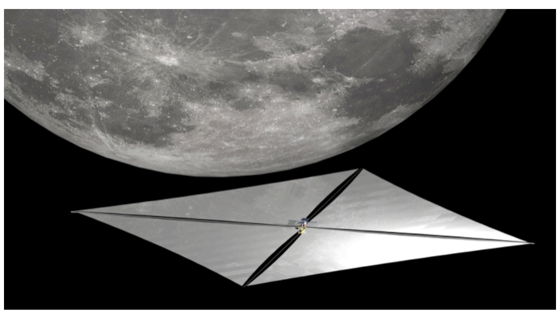
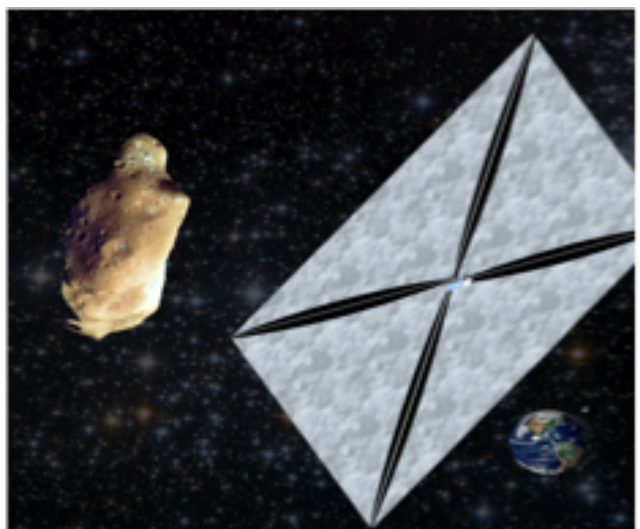
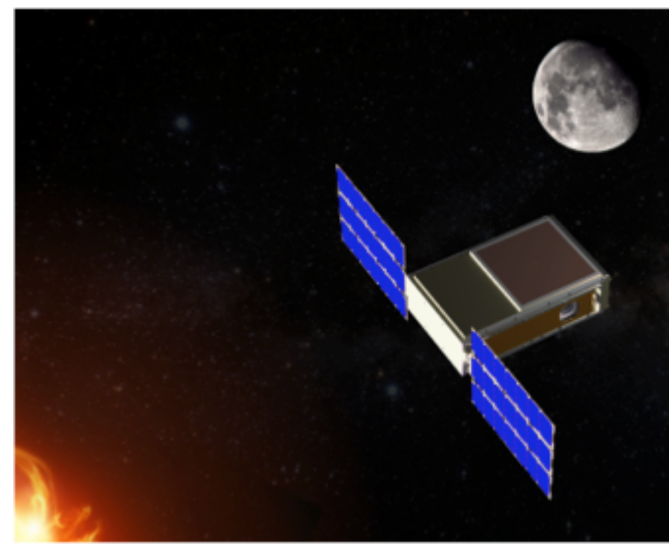
Ground Network Architecture for Interplanetary Smallsat Missions

Presenter: Kar-Ming Cheung

April 22-24, 2015







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Outline

- Introduction
  - List of Interplanetary CubeSat/smallsat Missions
  - Mission Characteristics and Communications/Tracking Challenges and Needs
- Near-Term Development
  - Flight Hardware Development – avionics and flight communication system
  - Streamlining and Upgrading Existing DSN Capabilities and Processes
  - Agile strategy and development to use and to enhance Multiple Spacecraft Per Antenna (MSPA) to support multiple smallsats/CubeSats
  - DSN Operation and Interfaces with Non-DSN Antennas
  - Multi-mission Ground Data System for CubeSats/smallsats
- Advanced Concepts and Technologies
  - Multi-hops communications
  - Deep space multiple access for simultaneous links
  - Collaborative communications

Interplanetary Smallsat Missions

Near-Term (now – 2017)

- INSPIRE (Late 2016?)
- InSight with 2 CubeSats (MarCO, March 2016)

Mid-Term (2018 – 2020)

- Launch vehicle for the KARI Pathfinder Lunar Orbiter (KPLO) plan to carry 2-4 CubeSats (TBC) in 2018
- EM-1 Missions (3 to 11 smallsats, 2018)
  - Lunar Flashlight, NEA Scout, Bio-Sentinel, Lunar IceCube, SIMPLEX…
- Others - Google X-Prize?

Far-Term (2020+)

- Deep space CubeSats ride along with flagship missions (e.g. Europa)
- Constellation of CubeSats (e.g. SOLARA/SARA, Relics)
- Uncoordinated CubeSat missions around a target body (e.g. planets)

network mission costs in using

DSN availability, and user

Link capacity, tracking capability, and number of simultaneous links

Interplanetary Smallsat Mission Characteristics, Challenges, and Needs

- Mission unique characteristics
  - Spacecraft are small, so they can benefit from multiple piggyback launches
  - Relatively speaking, they are cheap(er), compared to traditional spacecraft
  - Launched as secondary payloads – multiple spacecraft deployments
  - Short development life cycle – quick development and deployment, fast ROI and science

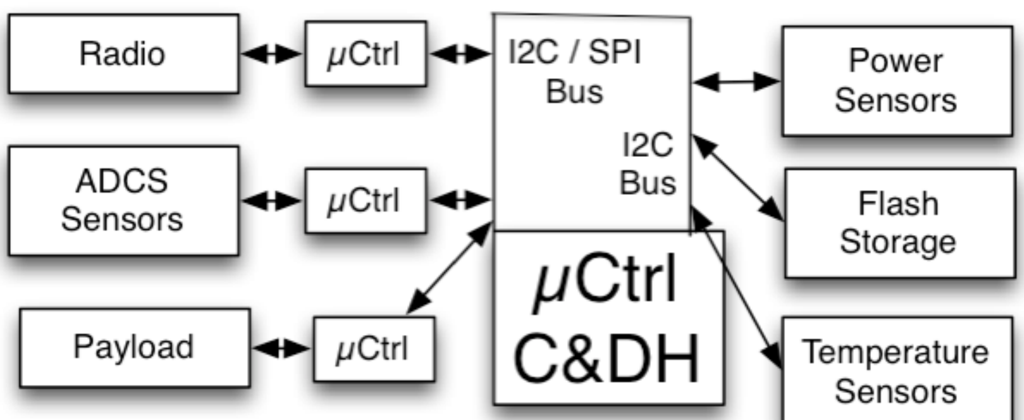
- Mission communications/tracking challenges and needs
  - Link capability for data delivery
  - Accurate spacecraft tracking for navigation state vector determinations (no GPS)
  - Precision timing and frequency references
  - Accurate spacecraft and ground antenna pointing
  - Communications and tracking of multiple spacecraft
  - Spectrum coordination and utilization
  - Deep space spacecraft commanding – RTLT latency
  - Low cost

- To compensate for the inherent limitations of smallsat/CubeSat form factor, missions need to shift the burden to the network infrastructure

