Next Generation Space Communications & Navigation Architecture

Presentation to GSAW 2018

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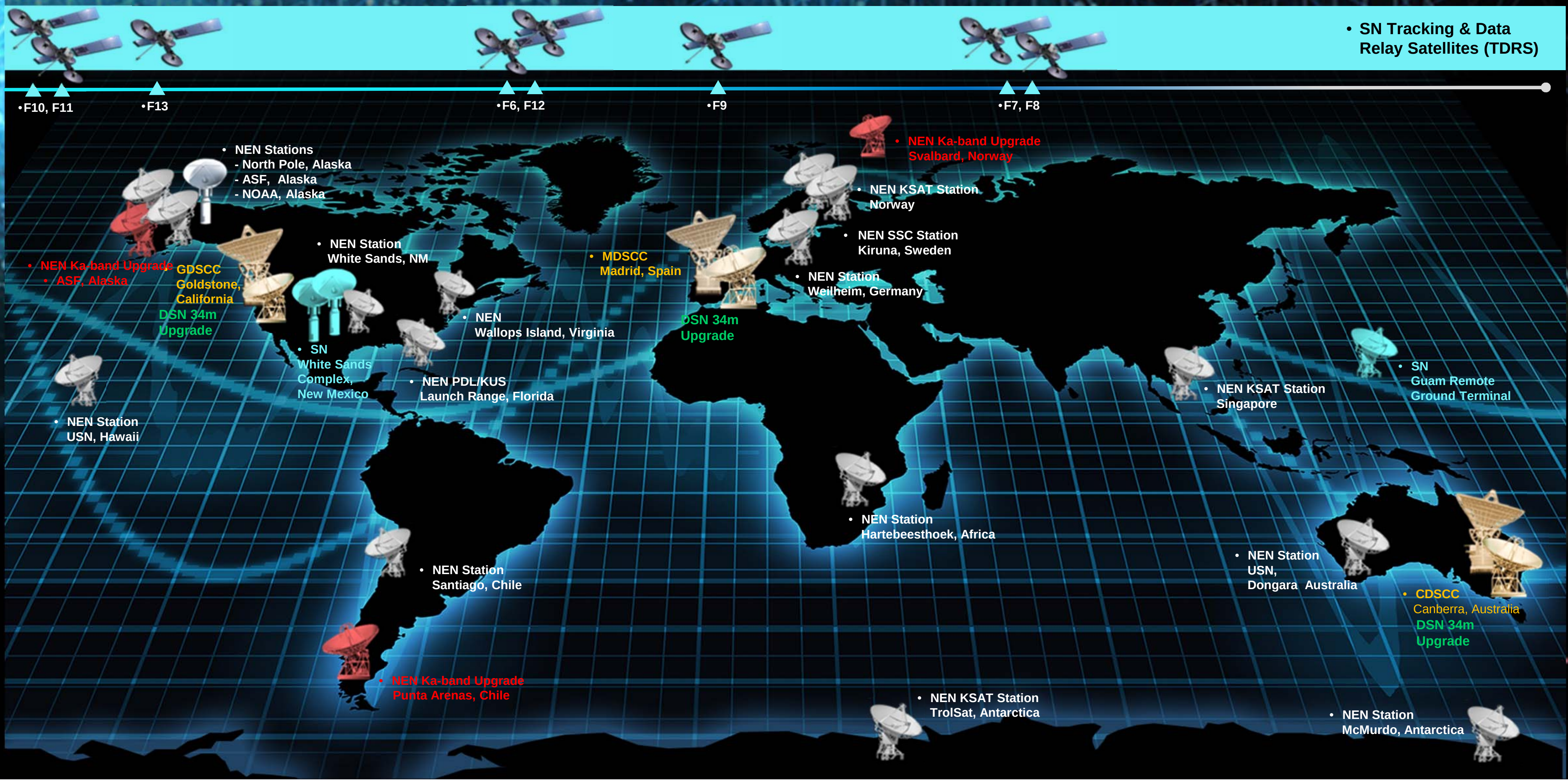
Background

- Studies started in 2012 to define future NASA Communications & Navigation (C&N) architecture and evolutionary path
  - Finding: Current networks have sufficient stability (15+ years) to introduce a Next Generation Architecture
  - Finding: Next Generation Architecture must be open to US government, commercial, & international participants to warrant magnitude of investment & support human expansion into the Solar System
- Current effort will complete the process through collaboration with national, international, and commercial stakeholders and the budget process
  - Earth Network:
    - Last TDRS became operational 2/2018; fleet drops enough to require new capacity starting in ~2025
    - Ground network expanding Ka-band capacity to meet multi-Gbps mission needs starting in 2021
  - Mars Network expansion being studied to support detailed reconnaissance, Sample Return, & humans
  - Lunar Network being defined to support Science missions (2019+) and human Lunar Orbiting Platform-Gateway (2023+)
  - Major technology investments already in development including Optical Communications (flight demo: 2019; operational target: 2025) and Solar System Internetwork (SSI) (limited operations on ISS: 2016)

➢ Next Gen Architecture offers the prospect of secure, resilient space communications designed in from the beginning

SCaN: Spanning the Globe – Serving the Solar System



Next Gen Paradigm Shifts

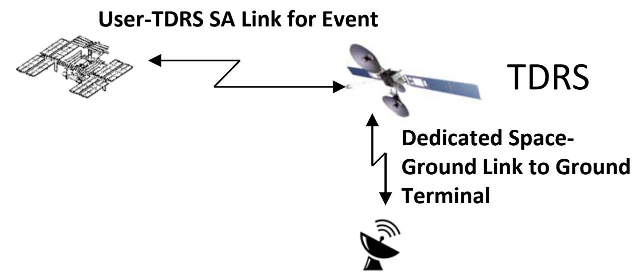
- RF ➔ RF + Optical
- Phase out Ku-band (over 20+ years) ➔ Expand Ka-band use
- Point-to-point (Connection-oriented, single access) links ➔ broadband (connectionless, multiple access)
- Link layer service provider ➔ network service provider
  - Supporting networks in space, not just over a space link
- Manual processes ➔ Automated & autonomous
  - Scheduled service ➔ unscheduled service
  - Ground control ➔ Autonomous navigation
- Different near Earth & deep space architectures ➔ common architecture
- Reactive Security ➔ Security inherent in architecture

