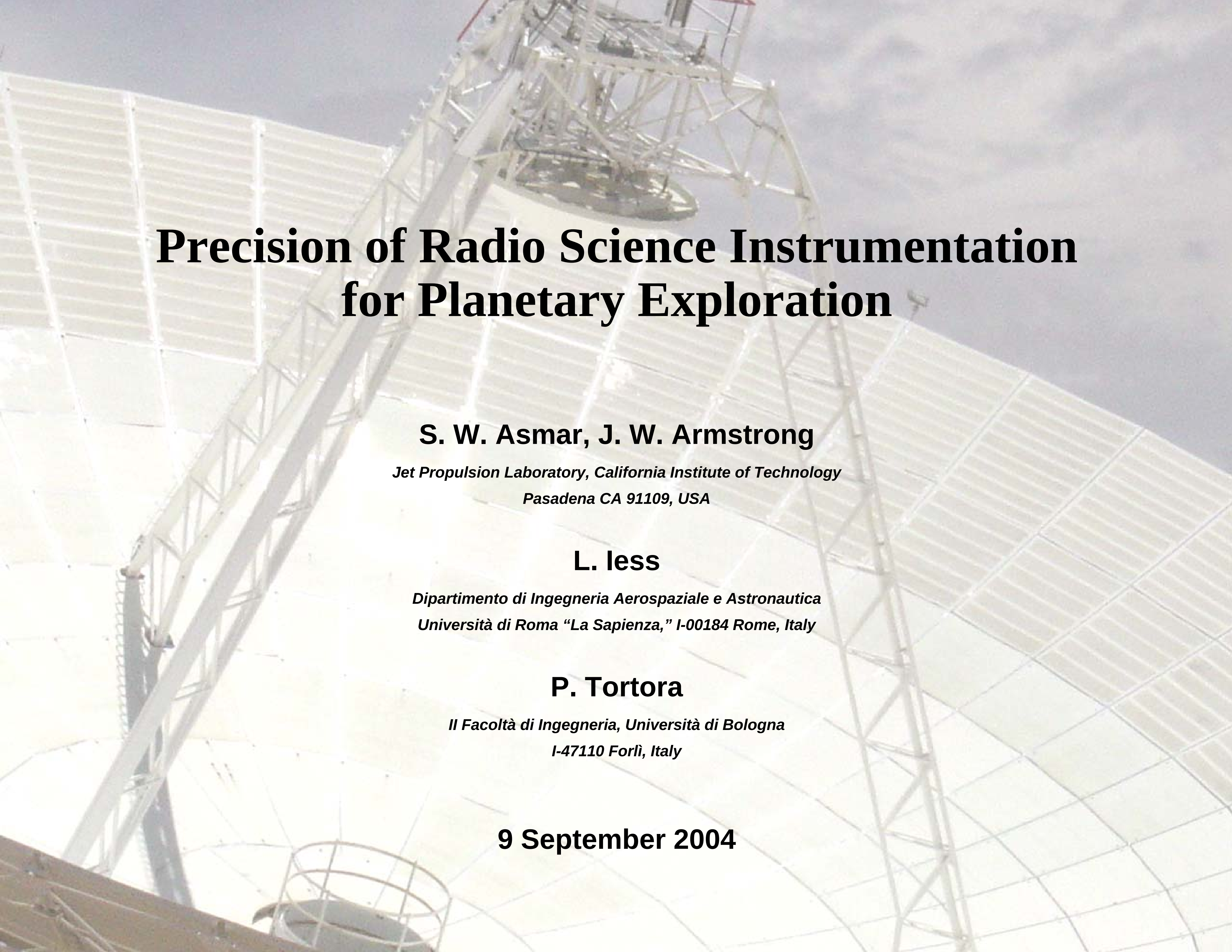


Precision of Radio Science Instrumentation for Planetary Exploration

S. W. Asmar, J. W. Armstrong

Jet Propulsion Laboratory, California Institute of Technology

Pasadena CA 91109, USA

L. Iess

Dipartimento di Ingegneria Aerospaziale e Astronautica

Università di Roma "La Sapienza," I-00184 Rome, Italy

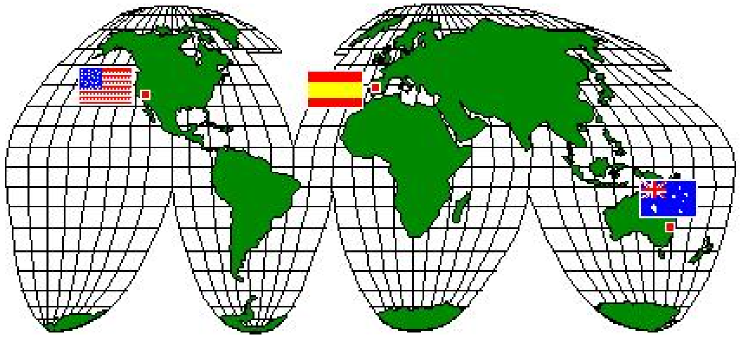
P. Tortora

II Facoltà di Ingegneria, Università di Bologna

I-47110 Forlì, Italy

9 September 2004

The Deep Space Network



- The Deep Space Network is the largest and most sensitive scientific telecommunications facility
- Primary function: provide two-way communication between the Earth and spacecraft exploring the solar system
  - Instrumented with large parabolic reflectors, high-power transmitters, low-noise amplifiers & receivers, etc.
- Three complexes ~ 120 degrees apart around the world at Goldstone, California; near Madrid, Spain; and near Canberra, Australia