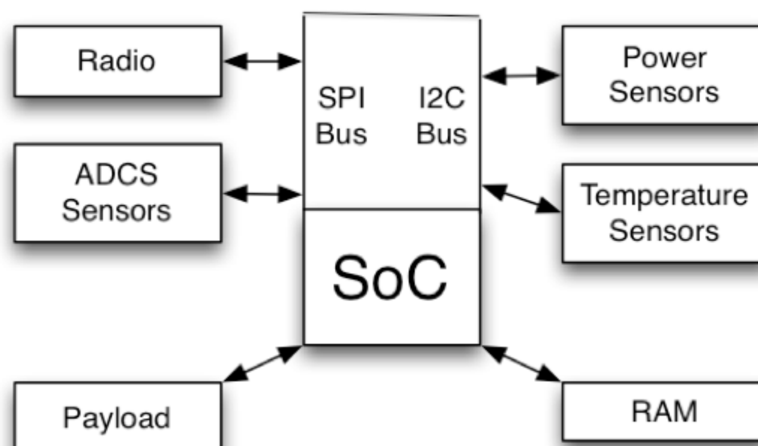
Flight Hardware Development - Avionics

- Two architectures
  - Traditional micro-controller architecture (hardware modularity)
    - Interchangeable hardware modules connected by a common bus
    - Require a dedicated control processor for each separate module
  - New system-on-chip (SoC) architecture (software modularity)
    - The CPU is order of magnitude more power than the micro-controller
    - Micro-controller functions are consolidated onto the CPU
    - The CPU runs a more sophisticated operating system (like Linux) to facilitate code reuse and rapid development

Micro-Controller Architecture



SoC Architecture



Flight Hardware Development - Communication System

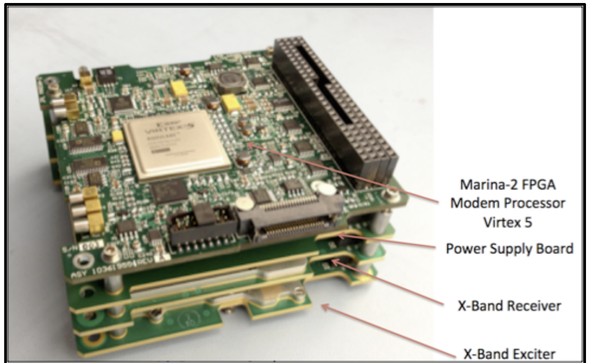
- Differences between LEO and Interplanetary

	LEO	Interplanetary
Frequency	UHF, S-band	X-, Ka-band
Radio	Communications only; rely on GPS for navigation	Require both communications and navigation (GPS-less) functions
Antenna	Low-gain patch antennas	Higher gain patch and directional antennas
Ops Support	Simple	Complex

- Interplanetary smallsat communication system: dependencies on other subsystems
  - Pointing and control: require precision pointing for HGA
  - Power: require high power for downlink
  - Structure: deployable solar panels and/or instruments might obstruct the antenna FOV
  - Instruments/payloads: might generate EMI with communication system

Flight Hardware Development – Iris Radio V2.0

Parameter	Value
CubeSat Compatible	Size: 0.4 U, Mass: 0.4 Kg
Power	20W DC in, 4 W out (transmit), 6.5 DC in (receive)
Frequency	Receive: X, UHF, Transmit: X
DSN Compatible (Nav)	Full-duplex Doppler, ranging, Delta-DOR
DSN Compatible (Telecom)	62.5 – 256000 bps telemetry, 1000 bps command
Sensitivity	25 dBm transmit, -130 dBm receive
Interface	SPI interface tp C&DH
CCSDS Signal Format	Direct and sub-carrier, BPSK
CCSDS Coding/Protocol	Turbo, Convolutional, AOS

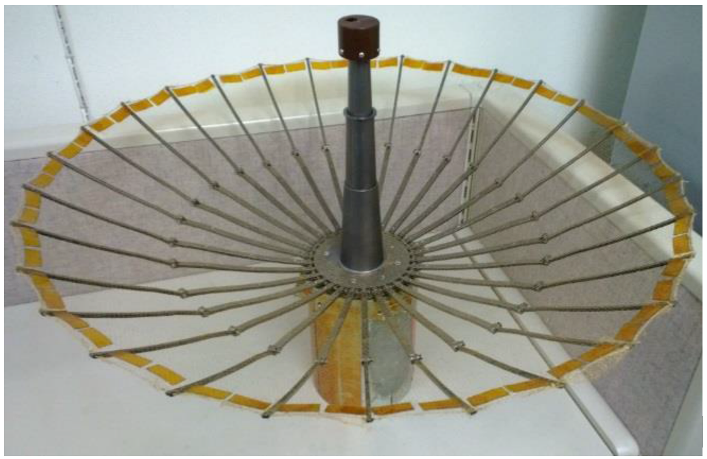


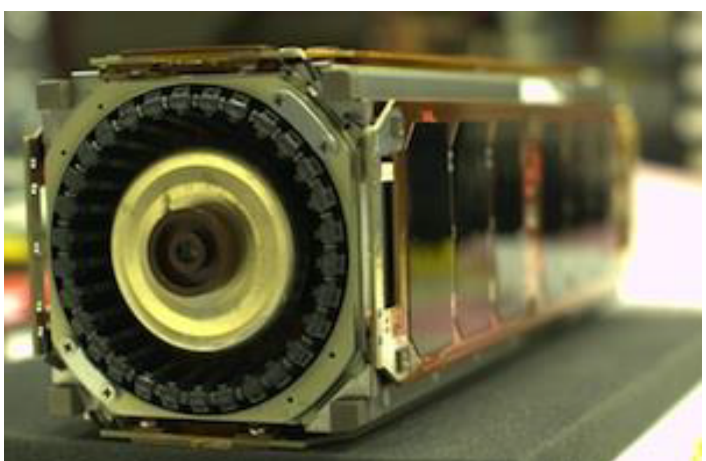
Flight Hardware Development – High Gain Antennas

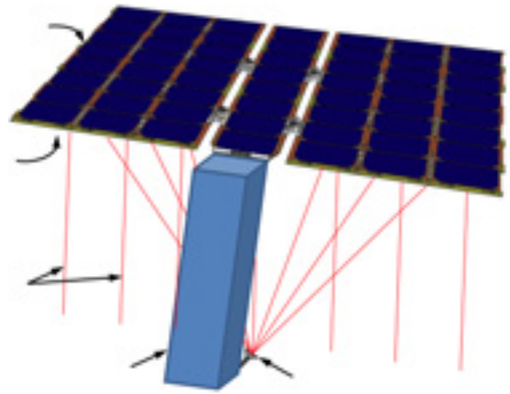
Deployable Antenna
- 1.5U, 0.5m diameter
- Ka-Band

