Architecture Study on Telemetry Coverage for Immediate Post-Separation Phase

Kar-Ming Cheung, Charles Lee, Kent Kellogg
Jet Propulsion Laboratory, California Institute of Technology

Frank Stocklin, David Zillig
Goddard Space Flight Center, National Aeronautics and Space Administration

Karl Fielhauer
Applied Physics Laboratory, John Hopkins University

SpaceOps 2008, Heidelberg, Germany
May 12, 2008

Acknowledgement

- **Bob Bukulic (APL)**
- **Ken Perko (GSFC)**
- **David Israel (GSFC)**
- **Doug Abraham**
- **Arv Vaisnys**
- **Laura Burke**
- **Greg Kazz**
- **Neil Mottinger**
- **Mike Davis**
- **Pablo Narvaez**
- **Dick Emerson**
- **Lynn Craig**

This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

Outline of the Talk

- **Introduction and Summary**
- **Network Coverage**
- **Transmitter/Transponder Options**
- **Preliminary Cost Driver List and Forward Plan**

Introduction and Summary

Problem Statement

- **Problem**
  - Spacecraft that do not utilize SN usually lack telemetry coverage during launch vehicle separation phase
  - As a result, no RT data is transmitted to the Ground during mission critical events
  - In the event of a catastrophe, no flight telemetry is available for anomaly investigation
- **JPL Design, Verification/Validation & Ops Principles for Flight Systems (Design Principles), Rev. 3**
  - 3.1.2.1 ***Uplink/Downlink capabilities*** - The mission design shall provide for a real time downlink capability during mission critical events
- **GSFC Rules for the Design, Development, Verification, and Operation of Flight Systems**
  - 1.14 ***Mission Critical Telemetry and Command Capability*** - Continuous telemetry coverage shall be maintained during all mission-critical events. Mission-critical events shall be defined to include separation from the launch vehicle; power-up of major components or subsystems; deployment of mechanisms and/or mission-critical appendages; and all planned propulsive maneuvers required to establish mission orbit and/or achieve safe attitude. After separation from the launch vehicle, continuous command coverage shall be maintained during all following mission-critical events.

JPL Design Principle

3.0 Mission Design

3.1 General

3.1.1 Launch Period - The launch period shall be of sufficient duration to provide a probability of successful launch equal to or greater than 99%. In the absence of sufficient launch vehicle history to justify a statistical analysis, a launch period of at least 20 days shall be chosen.

3.1.2 Communications during mission - critical events

Note: Mission-critical events are those that if not executed properly and in a timely manner could result in failure to achieve mission success, e.g. orbit insertion; entry, descent, and landing. A trajectory correction maneuver (TCM) is not mission-critical unless it must execute properly in the time scheduled for it, i.e. cannot be delayed.

Note: Protection against loss of unique data, e.g. one-time science is covered in 3.1.3.

3.1.2.1 ***Uplink/Downlink capabilities* -** The mission design shall provide for a real time downlink capability during mission critical events.

Note: Communications during other special mission events is addressed in 4.5.1.4.

3.1.2.2 ***Redundant data paths* -** Except for Earth orbiting missions, the mission design shall ensure that redundant data paths not vulnerable to potential single failure(s) exist for real time return of flight data from post-launch mission critical events.

Note: Scheduling of mission critical events to occur during the overlap of 2 tracking complexes is one way to satisfy this requirement.

10 Design Principles

GSFC Gold Rule

1.11	Mission Critical Telemetry and Command Capability						Systems Engineering
Principle:	Continuous telemetry coverage shall be maintained during all mission-critical events. Mission-critical events shall be defined to include separation from the launch vehicle; power-up of major components or subsystems; deployment of mechanisms and/or mission-critical appendages; and all planned propulsive maneuvers required to establish mission orbit and/or achieve safe attitude. After separation from the launch vehicle, continuous command coverage shall be maintained during all following mission-critical events.						
Rationale:	With continuous telemetry and command capability, operators can prevent anomalous events from propagating to mission loss. Also, flight data will be available for anomaly investigations.						
Phase:	A	A	B	C	D	E	F
Activities:	1. Identify anddocument potentialmission-critical eventsin concept of operations. 2. Identify and document in concept of operations all potential needs for communications coverage, such as TDRSS or backup ground stations.	1. Update concept of operations. 2. Identify requirements for critical event coverage in ground system design.	1. Address and document coverage of mission critical events in draft of Mission Operations Concept. 2. Address critical event coverage in requirements for ground system design.	1. In Operation Plan, identify telemetry and command coverage for all mission critical events.	1. Update Operations Plan. 2. Address telemetry and command coverage of critical events in Operations Procedures.	1. Perform critical events with telemetry and command capability.	N/A
Verification:	1. Verify at MCR.	1. Verify at MDR.	1. Verify at PDR.	1. Verify at CDR.	1. Verify at ORR	1. Verify telemetry capability during mission operations.	N/A

Revision Status:	Owner:	Reference:
Revision C, October 30, 2006	Guidance, Navigation and Control Systems Engineering (591)	

Check the GSFC Directives Management System at http://gdms.gsfc.nasa.gov to verify that this is the correct version prior to use 25

Assumed LEOP Planetary Mission Set Baseline

(Based on 5/9/06 Agency Mission Planning Model)