At Each Complex

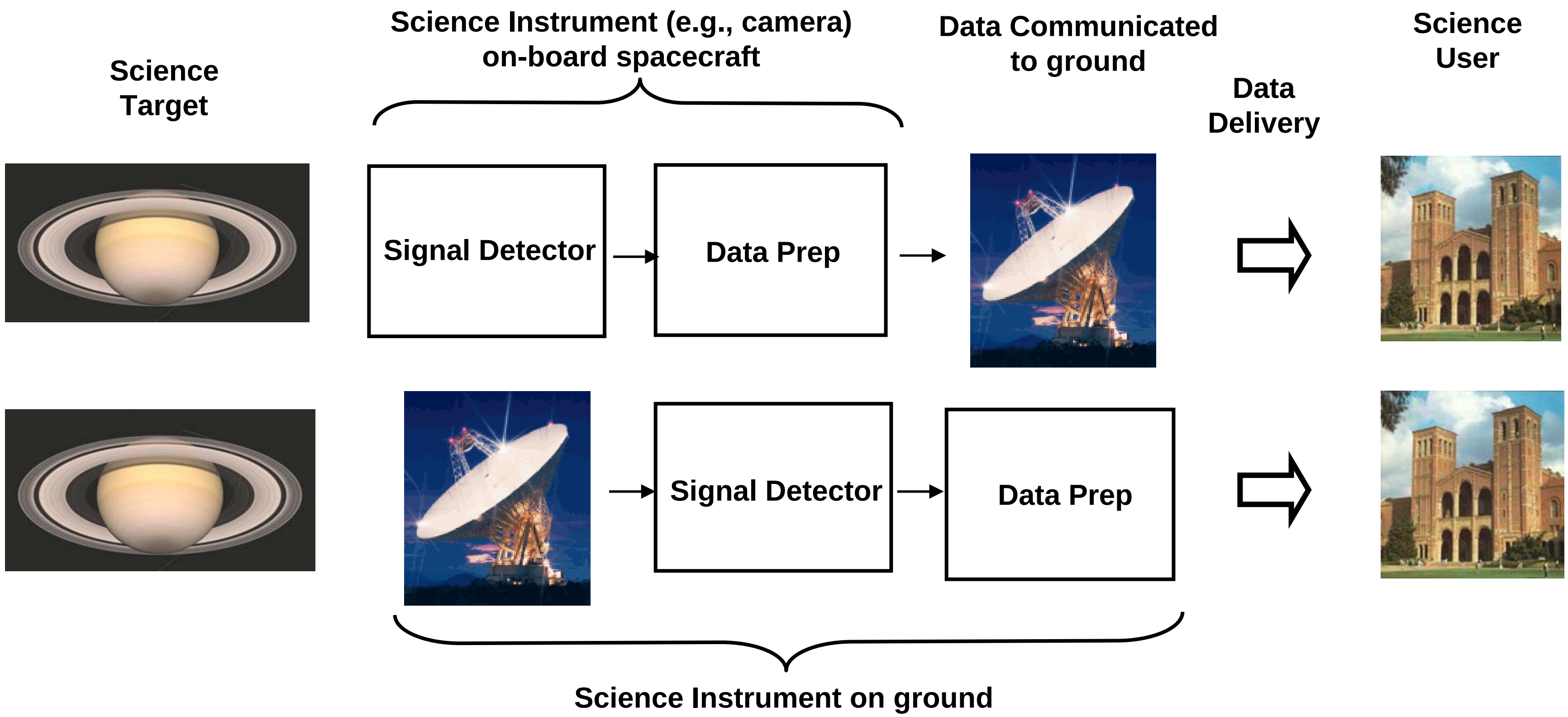
- 1 70-meter diameter antenna
  - Largest and most sensitive
- 1 34-meter diameter high-efficiency
  - Precision-shaped reflector
- 1 ***or more*** 34-meter beam waveguide
  - Instruments at ground level
- 1 26-meter diameter
  - Earth orbiting satellites
- 1 11-meter diameter
  - Space VLBI

Radio Science Investigations

Utilize the telecommunication links between spacecraft and Earth to examine changes in the phase/frequency, amplitude, and polarization of radio signals to investigate:

- Planetary atmospheres
- Planetary masses and interiors
- Planetary rings
- Planetary winds
- Planetary surfaces
- Planetary shapes
- Solar corona and wind
- Comet material
- Fundamental physics & relativity

The DSN: A Science Instrument



DSN's primary function is communication and data delivery - optimize links, e.g., G/T
Also an instrument for science research - optimize performance, e.g., phase stability

Radio science activities stretch DSN performance capabilities in:
frequency/amplitude stability, SNR, position/velocity accuracy, media calibration

Radio Science Receiver

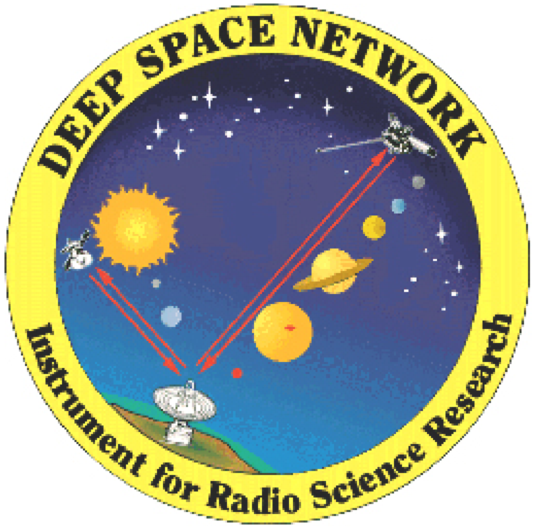
- Independent of the tracking and telemetry receiver
- Open-loop digital down-conversion
  - No lock, no tracking
  - Recording in pre-selected bandwidth / sampling rate
- Tuned by frequency prediction file
  - Generated from navigation solution
- Operated by scientists & their staff
  - Most familiar with experiment for quick reaction