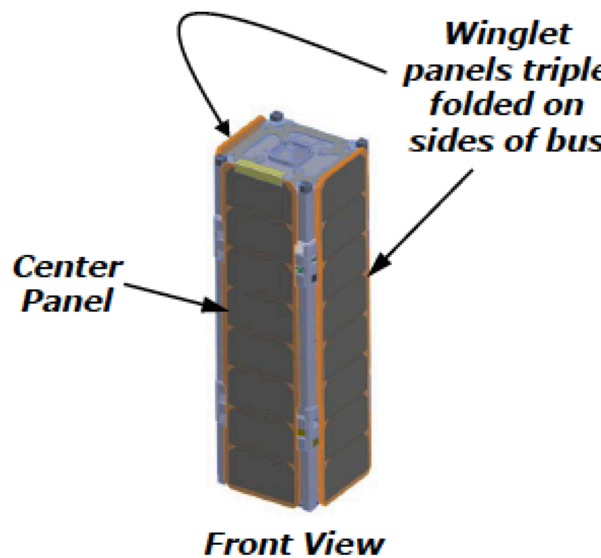
Reflectarrays Antenna
- Folded on 3 sides of SC
- Ka-Band

Inflatable Antenna
- 0.5U, 1m diameter
- S, X-Band



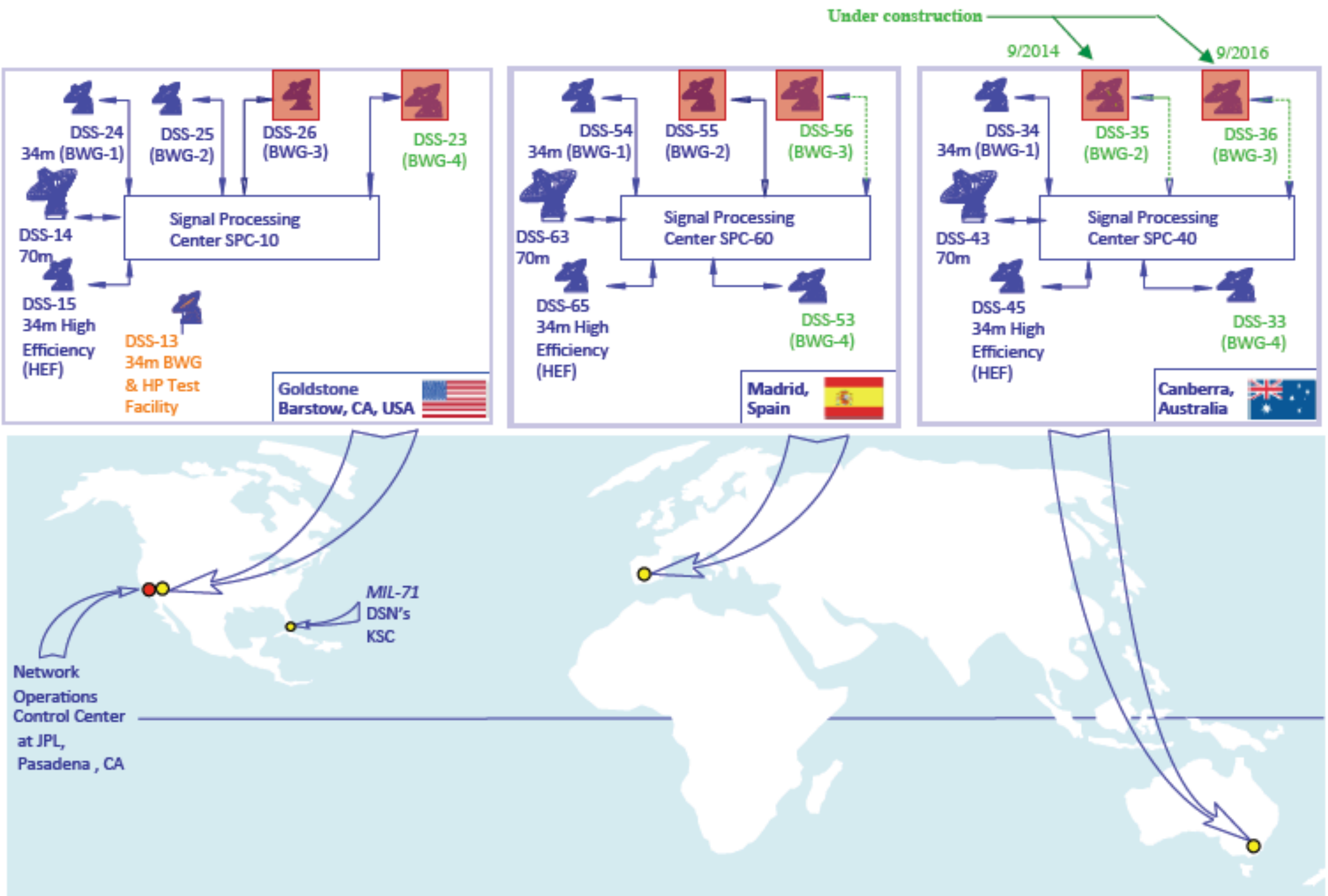






National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

DSN Resources



LEGEND

Future 34m BWG Antenna

New 80 kW Transmitter

New Antennas

Operational Dates

DSS-35	9/2014
DSS-36	9/2016
DSS-56	9/2019
DSS-53	9/2020
DSS-23	9/2023
DSS-33	9/2025

80 kW XTR

Operational Dates

DSS-26	9/2015
DSS-35	9/2019
DSS-55	9/2020
DSS-56	9/2021
DSS-23	9/2023
DSS-36	9/2025

Streamline and Upgrade Existing DSN Capabilities and Processes - DSN Resource Allocation Process

- Interplanetary smallsats require shorter passes and desire shorter planning cycle
- Current DSN resource allocation process is primary based on peer-to-peer negotiation among missions, and smallsat/CubeSat missions worry the big budget missions would have more leverage in getting preferred DSN passes when there is contention with the smaller budget missions
- In the near-future, DSN resource allocation will transition into a software-based process, and taking into account mission priority
- Priority is only based on engineering and science urgencies, and not on the budget size of a mission
- The hybrid peer-to-peer and priority-based resource allocation process takes into account the needs of smallsats, and should provide better footing for the interplanetary smallsat missions in the DSN resource allocation process

Streamline and Upgrade Existing DSN Capabilities and Processes - Standardize Mission Interface and Reduce Cost

- Establish Space-Link-Extension (SLE), CCSDS standard service protocol, for the interfaces between DSN and the mission ground systems. Missions can use
  - SLE's Command Link Transmission Unit (CLTU) for forward link
  - SLE's Transfer Frames for return link
  - Tracking Data Message (TDM) for tracking data
- CCSDS standard interfaces are also adopted by JAXA and ESA, and cross-support agreements are in place