Near-term Supports (15)	2007	Phoenix, Dawn
	2008	Kepler
	2009	MSL
	2010	
	2011	Mars Scout 2, Juno
	2012	Discovery 12
	2013	Mars Science Orbiter, Discovery 13, MMS (4 S/C)
	2014	
	2015	Sentinels (4 S/C), Discovery 14, New Frontiers 3, OP-1, SIM
Long-term Supports (19)	2016	Mars Astrobiology Field Laboratory, Beyond Einstein 1
	2017	Discovery 15
	2018	Mars Scout 3, Terrestrial Planet Finder
	2019	Discovery 16, New Frontiers 4
	2020	OP-2, MSR 1
	2021	Discovery 17, Beyond Einstein 2
	2022	MSR 2
	2023	Discovery 18, New Frontiers 5, SEC ‘23
	2024	Mars Scout 4
	2025	Discovery 19, Large UV/IR, SEC ‘25

Summary of Preliminary Study

- **Ground networks (including DSN) can only provide limited coverage at low altitude (< 10K km)**
  - See DSN coverage example (next chart)
  - Require time-phase the spacecraft launch to ensure that the critical events occur when there is ground station coverage
    - **Impose additional launch constraints**
    - **Might need to increase battery size**
    - **Small windows of opportunity for transmitting**
- **Space Network (SN) provides continuous and complete coverage for low altitude operation (< 10K km)**
  - Existing COTS SN compatible transponders and transmitters are available for use in immediate post-separation communications
    - **With low mass and power for small satellite applications**
  - Imposes no launch constraints for coverage
- **Further assessment needed to understand the end-to-end mission implementation impacts**

Interpretation of Requirements and Proposed FOM

- **Develop spacecraft telemetry recovery capability (2 kbps) to provide telemetry communication coverage immediately upon separation from the launch vehicle until solar panels and primary spacecraft telecom subsystem are activated**
  - No uplink commanding and tracking
- **Maximize network coverage**
  - Consider existing and future space-based and ground-based networks that provide coverage during this phase
- **Maximize spacecraft antenna coverage**
  - Cover nominal and off-nominal spacecraft attitude (tumbling)
- **Minimize additional mass* and volume* to spacecraft**
- **Minimize additional power* draw to spacecraft**
  - Spacecraft runs on battery during this phase (solar panel not deployed)
- **Minimize integration and testing cost***
  - Use standard interface to avionics
- **Minimize development cost***
  - Consider COTS transponder or minor modification of existing transponder
  - Assume using Class C or D parts