Shift: RF → RF + Optical

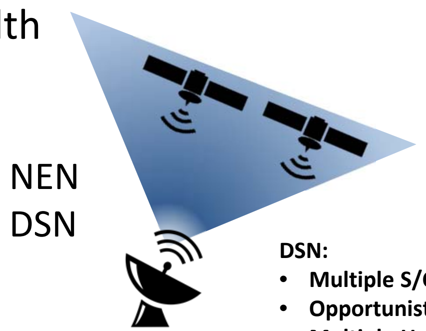
- Laser comm seen as cross-cutting, game-changing technology with investment by STMD, HEOMD & SMD + other government partners
- Transition Laser Comm Relay Demo (LCRD) launching in 2019 for flight demonstration phase
  - LEO terminal being developed for ISS as 1st user
  - LCRD moves to limited operations with ISS after demo
- Exploration Mission 2 (EM-2) will carry optical terminal for DTE demonstration in 2022
- Deep space optical demo on Psyche asteroid mission launching in 2022
- Developing Gen 2 10G & 100G terminals for Next Gen Architecture targeting initial operational capability by 2025
- Optical technology promises high-to-ultra high data rates with low SWaP and low cost for users and relays

Single Access ➔ Multiple Access

- Under-utilization: Missions use TDRSS Single Access at a fraction of capacity
  - Demand access: user requests access when he needs it and gets BW that he needs
- Single Access points one network antenna to one user antenna and commits both for duration of event ➔ connection-oriented like telephone switchboards

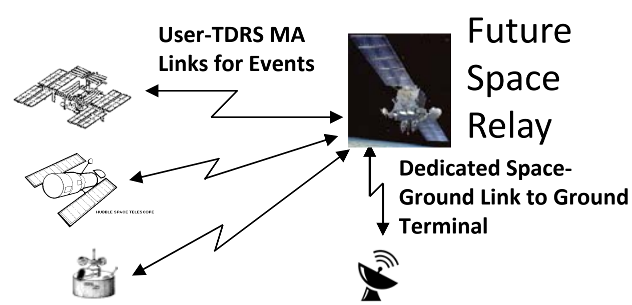


- Multiple Access enables one network antenna to talk to multiple users simultaneously in same overall system bandwidth



DSN:
- **Multiple S/C Per Antenna (MSPA)**
- **Opportunistic MSPA**
- **Multiple Uplink per antenna**

