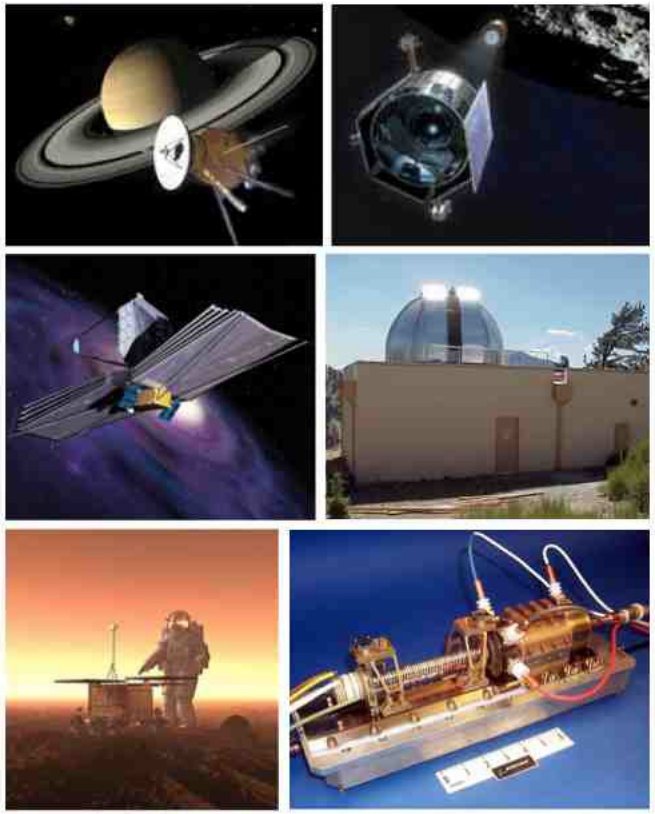
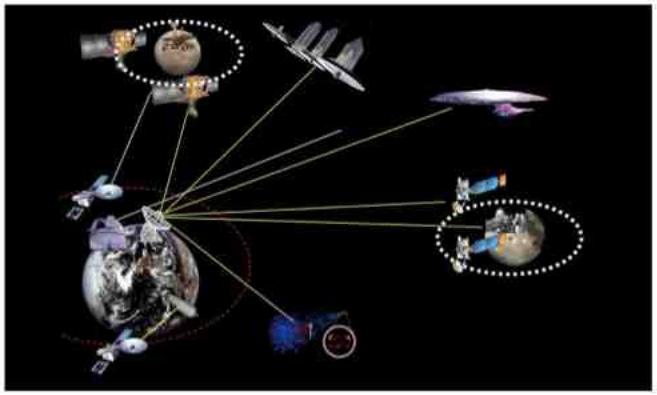
Jet Propulsion Laboratory
California Institute of Technology

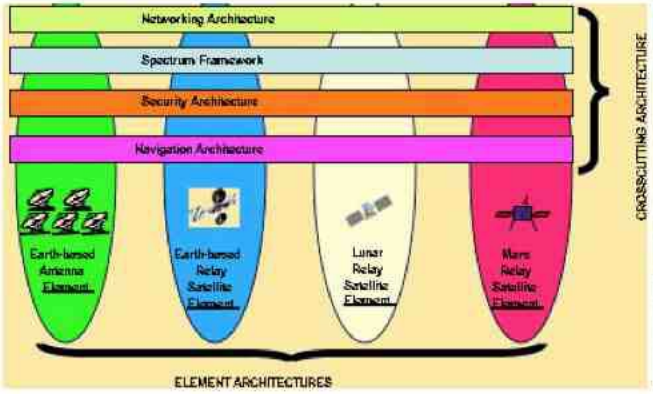
NASA's Deep Space Network: *Big Antennas with a Big Job*



Dr. Les Deutsch
Interplanetary Network Chief Technologist
Jet Propulsion Laboratory
California Institute of Technology

June 28, 2012





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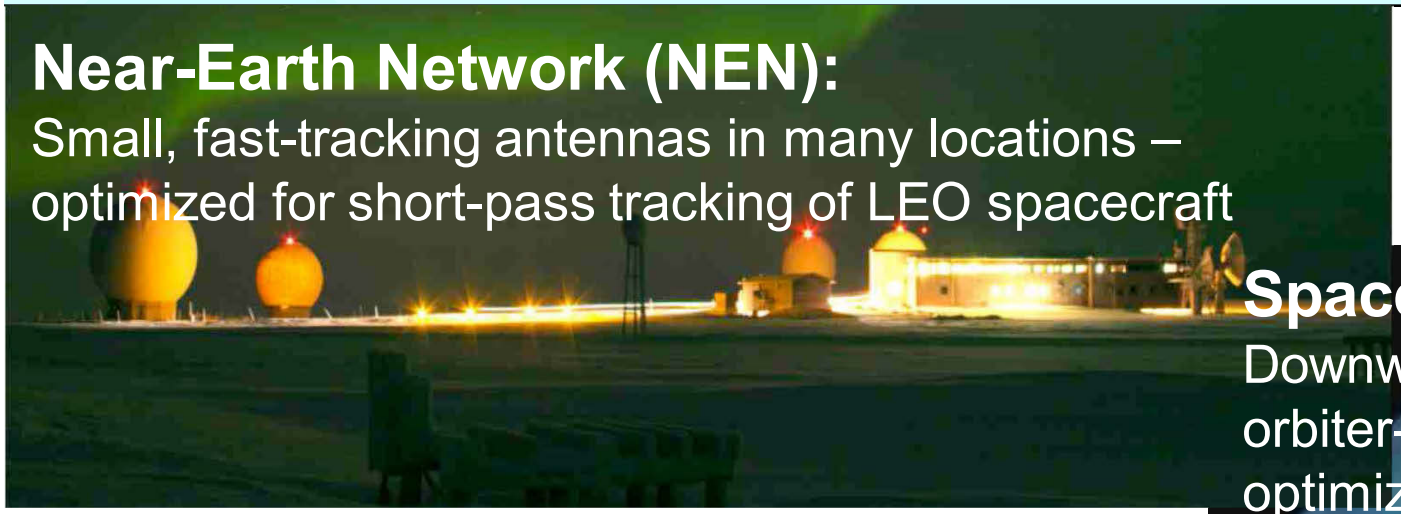
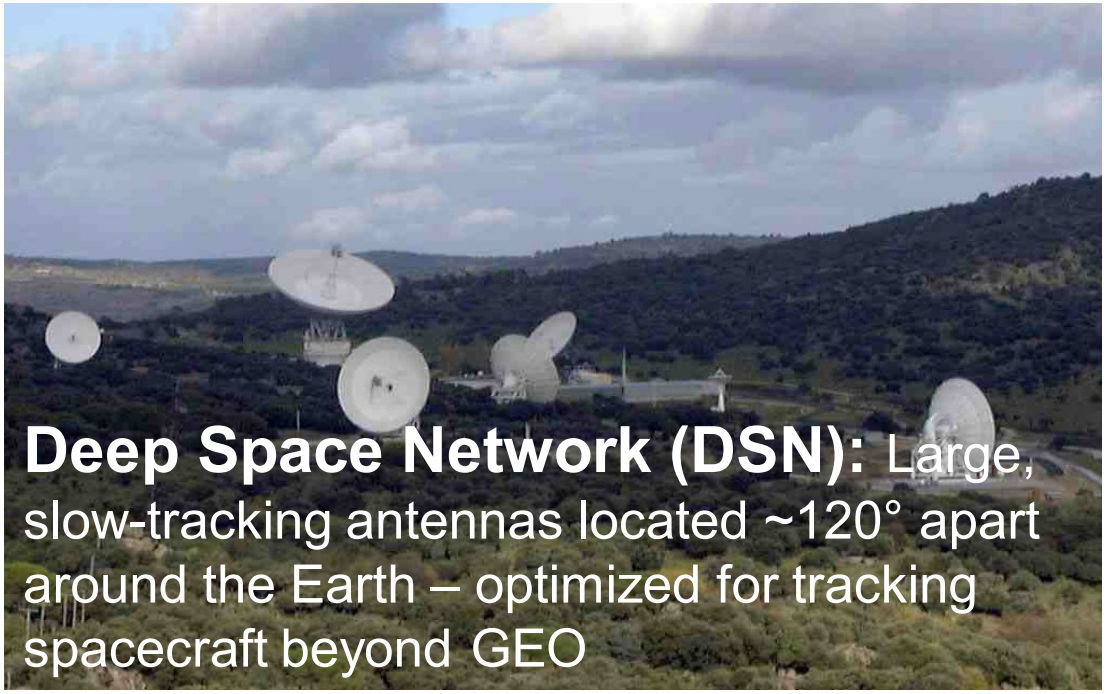
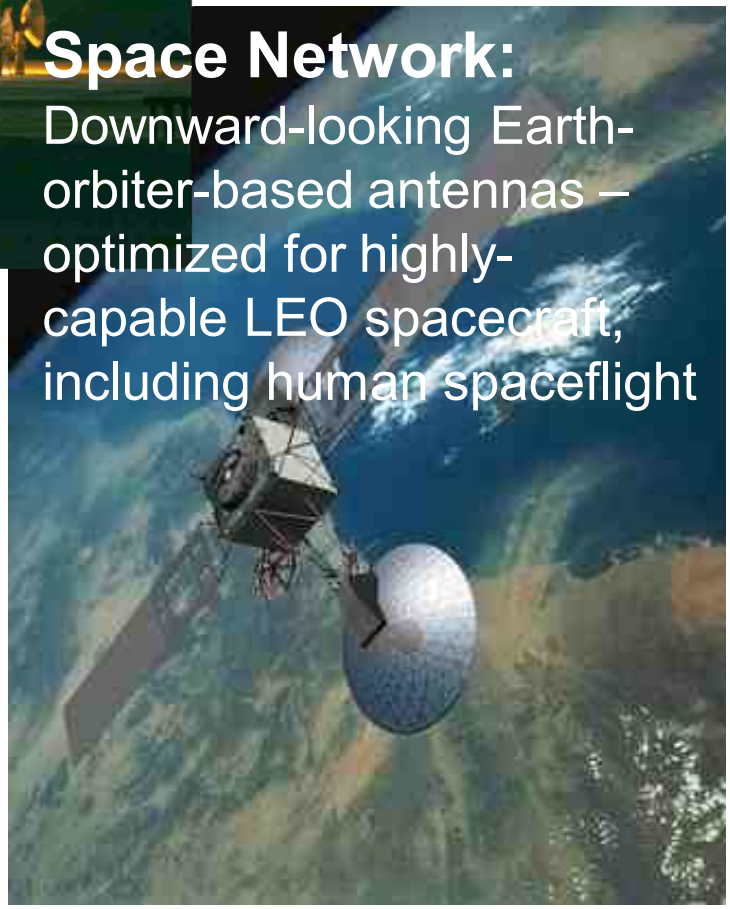
NASA Networks *at a Glance*



Near-Earth Network (NEN):
Small, fast-tracking antennas in many locations – optimized for short-pass tracking of LEO spacecraft

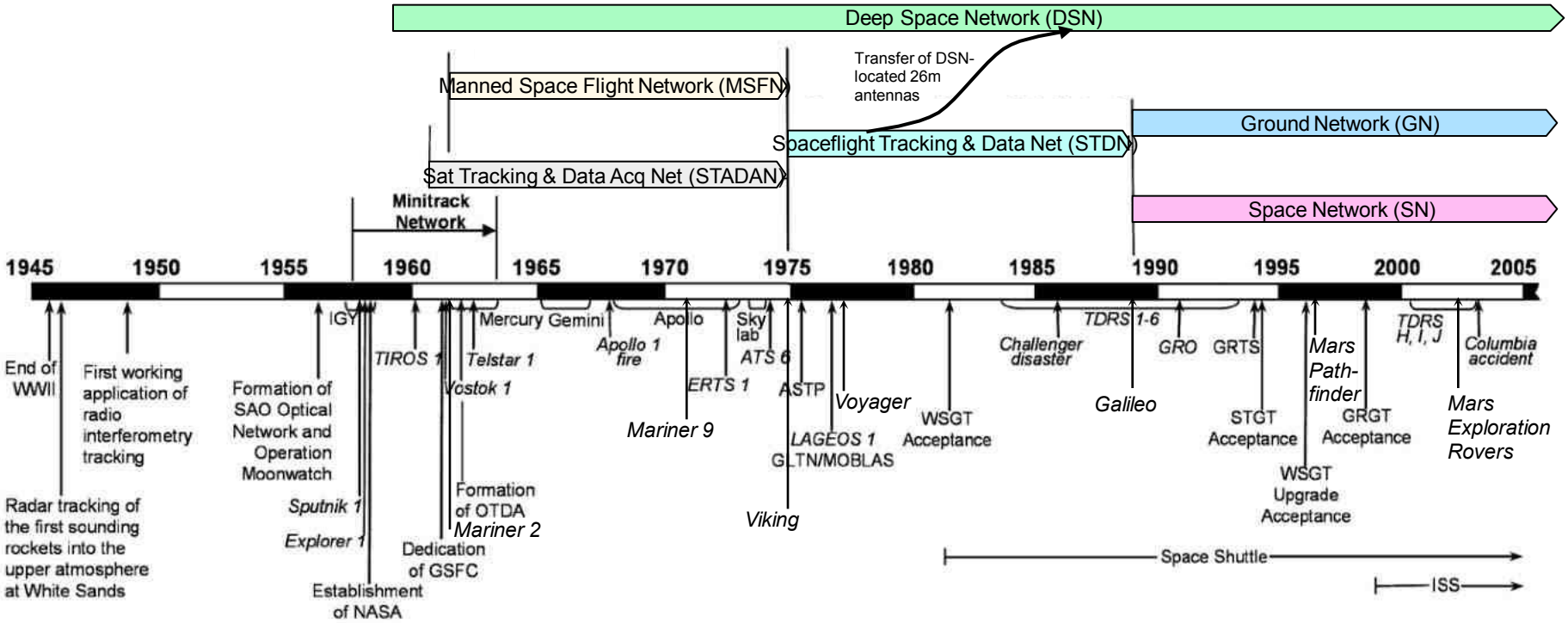


Deep Space Network (DSN): Large, slow-tracking antennas located ~120° apart around the Earth – optimized for tracking spacecraft beyond GEO



