NASA's Evolution to Ka-band Space Communications for Near-Earth Spacecraft

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Introduction

- NASA has explored a Ka-band system design for near-Earth communications
- Motivations for Ka-band operation:
  - Higher data rates (exceeding X-band spectrum capabilities)
  - X-band spectrum crowding
- Multiple Ka-band missions flying today…
  - Lunar Reconnaissance Orbiter (LRO)
    - 100 Mbps through 18.3m WS1 antenna at White Sands Complex (WSC)
  - Advanced Land Observing Satellite (ALOS)
    - 277.52 Mbps through Tracking and Data Relay Satellite (TDRS) to WSC
  - Solar Dynamics Observatory (SDO)
    - 150 Mbps through dedicated 18.3m assets at WSC

  … But future missions will need higher data rates (1 Gbps+) and expanded infrastructures
- Evolution to Ka-band for near-Earth missions has been expected
  - Ka-band capabilities will enable a new class of earth and space science missions
- Funding to begin formulation in FY2011 has been requested from the Space Communication and Navigation (SCaN) program office, the responsible program office at NASA Headquarters

Reference Mission Requirements

- DESDynI, SWOT, and HyspIRI missions recommended by National Research Council's 2007 decadal survey have significant daily data volume requirements, motivating 1 Gbps+ downlinks
- These three missions served as references for developing a near-Earth Ka-band communications capability
- HyspIRI's needs could be satisfied with a dual-polarization X-band solution

DESDynI

To study geologic hazards and global environmental change
Launch: *2015 – 2018+*

Orbit:
- *760 km altitude*
- *98^0 inclination*
- *Sun-synchronous (Dsc Node 1100)*

Data Volume (w/ Compression):
- *~40 Tbits of data per day*

Contact Requirements (@ 1 Gbps):
- *~667 minutes per day*
- *~45 minutes per orbit*

SWOT

To study both land hydrology and oceanography
Launch: *2016 – 2020+*

Orbit:
- *970 km altitude*
- *78^0 inclination*

Data Volume (w/ Compression):
- *~7.2 Tbits of data per day*

Contact Requirements (@ 1 Gbps):
- *~120 minutes per day*

HyspIRI

To study global surface reflectance, temperature, and emissivity
Launch: *2015 – 2020+*

Orbit:
- *626 km altitude*
- *98^0 inclination*
- *Sun-synchronous (Asc Node 1800)*

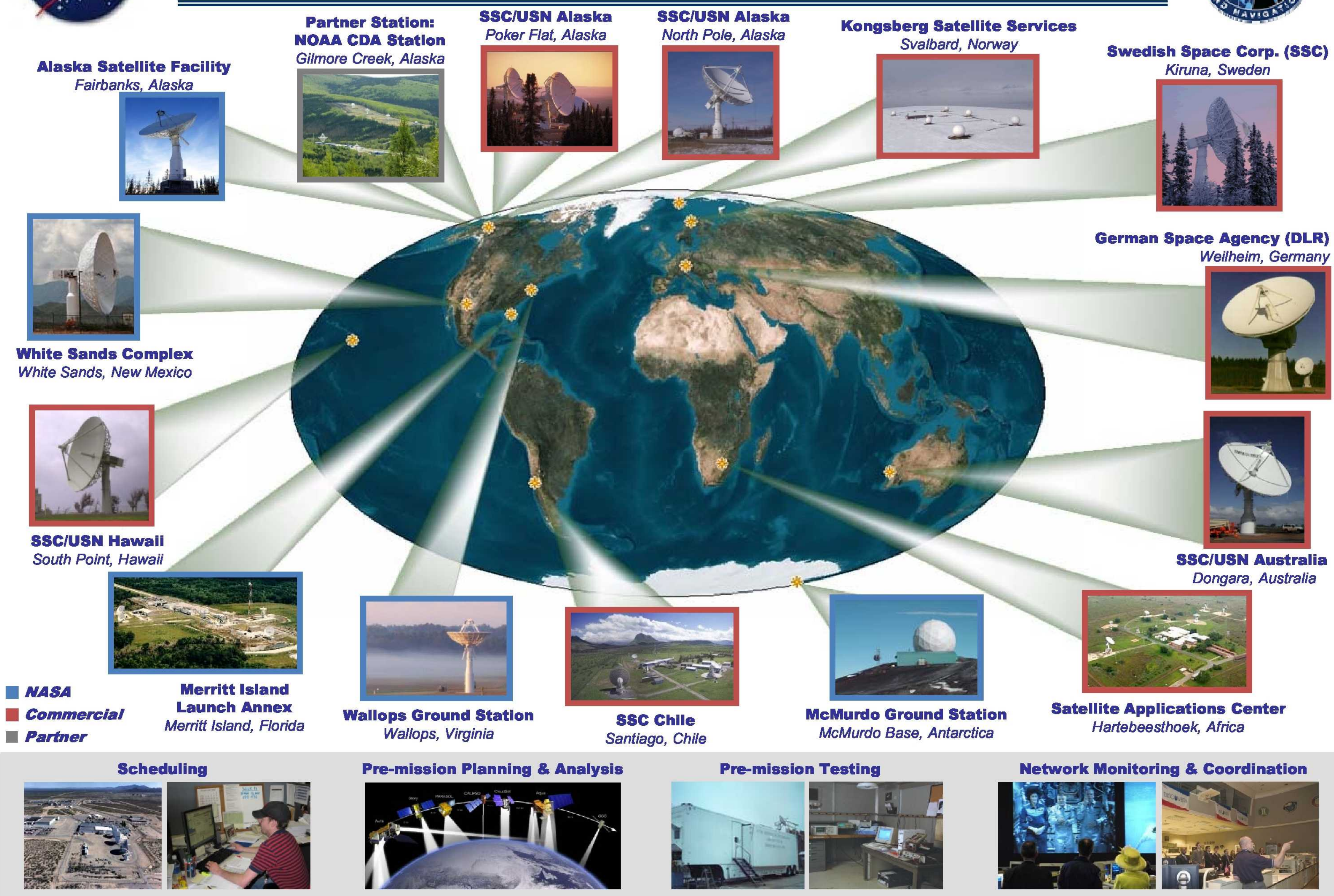
Data Volume (w/ Compression):
- *~3.5 Tbits of data per day*

