Design and Operations of NASA Deep Space Network

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Government sponsorship acknowledged

Speaker Background

Tim Pham is the Chief System Engineer of the NASA Deep Space Network. His interest is in system engineering and system development. Besides DSN system engineering work, he also supports the CCSDS activities in Cross Support Transfer Services and the ground system development at the Morehead State University.

Tim has published several papers on antenna arraying, spacecraft tracking, system modeling and performance analysis. He co-authored the book "Antenna Arraying Techniques in the Deep Space Network". He is recipient of the NASA Exceptional Service Medal, NASA Exceptional Achievement Medal, several NASA New Technology and Space Act Awards, and the IARIA Fellow.

Outline

1. Introduction to DSN
2. Design Considerations for Spacecraft Command and Telemetry
3. Design Considerations for Spacecraft Tracking
4. DSN as a Science Instrument
5. Operational Cost Effectiveness

1. Introduction to DSN

About the DSN

- A U.S. national asset for space communication and research
  - Supporting space exploration by providing communications for NASA and international missions
    - Cross supporting other space agencies (ESA, JAXA, ISRO, etc.)
- Managed by the Jet Propulsion Laboratory in Pasadena, California, under Caltech's contract to NASA

History of JPL

- Timeline
  - 1930's – a site for rocket propulsion research by professor Theodore von Karman of Caltech
  - 1944 – funded by U.S. Army's Ordnance Corp
    - Focused on missile aerodynamics and chemical propulsion
  - 1958 – became part of newly formed NASA
    - Responsible for design and execution of lunar and planetary exploration programs using robotic spacecraft
- Support robotic space exploration
  - Inner and outer planets
  - Orbiters, landers, rovers, planetary flyby missions

History of DSN

- First 26-m antenna at Goldstone, California constructed in1958 for Mariner mission support
- Addition of 64-m antenna (later expanded to 70-m) in 1960's, and 34-m antennas (1980s – present)
- 1958-1975
  - Supporting NASA's first spacecraft flyby to the Moon, Venus, Mars and Jupiter
- 1975- 2000 (highlighted samples)
  - Support Voyager's grand tour of solar system and long-term planetary orbiters: Galileo (Jupiter), Cassini (Saturn)
- 2000-present (highlighted samples)
  - Reconnaissance orbiters: MRO & Odyssey (Mars), Cassini (Saturn), Juno (Jupiter), Stereo & Parker Solar Probe (Sun)
  - Mars rovers: Spirit/Opportunity, Curiosity, Perseverance
  - Exoplanet search: Kepler, TESS
  - Human Exploration at Moon/Mars: Artemis, HLS
  - Cubesat missions – MarCO, Artemis cubesats

DSN as a tool for Space Exploration and Science

- Robotic missions and emerging crewed missions
  - Explorations of the Moon, Solar system bodies and their moons
    - e.g., LRO, Magellan, Juno, Cassini, New Horizons, Voyager
  - Search for evidences of past life
    - e.g., Mars rovers and orbiters
  - Astrophysics studies of exoplanets, cosmic evolution
    - e.g., Kepler, TESS, SIRTF, JWST
- 35+ missions currently supported by the Deep Space Network (DSN)
  - From high Earth orbit to the edge of Solar System
  - Many upcoming deep space cubesats and NASA's sponsored missions from commercial vendors

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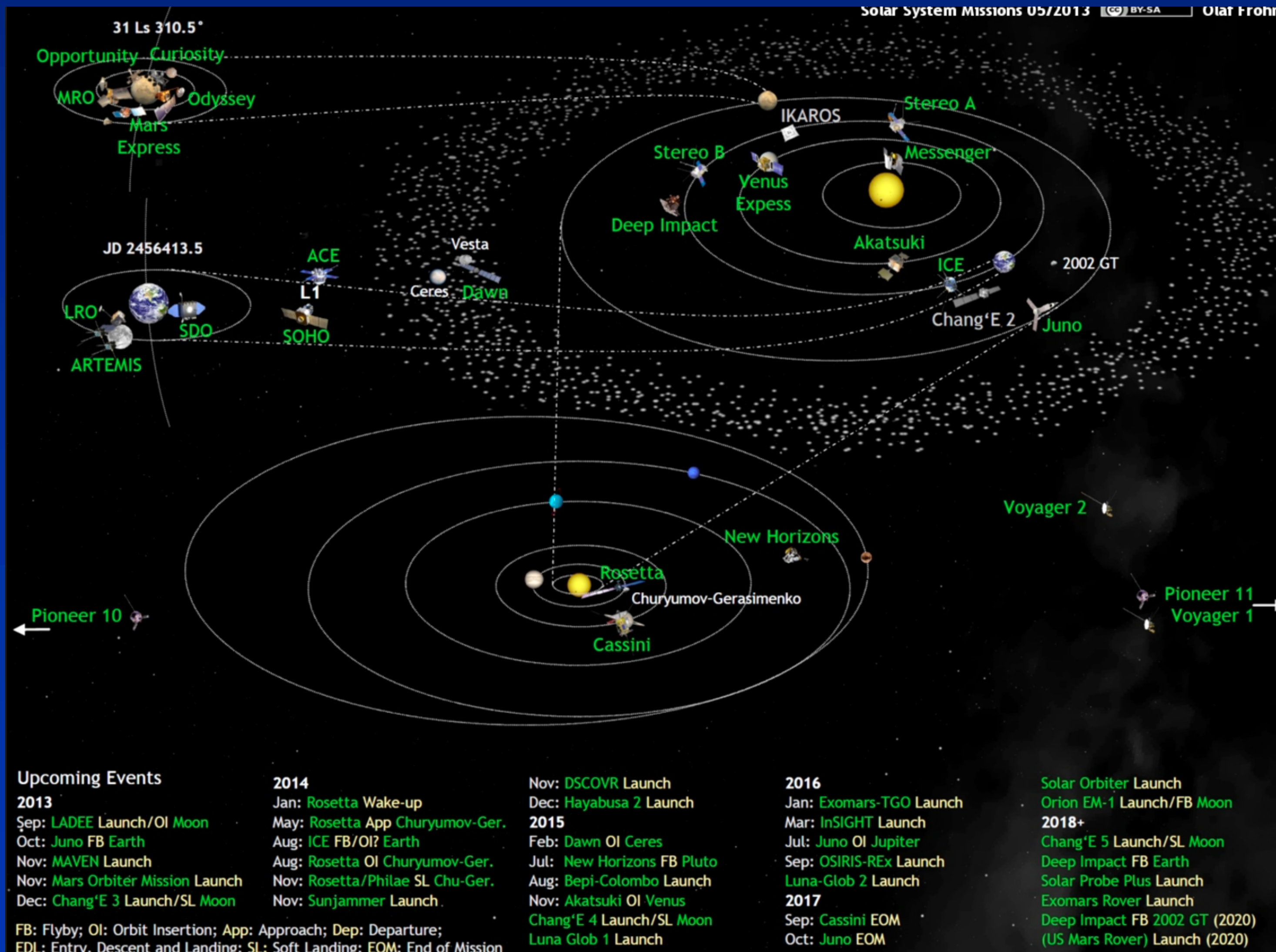
Supported Missions across Solar System



