Architecture and CONOPS of Next-Generation Ground Network for Interplanetary SmallSats

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Outline of Talk

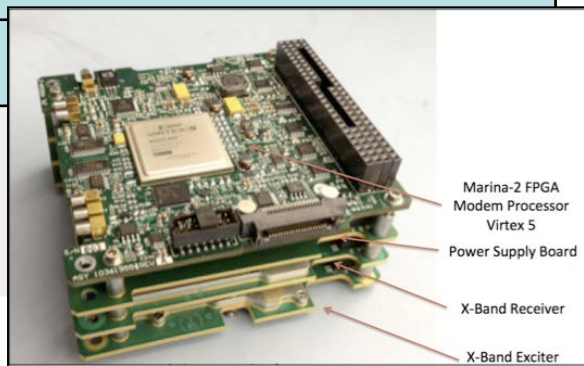
- Mission Characteristics, Comm/Nav Needs
- Summary of Architecture Study Results
  - Flight Communication Hardware Development
  - Ground Network Streamlining and Development
- CONOPS and Cross-Support for Interplanetary CubeSats
  - Mission Interface standardization to Reduce Cost
  - Challenges of Cross-Support with non-DSN Antenna
  - Potential cross-Support Partners
  - Network Scheduling Concept for Interplanetary CubeSats

Mission Characteristics, Communication/Navigation Needs

- Mission unique characteristics
  - Spacecraft are small – CubeSat form-factor
  - 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 communication and Navigation 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

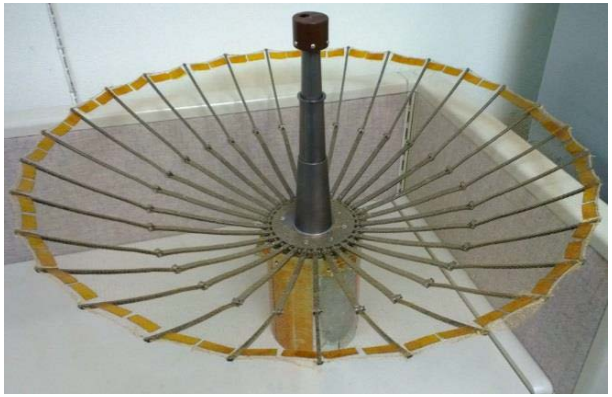
Flight Communication Hardware Development – IRIS Radio (1)

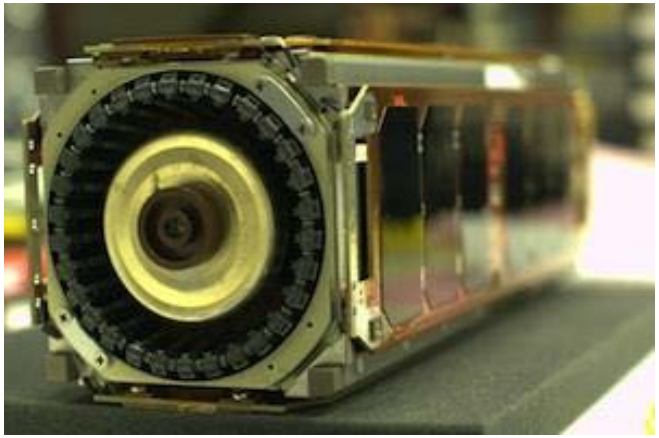
Parameter	Value
CubeSat Compatible	Size: 0.4 U, Mass: 0.4 Kg
Power	26W DC in, 4 W out (transmit), 8 DC in (receive)
Frequency	Receive: X, UHF, Transmit: X
DSN Compatible (Nav)	Full-duplex Doppler, ranging, Delta-DOR
DSN Compatible (Telecom)	62.5 – 256000 bps telemetry, 1000 bps command
Sensitivity	25 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



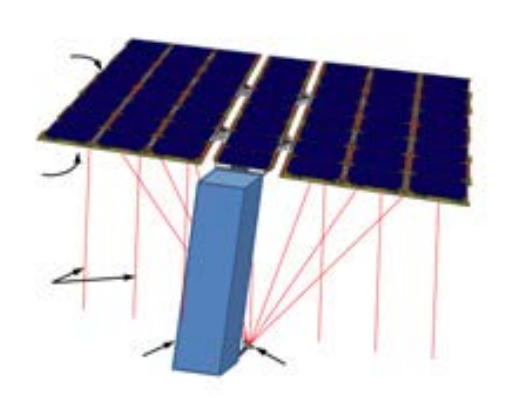
Flight Communication Hardware Development – HGA(2)

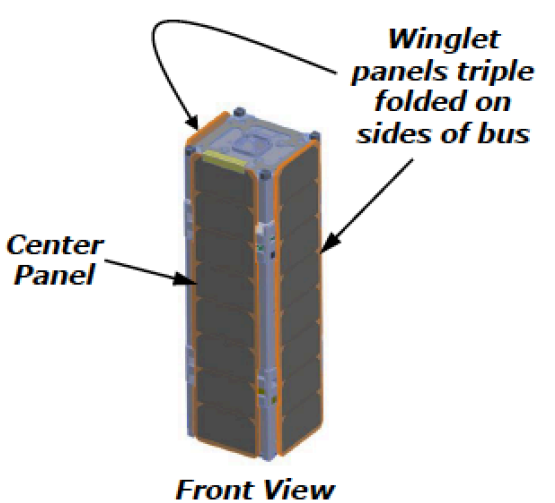
Deployable Antenna
- 1.5U, 0.5m diameter
- Ka-Band