Contact Requirements (@ 1 Gbps):
- *~60 minutes per day*

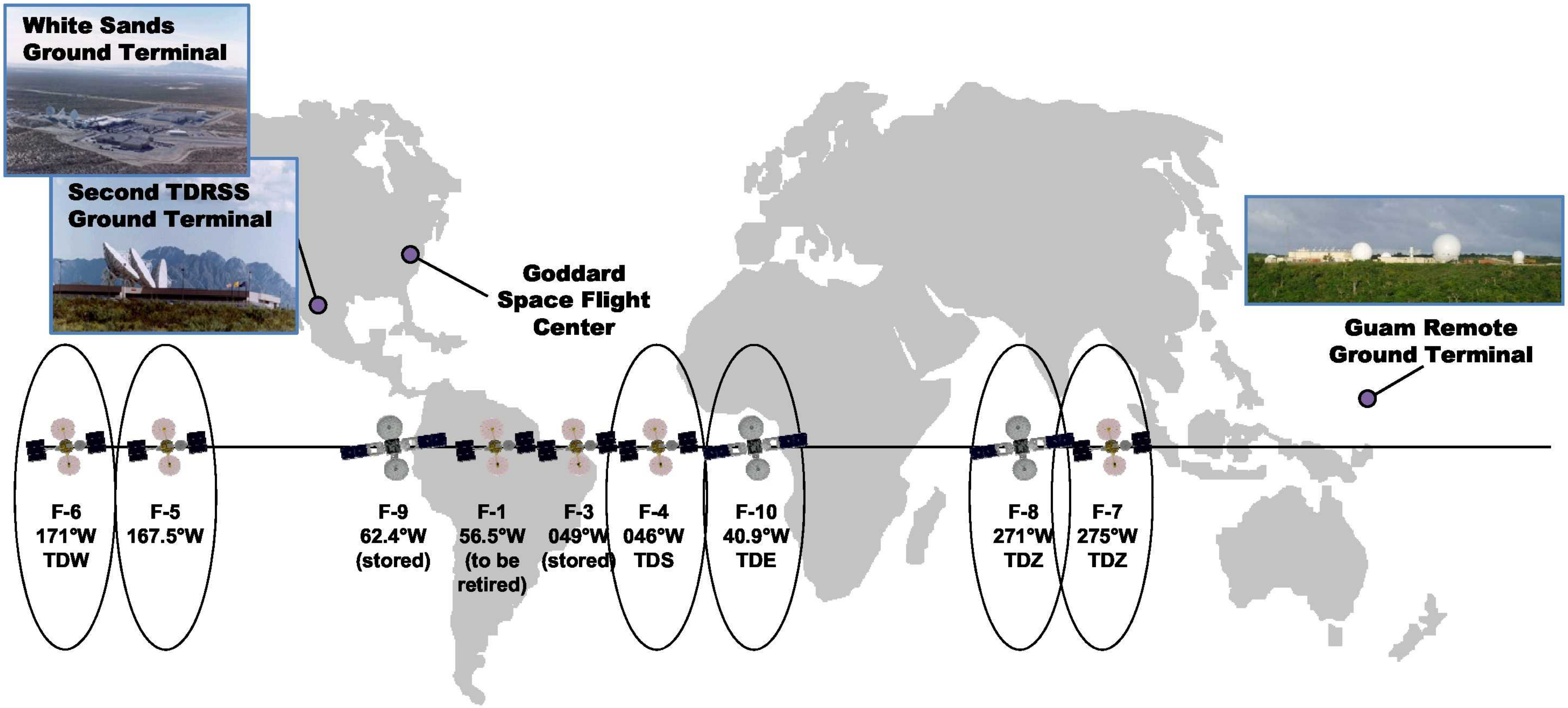
Additional Potential Ka-band Missions

GEO-CAPE	ACE	VEGBIOM	LEOMAC	PATH	SCLP	COPS	Future HSF
GEOMAC	ACE-Core	ACOB-A	LIST	GRACE-II	EXIST	GACM	Future Suborbital