*** Proposed Figure of Merit**

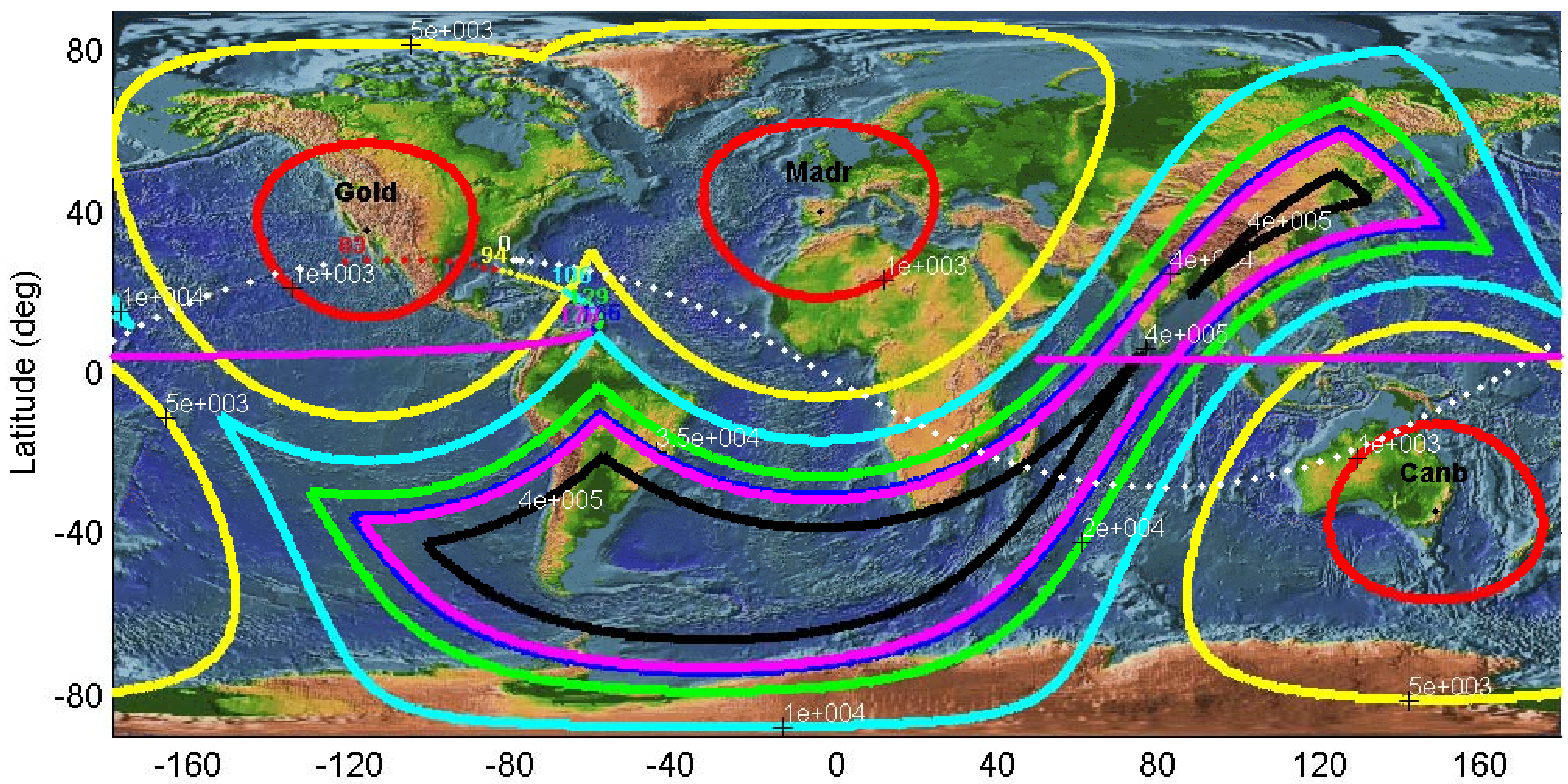
Network Coverage

Example of DSN Coverage

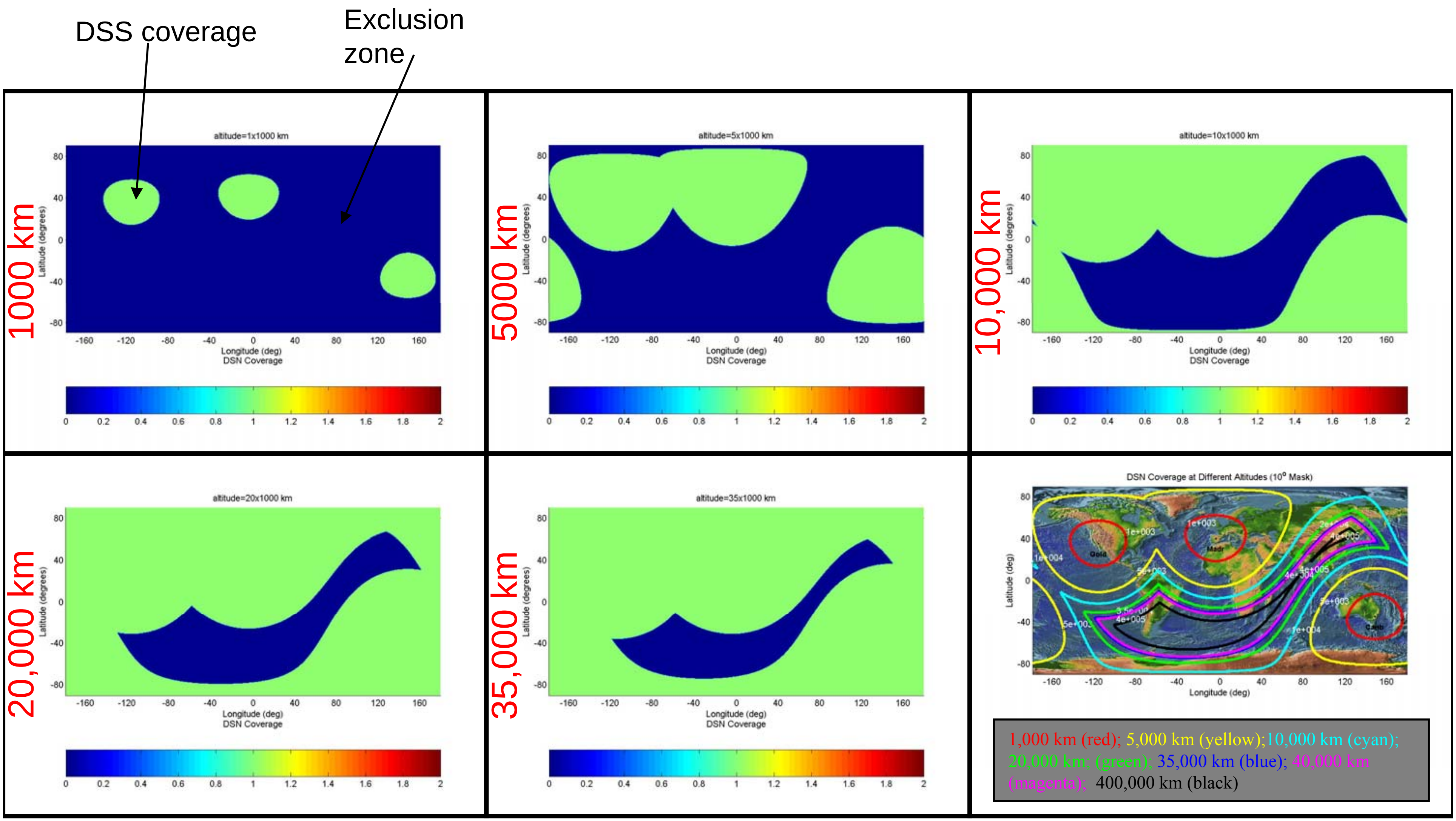
1,000 km (red)
5,000 km (yellow)
10,000 km (cyan)
20,000 km (green)
35,000 km (blue;~Roughly Geo-sync)
40,000 km (magenta)
400,000 km (black;~Average Moon distance)

Phoenix Launch
Separation at L+85 min
Return Telemetry at L+91 min

DSN Coverage of Phx at Different Altitudes (10° Mask)



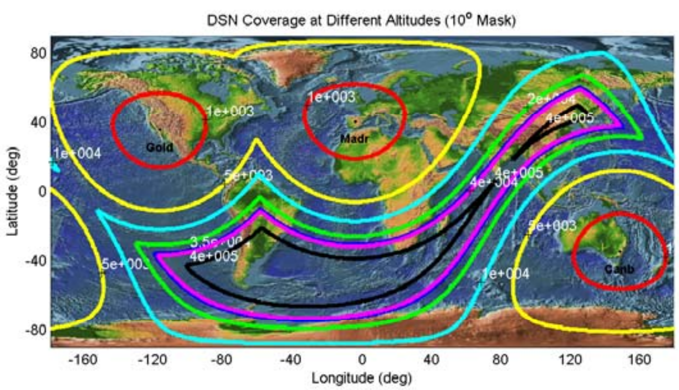
GN Coverage (Goldstone Canberra Madrid)