NEN: TBD

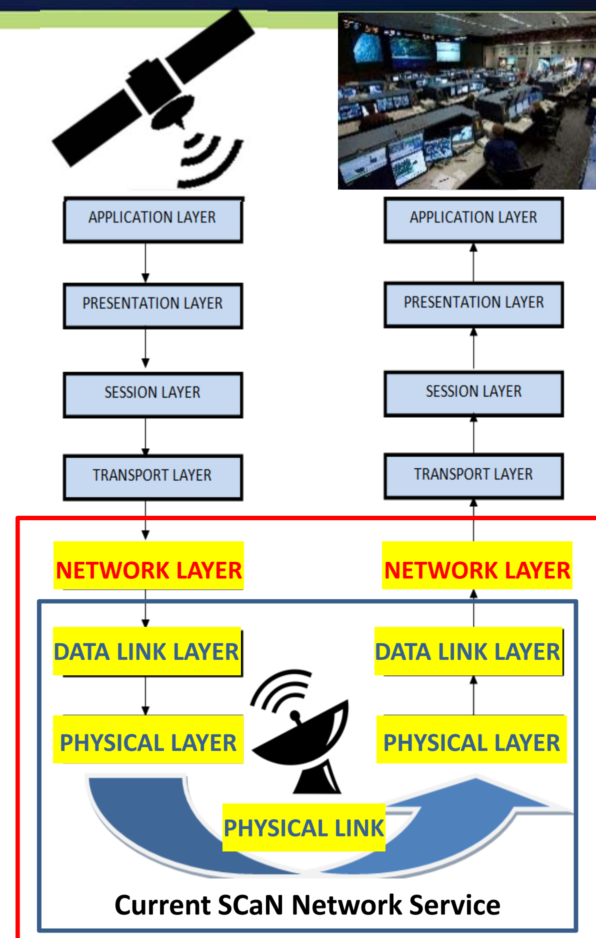


Shift: Scheduled → Unscheduled Access

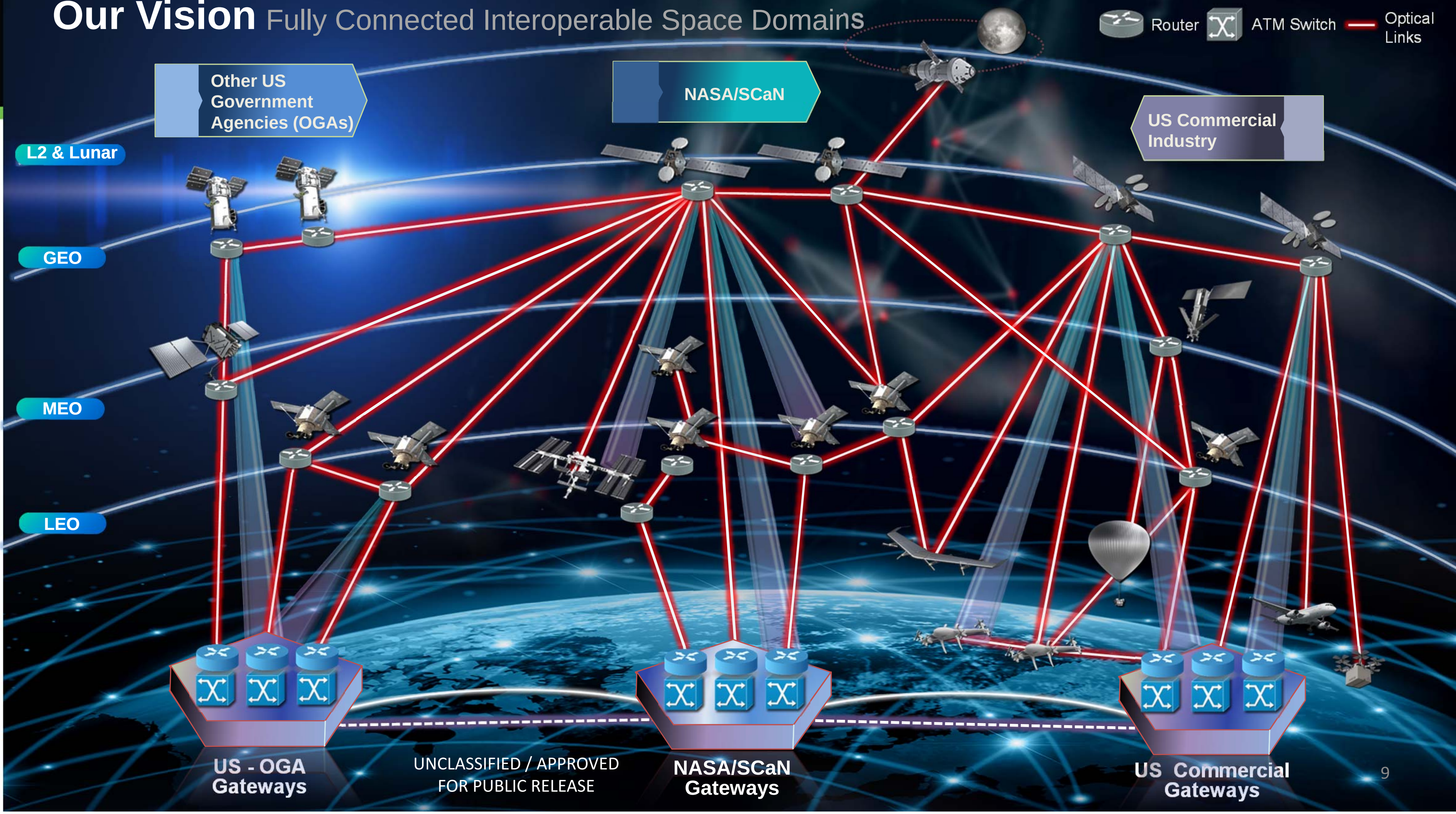
- All missions schedule events (passes) days-weeks in advance
  - Process is labor-intensive for networks and missions
- Unreliable data delivery forces missions to schedule extra events and repeat transmissions
  - Scheduling is hard – TDRSS schedules ~60% efficient
- Approach:
  - Expand use of Multiple Access; reduce Single Access
  - Introduce demand access services
  - Shift from (unreliable) link layer to (guaranteed) network layer service
- Result: Eliminate scheduling for most missions
  - Enables further system automation and operations cost reduction

Services: Link Layer → Network Layer

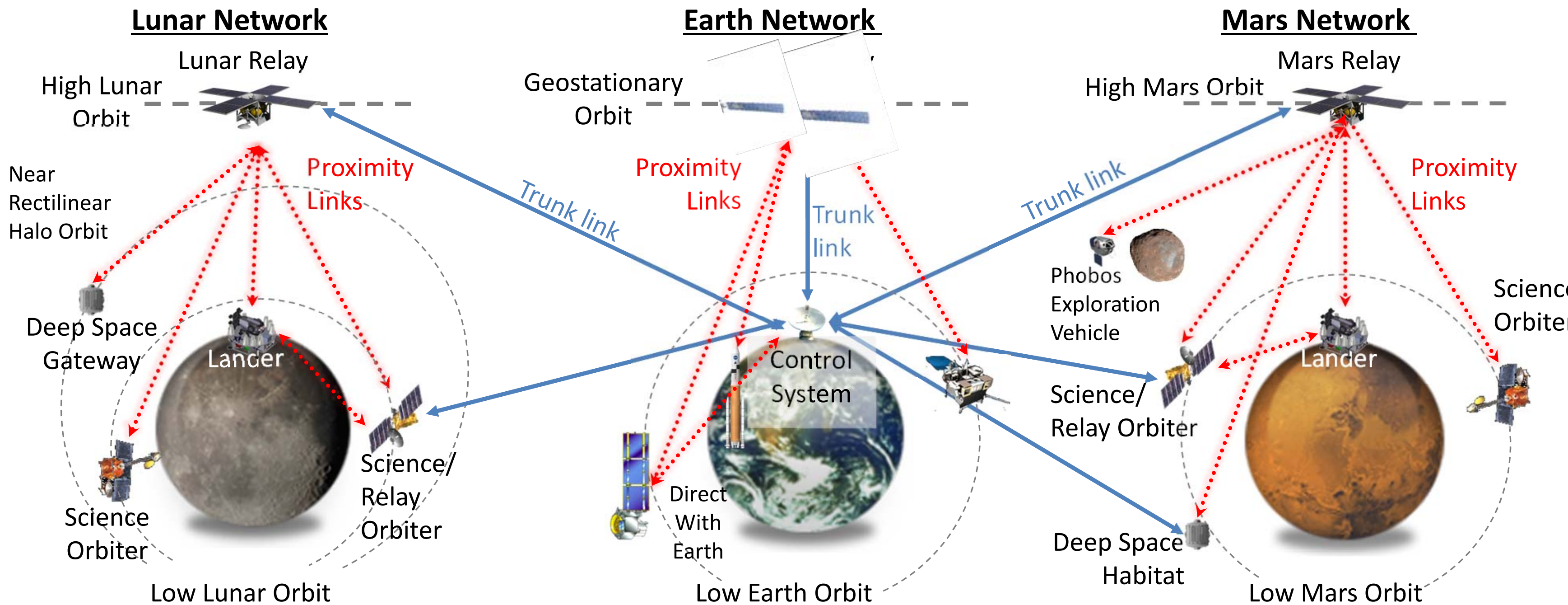
- Link layer services do not guarantee data delivery
  - Mission Operations Centers (MOC) develop SW to process data for errors, resend data, command s/c when to delete data from memory
  - Application layer protocols such as CCSDS File Delivery Protocol (CFDP) with Automatic Repeat Request (ARQ) provide reliable delivery over unreliable link layer protocols such as Space Packet
- Expand services to include space internetworking: Solar System Internet (SSI) using IP and Delay/Disruption Tolerant Networking (DTN)
  - DTN guarantees delivery obviating need for MOC processing and retransmission reducing burden on mission ground <u>and</u> flight segments
- SSI enables a Service-Oriented Architecture (SOA) that can use an application library
- Data can move directly from MOC to Principal Investigator or directly from spacecraft to PI