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





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

Ground Network Streamlining and Development - Scheduling

- Current DSN planning and scheduling is based on peer-to-peer negotiation
  - Traditional deep space missions typically have complicated science and engineering plans and dependencies, thus requiring rigid pass allocations
  - They are also conservative in their requests of coverage time
- DSN is a shared resource, supporting Class A missions as well as interplanetary CubeSats
  - CubeSats are Class D, assume greater risk and lower priority
  - Policy in spacecraft anomaly and schedule update request: initial DSN response will only affect other CubeSats' scheduled passes
- Interplanetary smallsats require shorter passes, and desire shorter planning cycle
  - Expect to be more flexible, thus easy to schedule in between passes of Class A missions
- CubeSat passes are more amenable to software-based and priority-based scheduling
  - Priority is based on engineering and science urgencies, not budget size of a mission
  - One can exploit the CubeSat pass flexibility to maximize network data return efficiency
- We demonstrate a network scheduling concept for CubeSats that maximizes pass opportunities and/or data return in later part of the talk

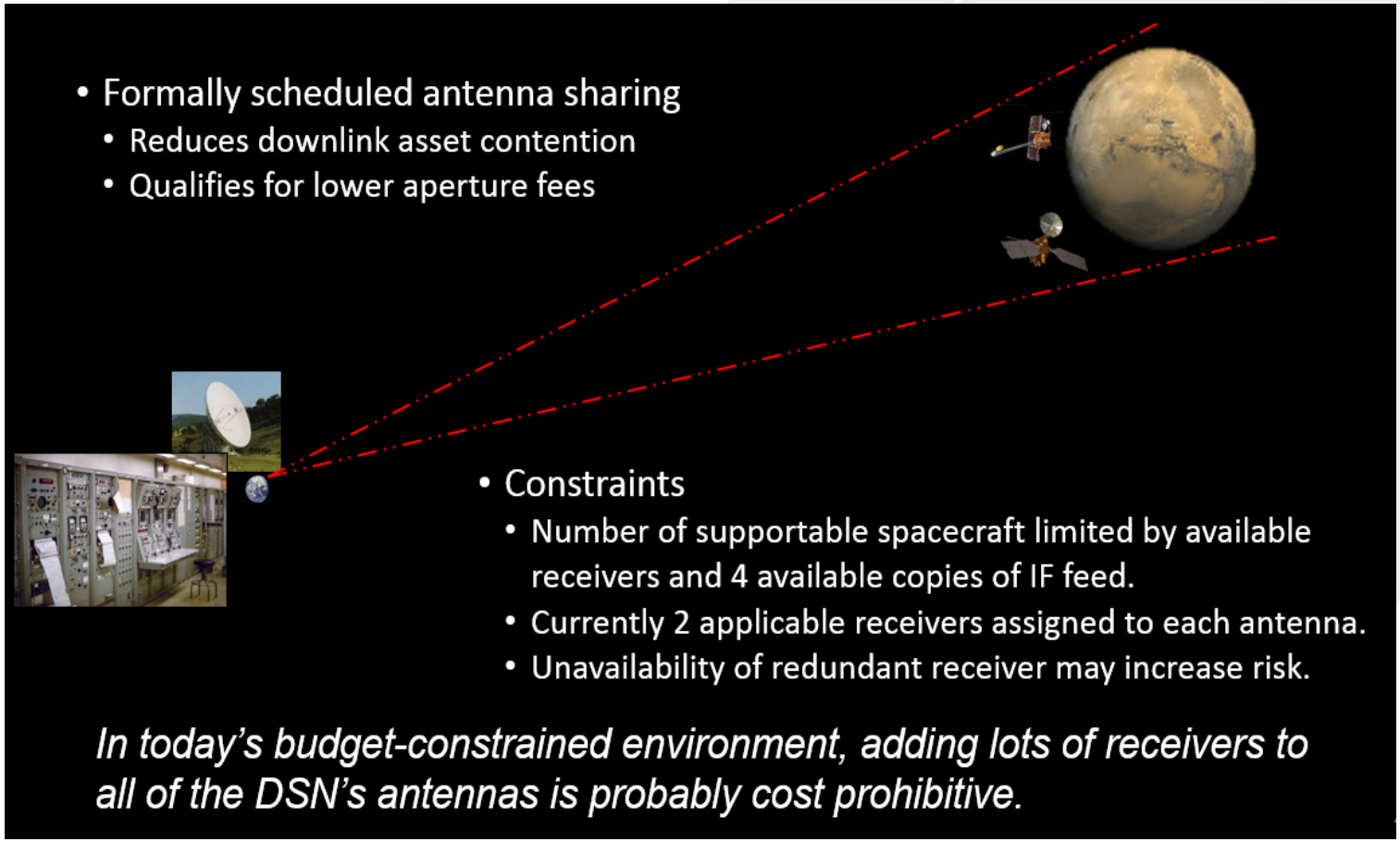
Ground Network Streamlining and Development – Spectrum

- Challenges in CubeSat spectrum coordination
  - CubeSat development cycle is typically short, e.g. 1 – 2 years
  - Spectrum coordination is a lengthy process
    - Frequency selection, RFI analysis, spectrum regulatory filing, etc.
  - Frequency assignments are often requested before the CubeSat 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

- Recommendations
  - Start early
  - In light of uncertainties, include all candidates (e.g. ground sites) in the spectrum analyzes; it is much easier to take things out than to add new things

