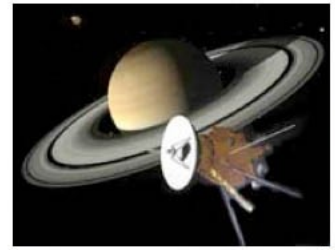
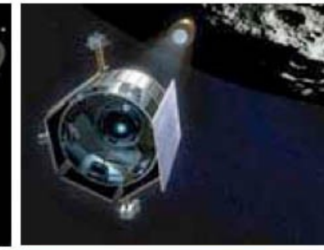
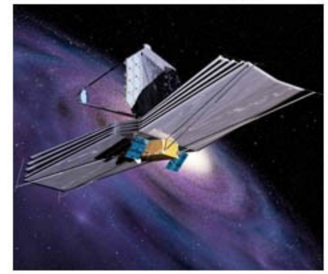
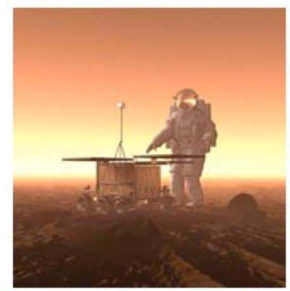
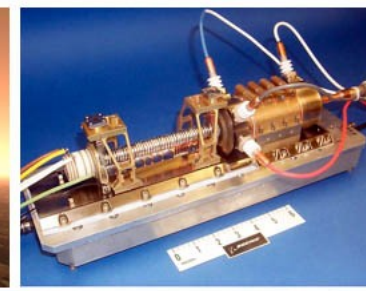
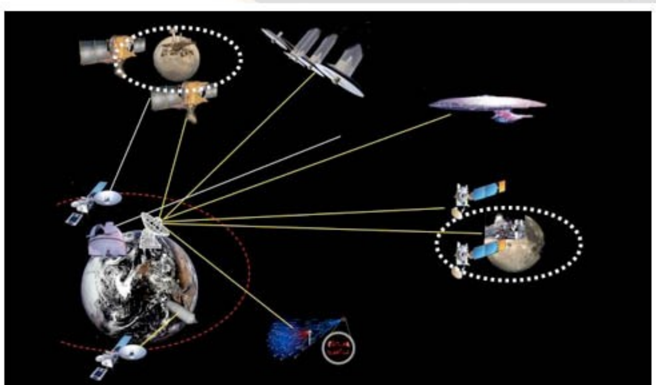
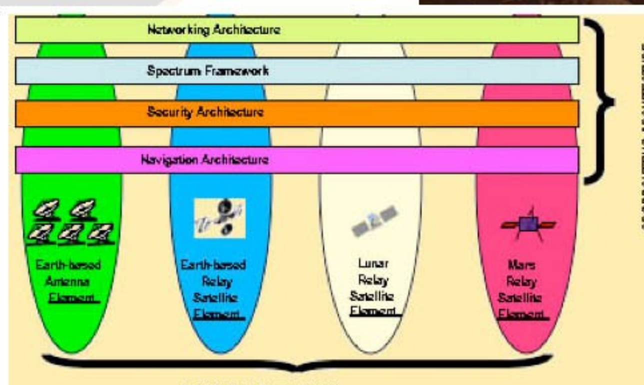
Deep Space Communication*

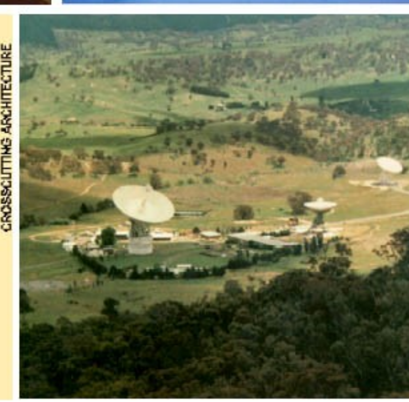




Farzin Manshadi
JPL Spectrum Manager
September 20-21, 2012

* Based on Material provided by Dr. Les Deutsch



Introduction

- ITU defines deep space as the volume of Space at distances from the Earth equal to, or greater than, 2×10^6 km
- Deep Space Spacecraft have to travel tens of millions of km from Earth to reach the nearest object in deep space
- Spacecraft mass and power are precious
- Large ground-based antennas and very high power transmitters are needed to overcome large space loss and spacecraft's small antennas and low power transmitters
- Navigation is complex and highly dependent on measurements from the Earth
- Every deep space mission is unique and therefore very costly to develop

