Unique Challenges in System Design and Operations for Deep Space Communications

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Outline

1. Deep space communications
2. Deep space tracking
3. Science observations
4. Frequency spectrum considerations
5. Operational considerations

1. Deep Space Communications

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Applications – Space Science Research

- Answer key scientific questions such as
  - Are we alone in the universe?
  - How did the universe start?
- Robotic missions and emerging crewed missions
  - Explorations of the Moon, Solar system bodies and their moons
    - e.g., LRO, STEREO, Magellan, Mars rovers, Juno, Cassini, New Horizons, Voyager
  - Astrophysics studies of exoplanets, cosmic evolution
    - e.g., Kepler, TESS, SIRTF, JWST

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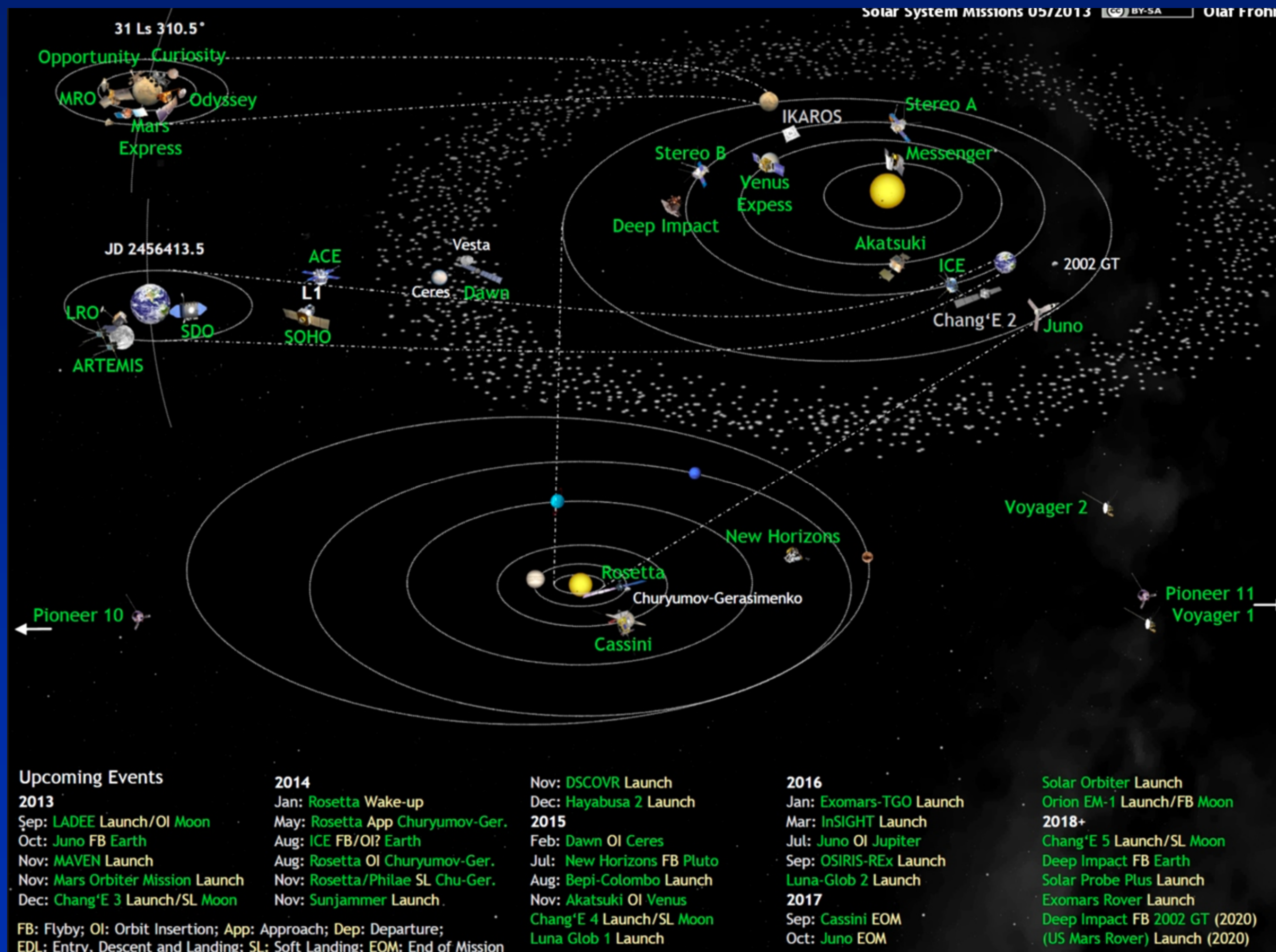
Missions in various corner of the universe



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NASA/JPL Missions

- 35^+ missions currently supported by the Deep Space Network (DSN)
- Many upcoming deep space cubesats

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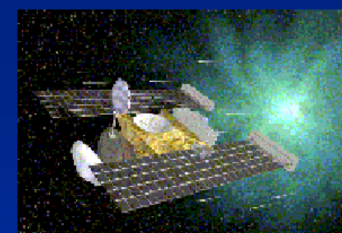
Vision: JPL's legacy by 2020

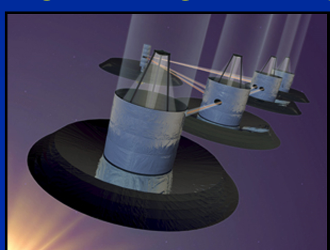
Established a continuous presence *around* and *on the surface* of Mars

Explored the Jovian and Saturnian satellites in detail and probed their surfaces and interiors for possible pre-biotic and life-favorable environments.

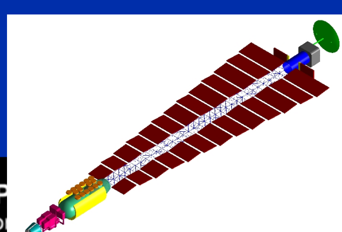
Returned first samples from other solar system bodies beyond the moon.



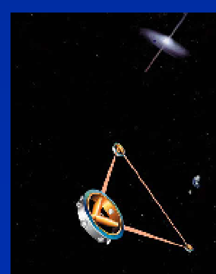
Began exploring neighboring solar systems.