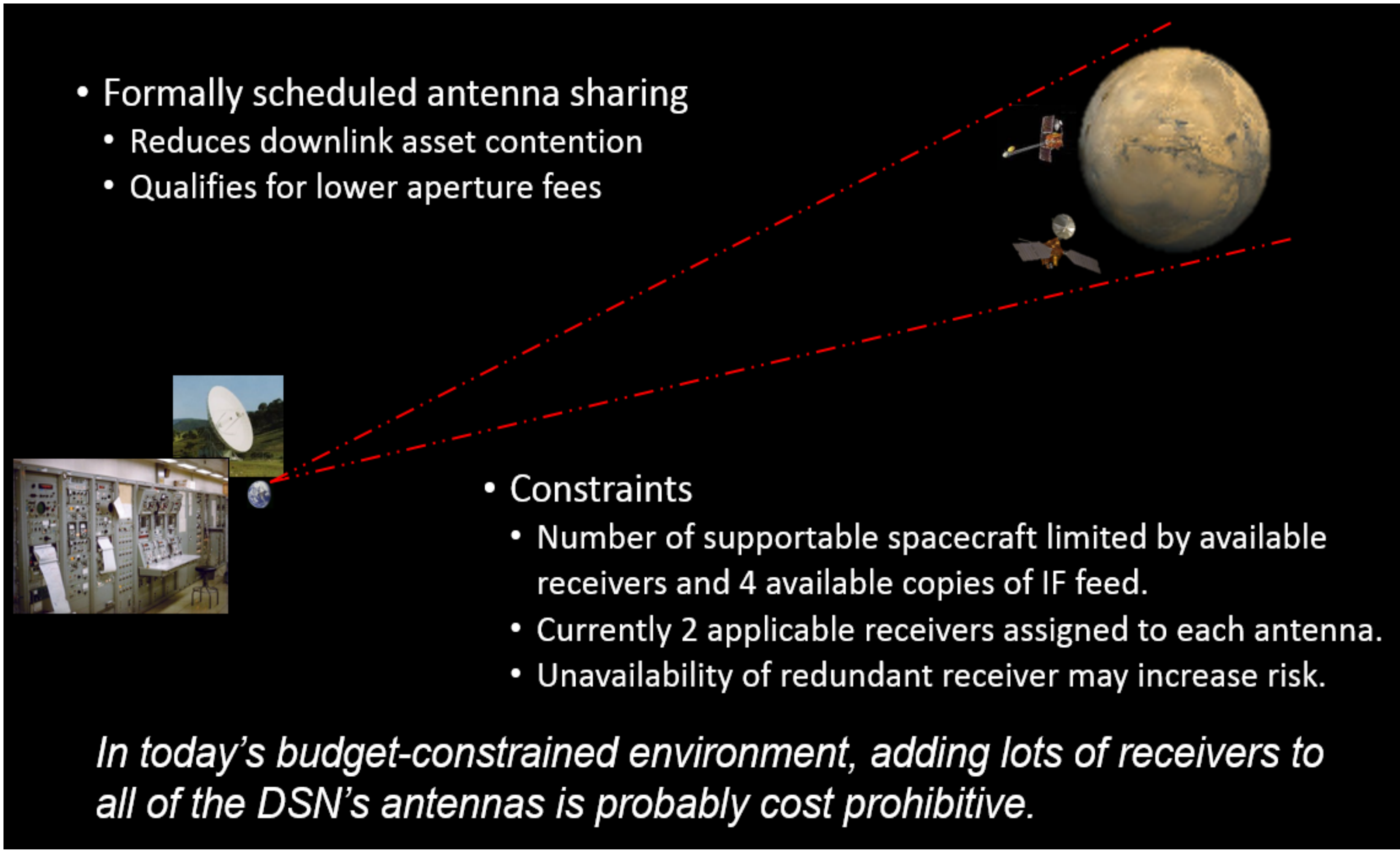
- Reduced pre-launch testing when a mission consists of several identical smallsats
- DSN would test one of the spacecraft fully (i.e. RF compatibility testing, GDS testing), and perform a subset of tests on other spacecraft

- Consider using internet instead of NISN line for ground data transfer to missions

- Consider reducing pre-cal (1 hour) and post-cal time (15 minutes)

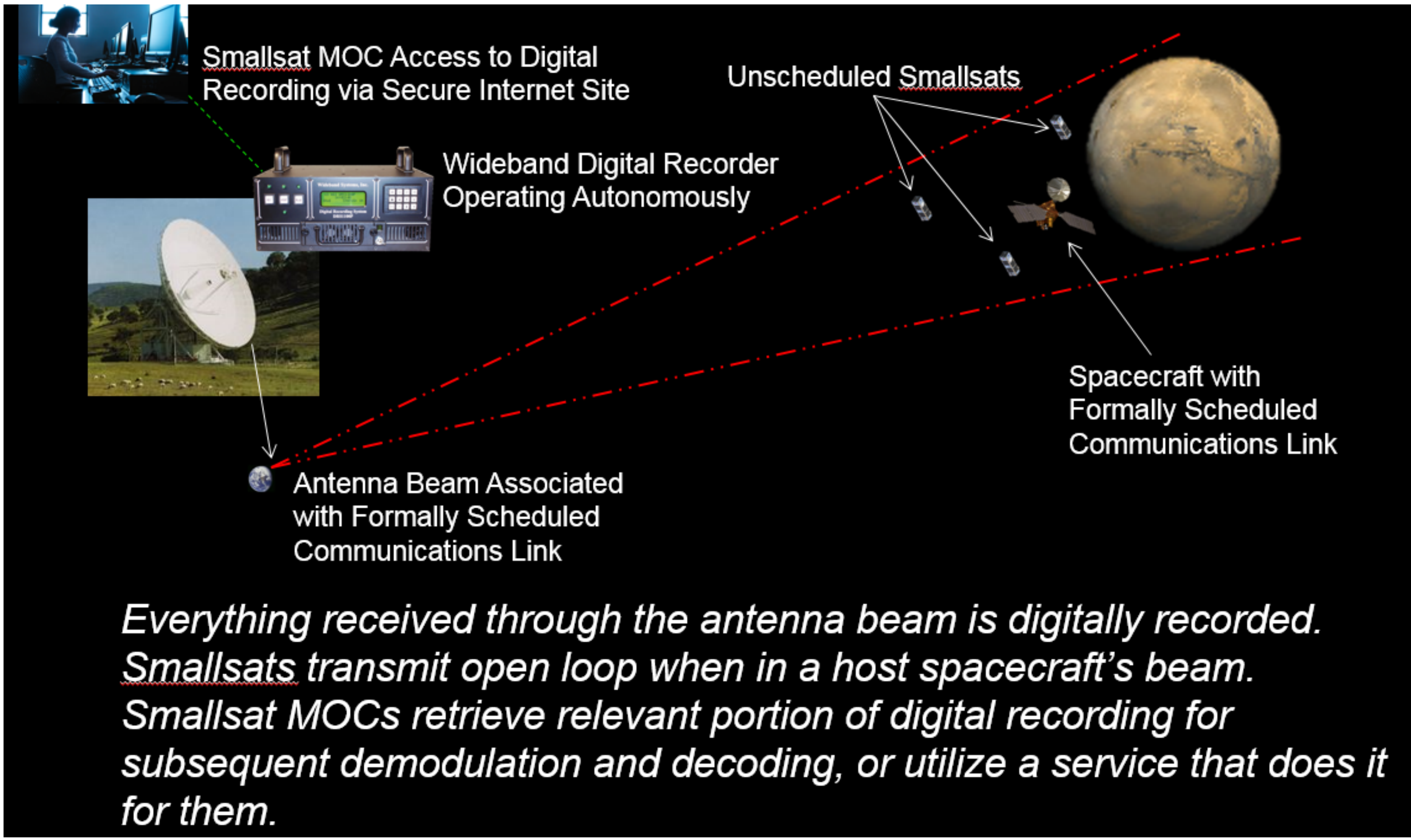
Techniques for Simultaneous Tracking of Multiple Spacecraft in an Antenna Beam

