Communicating with Astronaut and Robotic Explorers across the Solar System

Phil Liebrecht
Assistant Deputy Associate Administrator
and Deputy Program Manager
Space Communications and Navigation
NASA HQ

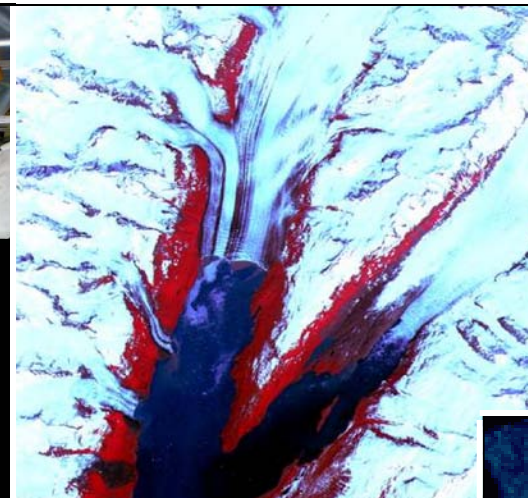
Meeting the Communications and Navigation Needs of Space missions since 1957

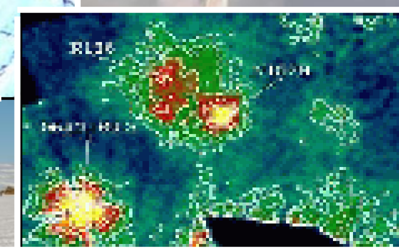
"Keeping the Universe Connected"

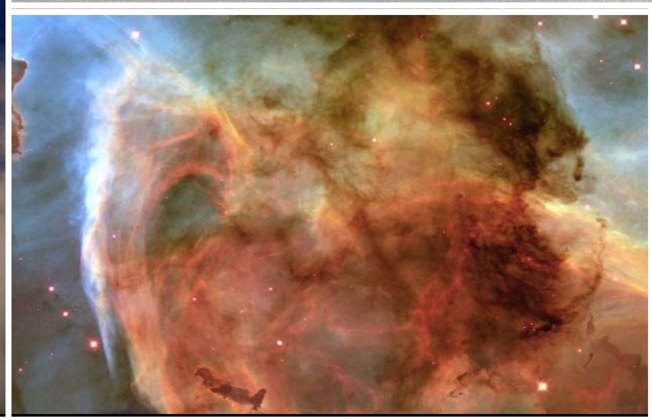
Public University of Navarra, 2010

Philip.E.Liebrecht@nasa.gov

Operations and Communications Customers

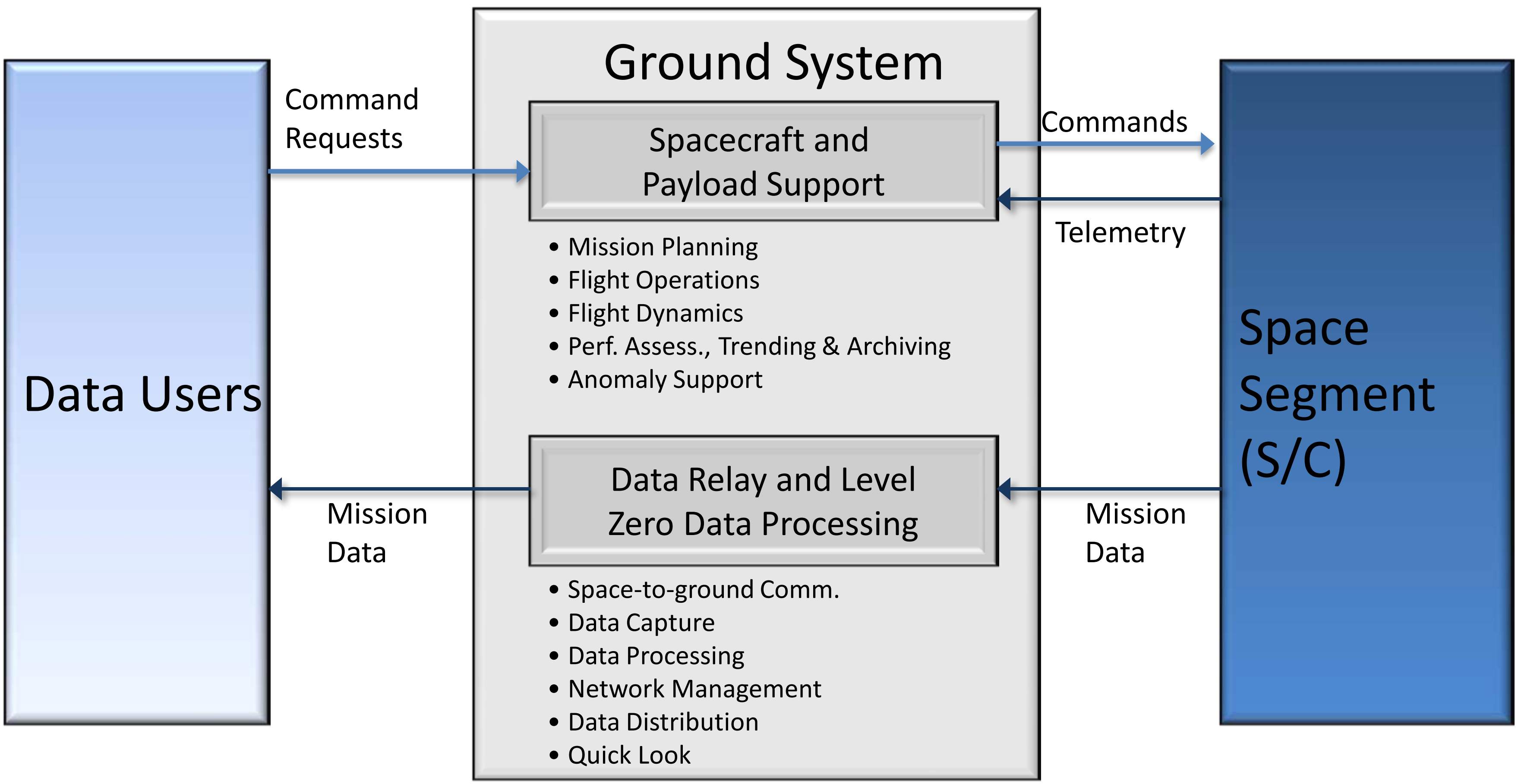






Space Operations 101

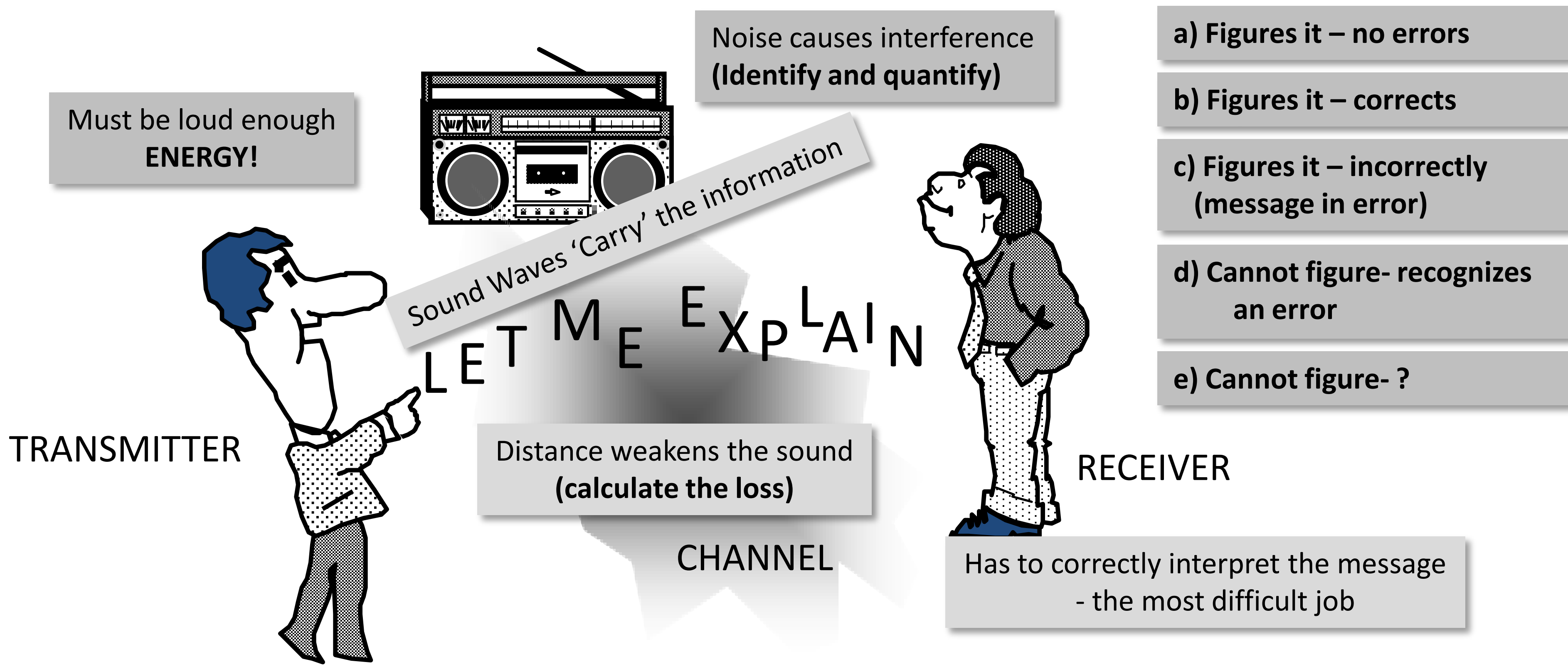
Relation Between Space Segment, Ground System, and Data Users*



* Based on Wertz and Wiley; Space Mission Analysis and Design

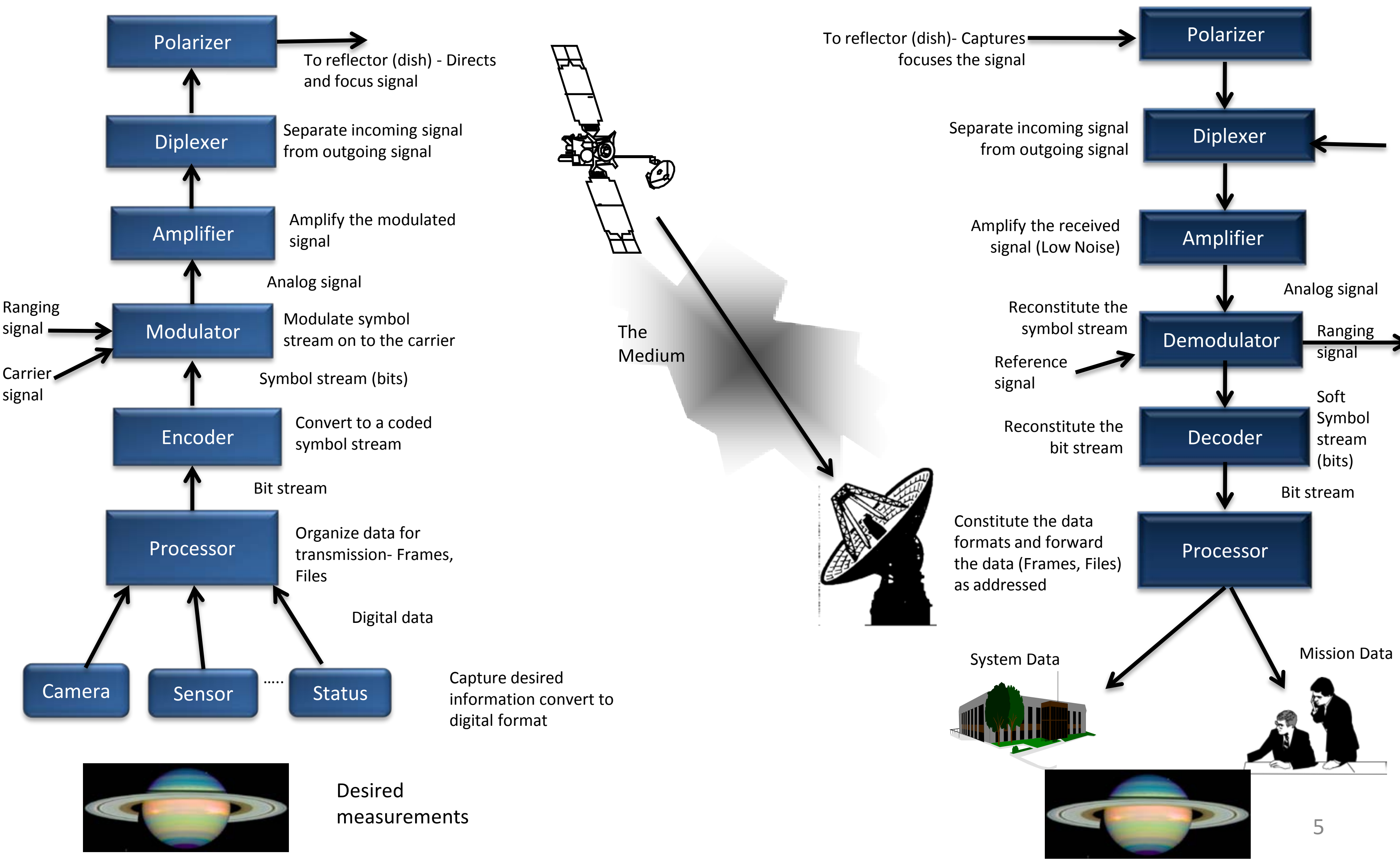
Communications Theory- Basic Concepts

Transmitter and Receiver must use the same language



The fundamental problem of communications is that of reproducing at one point either exactly or <u>approximately</u> a message selected at another point.

