Jet Propulsion Laboratory
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# The Deep Space Network: Connecting the Solar System

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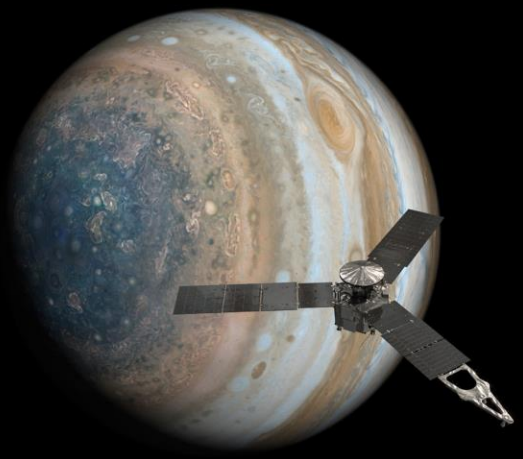
# Introduction

NASA's Deep Space Network (DSN) is the system we use on Earth to communicate with, and navigate, our spacecraft that venture beyond geosynchronous Earth orbit

One of the main functions of the DSN is communication

- It is like the Internet in some ways
- And not, in other ways

Hence, I suppose, DSN ≠ DNS



# Navigation Using the Communications Signal

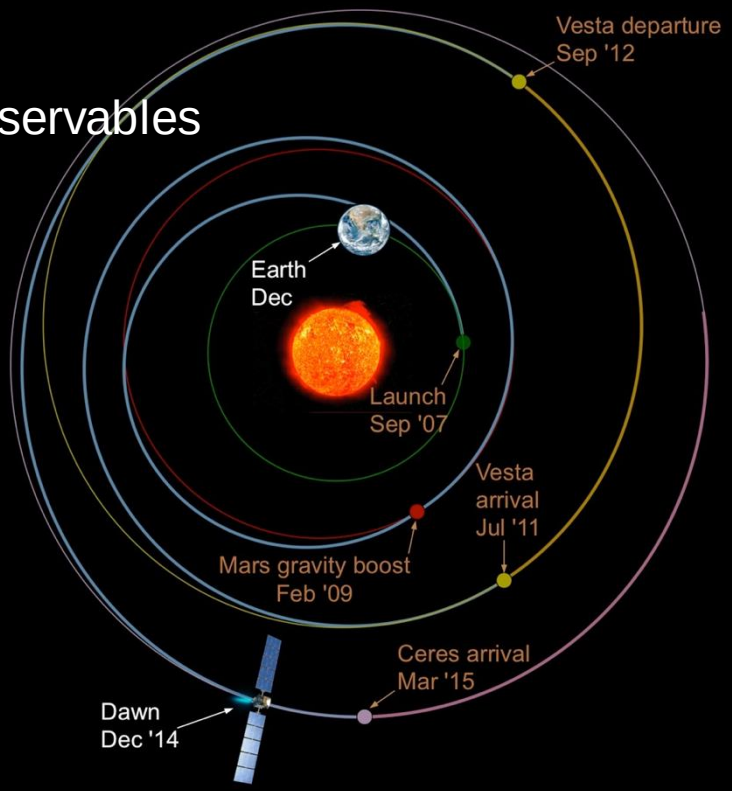
- There is no GPS in deep space
- Measurements of radio signal are the primary observables