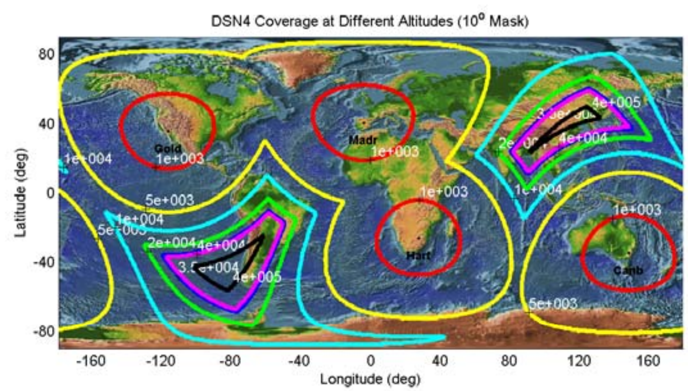
10° Elevation Mask

DSN Coverage at Different Altitudes

(Canb, Gold, Madr)

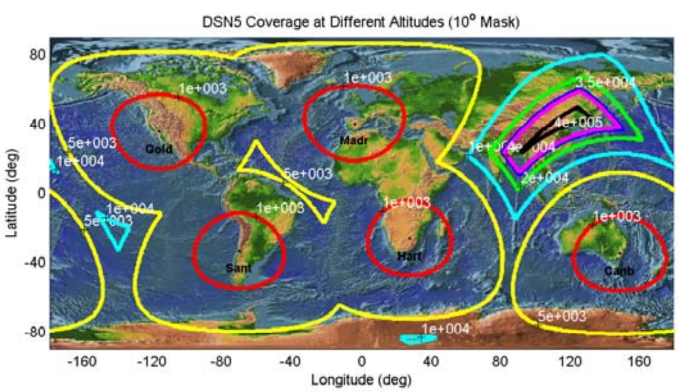


(Canb, Gold, Madr, Hart)

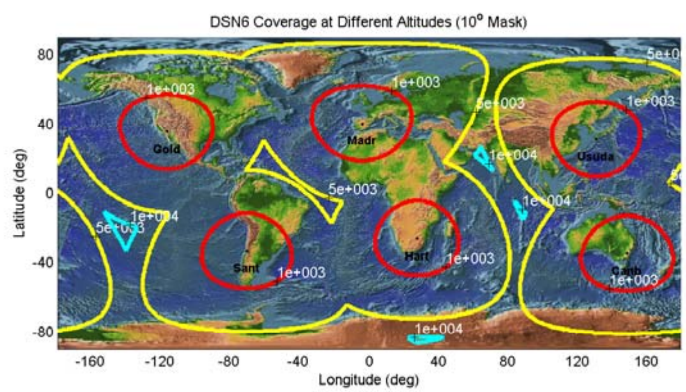


1,000 km (red) 5,000 km (yellow) 10,000 km (cyan) 20,000 km (green) 35,000 km (blue) 40,000 km (magenta) 400,000 km (black)

(Canb, Gold, Madr, Hart, Sant,)



(Canb, Gold, Madr, Hart, Sant, Usuda)