Our Vision Fully Connected Interoperable Space Domains



Planetary Networks: Earth, Moon and Mars – One Architecture



- **Strategy: Develop a flexible *planetary network* architecture adaptable to any celestial body to reduce development & operation cost**
- **User-network *proximity links* (space-space & space-ground/surface) provide standardized services & design for users of planetary networks**
- ***Network-network Trunk links* are internal network space-ground connections for long distance "back haul"**

Status: Inter-agency Operations Advisory Group (IOAG) Service Catalogs 1 & 2 approved; CCSDS protocol Standards approved or in development; International Standard to be approved by ISS Partners, Spring 2018, extends it to Lunar Network

Architecture Features

- Growing space market supports many vendors
- Architecture must meet requirements of all users in all domains
  - Implementation can be domain-specific
- Partnerships can be established to save cost – dial operational inter-operation up or down
  - No interoperability – organization provides its own stand-alone network
  - Interoperability for specific conditions/events, e.g., Continuity of Operations, national civil reserve
  - Full interoperability during normal operations
- The only thing imposed on other agencies adopting this architecture is the use of standard services & interfaces
  - Does not require common or coordinated acquisitions
- Affordability is enhanced by using a modular family line of components to reduce the unit cost of incremental capacity to be accommodated by in-guide sustainment funding
  - Does not require Congressional approval of major new starts

Solar System Internetwork (SSI)

- Similar to terrestrial Internet but designed for the space environment
- Based on international standards and voluntary agreements
- Enables cross support among missions without restricting any organization's control over its own resources
- Prevents unauthorized resource utilization and protects the integrity and confidentiality of mission data
- Handover of satellite data flow from one Earth station to the next is automated, ensuring continuity of data flow between spacecraft and Mission Operations Centers (MOCs)
- High-speed spikes in spacecraft data download are automatically buffered for transmission over lower-speed (and less expensive) terrestrial network links
- Data lost or corrupted are automatically retransmitted over interplanetary distances and intermittent links
  - High-speed transmission disruptions due to severe weather are automatically handled
- Multiple orbiters can easily and automatically forward data to and from multiple landed vehicles, honoring prioritization decisions made at the data source
- Path diversity is automatically used in the event of resource failure, increasing spacecraft safety and total mission data return