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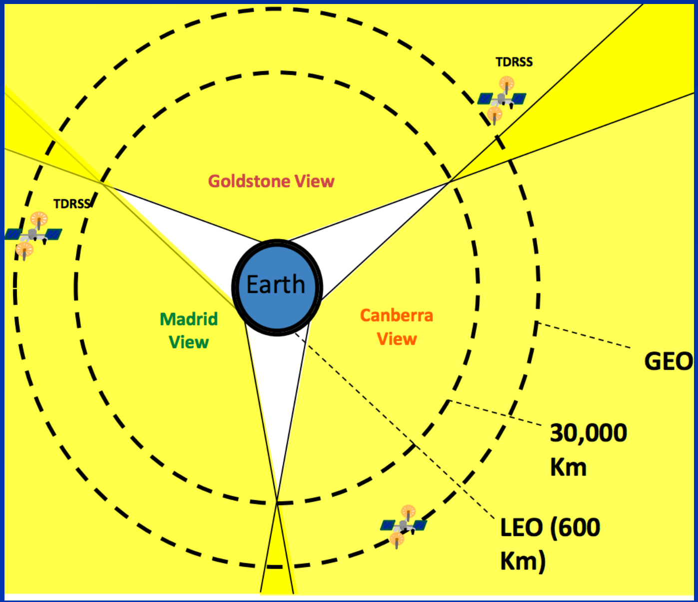
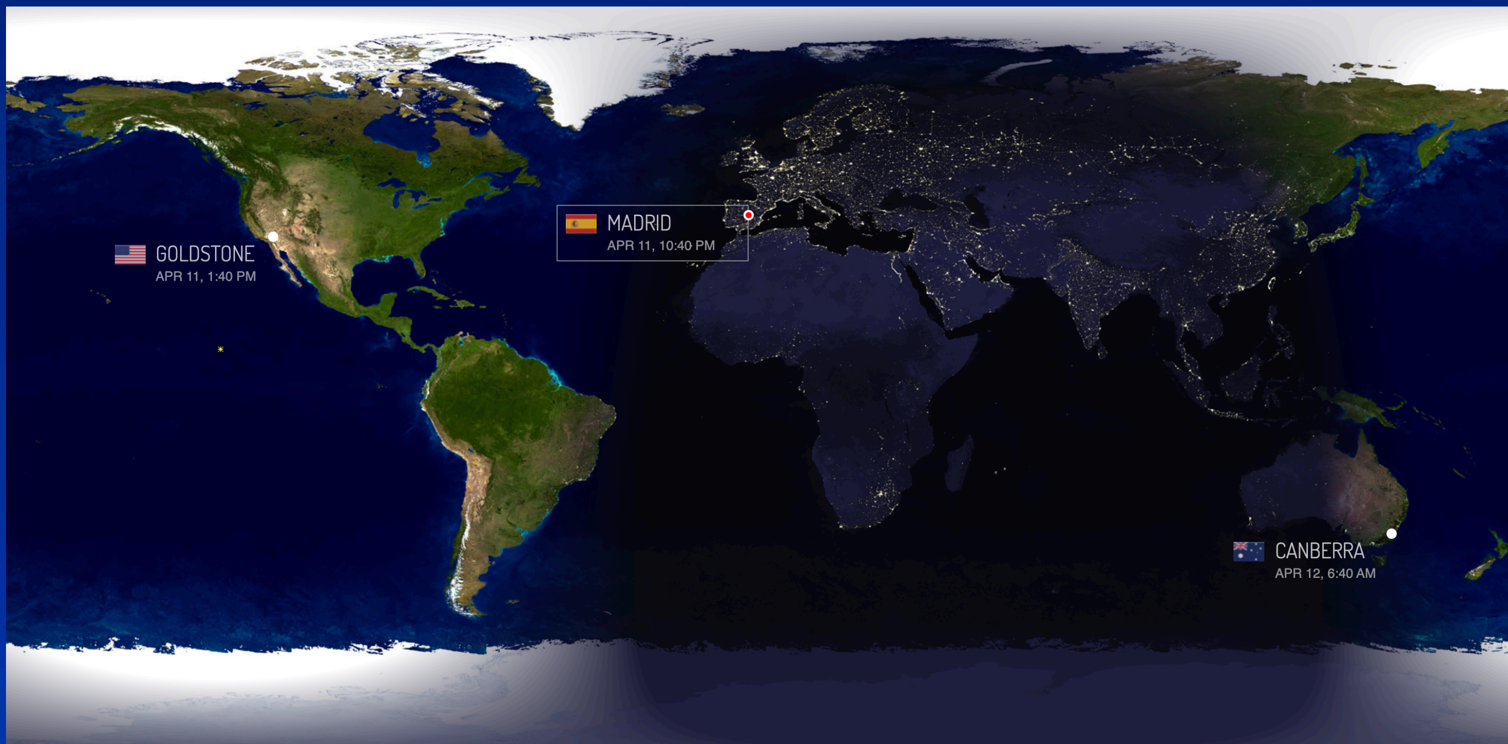
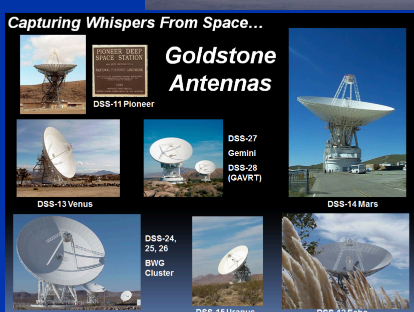
DSN Focus

- Interplanetary spacecraft communications
  - Telemetry, Tracking and Command (TTC)
  - Science (Radio Science, Radar, Very Long Baseline Interferometry & Radio Astronomy)
- Supported Missions
  - Most are NASA missions
  - Few missions from other international space agencies
    - ESA - Integral, Rosetta, Venus Express, Mars Express, etc.
    - JAXA - Hayabusa 1 & 2, etc.
    - ISRO – Chandrayaan 1 & 2, Mars Orbiter

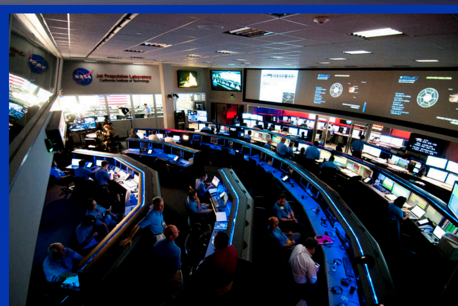


DSN Operations Facilities





Goldstone Complex



JPL Operation Center

Madrid Complex

Canberra Complex

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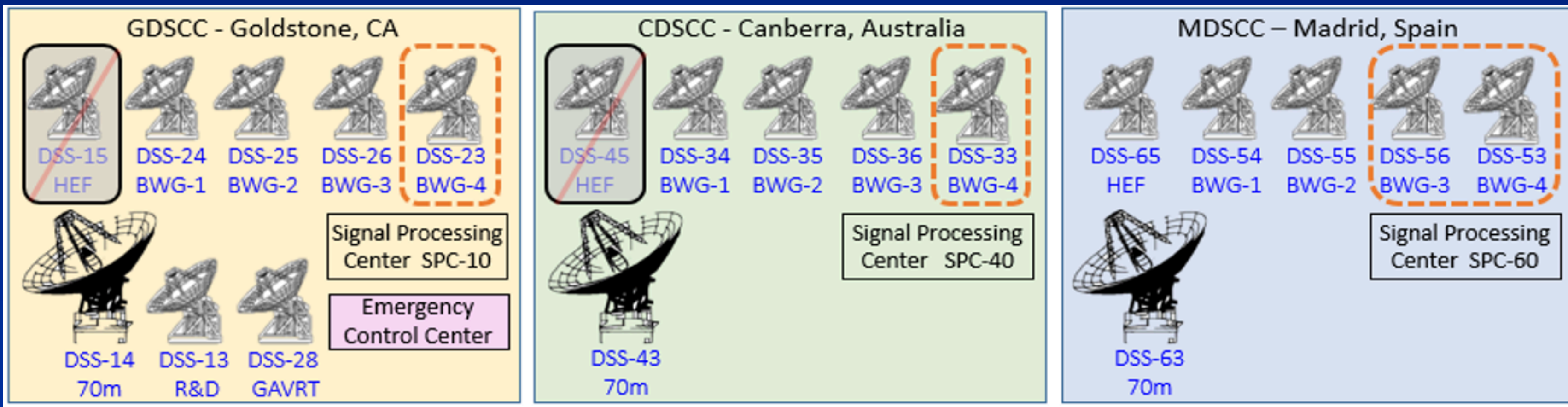
DSN Antennas and Capabilities