Space Network:
Downward-looking Earth-orbiter-based antennas – optimized for highly-capable LEO spacecraft, including human spaceflight

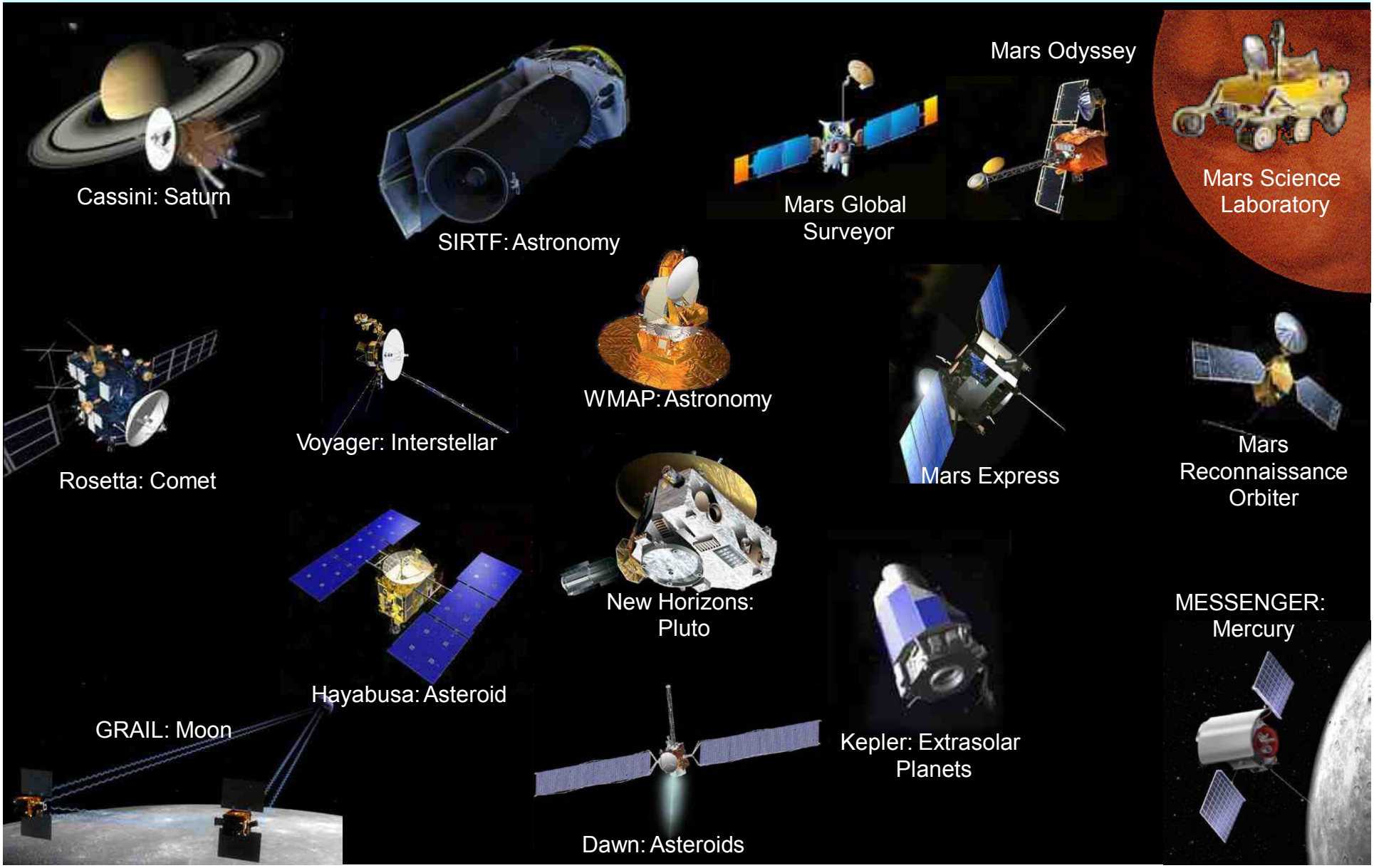
NASA Network History



*There was a name change from "Mercury" to "Manned" at the conclusion of Project Mercury

From ″Hear You Loud and Clear″ by Sonny Tsiao

Some Current Deep Space Missions



Deep Space is Unique

- Spacecraft mass and power are precious
- Spacecraft go huge distances from Earth
- Navigation is highly dependent on Earth
- DSN is a mission science instrument
- Every mission is unique

Spacecraft mass and power are precious

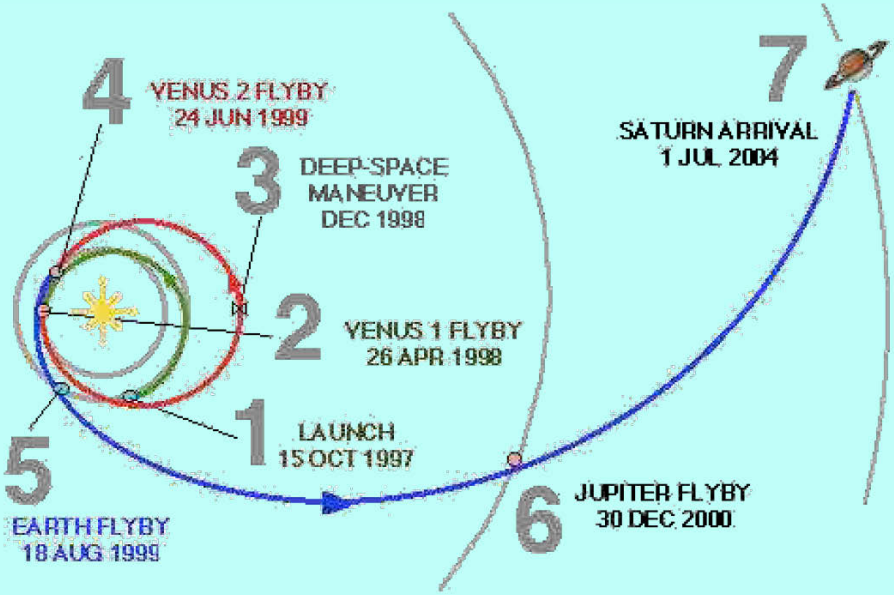
Spacecraft Mass & Power are Precious

- **Deep space missions must leave Earth's gravity well – very difficult**
  - **An Atlas V 551 can lift about 19,000 kg to LEO 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 times 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**

Mass and Power: Consequences

- **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 mission failure**

Example: Cassini Navigation

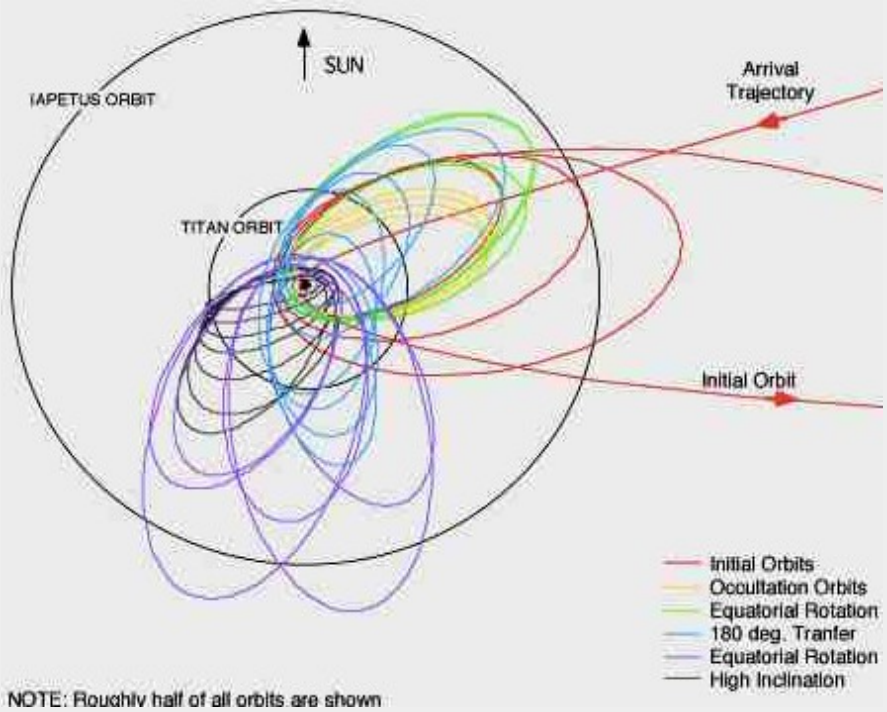


Cassini ″cruise″ trajectory:

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

Cassini ″tour″ trajectory:

- **Multiple moon ″encounters″ Each sets up the next**
- **Propellant used only at critical times between encounters**



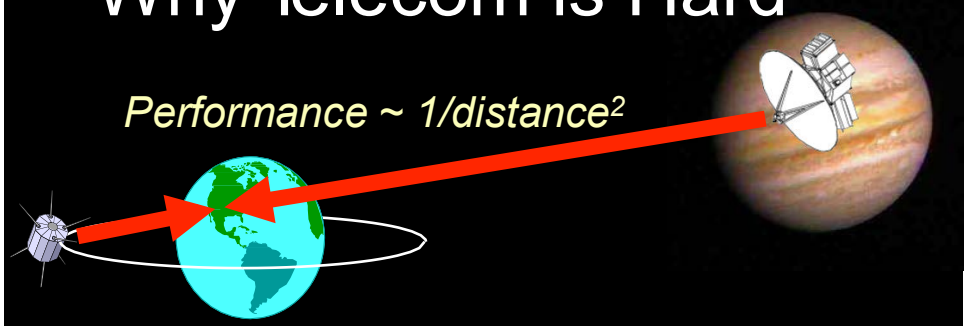
Spacecraft go huge distances from Earth

Spacecraft Go a Huge Distance

- **Communications performance is inversely proportional to distance squared**
- **DSN has huge antennas**
- **System cannot waste any dBs!**
- **Spacecraft must be autonomous**

Why Telecom is Hard

Performance ~ 1/distance^2

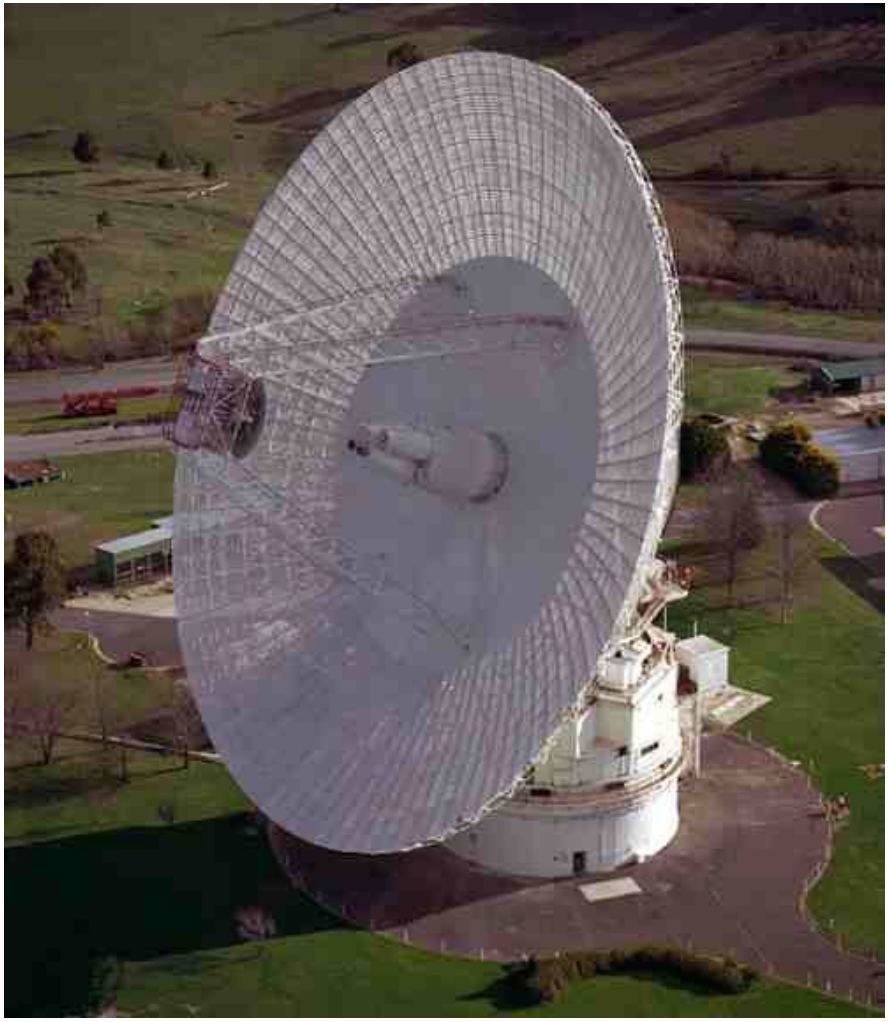


Relative Difficulty

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*	*$1.6x10^{10}$*

DSN has Huge Antennas

- **This is what people recognize most about the DSN**
- **DSN's 70m antennas are the largest steerable communication antennas in the world**
- **Each has a 20 KW transmitter**



But What Kind of Antennas?