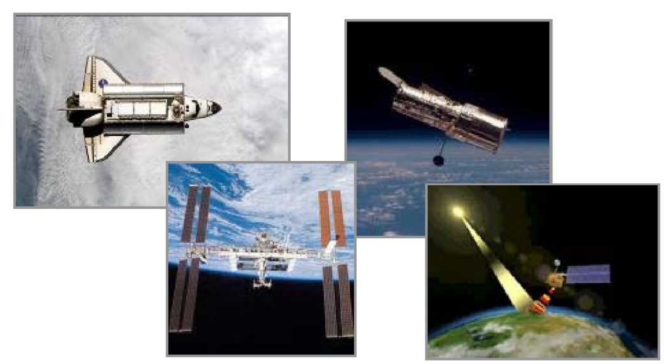
NASA Near Earth Network (NEN)



NASA Space Network (SN)



- **Tracking and Data Relay Satellites (TDRS) are arrayed in three regions:**
  - Atlantic Ocean Region
  - Pacific Ocean Region
  - Indian Ocean Region



Potential Solutions

Option	Considerations
NASA Near Earth Network (NEN)	• Leverage existing "WS1" 18.3m Ka-band asset at WSC with upgrades • Entails establishing new Ka-band assets and integrating into NEN • Locations for new assets to be determined by multiple criteria (coverage, rain attenuation, operational costs, backhaul costs, existing infrastructure, etc.)
NASA Space Network (SN)	• Leverage Ka-capable satellites: – TDRS-8/9/10 (on-orbit) – TDRS-K/L (on-order, to be launched 4/2012 and 2/2013, respectively) <u>1-Node Solution</u> • Risk-reduction/fallback solution from 2-node solution, to mitigate against TDRS launch slip/failure or SN upgrade schedule slips <u>2-Node Solution</u> • Greater coverage than 1-node solution • Avoids costly WAN bandwidth upgrade from Guam (required for 3-node solution) <u>3- Node Solution</u> • Worth considering if 2-node solution would not satisfy mission requirements • Would require potentially cost-prohibitive WAN bandwidth upgrade from Guam
NOAA NPOESS SafetyNet	• Leverage 15-station Ka-band infrastructure investment for operational weather satellites by sharing capacity between NOAA and NASA

NOAA: National Oceanic and Atmospheric Administration

NPOESS: National Polar-orbiting Operational Environmental Satellite System

SafetyNet

- NOAA's National Polar-orbiting Operational Environmental Satellite System (NPOESS) SafetyNet network of 15 Ka-capable ground stations potentially offers a large infrastructure to support earth and space science missions
  - NPOESS is being reformulated to support planned new Joint Polar Satellite System (JPSS)
- Constraints:
  - Small asset size (4m) reduces G/T (~10 dB) vs. 12m antennas proposed in alternative solution
    - Would require redesigning SWOT spacecraft antenna system
  - 150 Mbps receivers would require upgrades to support 1 Gbps
  - Limited backhaul connectivity (~45 Mbps)
  - Scheduling conflicts with primary SafetyNet mission constrain availability for NASA missions
  - Limited expansibility
  - Cannot supply sufficient contact time for DESDynI (667 minutes/day)
    - Even with all 15 stations and 1 Gbps downlink rate (!)

SafetyNet option was not recommended

Options: Mission Support and Recommendation

Option	Mission Support: DESDynI	Mission Support: HyspIRI	Mission Support: SWOT	Other Considerations
NEN	Would require unreasonably large number of stations	Mission requirements can be met with 2 or more Ka-band ground systems	Mission requirements can be met with 2 or more Ka-band ground systems	If DESDynI launch should slip past 2015, a 3 Gbps solution could potentially be used to meet mission requirements
SN	2-node and 1-node solutions could satisfy requirements	SN can satisfy mission requirements, although a NEN solution can do so more easily	Need to minimize antenna size to limit spacecraft jitter induced by antenna movement	• Large burden on spacecraft vs. ground • More expensive than ground solution
NPOESS SafetyNet	Does not satisfy daily contact requirement	Requires upgraded receivers, ground connectivity	Impact to S/C antenna system; requires upgraded receivers, ground connectivity	• Schedule conflicts with primary SafetyNet mission limit availability for NASA missions • Limited expansibility

Recommendation: Yes Possible No

Recommendation: Apply NEN and SN as best suited for each mission
Cost-effectively leverages each network's strengths
and offers maximum extensibility

Coverage and Loading Analysis

SN Analysis Summary for DESDynI

SN Support Scenario	DESDynI Priority	Contact time (average minutes/day)
2 satellites (TDE, TDW)	< HST, Terra	668
1 satellite (TDE)	> HST, Terra	691
1 satellite (TDE)	< HST, Terra	640
Mission Requirement		**667**

HST = Hubble Space Telescope.
Nominal spacecraft antenna configuration assumed for these approximate results.
Potential second antenna aboard spacecraft, for ground terminal operation, was not included.

NEN Analysis Summary for SWOT, HyspIRI

	Contact time per mission (average minutes/day)	
NEN Station	SWOT	HyspIRI
Alaska	51.9	21.2
Svalbard	55.1	27.5
Wallops	6.9	13.3
White Sands	16.6	7.9
McMurdo	66.6	55.7
Total	197.1	125.6
Mission Requirements	**120**	**60**

Coverage calculations have been adjusted for overlap.
Alaska and Svalbard together suffice for both missions' requirements, assuming optimized scheduling.
Figures for McMurdo assume SWOT and HyspIRI receive highest priority.