Spacecraft Mass and Power are Precious

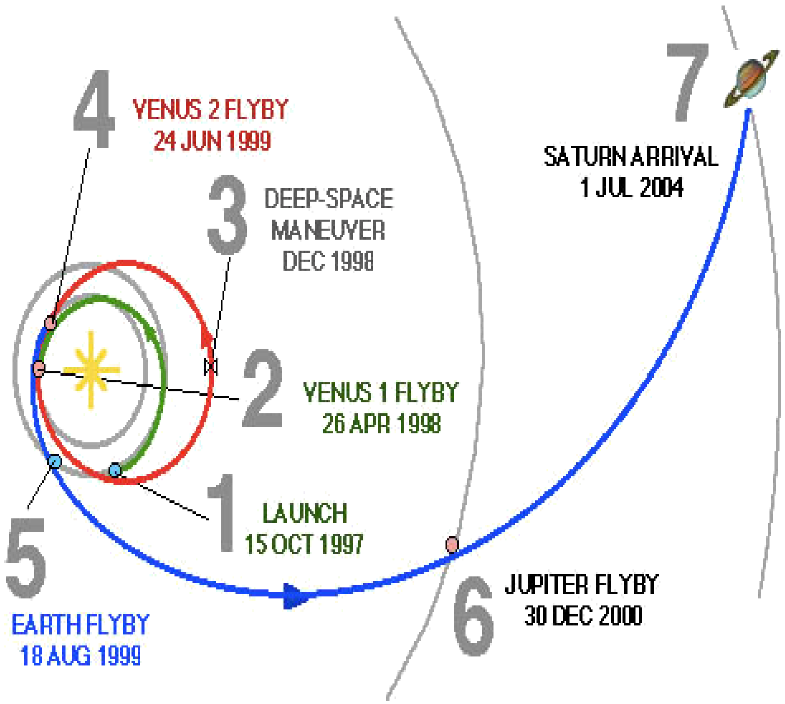
- Deep space missions must leave Earth's gravity – very difficult
  - An Atlas V 551 can lift about 19,000 kg to low Earth orbit but only ~500 kg to deep space
- Power generation is very difficult for a spacecraft far from the sun
  - Solar flux goes down by a factor of four each time the distance from the Sun doubles, so a solar panel at Jupiter can only generate a billionth the power as at Earth
  - Nuclear-based generators are both expensive and politically sensitive

Spacecraft Mass and Power are Precious-Consequence

- **Deep space spacecraft look like giant antennas with Instruments attached**
  - **Cannot afford high power**
  - **Transmitters typically tens of Watts**

- **Trajectories are optimized for lowest propellant consumption**
  - **Demands on navigation are extreme**
  - **Lots of critical events**
  - **Very minor mistakes can lead to mission failure**

Spacecraft Mass and Power are Precious-Example Cassini



Cassini "cruise" trajectory:

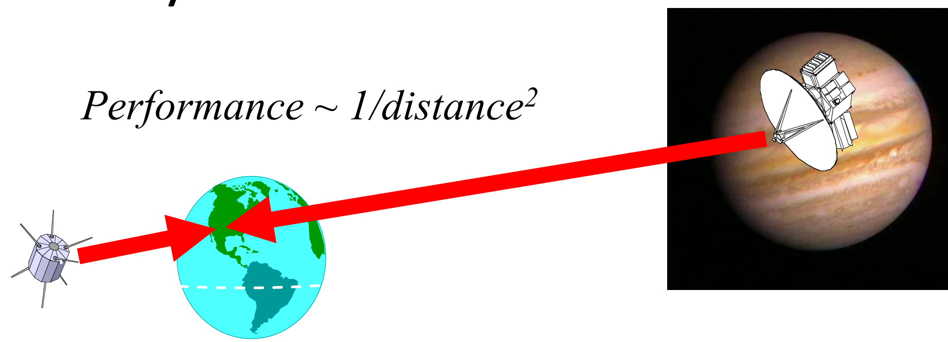
- **Multiple "swing-bys" generated "gravity assists" to save propellant**

Spacecraft Travel Very Long Distances from Earth

- **Communications performance is inversely proportional to distance squared**
- **Deep space ground antennas are very large**
- **System cannot waste any dBs!**
- **Spacecraft must be autonomous**