  Ranging: measurement of the distance to the spacecraft

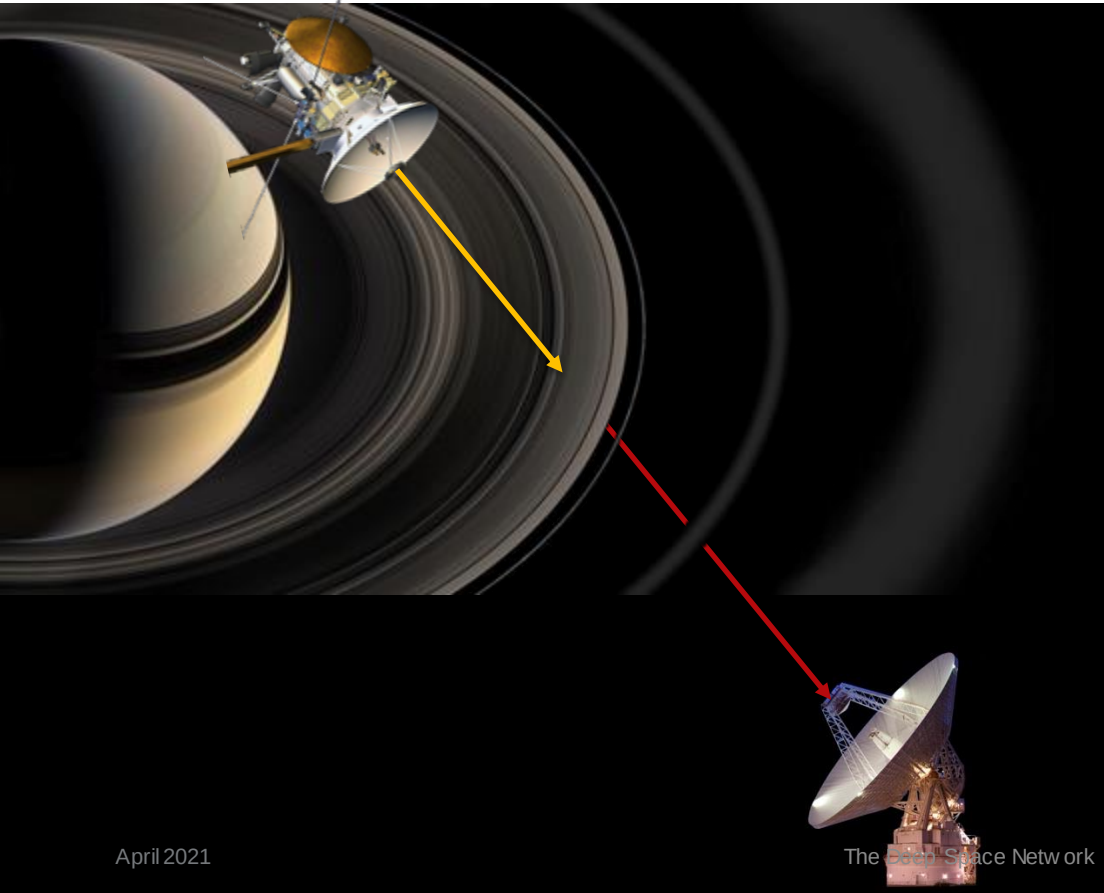
  Doppler: measurement of the relative spacecraft motion

  Delta Differenced One-Way Ranging (ΔDOR): Using multiple ground antennas to measure angle on the sky

- Supplemented with on-board sensors



# DSN Science



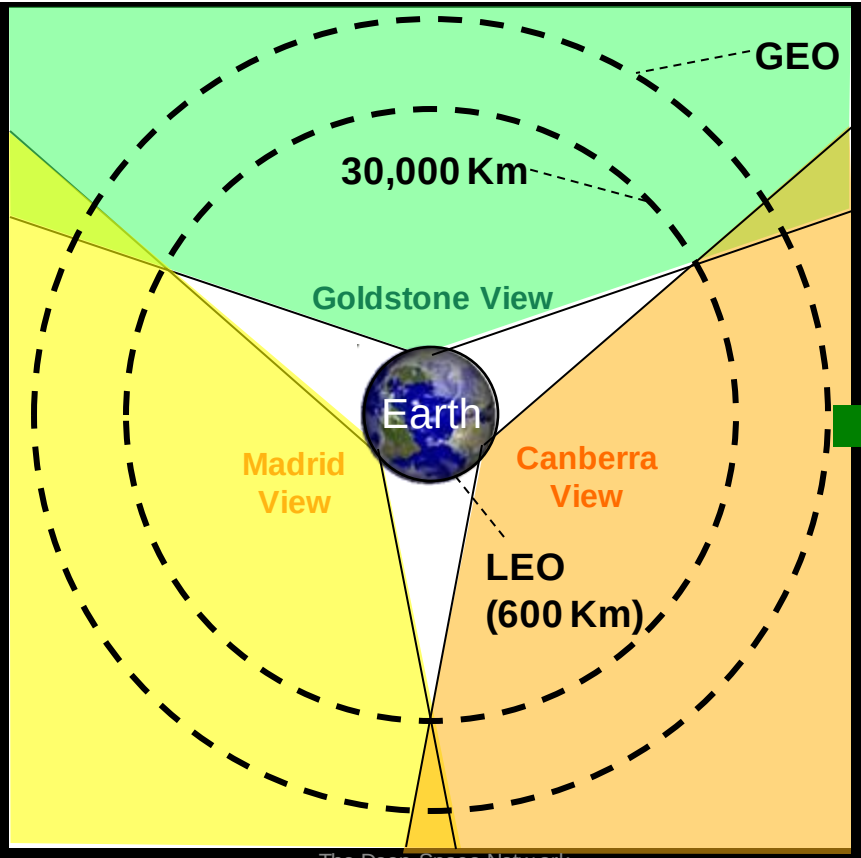
- Measuring perturbations in the link
  - Attenuations
  - Spacecraft wobble
  - Frequency deviation
- We learn things about
  - Rings and particles
  - Atmospheres
  - Interiors of bodies
- We even use the DSN as a radar
  - See through atmospheres
  - Study terrain
  - Assess danger from asteroids

# DSN Antennas in Canberra, Australia

# Some DSN Antennas at Goldstone, California

# DSN Antenna near Madrid, Spain

# A Global Enterprise by Necessity




Moon is thataway at 10x GEO

# How is Deep Space Comm like the Internet?

- Nodes are connected using international standards
  - Space links use radio today
  - Terrestrial links use Internet – but on private networks
  - Any country can have nodes – in space and on Earth
- The system is scalable
  - New nodes are (mostly) easy to add – on Earth and in space
- Some nodes serve as relays
  - All Mars orbiters also double as relays for Mars landers and rovers
- People always want more bandwidth
  - Upgrades are more expensive, though!
- People complain when there are outages