Advantages over tracking receiver

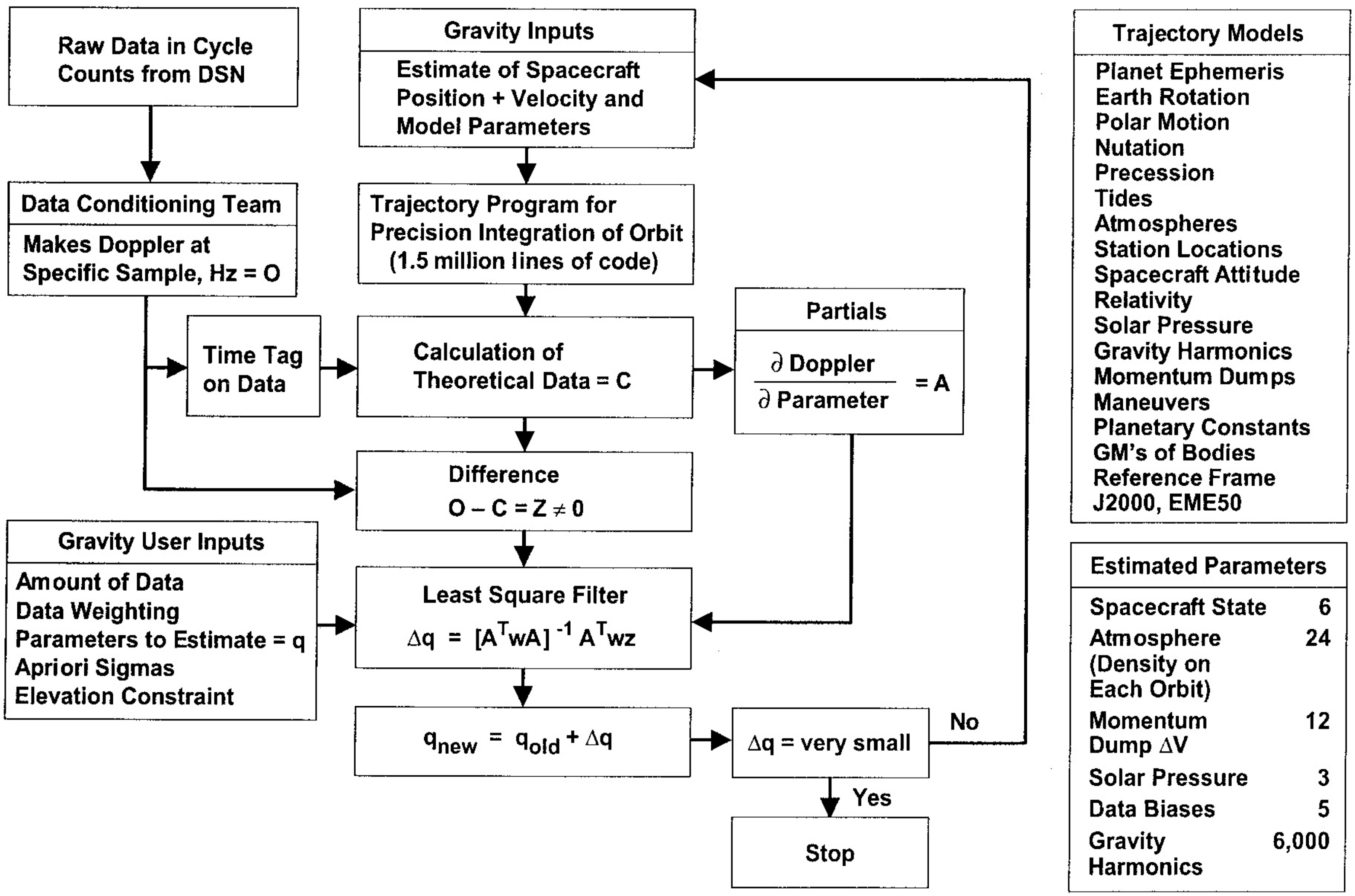
- Better stability
  - Design of components with Allan deviation and phase noise specifications
- Capture signal dynamics
- Capture multi-path
- Choices of bandwidth and sampling
- Higher quantization
- Creative post-pass processing
  - Arraying, landing tone processors, orbit insertion, etc.

What Limits Precision?

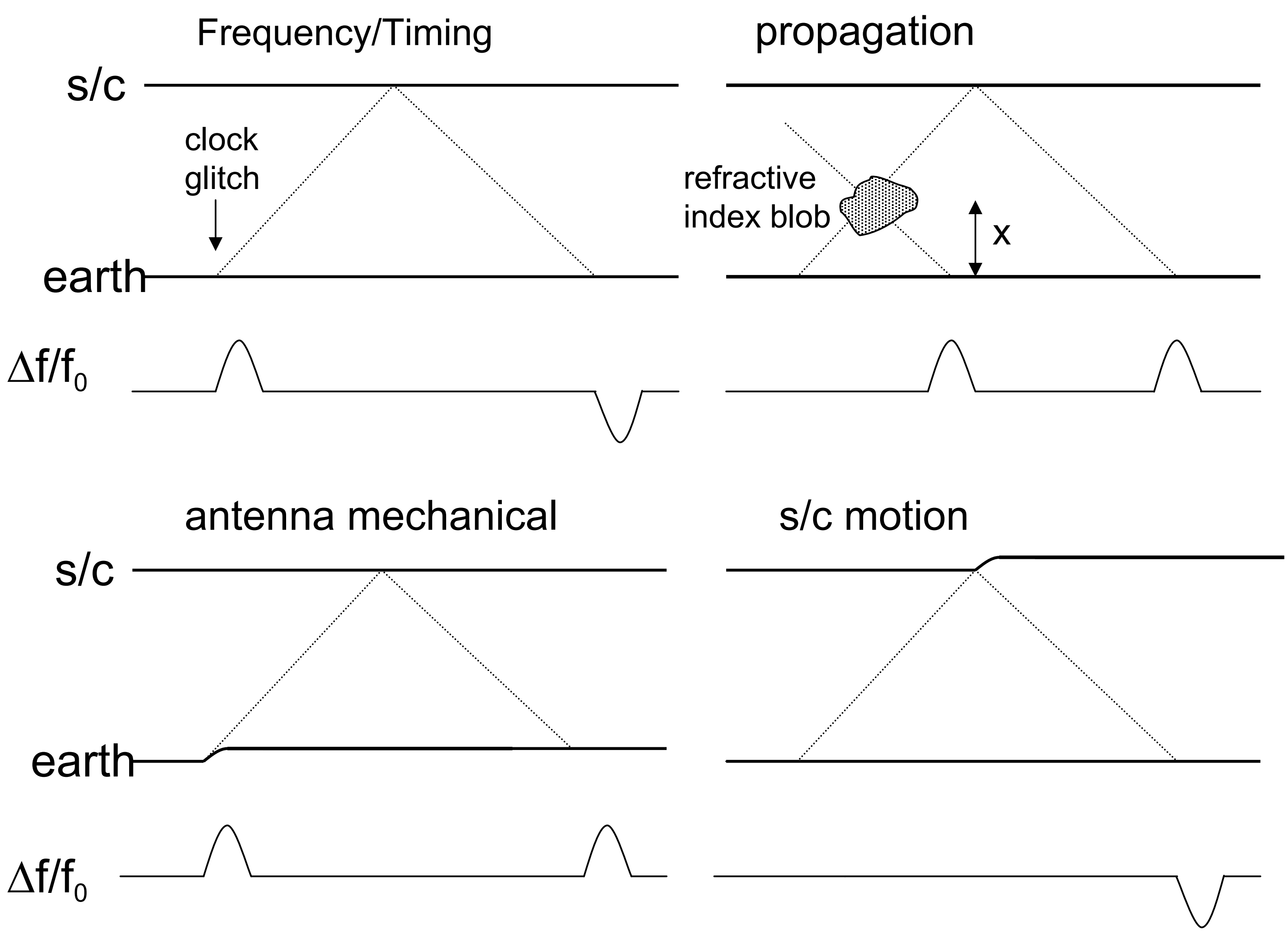
- Choice of frequency (link)
- Frequency/phase stability
  - Spacecraft & ground components
- Signal strength (signal to noise ratio)
- Amplitude stability
  - Electronic components
  - Mechanical components
  - Antenna pointing stability
- Intervening media
- Non-gravitational forces
- Accuracy of trajectory reconstruction