Pasadena & Monrovia, CA

- DSN Project Office Pasadena, CA
- Deep Space Operations Center Pasadena, CA
- Remote Operations Center Monrovia, CA
- DTF-21 Monrovia, CA / CTT-22 *Mobile* / MIL-71 KSC, FL

Legend: Decommissioned | New DAEP

Grey - Decommissioned
20kW* - 70m S-band Deep Space Only
20kW* - Will be upgraded to 80kW
400W* - Will be upgraded to 1kW array feed
Green – Upgrade in process now
Red – Future DAEP/DLEU/DSN deliveries
√*, 250W* - Delivered after DAEP shown

REF	Antenna	S-Band		X-Band		K/Ka-Band 22/26 GHz		K/Ka-Band 34/32 GHz		Optical 1550nm	Est. Deliv. Date
		Up	Down	Up	Down	Up	Down	Up	Down	Down	
DSS-14	70m	20kW*	√	20kW*	√						12/2025
~~DSS-15~~	~~34m HEF~~	~~250W~~	~~√~~	~~20kW~~	~~√~~						
DSS-23	34m BWG			20kW	√				√	√*	10/2025
DSS-24	34m BWG	20kW	√	20kW	√	250W	√		√		7/2024
DSS-25	34m BWG			20kW	√			400W*	√		9/2028
DSS-26	34m BWG	250W	√	80kW	√	250W	√		√		11/2022
DSS-33	34m BWG			80kW	√				√	(TBD)	10/2026
DSS-34	34m BWG	20kW	√	20kW	√	250W	√		√		6/2023
DSS-35	34m BWG			20kW	√			1kW	√		9/2026
DSS-36	34m BWG	250W	√	20kW	√	250W	√		√		2/2022
DSS-43	70m	100kW	√	80kW	√						2/2021
~~DSS-45~~	~~34m HEF~~	~~250W~~	~~√~~	~~20kW~~	~~√~~						
DSS-53	34m BWG			20kW	√				√		9/2021
DSS-54	34m BWG	20kW	√	20kW	√	250W	√		√		12/2023
DSS-55	34m BWG			20kW	√			1kW	√		5/2027
DSS-56	34m BWG	250W	√	20kW	√	250W*	√*		√		1/2021
DSS-63	70m	20kW*	√	20kW*	√						12/2023
DSS-65	34m HEF	250W	√	20kW	√						

https://deepspace.jpl.nasa.gov/files/820-100-G1.pdf

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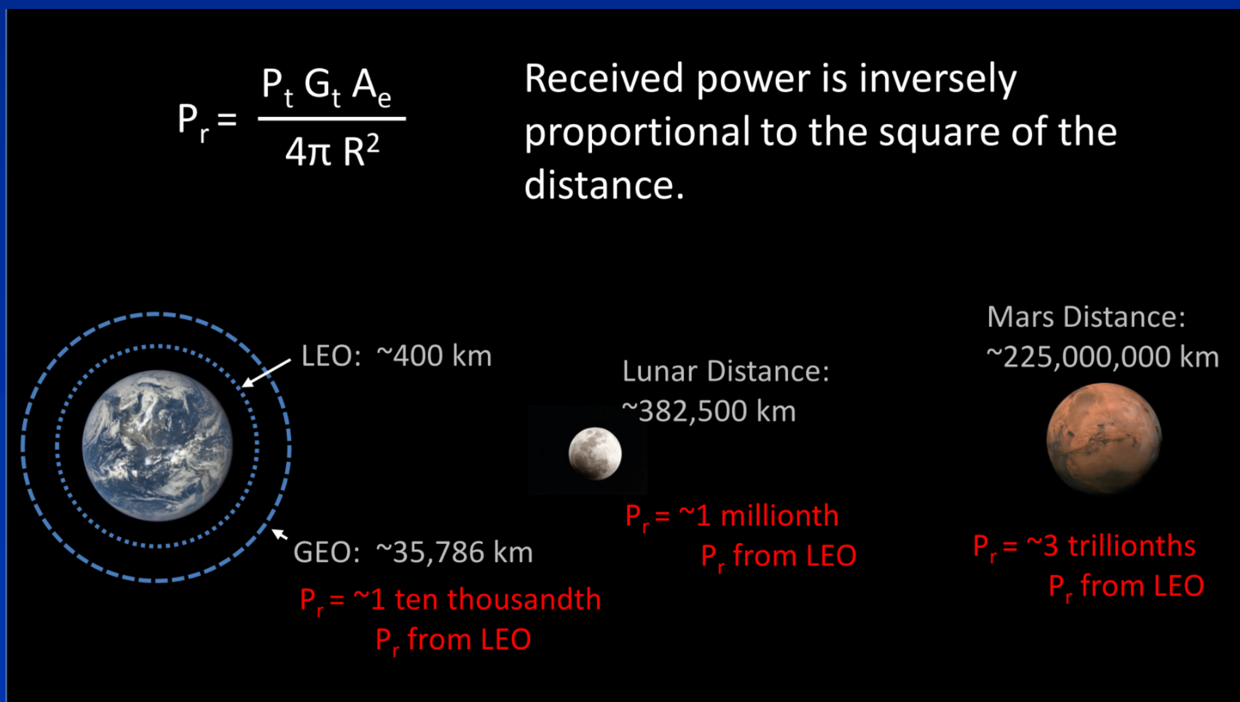
2. Design Considerations for Spacecraft Command & Telemetry

Long Distance, Low Power Communications

- Long distance communications
  - Lunar missions (0.002 AU) to Voyager at 140 AU



D. Abraham, Working Toward More Affordable Deep Space Cubesat Communications: MSPA and OMSPA, *https://www.dropbox.com/sh/fx8auva239g0wx9/AADMzWa7wgXpl0KmmoFk2rgaa/D2-Abraham?dl=0&preview=ISSC2016_WorkingTowardAffordableCommunications_URS257550.pptx#*