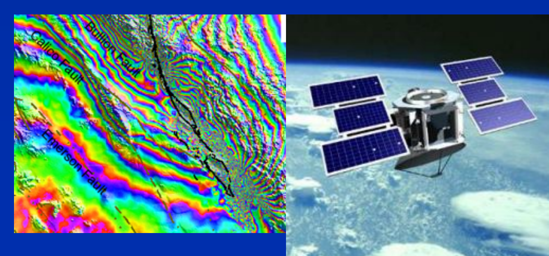
Enabled efficient access to all the bodies of the solar system



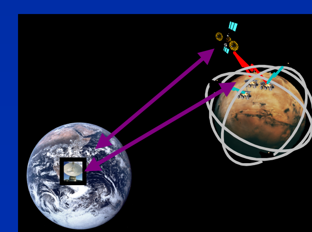
Explored the boundaries of physics to understand the forces that powered the Big Bang



Established operational capability to monitor dynamics of solid Earth and its oceans and atmosphere.



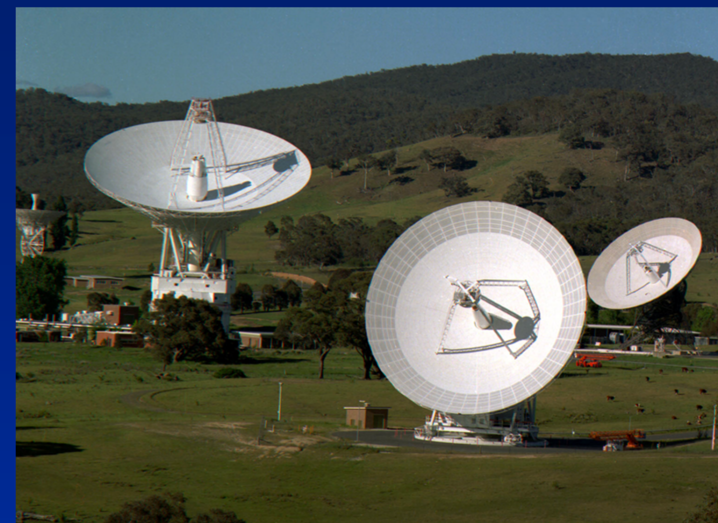
Established the Interplanetary Network, which is being commonly used by students.

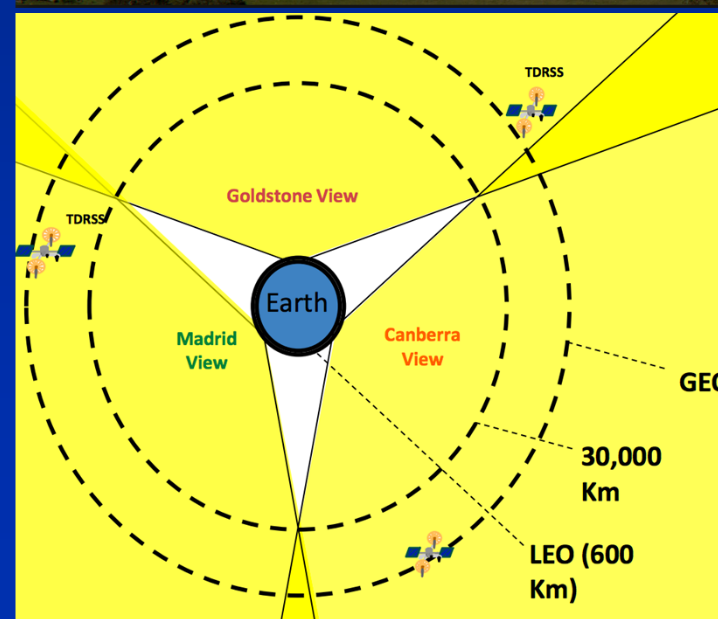


Ref.: Elachi, C., Space Exploration in the Next Decade: Challenges and Opportunities, Mar. 2004

Deep Space Communications Networks

- International space agencies
  - NASA, ESA, JAXA, etc.
    - Large aperture antennas (30-70 m)
  - Mission support
    - Mostly network centric
    - Some cross support
- Interplanetary spacecraft communications
  - Telemetry, Tracking and Command (TTC)
  - Science (Radio Science, Radar, Very Long Baseline Interferometry)





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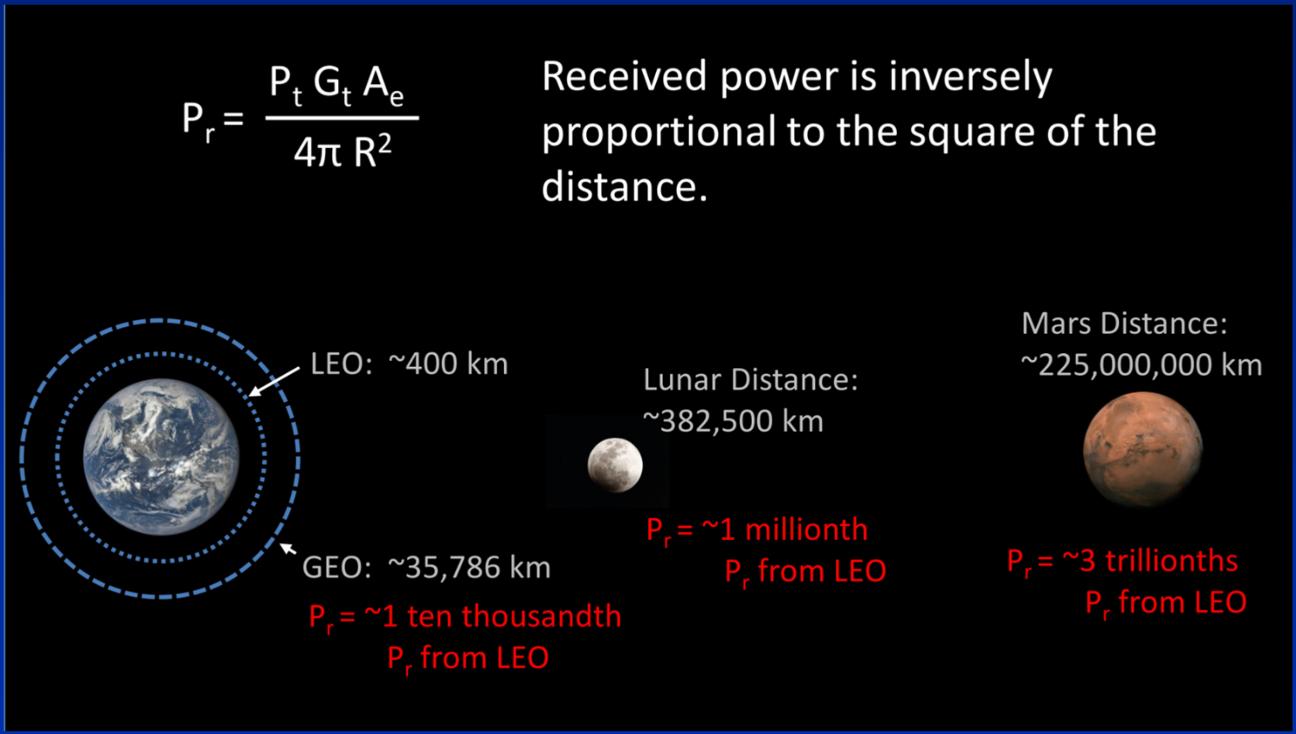
Large Distance, Low Power