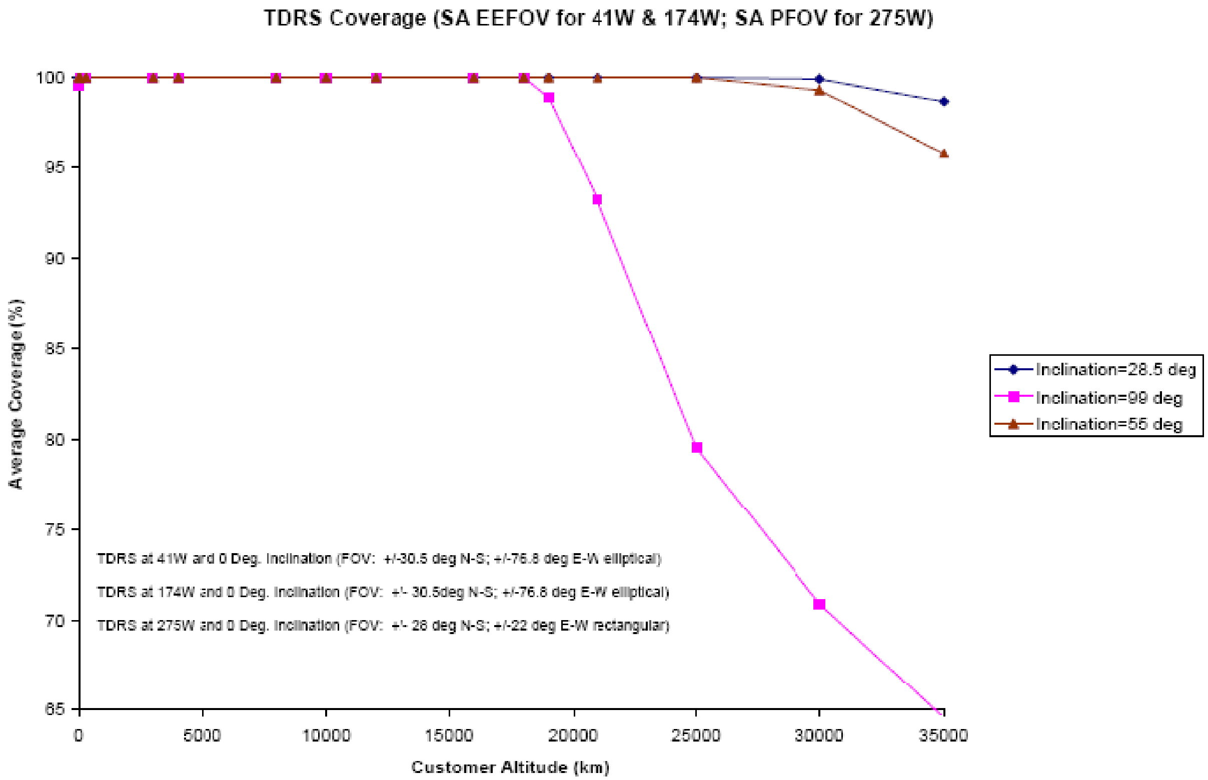


DSN Coverage @ Different Altitudes

DSN Coverage @ Different Altitudes (Area %)	DSN3 (Gold, Canb, Madr)	DSN4 (Gold, Canb, Madr, Hart)	DSN5 (Gold, Canb, Madr, Hart, Sant)	DSN6 (Gold, Canb, Madr, Hart, Sant, Usuda)
1,000km	11	14	18	21
5,000km	46	59	73	86
10,000km	65	79	90	100
20,000km	77	90	95	100
35,000km	84	94	97	100
40,000km	85	95	98	100
400,000km	93	99	100	100

SN Coverage as Advertised in SNUG

- **Space Network (from Space Network User's Guide (SNUG) Rev 9)**



Note: The customer minimum altitude for 100% line-of-sight coverage is 73 km.

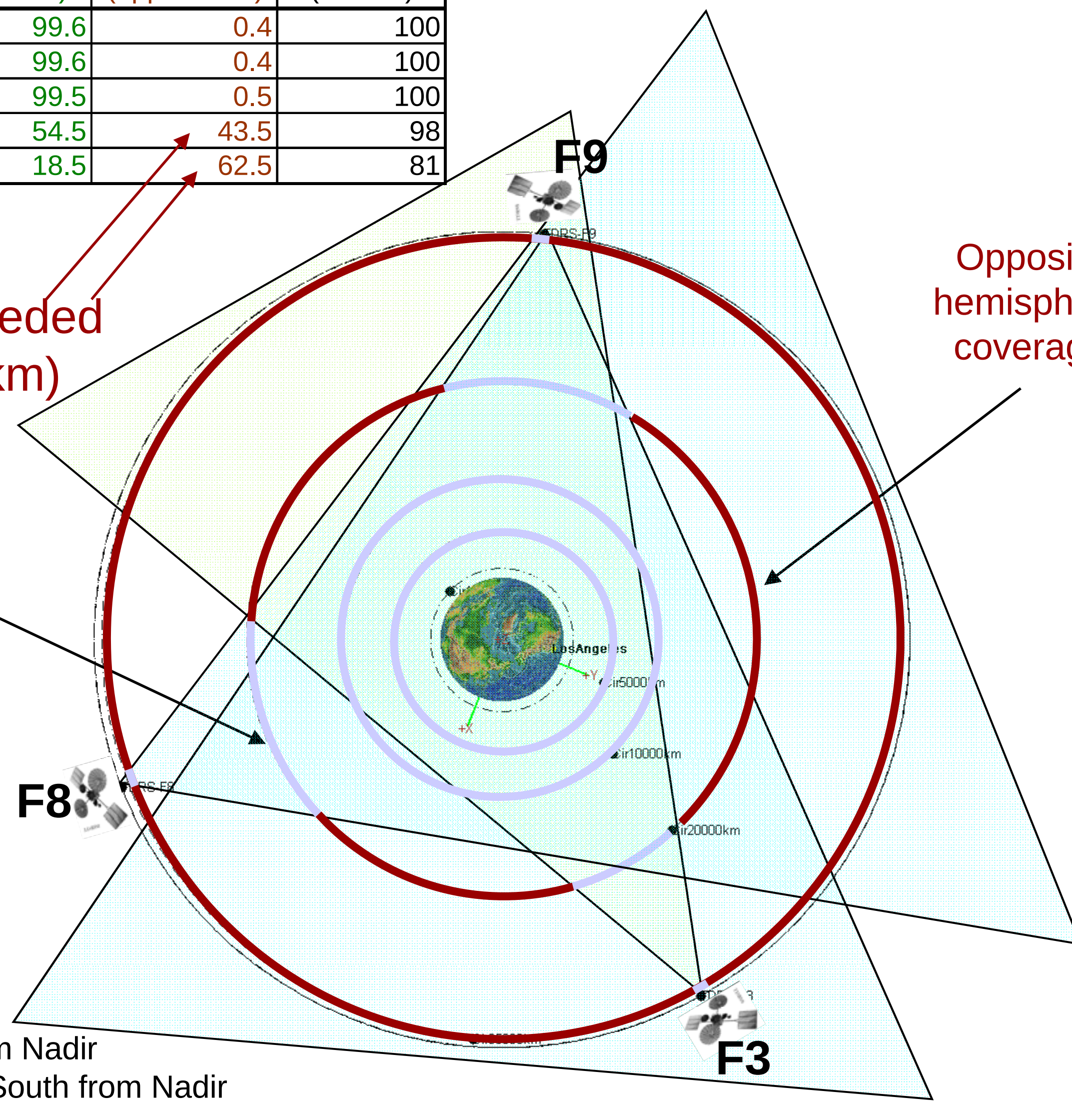
Figure 2-8. <u>Example</u> Average Line-of-Sight Coverage for SA EEFOV