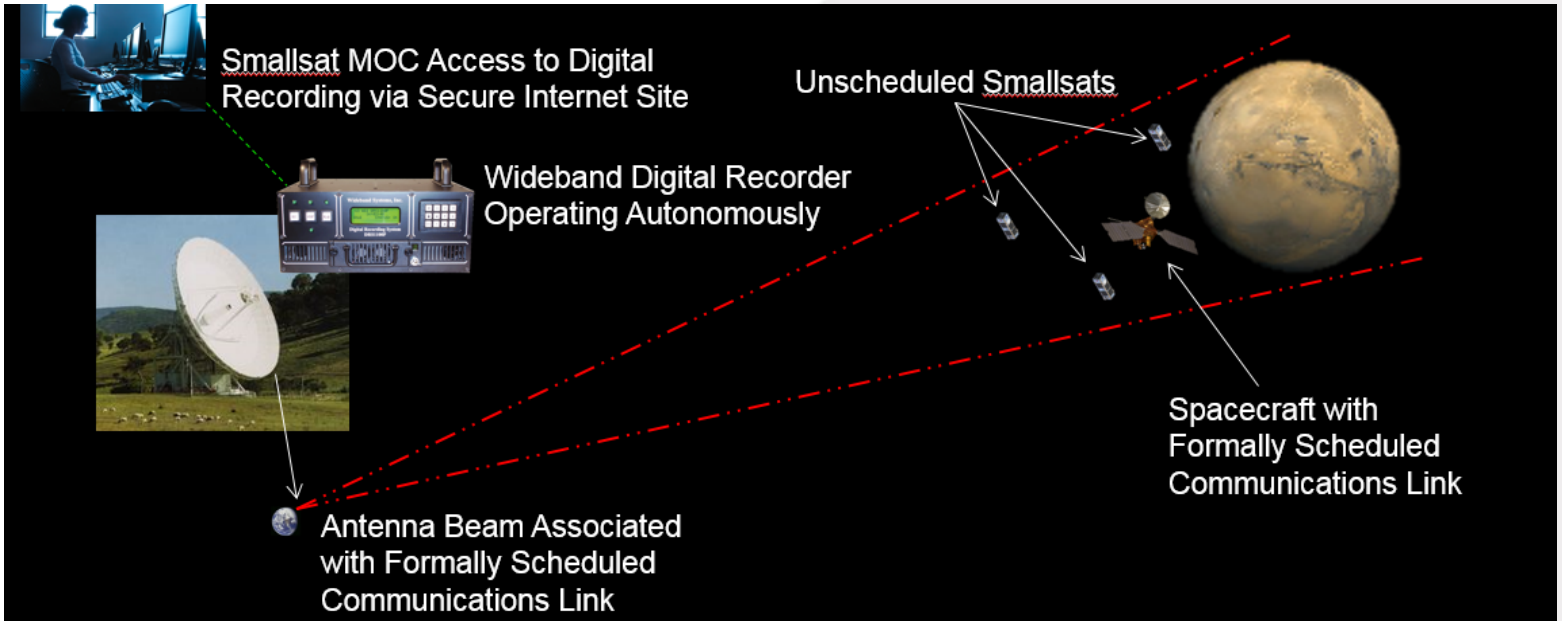
Ground Network Streamlining and Development – MSPA

- Current operational Multiple Spacecraft Per Antenna (MSPA) supports 2 spacecraft
- Near-term plan is to increase to 4 spacecraft



Ground Network Streamlining and Development – Opportunistic MSPA

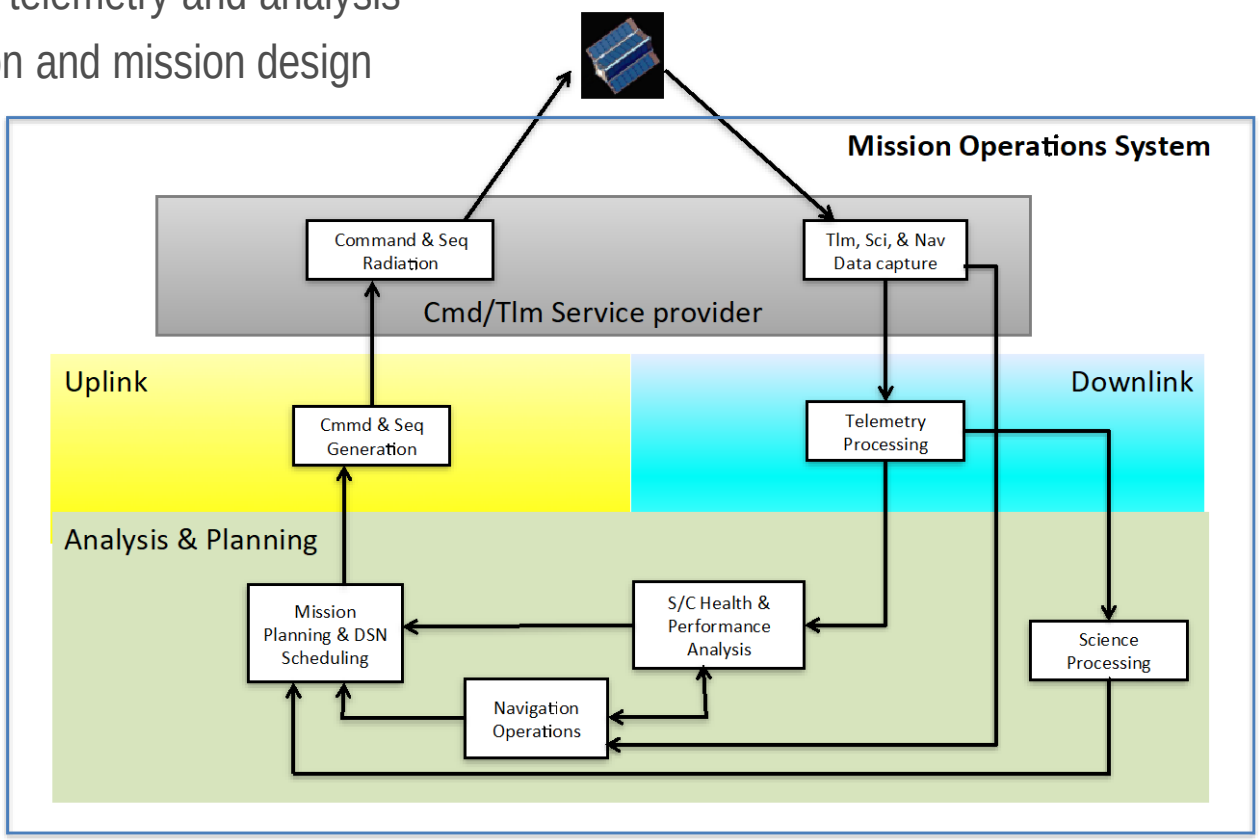
- Proposed Opportunistic MSPA
  - Use open-loop receiver to record IF for later processing of multiple signal streams



Everything received through the antenna beam is digitally recorded. Smallsats transmit open loop when in a host spacecraft's beam. Smallsat MOCs retrieve relevant portion of digital recording for subsequent demodulation and decoding, or utilize a service that does it for them.