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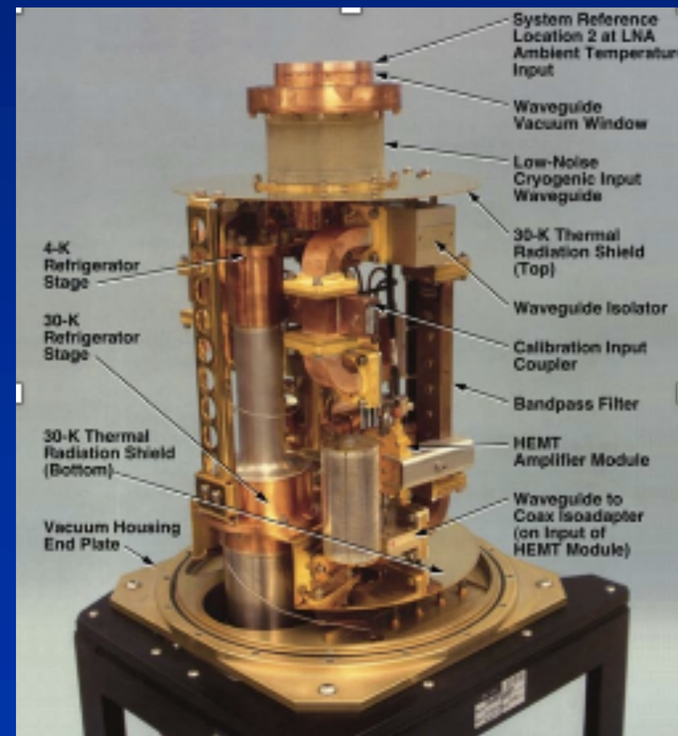
70-m Antennas

- Largest and most sensitive antenna in the DSN
  - First 64-m antenna constructed at Goldstone in 1966 to extend communications to missions beyond Mars
  - Later expanded to 70-m in 1988 for Voyager 2's Neptune encounter
- Weigh 2.7 million kg
- Antenna structure floats on a thin film of oil of thickness of a sheet of paper
- Surface accuracy within 1 cm across its 3850 sq-m parabolic reflector

Ref. https://www.nasa.gov/directorates/heo/scan/services/networks/deep_space_network/complexes

Design Focus in Deep Space Communications

- Low-power communications require
  - Antenna with maximum G/T
    - Large aperture (34-m/70-m)
    - Cryo-cooled LNA with very low system noise temperature (< 10 K)
  - Modulation & coding optimized for low power regime
    - Typical modulation: BPSK, QPSK
    - Typical coding: Convolutional, Reed Solomon, Concatenated, Turbo, Low-density parity check
    - Special operations:
      - MFSK for Entry Descent Landing for extreme low SNR and quick detection
      - Beacon for long duration flight
  - Maximum EIRP for emergency search



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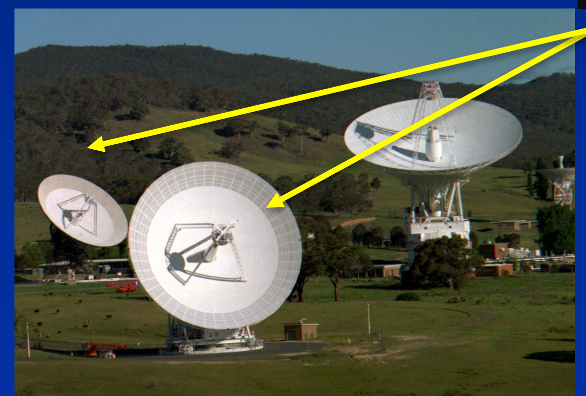
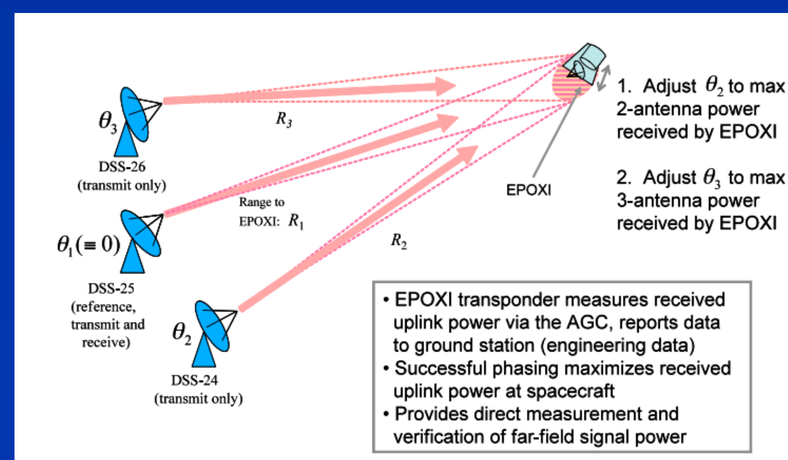
Antenna Array for Low Signal Conditions

- A way to enhance antenna aperture and signal reception
  - Used for support to Voyager, Spitzer, New Horizons missions
- Downlink array
  - Aperture combining - Multiple 34-m or in combination with 70-m antenna
  - Polarization combining on 70-m
- Uplink array (R/D capability)
  - Achieve gain proportional to N^2, instead of N as with downlink, where N=number of antennas





Ref.: Vilnrotter, Uplink Array Concept Demonstration with the EPOXI Spacecraft, IEEE Aerospace, 2009

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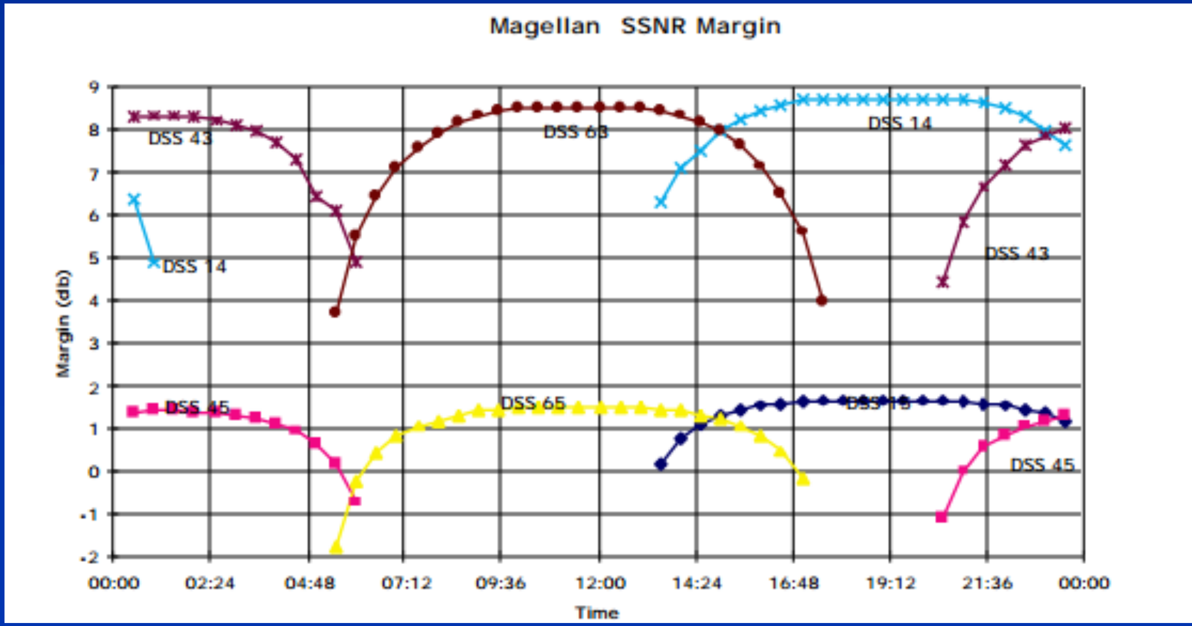
Maximizing Data Return via Adaptive Data Rate

- Adjusting data rate per available link margin during the pass
  - More important at higher operating frequency
    - Steeper curve of G/T vs. elevation
  - Higher performance with continual adjustment of data rate
    - Discreet data rate adjustment used in today operations
    - Continuous data rate adjustment in future spacecraft