Why Telecom is Hard

Performance ~ 1/distance^2

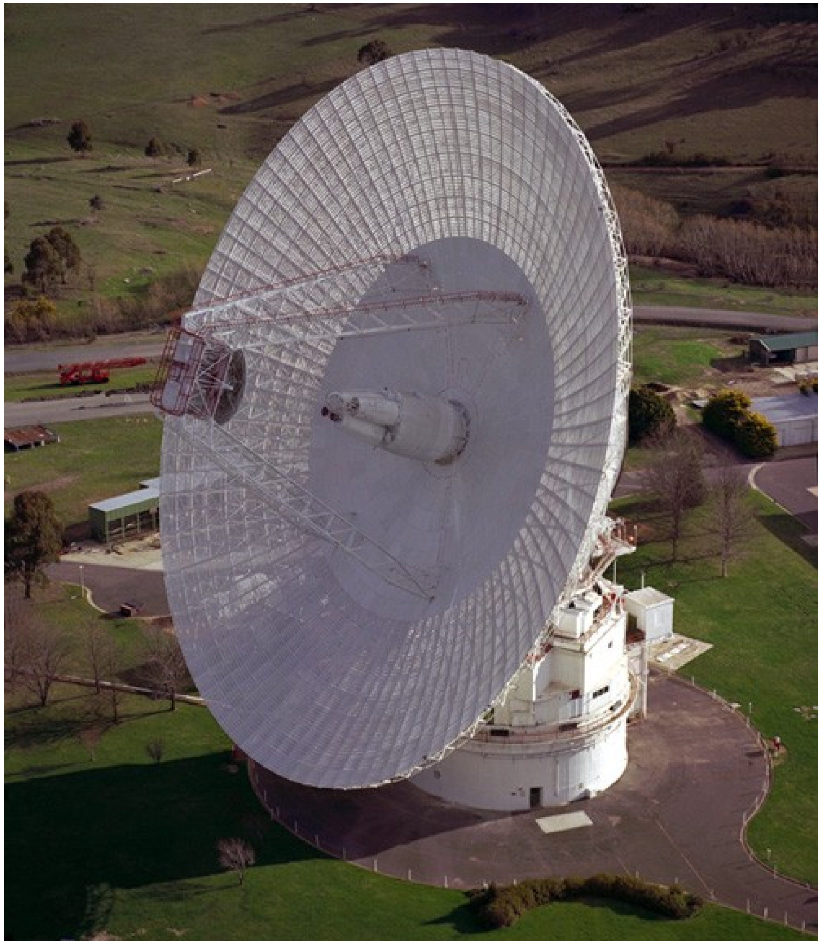


Relative Difficulty

Place	*Distance*	*Difficulty*
Geo	*4x10*^{4} *km*	*Baseline*
Moon	*4x10*^{5} *km*	*100*
Mars	*3x10*^{8} *km*	*5.6x10*^{7}
Jupiter	*8x10*^{8} *km*	*4.0x10*^{8}
Pluto	*5x10*^{9} *km*	*1.6x10*^{10}

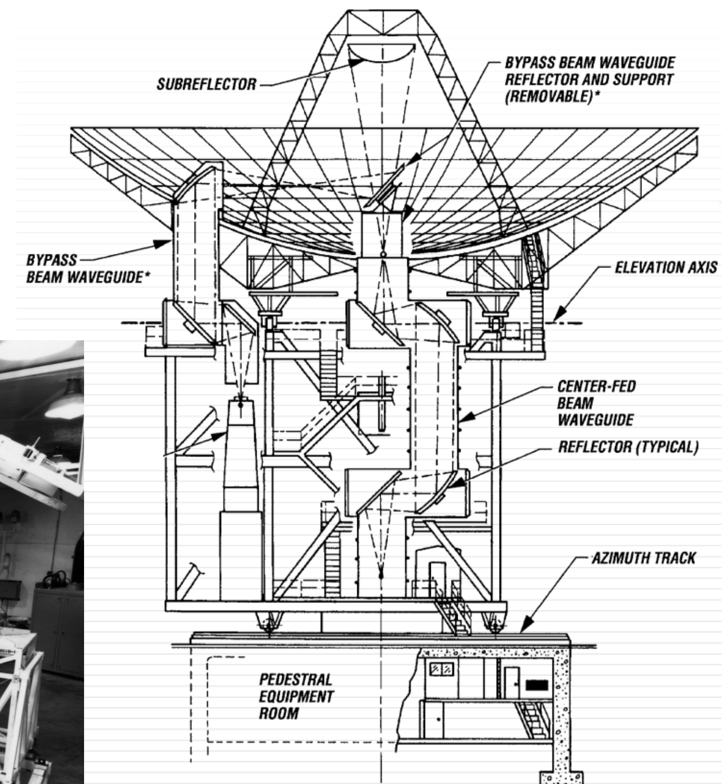
Spacecraft Travel Very Long Distances from Earth- Consequence