SN Hemispheric Coverage

SN Coverage	F3 & F9 (same %)	F3 & F9 (opposite %)	F3 & F9 (total %)	F3 F8 & F9 (same %)	F3 F8 & F9 (opposite %)	F3 F8 & F9 (total %)
1000km	90	10	100	99.6	0.4	100
5000km	90	10	100	99.6	0.4	100
10000km	87	12	99	99.5	0.5	100
20000km	34	54	88	54.5	43.5	98
35000km	10	51	61	18.5	62.5	81

Larger user's power is needed
(68,000 km to 83,000 km)

Same
hemisphere
coverage



Extended Elliptical Field of View

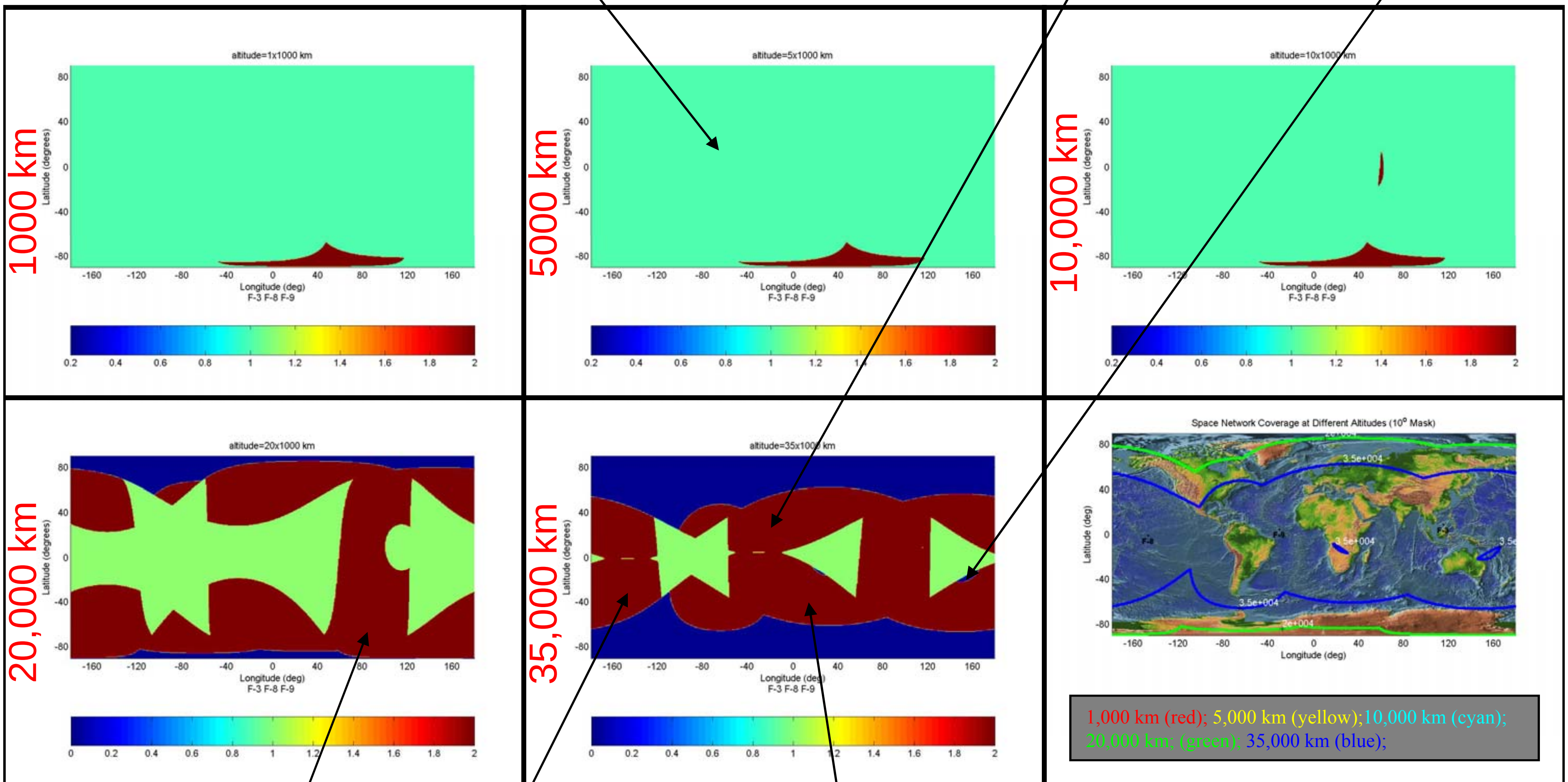
- F3: 22° East-West & 28° North-South from Nadir
- F8 & F9: 76.8° East-West & 30.5° North-South from Nadir

SN Coverage (F3 F8 & F9-TDRSS)