FLOW DIAGRAM FOR GRAVITY DATA REDUCTION

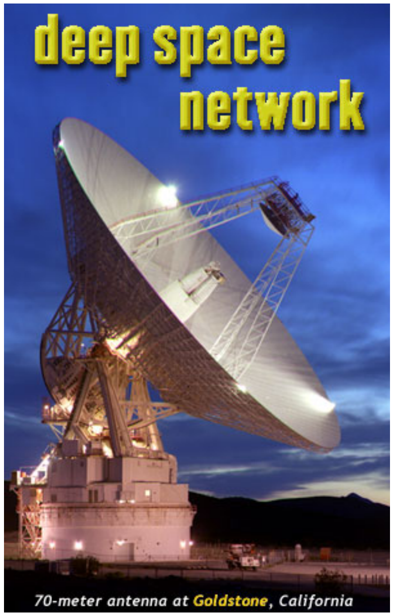


Noise Disturbances in Two-Way Doppler Link



Doppler Noise Model

- We examine noise processes in Radio Science data acquired by the Deep Space Network
- Most sensitive instrumentation and experiments to date achieve fractional frequency fluctuation noise of 3E-15 at 1000-second integration time
  - Corresponding to better than 1 micron per second velocity noise
  - Instrument: Cassini spacecraft and DSS-25
- Our model focuses on the Fourier range in the milli-Hz to 1 Hz
- We identify phenomena limiting current Doppler sensitivity and discuss prospects for significant sensitivity improvements
- This is useful to the science community
  - Estimating uncertainty in Doppler observations
  - Predicting performance of future observations



Cassini Meets Marconi:

Uplink Possibilities

X-band ~ 7.9 GHz - command

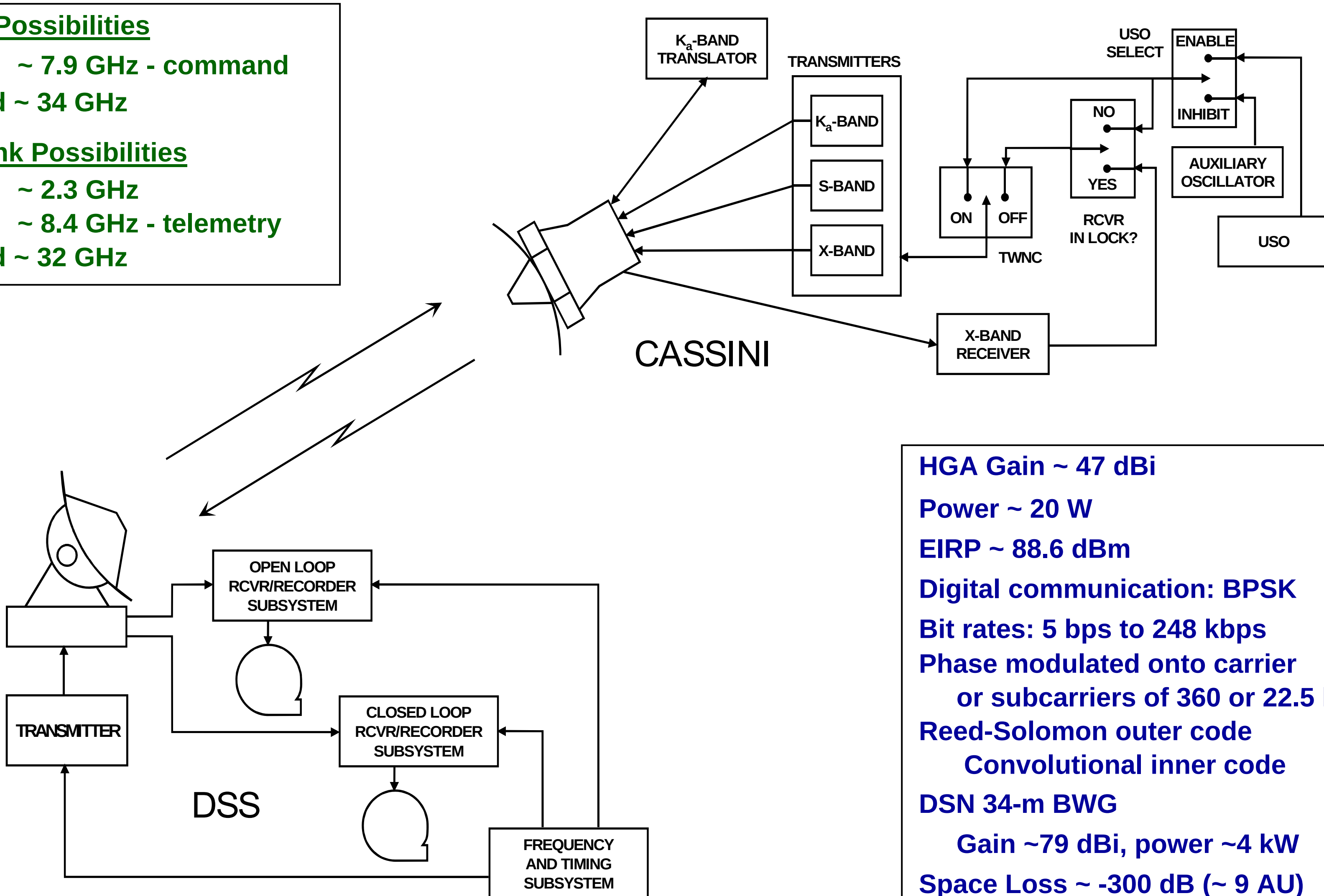
K_a-band ~ 34 GHz

Downlink Possibilities

S-band ~ 2.3 GHz

X-band ~ 8.4 GHz - telemetry

K_a-band ~ 32 GHz



HGA Gain ~ 47 dBi

Power ~ 20 W

EIRP ~ 88.6 dBm

Digital communication: BPSK

Bit rates: 5 bps to 248 kbps

Phase modulated onto carrier
or subcarriers of 360 or 22.5 kHz

Reed-Solomon outer code
Convolutional inner code

DSN 34-m BWG
Gain ~79 dBi, power ~4 kW

Space Loss ~ -300 dB (~ 9 AU)