MAVEN relaying with Mars2020

# How is Deep Space Comm unlike the Internet?

- Where shall I start?
- Large distances between nodes – really low signal levels

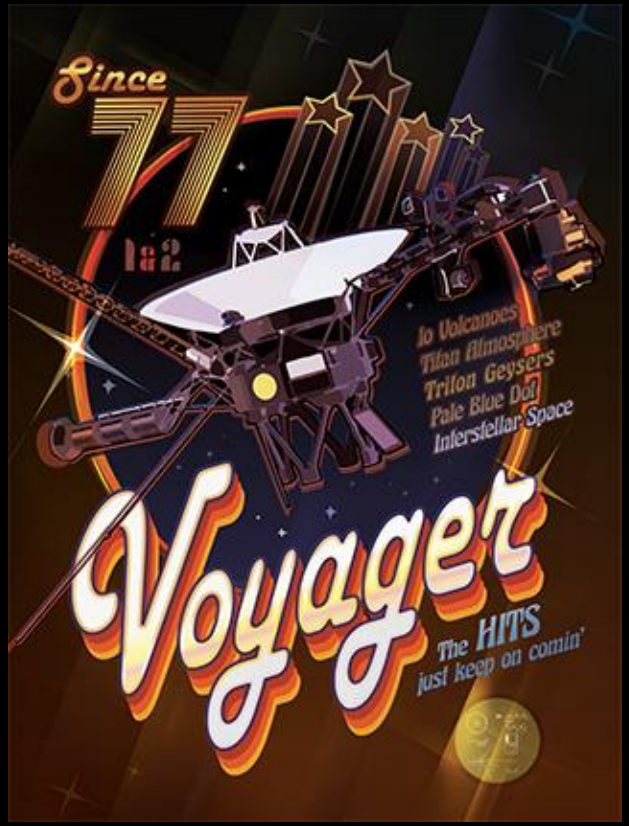
$E_b/N_0$ = constant / $d^2$

***Relative Difficulty***

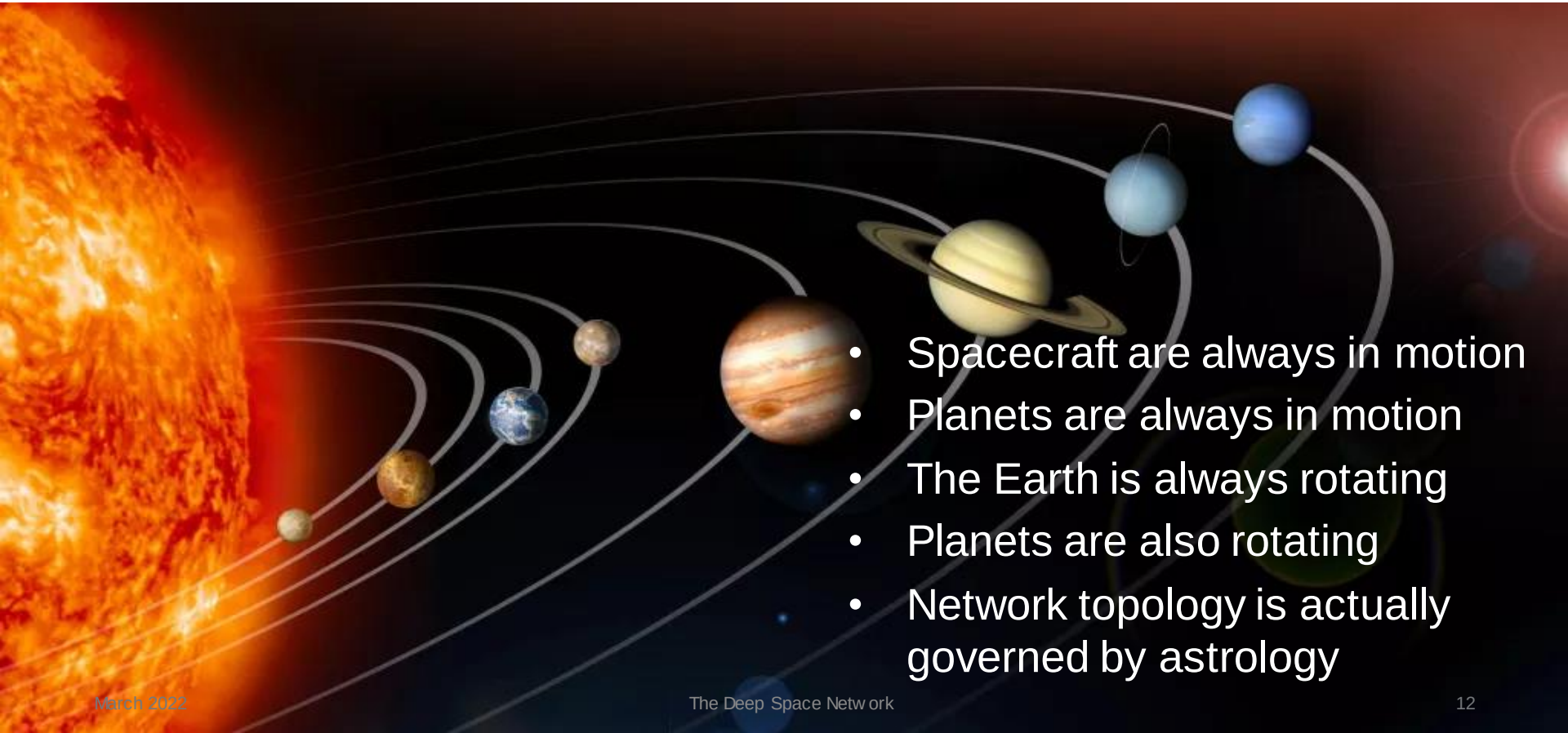
| *Place* | *Distance* | *Difficulty* |
|---|---|---|
| *GEO* | *$4x10^4$ km* | *Baseline* |
| *Moon* | *$4x10^5$ km* | *100* |
| *Mars* | *$3x10^8$ km* | *$5.6x10^7$* |
| *Jupiter* | *$8x10^8$ km* | *$4.0x10^8$* |
| *Pluto* | *$5x10^9$ km* | *$1.6x10^{10}$* |