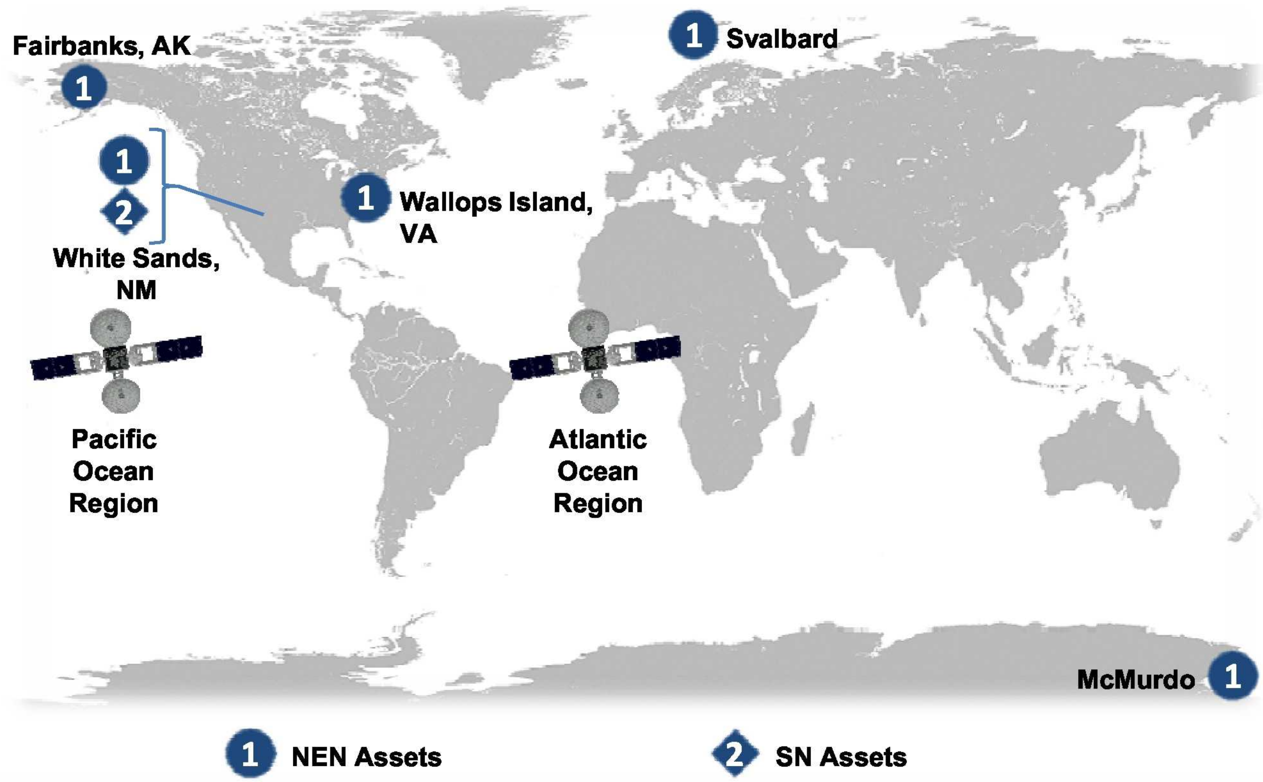
- Analysis results are based on expected orbital parameters
- Required contact times could be reduced with data rates greater than 1 Gbps

Analysis confirms viability of SN-based solution for DESDynI and NEN-based solution for SWOT and HyspIRI