- 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/AADMzWa7wgXpI0KmmoFk2rgaa/D2-Abraham?dl=0&preview=ISSC2016_WorkingTowardAffordableCommunications_URS257550.pptx#*

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Technical Focus in Deep Space Communications

- Low-power communications require:
  - – Large antenna with maximum G/T
    - Cryo-cooled LNA
  - – Modulation & coding optimized for low power regime
    - Typical modulation: BPSK, QPSK
    - Typical coding: Convolutional, Reed Solomon, Concatenated, Turbo, Low-density parity check
    - Special operation:
      - – MFSK for EDL
      - – Beacon for long duration flight
  - – Maximum possible EIRP for emergency search

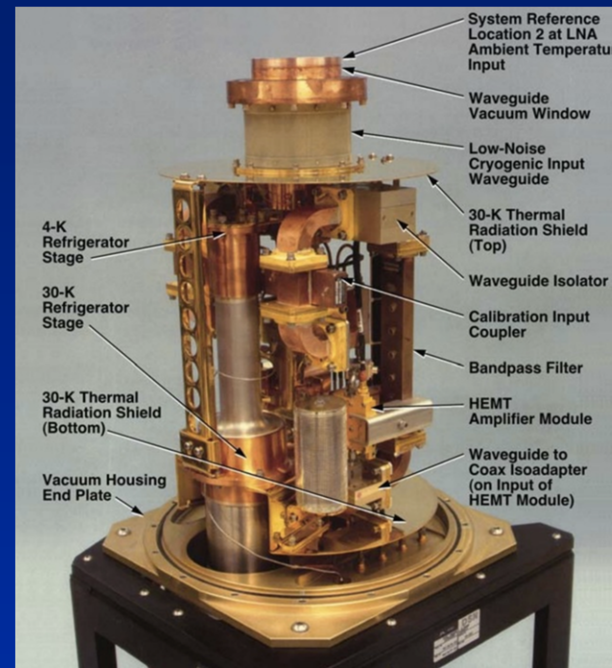

Fig. 2-12. Goldstone 70-m antenna XTR cone X-band HEMT amplifier.

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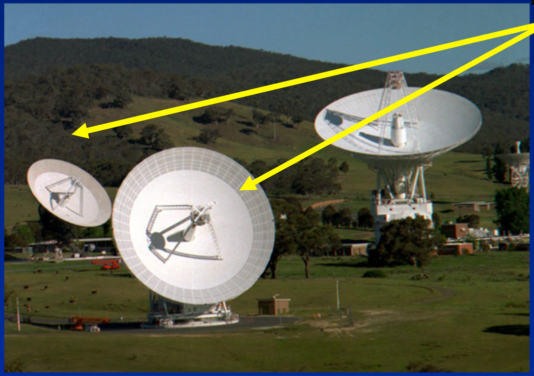
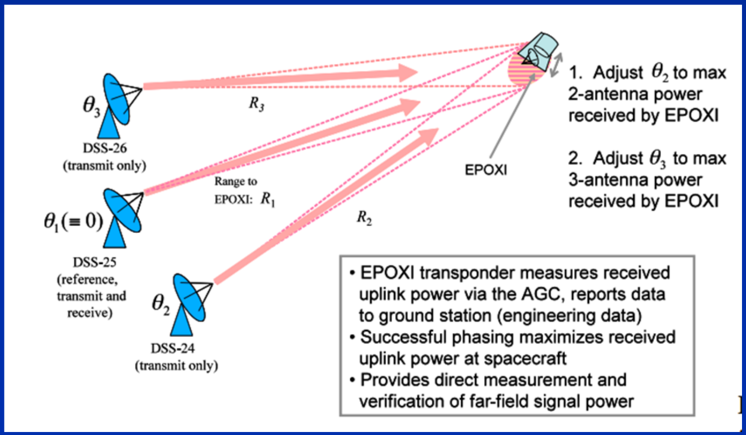
Antenna Arraying to Aid Really Low Signal

- A way to enhance antenna aperture
  - Routinely used by Voyager, Spitzer, New Horizons
- Downlink array
  - 34-m/70-m arraying
  - Polarization combining
- Uplink array (R/D capability)
  - Gain proportional to N^2 instead of N (as with downlink)





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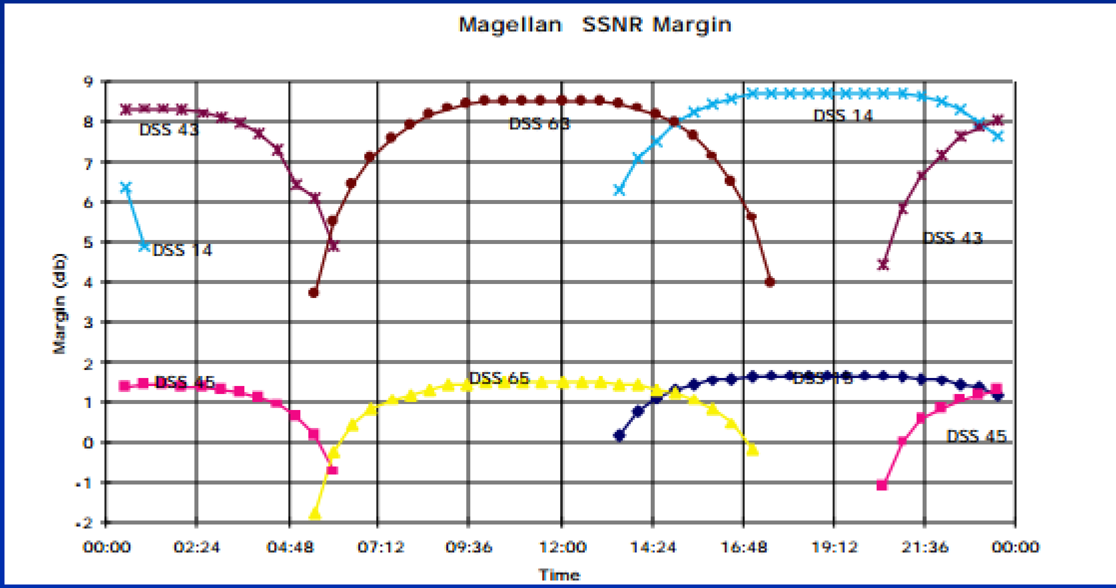
Ref.: Vilnrotter, Uplink Array Concept Demonstration with the EPOXI Spacecraft, IEEE Aerospace, 2009