Typical OWLT ~ 90 minutes

Principal Noises

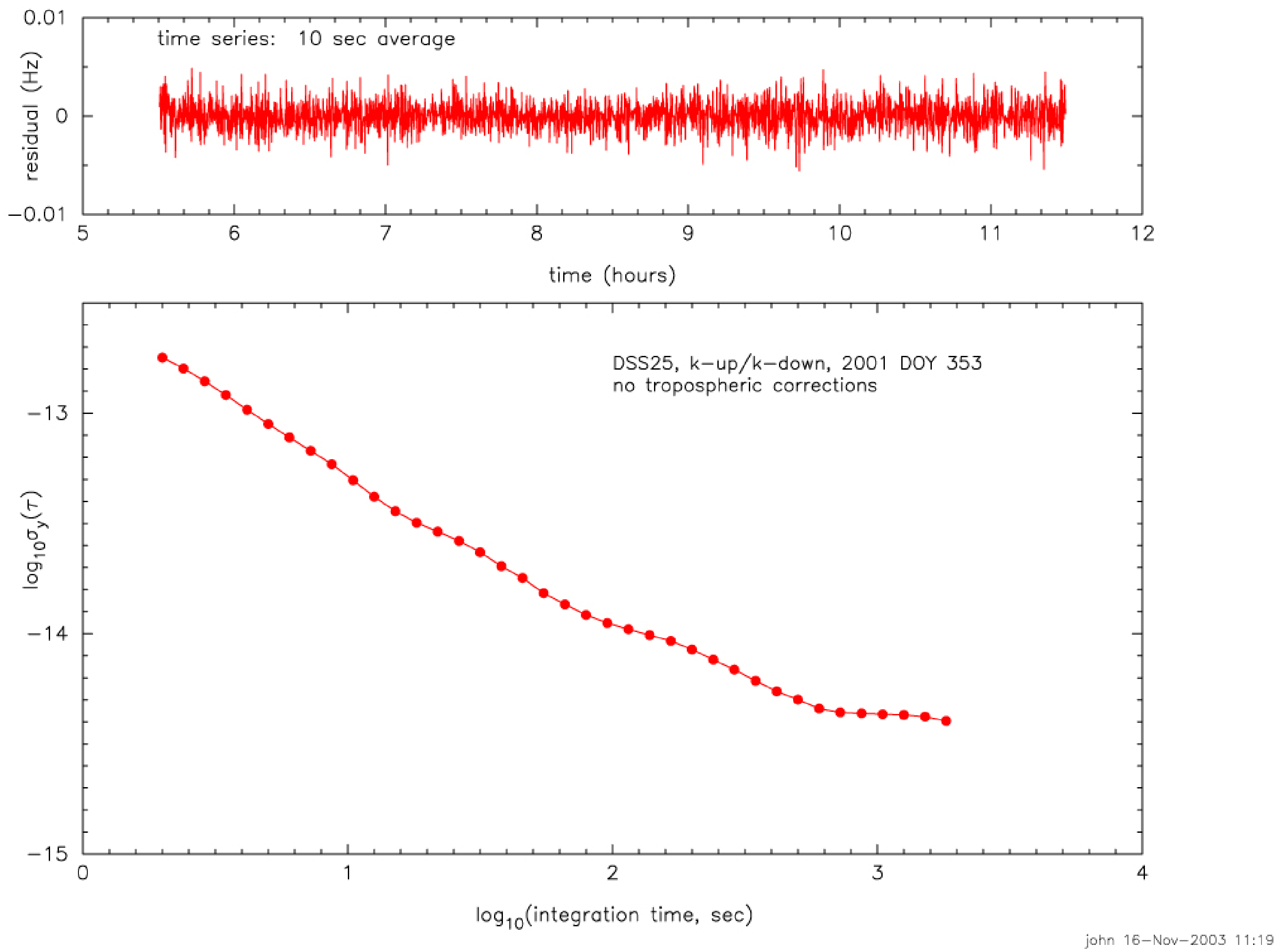
- **Instrumental noises**: random errors introduced by ground or spacecraft
  - phase fluctuations associated with finite signal-to-noise ratio
  - noise due to the ground and spacecraft electronics
  - un-modeled bulk motion of the spacecraft or ground station
  - frequency standard noise
  - the spacecraft oscillator to which the downlink is referenced
  - antenna mechanical noise
- **Propagation noises**: random frequency/phase fluctuations caused by refractive index fluctuations along the line of sight caused by phase scintillation as the radio wave passes through
  - Troposphere
  - Ionosphere
  - solar wind
- **Systematic errors**

Table 1: Representative noise sources and the corresponding Allan deviation

(DSS = 'Deep Space Station" = numeric designation of antenna in the Deep Space Network; CEI = connected element interferometer; AMC = Advanced Media Calibration system)