Recommended Solution: Proposed Ka-band Assets

Location Selection Criteria

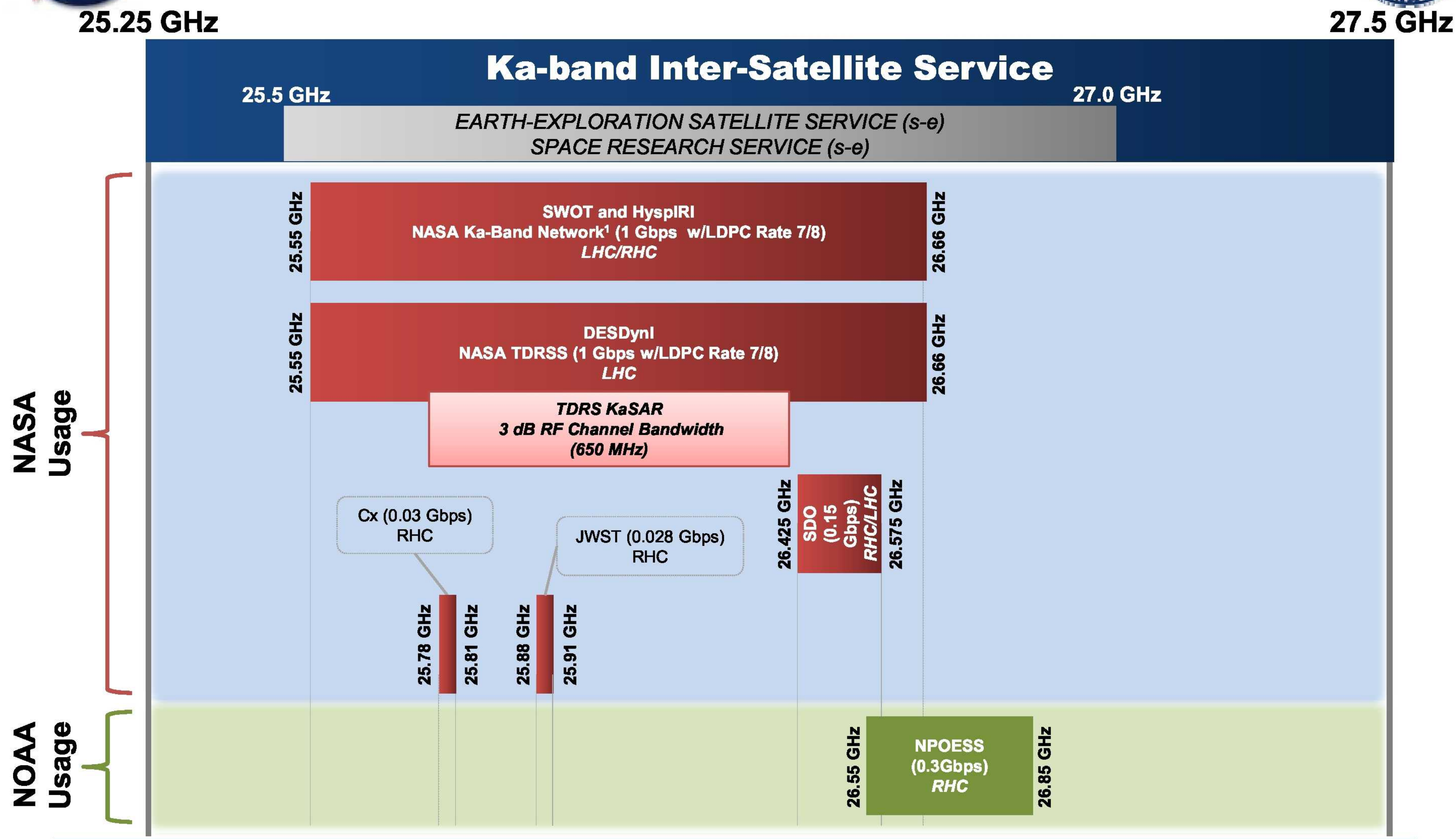
- Coverage
- Rain attenuation
- Operational costs
- Backhaul costs
- Existing infrastructure



Asset Information

- SN assets:
  - 2 TDRS spacecraft in Atlantic and Pacific Ocean Regions supported by WSC
- 5 NEN assets:
  - 12+ m assets (new) at Alaska, Wallops, Svalbard
  - 18.3 m WS1 asset (existing) at White Sands, upgraded to accommodate higher data rates
  - 5.4m asset (under development) at McMurdo, with additional back-end equipment to support higher data rates, and refurbished McMurdo-TDRS Relay System 2 (MTRS-2) link

Recommended Solution: Proposed Ka-band Spectrum Plan



Proposed Ka-band spectrum plan provides NASA missions with adequate protection from interference with NPOESS. Potential interference between NASA Ka-band missions (e.g., SDO, Cx, JWST) can be accommodated through scheduling

[1] *The proposed NASA Ka-band Network will procure antennas that have dual polarization capability, allowing for both LHC and RHC.*

Recommended Solution: Link Analysis Summary

Mission	SN	Alaska (12m)	Svalbard (12m)	Wallops (12m)	WS1 (18.3m)	McMurdo (5.4m)
DESDynI (1 Gbps, OQPSK, Rate-7/8 LDPC) – EIRP to SN = 60.3 dBW	M = 2 dB AA = 99%	N/A	N/A	N/A	N/A	N/A
SWOT (1 Gbps, OQPSK, Rate-7/8 LDPC) – EIRP to NEN = 28.8 dBW	N/A	M = 3 dB AA = 99% EA = 10 deg	M = 4.7 dB AA = 99% EA = 10 deg	M = 3 dB AA = 95% EA = 12.1 deg	M = 4.9 dB AA = 99% EA = 10 deg	M = 3 dB AA = 99 % EA = 17.5 deg
HyspIRI (1 Gbps, OQPSK, Rate-7/8 LDPC) – EIRP to NEN = 26.2 dBW	N/A	M = 3 dB AA = 99% EA = 10 deg	M = 4.7 dB AA = 99% EA = 10 deg	M = 3 dB AA = 95.3% EA = 12 deg	M = 4.9 dB AA = 99% EA = 10 deg	M = 3 dB AA = 99% EA = 16 deg

M = Margin   AA = Annual Availability   EA = Elevation Angle

- DESDynI:
  - Ground-based solution would require unreasonably many antennas (>15) to provide sufficient contact time
  - TDRS solution can support required contact time
- SWOT, HyspIRI:
  - Link closure to TDRS deemed infeasible
  - NEN-based solution suffices
  - NEN availability target reduced and/or elevation angle increased for Wallops and McMurdo sites to obtain desired 3 dB link margin

Combination of SN and proposed NEN Ka-band network can satisfy mission requirements with viable RF link designs