Functional - End to End Process



Antenna Gain and Propagation Loss

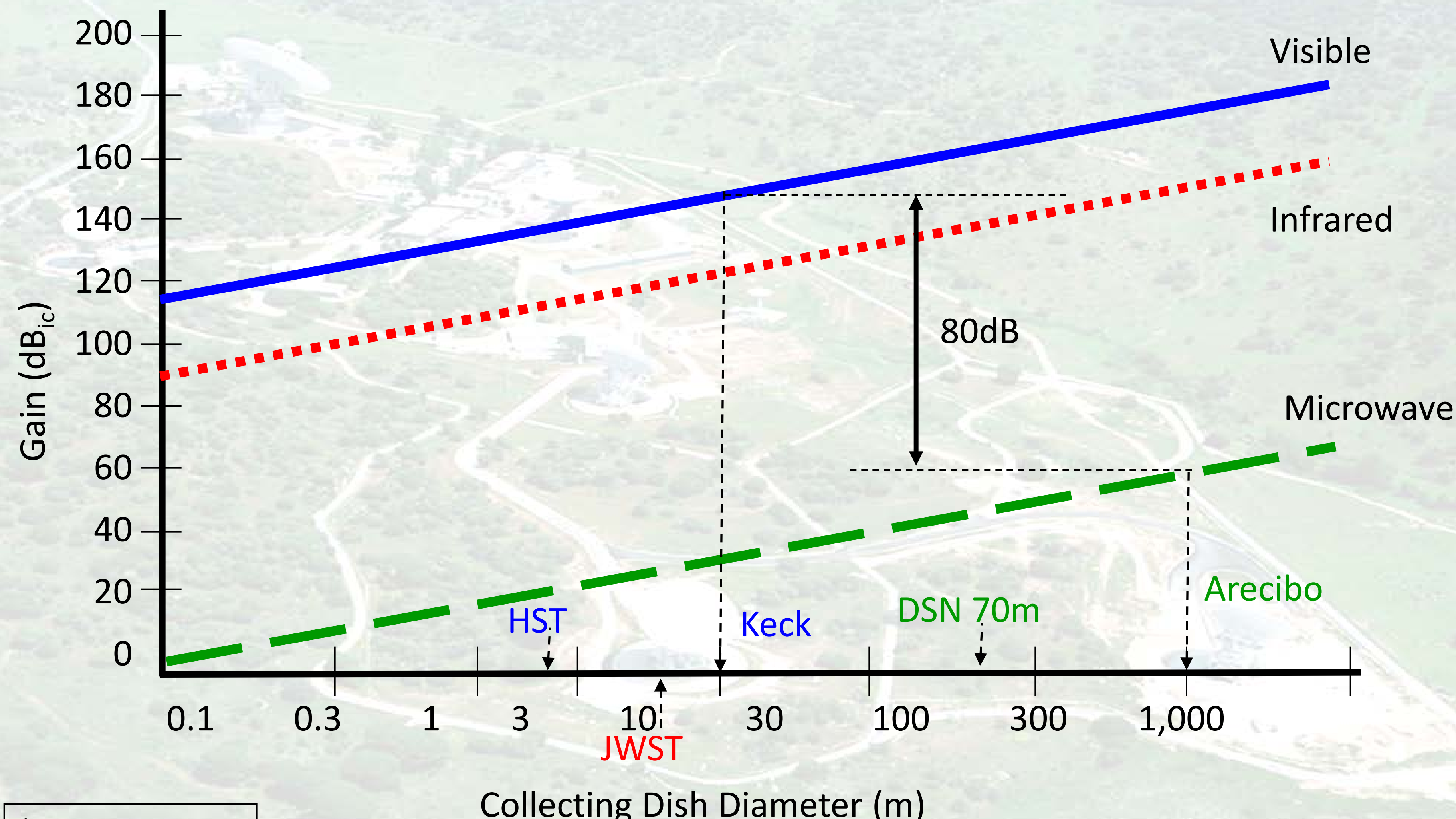
$$P_r = P_t \frac{1}{4\pi R^2} Ae = P_t \left(\frac{\lambda}{4\pi R}\right)^2 \left(\frac{4\pi A}{\lambda^2}\right) e$$

Propagation Loss ($1/L_P$)

Receive Antenna Gain (G_{ant})

In dB: $P_r = P_t - L_P + G_{ant} - (L_{other})$

Antenna – Operation – Directional Antenna – Size Matters

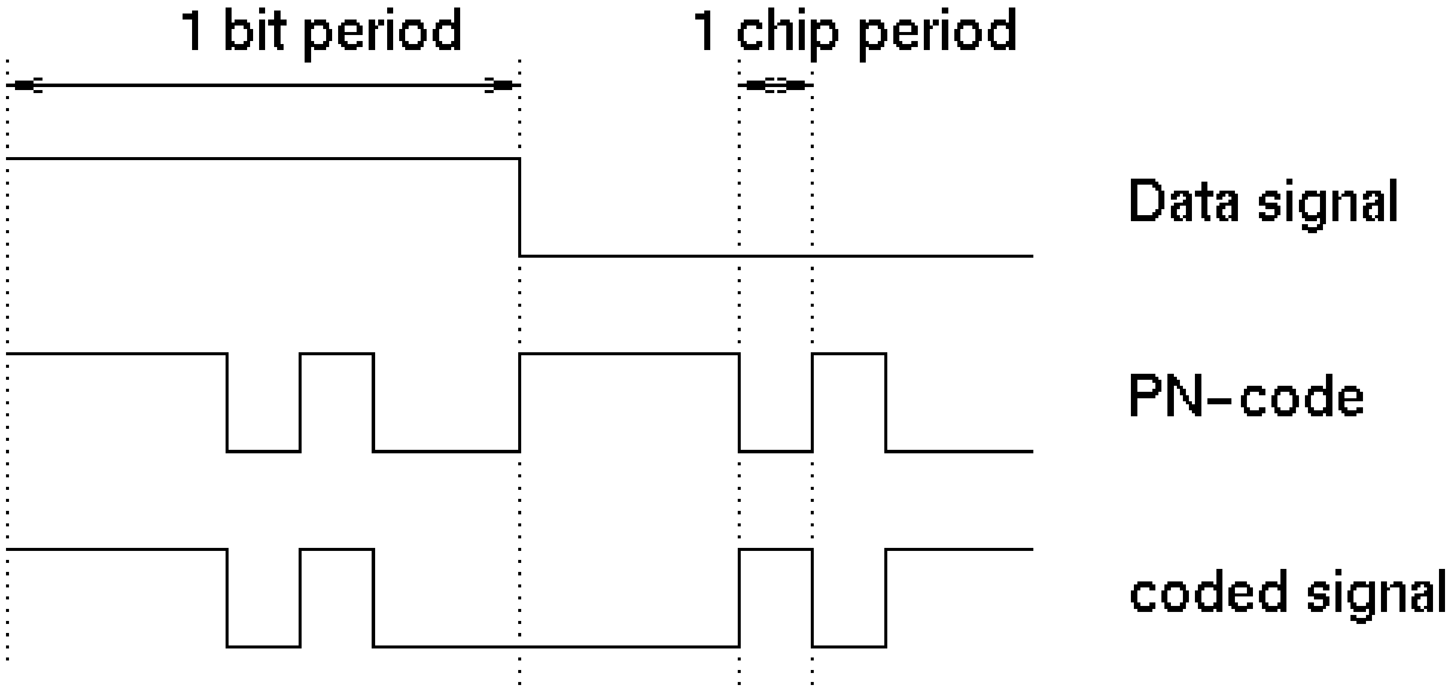


Assumes antenna efficiency of 100%

What is Noise?

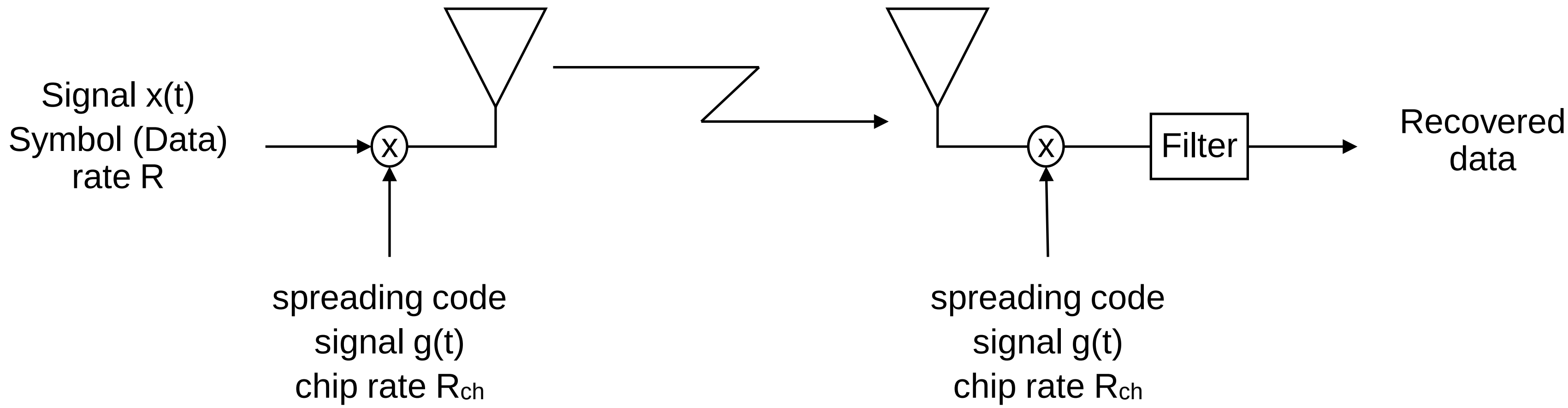
- Noise is additional “signal” that does not correspond to the information you are trying to convey.
- Noise in a signal takes several forms:
  - **Signal noise**
    - Amplitude noise – error in the magnitude of a signal
    - Phase noise – error in the frequency / phase modulation
  - **System Noise**
    - Component passive noise
    - Component active noise (amplifiers, mixers, etc…)
  - **Environmental Noise**
    - Atmospheric noise
    - Galactic noise
    - Precipitation
- Noise introduces error in the “ideal” modulation and signal in free space which results in errors in the received signal at the destination

Direct Sequence Spread Spectrum



A DS-CDMA signal is generated by multiplication of a user data signal by a code sequence. *Source: Jack Glas, T.U. Delft*. http://www.wirelesscommunication.nl/reference/chaptr05/cdma/dscdma.htm)

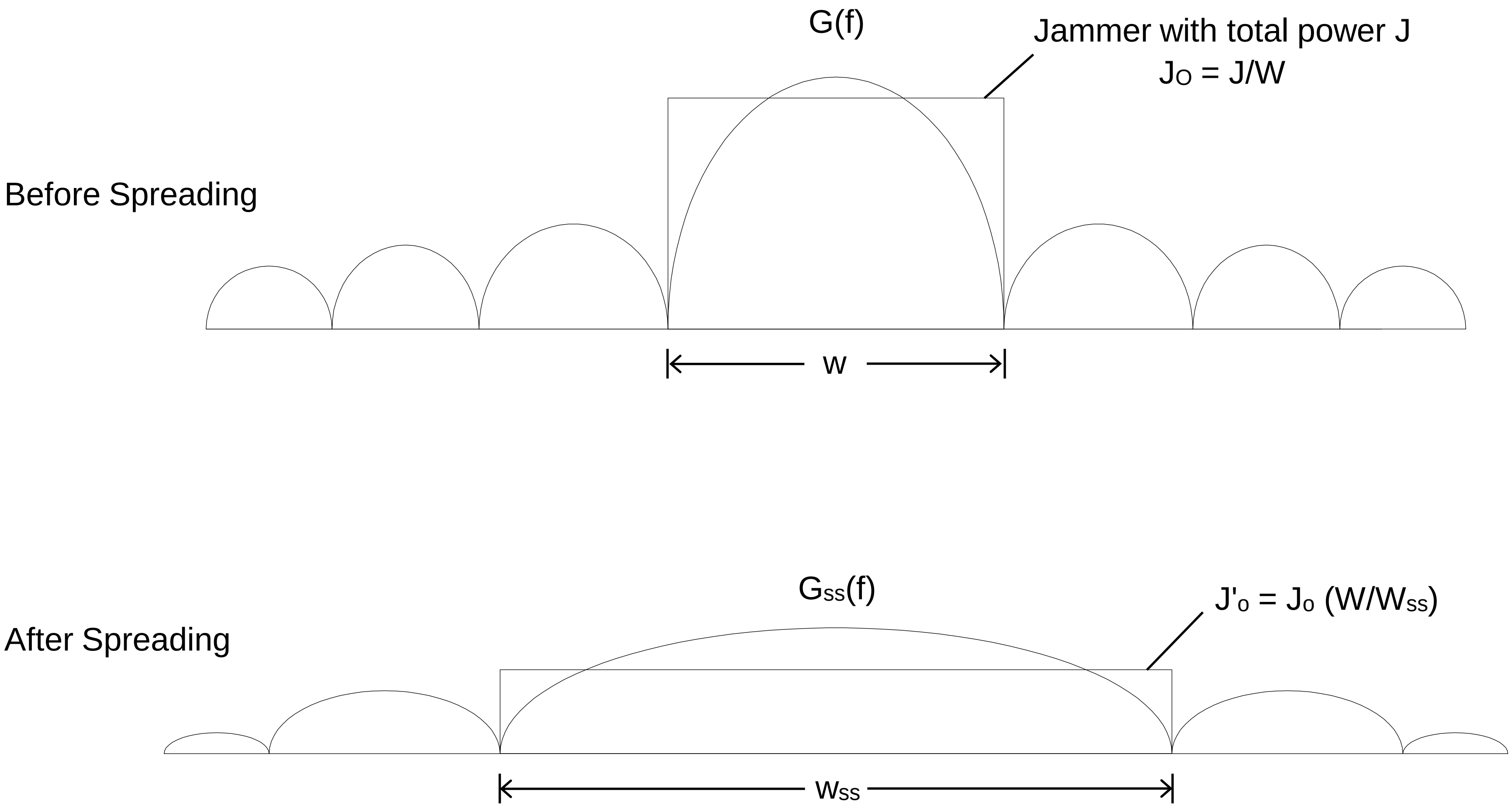
Receiving Direct Sequence Spread Spectrum Signals