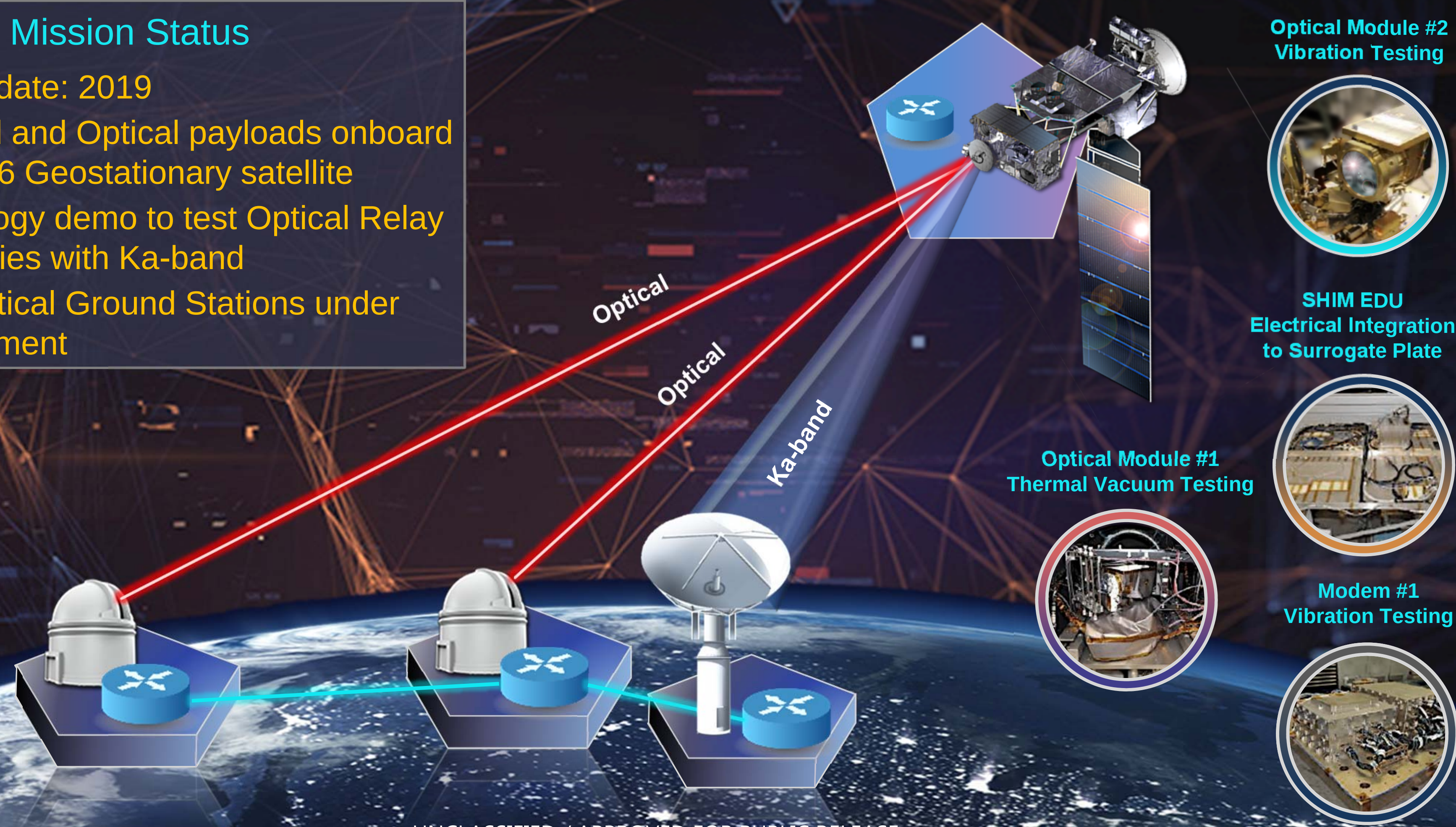
International Partnerships

- Inter-Agency Operations Advisory Group (IOAG)
  - Members: NASA, ESA, JAXA, CSA, Roskosmos, CNSA, ASI, CNES, DLR, UKSA, KARI, INPE
  - Establishing interoperability among partner space agencies via agreements & standards
  - Conducts studies to determine way forward on: Coding & Modulation, Link Protocols, Optical Links, Solar System Internetworking, Spacecraft Emergency Ops, Lunar Comm Architecture
- Consultative Committee on Space Data Standards (CCSDS): develops & tests standards for space comm, PNT, & mission operations
  - Larger government membership + commercial participants
  - Also an ISO Technical Committee so standards becomes ISO standards
- Space Frequency Coordination Group (SFCG): recommends specific frequency bands for all near Earth & deep space
  - Analyses RFI & other countries' policies, e.g., Europe's IMT-2000
  - Coordinates with FCC, NTIA, ITU and WRC to defend space RF allocations

Laser Communications Relay Demonstration (LCRD)

Mission Status

- Launch date: 2019
- Ka-band and Optical payloads onboard STPsat-6 Geostationary satellite
- Technology demo to test Optical Relay capabilities with Ka-band
- New Optical Ground Stations under development



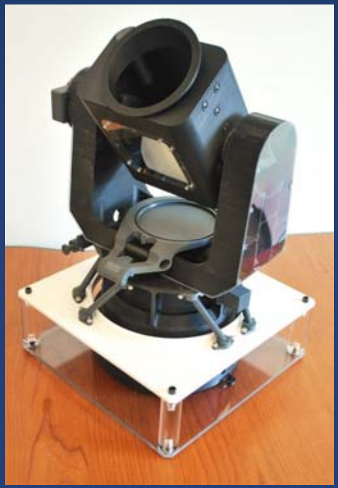
Optical Ground Station: OGS-2 at AMOS

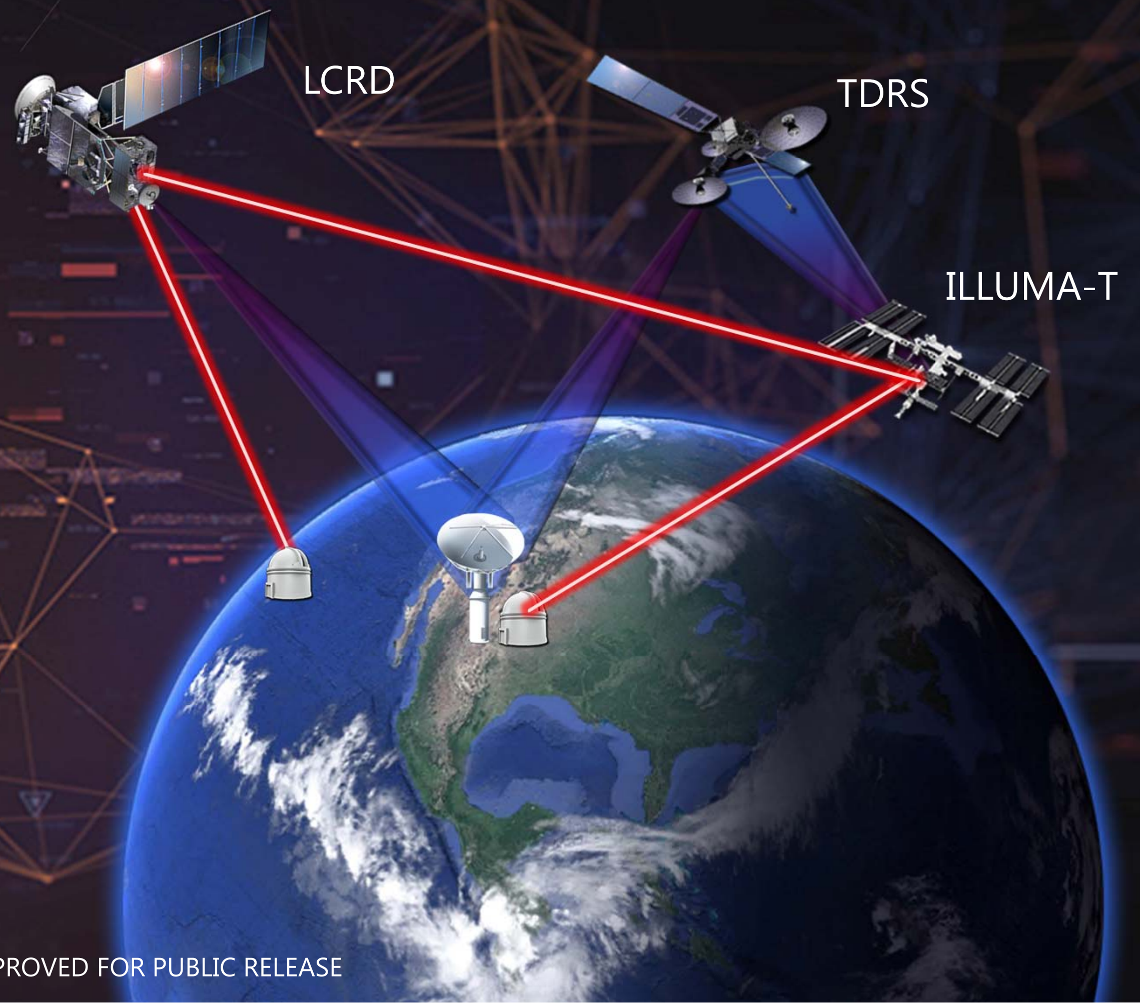
Dome Lift in Progress

Dome Installed
(lightning poles in foreground)