- Current operation Multiple Spacecraft Per Antenna (MSPA) support 2 spacecraft
- Near-term plan is to increase the number of spacecraft to 4



Techniques for Simultaneous Tracking of Multiple Spacecraft in an Antenna Beam

- Proposed Opportunistic MSPA
  - Use open-loop receiver to record IF for later processing of multiple signal streams
  - Proof-of-concept with MRO and ODY is successful



DSN Operation and Interfaces with non-DSN stations - Deep Space Spectrum Coordination (1)

- Smallsats pose many challenges in spectrum coordination
  - The quick development cycle for most smallsats reduces time available for spectrum management to perform frequency selection, RFI analysis, coordination, and spectrum regulatory filings
  - Frequency assignments are often requested before the smallsat launch date and trajectory have been determined, which introduces critical unknowns into the RFI analyses and frequency coordination with other agencies
  - Frequent changes in mission parameters, including opportunistic launches, often necessitate performing multiple iterations of the spectrum analyses
- Frequency licensing process for all satellites operated by United States federal agencies, including smallsats, is controlled by the National Telecommunications and Information Administration (NTIA)
  - Universities and non-federal US entities: Federal Communications Commission (FCC)
- Proper frequency licensing is required before any satellite can be launched, so smallsat projects are encouraged to work with their spectrum managers as early in their development as possible
  - The frequency licensing process can take considerable time depending on the number and severity of issues that arise during the NTIA system review and coordination process
- See backup and/or paper on detailed spectrum allocation process

Upgrade University Antennas: Morehead State University (MSU) 21m (1)

- Student internship as part of the education and outreach effort
  - Develop an internship program where MSU students would become interns at JPL in the areas of communication system, spacecraft and ground system, software development, and operations
  - Identify and initiate MSU-led development projects for implementing capabilities to support deep space smallsat missions with JPL mentorship
- System engineering and planning
  - Jointly perform downlink analysis
  - Define security upgrades needed to support NASA missions and be compatible with DSN operations
  - Devise the approach to mission support as it relates to scheduling of DSN and MSU spacecraft tracking passes
  - Define MSU upgrades needed to support deep space navigation and conduct experiments to jointly evaluate performance (Doppler, ranging)
- System upgrades and experiments
  - Implement capabilities relating to data handling and antenna control
  - JPL provides Government Furnished Equipment (GFE) to process downlink
  - Conduct downlink experiments tracking one or more NASA spacecraft and evaluate performance results
  - Conduct navigation experiments

Upgrade University Antennas: Morehead State University (MSU) 21m (2)

Figure F.1 The Morehead State University 21-m Antenna, *(Lat: 38° 11 30.773 N, Long: 83° 26 19.948 W)*

Table T.1 MSU 21 Meter Dynamical and Mechanical Properties

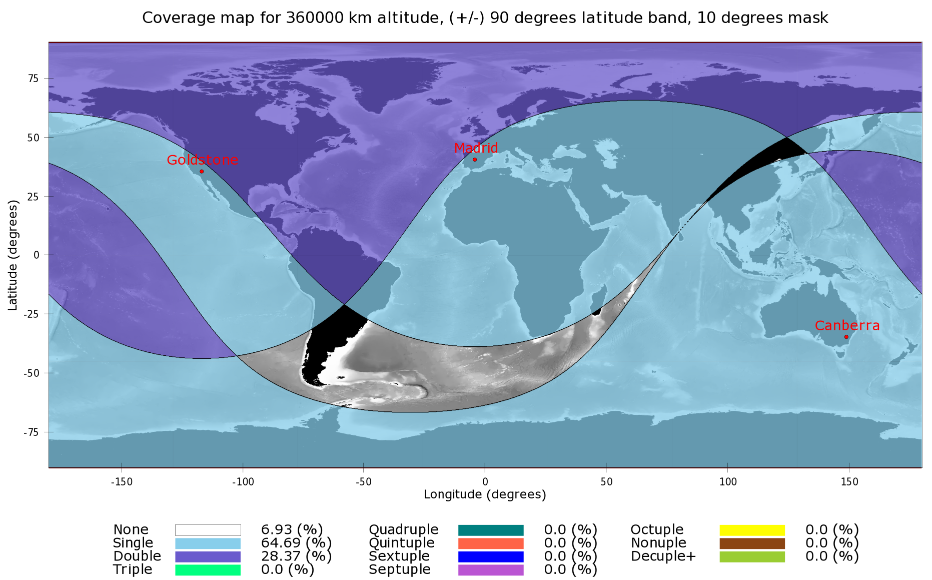
Dynamical/Mechanical Properties	Measured Values
Aperture Size	21 meters
Surface Accuracy	0.0166" RMS
Azimuth	> 3.0 °/sec
Elevation	> 1.6 °/sec
Polarization	± 90.9°
Azimuth Acceleration	> 1.0 °/sec^2
Elevation Acceleration	> 1.0 °/sec^2
Azimuth Travel	± 270° from 180°
Pointing Accuracy	0.01° RMS
Tracking Accuracy	0.0004° RMS