- **Very large ground antennas are needed to compensated the space loss**
- **Example: NASA's Deep Space Network 70m antennas**
  - **largest steerable communication antennas in the world**
  - **Each has a 20 KW transmitter for communication with deep space spacecraft**



Other Antenna Designs for Deep Space Communications

- **34m class Beam Waveguide Antenna is today's standard for deep space communication**
  - **Electronics in basement lab environment**
    - **Signal is transmitted or received through a system of mirrors**
  - **Easy to update**
  - **Easy to service**
  - **Safer to operate**



Deep Space Communication Must be Very Efficient

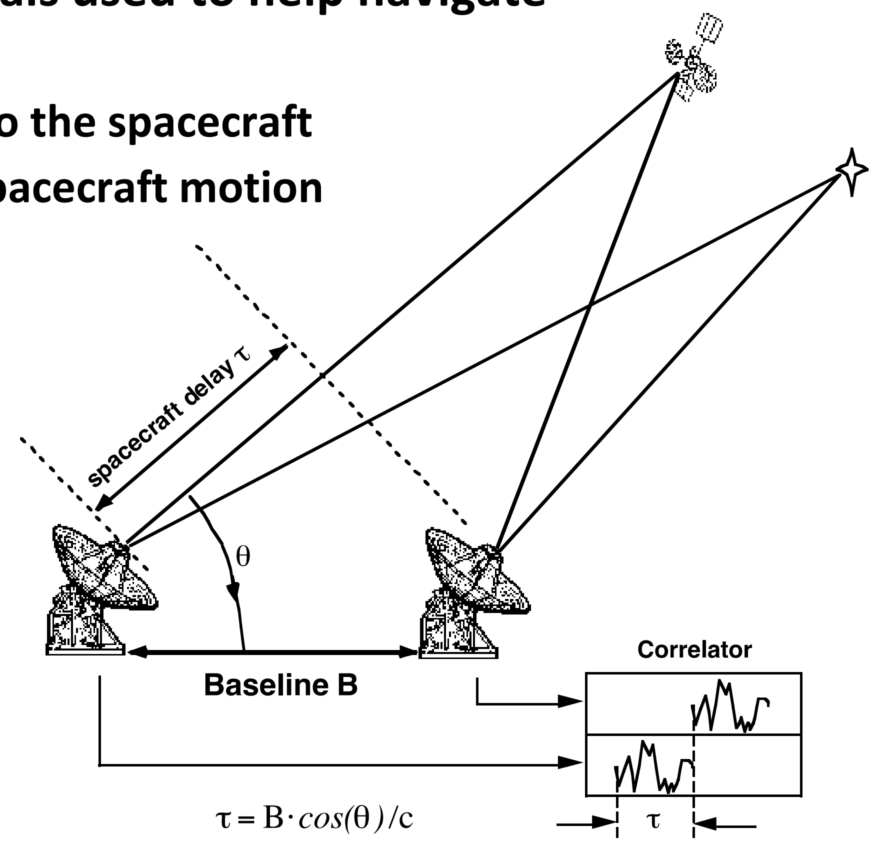
- Cannot waste a fraction of dB of performance
- Deep space missions operate close to theoretical communications efficiency limit (within 1 dB, typically)
- Example: If a spacecraft designed to work with a 70-m antenna lost a dB of performance it would take an additional 32-m antenna to make up the difference!
  - Cost for three 32m antennas = ~$100M!