User Terminal: ILLUMA-T Next Gen Optical Module

- 2-axis gimbal with brushless torque motors for hemispherical field of regard
  +/- 175 degrees Azimuth
  +/- 120 degrees Elevation
- ~13 kg total mass for 10 cm model
- Would develop 20 cm model for GEO terminals, including GEO crosslinks
- Launch to ISS in 2021





Roadmap **Quantum Activities**

NASA Quantum Systems Space Development Vision/Plan

Quantum Key Distribution (QKD)
Superdense Teleportation (SDT)
s/g = space/ground

- **Cryptography**
- **Q Computer Interconnections**
- **Entanglement Sharing Enable Sensing**
- **Pure Physics Experiments**

QKD-Relevant Experiment with LCRD

QKD-Pad Dissemination ISS/Ground

Space/Ground Demo of Teleportation of Toroidal Q State using SDT

Space/Ground Entanglement-Sharing Demo

QKD-Based Secure Comm Between Microsats

Entanglement Sharing Between Q Memories

Entanglement Sharing in Microsat Swarm

Planetary Distance Quantum Properties

Relativistic Speed Quantum Properties

High-rate, On-the-fly Q Encryption

Teleportation Between Q Memories for Q Comp

Long Baseline Interf. Imaging Space Demo

2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Study of detailed strategy and plans for 1st phase	Lab demo of 1st phase designs & LCRD ground terminal modification	Space and Ground design/fab for 1st phase & LCRD QKD experiment	Fab of S/G 1st phase. Design and lab demo of 2nd phase designs	2nd Phase demo ISS-GRD, SDT, & QKD demo. Detailed design of 3rd phase	S/G design/fab for 2nd phase. Design and lab demo of 3rd phase	Space and Ground design/fab for 3rd phase	3rd Phase demo space-space SDT and QKD smallsat demo	Space and Ground design/fab for 4th phase	QKD demo 2026 Mars to Earth

Resilience

- PDD-21 defines resilience as the ability to
  - prepare for & adapt to **changing conditions**
  - withstand & recover rapidly from **disruptions**

Includes changes that affect the ability to perform essential functions & maintain mission assurance

Includes deliberate attacks, accidents, or naturally occurring threats or incidents

Technical Strategies to Enhance Resilience

- Open, interoperable architecture with standard services & modular components
  - Enables flexible use of commercial, international, OGA &/or NASA capabilities
  - Broad industrial base lowers unit costs & vendor risk enabling adoption by broader communities
- Disaggregated architecture provides shorter acquisition time, launch flexibility (rideshare, hosted, dedicated), failure tolerance, & operational flexibility
- Overlap NEN & DSN coverage from ~30,000 km to 2M km for resource allocation flexibility
- Use SW-Defined Radios & onboard processing to upgrade on-orbit assets
  - Switch between near Earth & deep space bands or between government & non-government bands
  - Upload new coding, modulation, compression & security options
- Invest in cognitive radios & networking
  - Let radios & networks manage themselves & optimize performance
  - Automate networks to reduce O&M
  - Use DTN & IPv6 with IPsec
- Invest in optical communications & navigation
  - Enhances security (Low Probability of Detection & Interference)
  - Lowers user burden (SWaP) & cost
- Potential use of dissimilar NASA/OGA architecture to enhance DOD resilience

Programmatic Strategies to Enhance Resilience

- Establish partnerships to pool resources, spread risks & share benefits
  - NASA/AFSCN Launch Comm investment enhances launch for multiple agencies
- Disaggregate architecture for flexible budgeting, scheduling & technology infusion
  - Targets: Reduce funding peaks to in-guide budget level. Reduce schedule lead time to within PPBE window.
- Develop new technology until it costs less than current technology
  - Block purchase initial sets & GFE equipment to early adopter missions to mitigate technology infusion risk
  - Block purchase reduces unit cost so subsequent units cost ≤ old technology
- Design technology flight demonstrations to transition to operations
  - Get technologists to plan for operations; Get Operations to anticipate steady evolution
  - Gain early user community involvement & builds confidence
- Pursue operations efficiencies, e.g., automation & autonomy including shifting autonomy to missions
- Manage Solar System Internet (SSI) like terrestrial networks to reduce O&M and avoid burden of specialized environment
  - **Assume every network vulnerability on Earth gets carried into Space**
- Use mixed asset ownership for dissimilar design & flexible capacity & price
  - NEN schedules NASA-owned antennas 1st, pre-priced commercial antennas 2nd, spot market commercial antennas 3rd

Technologies to Enhance Resilience

- **Antenna arraying** with diverse locations improves weak signal reception, power combining, RFI nulling, failure tolerance, ability to exploit interferometry, and maintenance flexibility
- **SW Defined Radios** enable upgrades after launch enabling on-orbit performance enhancements & installing security upgrades
- **Cognitive radios & networks** provide adaptive coding & modulation, frequency agility, dynamic transmitter power adjustment, and ability to learn
- **Optical communications** produces LPD/LPI
- **Optical navigation** produces measurement diversity from RF reducing errors in position & orbit determination
- **Continuous Diagnostics and Mitigation** (CDM)
  - SCaN is installing CDM on all networks
- **Delay/disruption Tolerant Networking** (DTN)
- **Quantum** communications, encryption, & key distribution
- Position, Navigation, & Timing (PNT)
  - **Low SWaP atomic clocks**: tolerate failure of GPS & terrestrial time sources
  - **X-ray pulsar navigation**: position & orbit determination independent of GPS
- **Autonomy**: Onboard capability to detect changing conditions and respond to them without human help
  - Uses **SDRs**, **cognitive** technologies, **network-layer services**, and **PNT**