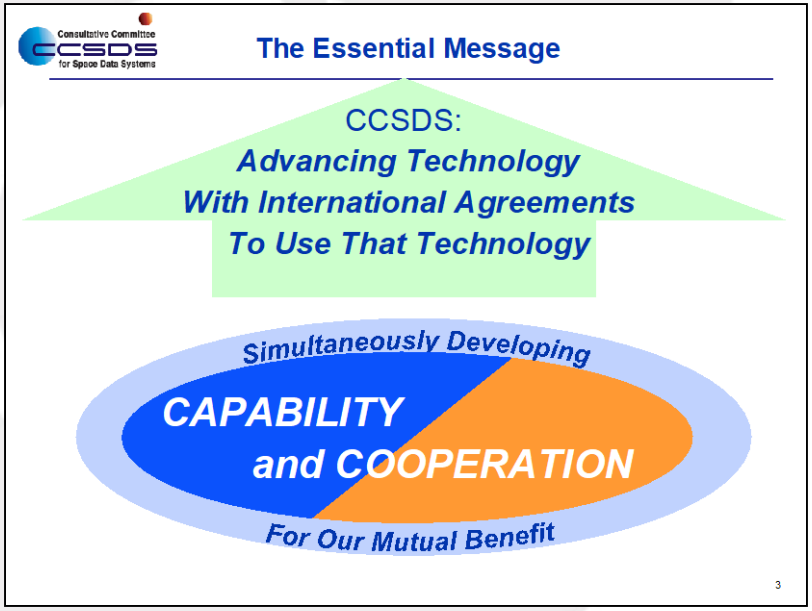
Ground Network Streamlining and Development – Mission Operation System (MOS) Architecture for CubeSats

- MOS architecture includes the following functions to design, develop, and operate missions
  - Planning and sequencing for uplink
  - Downlink telemetry and analysis
  - Navigation and mission design



Mission Interface Standardization
- Reduce Cost and Enable Cross-Support

- 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 links
  - SLE's Transfer Frames for return links
  - Tracking Data Message (TDM) for tracking data
- CCSDS standard interfaces are also adopted by JAXA and ESA, and this enables cross-support



Challenges of Cross-Support with Non-DSN Antennas (1)

- Standardization of signal and data formats
  - All stations in the federated network have to conform to a minimal set of DSN-compatible signal and data formats
- Ground station diversity
  - Different ground antennas consist of different hardware and software components
  - Standardized interfaces or proxy translations are needed in the seamless control and operation of the heterogeneous set of antennas
  - The qualities of communications and tracking services can be different for different antennas, and this creates complexity in the management and provision of services
- Security
  - University ground stations typically have relax security requirements
  - NASA interplanetary Smallsat missions would levy stringent requirements of physical (site) security and cyber security

Challenges of Cross-Support of Non-DSN Antennas (2)

- Different level of participation from non-DSN antennas
  - Non-DSN antennas would have their own business bases, thus would offer different degree of participations in the collaboration to track interplanetary Smallsats
  - In addition to different interfaces, different antenna stations might offer different access and control levels of their HW and SW
  - Availability of antenna resources might be well-coordinated, so they can be provisioned for services in a timely manner
  - The federated ground network must mask the antenna idiosyncrasies to the extend possible, so mission users would experience consistent services
- Ground data transport (see DSN Traffic Modeling Paper in SpaceOps 2016)
  - Spacecraft data consists of different data types, each associated with a latency requirement
  - The non-DSN antennas have to implement ground links with sufficient bandwidths that would meet the data latency requirements of the spacecraft users

Potential Cross-Support Partners - Universities

- Morehead State University 21-m Antenna

Table T.1 MSU 21 Meter Dynamical and Mechanical Properties

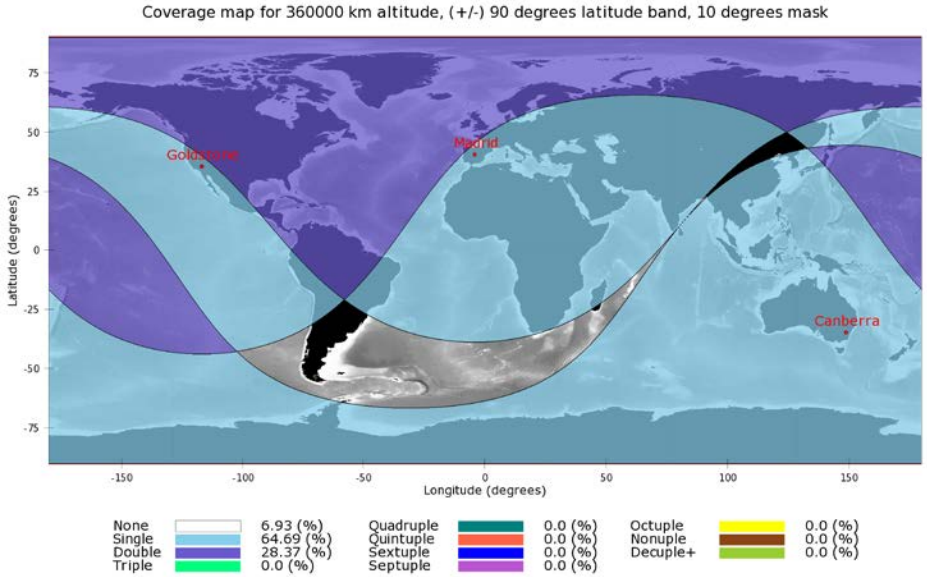
Dynamical/Mechanical Properties	Measured Values
Aperture Size	21 meters
Surface Accuracy	0.0166" RMS
Azimuth	> 3.0 °/sec
Elevation	> 1.6 °/sec
Polarization	± 90.9°
Azimuth Acceleration	> 1.0 °/sec^2
Elevation Acceleration	> 1.0 °/sec^2
Azimuth Travel	± 270° from 180°
Pointing Accuracy	0.01° RMS
Tracking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