Deep Space Spacecraft Must be Autonomous

- It can take minutes to many hours for signals to travel between a deep space spacecraft and Earth
- Decisions must often be made faster than this – requiring spacecraft autonomy
- Spacecraft are usually "sequenced", meaning they are programmed to operate for long periods without commands from Earth
- Spacecraft manage the data they acquire, storing it until it can be sent back to Earth
- Emergencies require special "safing" algorithms

Navigation Is Complex and Highly Dependent on Earth

- Precise measurements of the radio signals used to help navigate spacecraft
  - Ranging: measurement of the distance to the spacecraft
  - Doppler: measurement of the relative spacecraft motion
  - Interferometric techniques: using multiple ground antennas to measure precise spacecraft angle on the sky
- Beyond GPS orbit, these are the best source of navigation data
- Usually augmented by on-board spacecraft sensors
  - Gyroscopes
  - Star and sun sensors
  - Spacecraft photos of targets against stellar background



An interferometric technique, ΔDOR: delta differenced one-way ranging

Every Deep Space Mission is Unique

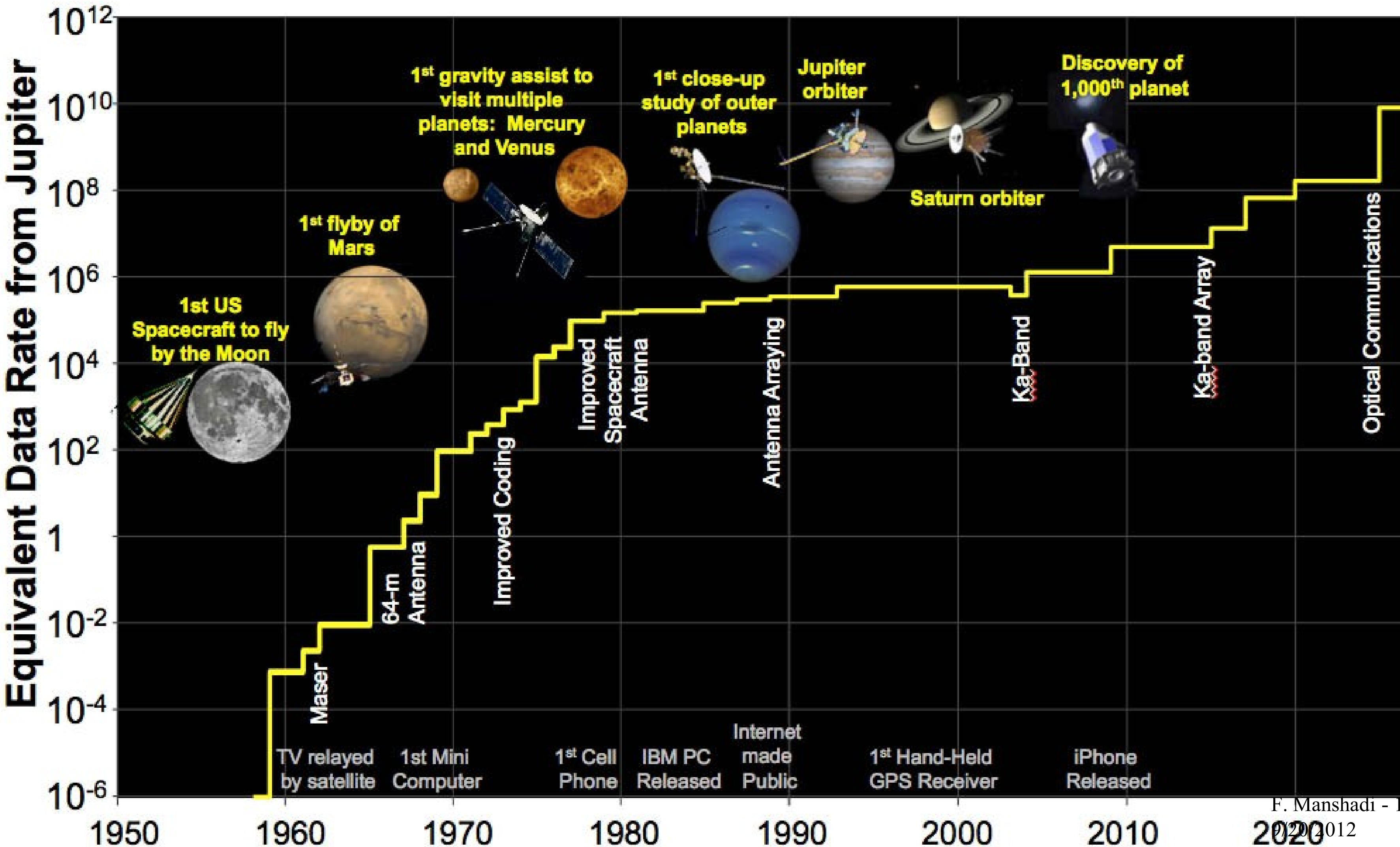
- There are a myriad of deep space targets: planets, moons, asteroids, comets, and parking spaces for astronomical observatories - each with their own
  - Set of scientific questions
  - Unique trajectory challenges
  - Unique spacecraft bus, instruments, and propulsion
- Even popular targets (e.g. Mars) are visited only every few years, with differing spacecraft
- Communications and navigation can be different for each mission
  - Often requires special studies to optimize performance and maximize success
- New technology is often infused in both the spacecraft and the ground network – creating something new for every mission