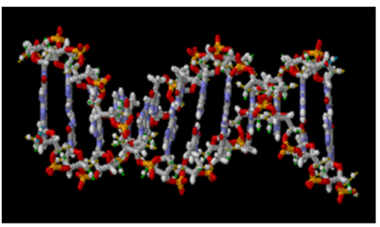
, April 1996, Pages 168-173

Biological Metaphor: Genetics, Epigenetics & Plasticity

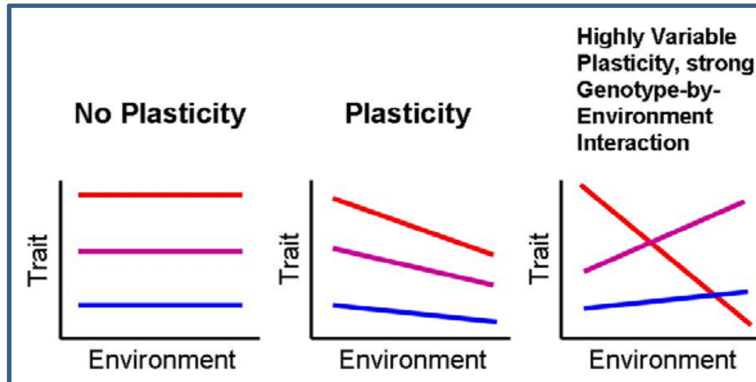
Environment: Nature

Genetics
Study of genes (based on ***DNA***), genetic variation (through errors & mutation), and heredity in living organisms.[1]

Epigenetics
Study of heritable *changes in gene function without changes in DNA* sequence; denotes changes in chromosomes that affect gene activity & expression



DNA "read" by Gene regulation mechanisms



Examples		
Panda	Red Squirrel	Aphid
Koala	Rainfrog	Gray Wolf
Cassowary	Penguin	Human

Phenotypic plasticity is the ability of one genotype to produce more than one phenotype when exposed to different environments. Horizontal lines show that the phenotype is the same in different environments; slanted lines show that there are different phenotypes in different environments, and thus indicate plasticity.

Phenotypic Plasticity
Refers to changes in an organism's behavior, morphology & physiology due to *Gene regulation mechanisms* that respond to environmental variation including acclimatization & learning.[2, 3, 4]

1. "Genetics", https://en.wikipedia.org/wiki/Genetics
2. "Phenotypic plasticity", Wikipedia, https://en.wikipedia.org/wiki/Phenotypic_plasticity
3. Massimo Pigllucci, "How organisms respond to environmental changes: from phenotypes to molecules (and vice versa)", Trends in Ecology and Evolution, April 1996, Pages 168-173.
4. Marc Srour, "Phenotypic Plasticity", http://bioteaching.com/phenotypic-plasticity-2/

Architectural Counterpart: Architecture Plasticity

Environment: Laws, Regulations, Policies

Refers to the portion of the external Environment that is induced (man-made)

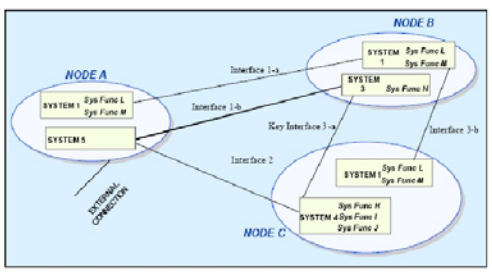
Architecture

Defines System entities, organization, performance, internal interfaces & external Environment

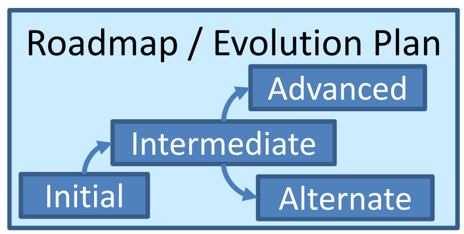
Concept of Operations (ConOps)

Defines Scenarios that describe Architecture behavior & performance to achieve system goals. Scenarios may be actual missions or may bound the trade space for defining future capabilities.

SV-1 – System Interface Description

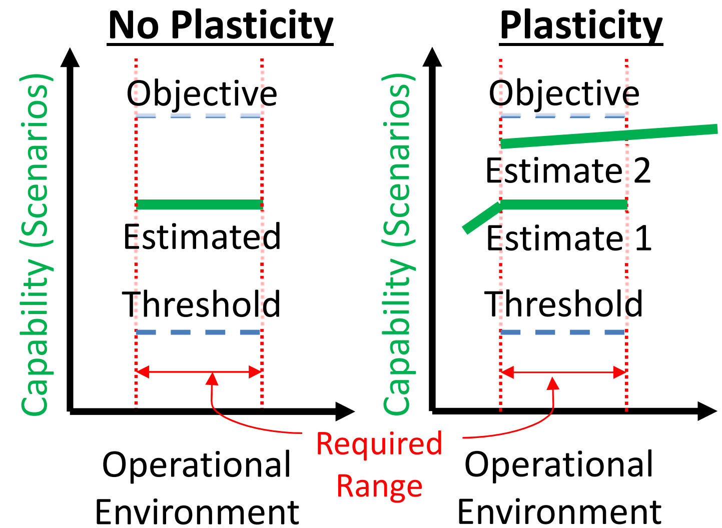


Architecture interpreted by ConOps & time-phased



Architecture Plasticity

Refers to the degree to which an Architecture can be adapted to respond to environmental variation including learning & overcoming constraints.



- Architecture on left exceeds threshold capability & meets environment range; cannot operate outside that environment or provide other capabilities.
- Architecture on right operates over wider environment range & extra investment in architecture (Est. 2) "stores" ability to "express" additional capabilities.