# Long Distance – More Problems

- Light takes signals a long time to travel between nodes
  - Voyager 1 is more than 155 AU from us
  - Round trip light time (RTLT) is about 42 hours!
  - Even at Mars, RTLT is up to 48 minutes
- TCP-IP does not work
- Spacecraft memory is precious and cannot be erased until communications is verified
  - Mostly a manual process today



# Network Topology is Always Changing



- Spacecraft are always in motion
- Planets are always in motion
- The Earth is always rotating
- Planets are also rotating
- Network topology is actually governed by astrology

# Connections Are Temporal

- As the Earth rotates, DSN stations move into and out of view of spacecraft
- Spacecraft are occulted by the planets they orbit or land upon
- Spacecraft are periodically occulted by the Sun
- Spacecraft may need to turn from their science observations to communicate with Earth
- Spacecraft may not have enough power to do observation and communications simultaneously

# Connections are Scheduled in Advance

- Often 12 weeks or more!
  - Missions usually need long-term plans for their own automation
- Scheduling process is collegial
  - Users meet to discuss their requirements over the next period of time
  - Agree to a mutually-beneficial schedule
- *Today, essentially every bit on every hop of every link is scheduled*

# DSN is a Constrained Resource

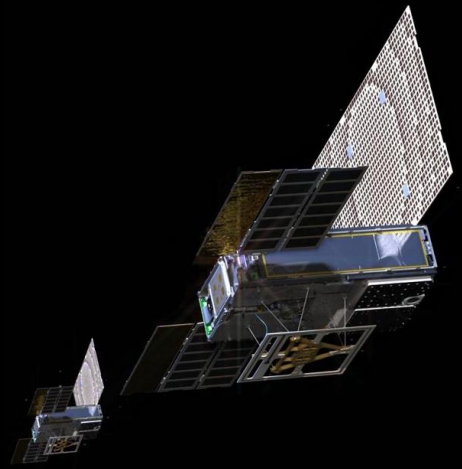
- The DSN communicates with ~35 missions in flight every day

- But the DSN has only 13 antennas!
  …and often some are “down” for maintenance

# And We Have New Customers with Special Needs

- Human Space Flight – Astronauts will soon travel beyond LEO for the first time since Apollo
  - Gateway, Artemis, …
  - Commercial Space

- NanoSats (including CubeSats)
  - Successfully flew MarCO, 1st deep space CubeSats
  - Artemis 1st flight will carry 11 CubeSats into deep space

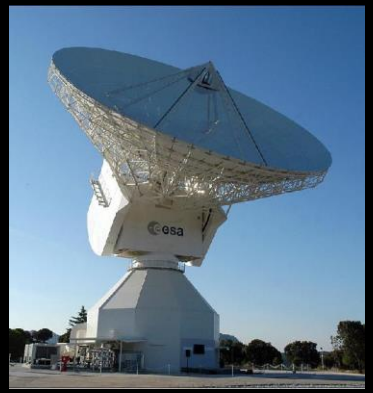


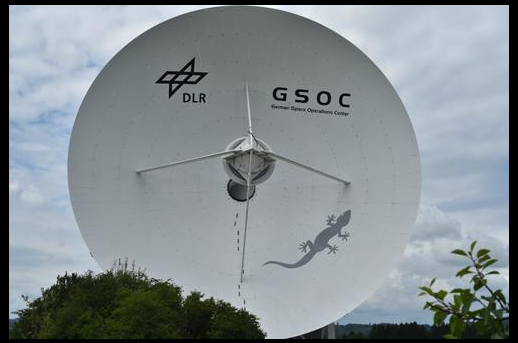
# How Do We Cope With These Challenges?