Recommended Solution: Propagation Impairments

- Ka-band propagation impairments include rain attenuation, cloud attenuation, gaseous absorption, and scintillation fading
- New Ka-band NEN antennas will be designed to support orthogonal polarizations, so cross-polar discrimination (XPD)—a measure of the polarization isolation—is a concern as well
- Literature survey and analysis were conducted to investigate these phenomena.
  Analysis results (@ 26 GHz; based on ITU-R Recommendation P.618-9):

Ground Station Information		Propagation Impairments for Percent Availability														
		95%					97%					99%				
Name, Latitude, Longitude, Height above MSL	Elevation Angle (°)	Rain Atten. (dB)	Gas Abs. (dB)	Scint. Fade (dB)	Total Fade (dB)	XPD (dB)	Rain Atten. (dB)	Gas Abs. (dB)	Scint. Fade (dB)	Total Fade (dB)	XPD (dB)	Rain Atten. (dB)	Gas Abs. (dB)	Scint. Fade (dB)	Total Fade (dB)	XPD (dB)
Fairbanks, AK	5	1.32	1.82	0.83	3.38	32.51	1.92	1.82	1.00	3.99	29.92	4.06	1.82	1.36	6.10	24.56
65.974° N	10	0.77	0.95	0.29	1.77	36.97	1.14	0.95	0.35	2.13	34.36	2.44	0.95	0.48	3.44	28.96
147.512° W	15	0.57	0.64	0.15	1.23	39.70	0.84	0.64	0.18	1.50	37.09	1.83	0.64	0.25	2.48	31.67
549.0 m	20	0.46	0.48	0.10	0.96	41.77	0.68	0.48	0.12	1.18	39.15	1.50	0.48	0.16	1.99	33.72
Svalbard, Norway	5	0.71	1.87	0.83	2.96	37.54	1.04	1.87	1.00	3.31	34.93	2.24	1.87	1.37	4.49	29.51
78.23072° N	10	0.40	0.97	0.29	1.46	42.27	0.59	0.97	0.35	1.66	39.64	1.31	0.97	0.48	2.36	34.18
15.3896° E	15	0.29	0.65	0.15	0.98	45.17	0.43	0.65	0.19	1.12	42.53	0.96	0.65	0.25	1.65	37.05
466.3 m	20	0.23	0.50	0.10	0.75	47.35	0.34	0.50	0.12	0.86	44.71	0.78	0.50	0.16	1.29	39.22
White Sands, NM	5	3.18	2.08	0.83	5.37	25.49	4.56	2.08	1.00	6.74	22.93	9.28	2.08	1.37	11.46	17.66
32.5425° N	10	1.88	1.07	0.26	2.97	29.86	2.72	1.07	0.32	3.81	27.29	5.65	1.07	0.44	6.74	21.97
106.6121° W	15	1.40	0.72	0.13	2.13	32.49	2.03	0.72	0.16	2.76	29.91	4.28	0.72	0.22	5.01	24.58
1485 m	20	1.15	0.55	0.08	1.7	34.45	1.68	0.55	0.1	2.23	31.86	3.56	0.55	0.13	4.11	26.52
Wallops Island,	5	4.12	4.02	1.45	8.40	23.42	5.87	4.02	1.75	10.15	20.87	11.85	4.02	2.39	16.11	15.62
VA 37.9235° N	10	2.54	2.07	0.51	4.66	27.46	3.65	2.07	0.62	5.77	24.90	7.49	2.07	0.85	9.61	19.61
75.4761° W	15	1.93	1.40	0.27	3.34	29.93	2.78	1.40	0.33	4.20	27.37	5.78	1.40	0.44	7.20	22.06
4.3 m	20	1.60	1.06	0.17	2.67	31.80	2.32	1.06	0.20	3.39	29.23	4.86	1.06	0.28	5.92	23.92
McMurdo, Antartica	5	0.02	1.28	0.78	2.06	65.16	0.03	1.28	0.94	2.22	62.42	0.09	1.28	1.29	2.57	56.69
77.83913° S	10	0.01	0.67	0.31	0.98	71.73	0.02	0.67	0.38	1.05	68.96	0.04	0.67	0.52	1.19	63.16
193.333° E 206.4	15	0.01	0.45	0.18	0.64	75.56	0.01	0.45	0.22	0.67	72.79	0.03	0.45	0.30	0.76	66.95
m	20	0.00	0.34	0.12	0.47	78.35	0.01	0.34	0.15	0.49	75.57	0.02	0.34	0.20	0.55	69.72