Next Gen Architecture: Conclusions

- Architecture with Roadmap defines a broad evolutionary path for Space Communications & Navigation using many strategies to enhance resilience
  - Open, standards-based Architecture designed with disaggregation, modularity, reconfigurability, automation, and autonomy
  - Extends terrestrial telecom & networking technologies into space
  - Design to evolve faster & deploy incrementally to outpace evolving threats
- Architecture requires a Broad ecosystem involving many government and industry partners + technical & programmatic elements to realize full benefits
  - Yet requires each partner only to adhere to common standards
  - Degree of interoperation can be set to full, partial none, or dynamic
- Introduced new concept of **Architecture Plasticity** to measure degree to which an architecture can encode & express capabilities beyond requirements for added resilience against environment that is slow to adapt
- Architecture will be baselined in 2018-19 with initial capability by mid-2020s
  - Coordination with government, international and industry partners is underway

NASA

www.nasa.gov

NASA Space Communications and Navigation

https://www.nasa.gov/scan

Facebook: NASASCaN

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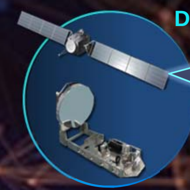
Eyes on the DSN:

http://eyes.nasa.gov/dsn/dsn.html

Technology Development, Demonstration, & Operational **Timeline**

Near Earth
DTE Technologies
- 200 Gbps user terminal
- 200 Gbps low cost ground station

Near Earth
Relay Technologies
- 1.244 Gbps GEO relay two ground stations (2019)
- 1.244 Gbps user terminal (2021)
- 100 Gbps GEO relay, user & ground station (2023) – 2nd Gen



Deep Space
DTE Technologies
- Space user terminal for 125 Mbps at 40 Mkm range
- 5 meter Optical Ground Station

Technology: 2019 — 2019-2021 — 2021 — 2022

Terabyte Delivery System: 200 Gbps Demo
- Space technologies based on COTS products
- CubeSat-sized, low SWaP user terminal
- User-site installable ground station: eliminates data backhaul

LCRD: 1.244 Gbps Optical Relay Demo
- Hosted GEO payload on AFRL's STPSat-6; uses LADEE technology
- Routing of optical signals in a hybrid environment (RF/optical)
- NASA's 1st frame-layer switch in space

ILLUMA-T on ISS: 1.244 Gbps Relay User
- LEO satellite acquisition and tracking in a GEO relay system (LCRD)
- ISS ⇔ LCRD ⇔ Earth

Discovery Psyche: 125 Mbps Demo
- Deep space optical link
- Launch on Discovery 2022 mission
- Five (5) meter Palomar telescope

Demonstrations: 2019 — 2019 — 2021 — 2022

Terabyte Delivery System
Near Earth DTE Demonstration

Near Earth DTE Operational Services
- Initially two SCaN operated ground stations; others added incrementally
- Scheduling
- Ground data buffering & routing
- Cognitive algorithms

LCRD
GEO Relay Technology Demonstration

ILLUMA-T
User Relay Technology Demonstration

Relay Operational Services

Reuses LCRD and adds two more GEO relay node to the network
- Based on LCRD design
- Augments near earth DTE network
- Cognitive network operations

Discovery Psyche
Deep Space Technology Demonstration

Deep Space Operational Services

Adds deep space class terminals to the architecture
- Based on first generation terminals
- Ready to support missions starting in 2026

Operations: 2022 - 2024 — 2025 - 2027 — 2026

Ensuring Resilience of NASA Comm Assets in "Congested & Contested" Environment 1/2

- Space Network
  - Fleet of 7 operational TDRS + 3 spares including 3 generations of spacecraft
    - TDRS-M became operational TDRS F13 in Feb 2018
    - Variety of orbital slots enable fleet management by drifting satellites to assigned longitude – assignment based on s/c health & demand
  - Three Ground Stations (White Sands, Guam, Blossom Point)
    - Limited resilience due to spacecraft visibility & non-uniform ground station equipment
  - Replacing White Sands with all digital architecture & pooled resource allocation for higher reliability & availability
  - Missing: Dissimilar redundancy for TDRSS/SN
- Near Earth Network
  - 50/50 Balance of NASA-owned & commercially procured capacity
    - 2 commercial service providers, both foreign-owned
    - Able to augment existing global site distribution as required on short notice
    - Evaluating new domestic service providers

Ensuring Resilience of NASA Comm Assets in "Congested & Contested" Environment 2/2

- Deep Space Network
  - Mix of 70m & 34m antennas at 3 sites for global coverage
  - 50 year old antennas received service life extension to ~2030
  - Building new 34m antennas: 4x34m = 70m performance but with more flexible management
  - Transitioned Australian & Spanish sites to full network operations partners
    - All sites can operate entire DSN
    - Foreign sites are staffed by foreign citizens
  - Provides backup TT&C for TDRSS
  - Agreement with Italian Space Agency (ASI) for 500 hours/year on their 64m Sardinia Radio Telescope
    - Upgrading to add X-band transmit & receive

- Agreements in place with international space agencies for Cross support

Understanding the role of industry & private sector innovation

- Existing NEN commercial ground station contracts: Kongsberg Satellite (KSAT) (Norway), Swedish Space Corp. (SSC)
  - Extensive & growing set of ground stations
  - New capabilities added as required to meet customer (US & other government) needs – not leaders
- New contractors being evaluated: Spaceflight Network, RBC Signals, Audacy
  - May meet needs for small/CubeSat support
  - Audacy promises TDRSS-compatible support & lunar communications
- SBIR/STTR programs offer opportunity to fund commercial innovation into targeted technologies
- New SCAN Pathfinder initiative (RFI responses received Nov 6): looking for industry innovation & leadership in technology & business model
  - Push by NASA/SCaN towards commercial services
  - Broader push by NASA/Human Exploration and Operations to stress commercial services, products
  - Seeking to establish new or expand existing space comm market to create opportunities
  - Must have at least 2 suppliers & at least 2 customers with at least 1 non-government customer
  - Purpose is to create a more robust commercial market using competition to lower prices, reduce lead time, prevent vendor lock, reduce risk & enhance resilience based on an open architecture