Radio Science

- Tracking spacecraft near or behind targets yields important science
- Atmospheric dynamics
  - Circulation
  - Vertical structure
  - Turbulence
- Atmospheric density
- Gravity field mapping

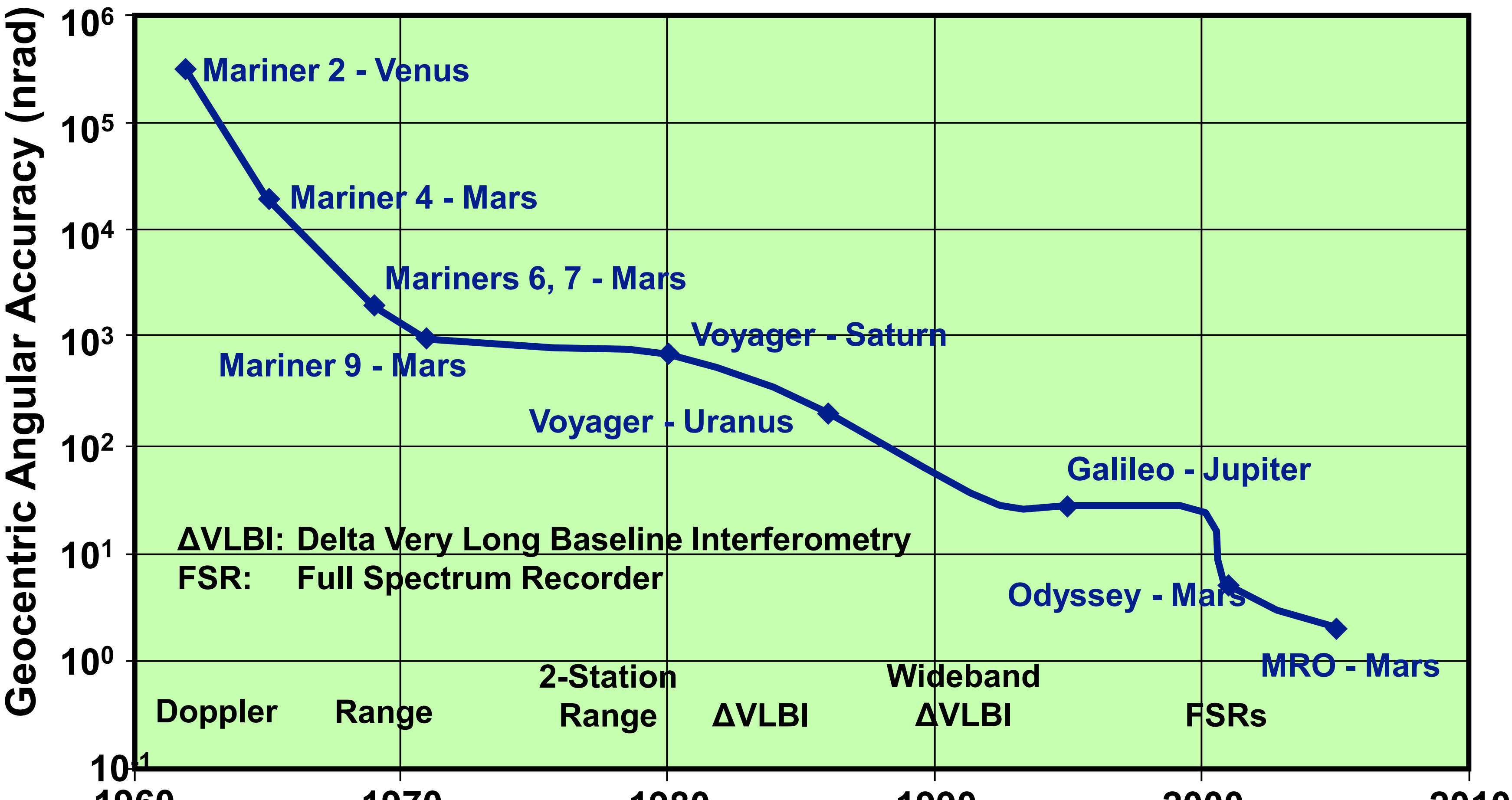
Deep Space Communication

Trends in Deep Space Communications and Navigation (Data Rate)