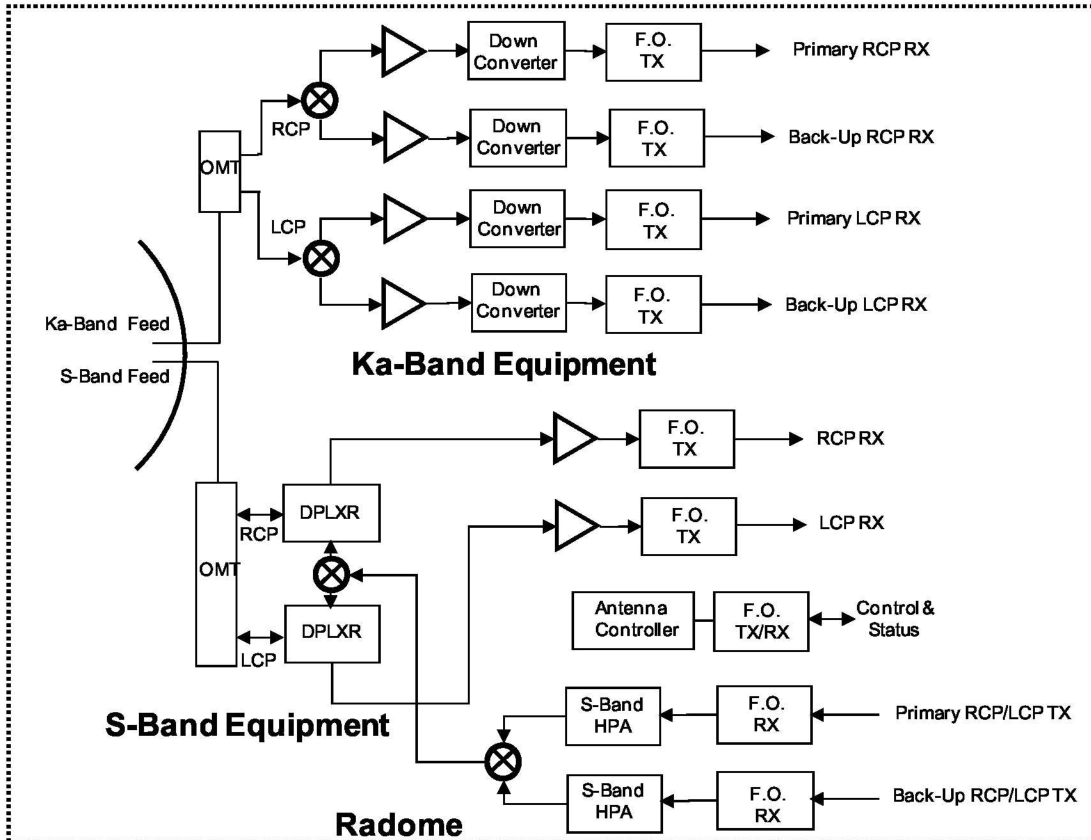
Key conclusions:

- **Careful attention must be paid to the axial ratios of both the transmitting and receiving antennas**
- **Snow accumulation on radomes should be reasonably managed but does not significantly reduce polarization isolation**
- **Ice particles and freezing rain can reduce polarization isolation**

Recommended Solution: Ka-band NEN Ground Station Antenna Systems

- June 2009 Request for Information (RFI):
  - Obtain technical and costing information from industry in response to draft Ka-Band antenna system requirements
- Key antenna system requirements (based on link calculations):
  - Aperture size >=12m
  - Continuously track LEO satellites >= 500 km above the earth
  - Ka-band:
    - Simultaneous LHCP and RHCP receive
    - G/T: 42.7 dB/°K
  - S-Band:
    - Simultaneous LHCP and RHCP receive
    - G/T: 23 dB/°K
    - Transmit EIRP: 63 dBW

RFI Proposed Antenna System Configuration



Conclusion (based on RFI responses):
Three-axis antenna system requirements are reasonable and technically achievable by industry

Recommended Solution: Wide Area Network

- NASA Integrated Services Network (NISN) infrastructure will service missions' WAN needs
- Bandwidth requirements for transferring daily data volumes for 3 reference missions studied:
  - 490.1 Mbps: minimum needed for transferring expected daily volumes
  - 735.1 Mbps: includes recommended 50% margin
    - Margin allows for recovering from data transfer reduction or disruption due to equipment outages, retransmissions, or unforeseen issues
- All NEN sites, except for McMurdo, lie on NISN WAN sites, enabling low-cost service by expanding upon existing requirements
- For McMurdo, NASA proposes to refurbish the McMurdo-TDRS Relay System-2 (MTRS-2)
  - 300 Mbps-capable ground station
  - Data is returned through TDRS to WSC
  - Ka-band transmission to TDRS will be needed to support NEN customer missions' high data rates

Enhanced NISN infrastructures and refurbished MTRS-2 will economically satisfy the proposed Ka-band network's WAN requirements

Technology Considerations

- Key considerations affecting technology selection:
  - Capability
  - Maturity
- Spacecraft elements:
  - On-board data storage: Multi-terabit space-qualified systems are available
  - Coding (error protection): Hardware supporting 600 Msps for each I & Q channel has been demonstrated
  - Compression: Available
  - Modulator: Space-qualified high-rate modulator (1.0+ Gbps) forecasted to exist in time for reference missions considered
  - Amplifiers (TWTA): Ka-band flight-heritage amplifiers available
  - Physical link components: Flight-heritage S- and Ka-band components available
- Ground segment elements:
  - Antennas: Ka-band systems (12-14 m) available
  - Radomes: Available
  - SN ground receivers: Planned for procurement (subject to funding)
  - NEN ground receivers: 1 Gbps receivers currently commercially available