Maximizing Data Return via Adaptive Data Rate

- Adjusting data rate per available link margin during the pass
  - More important at higher operating frequency
    - Steeper curves
  - Higher performance with continual adjustment of data rate
    - Requiring more capable flight system



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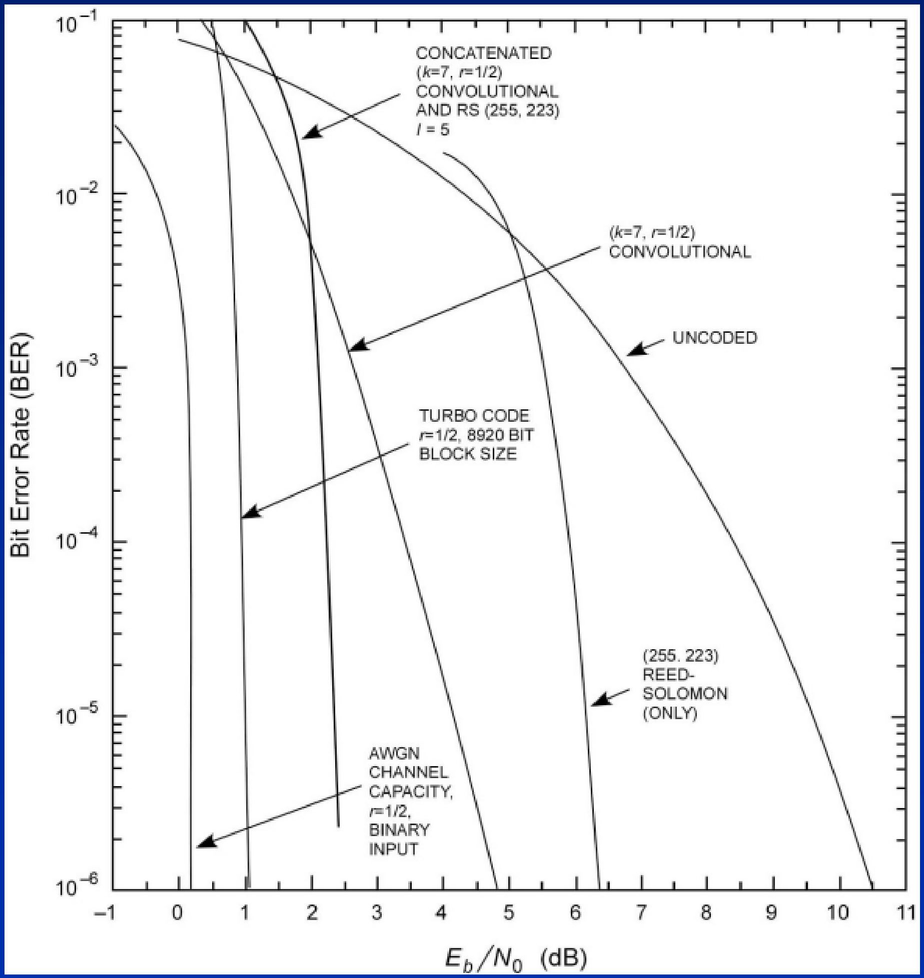
High Performance Coding

- Trading complexity (with lower processing rate) to gain better Eb/No performance
  - Within 1 dB of AWGN channel capacity
  - Convolutional, Reed Solomon, Concatenated, Turbo, and Low-Density Parity Check codes



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

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2. Deep Space Tracking

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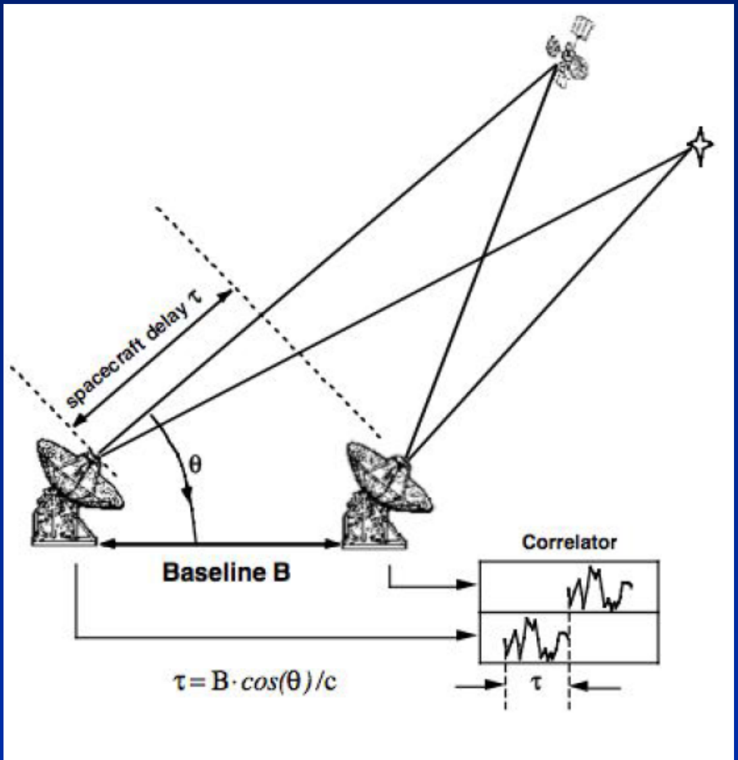
Tracking data products

- Enable mission navigation via orbit determination
- 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 needed to minimize systematic errors
  - System ranging calibration
  - Earth orientation parameters
  - Media delay in Earth troposphere and ionosphere
  - Time and frequency offset among sites of data collection

Delta-DOR Technique

- Use of Delta-DOR to complement Doppler/Ranging
  - Best for plane-of-sky position measurement
  - 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