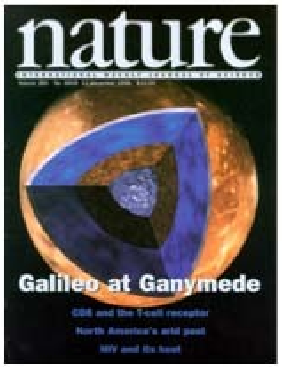
Deep Space Communication

Trends in Deep Space Communications and Navigation (Angular Tracking)

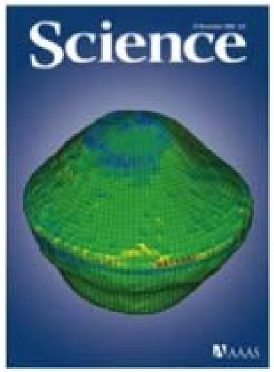


The Impact of Deep Space Science

Deep Space science has provided a continuing torrent of forefront discoveries – many high impact papers and mission investigators



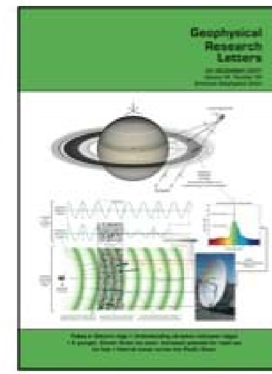
Interior of Ganymede



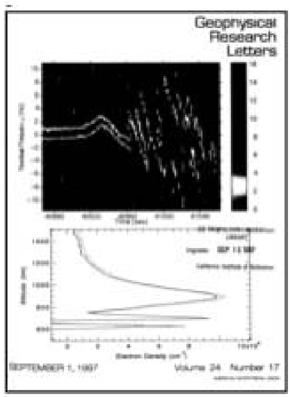
Asteroids in 3-D

Oceans on Europa?