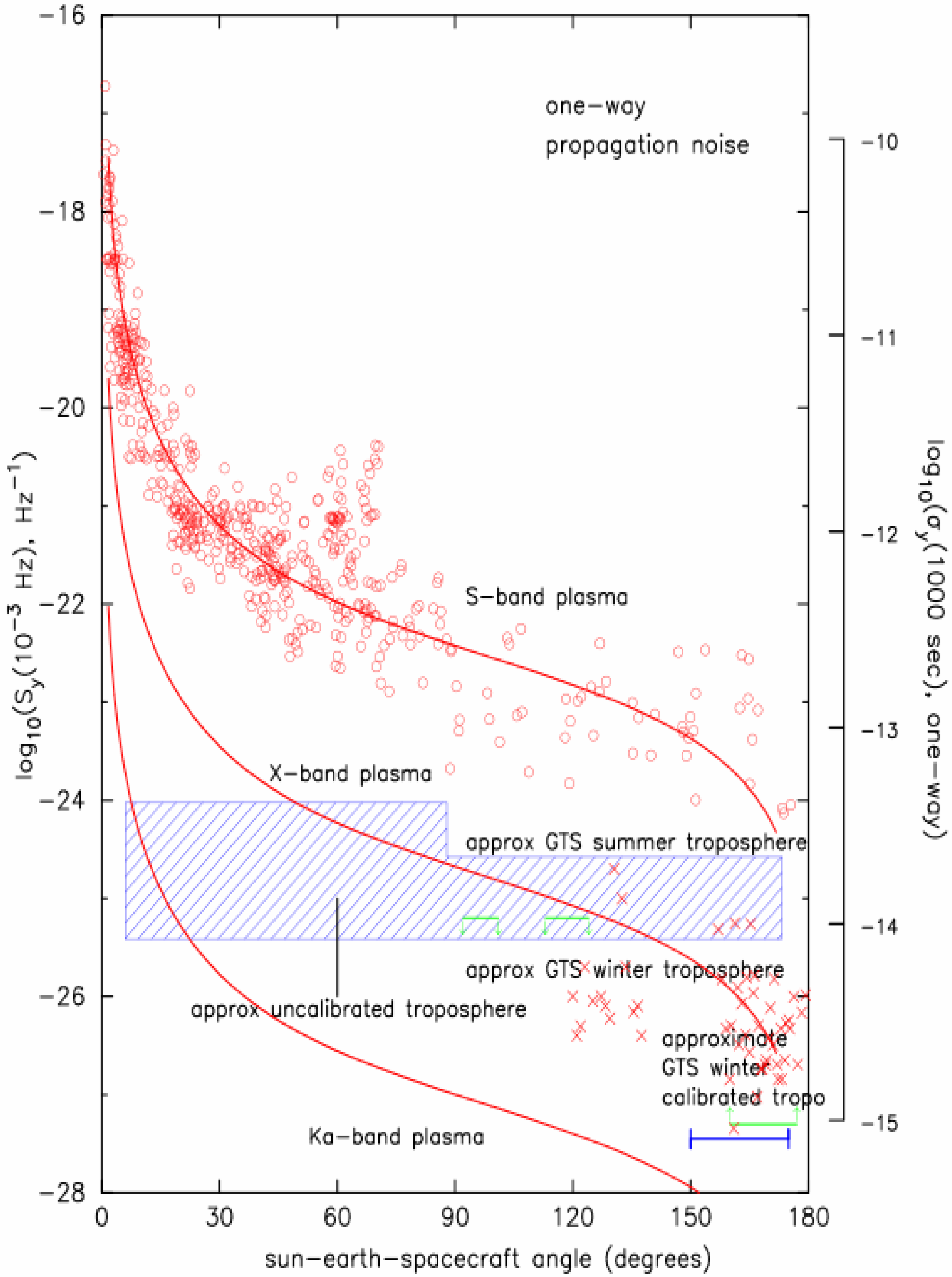
Noise source	Allan deviation at 1000 sec (2-way unless noted)	Comments/references
ground FTS (including distribution)	< 1E-15	• *Kuhnle [1989]*
USO	≈1E-13 (one-way)	• Test data *Asmar [2003]*
antenna mechanical noise	< 4E-15 (favorable conditions)	• DSS-25 measured 3.6E-15 under static conditions at elevation = 47 degrees (*Rochblatt, Richter, and Otoshi [1997]*) • DSS-13 measured <3.1E-15 under static conditions at elevation = 37 and 46 degrees (*Otoshi and Franco [1992]*) • DSS-15, 45, 65 measured <1E-14 under operational conditions with antenna moving (*Armstrong [1998]*) • DSS-25 < 3E-15 for winter/nighttime (*Armstrong et al [2003]*)
ground electronics (excludes FTS)	2.3E-16	• DSS-25 test data with antenna stationary on 2001 days-of-year 152-153 (*Abbate et al. [2003]*)
plasma phase scintillation at Ka-band	<1E-15 for sun-earth-spacecraft angles greater than 160 deg	• *Armstrong, Woo, and Estabrook [1979]* + Figure 2
Cassini spacecraft motion ("buffeting)	2.6E-16	• *Won and Lee [2001]*
thermal noise (finite SNR in the link)	~1E-16 (1000 sec/τ)	• Depends on link SNR and configuration. General formula in *Barnes et al. [1970]* for white phase noise.
Ka-band translator noise (transponder)	< 1.7E-15	• prelaunch tests show ≈1E-16 with –127 dBm signal input level • in-flight determination by L. Iess: < 1.7E-15 using method of *Bertotti, Comoretto, and Iess [1993]* to isolate Ka-band translator
raw tropospheric scintillation	< 3E-15 to 30E-15 (Goldstone winter/night; highly variable)	• *Keihm [1995]; Keihm et al. [2004]* • *Armstrong and Sramek [1982]*
tropospheric scintillation after AMC calibration	< 1.5E-15 (favorable conditions); ≈3.2E-15 (median conditions in AMC/CEI tests)	• *Resch et al. [2002]*, comparing AMC and connected element interferometer (CEI) data; median improvement after applying AMC corrections was factor of 2.8

Example of Cassini Data Quality



Noise Budget

- Characterize contributions to noise from instrumental and natural sources
- Noise in one-way propagation at S-, X-, and Ka-bands as function of angular distance from the Sun
- Plasma scintillation scales with Sun-Earth-Probe (SEP) and radio frequency
- Tropospheric scintillation is independent of RF -- better at night and in winter
- AMC-calibrated troposphere
- Antenna mechanical noise shown at SEP where measured



DSN: Pointing Schemes

- Blind Pointing
- Conscan
- Monopulse
- Aberration Correction

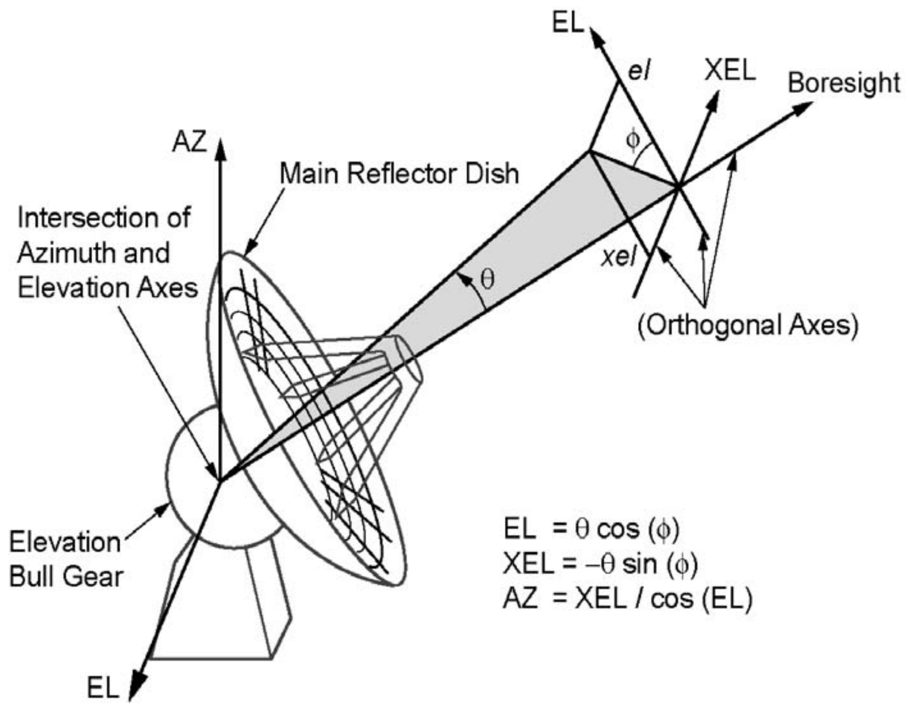


Fig. 8-18. The relationship between the multiple coordinate systems within the monopulse implementation.