- ″Antennas″ are simply telescopes for radio
- Most early powerful telescopes used ″equatorial″ or ″hour-angle/declination″ (ha/dec) design
  - ″Tilt″ is set to compensate for latitude
  - Simple drive then tracks objects in celestial sphere
- Design is elegant
  - Good for high-speed tracking
  - Minimizes ″zone of exclusion″ (ZOE) around zenith

Echo: The First DSN Antenna

This 26m antenna was constructed at Goldstone in support of the US Echo Satellite program – the first communications satellites

Early DSN Antennas

- **The first DSN antennas used equatorial mounts**
- **When the STDN closed, its three DSN-colocated 26m equatorial antennas became DSN antennas**

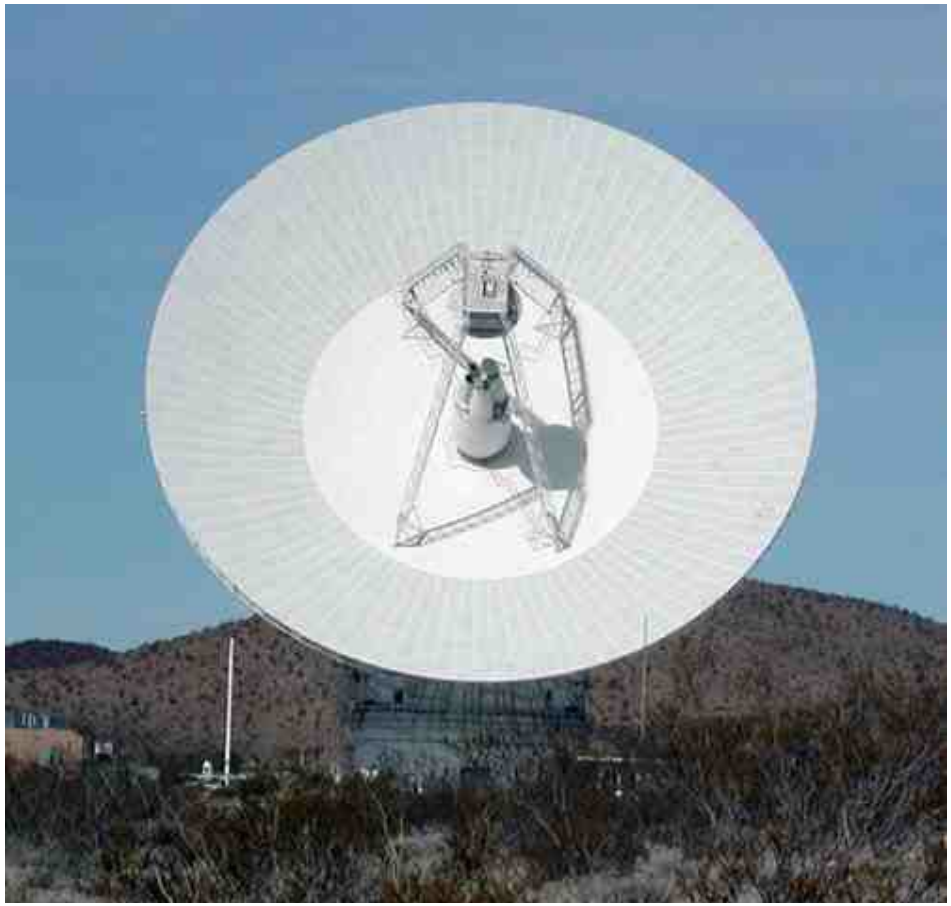
DSS-12 at Goldstone, a 34m Equatorial Mount Antenna

Azimuth/Elevation Antennas

- **Many modern telescopes use an ″Azimuth/ Elevation″ or ″Az/El″ mount**
  - **Bottom of telescope rotates parallel to the ground**
- **This is a simpler, less expensive design**
- **Modern computer control systems have made this pervasive in recent years**
- **However, these suffer from ZOE problems**
  - **Not important for deep space tracking, but critical for LEO tracking**

DSN Antennas Are Mostly Az/El

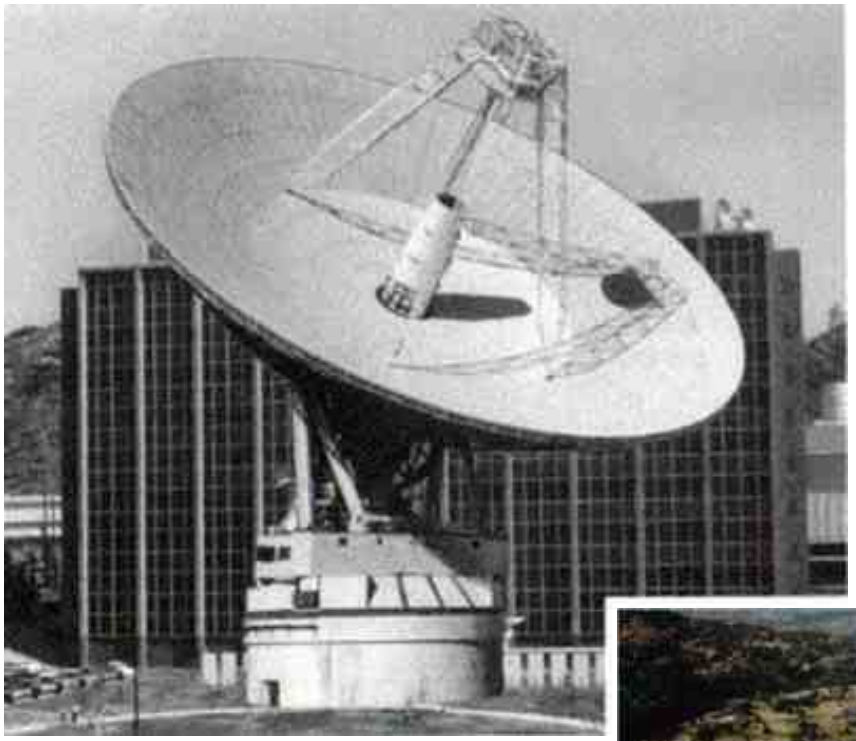
- **All DSN antennas built since the 70m's are Az/El**



DSS-14 at Goldstone, a 70m Az/El Mount Antenna

DSS-15 at Goldstone, a 34m Az/El Mount Antenna

64m: How Large is Large?

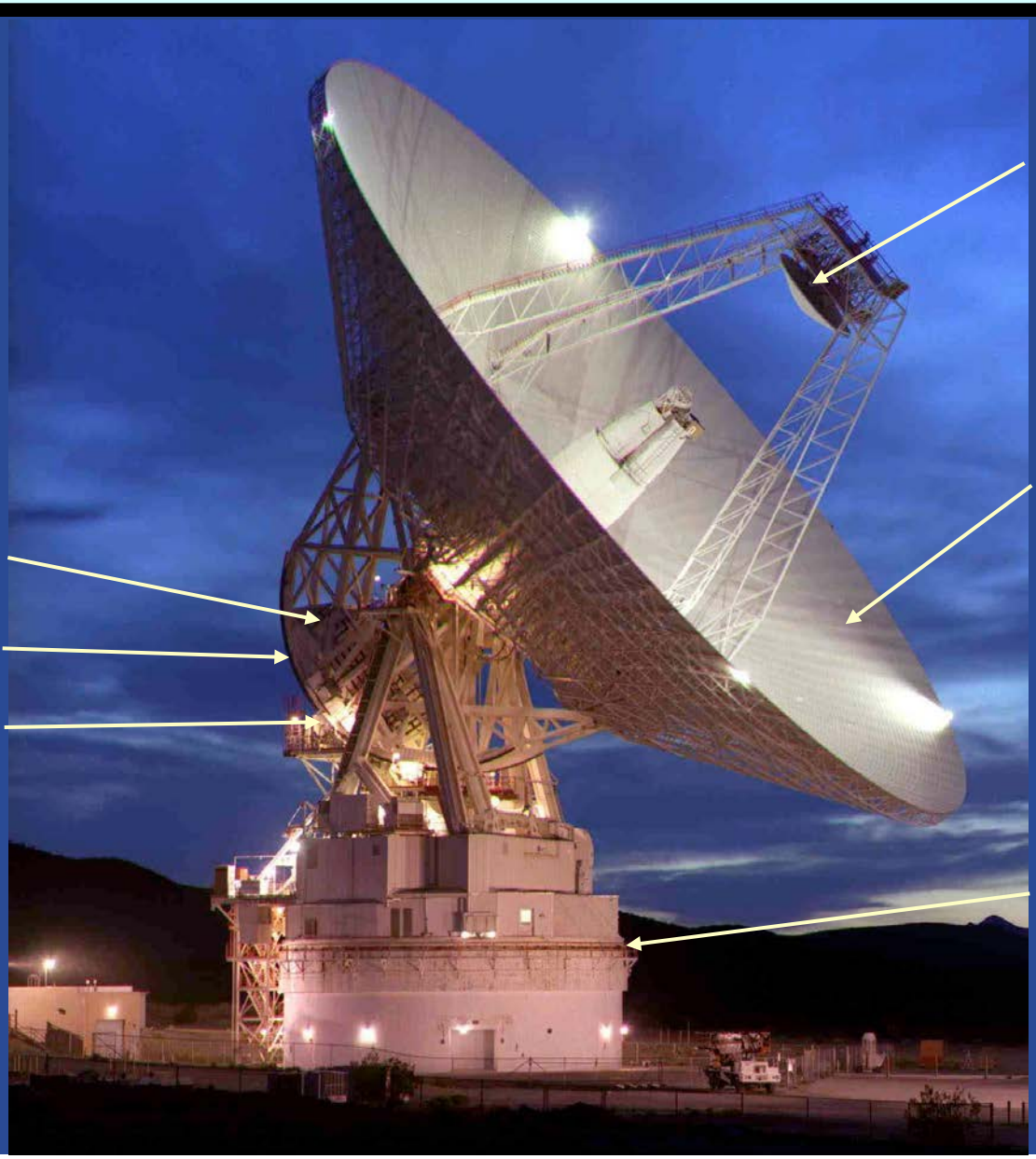


Not Large Enough!

Between 1992 and 1988, the three DSN 64m were enlarged to 70m in support of Voyager's ever-increasing distance from the Earth

Big Antennas with a Big Job

DSN 70m Antennas

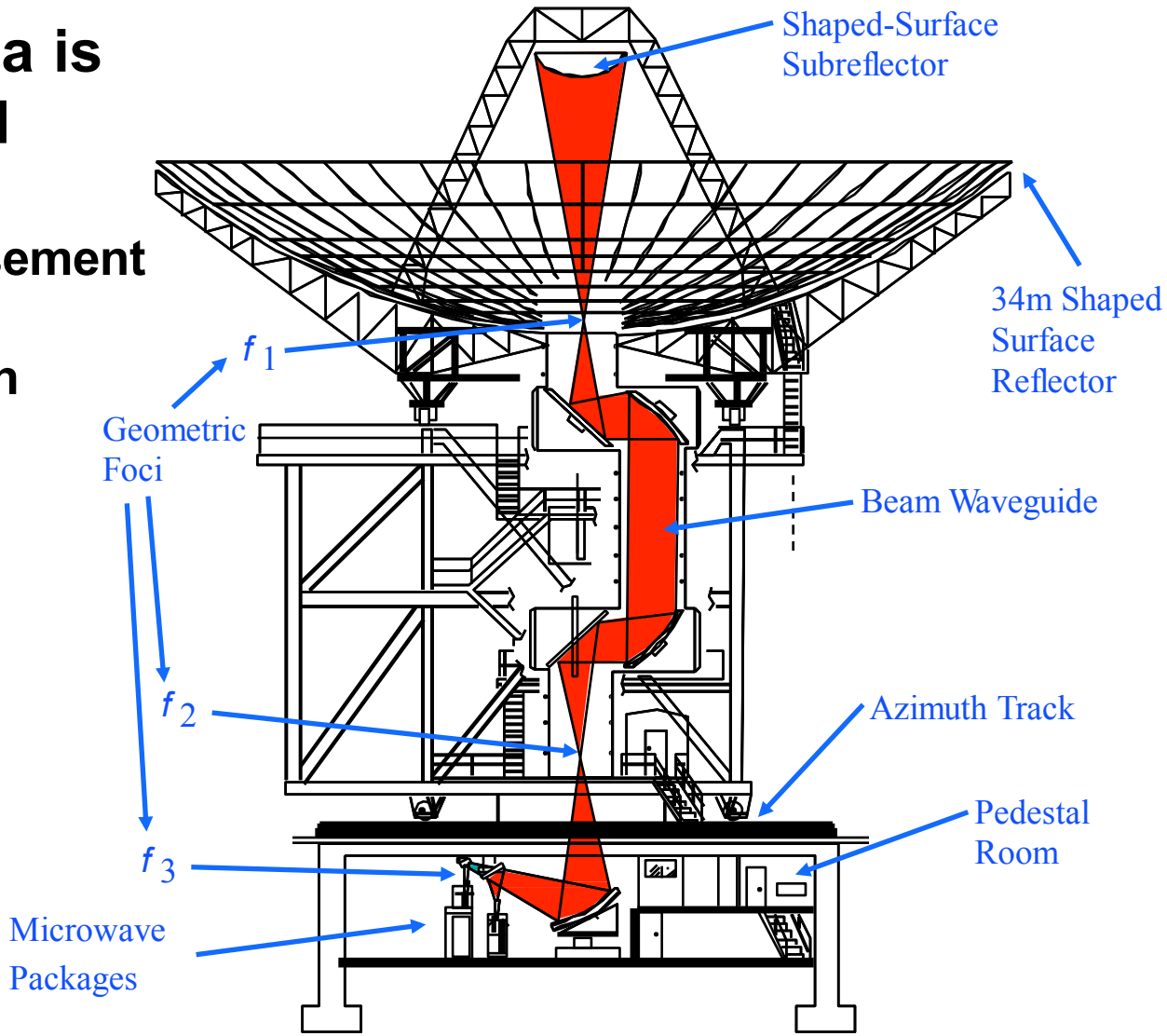


70m Antenna: Cones

- **The 70m antennas support many different spectral bands and require many feeds – too many to fit at a single prime focus**
- **Instead, the feeds are grouped into three ″cones″ that are selectively illuminated by moving the antenna' s subreflector**
- **Feeds and amplifiers are cooled to ~14K**
- **Transmitters are 20 KW (400 KW for radar)**