$R_{ch} \approx \geq 10$ symbol (data) rate

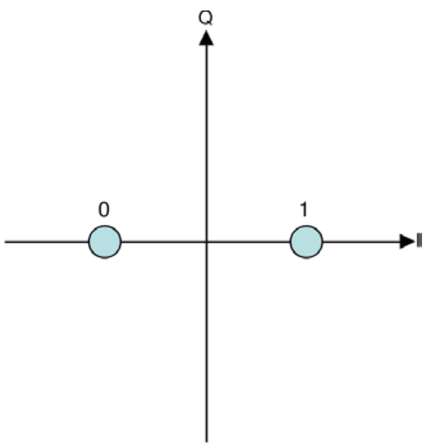
- Multiplication by the spreading signal once spreads the signal bandwidth.
- Multiplication by the spreading signal twice recovers the original signal.
- The desired signal gets multiplied twice, but the jamming signal gets multiplied only once.
- g(t) must be deterministic, since it must be generated at both the transmitter and receiver, yet it must appear random to authorized listeners.
  - Generally g(t) is generated as a pre-defined pseudo-random sequence of 1s and –1s through the use of prescribed shift registers.

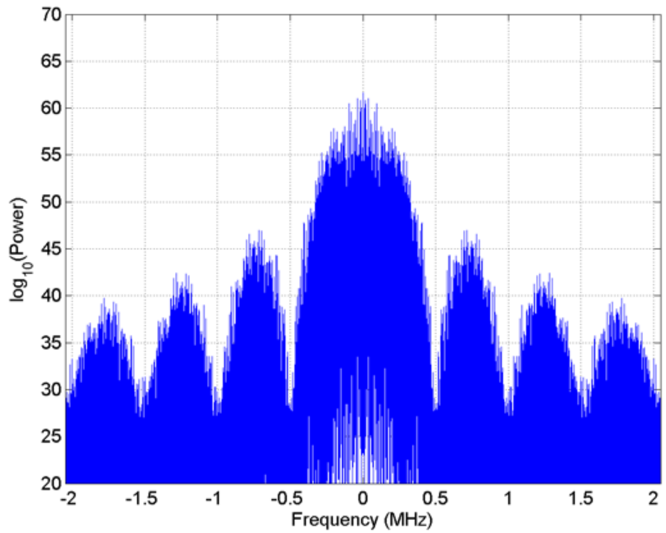
Spreading: Effect of Spread Spectrum



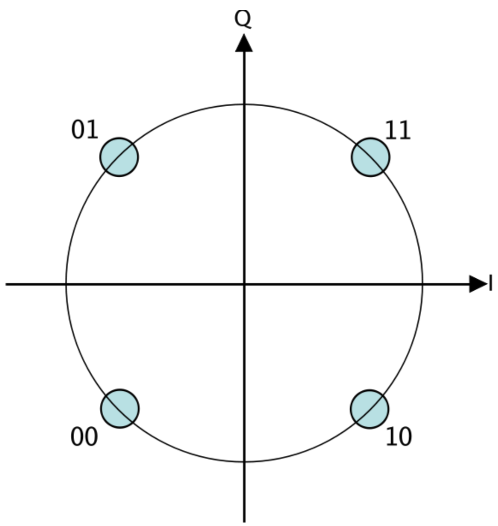
Digital Modulation

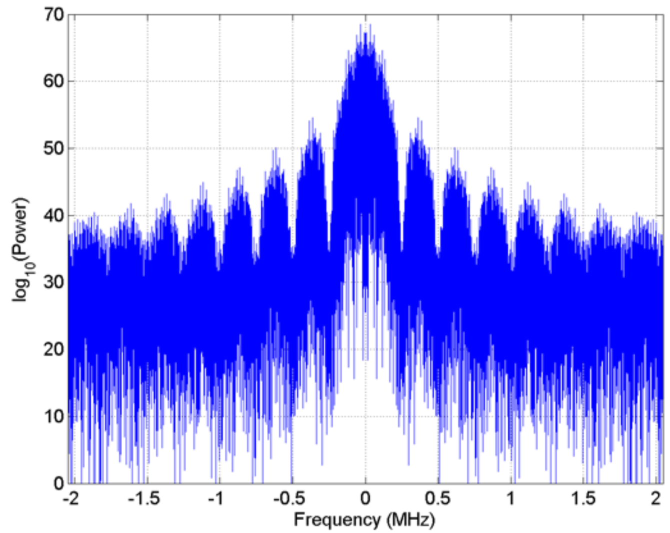
Bi-Phase Shift Keying (BPSK)



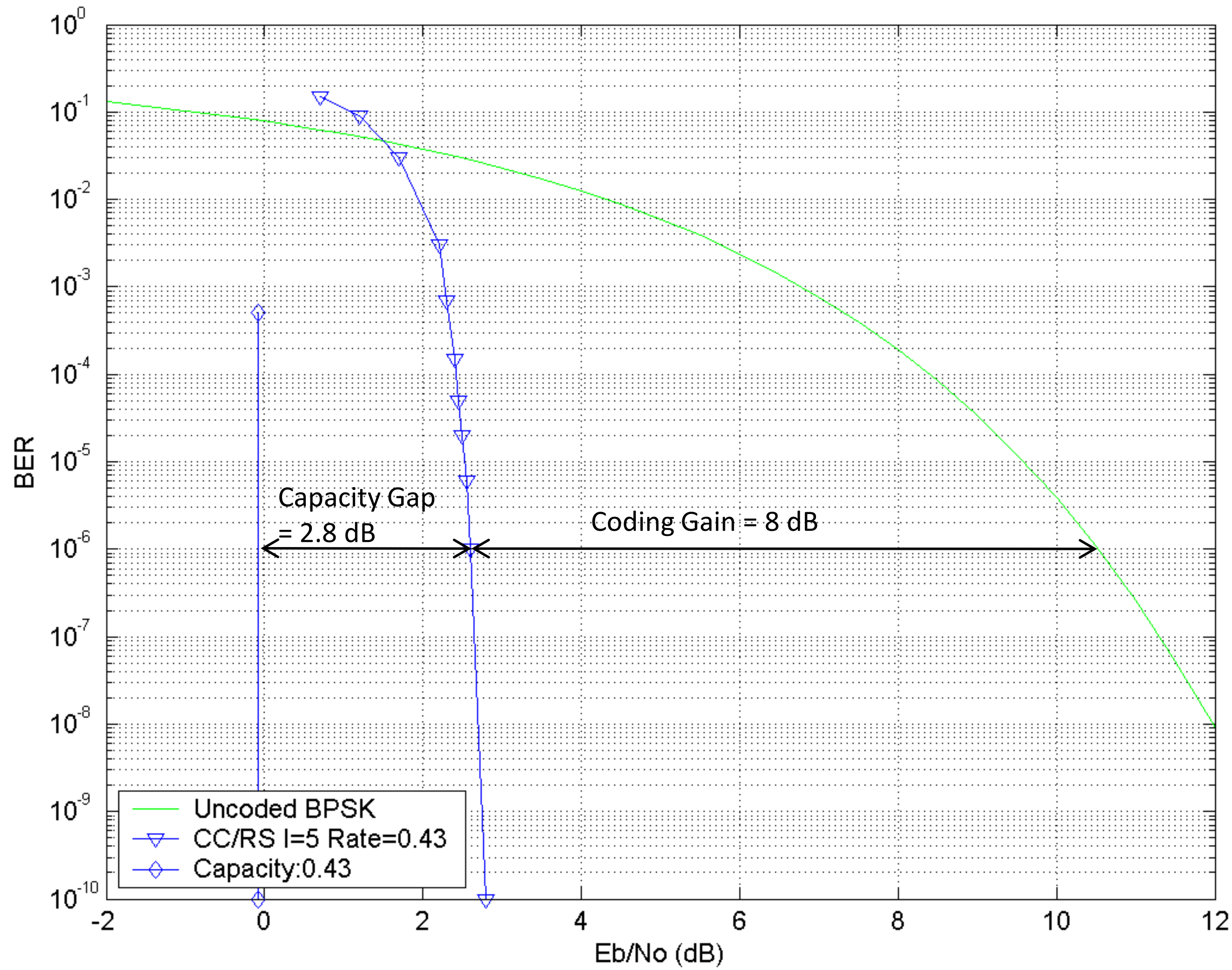


Quadrature Phase Shift Keying (QPSK)