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3. Spectrum Considerations

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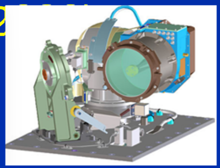
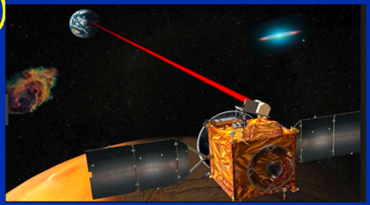
Spectral Migration

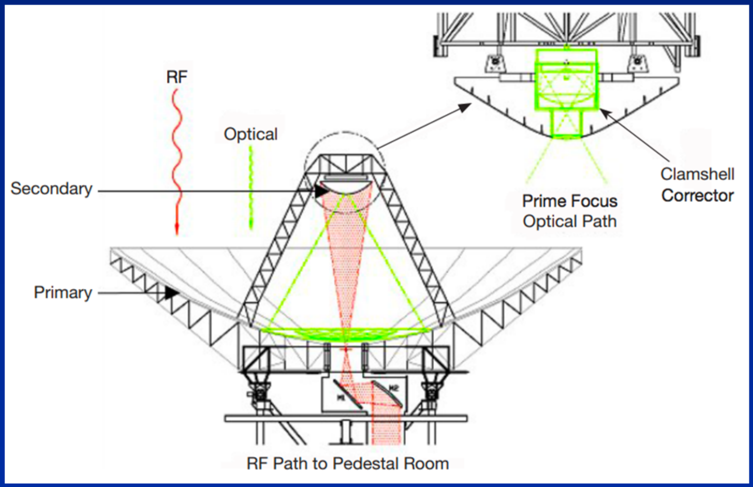
- Performance vs. Risk
  - Better performance at higher frequency (more gain, lower mass)
  - Avoidance of spectral congestion
    - Among missions
    - Between scientific and commercial users
  - Balanced by the risk and cost consideration on new technology
    - Missions typically prefer proven hardware
- Transition time (among NASA deep space missions)
  - S-band missions (~1960, Explorer/Pioneer)
  - X-band missions (~1976, Voyager)
  - Ka-band missions (~2009 Kepler)
    - Cassini radio science carrier only, ~1997
  - Optical missions
    - Demo - Galileo (1992), Messenger (2012), LADEE (Lunar, 2013) ISS/OPAL (2014), ISS/LCRD & Psyche (planned, ~2
  - Transition takes time!!!





Optical Terminal/Antenna Options

Optical Communications Telescope



DSN RF/optical hybrid antenna concept

Ref:, T. Torrez – RF/Optical Hybrid Antenna, https://ipnpr.jpl.nasa.gov/progress_report/42-201/201B.pdf

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Performance Consideration

Lower frequency operation

+ Better immune to weather condition, more tolerant to pointing error
- Lower G/T, heavier flight equipment

Higher frequency operation

- More subject to weather, special pointing control (monopulse rather than conscan, abberation)
+ Higher G/T, less equipment mass

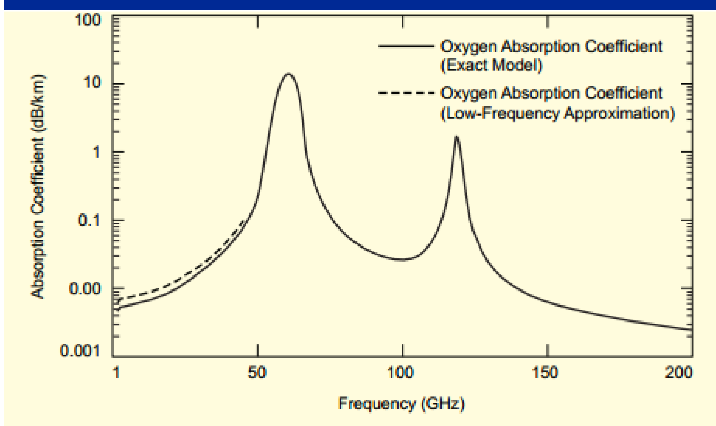
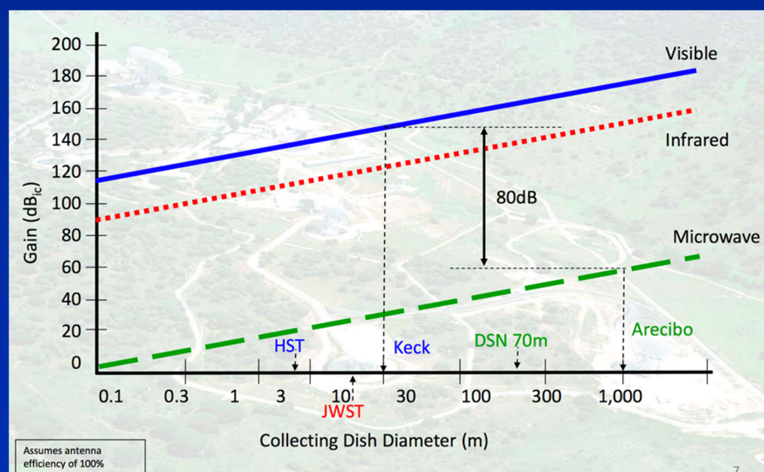


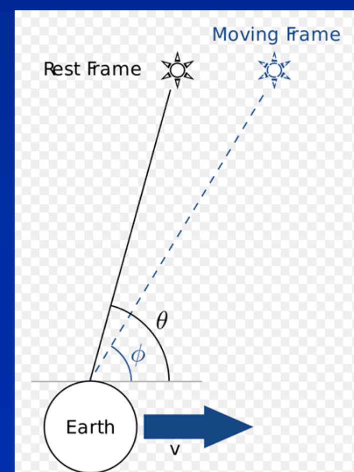
Fig. 6-3. Oxygen absorption coefficient versus frequency, $T = 300$ K, $P = 1013$ mbar (1.013×10^5 Pa).