- Leverage resources around the globe
- Optimize the links to get the most from them when they are used
- Find novel ways to share DSN antennas among missions
- Introduce autonomy and automation wherever we can

# The Global Deep Space Community

- Consultative Committee for Space Data Systems (CCSDS) standards have enabled the world's space agencies to share servicing of deep space missions
- Creates huge flexibility in planning ground station deployment, maintenance, and upgrades



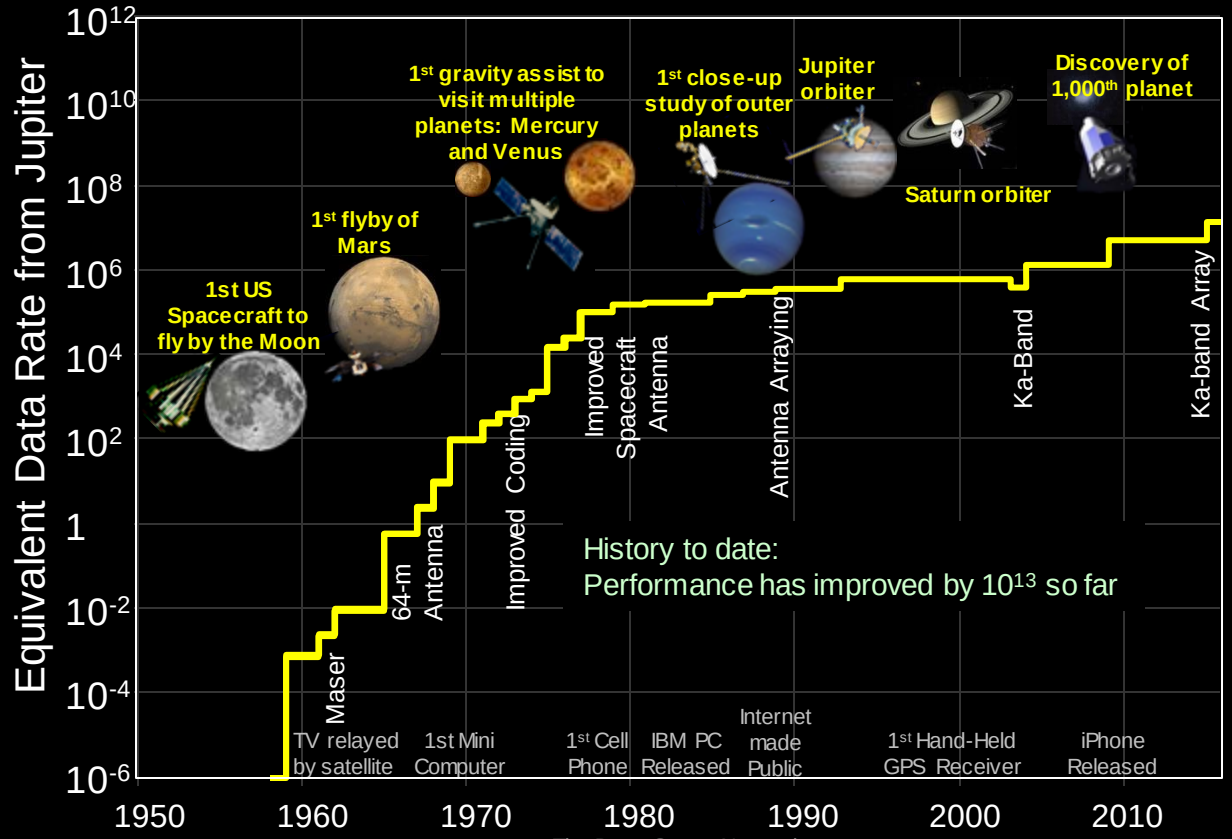


# Federated Network Including Astronomy Dishes

Developing processes to include other DSN-compatible assets in a federated system

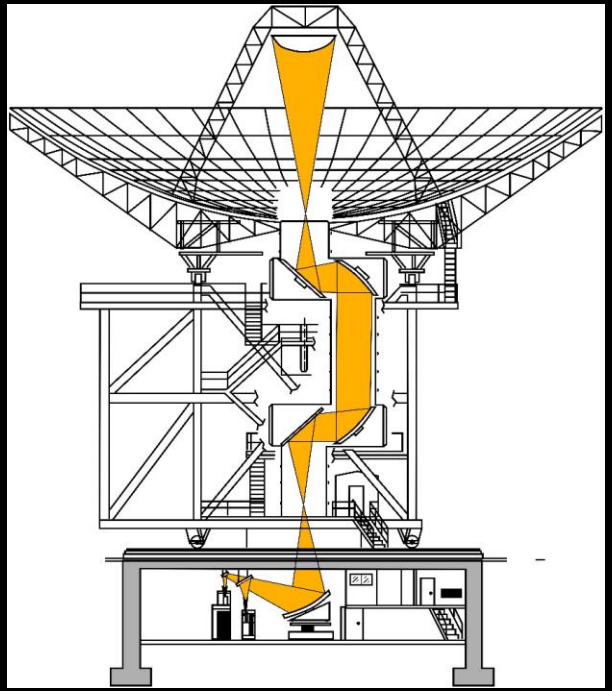
- Parkes 64m antenna tracked Voyager 2 through Heliopause
- Working with ESA and ASI to enable 64m Sardinia Deep Space Antenna