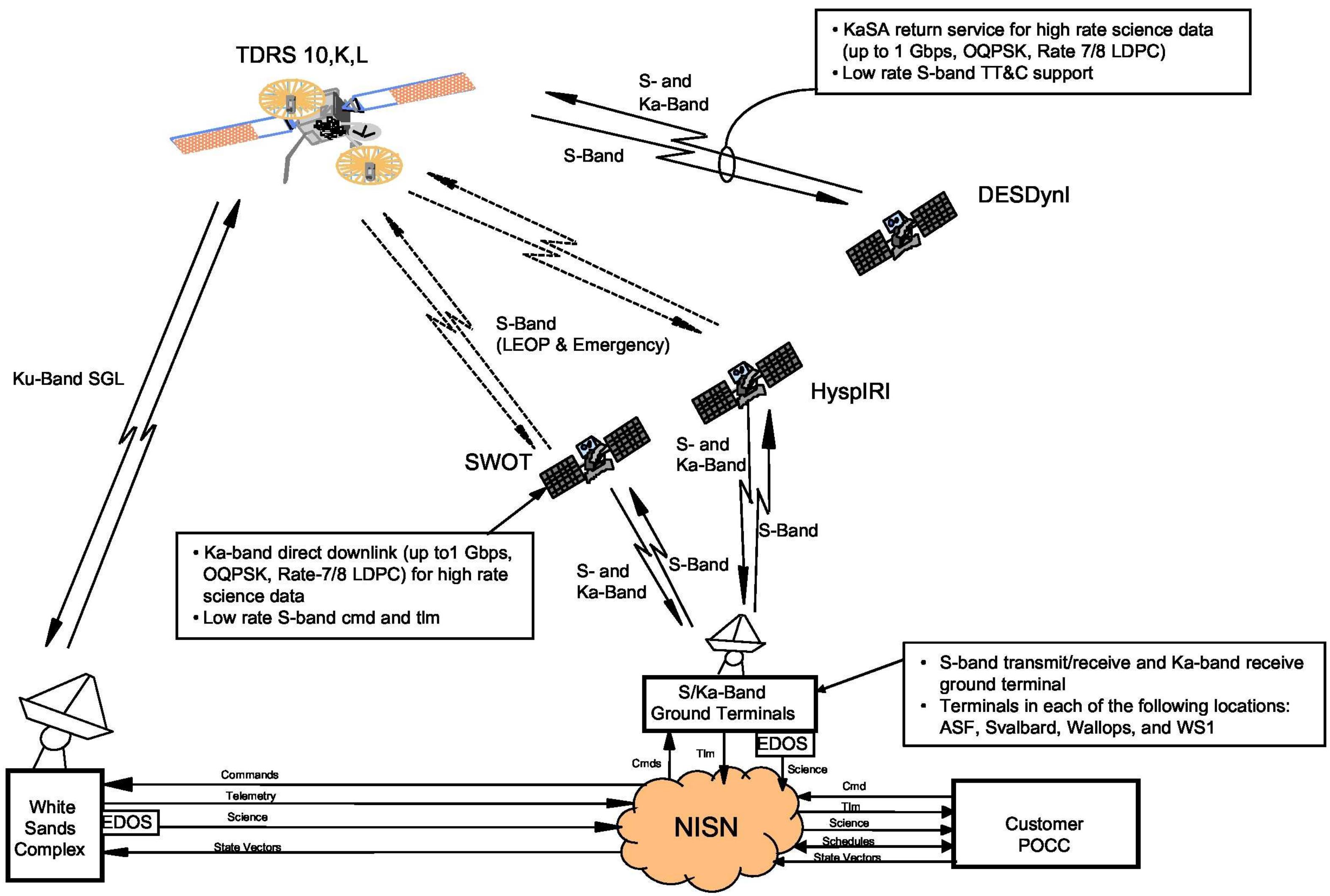
No significant technology impediments to achieving 1 Gbps Ka-band communication

Future Considerations

- Technology Insertion
  - Selective retransmission, e.g. CCSDS File Delivery Protocol (CFDP)
    - LRO experience indicates prudence of protocol-based recovery for weather-induced data losses
      - LRO employs CFDP; no science (Ka-band) data lost since June 2009 launch (>1700 LRO supports, >1800 hours of communications)
  - CCSDS Space Link Extensions (SLE)
    - Promotes commonality and international interoperability at the link layer
  - Delay/Disruption Tolerant Networking (DTN)
    - Enables standardized network layer cross support
- Expansibility Options
  - Additional antennas, as needed
  - Potential partnerships with other space agencies, commercial providers
  - Dual-polarization Ka-band reception (1.5 Gbps per polarization) could provide 3 Gbps downlink
    - Single-polarization initial deployment meets currently-known mission requirements and allows deferring investments until needed

The recommended solution allows for expanding coverage, daily volume, and availability

Recommended Solution: Reference Diagram



A combination of SN and NEN capabilities will jointly satisfy high-data-rate Ka-band missions

Summary

- Future Earth- and space-science missions will need Ka-band communications to support their extremely high data rates
- SN Ka-band communication feasible today; upgrades to support high data rates are planned
- NEN Ka-band capabilities can be implemented using COTS technology in time to support upcoming high-data-rate missions
- Proposed Ka-band architecture leverages existing assets, where possible, to contain costs
- Continued cooperation between NASA's Science Mission Directorate and SCaN will ensure developing Ka-band communications capabilities to support upcoming spacecraft missions
- The proposed Ka-band network will:
  - Enable studying Earth and space phenomena in unprecedented detail
  - Help answer scientific questions important to society

NASA