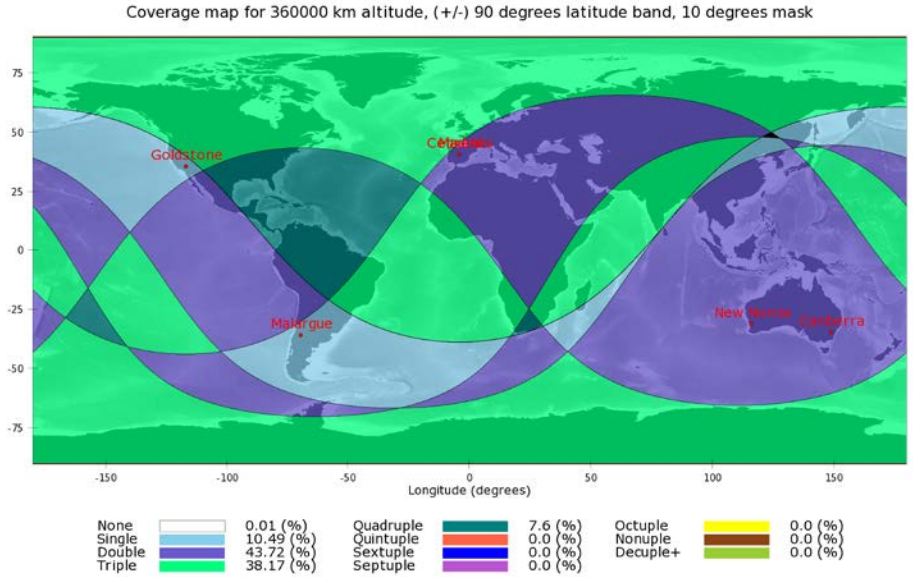
Table T.2 MSU 21 Meter RF Capabilities

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

Potential Cross-Support Partners – Other Space Agencies

- ESA has 3 35-m deep space Antenna, all DSN-compatible
  - 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





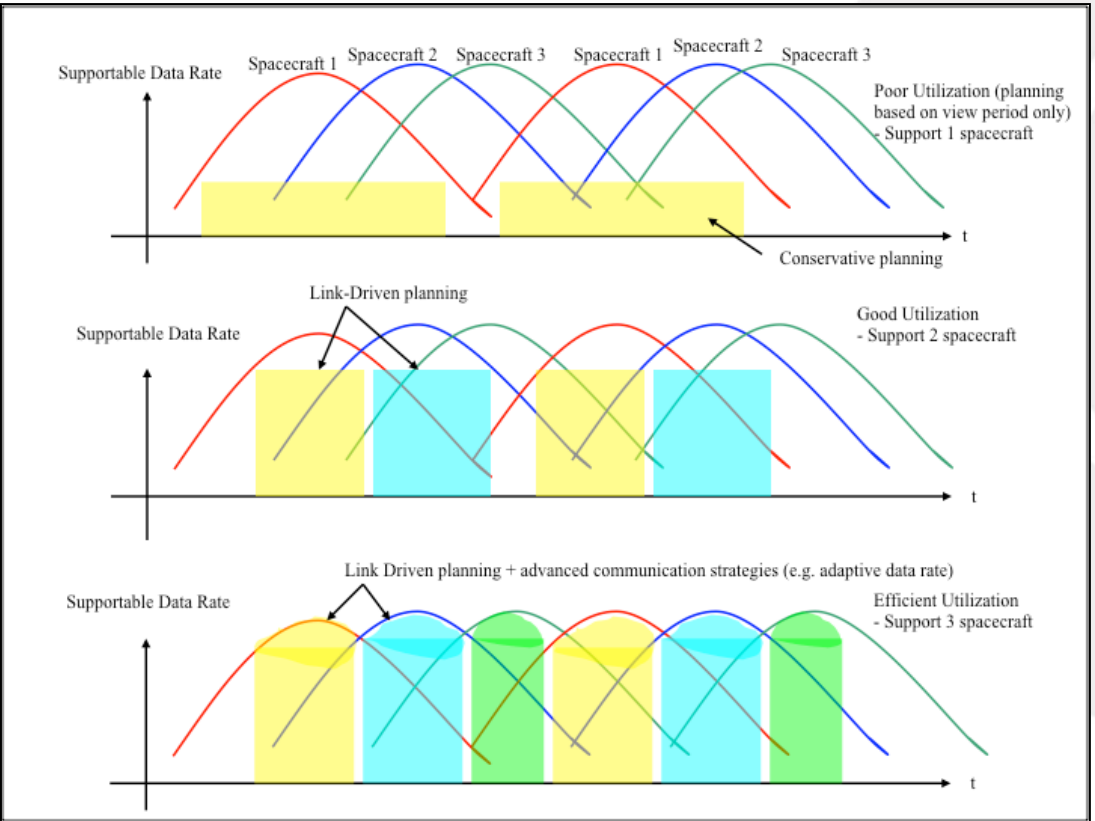
Potential Cross-Support Partners – Other Research Centers

- APL's 18.3-m antenna supports S-band (Up/Down) and X-band (Down)
- Supports Space-Link-Extension (SLE)
- Cross-support with DSN on Chandrayaan-1 during the LEOP phase in 2008

Downlink	S-band	X-band
Frequency Range	2200-2400 MHz	8000-8500 MHz
Polarization	RHC and LHC	RHC and LHC
G/T	>28.3 dB/K	>38.5 dB/K
Beamwidth	0.5 deg	0.13 deg
Uplink	**S-band**	
Frequency Range	2025-2120 MHz	
Polarization	Selectable LHCP or RHCP	
Beamwidth	0.5 deg	
EIRP	>80 dBW	
Transmitter	2000 W Klystron	
Antenna Pointing Control		
Program track, S-band Autotrack, S/X-band Steptrack		
CCSDS Compliant		
Command, Ranging, Doppler & Telemetry, including Turbo, Convolutional, and Reed-Solomon decoding; SLE		