Atmospheric Absorption



Antenna Gain vs. Frequency/Aperture

https://www.nasa.gov/pdf/694635main_Pres_Public_University_Navarra_Astronaut_Robotic.pdf



Aberration consideration

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4. Science

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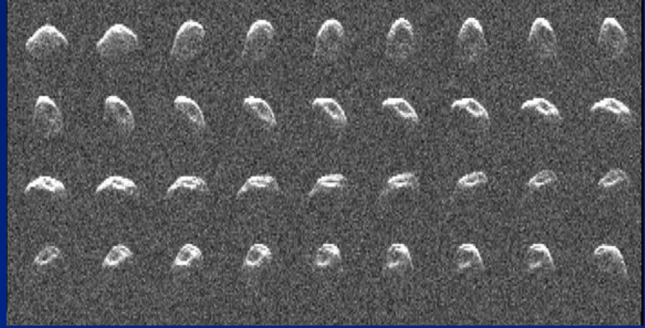
Goldstone Solar System Radar

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

2010-JL33



Ref. 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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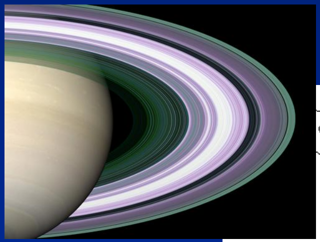
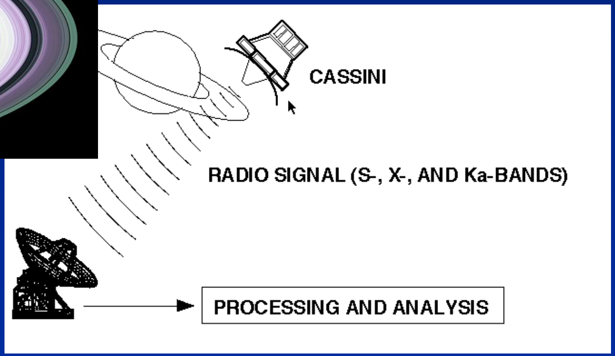
Radio Science

- Affected phase and amplitude of spacecraft signal under influence of planets and their satellites, along with their atmosphere , enable the study of these planetary bodies
  - Signal attenuation during occultation yield information on object's density





Ref http://saturn.jpl.nasa.gov/spacecraft/cassiniorbiterinstruments/instrumentscassinirss/

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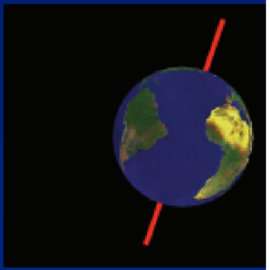
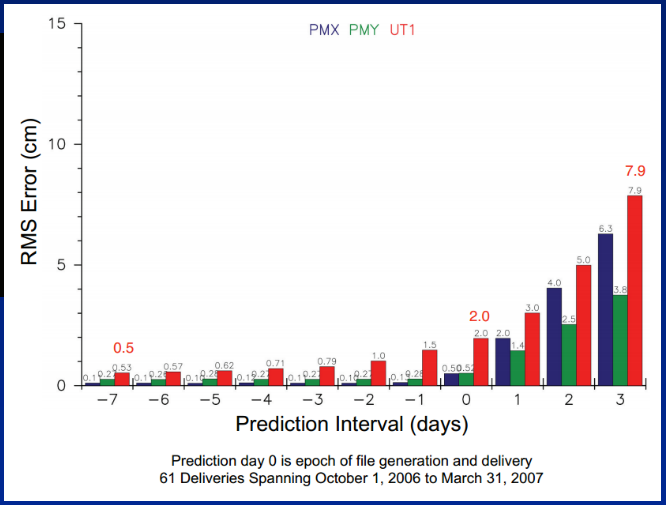
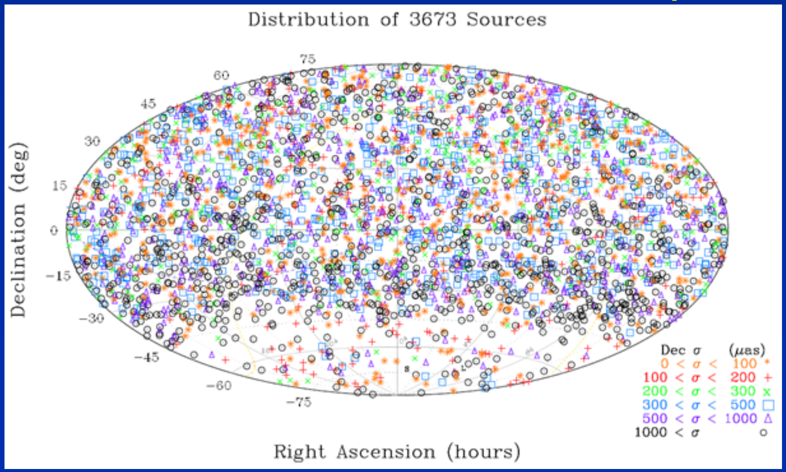
Very Long Baseline Interferometry

- Study Earth deformation and rotational change through Time/Earth Motion Precision Observation (TEMPO)
  - Location of spin axis w.r.t. celestial frame (precession-nutation motion), terrestrial frame (polar motion), angle that Earth rotates about spin axis (spin)
- Characterize signal fluctuation of cataloged quasars





Ref. 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
  - Data transfer over WAN is a challenge
- High power transmitter
  - Reliability considerations

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5. Operations

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Operational Efficiency

- Cost saving emphasis!!!
- 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 input, less real-time changes
- Use of CCSDS standard service/data interface
  - Increase cross support with other space agencies (e.g., ESA) while reduce engineering effort