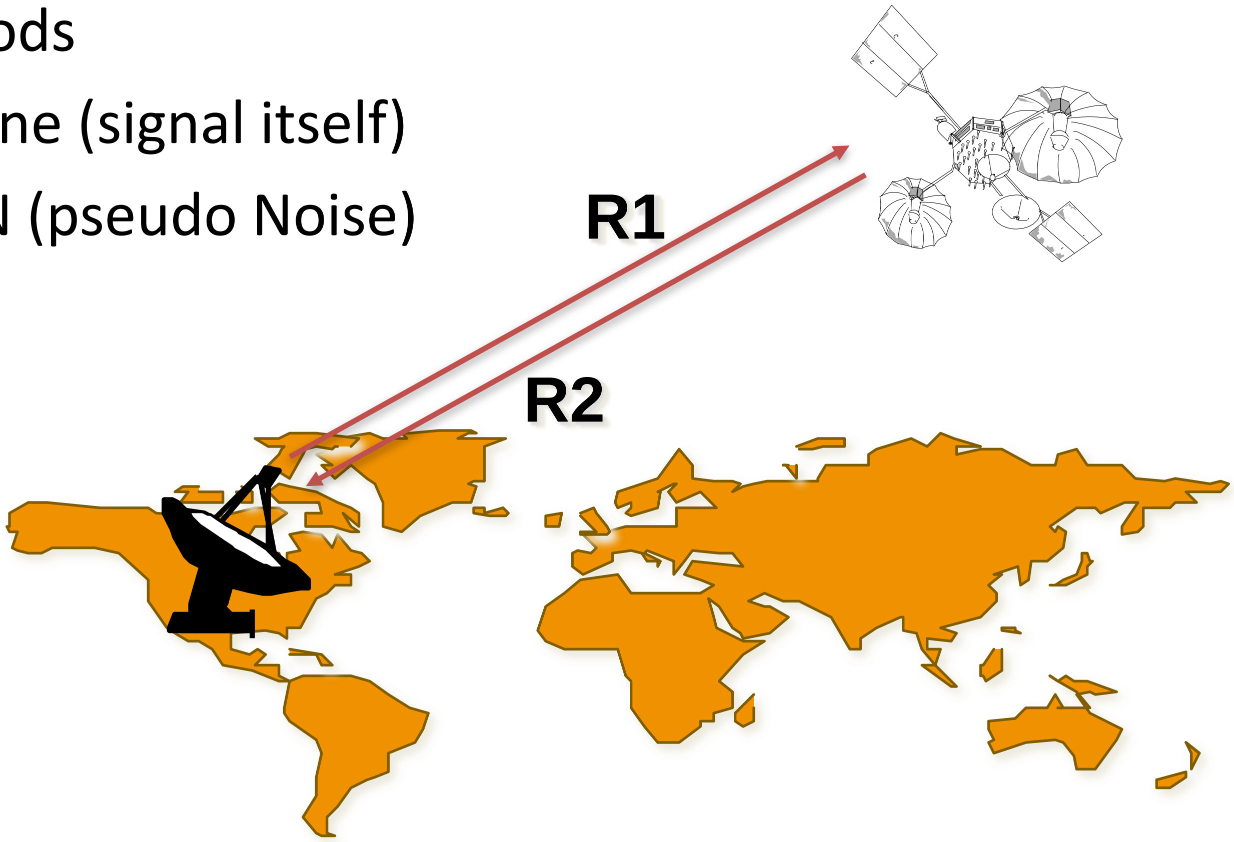


CC/RS Concatenated Coding Performance



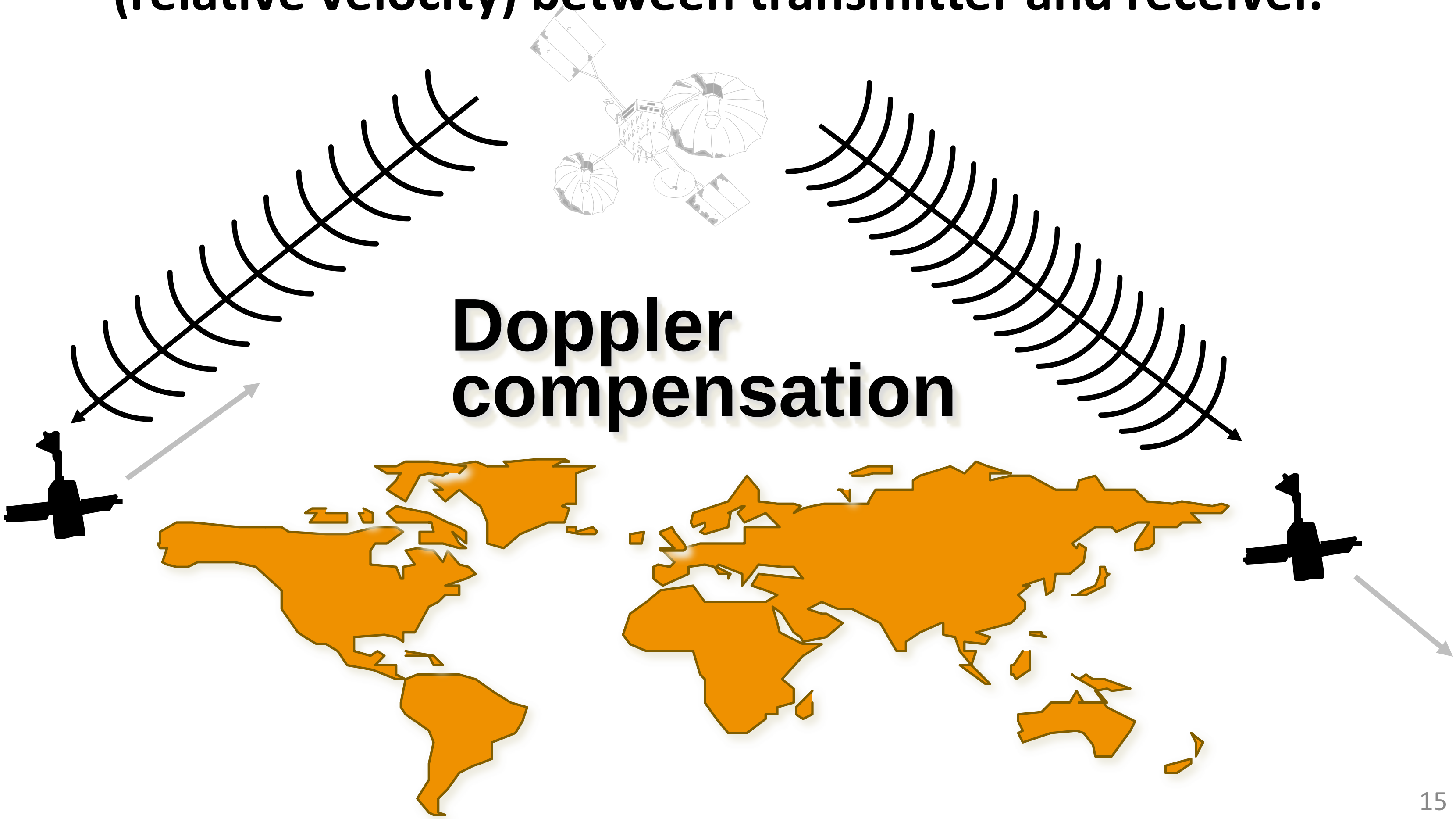
Metric Tracking Ranging

- Range is the distance from ground station to spacecraft.
  - Usually measured as "Round-trip" ranging: station, to spacecraft (R1), to station (R2). AKA, RTLT, Round-trip light time.
  - Distance = (RTLT/2) * light speed
- Methods
  - Tone (signal itself)
  - PN (pseudo Noise)



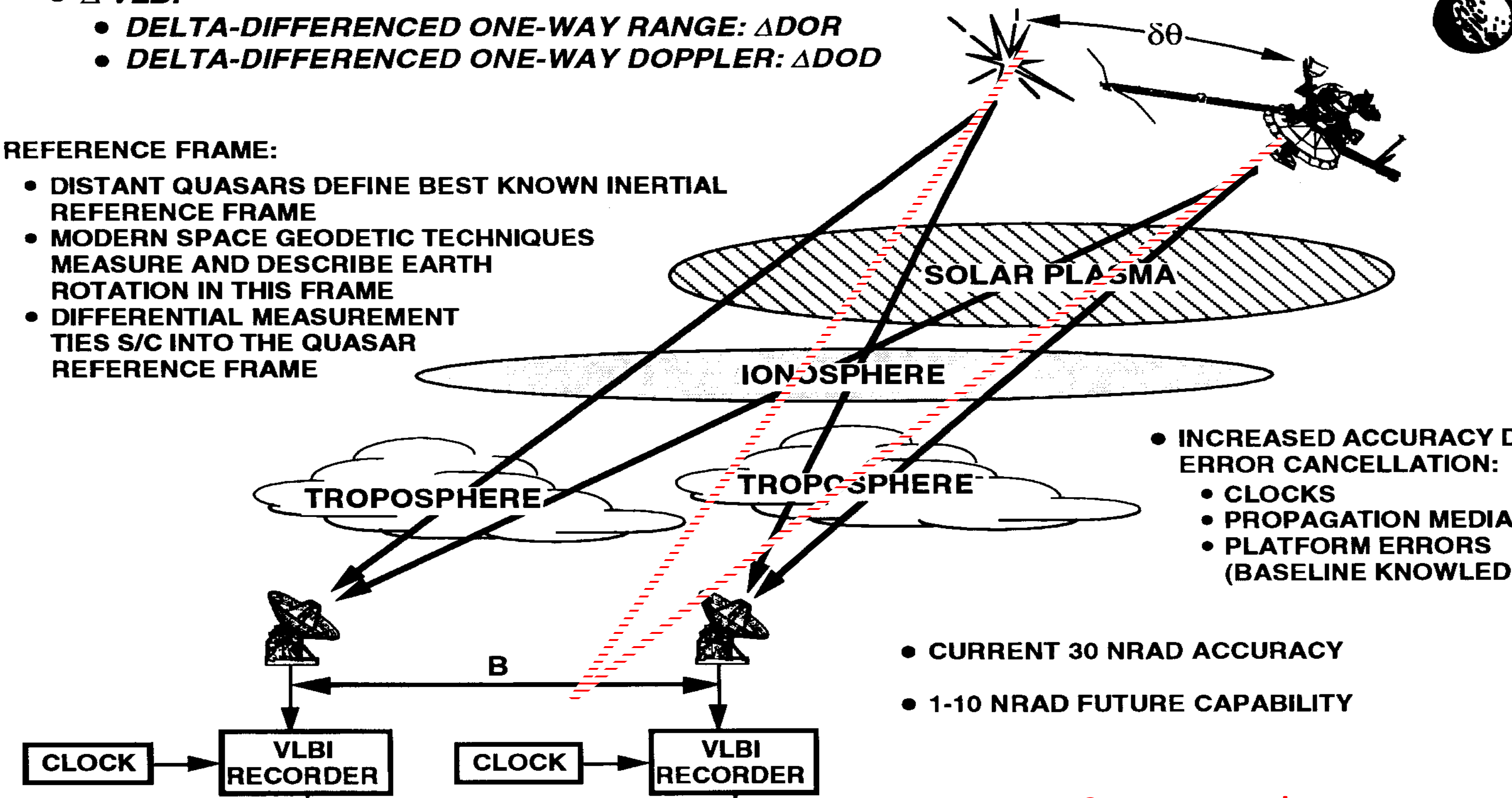
Metric Tracking Doppler = Range Rate

An observed/perceived change in the frequency of a radio wave due to the rate of change in distance (relative velocity) between transmitter and receiver.



Spacecraft-Quasar Differential Angular Techniques

- *Δ VLBI*
  - *DELTA-DIFFERENCED ONE-WAY RANGE: ΔDOR*
  - *DELTA-DIFFERENCED ONE-WAY DOPPLER: ΔDOD*
- REFERENCE FRAME:
  - DISTANT QUASARS DEFINE BEST KNOWN INERTIAL REFERENCE FRAME
  - MODERN SPACE GEODETIC TECHNIQUES MEASURE AND DESCRIBE EARTH ROTATION IN THIS FRAME
  - DIFFERENTIAL MEASUREMENT TIES S/C INTO THE QUASAR REFERENCE FRAME



- INCREASED ACCURACY DUE TO ERROR CANCELLATION:
  - CLOCKS
  - PROPAGATION MEDIA
  - PLATFORM ERRORS (BASELINE KNOWLEDGE)
- CURRENT 30 NRAD ACCURACY
- 1-10 NRAD FUTURE CAPABILITY

$$\Delta\rho_{s/c} = B\cos\theta_{s/c} + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + \text{NOISE}$$

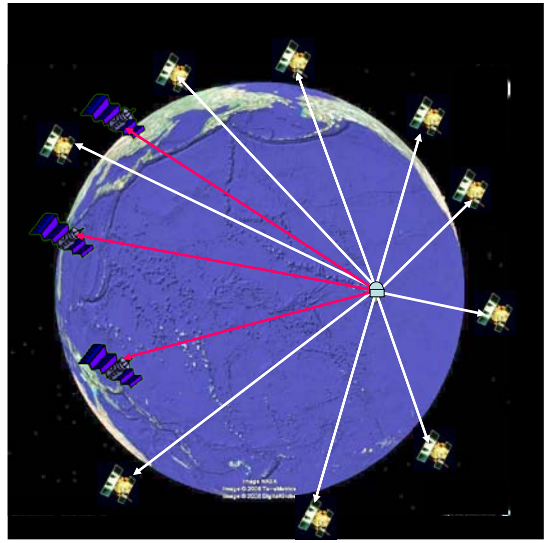
$$\Delta\rho_{Q} = B\cos\theta_{Q} + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + \text{NOISE}$$

- Common-modes out most error sources
- Leaves accurate measure of S/C-to-Quasar separation angle

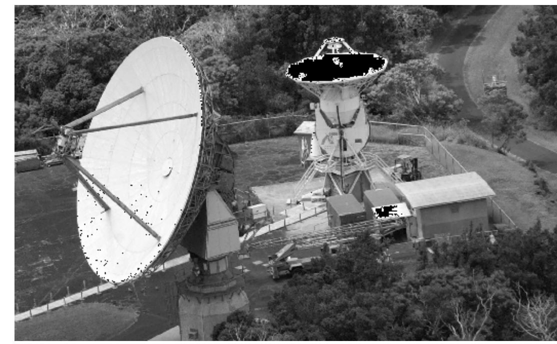
GPS Space Applications Critical to a Range of Space Operations, Science, and Exploration Enterprises

GPS services already enable:

- **Real-time On-Board Autonomous Navigation:**
  - Reduces the burden and costs
  - Enables new methods of spaceflight such as precision formation flying and station-keeping
- **Attitude Determination:**
  - Used on the ISS
- **Earth Sciences:**
  - Remote sensing tool supports atmospheric and ionospheric sciences
  - Geodesy, and geodynamics -- from monitoring sea level heights and climate change to understanding the gravity field
- **International space agencies planning to use similar robust capabilities from Galileo and other GNSS constellations**



GPS / QZSS monitoring station at Kokee Park, Hawaii (NASA –JAXA 2009 Agreement)



Jules Verne ATV during rendezvous with ISS in 2008

- GPS relative navigation used
- Future navigation on ATV to be performed via combined GPS/Galileo receiver

Space Communications and Navigation Systems Engineering Fundamentals

- To achieve successful space communication with microwaves you need:
  - **Line of sight** between the space vehicle and the receiver
  - **Ability to point** the antennas at each other (PAT)
  - Need **sufficient received signal power** compared to background noise
    - Large antennas
    - Ultra low noise cooled preamplifiers
    - Large transmitters (ground stations)
  - Use of **error correcting coding** and **disruption tolerant protocols** to improve performance in **noise**
  - Typically integrated **metric tracking** measurements
  - With increased distances these become even more important (and difficult)