Network Scheduling Concept for Interplanetary CubeSats (1)

- Consider each spacecraft plans to download a known data volume to ground
- The higher the data rate, the lesser time is required to download the same data
- Efficient and flexible scheduling generates shorter passes that meet individual mission's data return requirements, thus helps to create additional pass time for other spacecraft



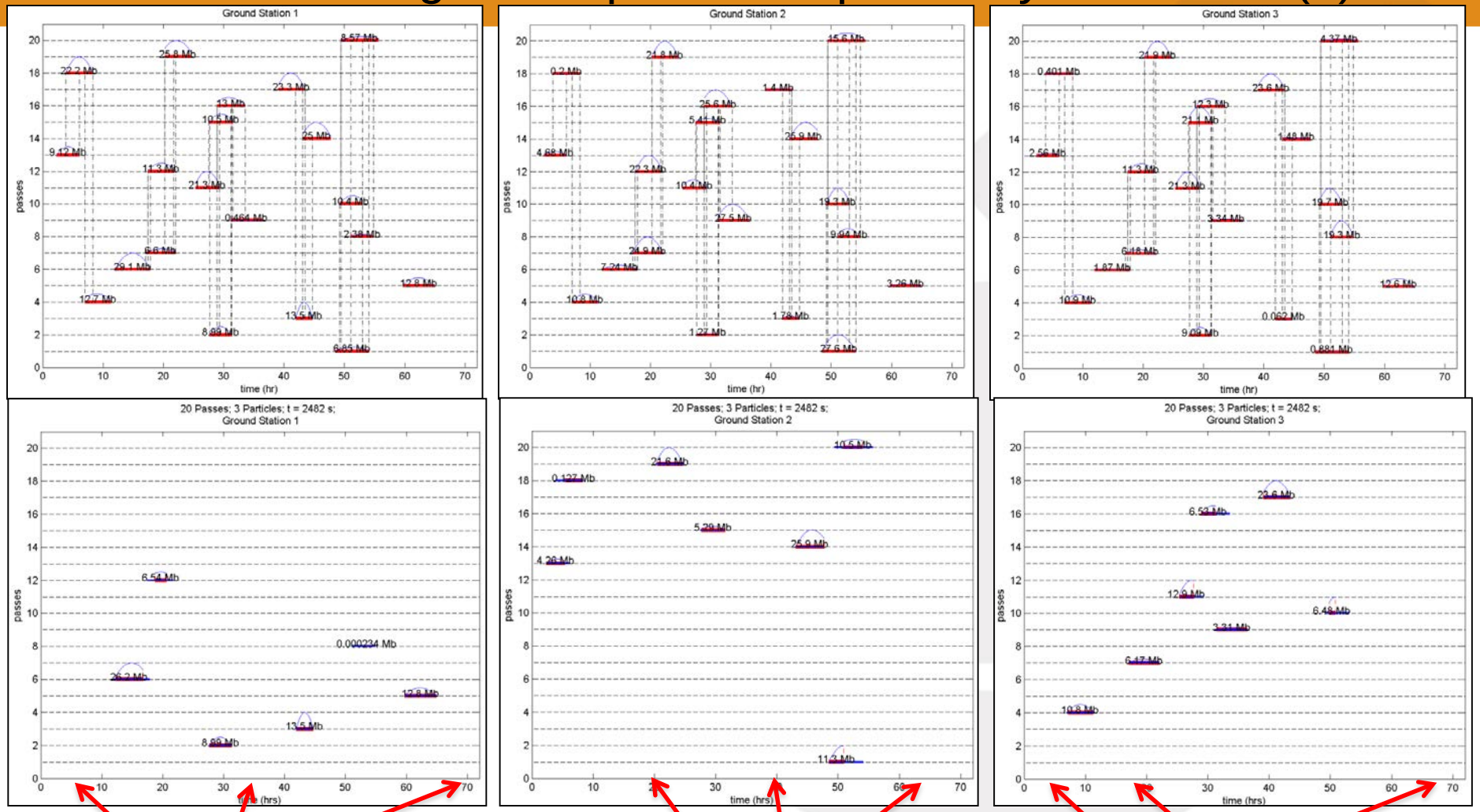
[24] K.-M. Cheung, et. al., "Link-Capability Driven Network Planning and Operation," *IEEE Aerospace Conference 2002*, Big Sky, Montana, March 2002.

[25] C. H. Lee, K.-M. Cheung, "Mixed Integer Programming and Heuristic Scheduling for Space Communication Networks," *Proceedings of the IEEE Aerospace Conference 2012*, Big Sky, Montana, March 2012.

Network Scheduling Concept for Interplanetary CubeSats (2)

- We developed framework and the mathematical formulation for optimizing communication network using mixed integer programming (MIP)
- Our constrained network optimization takes into account the dynamics of link performance along with mission and operation requirements
- A unique penalty function is introduced to transform the mixed integer programming into the more manageable problem of searching in a continuous space
- The constrained optimization problem was solved in two stages:
  - Use the heuristic Particle Swarming Optimization algorithm to get a good initial starting point
  - Feed the result into the Sequential Quadratic Programming algorithm to achieve the final optimal schedule
- We demonstrate the above planning and scheduling methodology with a scenario of 20 spacecraft and 3 ground stations of a Deep Space Network site, for a time-horizon of 3 days (see next slide)
- Our approach and framework have been simple and flexible so that problems with larger number of constraints and network can be easily adapted and solved.