# A Long History of Improving Communications



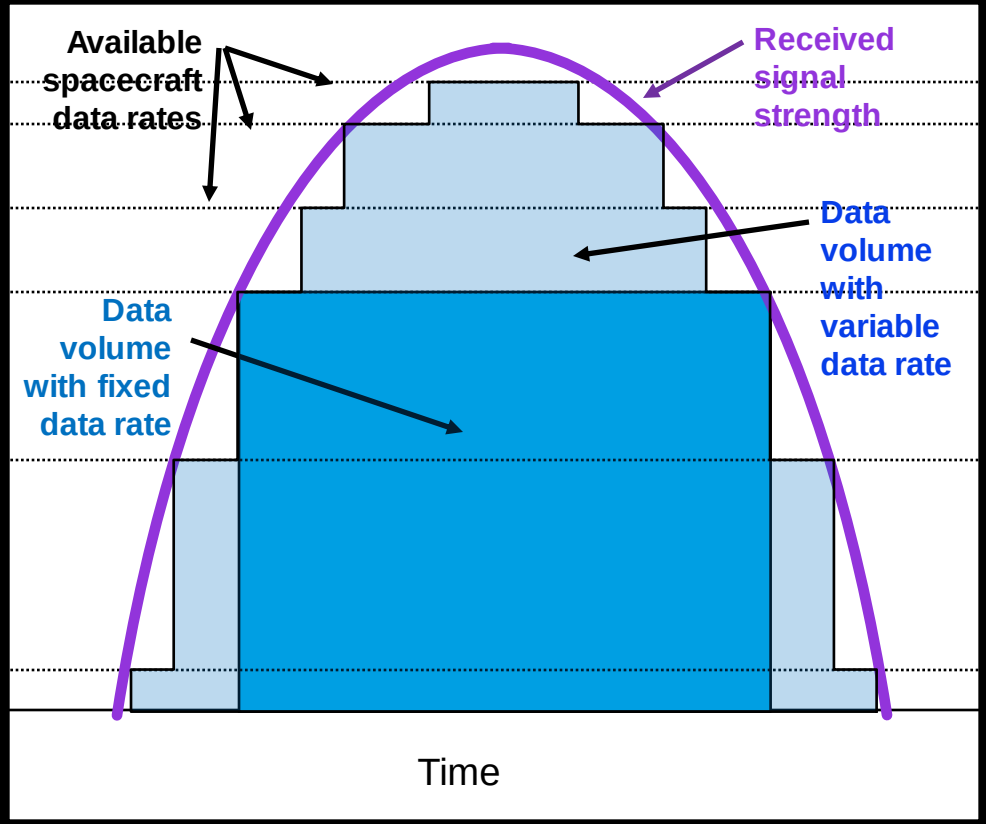
# Beam Waveguide Antennas

- Most DSN antennas are “beam waveguide” in configuration
- All electronics is in environmentally-controlled basement
- Rotating mirror allows many combinations of receivers and transmitters
  - Facilitates multiple link types
- Reduces costs for operations maintenance
  - Reducing mass of tipping structure
  - Cryogenics do not have to tilt
  - Increases safety for maintenance (much less climbing)
  - Stable conditions for electronics means they last longer



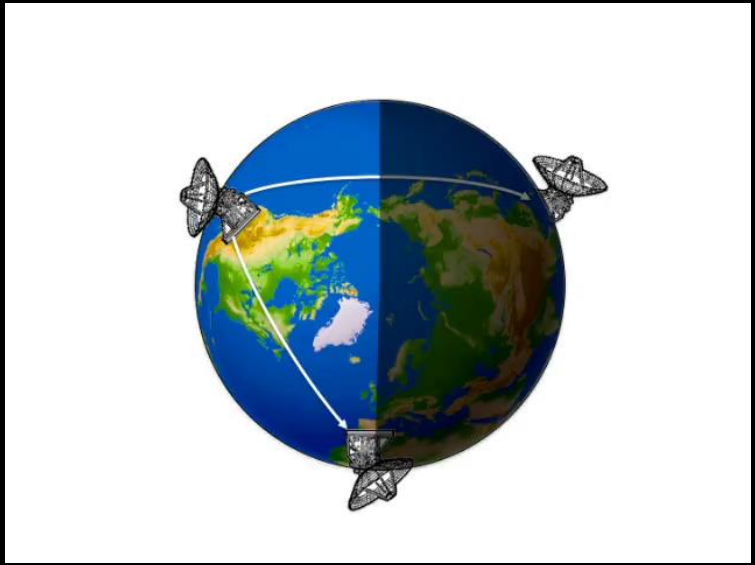
# Variable coding and modulation (VCM)