SCaN Current Networks

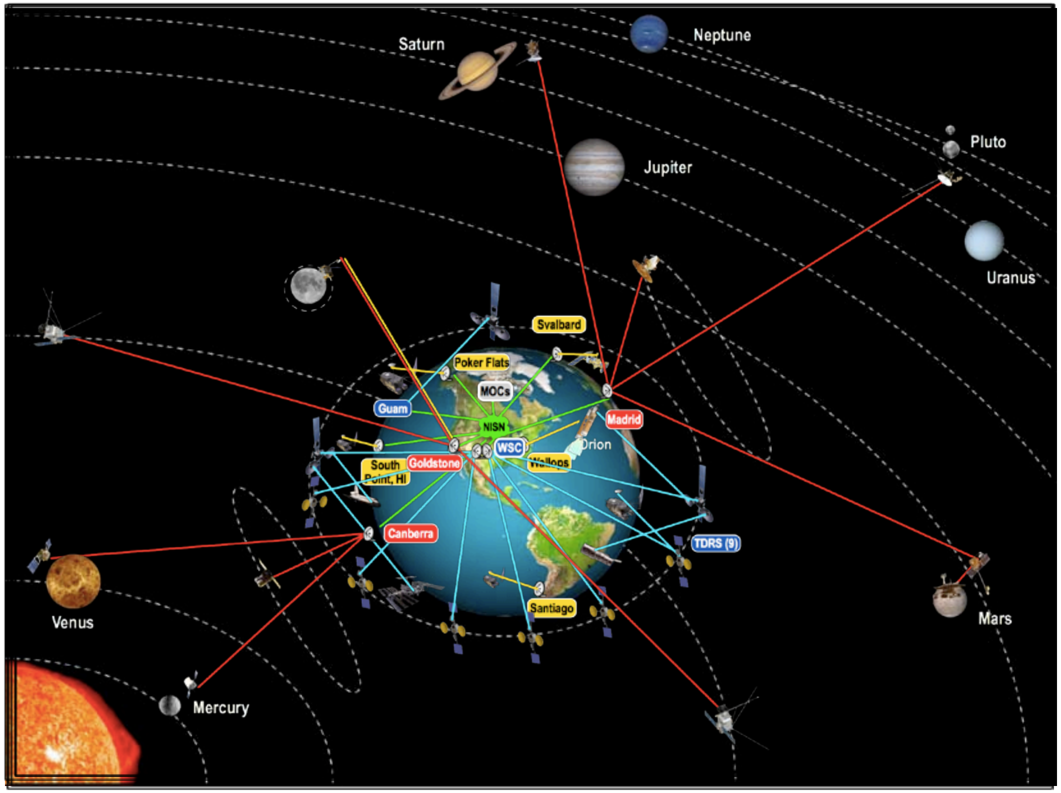
The current NASA space communications architecture embraces three operational networks that collectively provide communications services to supported missions using space-based and ground-based assets

Near Earth Network - NASA, commercial, and partner ground stations and integration systems providing space communications and tracking services to orbital and suborbital missions

Space Network - constellation of geosynchronous relays (TDRSS) and associated ground systems

Deep Space Network - ground stations spaced around the world providing continuous coverage of satellites from Earth Orbit (GEO) to the edge of our solar system

NASA Integrated Services Network (NISN) - not part of SCaN; provides terrestrial connectivity



Orbits and View

Deep Space Network

Provides continual tracking to spacecraft above 30,000 km altitude

- 3 complexes around the Earth
- 34 to 70 meter antennas on the Earth

Space Network

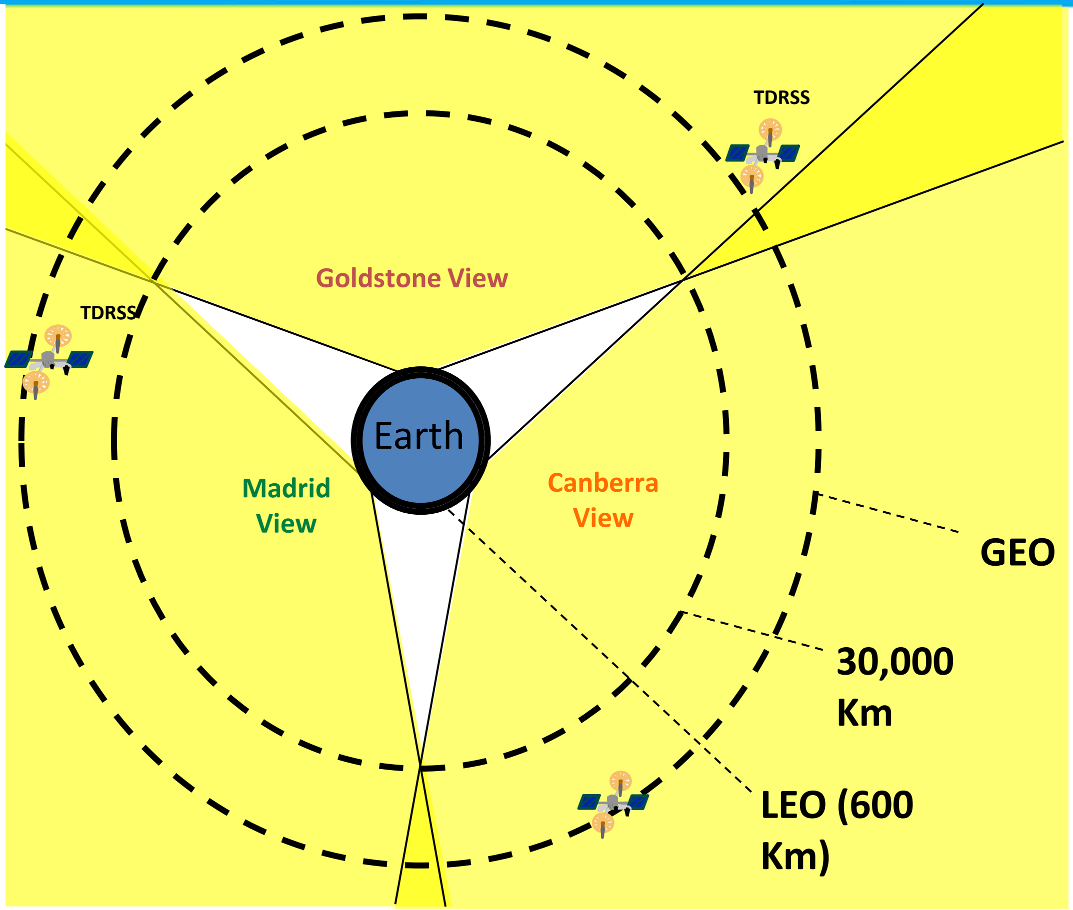
Provides continuous tracking of spacecraft below GEO

- Constellation of relay spacecraft at three nodes around the Earth
- 5 meter tracking antennas in space

Near Earth Network

Provides tracking of near earth orbiting spacecraft.

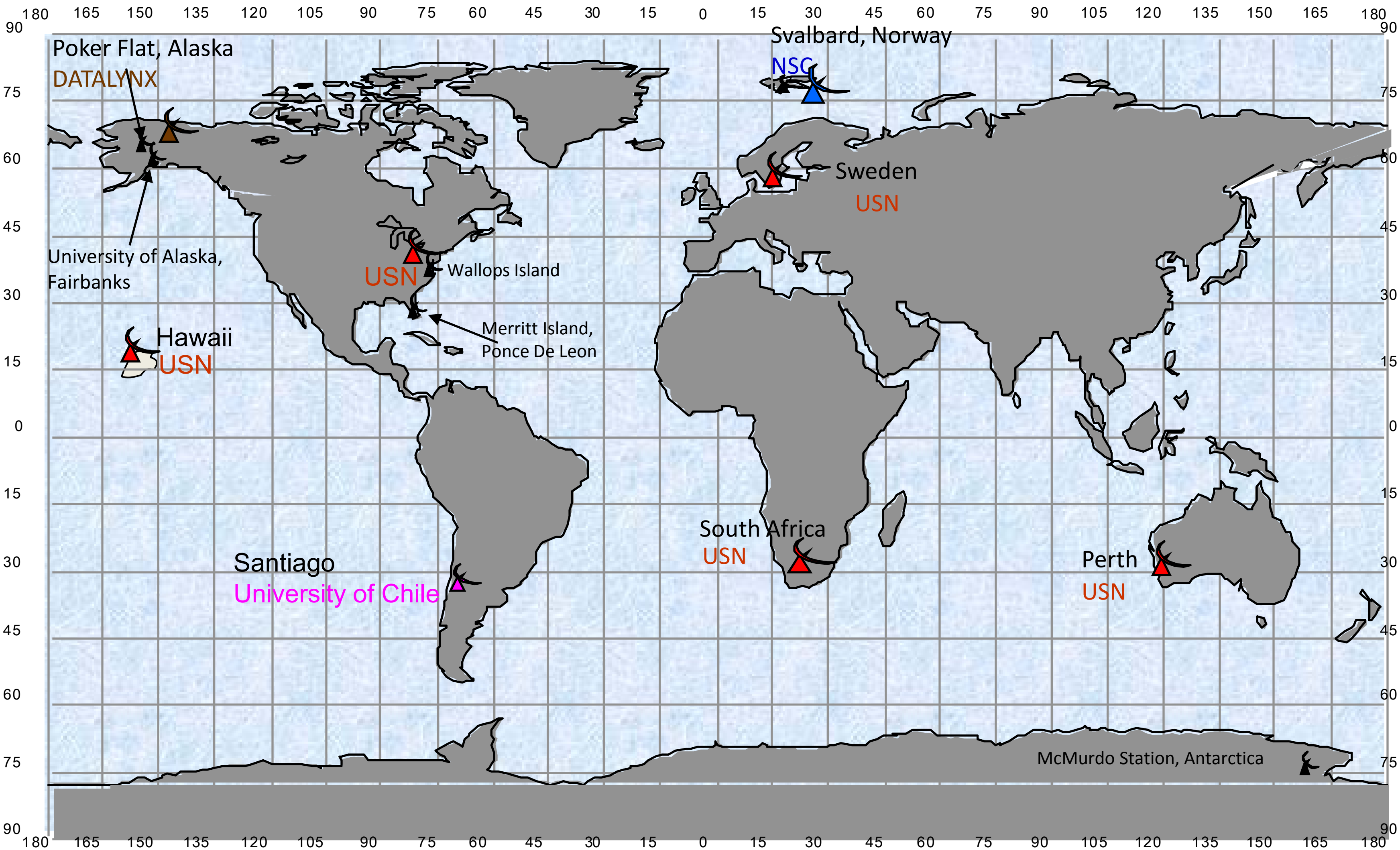
- 10 to 18 meter antennas on the Earth



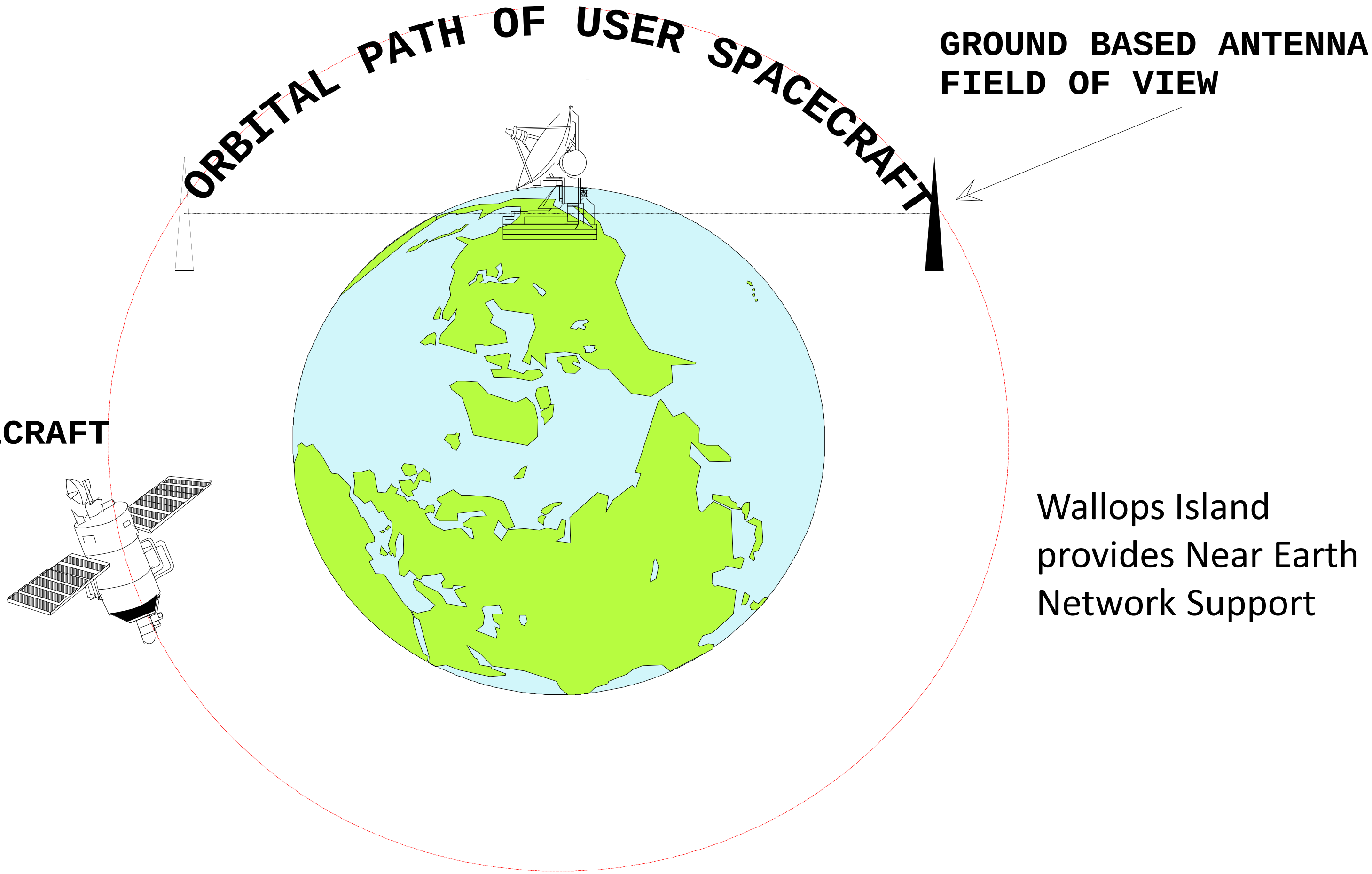
View looking down on the Earth's North Pole

Together they provide nearly continuous coverage across the Solar System!