Network Scheduling Concept for Interplanetary CubeSats (3)



Add'l Pass Opportunities

Add'l Pass Opportunities

Add'l Pass Opportunities

Concluding Remarks and Future Trends

- We discuss the following in this paper pertinent to the support of interplanetary smallsats
  - DSN architecture and evolution path
  - Ongoing development both on the flight system and ground network sides
  - Preliminary thoughts on ground network CONOPS
  - Cross-support with non-DSN antennas and interfaces
  - Network scheduling concept that maximizes tracking time and/or data return

- Future trends
  - Miniaturization of flight system components and instruments
  - Migration to higher frequencies
  - Deep space multiple access schemes
  - Multi-hop communications for fleet of CubeSats

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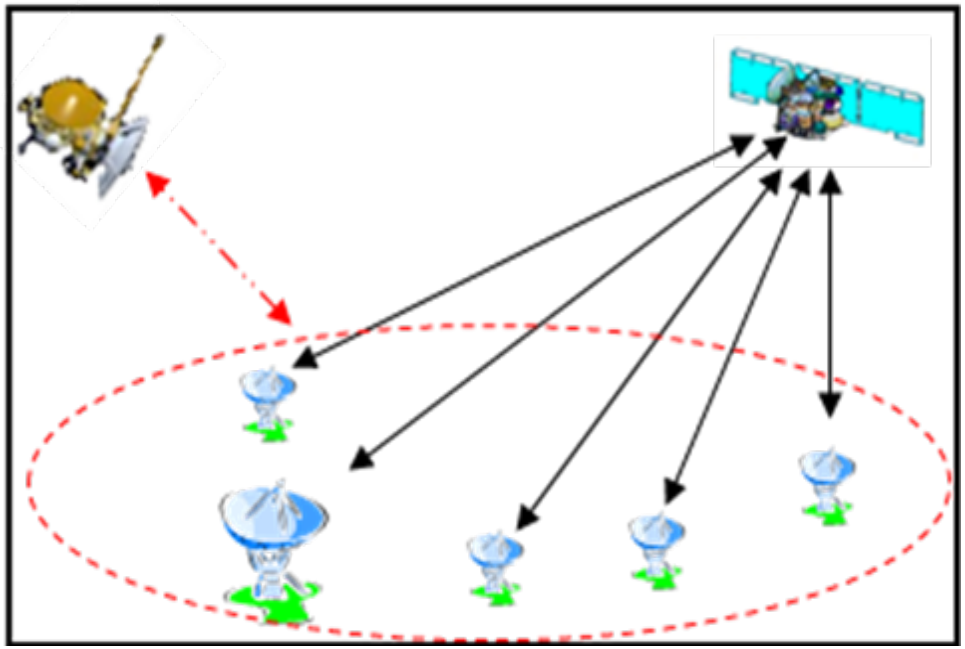
Backup

Network Scheduling Concepts that Maximize Pass Opportunities – Analysis Framework of Link-Driven Network Scheduling

Case 2 (2012 IEEE Aerospace Paper):

- **Multiple Antenna Per Site (M-to-N)**

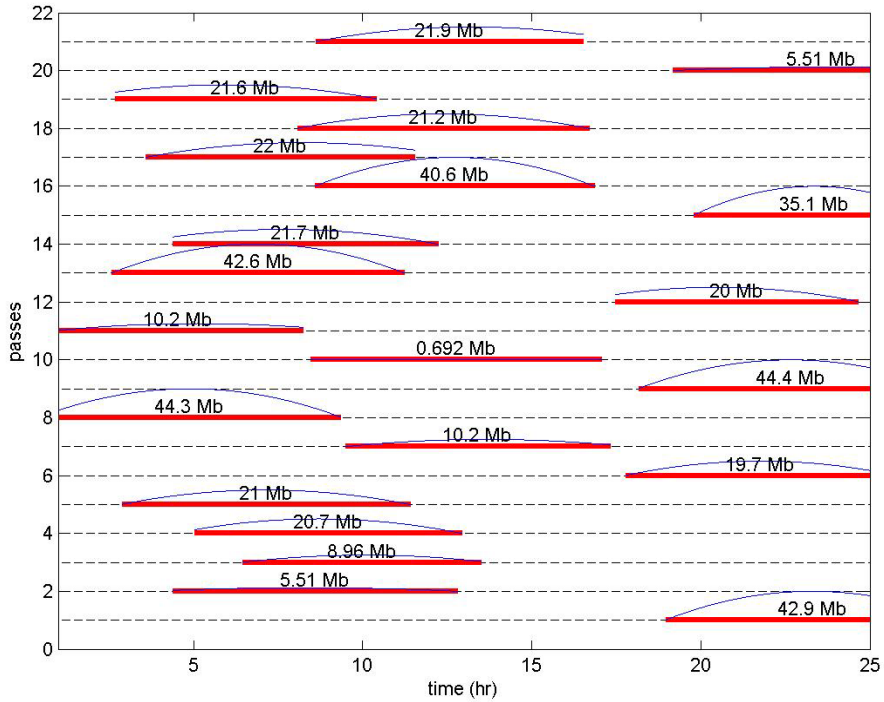
One S/C per ground antenna



An arraying scenario

- N_{sc} spacecraft passes are in view with a DSN site with N_{gs} stations
- For one spacecraft per antenna the search space is ~$2N_{sc}N_{gs}$
- If antenna arraying/MSPA are considered, then the search space ~$2N_{sc}(2^{N_{gs}}-1)$
- Key to solving constrained-optimization problem is to minimize the search space
- If Mixed Integer Programming (MIP) is considered (allow discrete and continuous search space), the search space becomes just $3N_{sc}$ (ground station/configuration index, start time, end time)

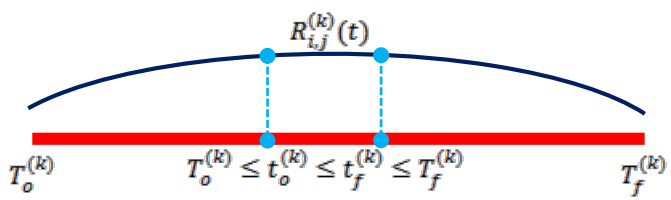
Network Optimization Problem Setup



Spacecrafts $1 \le i \le N_{sc}$

Ground Stations $1 \le j \le N_{gs}$

Passes $1 \le k \le N_p$



What are the start and end times?