Same hemisphere coverage

Opposite hemisphere coverage

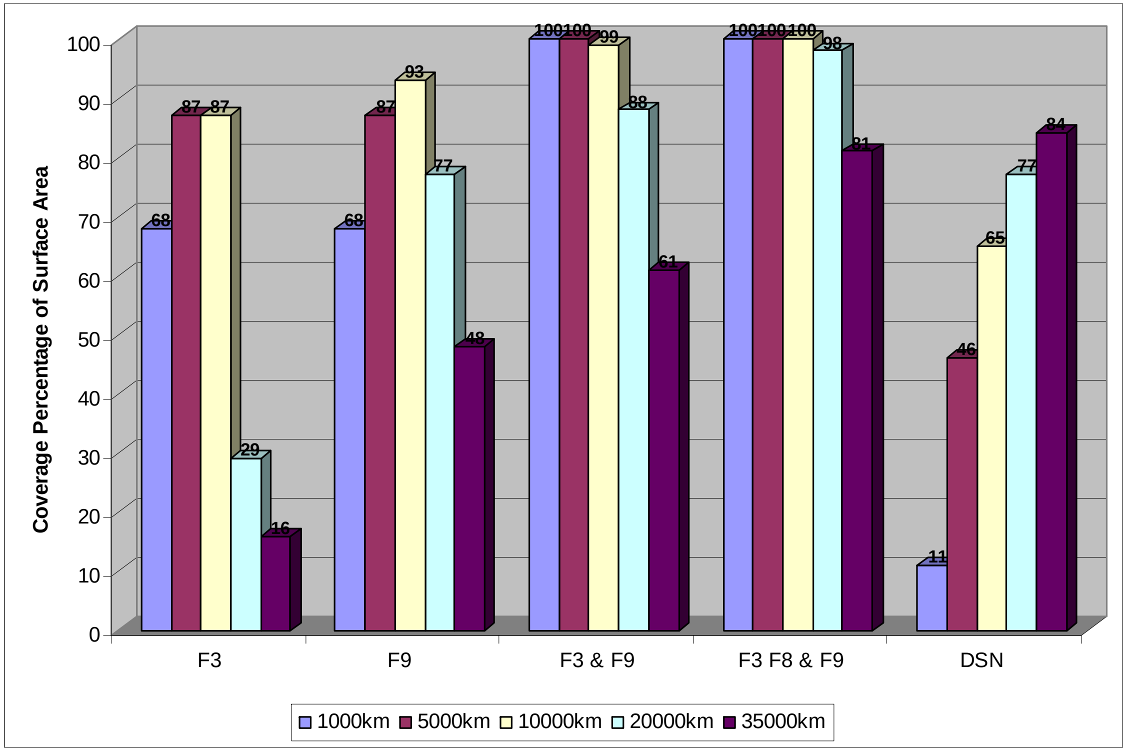
Exclusion zone



A Lot More of Opposite Hemisphere Coverage (not good for communications)

62.5% opposite hemisphere coverage

GN & SN Coverage
Summary & Recommendation



- While SN can provide high surface area coverage percentage even at higher altitudes (20,000km & 35,000 km), most of the links occur when SN and the user are on the opposite hemispheres (slanted ranges ~ 68,000 km & 83,000 km, respectively)
- 10,000-plus-km altitude switch-over between SN & GN seems to be appropriate
- Even though the GN covers 65% or more of the surface area at 10,000 km or higher altitudes, most of its coverage is centered around the equator, where majority of the missions stay.
- With the proposed 10,000-plus-km altitude switch-over, only F3 and F9 are needed.

Transmitter/Transponder Options

Preliminary Flight Telecom Architecture Trade

- **RF Approach Using TDRSS Network and TDRSS Compatible Transmitter (High TRL)**
  - Low Cost TDRSS Transmitter (Wallops)
  - T710 (L3 Communications)
  - T709 (L3 Communications)
  - T719 (L3 Communications)
  - EW C12 (Thales)
  - AeroAstro Transmitter (AeroAstro)
  - MST-765 (L3 Communications)

- **Other Possible Approaches**
  - RF Approach Using Upper Stage and Low Power/Mass Transmitter on spacecraft (Mid TRL)
  - Photonic Approach Using Upper Stage and Retro-Reflector (Low TRL)
  - SDST Modifications: Add a S-band slice on existing SDST

Preliminary Flight System Findings (1)

SN Compatible Options	LCT2	T710/T710A/T710B	T709	T719	EW C12 0000
Manufacturer	Wallops	L3	L3	L3	TES (Thales)
Transmitter Mass (Kg)	< 0.9 Kg	< 2.0 Kg	< 4.7 kg	< 2.3 Kg	< 0.5 Kg
Transceiver Mass (Kg)					< 1.0 Kg
Transmitter Dimenions (cm)	10.16 x 12.70 x 3.81	13.34 x 17.78 x 6.60	17.78 x 17.78 x 18.42	13.97 x 19.18 x 10.16 (from phone)	12.7 x 16.00 x 2.03
# of antenna ports		2	2	1?	1
Spacecraft Bus IF	RS232		RS422		RS422
Approximate Lead time		18 - 24 months.			
Parts and Grades		NASA B+			
Testing and Certification Process					Space Qualified
Approxmate Cost		Depends on aceptance test plan and part selection requirements.			Low Cost
Previous Users	ELV Sounding Rocket	T710-ATLAS LV T710B CloudSat spacecraft T710A ATLAS-V LV	Marshall ordered for CLV - Ares-1 Upper Stage S-Band Txr	NPP satellites (NPOESS Preparatory Project Spacecraft).	Deep Impact, Rosetta
Other Notes	No radiation harden or tolerate.	Rugged Version of T719, no digital processing slide for spread spectrum.	Very similar to T710, but with higher power output.	Digital dual mode	
Tx/Rv Mode	Tx only. DG2	Tx only. DG2	Can support TDRSS MA when user provides PN spreading code.	DG1: mode2, DG1:mode3, DG2	QPSK, Rate 1/2 coding
Ocillator		TCXO reference	TCXO reference		OCXO
Frequency	2200 - 2300	2200 - 2300	2200-2300	2200-2300	2200-2290
RF Power Onput	10W (20W in development)	3W min. (total), 1.5W min (each)	26 W	7 W	2 W (5W option Available)
DC Power Input	< 69W	< 35W	145 W	37 W	10 W, 2.5 W standby

Preliminary Flight System Findings (2)