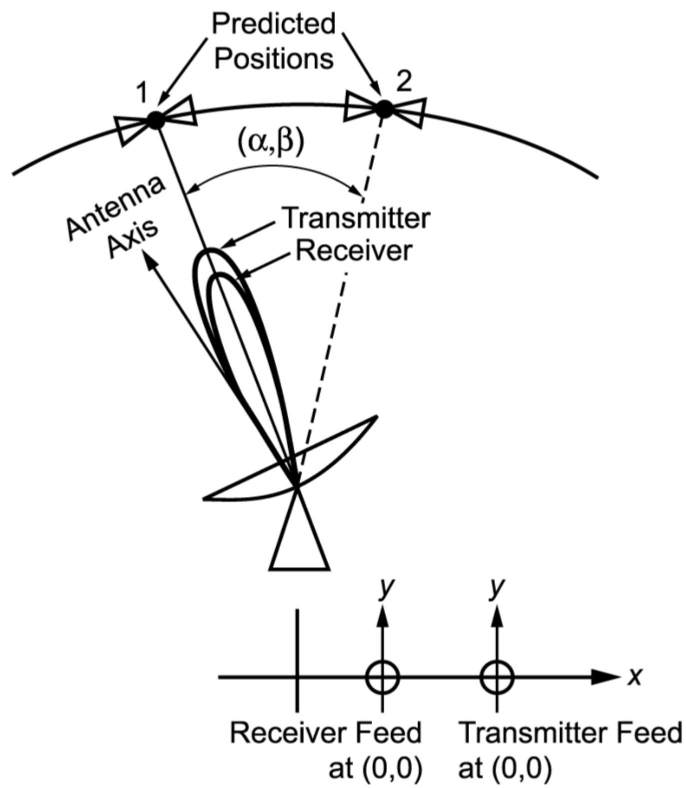
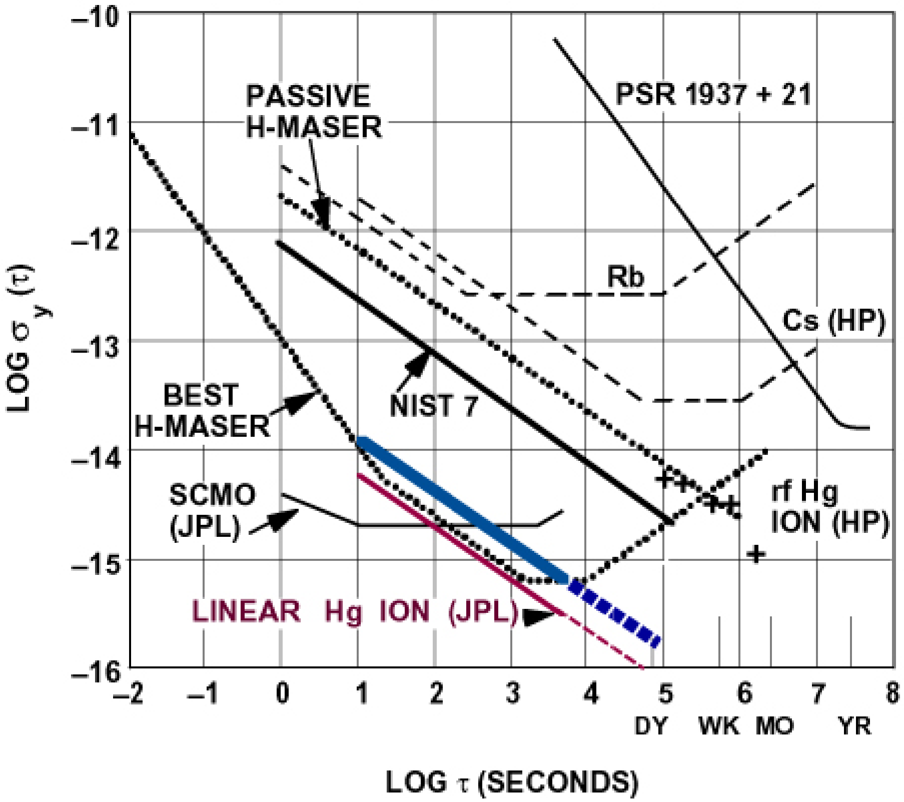


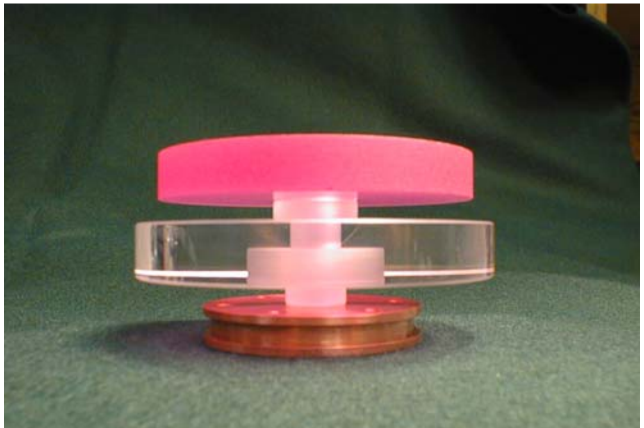
Fig. 8-19. Without antenna-pointing correction for beam aberration.