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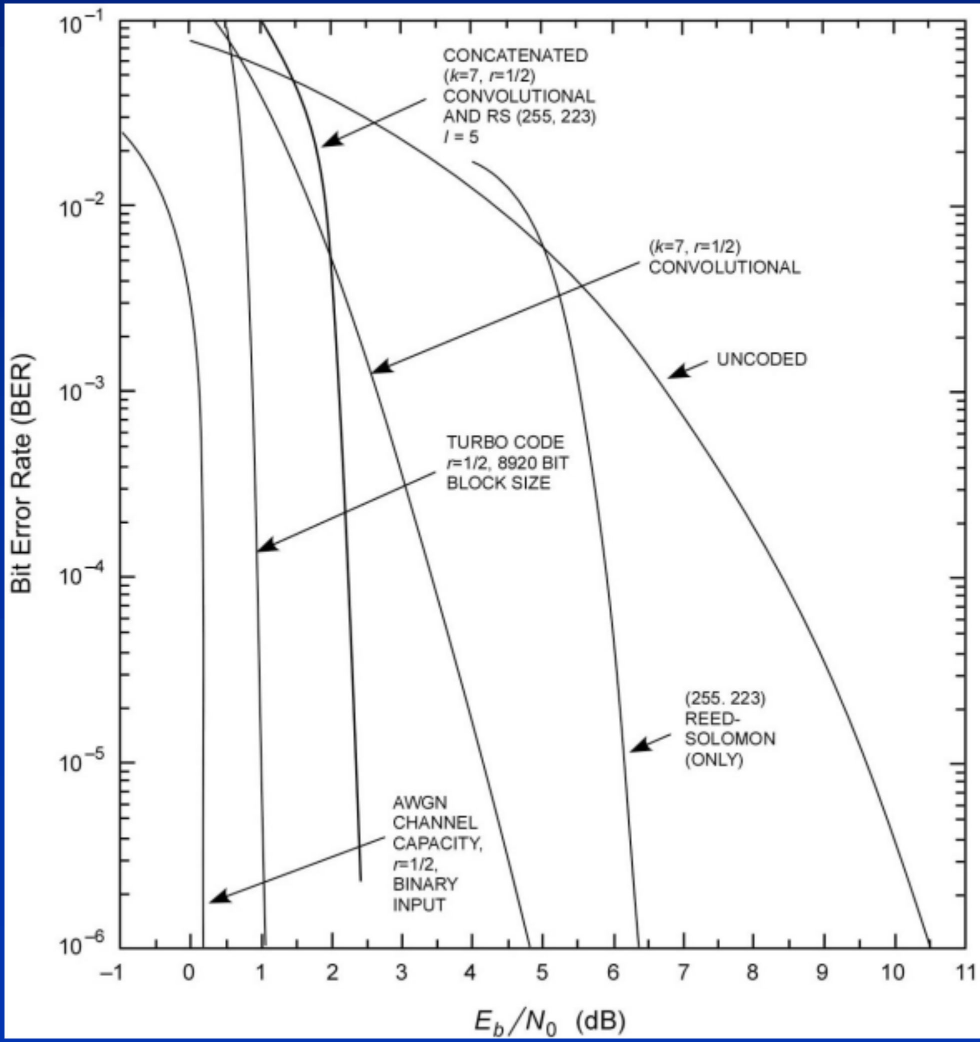
High Performance Coding

- Trading complexity (with forward error correction processing) for better coding gain
- Reach within 1 dB of AWGN channel capacity
- Various codes supported: Convolutional, Reed Solomon, Concatenated, Turbo, and Low-Density Parity Check



http://deepspace.jpl.nasa.gov/dsndocs/810-005/208/208A.pdf

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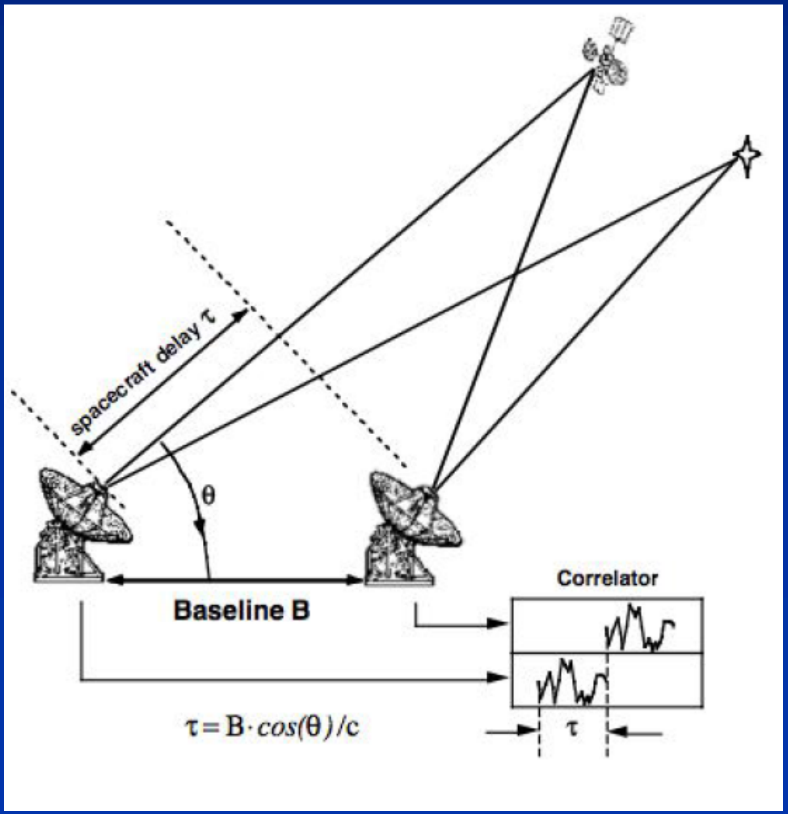
3. Design for Spacecraft Tracking

Doppler & Ranging

- Doppler & Ranging data enable accurate orbit determination and precise mission navigation
- Precise measurement of Doppler and Ranging
  - 50 microHz/s Doppler (7E-16 of X-band carrier freq)
  - 1-m ranging (2E-13 of Pluto distance/New Horizons flyby)
  - 2-way vs. 3-way measurements
- Calibration data improve accuracy and minimize systematic errors
  - System ranging calibration
  - Earth orientation parameters
  - Media delay in Earth troposphere and ionosphere
  - Time and frequency offset among the three DSN sites

Delta-Differential One Way Ranging Technique

- Use of Delta-DOR to complement Doppler/Ranging
  - Best for plane-of-sky position measurement where traditional Doppler and ranging are less sensitive
  - Delta measurement with quasar and spacecraft remove systematic error in equipment and Earth media
  - Require Catalog for X- and Ka- band radio sources
  - Require equipment with wideband recording and stable delay



Ref:, J. Border et al. – Radiometric Tracking for Deep Space Navigation, American Astronautic Society, 2008