Near Earth Orbit Ground Network



Near Earth Network Support Limits

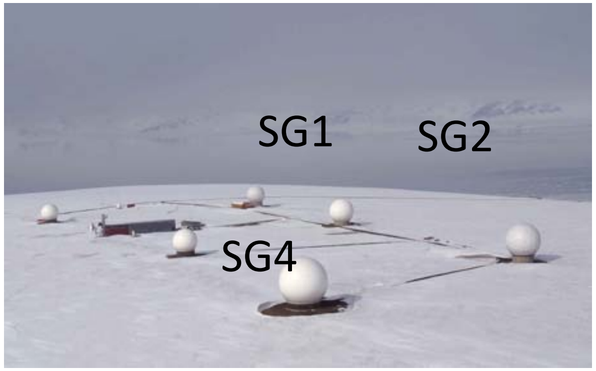


Wallops Island provides Near Earth Network Support

CAN ONLY SUPPORT UP TO 20% OF USER ORBIT, UNDER IDEAL CONDITIONS.
MANY ORBITS GO UNSUPPORTED OR HAVE VERY LIMITED SUPPORT.
RESPONSE TO USER SPACECRAFT EMERGENCIES DEPENDENT ON ORBIT POSITION.
DATA RATES LIMITED.

Near Earth Network Resources

SGS, Longyearbyen,
Spitzbergen, Norway



Svalbard Antennas

WGS, Wallops Flight Facility
Wallops Island, Virginia

McMurdo Ground Station

Commercial Network Support

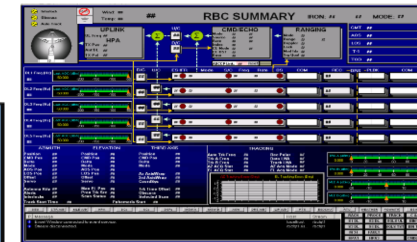
USN Dongara Australia Ground Station

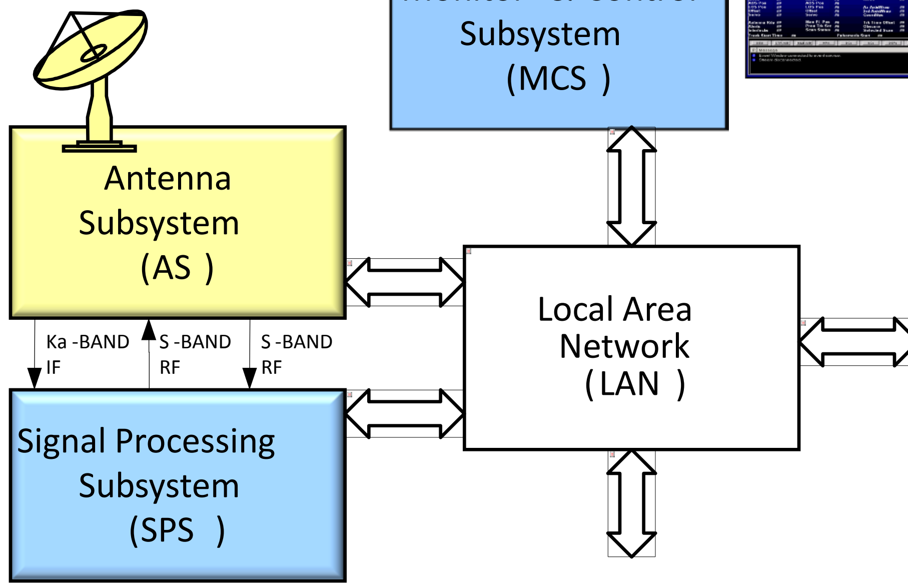
USN South Point, Hawaii Ground Station

WS1 Subsystems

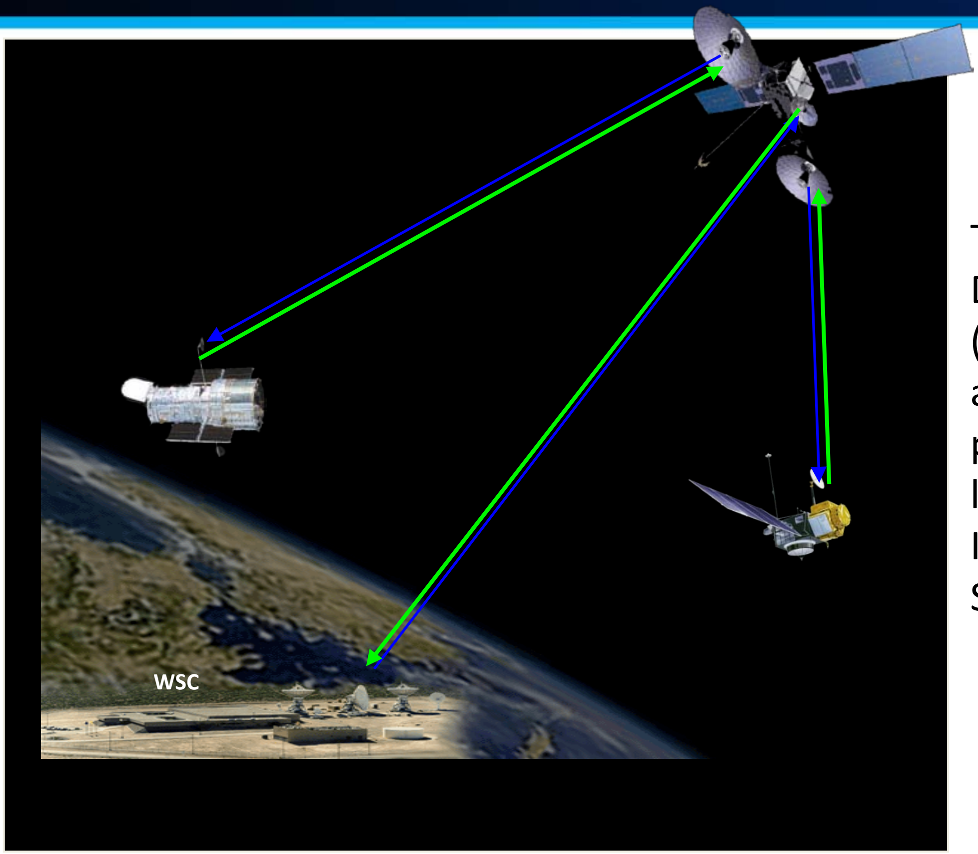
Prime LRO science downlink station

Four main subsystems: AS, SPS, MCS, and LAN





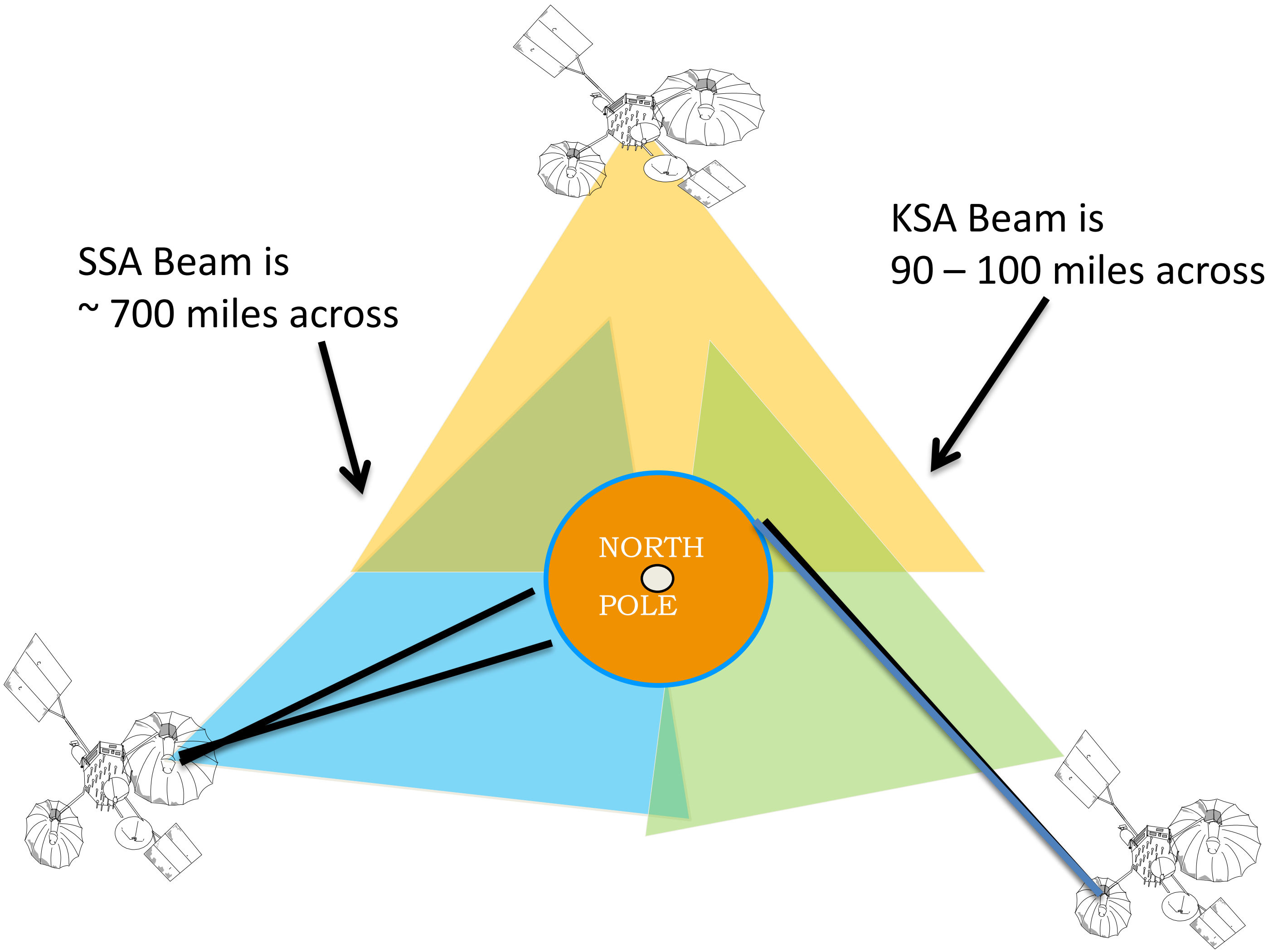
Space Network (TDRSS) Concept



The Tracking and Data Relay Satellite (TDRS) provides an analog, radio relay platform which is located in space, thus It provides a Space Network (SN).

Provide communications, data relay, and tracking services for Low Earth Orbiting (LEO) satellites, Human Space Flight, Space Shuttle, ISS, Expendable Launch Vehicles (ELV), and Scientific Customers.

Space Network (TDRSS) Concept



Space Network
Space Segment

TDRS F-1 through F-7

- The most complex communications satellite ever build at that time
- Single access S-Band & Ku-Band services and Multiple Access system
- 10 year design life
- Series launched from 1983 - 1995
  - Original series still in operation
  - TDRS-B lost with the Challenger
  - TDRS 1 retired this past year

TDRS F-8 through F-10

- Backwards compatible S-Band and Ku-Band services.
- New Ka-Band Service, up to 1.2 Gbps Capability
- Enhanced Multiple Access system
- Increased on-orbit autonomy
- 15 year design life
- Series launched from 2000 - 2002

•TDRS K & L In development, LRD 2012

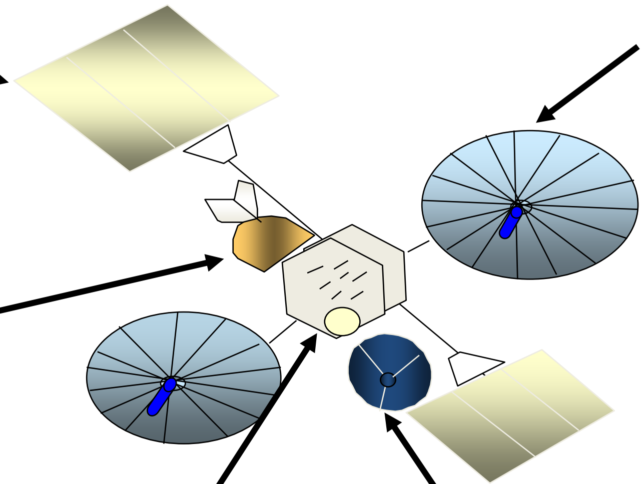
First Generation TDRS F-1 through F-7

Second Generation TDRS F-8 through F-10

Space Segment: Tracking and Data Relay Satellite (F1 - F7)

Solar array
Power output is approximately 1800 watts

Omni Antenna (S-band) and Solar Sail



Single Access Antenna
Dual frequency communications and tracking functions:
- S-band TDRSS (SSA)
- Ku-band TDRSS (KuSA)
- Ku-band auto-tracking

4.9 meter shaped reflector assembly
SA equipment compartment mounted behind reflector
Two axis gimballing

Multiple Access Antenna
30 helices:
- 12 diplexers for transmit
- 30 receive body mounted