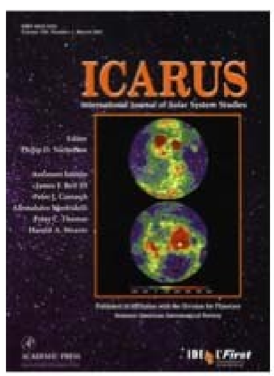
Mercury Liquid Core



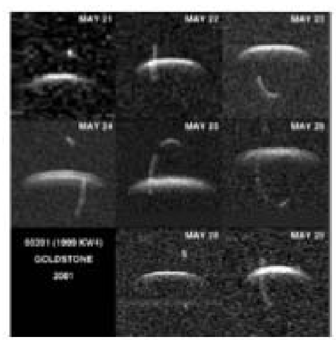
Saturn's Rings



Mars Ionosphere



Moon Gravity Field

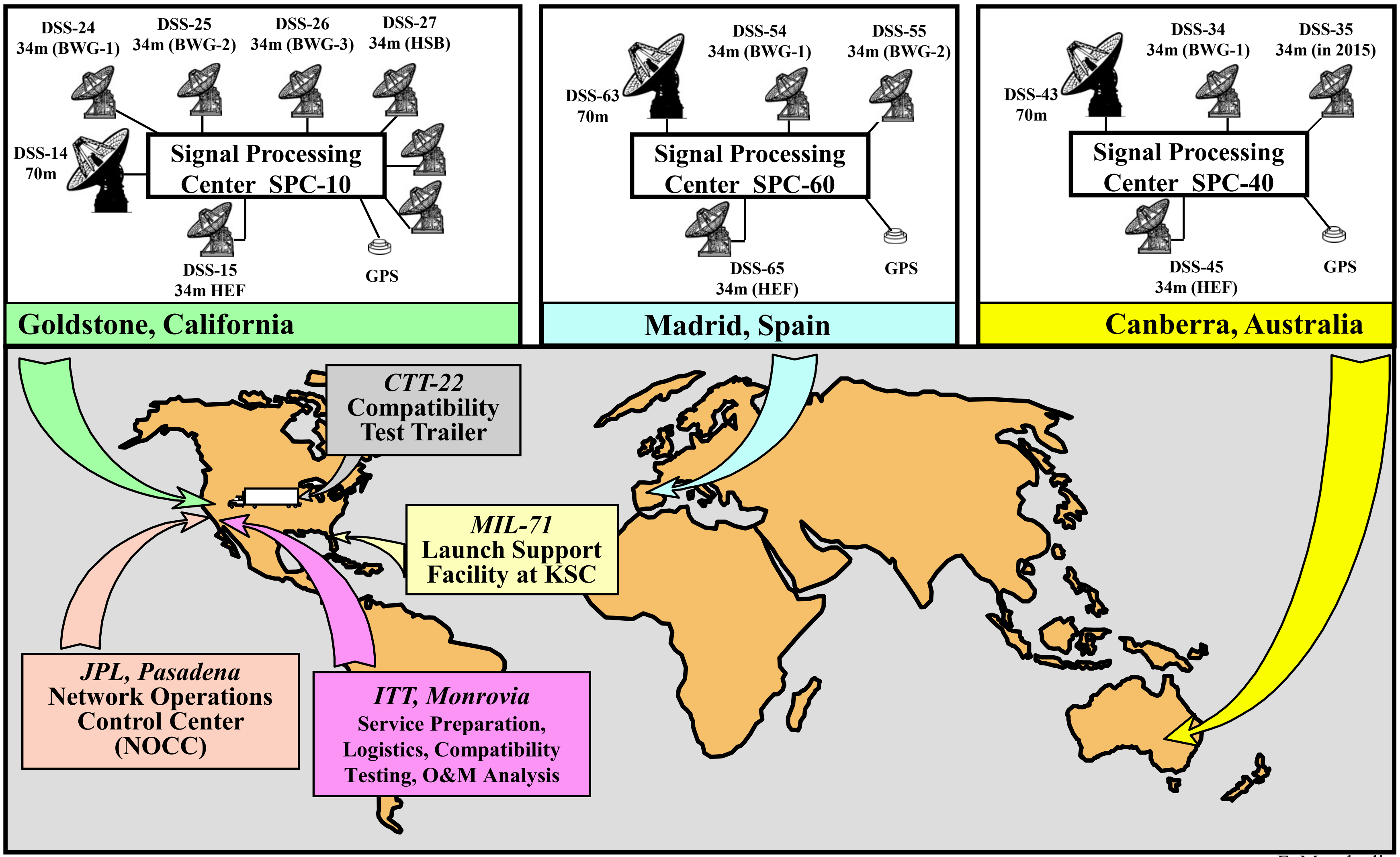


Binary Asteroids

Student Study of Juptier Radio Emission

Saturn's Rings

NASA's Deep Space Communication (DSN) Network



DSN Antennas in Madrid, Spain

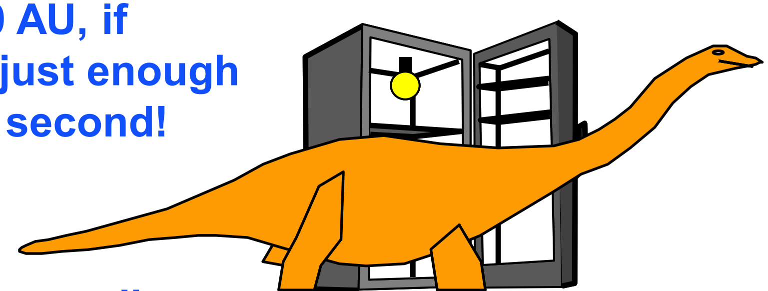
Deep Space Communication

Some Amazing DSN Facts

Received Signal Sensitivity:

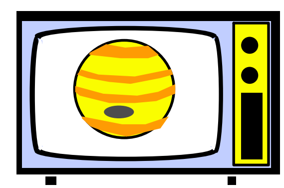
The received energy from Voyager at 100 AU, if integrated for 10 trillion years, would be just enough to power a refrigerator light bulb for one second!

Received power = 6.3×10^{-19} W



Command Power:

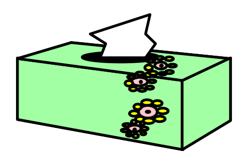
The DSN puts out enough power in commanding Voyager that it could easily provide high quality commercial TV at Jupiter!



Transmitted power = 400 kW

Dynamic Range of the DSN:

The ratio of the received signal power to the DSN transmitting power is like comparing the thickness of a sheet of tissue paper to the entire Earth!



Ratio = 10^{27}

Reference Clock Stabilities:

The clocks used in the DSN are so stable that they would drift only about 5 minutes if operated over the age of the universe! 1 part in 10^{15}