- Beginning with the Galileo Jupiter mission in the 1990s, deep space comm has used VCM techniques to maximize data on links
- Easy example: variable data rates



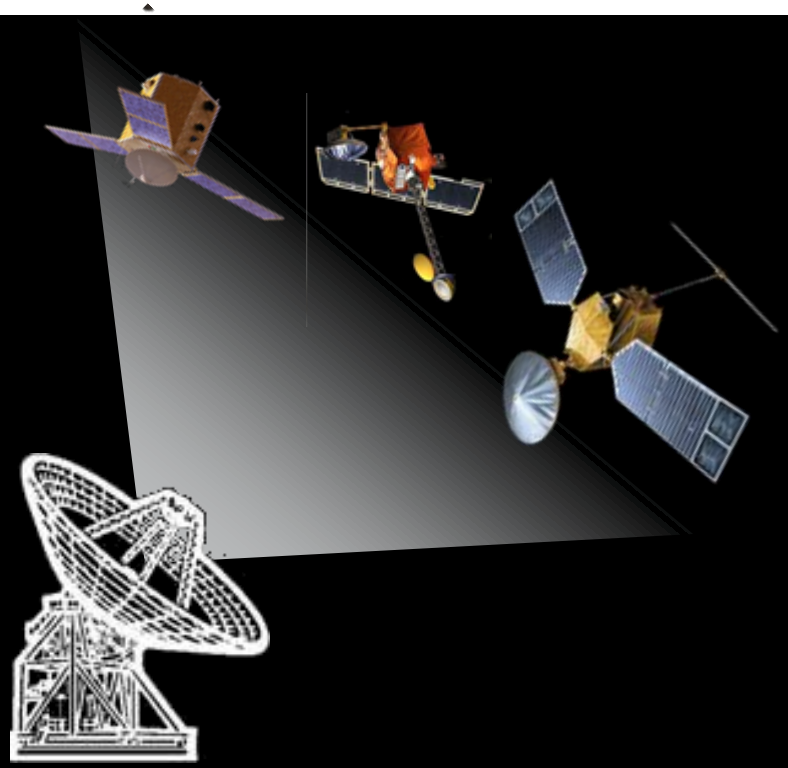
# Automation and Remote Operations

- Gradually, all DSN systems were upgraded to allow for reliable remote operations
- This allowed each operator to controll two links
- We implemented the ability to control links from any of the three locations
- We moved to “Follow-the-Sun” operations
- We are now moving to three links per operator
- All of this enabled the DSN to add six antennas while reducing operations costs by ~40%
- Invested the savings back into DSN upgrades