DSN Beam Waveguide Antennas

- **34m BWG Antenna is today's standard DSN design**
  - **Electronics in basement lab environment**
    - **Its all done with mirrors!**
  - **Easy to update**
  - **Easy to service**
  - **Safer to operate**

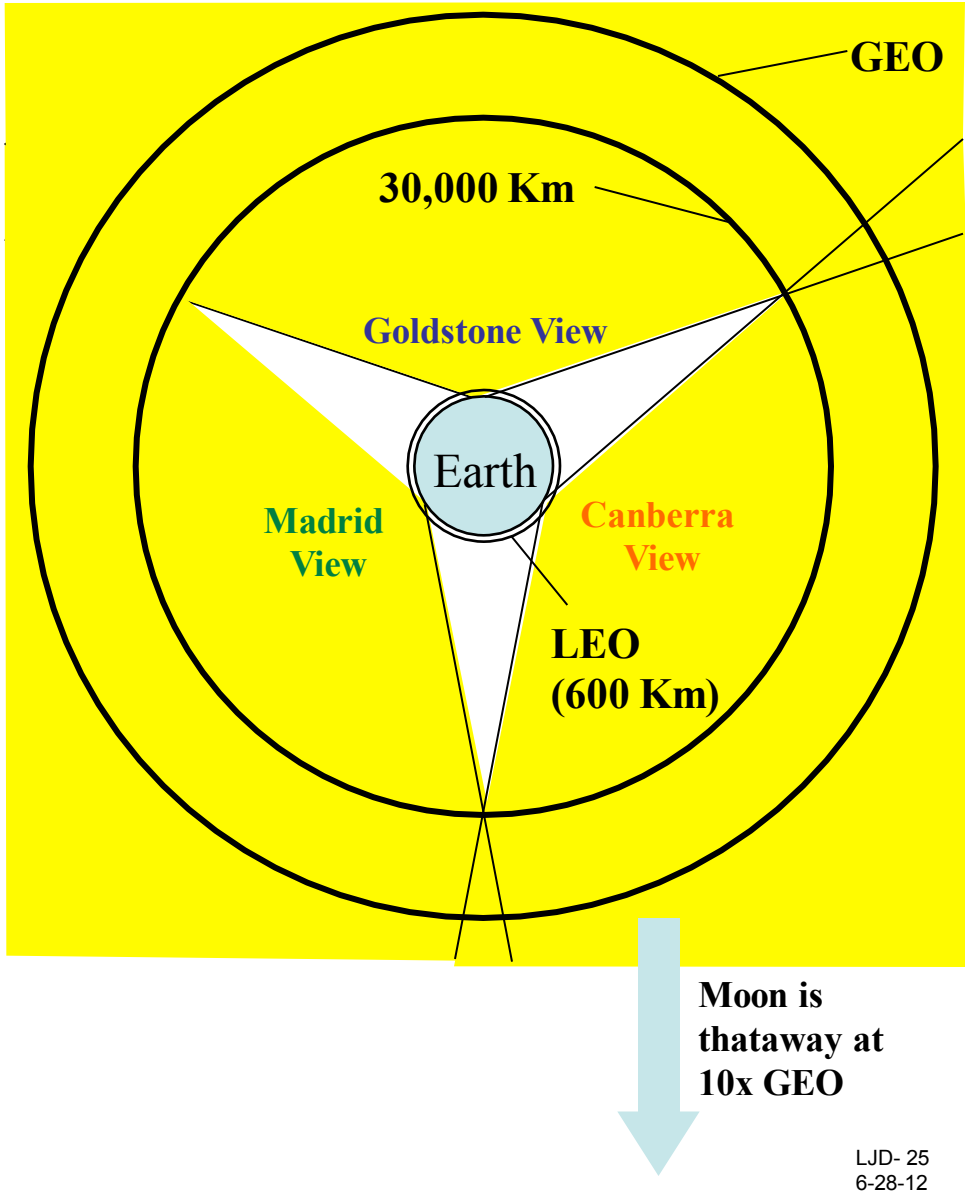


DSN-13 The Prototype DSN BWG

In the Basement of a BWG

DSN Sites

- Three ″complexes″, ~120° around the Earth
- Can ″see″ spacecraft in deep space almost all the time
- Not great for low spacecraft – such as deep space mission *launches*!

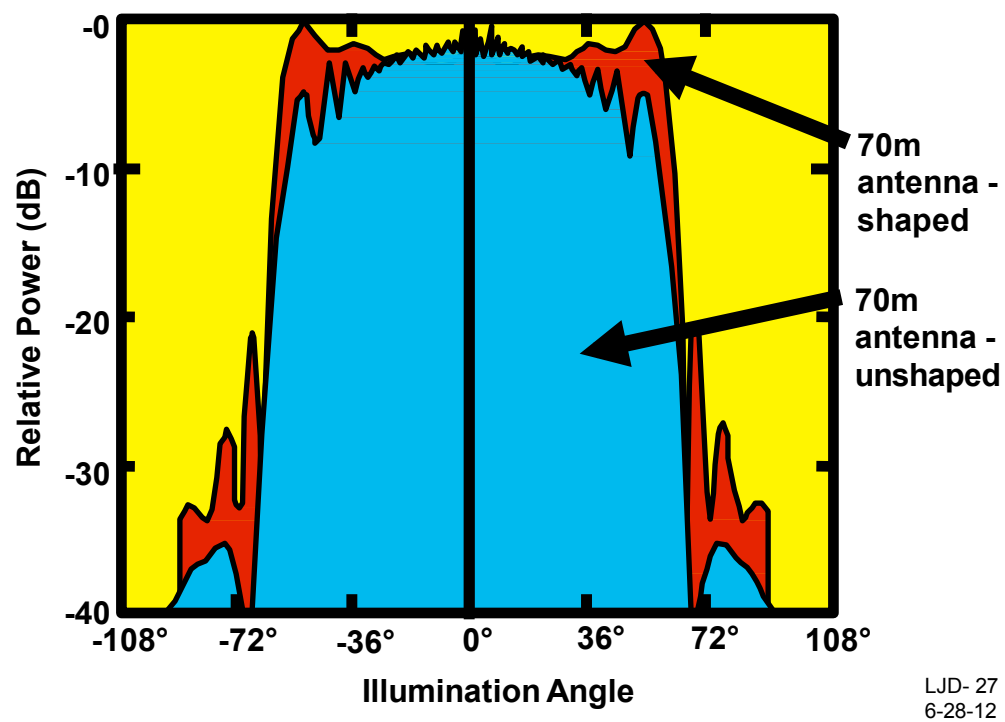


Cannot Waste a dB

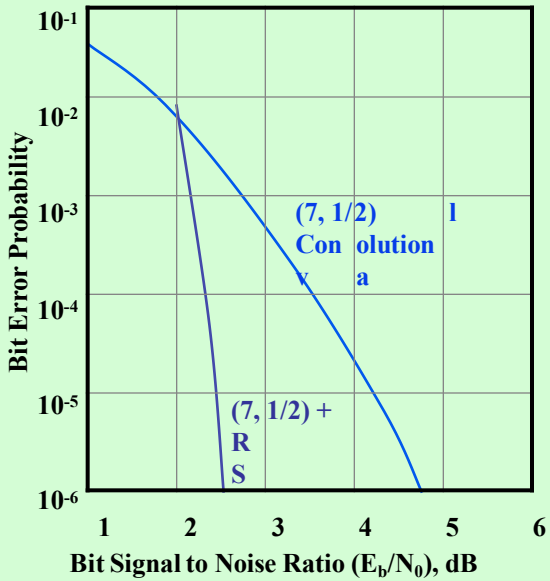
- **Deep space missions operate close to theoretical communications efficiency limit (within 1 dB, typically)**
- **Example: If a spacecraft, designed to work with a 70m antenna, lost a dB of performance, it would take an additional 32m antenna to make up the difference!**
  - **Cost for three 32m antennas = ~$100M!**

Cannot Waste a dB – Examples

- **The DSN HEMT amplifiers are cooled to a few Kelvin to produce extremely low noise temperatures**
- **DSN antennas use "shaped reflectors" to provide better signal capture than simple paraboloids**
- **DSN antennas use precision pointing systems to minimize pointing loss**
  - **Active pointing**
  - **Quadrapulse systems**
  - **Master equatorials**



Not Wasting dBs: More Examples



Coding: Add Reed-Solomon coding to spacecraft and DSN 70m – very low cost

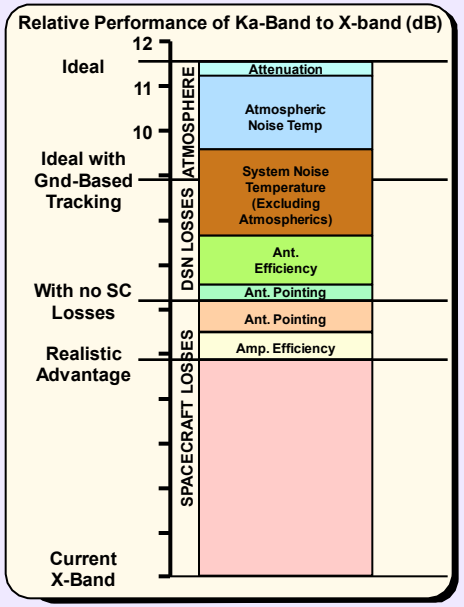
Performance improved by 2.5 dB (78%)

Avoid building ~9 34m antennas at a cost of ~$360M in today's $

Ka-Band: Add 32 GHz radios to spacecraft and DSN 34m for a moderate cost

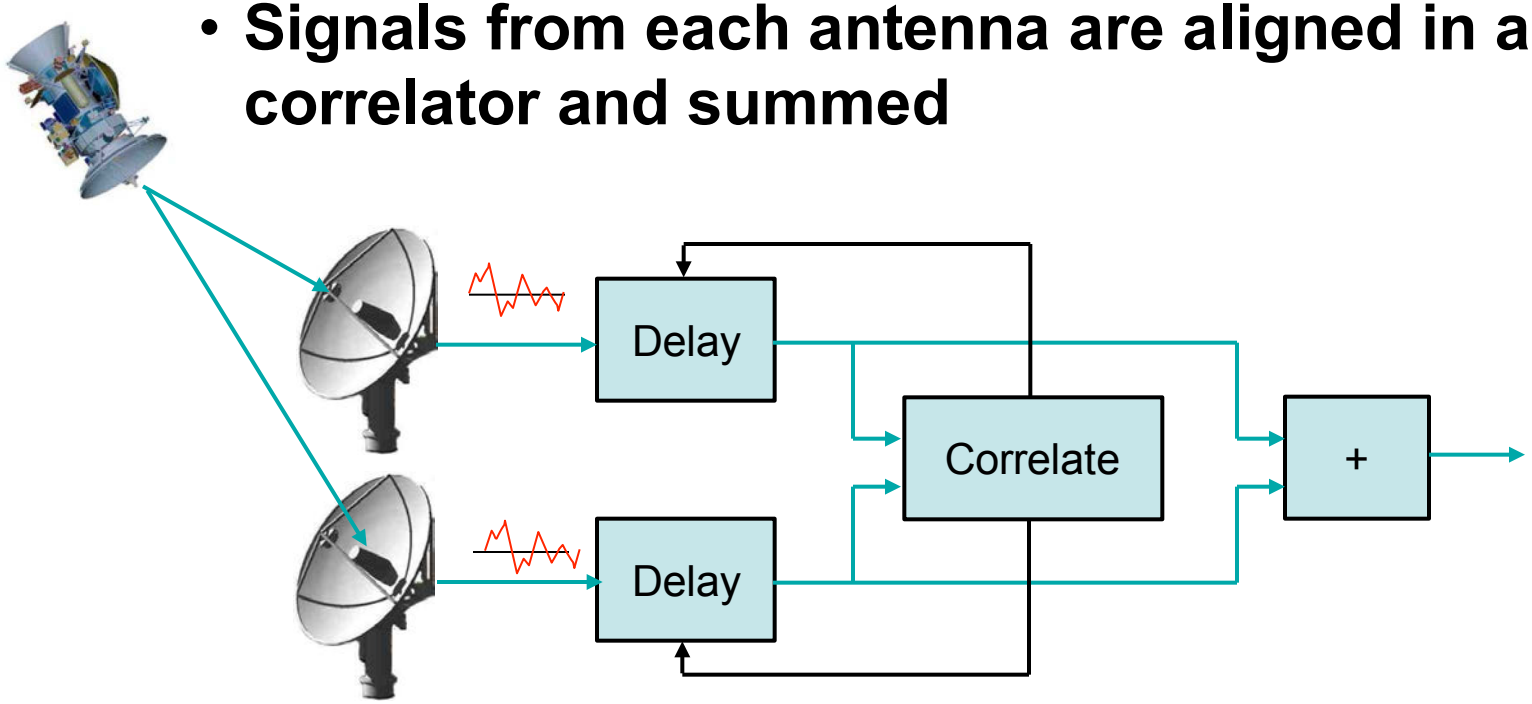
Performance improved by 6 dB (x4)