Source: W. Imbriale, DESCASNO monograph

Timing Is Everything

- High stability frequency and timing reference
  - Hydrogen Maser
  - Superconducting Cavity Maser Oscillator
  - Linear Trapped Ion





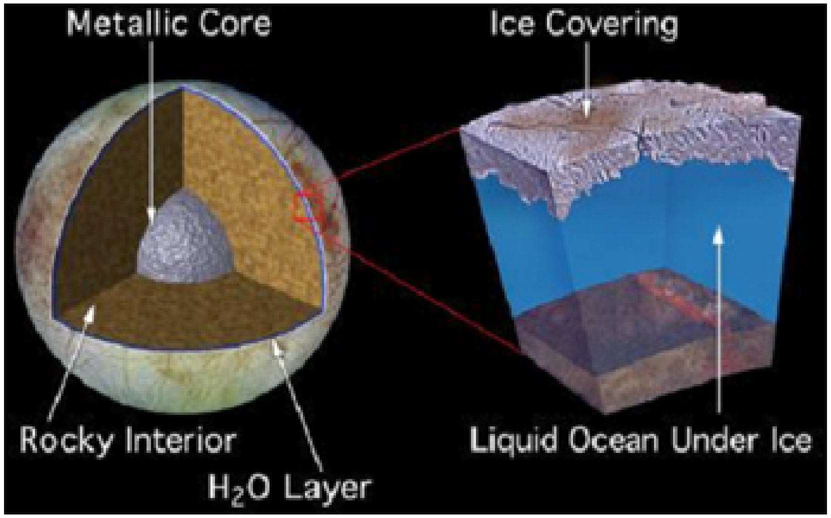
Compensated sapphire oscillator

Advanced Media Calibration

- Advanced Water Vapor Radiometer along with other meteorological systems
- Measures path delay due to Earth troposphere
- Critical to supporting precision experiments at Ka-band
- Remotely operated by *Radio Science Systems Group*
- Results of calibration capability shown here are from Cassini Solar Corona Experiment and Gravitational Wave Experiments with AMC units boresighted with the DSS-25 beam and co-located with DSS-25

Application to Future Missions: Europa Subsurface Ocean?

- Galileo mission indicated possible presence of ice surface with tide-raising forces generating heat to melt underside of the icepack
  - Given the possibility of liquid water, there is the exciting possibility of life
- Presence or absence of a subsurface ocean is of considerable interest
  - Can be resolved with observations including Radio Science data
- A future mission to Europa operating at X-band coherent link, estimate of Doppler accuracy required for ocean detection is 0.1 mm/sec
  - 1 sigma, t = 60 sec, over 3 Europa days (Europa day = 3.55 Earth days)
- Corresponds to 6.7×10^{-13}
- Examine noises



Mission to Explore Subsurface Ocean on Europa

- Interplanetary plasma scintillation noise = 4 X 10^{-13}
  - Assuming Kolmorgrov spectrum scaled to 1000 seconds
- 34-m antenna mechanical noise should be less than this
- Station timing system noise is less than this
- Mission can achieve objective with only X-band link at SEP > 20 deg.
- Tropospheric calibration should not, in this case, be required to meet the specification for a simple detection of the candidate ocean
- Robustness of the mission against large solar events, observational margin, and the possibility of detecting more subtle signals in the data would accrue with
  - multi-link observations
  - tropospheric calibration
- These would be especially important if the mission were of short duration

When this is not good enough

- If requirements for detection turn out to be smaller than 0.1 mm/sec
- If robustness is required against large solar events, observational margin, and the possibility of detecting more subtle signals in the data
- If mission is of short duration
- If mission target body is in the inner solar system
  - E.g., Mercury mission
- We demonstrate from Cassini experience the requirements for
  - Multi-link observations
  - Tropospheric calibration

Long Term Goals and Future Directions

- Improve clock stability (spacecraft & ground stations)
- Apply multi-frequency links (spacecraft & ground stations)
- Next generation media calibration systems
- Design stable & quiet modes for precision Doppler
- Dual-polarization receiving systems
- Advance technology for quiet and precisely pointed spacecraft
- Advance technology for spacecraft-to-spacecraft links

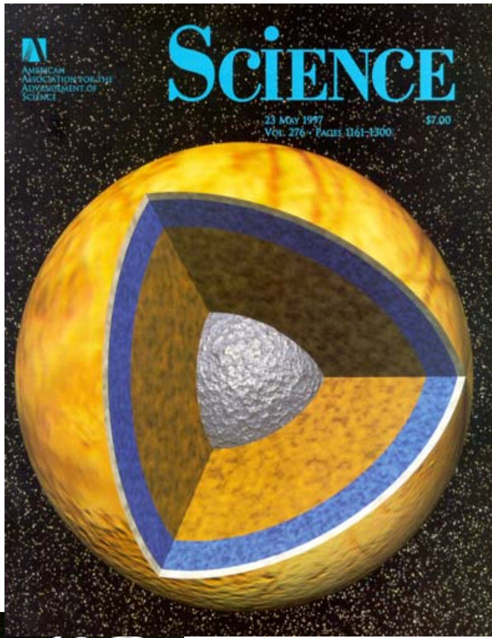
Order of Magnitude Improvement in Doppler & Range

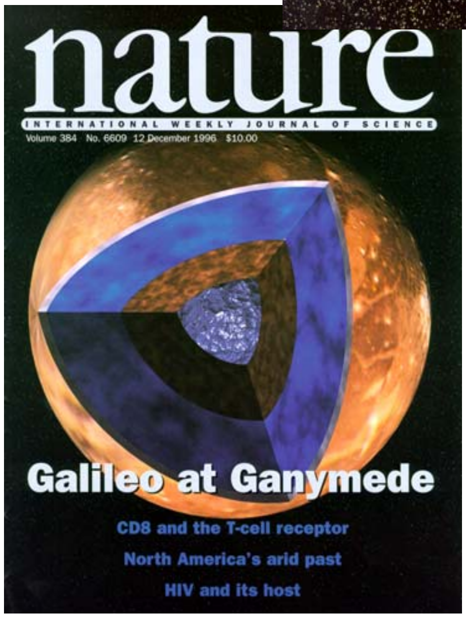
- Advance planetary interior studies
- Improve precision tests of relativity and gravitational waves
- Advance planetary atmospheric occultation
- Improve navigation
- Improve engineering applications

Future Directions

- Uplink Radio Science
- Optical Science
- Station Arrays

Conclusion





- Cassini & DSN hold “record” for deep-space Doppler sensitivity ≈ 500 nanometers/sec under favorable conditions)
- Based on noise transfer functions and (in some cases) independent tests, the aggregate Doppler noise can be decomposed into FTS, plasma, troposphere, antenna mechanical, etc. to create a noise budget
- This budget can be used for
  - Error model of Doppler observations
  - Prediction of noise in future observations/specification of required configuration for a given required sensitivity
- http://***radioscience.jpl.nasa.gov***