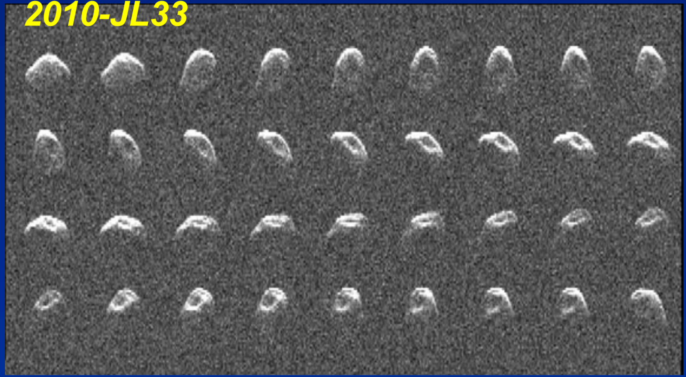
4. DSN as a Science Instrument

Goldstone Solar System Radar

- Research focus
  - Planetary radar
  - Asteroid detection
- High power transmitter 500 kW, X-band
- Co-observing with Arecibo Observatory(1)
  - Aerocibo: 305-m, S-band, 30% sky view, 20x sensitivity
  - GSSR: 70-m, S/X-band, 80% sky view, higher resolution

(1) *Arecibo became non-operational in 2020*

2010-JL33



http://www.spaceref.com/news/viewpr.html?pid=32483

2012-DA14

http://www.space.com/19804-asteroid-flyby-nasa-radar-2012-da14.html

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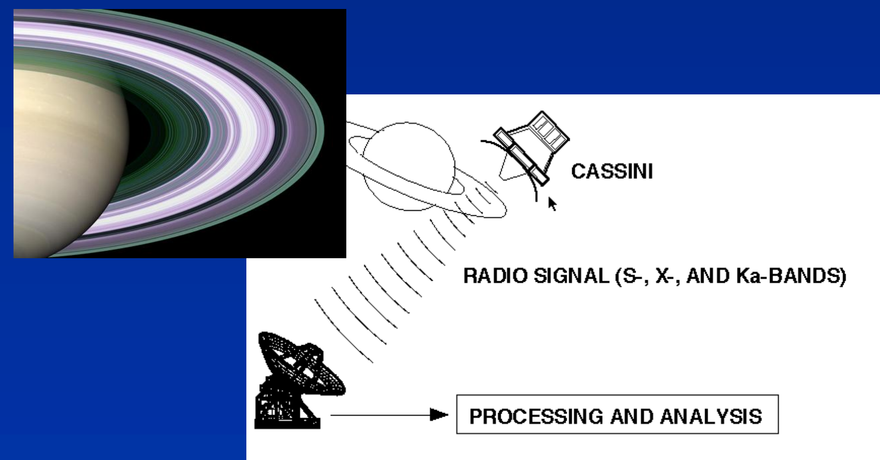
Radio Science

- Properties of planet's atmosphere or planetary ring can be studied from measurements of received signal's phase, frequency and amplitude
  - Change in signal amplitude reveals information on object's density
  - Change in signal frequency, with proper signature, reveals possible passing gravitation wave
- Require very high frequency stability and spectral purity in system performance



http://saturn.jpl.nasa.gov/spacecraft/cassini orbiterinstruments/instrumentscassinirss/

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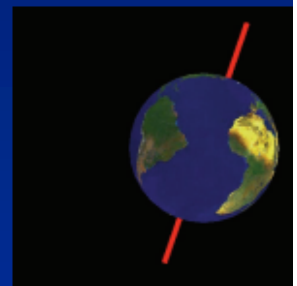
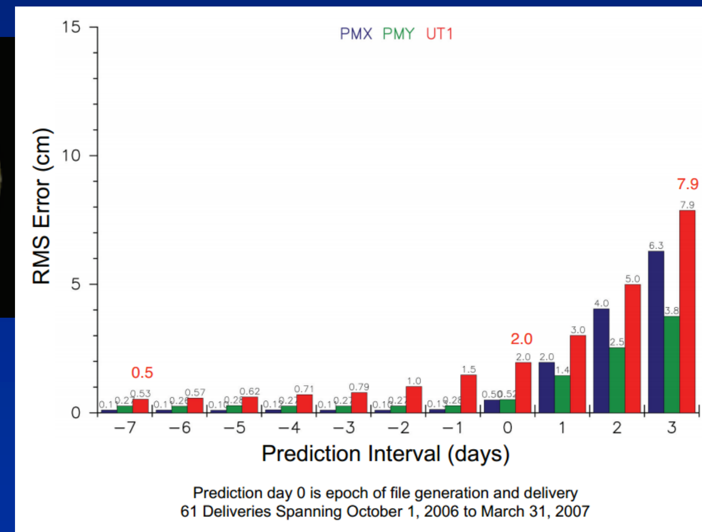
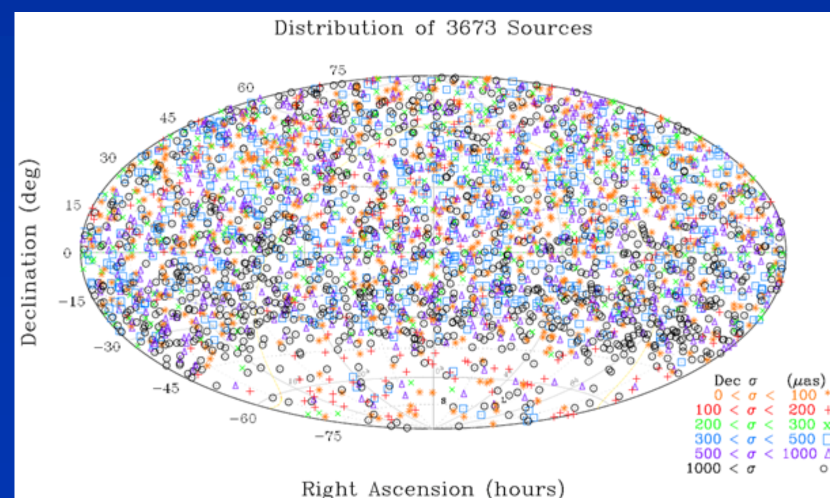
Very Long Baseline Interferometry & Radio Astronomy

- Study Earth deformation and rotational change through Time/Earth Motion Precision Observation (TEMPO) measurements
  - Location of spin axis relative to celestial frame (precession-nutation motion), terrestrial frame (polar motion), angle that Earth rotates about spin axis (spin)
  - Data also used to improve spacecraft navigation
- Characterize signal fluctuation of cataloged quasars at X- and Ka-band





http://www.cbk.waw.pl/~kosek/EOPPW2009/contributions/session1/session1.3/tue04_Gross.pdf



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Performance Considerations

- High frequency/phase stability
  - Co-observing phase calibration required
- High recording bandwidth
  - The signal is in the noise!
- Low latency in data delivery
  - Data transfer over WAN is a challenge
- High power transmitter for radar
  - Reliability considerations