Avoid building ~9 34m antennas at a cost of ~$360M in today's $



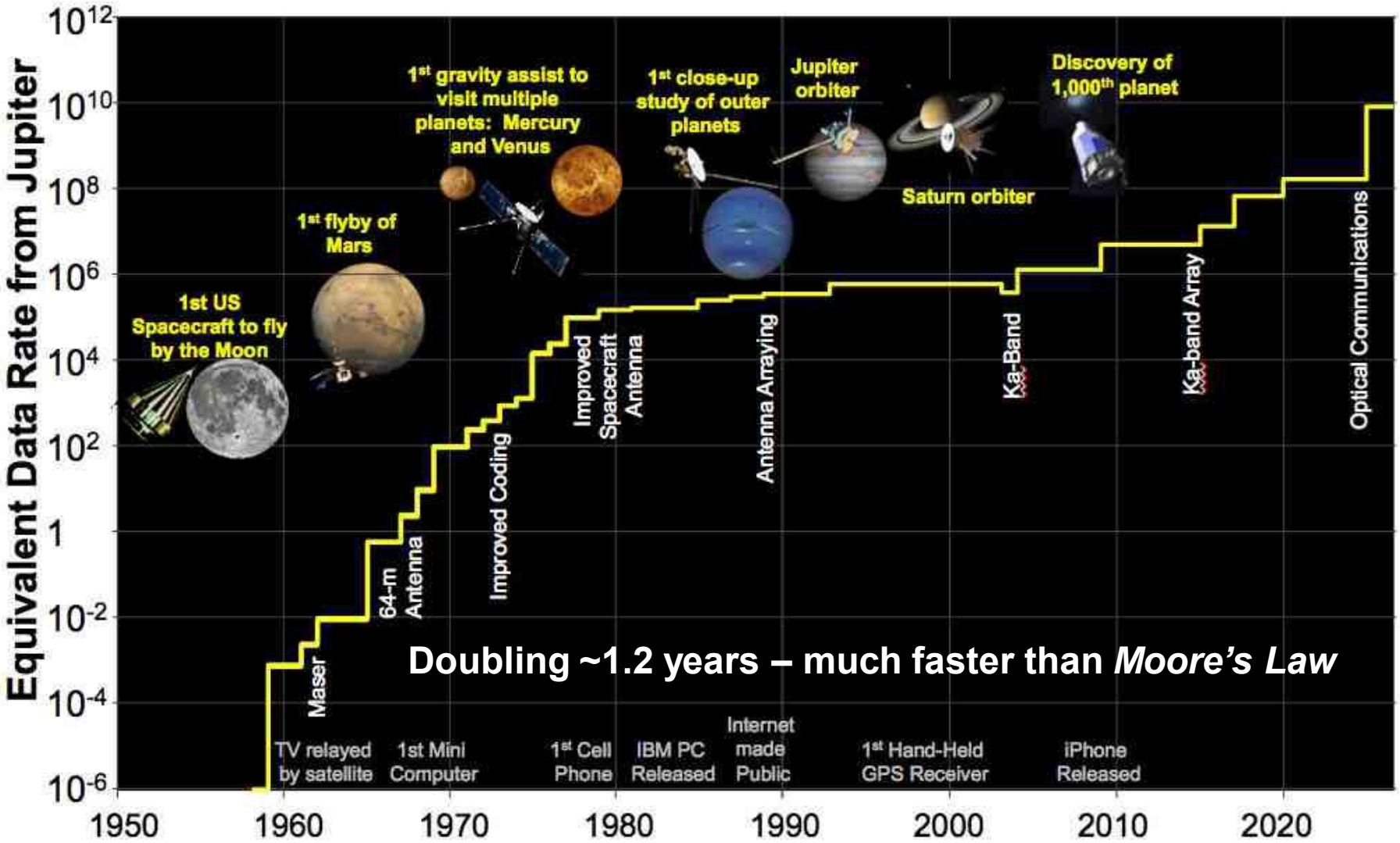
Downlink Arraying

- **Signals from each antenna are aligned in a correlator and summed**



- **The result (ideally) is performance equal to the sum of the two antennas**
- **In reality, there is a small loss (typically less than 1 dB) from approximations in the combining algorithm and hardware losses**

Deep Space Telemetry



Downlink Data Rate Possibilities

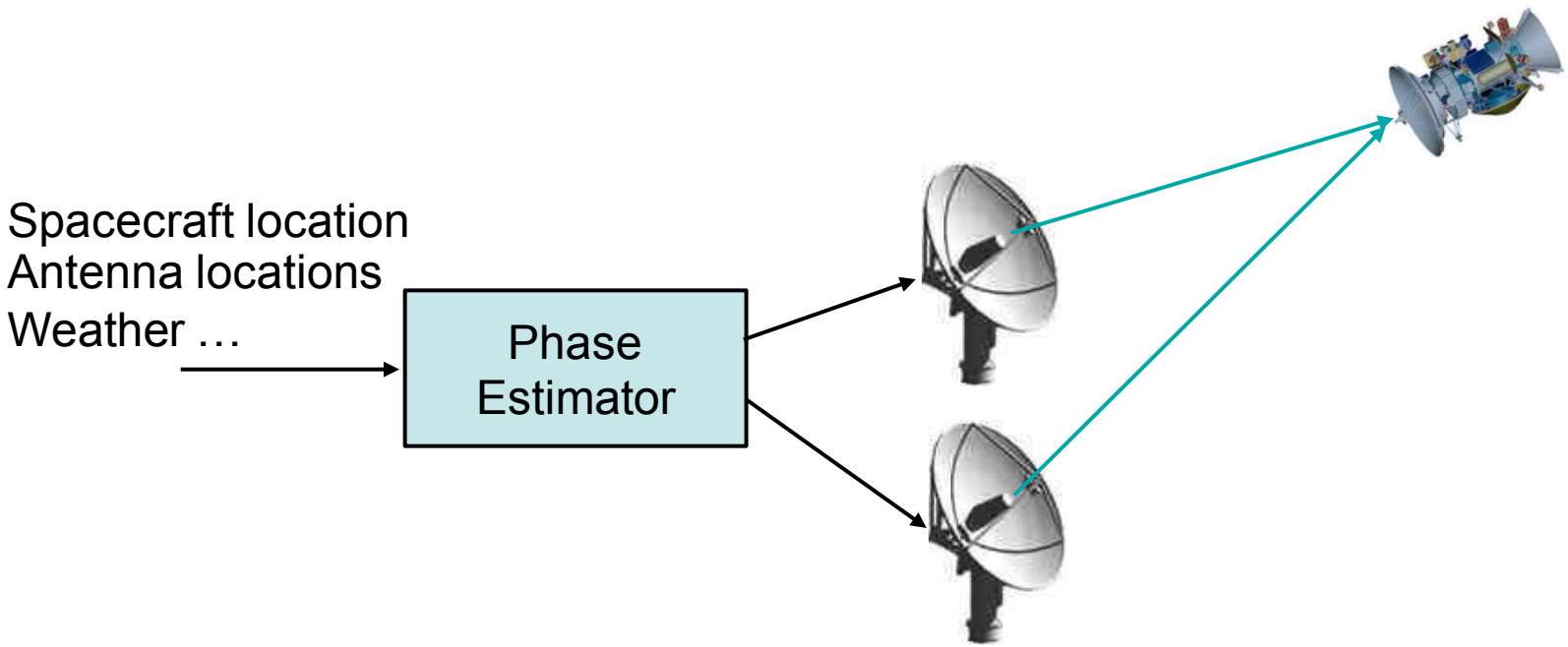
	Data Rate Today		Data Rate ~2020		Data Rate ~2030	
Spacecraft Capabilities	3m Antenna X-Band 100 W Xmitter		3m Antenna Ka-Band 180 W Xmitter		5m Antenna Ka-band 200 W Xmitter	
DSN Antennas	1 x 34m	3 x 34m	1 x 34m	Equiv to 3 x 34m	1 x 34m	Equiv to 7 x 34m
Mars (0.6 AU)	20 Mbps	60 Mbps	400 Mbps	*1.2 Gbps	*1.3 Gbps	*9.3 Gbps
Mars (2.6 AU)	1 Mbps	3 Mbps	21 Mbps	64 Mbps	71 Mbps	*500 Mbps
Jupiter	250 Kbps	750 Kbps	5 Mbps	15 Mbps	16 Mbps	115 Mbps
Saturn	71 Kbps	213 Kbps	1.4 Mbps	4 Mbps	4.7 Mbps	33 Mbps
Neptune	8 Kbps	24 Kbps	160 Kbps	470 Kbps	520 Kbps	3.7 Mbps

* Reference spacecraft is MRO-class (power and antenna), Rate 1/6 Turbo Coding, 3 dB margin, 90% weather, and 20° DSN antenna elevation

** Performance will likely be 2 to three times lower due to need for bandwidth-efficient modulation to remain in allocated spectrum

Uplink Arraying

- **Unlike downlink, there are no signals to correlate**
- **We have to estimate the phasing correctly on the ground**
- **However, if we get it right, we are rewarded with a bonus**
  - **The voltages all add up coherently at the spacecraft giving us the sum of the squares on the performance of the individual transmitters**



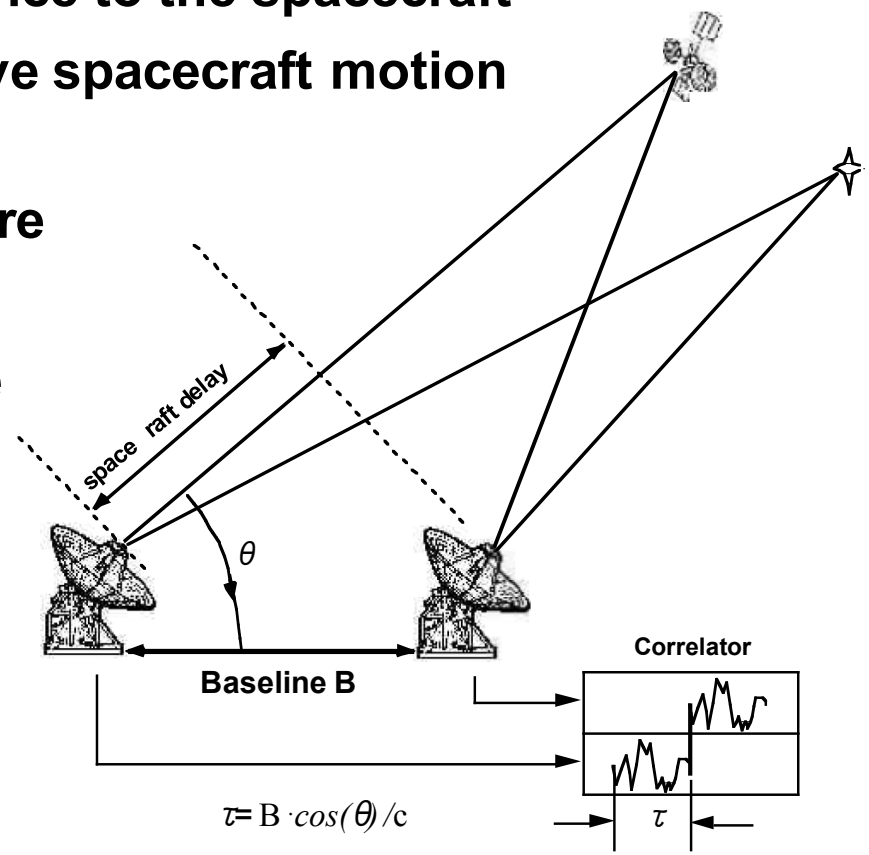
Navigation is highly dependent on Earth

Navigation is Highly Dependent on Earth

- It can take minutes to hours for signals to travel between the 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

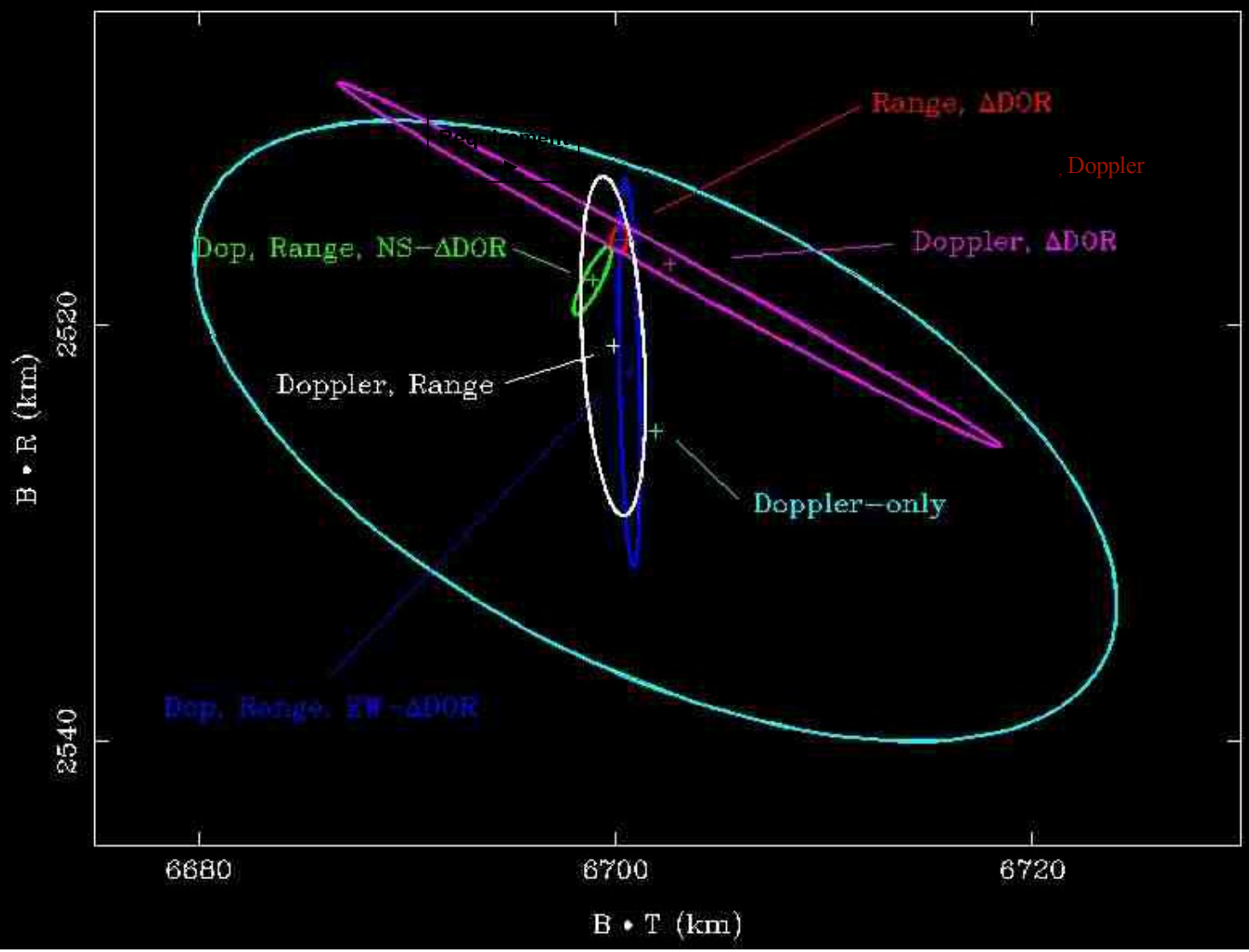
Radiometric Measurements

- **Precise measurements of the radio signal used to help navigate spacecraft**
  - **Ranging: measurement of the distance to the spacecraft**
  - **Doppler: measurement of the relative spacecraft motion**
  - **Interferrometric 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**