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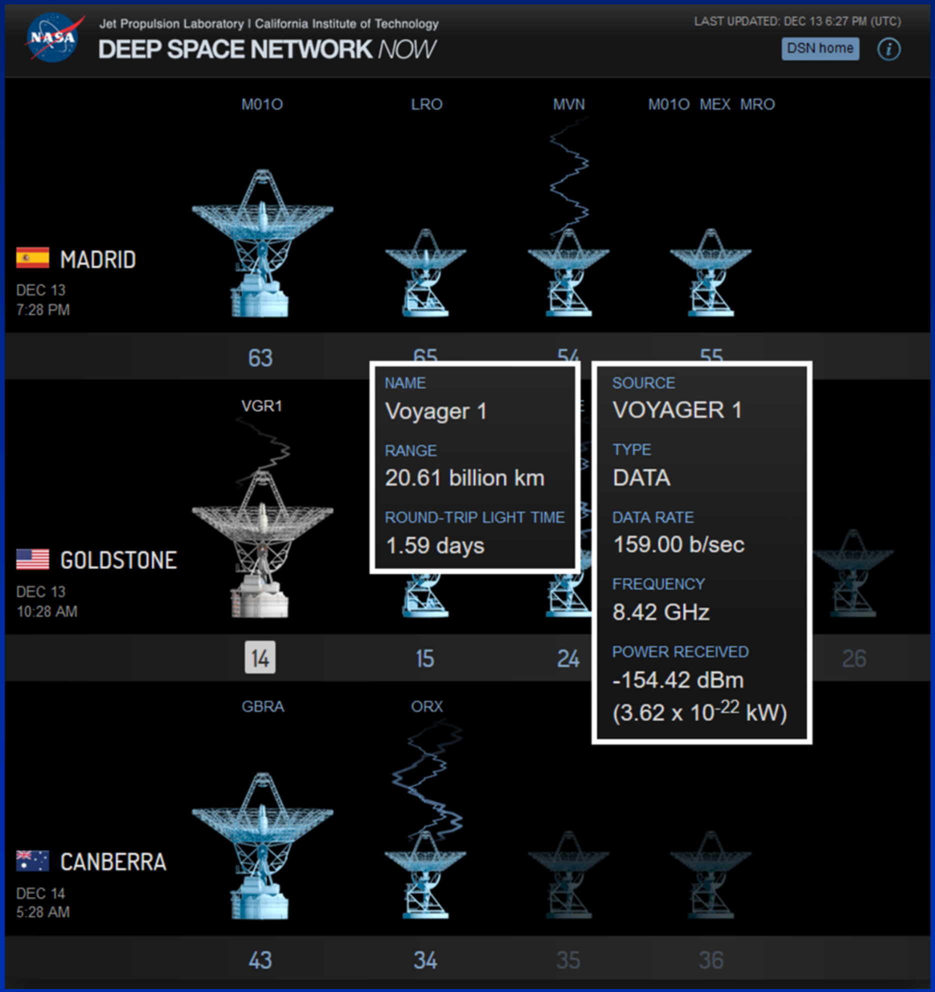
Follow the Sun Operations

- Moving from each site controlling its antenna 24-hrs/day to just day time (~8-9 hrs/day)
  - But during uptime, the controllers controlling the entire DSN network.



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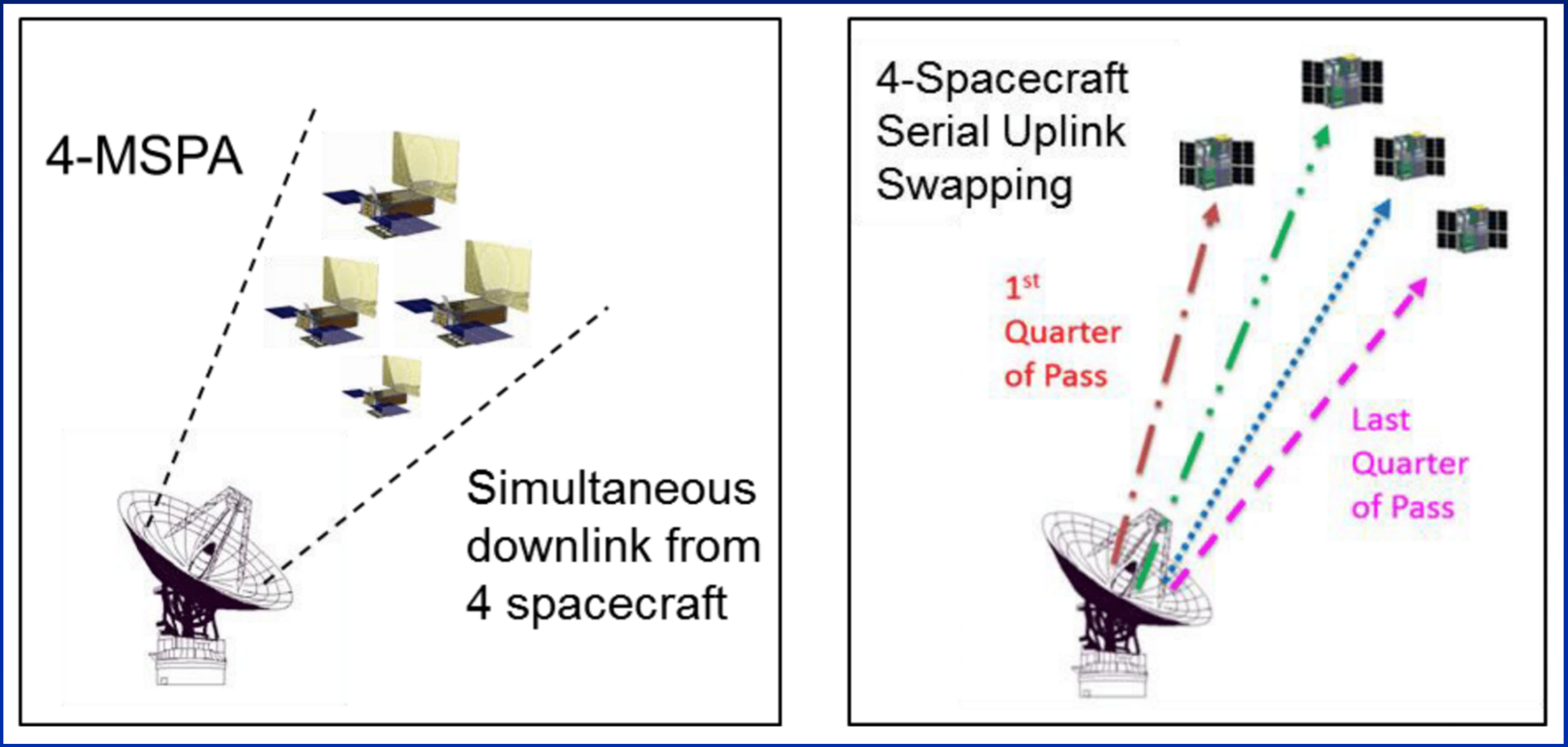
Multiple Spacecraft per Antenna Operations