Constrained MIP Problem

Search space variables

$$\vec{x} = [\vec{x}^{(k)}]_{k=1}^{N_p}$$

$$\vec{x}^{(k)} = \left[\ gs^{(k)},\quad t_o^{(k)},\quad t_f^{(k)}\ \right]^T$$

$$gs^{(k)} \in \{1, 2, \ldots, N_{gs}\}$$

Ground Stations

$$T_o^{(k)} \le t_o^{(k)} \le t_f^{(k)} \le T_f^{(k)}$$

$$1 \le k \le N_p$$

Passes

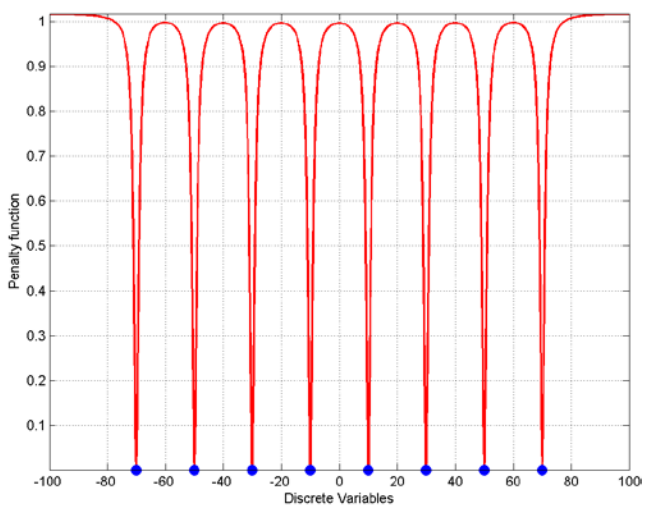
Cost (Penalty) Function

$$P(gs^{(k)}) = \prod_{j=1}^{N_{gs}} \frac{\left(gs^{(k)} - j\right)^2}{\left(gs^{(k)} - j\right)^2 + 1}$$

$$1 \le gs^{(k)} \le N_{gs}$$

$$J(\vec{x}) = \sum_{k=1}^{N_p} (t_f^k - t_0^k)$$

Minimize $J_\sigma(\vec{x}) = J(\vec{x}) + \sigma \sum_{k=1}^{N_{gs}} P(gs^{(k)})$



Time & Mission Constraints

Communication in a view-period must happen within the view-period itself

$$T_0^{(k)} \le t_0^{(k)} \le t_f^{(k)} \le T_f^{(k)}$$

The ground station number is bounded by

$$1 \le gs^{(k)} \le N_{gs}$$

Each pass must be longer than a minimum pass length

$$t_f^{(k)} - t_0^{(k)} \ge T_{\min}$$

Transmission time cannot overlap

$$[t_0^{(k_1)}\ t_f^{(k_1)}] \cap [t_0^{(k_2)}\ t_f^{(k_2)}] = \varphi$$

Minimum Required Data Throughput

$$\sum_{\substack{k=1 \\ sc^{(k)}=i}}^{N_p} DV(\vec{x}^{(k)}) \ge DV_{req}^{(i)}$$

Heuristic Scheduling

Constrained
MIP Problem

↓

Probabilistic Optimization
(Particle Swarm Optimization,
MATLAB Genetic Optimization)

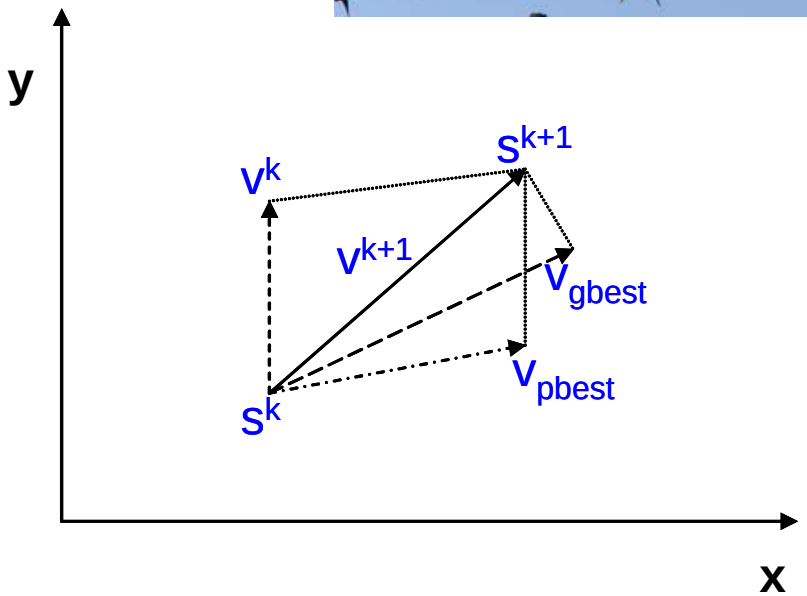
↓

Deterministic Optimization
(MATLAB fmincon)

↓

Optimal Schedule

Particle Swarm Optimization(PSO) Concept



s^k : current searching point

s^{k+1}: next searching point

v^k: current velocity

v^{k+1}: modified velocity

v_{pbest} : velocity based on personal best

v_{gbest} : velocity based on global best

Optimal Communication Scenarios Proof-of-Concept

- A network of 20 spacecraft with one DSN site (consists of 3 34m BWG antennas)
- Goal: maximize network data throughput in the 3-day time horizon
- Constraints considered are:
  - (i) the individual mission data volume requirements are met,
  - (ii) each ground station supports one spacecraft at any one time (non-overlapping pass),
  - (iii) each pass must be sufficiently long to ensure efficient usage of a ground station, and
  - (iv) each pass must start and end within its bounds.
- The dimension for the search space is 60 in this scenario.
- There are 20 linear bounds, 60 upper bounds, 60 low bounds, and 23 nonlinear constraints (3 non-overlapping and 20 mission data volume).
- 200 randomly generated particle elements.
- The process for both PSO and FMINCON with 200 iterations takes about 2482 seconds in an Intel Dual-Core 2.3 GHz laptop.