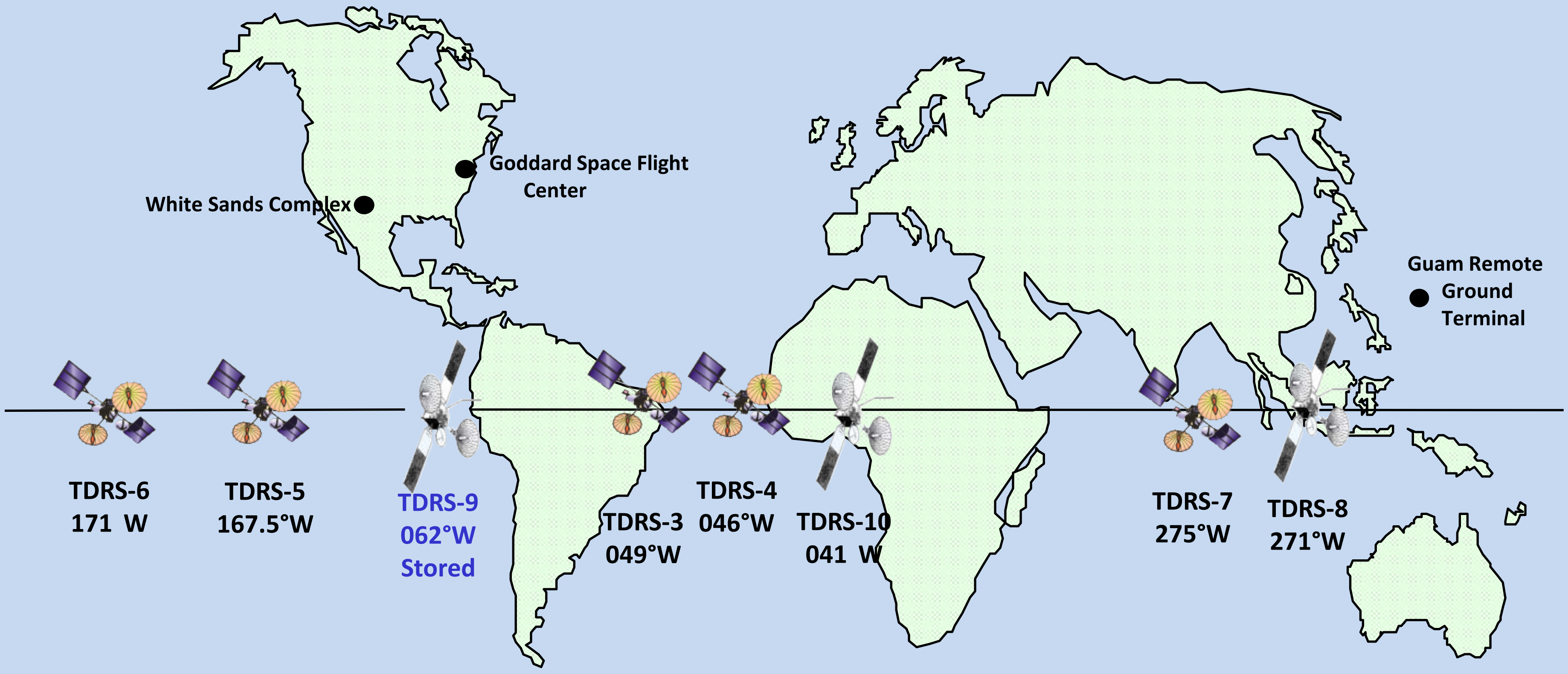
Single commanded beam, transmit
20 adapted beams for receive
Ground implemented receive function

Space-to-Ground-Link Antenna
TDRS downlink
2.0 meter parabolic reflector
Dual orthogonal linear polarization TDRS:
- single horn feed
- orthomode transducer

Two axis gimballed

- Forward (FWD): link from TDRSS Ground Station through TDRS to Customer Spacecraft
- Return (RTN): link from Customer Spacecraft through TDRS to TDRSS Ground Station

Present TDRSS Constellation



In a typical month the SN supports approximately 10,000 scheduled customer service events.

SN Ground Segment

White Sands Ground Terminal (WSGT) and the Second TDRSS Ground Terminal (STGT).

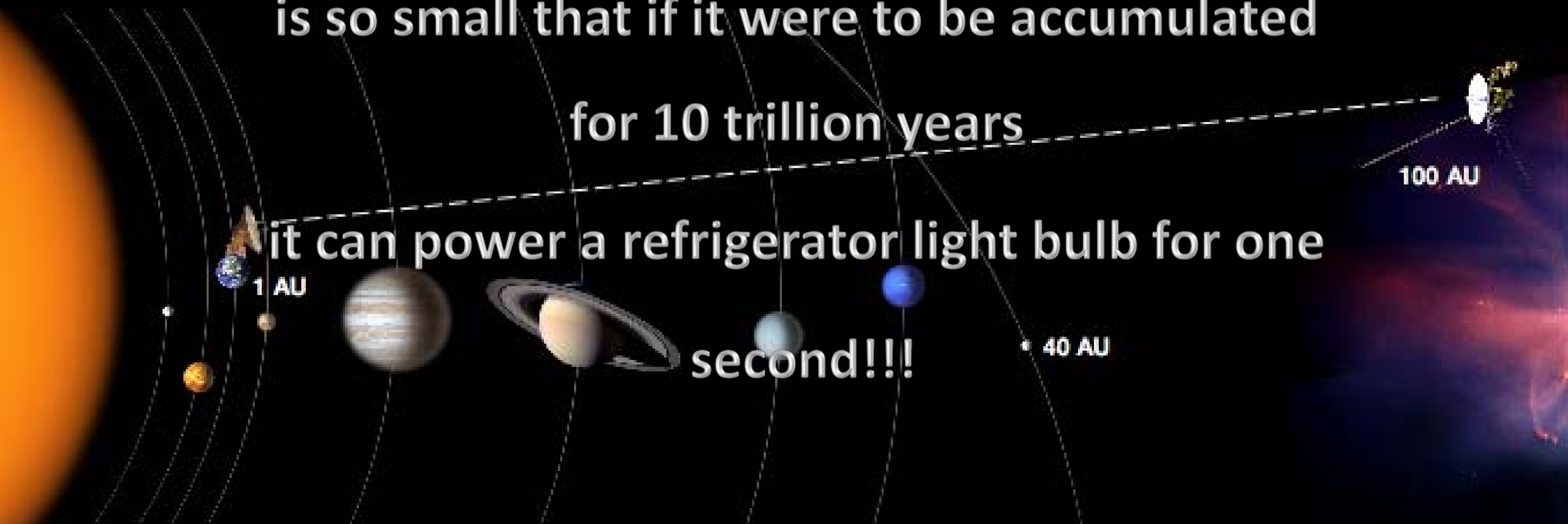
Guam Remote Ground Terminal (GRGT). The GRGT allows for the closure of the the Zone of Exclusion.

Deep Space Communications

Deep Space Network 70m antennas are in Canberra, Goldstone, and Madrid.

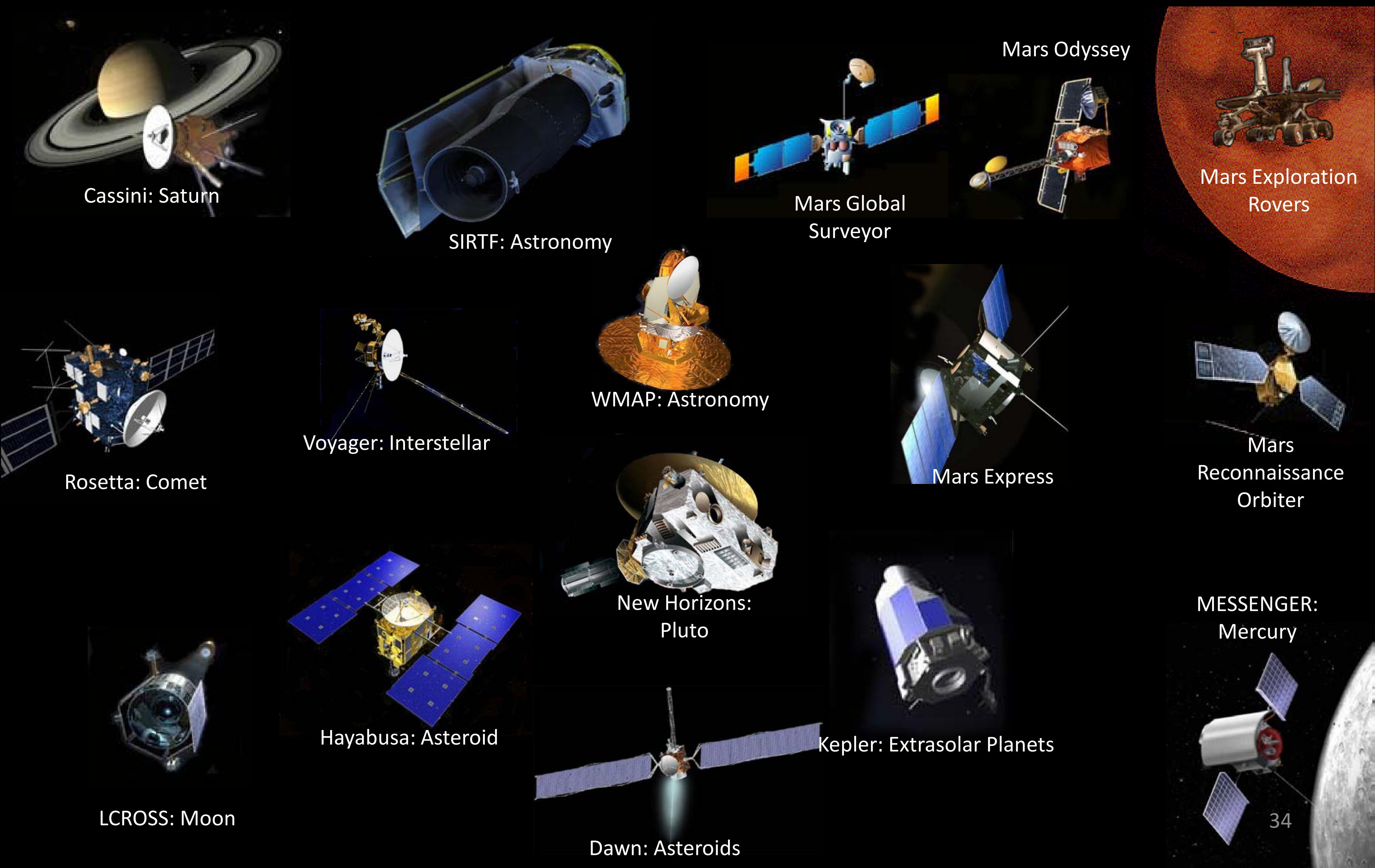
The Challenge of Deep Space
The Ultimate in Long Distance Communications

The power received by the 70m DSN antenna from Voyager is so small that if it were to be accumulated for 10 trillion years it can power a refrigerator light bulb for one second!!!



can you hear me now?

Some Current Deep Space Missions

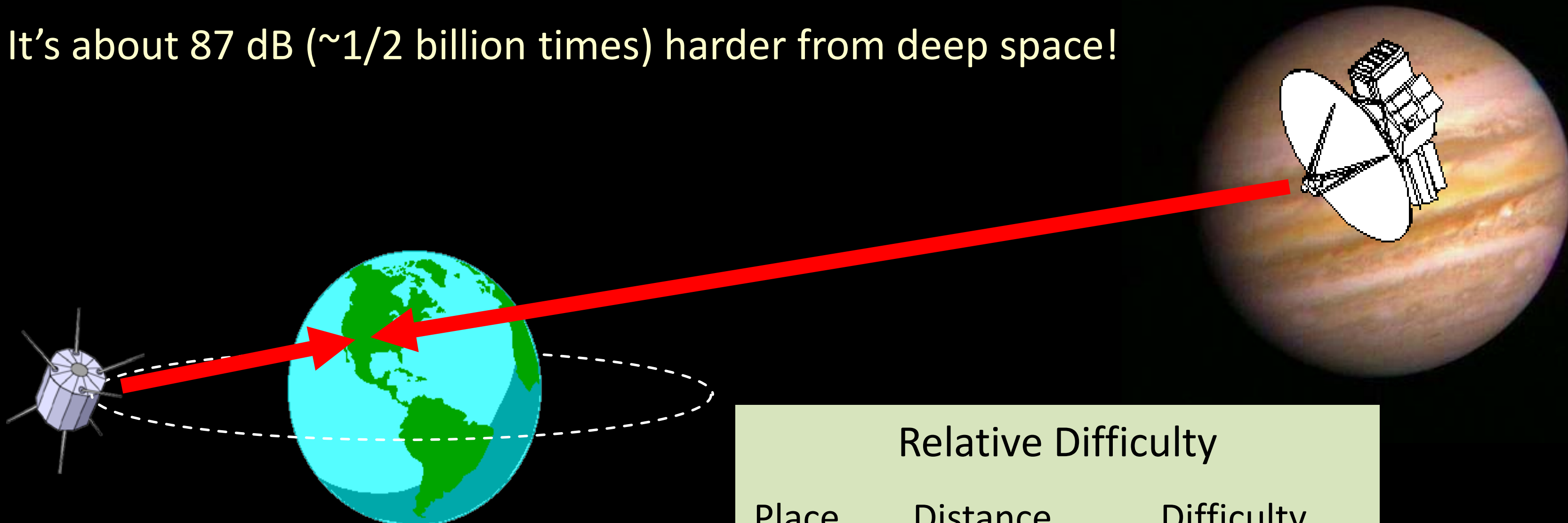


Why is Deep Space Communications Difficult?