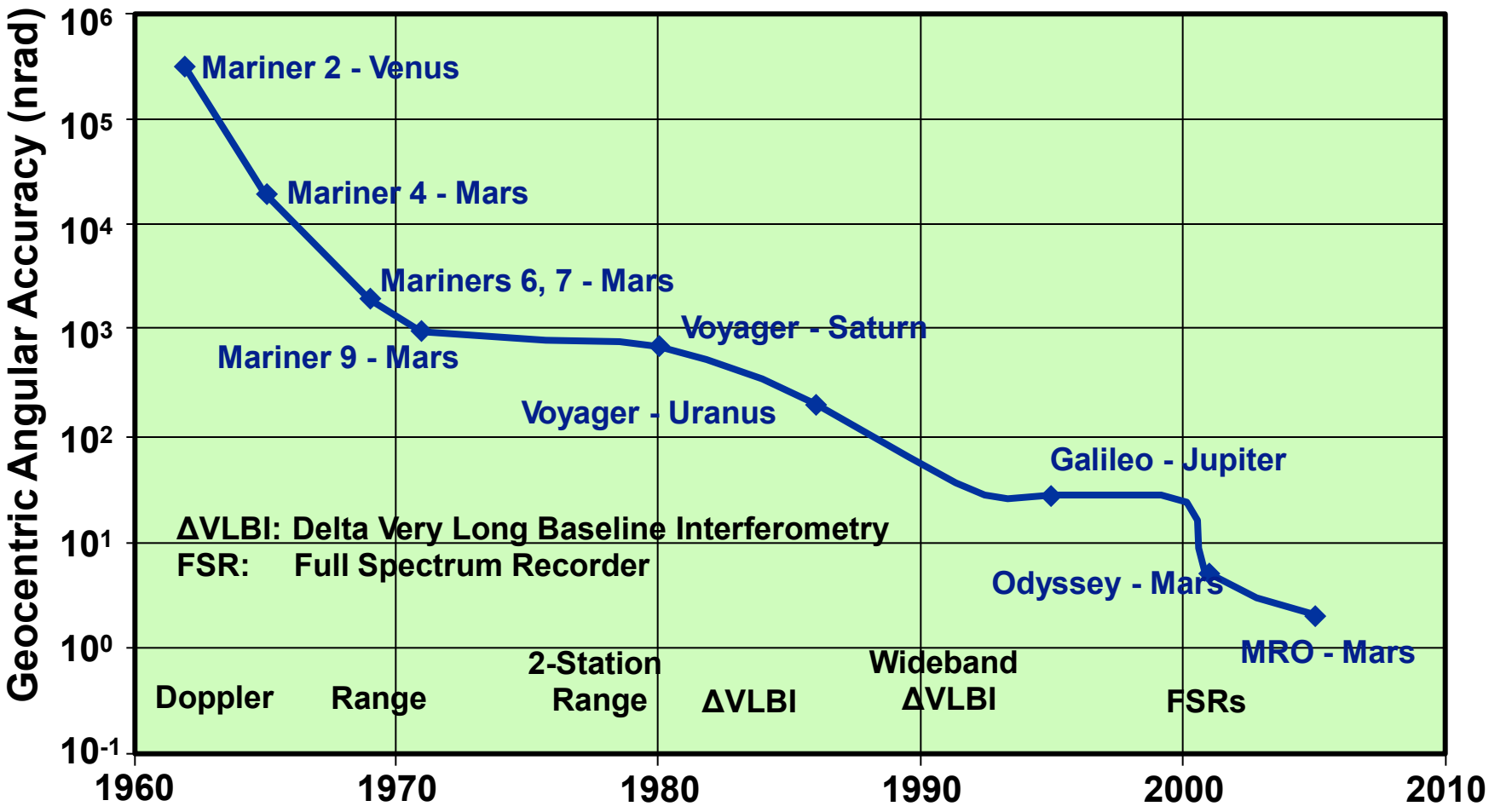


An interferrometric technique, ΔDOR: delta differenced one-way ranging

Putting it All Together: Radiometrics & MER Targeting



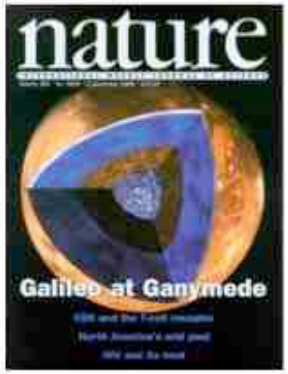
Deep Space Angular Tracking



DSN is a mission science instrument

The Impact of DSN Science

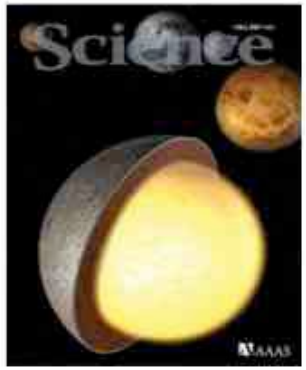
DSN science has provided a torrent of forefront discoveries – many high impact papers and mission investigators



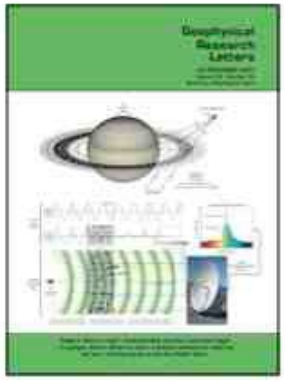
Interior of Ganymede

Asteroids in 3-D

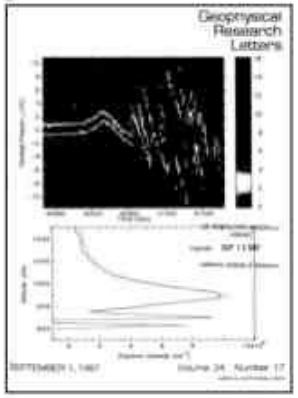
Oceans on Europa?



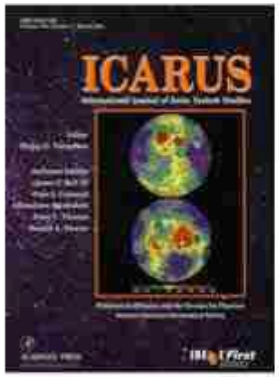
Mercury Liquid Core



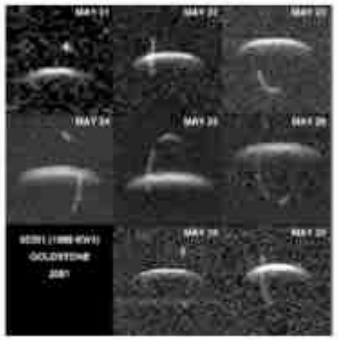
Saturn's Rings



Mars Ionosphere



Moon Gravity Field



Binary Asteroids

Student Study of Juptier Radio Emission

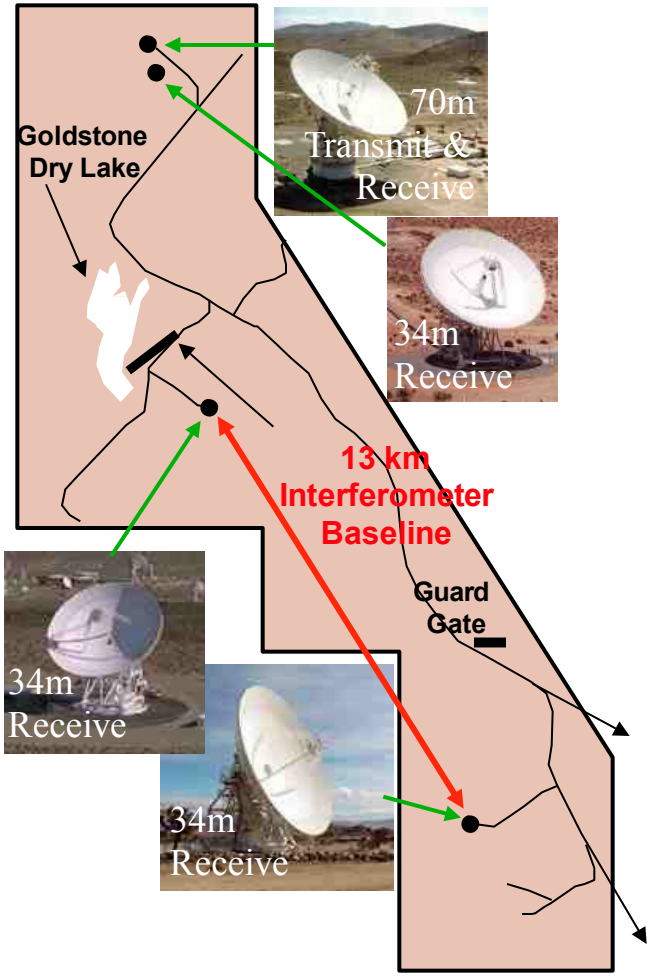
Saturn's Rings

Radio Science

- **Tracking spacecraft near or behind targets yields important science**
- **Atmospheric dynamics**
  - **Circulation**
  - **Vertical structure**
  - **Turbulence**
- **Atmospheric density**
- **Gravity field mapping**
- **Special high dynamics receivers are used for this in the DSN**

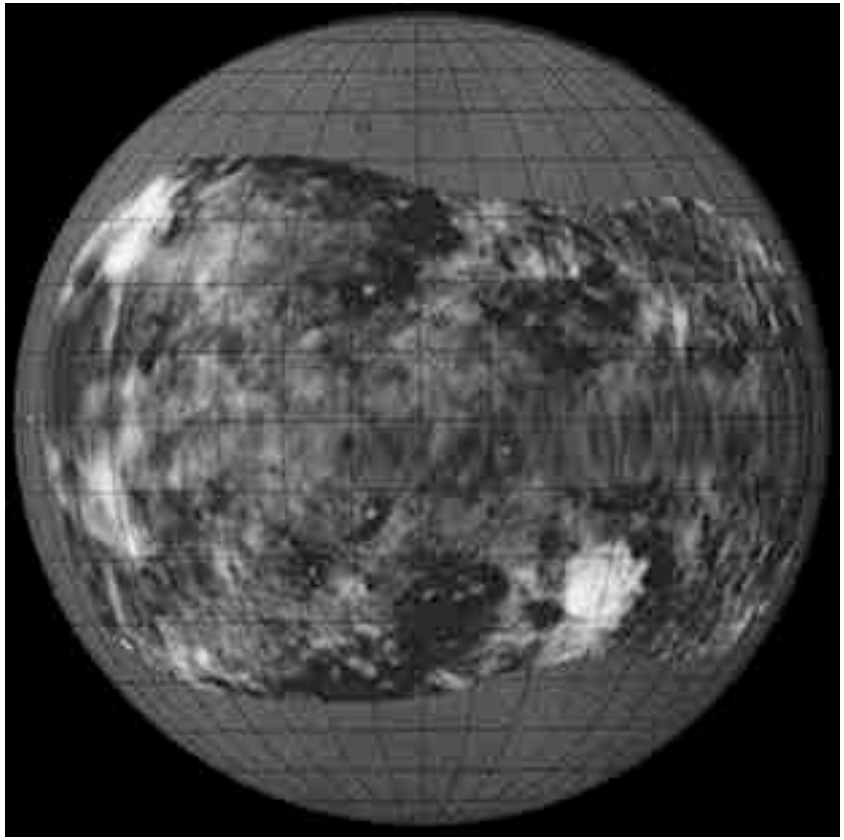
The Goldstone Radar Facility

- **Unique for high-res ranging and imaging of planets, small-bodies**
  - **500 kW X-band transmitter**
  - **Can be used with Arecibo**
- **Wide variety of science**
  - **Surfaces: images, topography, ice, physical characteristics, chemical composition**
  - **Dynamics: Orbits, rotations, spin axes**
- **Mission use**
  - **Landing site evaluation, emergency support, …**
  - **Mission science support**
- **NASA approved science investigators**