SN Compatible Options, GN Mode Only	AeroAstro	SDST Modifications	MST-765		
Manufacturer	AeroAstro	General Dynamics	L3		
Transmitter Mass (Kg)	0.6 Kg	0.72 Kg increase	0.80 Kg		
Transceiver Mass (Kg)	0.9 Kg	0.72 Kg increase	1.60 Kg		
Transmitter Dimenions (cm)	8.89 x 5.08 x 2.79	52.26 cm^2 increase in footprint	15.24 x 12.7 x 3.81		
# of antenna ports	1	1	1		
Spacecraft Bus IF	RS422	Same as SDST	RS-422		
Approximate Lead time					
Parts and Grades		Same as SDST			
Testing and Certification Process					
Approxmate Cost					
Previous Users	MOST Mission, Canada	Heritage from SDST	ROCSAT III		
Other Notes	10 kRads (Si)	Same as SDST	100 kRads		
Tx/Rv Mode	Tx only. PCM/PSK/PM PCM/PM (DG2?)	Tx only. PCM/PSK/PM PCM/PM (DG2?)			
Ocillator					
Frequency	2200 - 2300	2200 - 2300	2200-2300		
RF Power Onput	5W	5W	5W (6.5W available)		
DC Power Input	~32W	26.3W	35W		

Non-spread, residual carrier PCM/PSK/PM and PCM/PSK/PM signal designs can be used for short duration with prior coordination with GSFC Space Communications Program/Code 450

Example of AeroAstro Transceiver

Capabilities

- SGLS, STDN and TDRS variants
- Interface for MCU-110 crypto unit
- SPA-U, RS-422, RS-485 & custom I/F
- PRN ranging / coherency supported
- Uplink at 1, 2 or 10kbps
- Downlink at rates up to 25 Mbps

Characteristics

- 1-4 modules; each 3.5 x 2 x 1 inches (RX,TX,HPA & interface/power)
- Mass: <200g per module
- Receiver power: < 1 Watt
- Transmit (0.5Wrf): <8 Watts
- Transmit (5.0Wrf): <32 Watts
- Primary/secondary isolation: >1MΩ

Example of Thales Transceiver

Space Flight Qualified S band Transceiver in three Modules: Transmitter + Receiver + Diplexer = 1150 grams

Transmitter Module:

- 2 Watts RF, 8 W DC
- Data Rate as low as 2 kbps
- Weight < 500 grams

LINK BUDGET - SSA Return		TDRS
Frequency Band		S
FEC Coding		Rate 1/2
Xmitter power watts	watts	2.00
Xmitter power	dBW	3.0
Frequency	MHz	2287.0
Transmit antenna gain	dB	0.0
Polarization	CP/LP	cp
Circuit Loss		-3.0
Antenna Pointing Loss	dB	0.0
EIRP	dBm	0.0
Range	km	44000.0
Free space loss	dB	-192.5
Atmospheric attenuation	dB	0.0
Receive antenna gain	dB	37.0
Receive Antenna Polarization		cp
Receive Antenna Polarization Loss	dB	0.0
Antenna pointing loss	dB	0.0
Circuit Loss	dB	-1.0
Received Signal Power	dBW	-156.4
Receiver NF	dB	3.5
Tsky	K	20.0
Tsys	K	434.8
Tsys dB K	dBK	26.4
Receive G/T	dB/K	10.6
No	dBw/Hz	-202.2
Pt/No	dBHz	45.8
Data Rate	kbps	2
DATA RATE	dB	33.0
Eb/No Available	dB	12.8
Eb/No Required	dB	4.5
Receive System Impl. Loss	dB	-3.0
LINK MARGIN	dB	5.3

Preliminary Cost Driver List and Forward Plan

Mission Cost Elements

1. **Telecom Hardware**
   – Radio, antenna, coaxial cables, switches, etc.
2. **Flight System Accommodation**
   – Power, thermal, C&DH, field of view, cable routing, switching, S/W
   – Logics for fault-tolerant
   – May require new reviews, decision gates, and testing/verification processes in development and operation phases
3. **ATLO/Test Cost**
   − EMC/EMI
   − Compatibility
   − Qualification
4. **MOS/GDS Cost**
5. **Network Cost**

Cost impacts to be evaluated in next step

Study Plan (1)

- **SN network coverage analysis and detailed SN coverage requirements (Completed)**
- **Summary of prior studies**
- **Feasibility study on spacecraft separation at TBD km or higher**
  - If feasible, kickoff architecture study of ground asset option
  - 1000 km is feasible in recent missions (Phoenix and DAWN)
- **Analyze nominal and off-nominal (3 σ dispersion) vehicle separation scenarios**
  - Obtain representative spacecraft launch trajectory and altitude profiles
  - Derive range, range rate, and compile Doppler, Doppler rate statistics
  - Compile detailed launch vehicle separation sequence of events
  - Estimate spacecraft critical telemetry generation rates
- **Analyze spacecraft antenna coverage and derive spacecraft coverage requirements**
- **Develop communication performance requirements**
- **Re-assess and update the list SN transmitter options, and assess the SN return link performance**
  - Mass, DC power, output power, cost, etc.
  - Take into account communication performance requirements in dynamic environment

Study Plan (2)

- **Spacecraft accommodation**
  - Total additional mass, integration cost, additional telemetry channels, etc.
  - Will this post-separation communication be part of the go-no-go decision of launch?
  - Identify decision points in mission planning life cycle as on whether post-separation transmitter is needed or not
- **ATLO/testing**
  - Testing process, cost
- **MOS/GDS Setup**
  - Operation development, training, and cost
- **SN coordination**
  - Coordination for launch support, interface to mission MOS/GDS, cost
- **Identify other space-based and ground-based improvements and forward works**