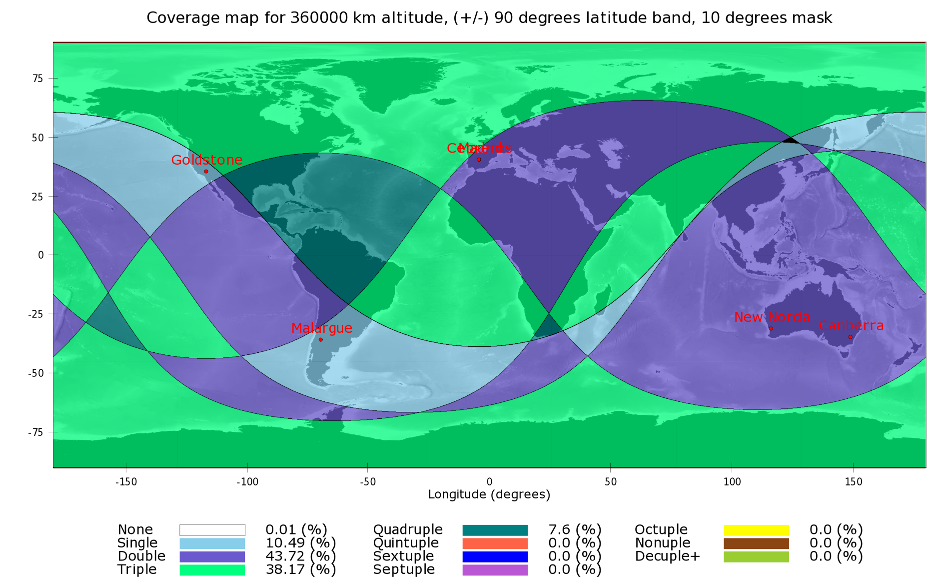
Table T.2 MSU 21 Meter RF Capabilities

Radio Band	Frequency Range	Gain	Uses of Band
UHF	400-480 MHz	30 dBi	Smallsat Telecom
L-Band	1.4-1.7 GHz	47.8 dBi	Primarily Radio Astronomy
S-Band	2.2-2.5 GHz	52.8 dBi	Both
*Low-C-Band	4.8-5.0 GHz	TBD	Primarily Radio Astronomy
High C-Band/ X-Band	7.0-8.4GHz	62.0 dBi	Deep Space Telecom
Ku-Band	11.2-12.7 GHz	65.50 dBi	Primarily Satellite Telecom

DSN Operation and Interfaces with non-DSN stations - Cross-Support with other Space Agencies, e.g. ESA

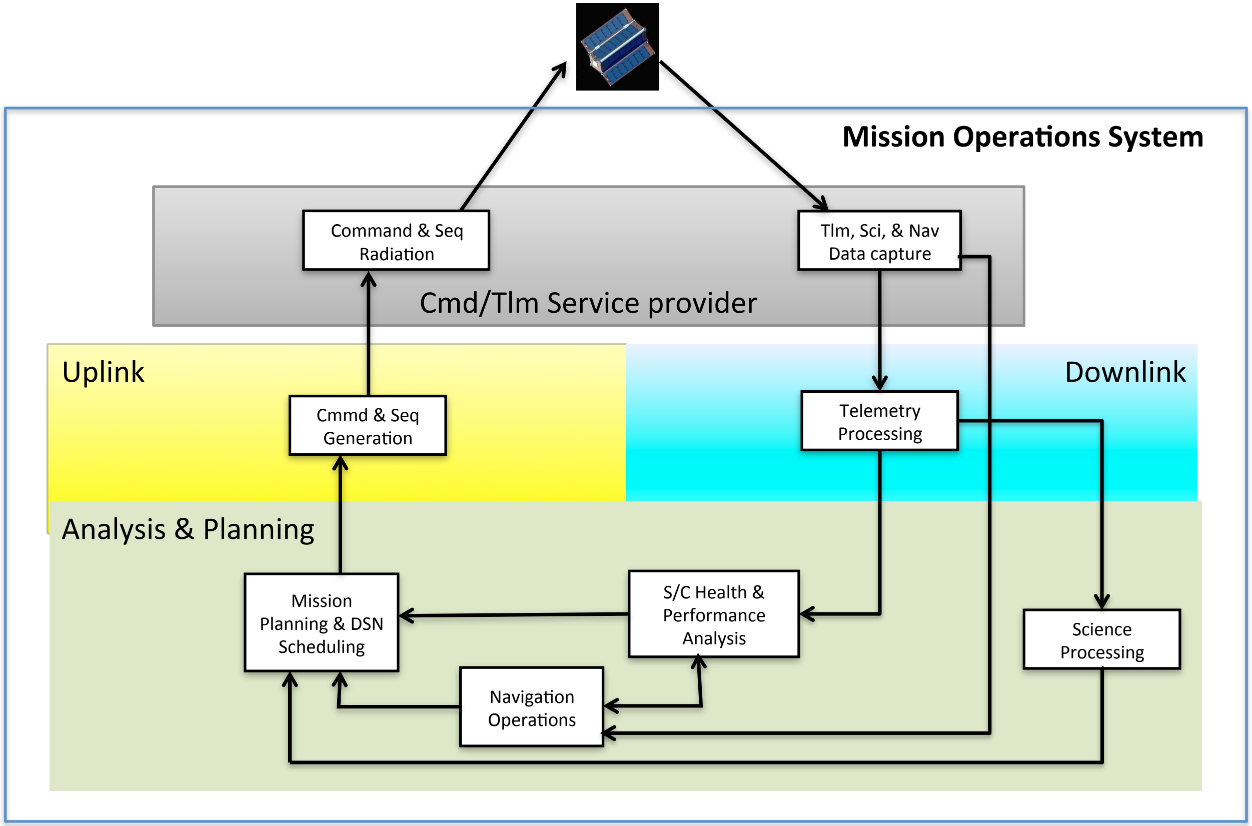
- ESA has Three 35-m Deep Space Antennas (DSA)
  - New Norcia, W. Australia (DS1), Cebreros, Spain (DS2), Malargüe, Argentina (DS3)
- Communications: S-band and X-band uplink/downlink, and Ka downlink
  - Ka-band uplink is being considered for DS3
- Navigation tracking: Doppler, ranging, and delta-DOR





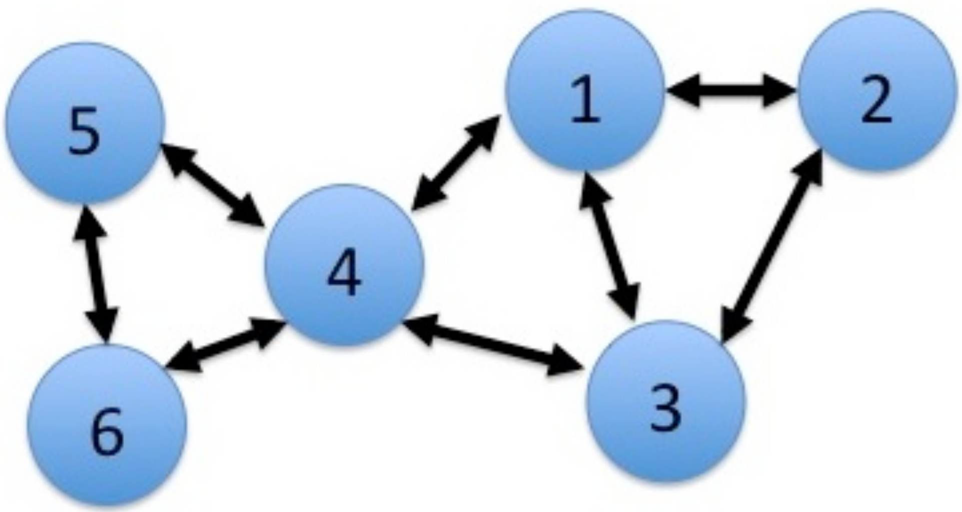
Mission Operation System Architecture for Interplanetary Smallsats