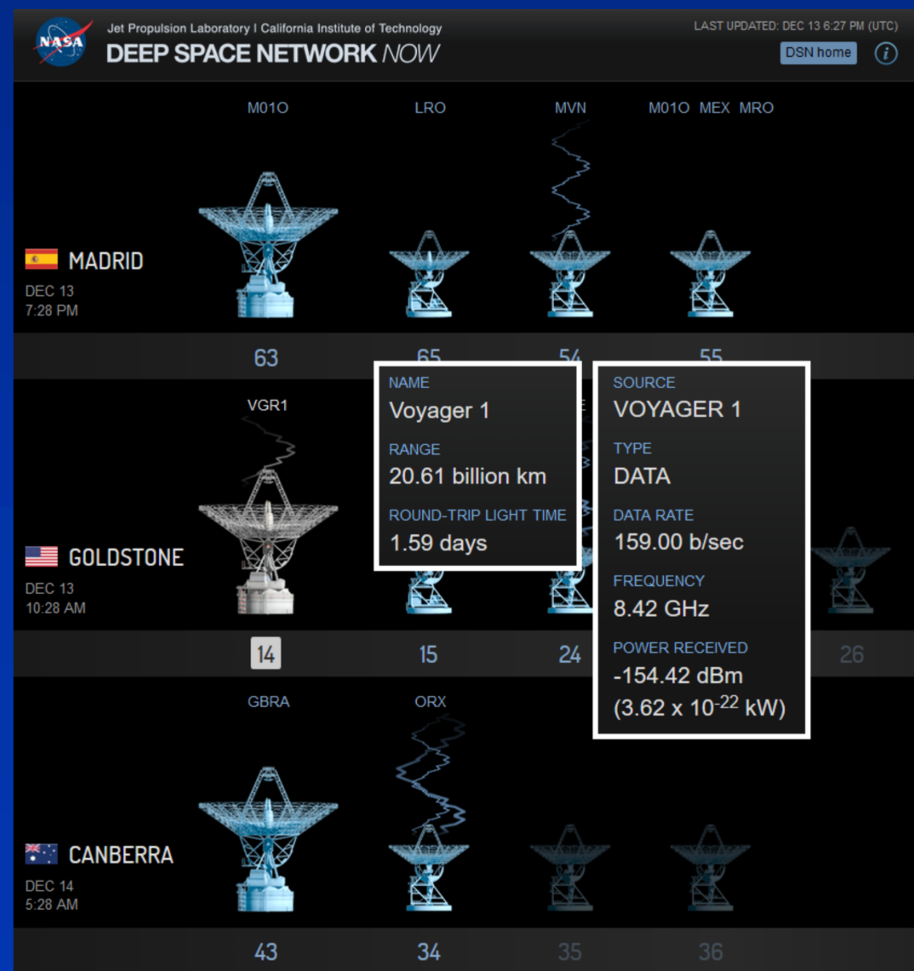
5. Operations Effectiveness

Operational Efficiency

- Emphasis on cost saving via operational efficiency
- Increase tracking time via multiple spacecraft per antenna
  - Required co-location, e.g., Mars or lunar orbiters
- Operated with multiple-link per operator and follow-the-Sun operations
  - Automation of equipment setup and execution of pre-defined events during track
  - Promote more standard procedures and preplanned inputs, and less on real-time changes
- Use of CCSDS standard data interface
  - Increase cross support with other space agencies (e.g., ESA) while reduce engineering effort on mission-specific interfaces

Follow the Sun Operations

- Moving DSN operations from where each DSN Complex controlling its antennas to a global operations where each Complex takes turn to operate the entire DSN
  - Reducing the Complex staffing from around the clock to 8-9 hrs/day



https://eyes.nasa.gov/dsn/dsn.html

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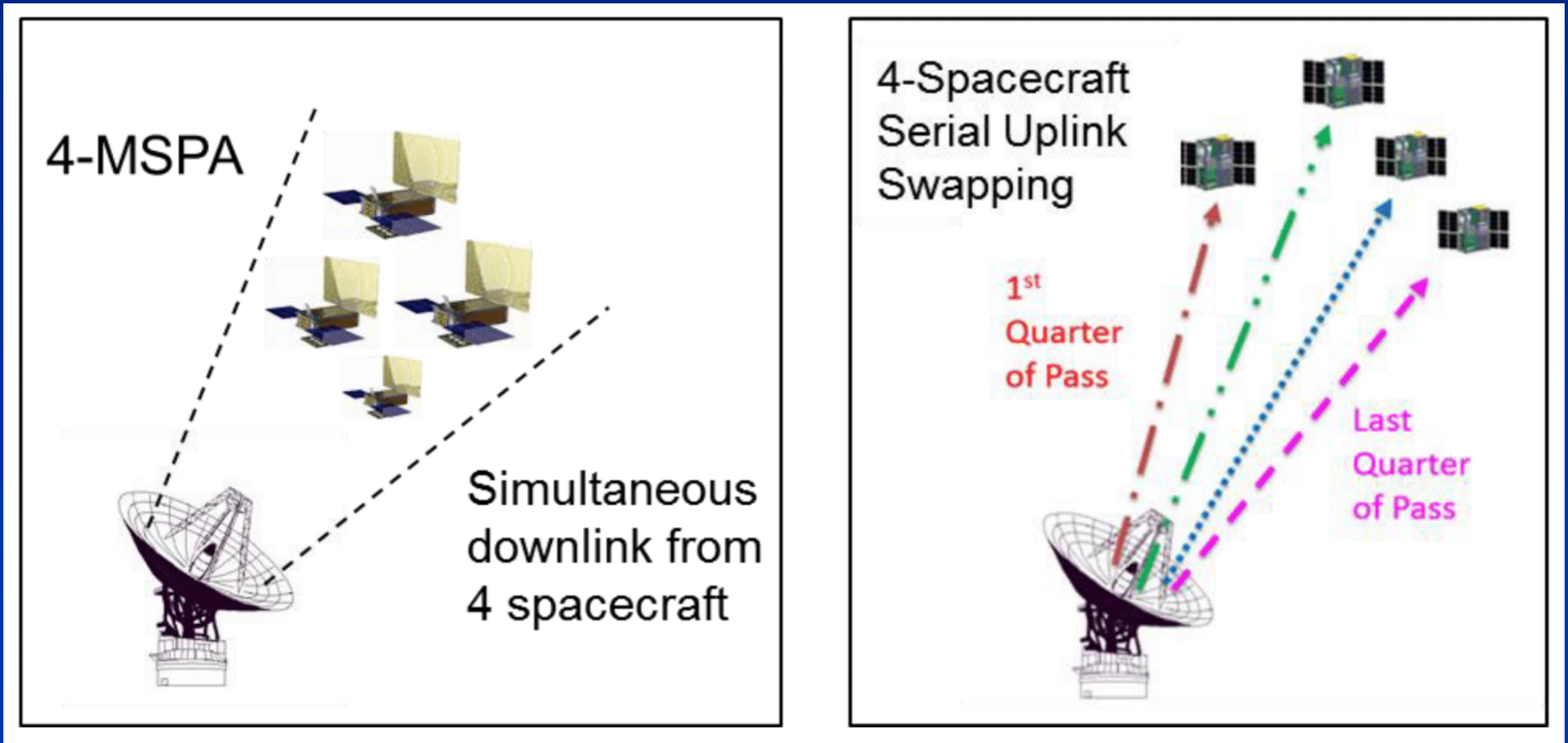
Multiple Spacecraft per Antenna Operations



D. Abraham, Working Toward More Affordable Deep Space Cubesat Communications: MSPA and OMSPA, *https://www.dropbox.com/sh/fx8auva239g0wx9/AADMzWa7wgXpI0KmmoFk2rgaa/D2-Abraham?dl=0&preview=ISSC2016_WorkingTowardAffordableCommunications_URS257550.pptx#*