Goldstone Radar and Venus

Venus viewed through Earth-based optical telescopes

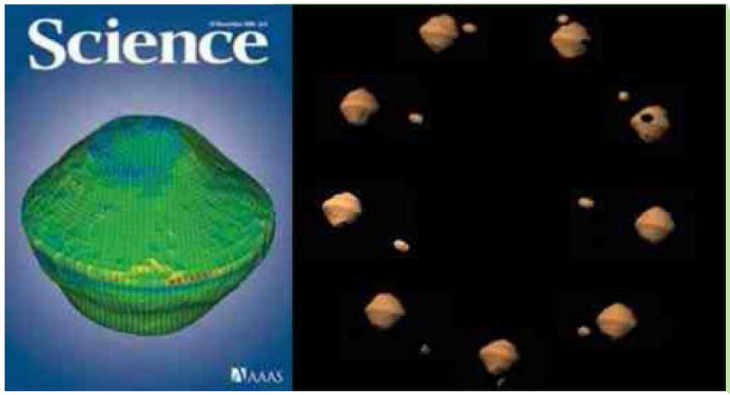


Radar (including this 1972 Goldstone image) gave scientists their first views of the surface

Goldstone Radar: Recent Highlights

Discovery of Mercury liquid core

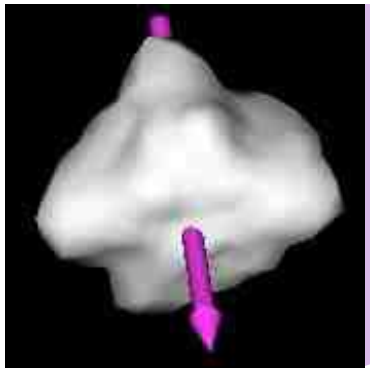
- Supports Messenger mission



Radar Imaging and Topography of Unusual Asteroids

- Support NEO Program

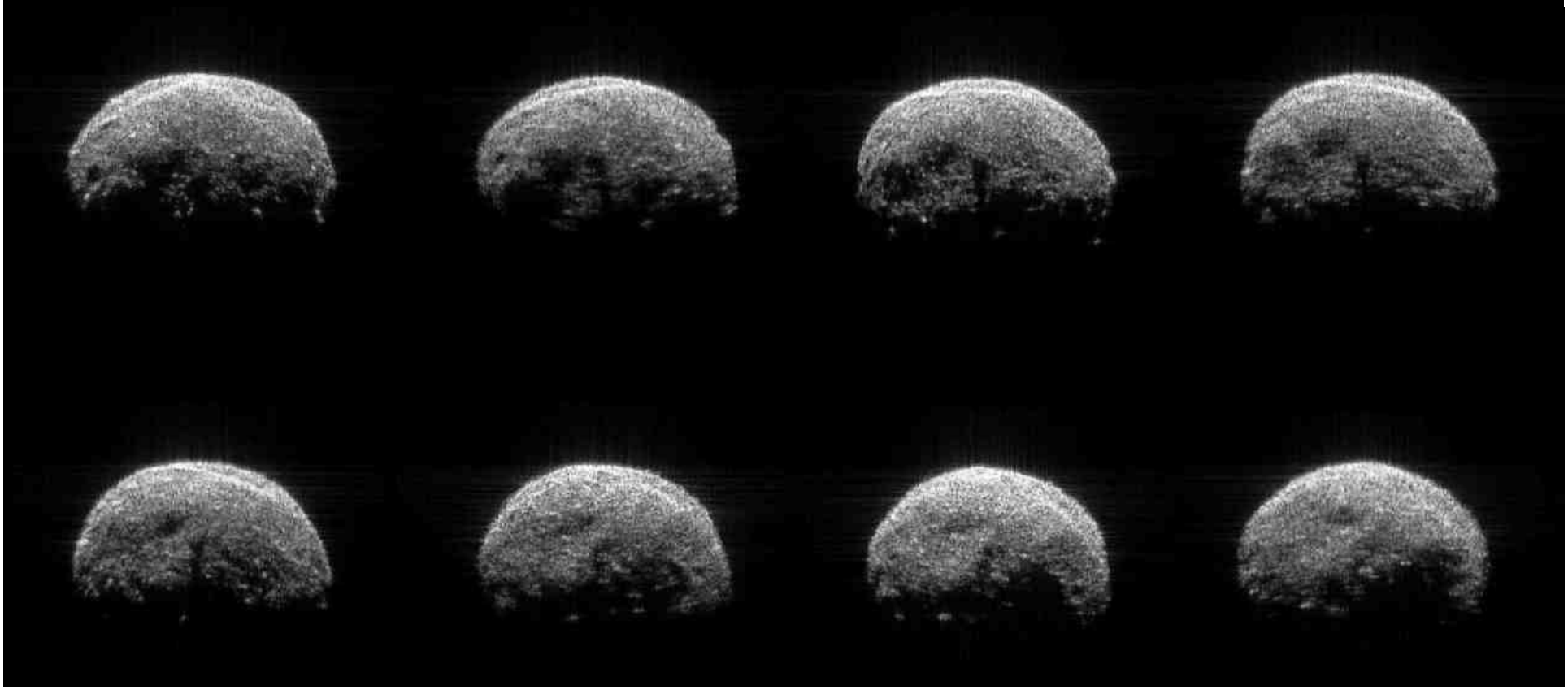
- **Asteroid 1999 KW4** – A binary pair of asteroids, with the larger object being extremely oblate because it is close to it's breakup rotation rate



- **Asteroid 2000 PH5** – Asteroid found to increase spin rate due to sunlight torque (Science, 13 April 2007)

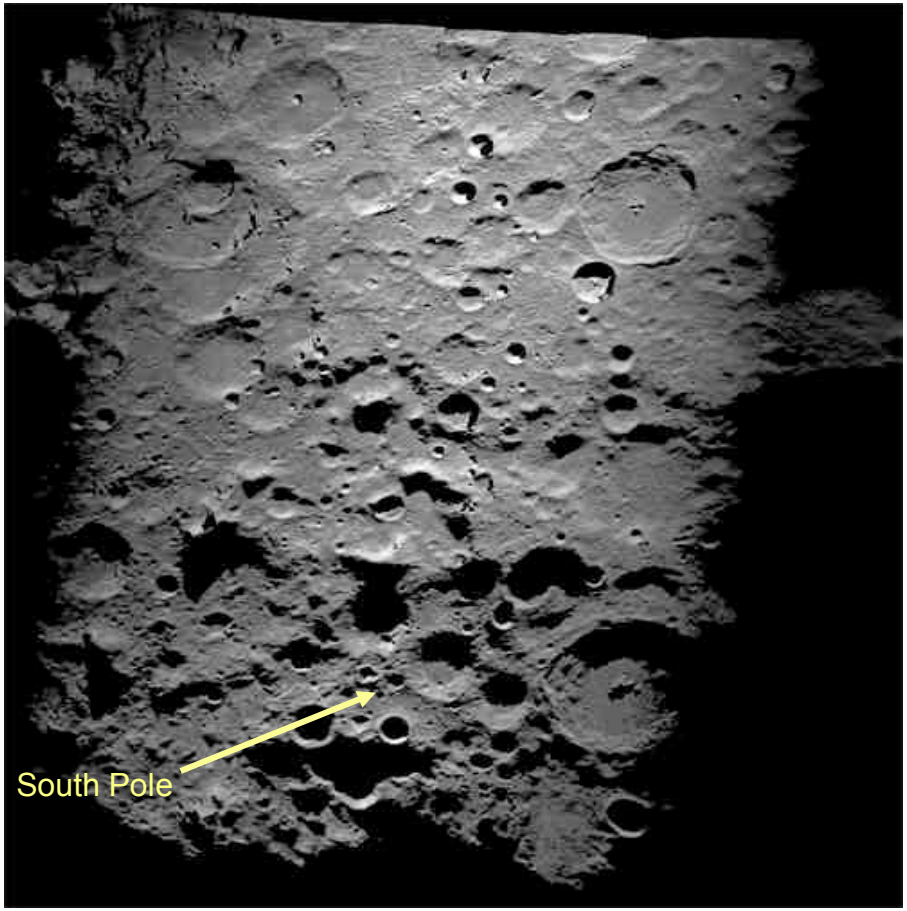
A Very Close Encounter

- **In November 2011, Asteroid YU55 came closer to the Earth than our own Moon**
- **The Goldstone Radar imaged YU55 at 3.75 m resolution – better than encounter quality!**

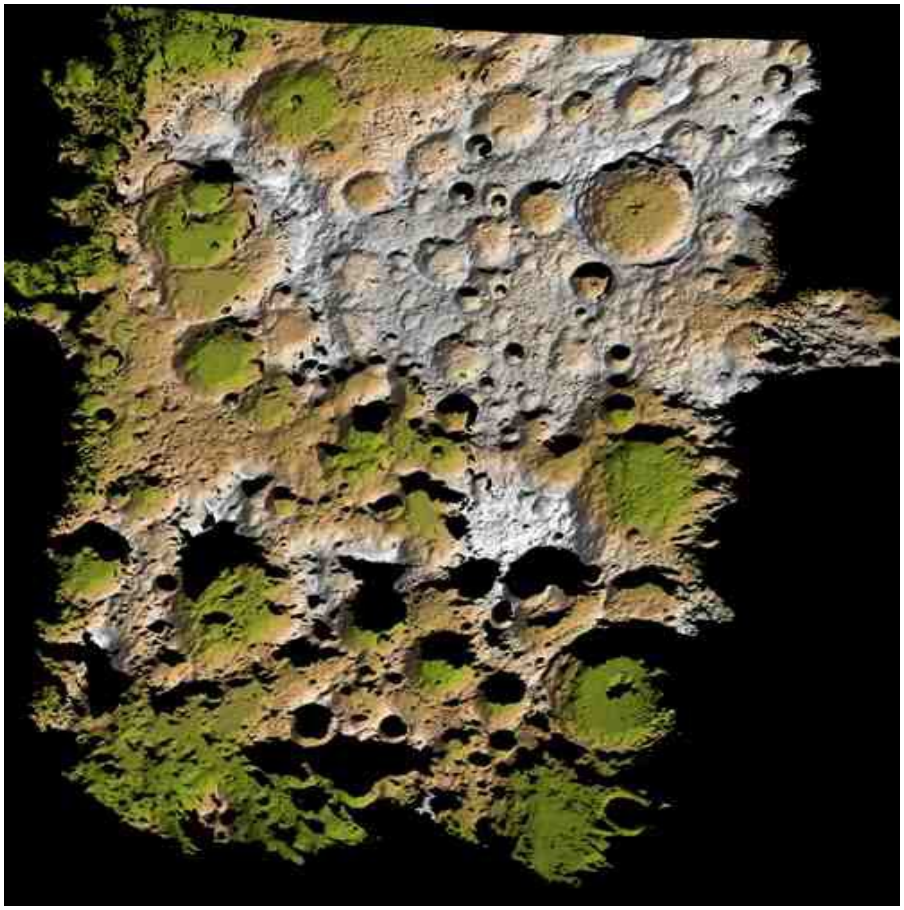


Goldstone Radar: Lunar Science

Unprecedented imaging (20m resolution) and topography resolution of Lunar South Pole where the Sun never shines!



Radar Image



Digital Elevation Map

Every mission is unique

Every Mission is Unique

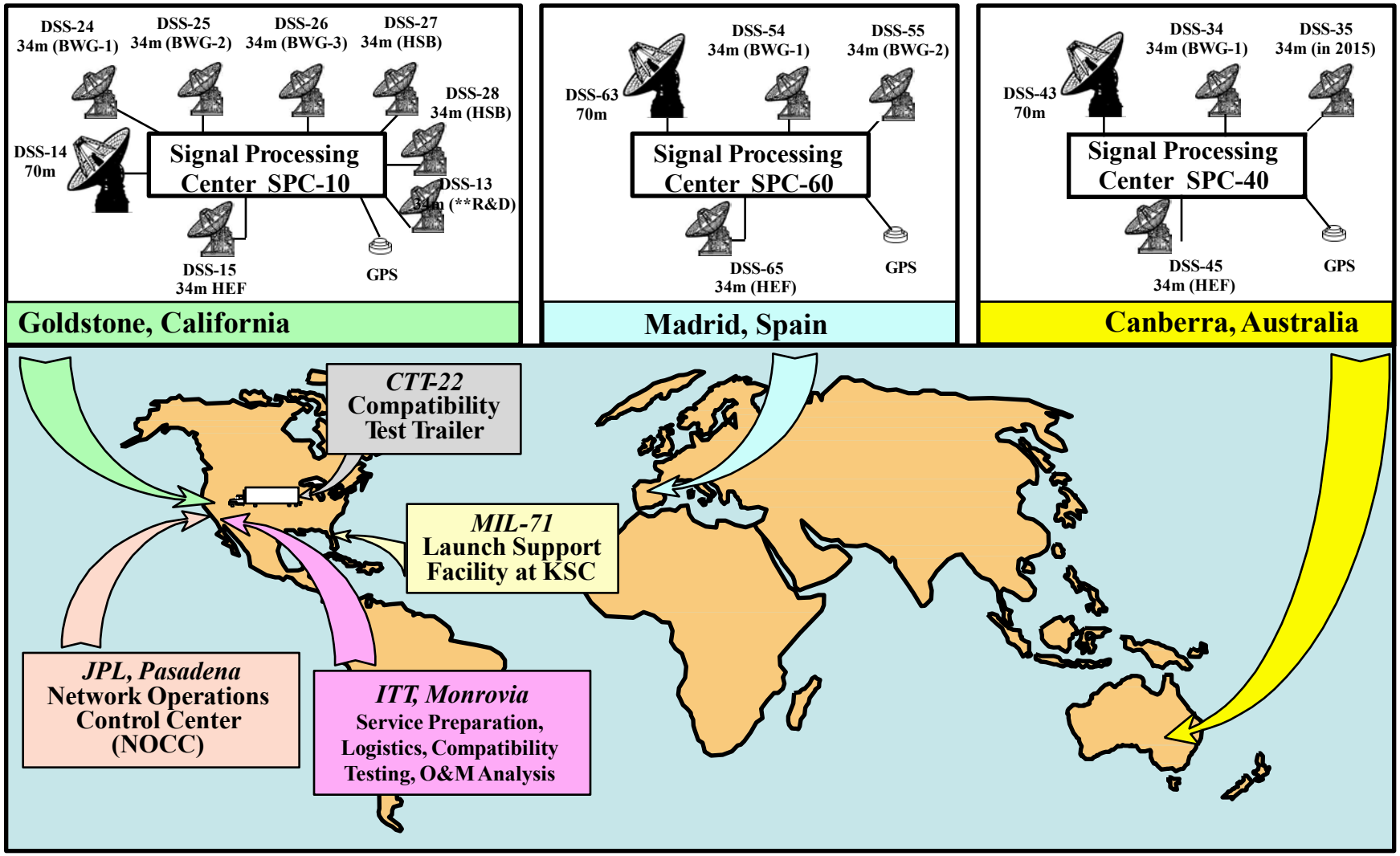
- **There are a myriad of deep space targets: planets, moons, asteroids, comets, and parking spaces for astronomical observatories - each with their own**
  - **Set of scientific questions**
  - **Unique trajectory challenges**
  - **Unique spacecraft bus, instruments, and porpulsion**
- **Even popular targets (e.g. Mars) are visited only every few years, with differing spacecraft**