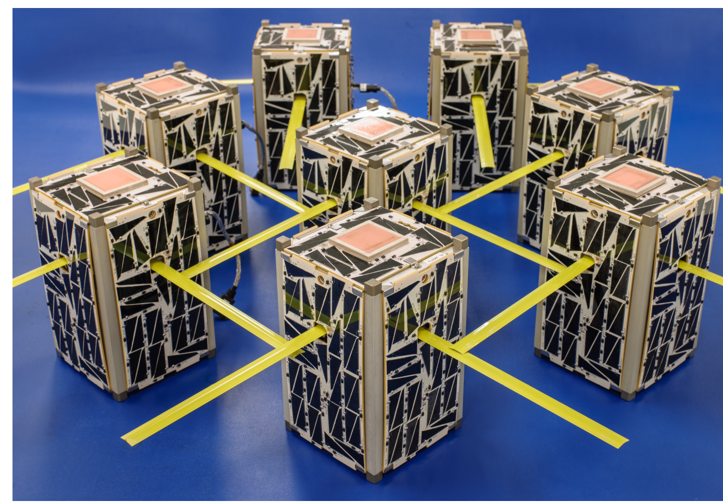
- The MOS architecture should include, at a minimum, the following functions to design, develop, and operate the missions
  - Planning and sequencing for uplink
  - Downlink telemetry and analysis
  - Navigation and mission design
  - Ground Data System (GDS) integration, test, and deployment



Advanced Concept and Technology

- Ground network capability to support end-to-end multi-hop communications (mother-daughter spacecraft configurations)
  - INSPIRE, MarCO, Ames' Edison Demonstration of Smallsat Network (EDSN) mission
  - Advanced protocol, routing will be needed
  - A tailored, light-weight version of DTN?





Advanced Concept and Technology

- Development of deep space CDMA schemes (Ground and Space Networks)
  - Improve terrestrial CDMA scheme to function in deep space's low SNR and high-dynamic environment, and to provide navigation/tracking functions
  - Ongoing low level R&D effort with MIT funded by PSE
  - Two interim reports published as papers
    - Code Division Multiple Access Communications Systems for CubeSats at Lunar Lagrangian L1, IEEE Aerospace Conference 2014
    - CDMA Communications Systems with Constant Envelope Modulation for CubeSats, IEEE Aerospace Conference 2015

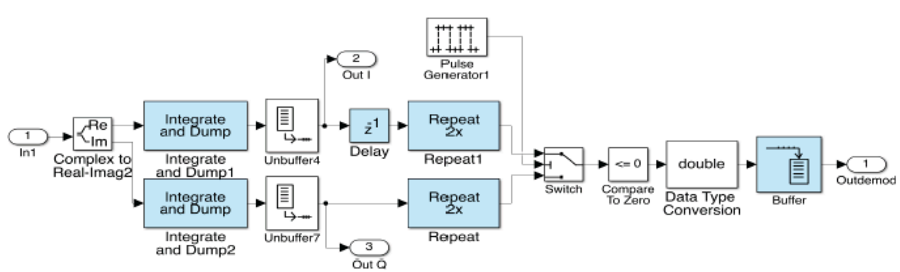


Figure 5. OQPSK demodulator block diagram.

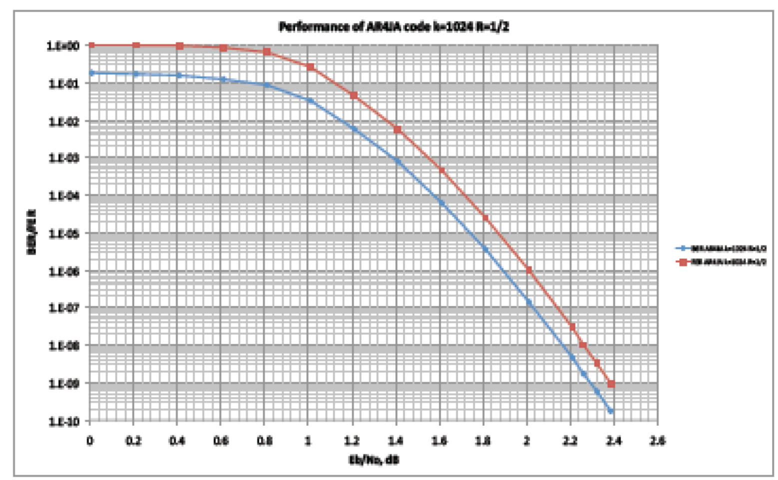
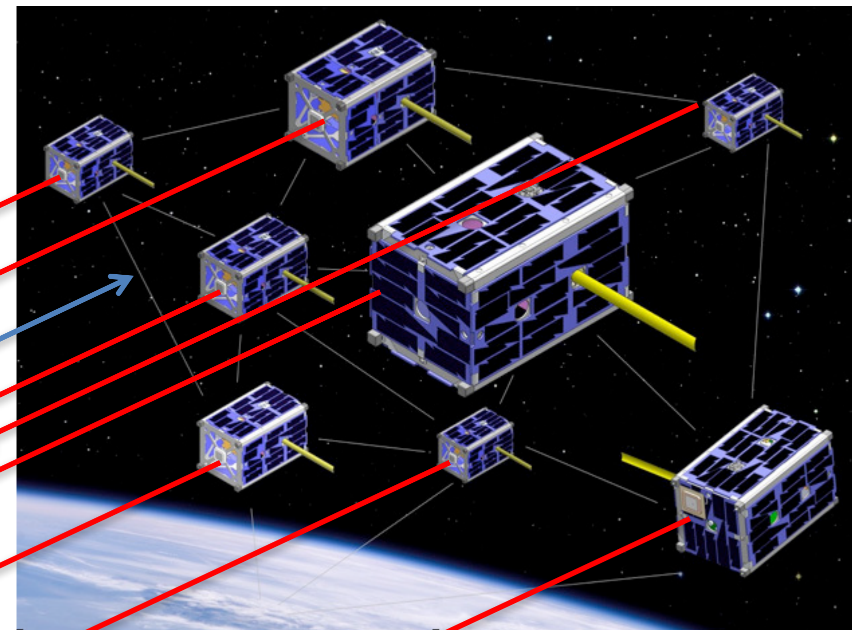


Figure 10. Bit error rate and frame error rates performance of AR4JA LDPC CCSDS Standard code.