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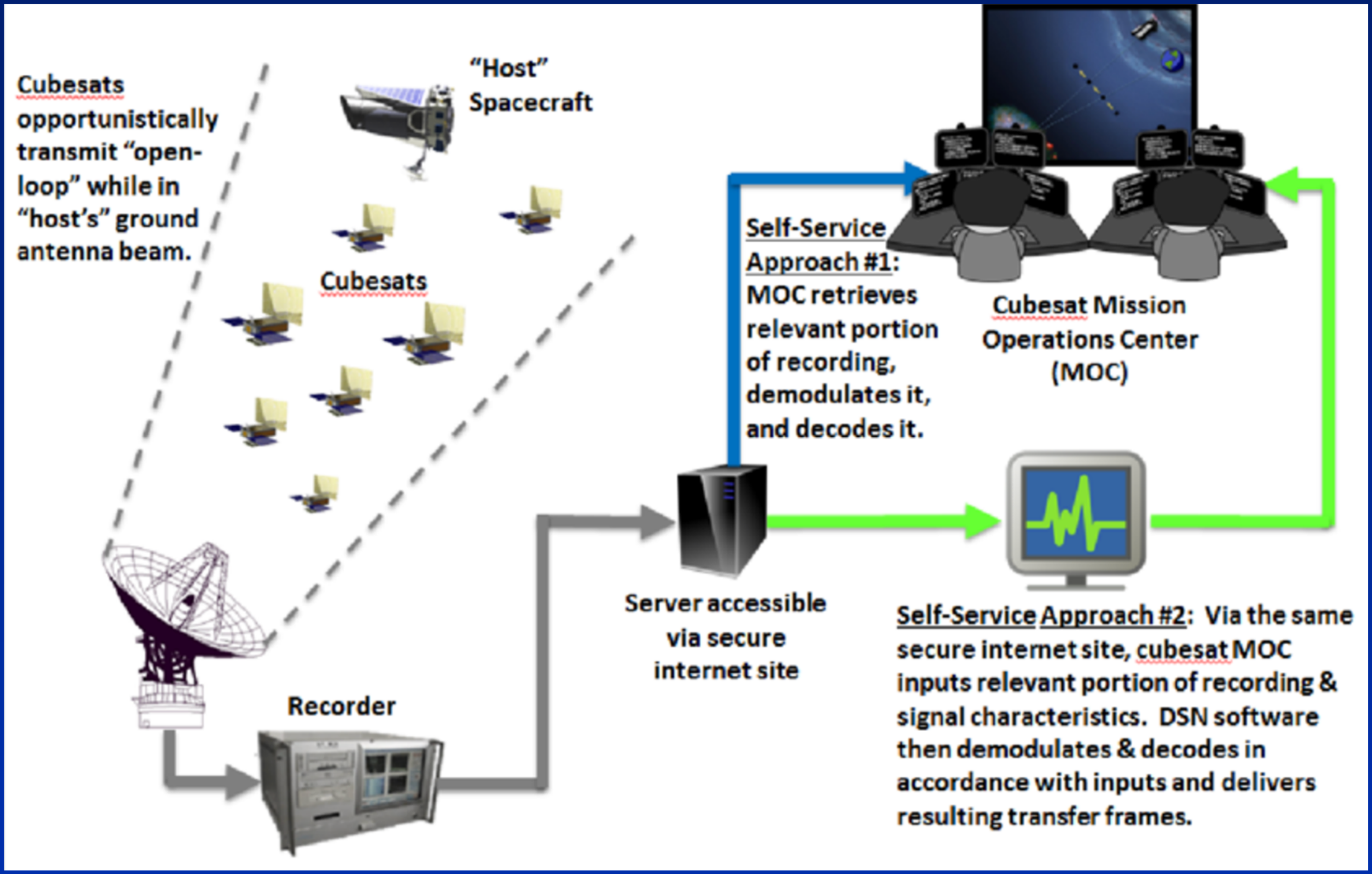
Opportunistic Multiple Spacecraft per Antenna Operations



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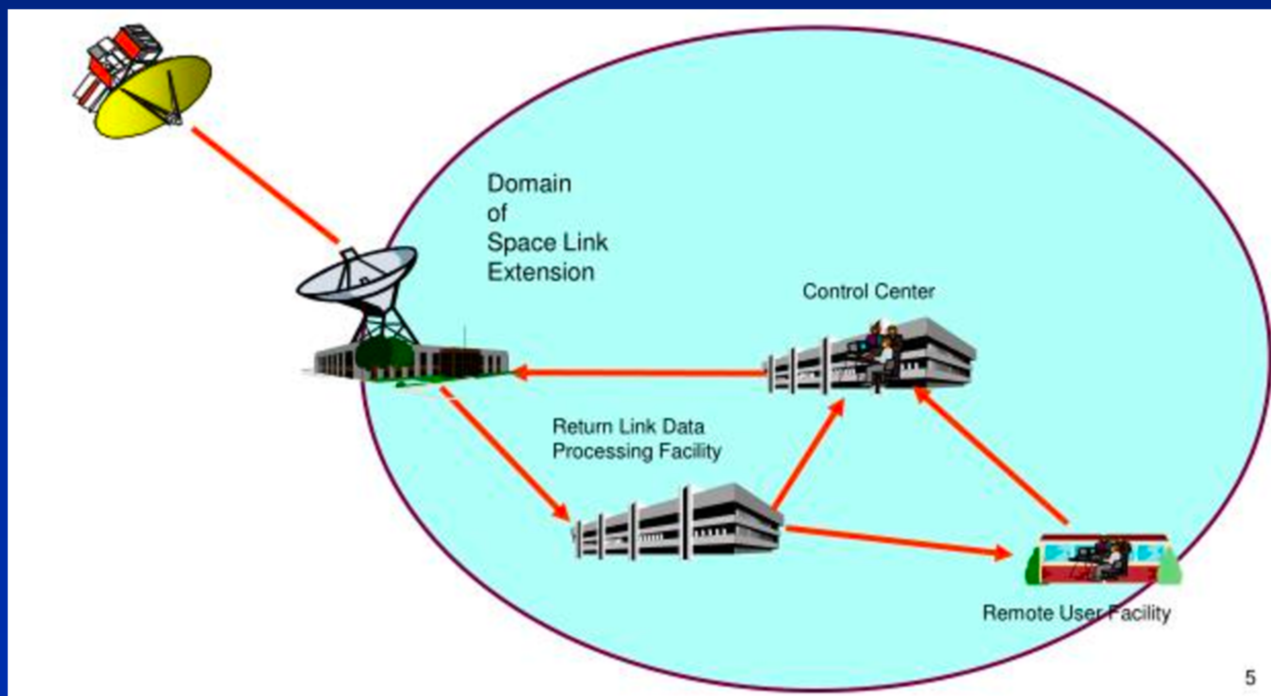
Space Link Extension Concept

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



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

Summary

- Deep space communication challenge due to weak signal
  - Maximize signal reception via different technique of modulation & coding, arraying
- Deep space navigation require highly accurate radiometric measurements
  - Need for other technique (e.g., DOR) & calibration
- Deep space science
  - Amplitude & phase stability are key to science observations
- Spectrum
  - Migration to higher frequencies for better performance
- Deep space operation challenge on operational efficiency
  - Via use of multi-link per operator, follow-the-sun operations, multiple spacecraft per aperture, standard interfaces