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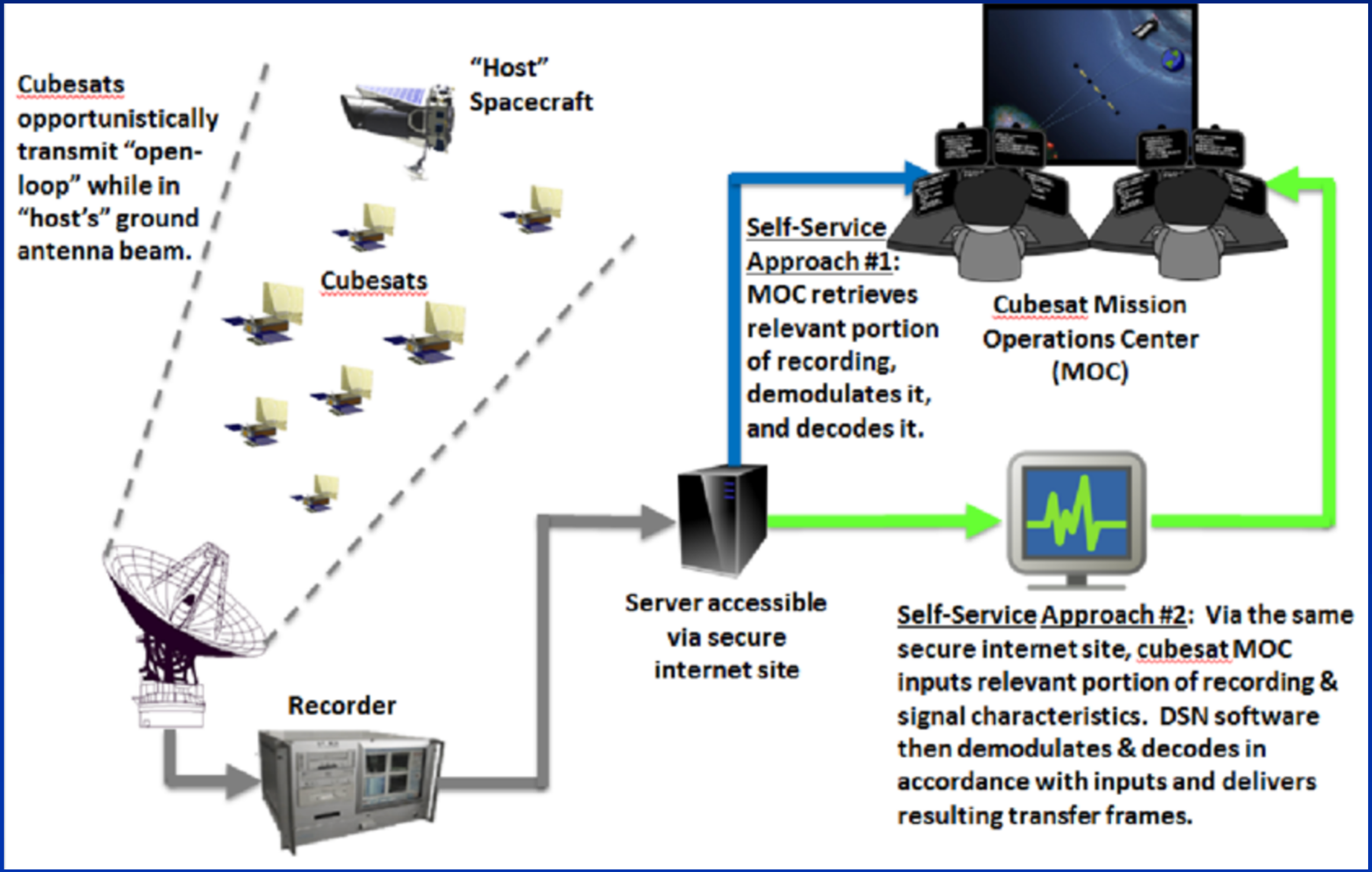
Opportunistic Multiple Spacecraft per Antenna Operations



D. Abraham, Working Toward More Affordable Deep Space Cubesat Communications: MSPA and OMSPA, *https://www.dropbox.com/sh/fx8auva239g0wx9/AADMzWa7wgXpI0KmmoFk2rgaa/D2-Abraham?dl=0&preview=ISSC2016_WorkingTowardAffordableCommunications_URS257550.pptx#*

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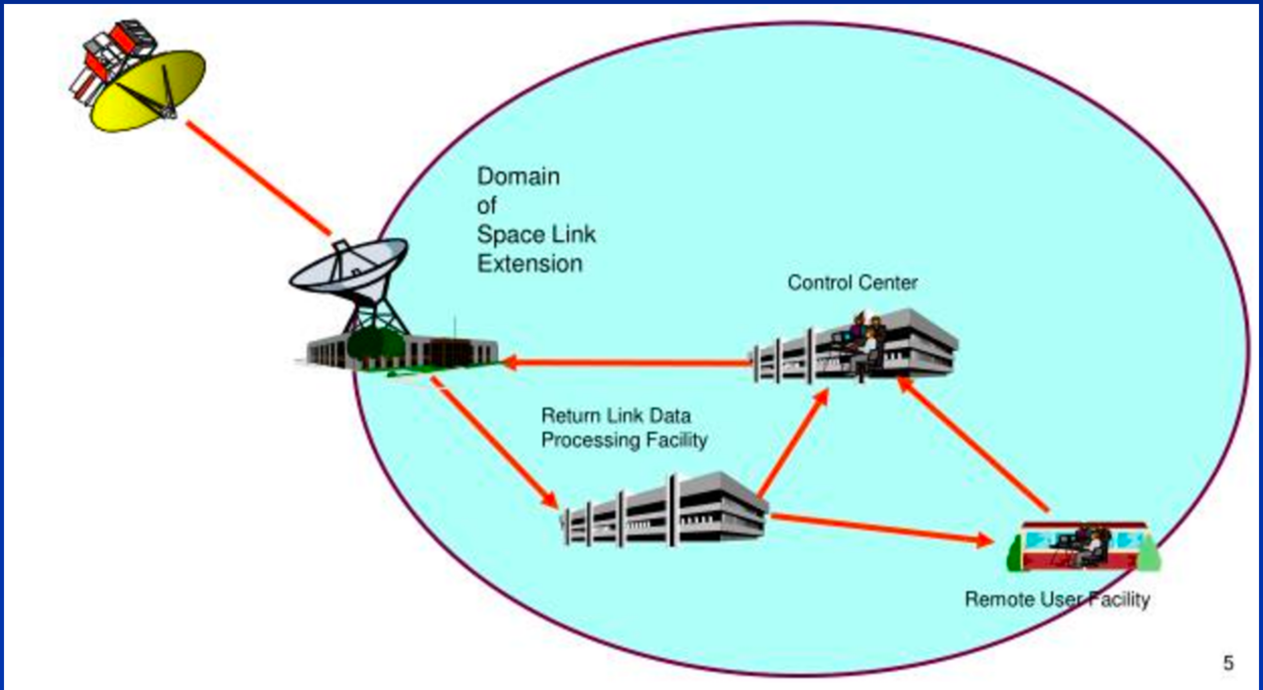
Standard Data Delivery via CCSDS Space Link Extension

- Enable one mission user to interface with the ground station in a standard way (CCSDS specifications)
  - Cross support service from one space agency to another



M. Kearny & E. Barkley, CCSDS SLE and CSS Space Link Extension Cross Support Services

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Summary

- DSN is a key contributor to robotic and human space exploration
- Designed for maximal signal reception with extremely low noise and large antennas, and different techniques of modulation, coding, and arraying
  - Migration to higher operating frequencies for better link performance and wider bandwidth allocation
- Produce highly accurate radiometric measurements for mission navigation
  - Delta DOR technique & media calibration enhance standard Doppler & Ranging
- Serve as a ground-based science instrument for radio science, planetary radar and radio astronomy research
  - Amplitude & phase stability are key to science observations
- Continually improve operational efficiency
  - Achieved through use of multi-links per operator, follow-the-sun operations, multiple spacecraft per aperture, CCSDS standard interfaces