Advanced Concept and Technology

- Development of ground-assisted collaborative communication schemes
  - Use of ground pilot tone to phase align N CubeSat signals
  - Use of atomic clock to establish precision time reference among CubeSats
  - Ongoing low level R&D effort with MIT
  - Science & Communication dual use



Artist rendition of CubeSat Constellation Of the Solar Observation Low-frequency Array for Radio Astronomy/Separated Antennas Reconfigurable Array (SOLARA/SARA)

Concluding Remarks – Notional Development Plan

- This paper describe the next-generation ground network architecture to support communications and tracking of interplanetary smallsats
- Near-term plan:
  - Streamline existing network capabilities and reduce mission cost
  - Upgrade 2-MSPA to 4-MSPA
  - Cross-support with non-DSN antennas: universities, other space agencies, etc.
- Mid-term plan
  - Develop and deploy OMSPA (1-uplink, multiple downlinks)
  - Develop and deploy enhanced OMSPA (multiple uplinks, 2-way, commanding)
- Long-term plan
  - Multi-hops communications (mother-daughter architecture)
  - Deep space multiple access schemes (e.g. CDMA)
  - Collaborative communications

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Acknowledgement

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Backup

Notional Ground Network Development Plan

- Near-Term (now-2017): streamline and upgrade existing DSN capabilities
  - Update DSN resource allocation that accommodates smallsat/CubeSat needs
  - Simplify missions' interface, and reduce missions' testing and setup cost in using IND
  - Upgrade current 2-MSPA to 4-MSPA
  - Coordinate with non-DSN stations to support smallsats
- Mid-Term (2017/2018 – 2020): increase number of simultaneous links
  - Develop and deploy OMSPA (1-uplink, multiple downlinks)
  - Develop and deploy enhanced OMSPA (multiple uplinks, 2-way, commanding)
- Far-Term (2020+): develop advanced concepts and capabilities
  - Develop capability to support mother-daughter spacecraft (multi-hop communications)
  - Develop deep space CDMA receiver and signal processing system
  - Develop DSN-assisted collaborative communication scheme

- Development of CubeSat-compatible flight hardware
  - Avionics
  - Iris radio
  - High-gain antennas that fit into CubeSat form factor

DSN Operation and Interfaces with non-DSN stations - Deep Space Spectrum Coordination (2)

- Typical Spectrum Process for smallsats
  1. Project contacts spectrum manager and requests a frequency assignment
  2. Spectrum manger consults with the project to determine their mission/ telecommunication parameters and bandwidth requirements.
  3. A frequency selection study is performed to determine a frequency in the appropriate band (per the NTIA Table of Frequency Allocations) which is least likely to receive from, or cause interference to, other missions sharing the band
  4. The project is briefed on the frequency selection and provides feedback as necessary
  5. A Stage 2 system review filing is prepared for experimental projects, typically smallsat missions of shorter duration and not requiring protection from interference. The filing provides information on the smallsat transmitter and receiver characteristics, and shows project compliance with power flux density limits, emission masks, and other NTIA regulations.
  6. If interference protection is required or if the smallsat mission is operational rather than experiment in nature, then a Stage 4 filing is needed. This requires hardware measurements of the smallsat transmitter emissions and receiver characteristics.
  7. The filing is reviewed by the NTIA Spectrum Planning Subcommittee (SPS) and the System Review Branch.

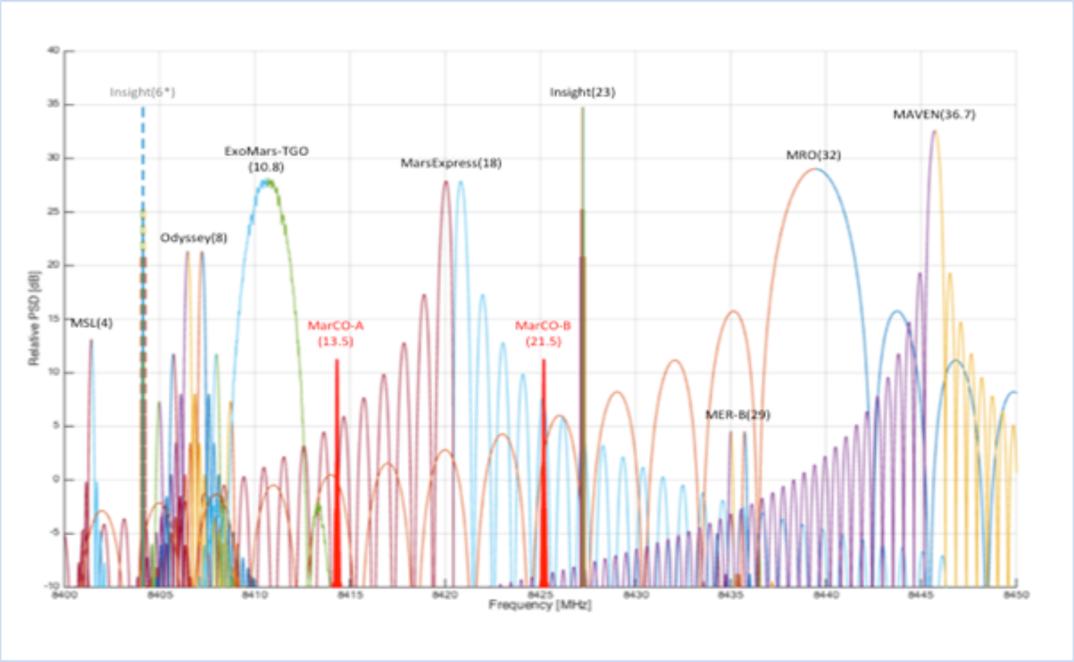
DSN Operation and Interfaces with non-DSN stations - Deep Space Spectrum Coordination (3)

8. Concurrently, the spectrum manager works through the Space Frequency Coordination Group (SFCG) and other forums to coordinate with domestic and international agencies sharing the same frequency band to minimize RFI issues. The spectrum manager also works to address issues/concerns on the filing from the NTIA
9. The NTIA will issue a certification (Stage 2 or 4) upon successful completion of the systems review, along with a list of SPS recommendations
10. After receiving the certification, the spectrum manager requests a Radio Frequency Authorization (RFA) from the NTIA Frequency Assignment Subcommittee (FAS)
11. Once the RFA is granted by the FAS, the project is permitted to use those frequencies for the mission. The project is responsible for notifying the spectrum manager if there are changes in the mission or operational plan (e.g., change in ground station or data rate, extended mission duration) compared to what was provided in the filing.

- Deep space interplanetary smallsats usually are classified as belonging to the Space Research Service (SRS)
  - Per the NTIA Table of Allocations, spectrum available for deep space SRS include 2110-2120 MHz, 7145-7190 MHz, and 34200-34700 MHz for Earth-to-space links, and 2290-2300 MHz, 8400-8450 MHz, and 31800-32300 MHz for space-to-Earth links

DSN Operation and Interfaces with non-DSN stations - Deep Space Spectrum Coordination (4)

- Many NASA deep space missions, including several smallsats, use the 8400-8450 MHz band for space-to-Earth downlinks which creates a problem with spectrum congestion particularly when near Mars
- Appropriate channel assignments can help mitigate interference by separating high and low rate data mission within the same frequency band.
- Use of different antenna polarizations, pulse shaped modulations, and transmit filters are on-board hardware solutions recommended for reducing the probability of RF interference
- If interference is unavoidable, the spectrum manager will conduct analyses to predict the time periods and severity of the interference.
- Operational workarounds to avoid interference, such as turning off the transmitter during certain intervals, reductions in data rate, or downlinking to a different ground station can then be implemented.



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