Unique Missions => Unique Solutions

- **Communications and navigation can be different for each mission**
  - **Often requires special studies to optimize performance and maximize success**
  - **Missions have their own comm and nav experts**
- **New technology is often infused in both the spacecraft and the DSN – creating something new for every missions**

So, the DSN looks like this …

DSN Facilities



The Mojave Desert in 1958

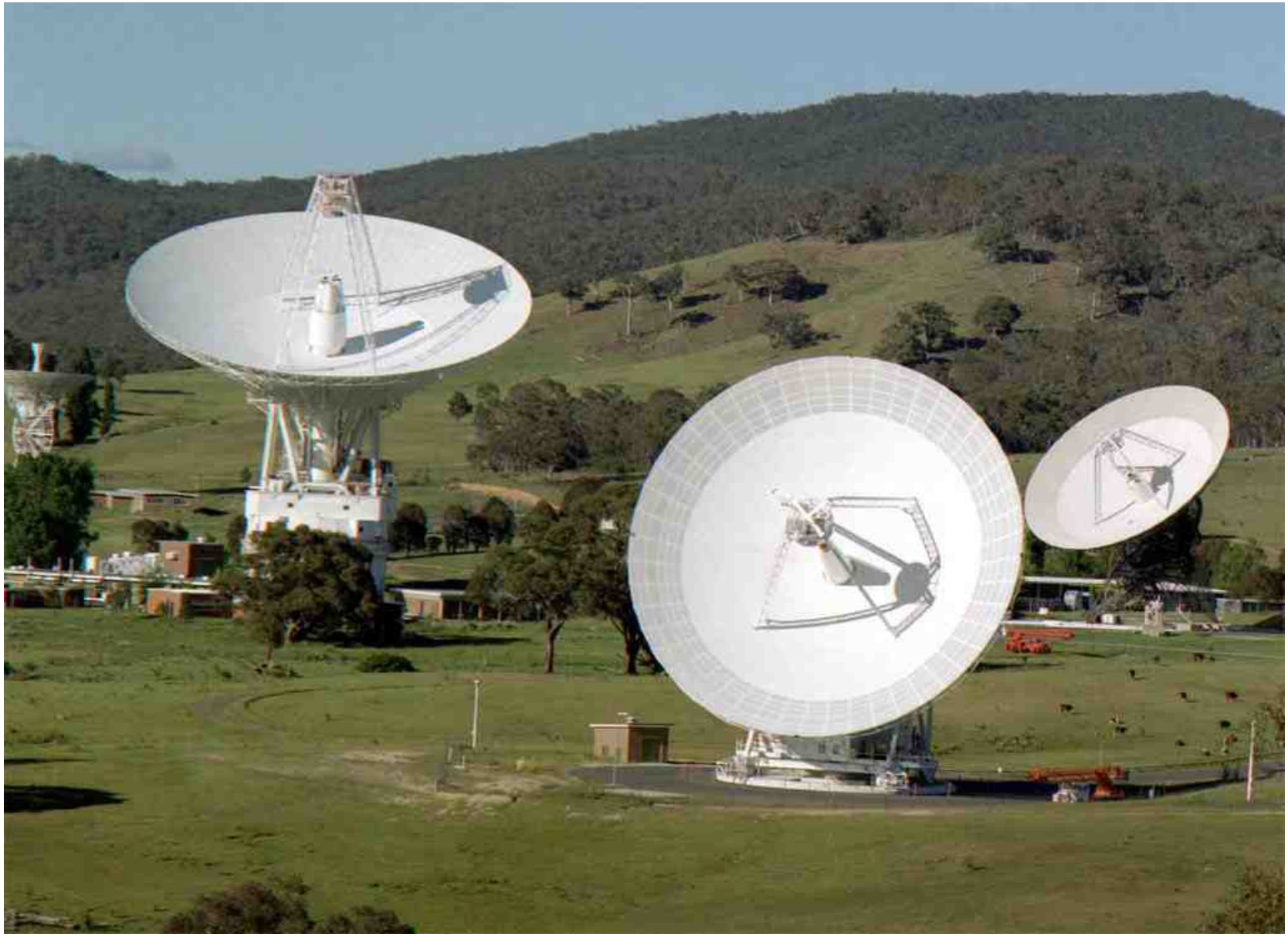
Goldstone, California

DSN Antennas in Australia

After Goldstone, the next DSN site to open was at Woomera, Australia in 1960.

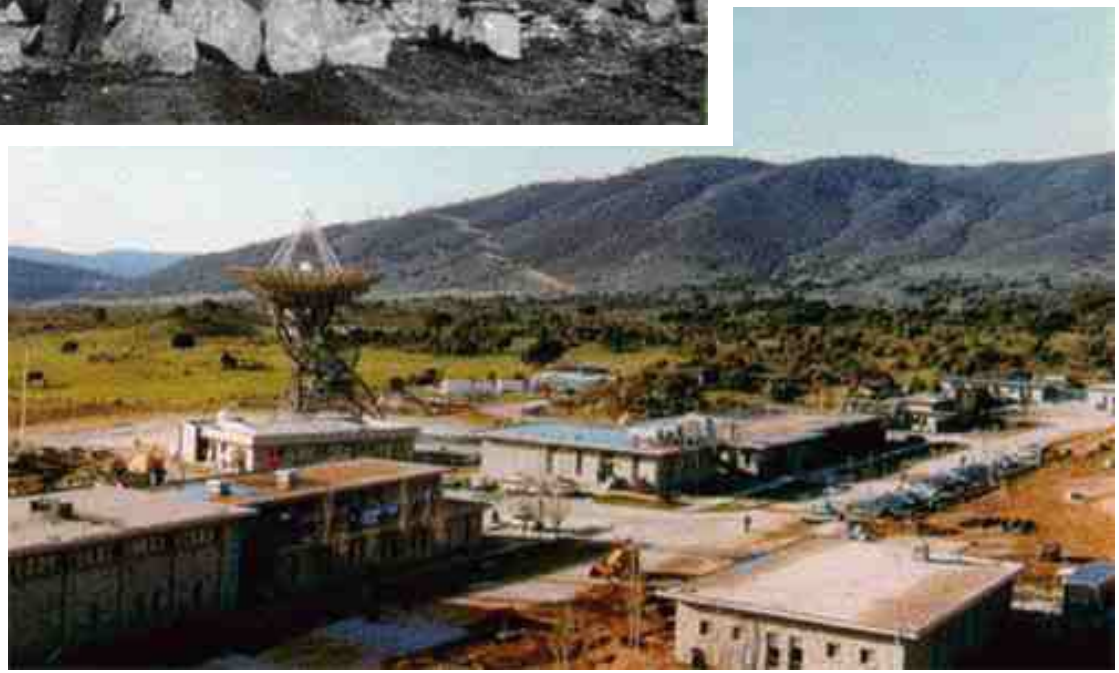
It was closed in 1972 when operations were consolidated at Canberra.

Canberra, Australia

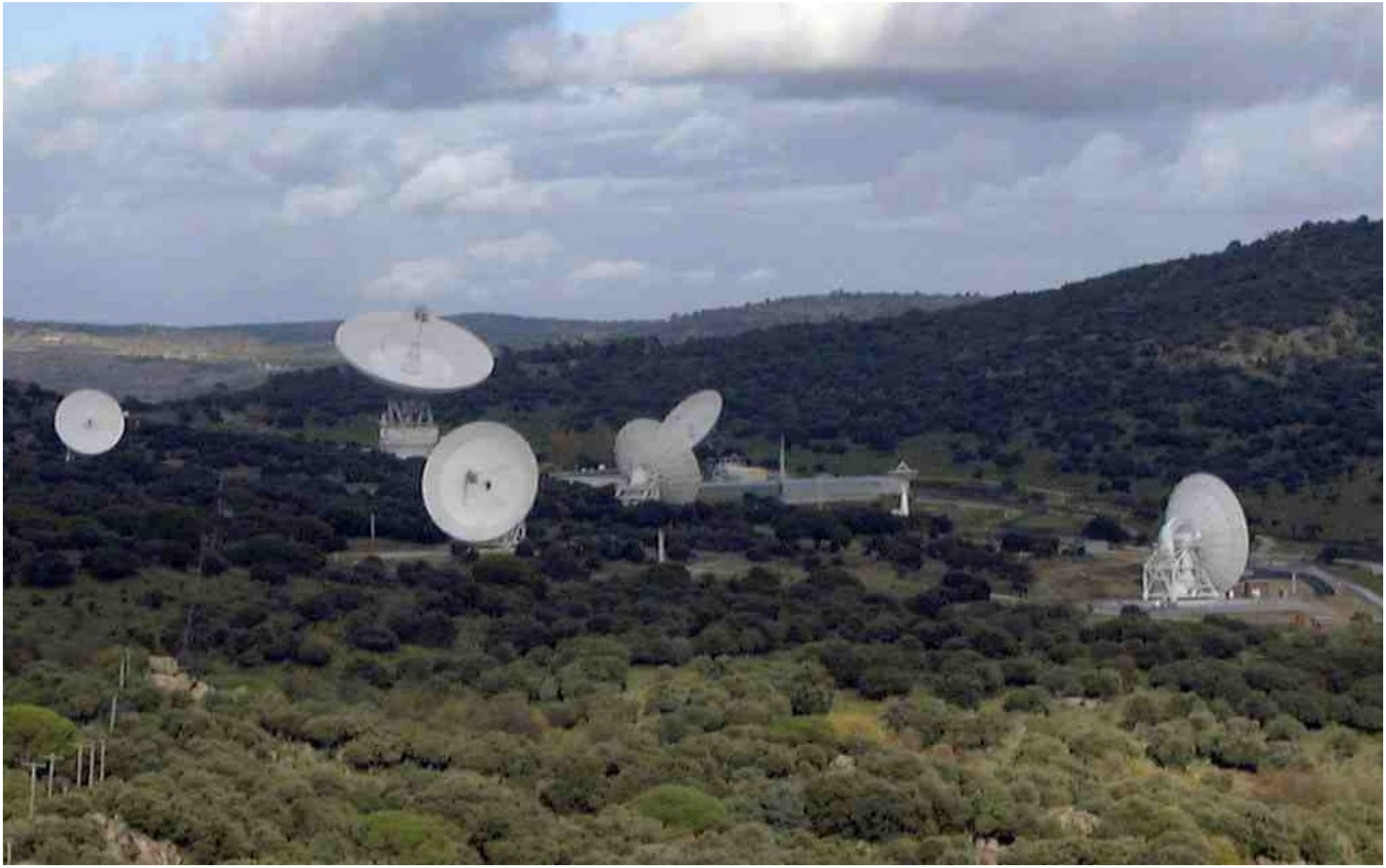


First Deep Space Station in Spain

When US relations with South Africa became problematic, NASA opened the DSN tracking site in Spain – outside Robledo, near Madrid – in 1965



DSN Antennas in Madrid, Spain

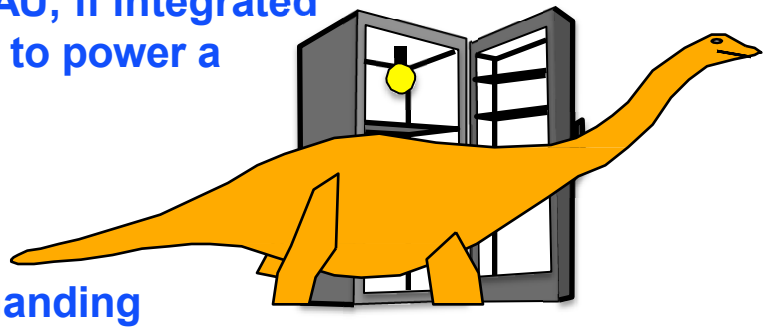


Some Amazing DSN Facts

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!

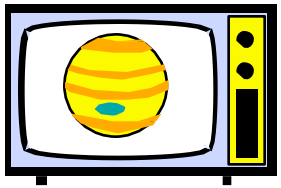
Received power = 6.3×10^{-19} W



Command Power:

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

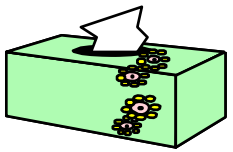
Transmitted power = 400 kW



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}

Future Challenges for the DSN

- **Space mission communication needs follow a "Moore's Law" requiring ~factor of 10 improvement per decade**
- **Human spaceflight will venture beyond low Earth orbit into deep space**
  - **Data rates will have to be much larger to support both the needs of the astronauts and the desires of the public**
- **Deep space optical communication will come into its own in the next couple of decade**
- **The DSN will evolve to meet these challenges and continue to enable space missions for at least the next 50 years**