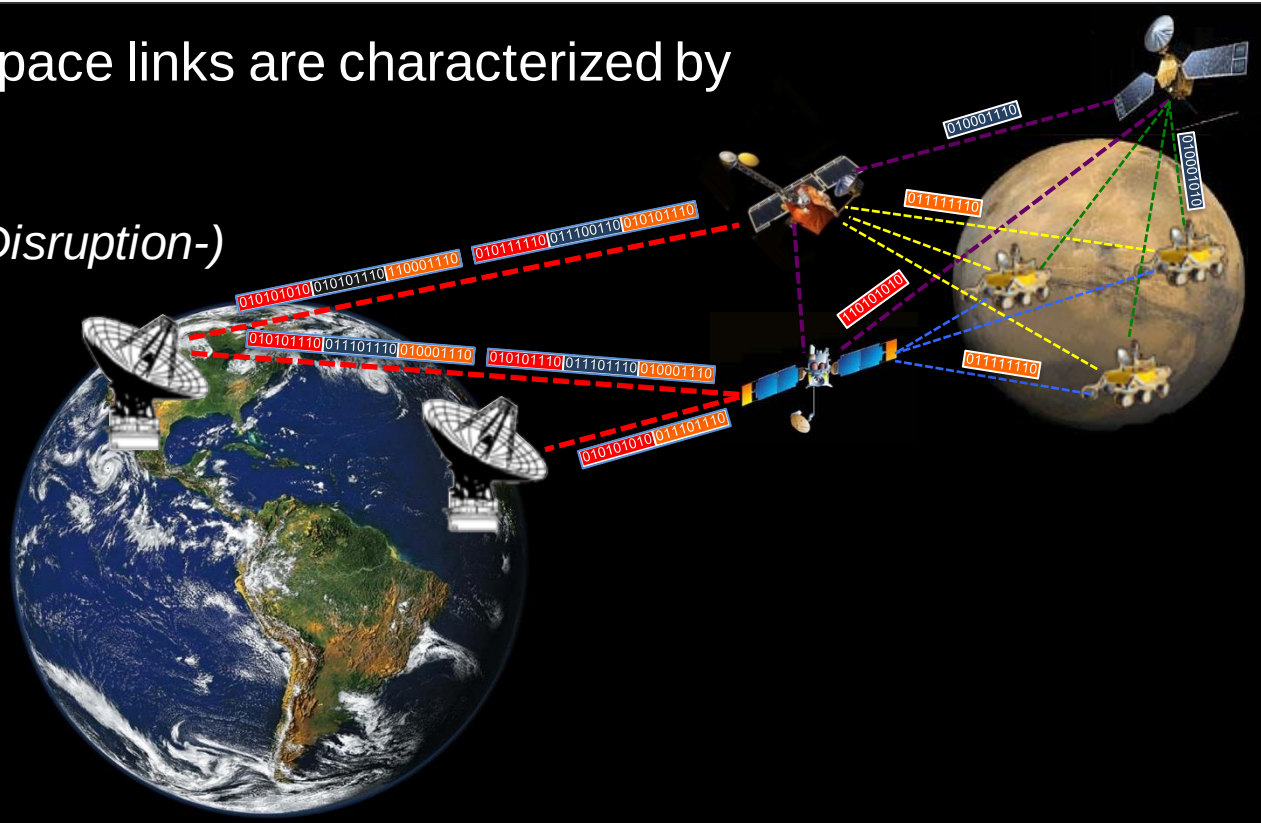
# Multiple Spacecraft per Aperture

- Switching gear and signal processing allow up to four spacecraft in the same antenna beam to be serviced by one DSN antenna
- This means, for example, we can usually track all missions at Mars (and there are a lot of these) with a single antenna at a time
- Working to expand this to essentially an unlimited number of spacecraft – *and receiver crowdsourcing* – to help with NanoSats



# Making Deep Space more Internet-Like

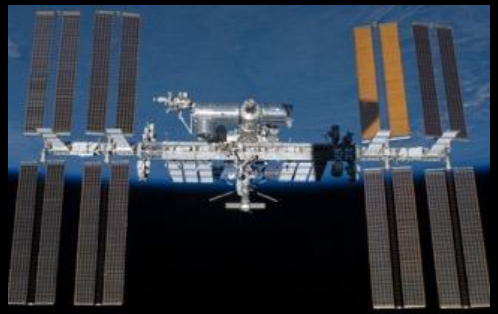
- As mentioned, deep space links are characterized by
  - Delays
  - Disruptions
- So, perhaps *Delay- (or Disruption-) Tolerant Networking* make sense!
- We have been working on DTN for about 15 years



# DTN Benefits for Deep Space Communications

- **Improved Operations and Situational Awareness:** Store-and-forward mechanism and automatic retransmission provides more insight into communication outages and significantly reduces the need for ground-based scheduling
- **Interoperability and Reuse:** DTN protocol suite enables interoperability of communication assets and allows us to use the same stack in LEO, NEO and Deep Space
- **Space Link Efficiency, Utilization and Robustness:** Enables more reliable and efficient data transmission resulting in more usable bandwidth and also improves link reliability by having multiple network paths for communication hops
- **Security:** The DTN Bundle Security Protocol (BSP) allows for integrity checks, authentication and encryption, even on links where not previously used
- **Quality of Service:** The protocol suite allows multiple priority levels to be set for different data types, ensuring that the most important data is received first

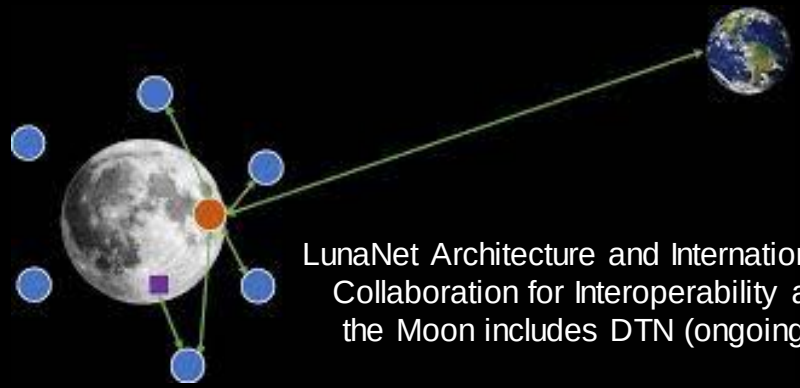
# DTN Infusion – Making it Real



International Space Station
Payload Data Management
Service (2014-Pressent)

Lunar IceCube
First Deep Space
CubeSat DTN
Flight Validation
(June 2022)

Korea Pathfinder
Lunar Orbiter (KPLO)
DTN Experiment
(August 2022)



LunaNet Architecture and International
Collaboration for Interoperability at
the Moon includes DTN (ongoing)

# Conclusion

- Deep space comm is like the Internet – and also unlike the Internet
- We have enabled communications with spacecraft for more than 60 years
  - Communication has improved by a factor of $10^{13}$
- Much more is needed in the future
- The goal is the *Interplanetary Network*, a true Internet-like experience across the Solar System
- JPL is working on this – together with universities and the international community
- This is an exciting field!