Communications performance decreases as the square of the distance.

Jupiter is nearly 1 *billion* km away, while a GEO Earth communications satellite is only about 40 *thousand* km away

– It's about 87 dB (~1/2 billion times) harder from deep space!

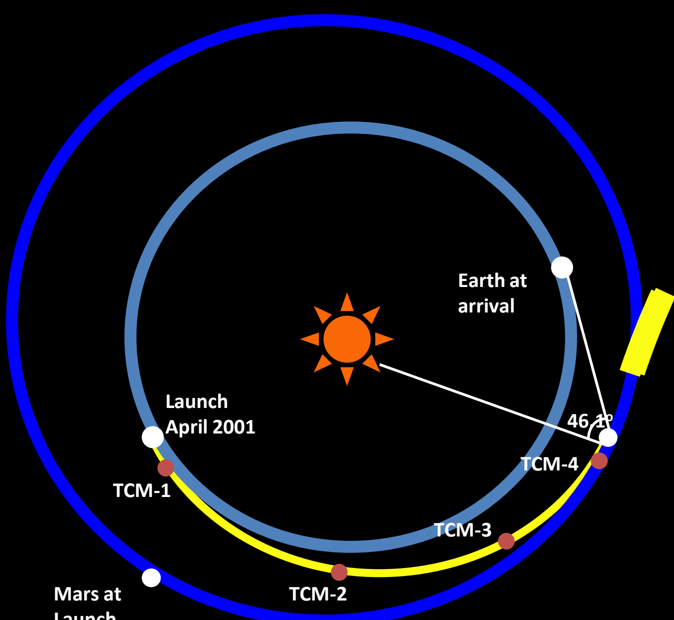


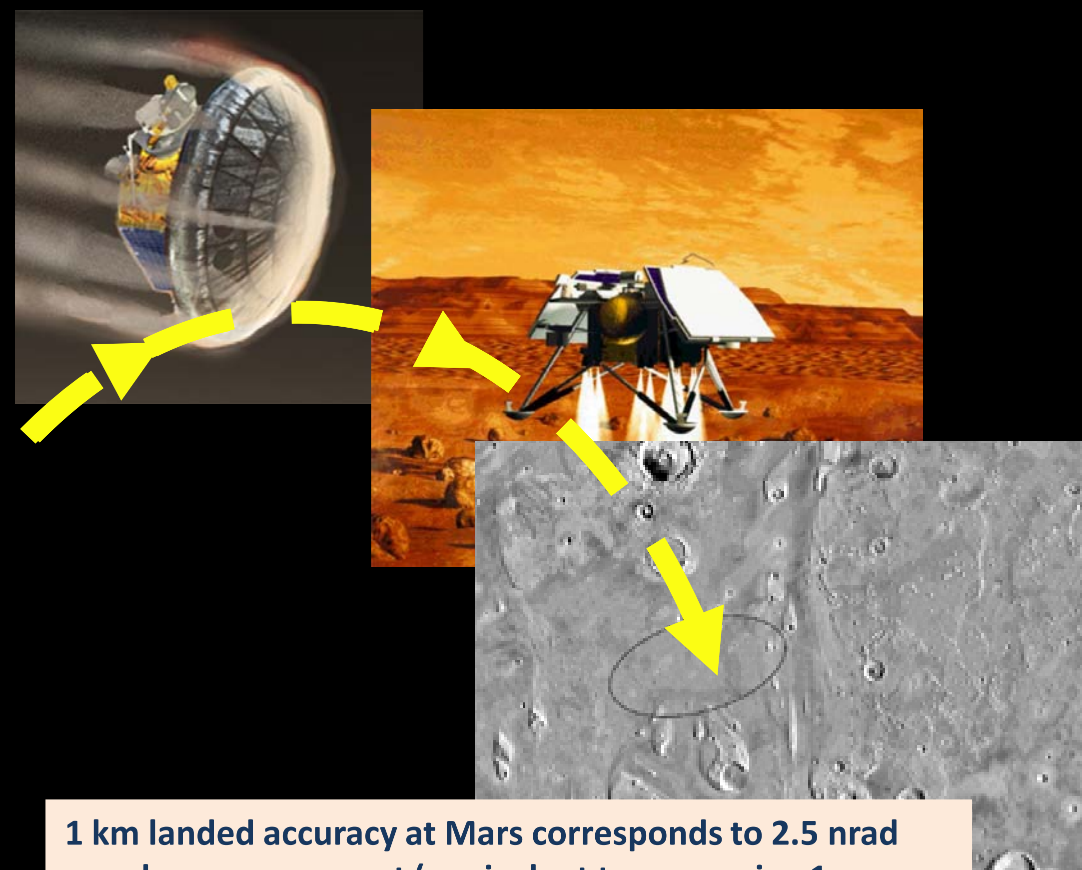
Relative Difficulty

Place	Distance	Difficulty
Geo	$4x10^4$ km	Baseline
Moon	$4x10^5$ km	100
Mars	$3x10^8$ km	$5.6x10^7$
Jupiter	$8x10^8$ km	$4.0x10^8$
Pluto	$5x10^9$ km	$1.6x10^{10}$

Why is Deep Space Navigation Difficult?

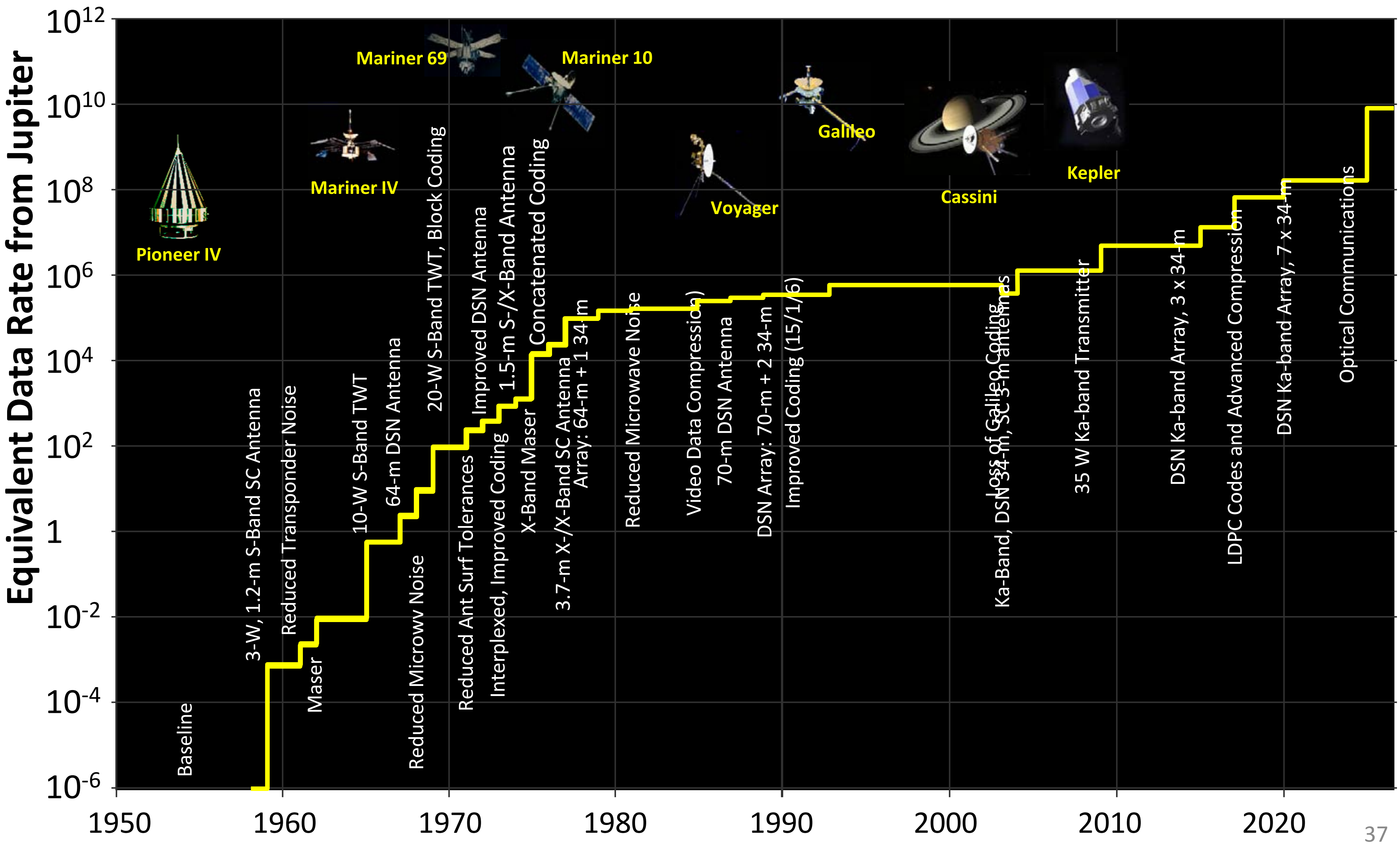
- Deep space missions use communication links to help with navigation
- Very accurate positions needed over very large distances
- Also must “navigate” the target bodies!



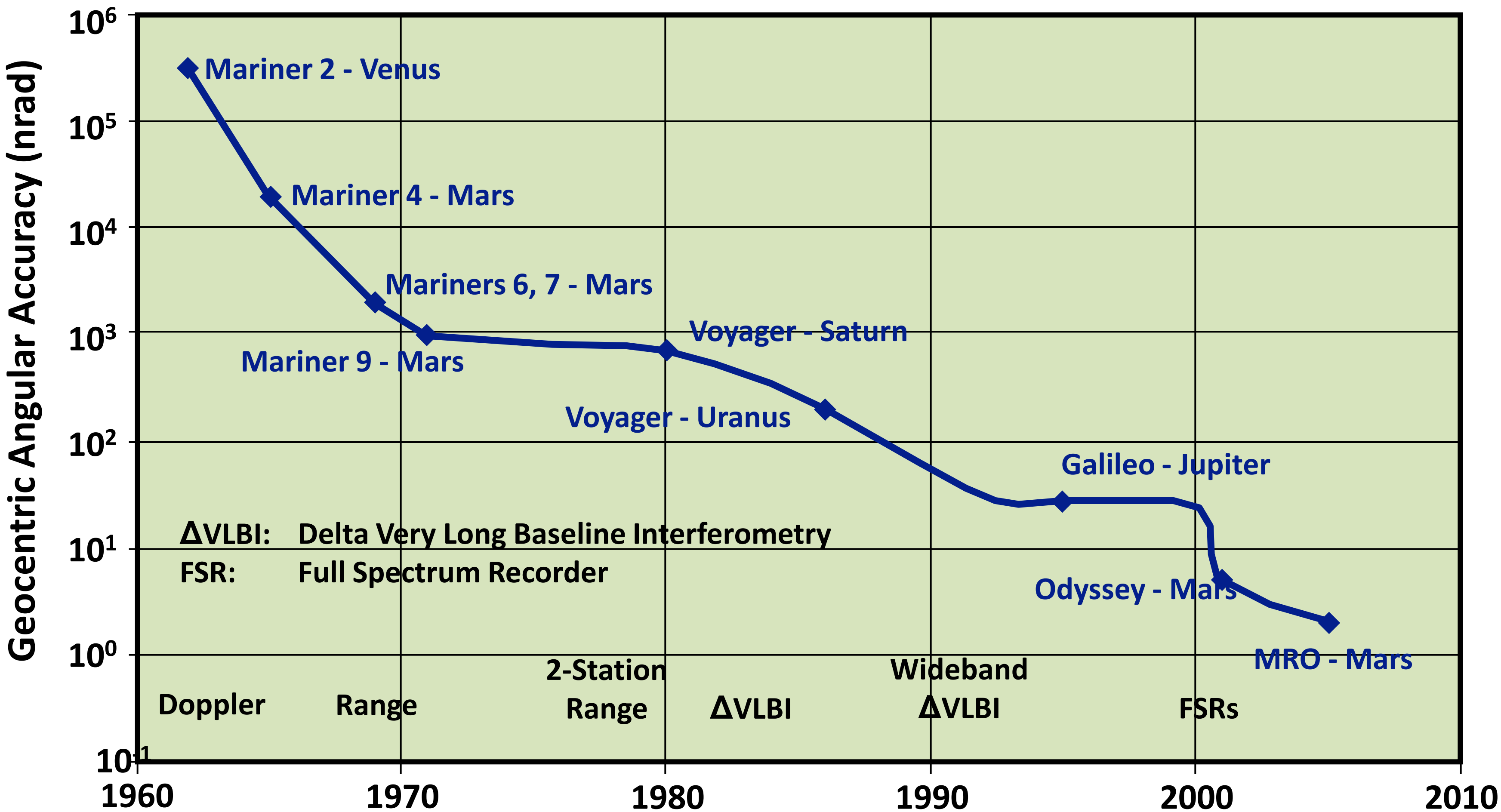


1 km landed accuracy at Mars corresponds to 2.5 nrad angular measurement (equivalent to measuring 1 cm items in Washington DC by observing from L.A.)

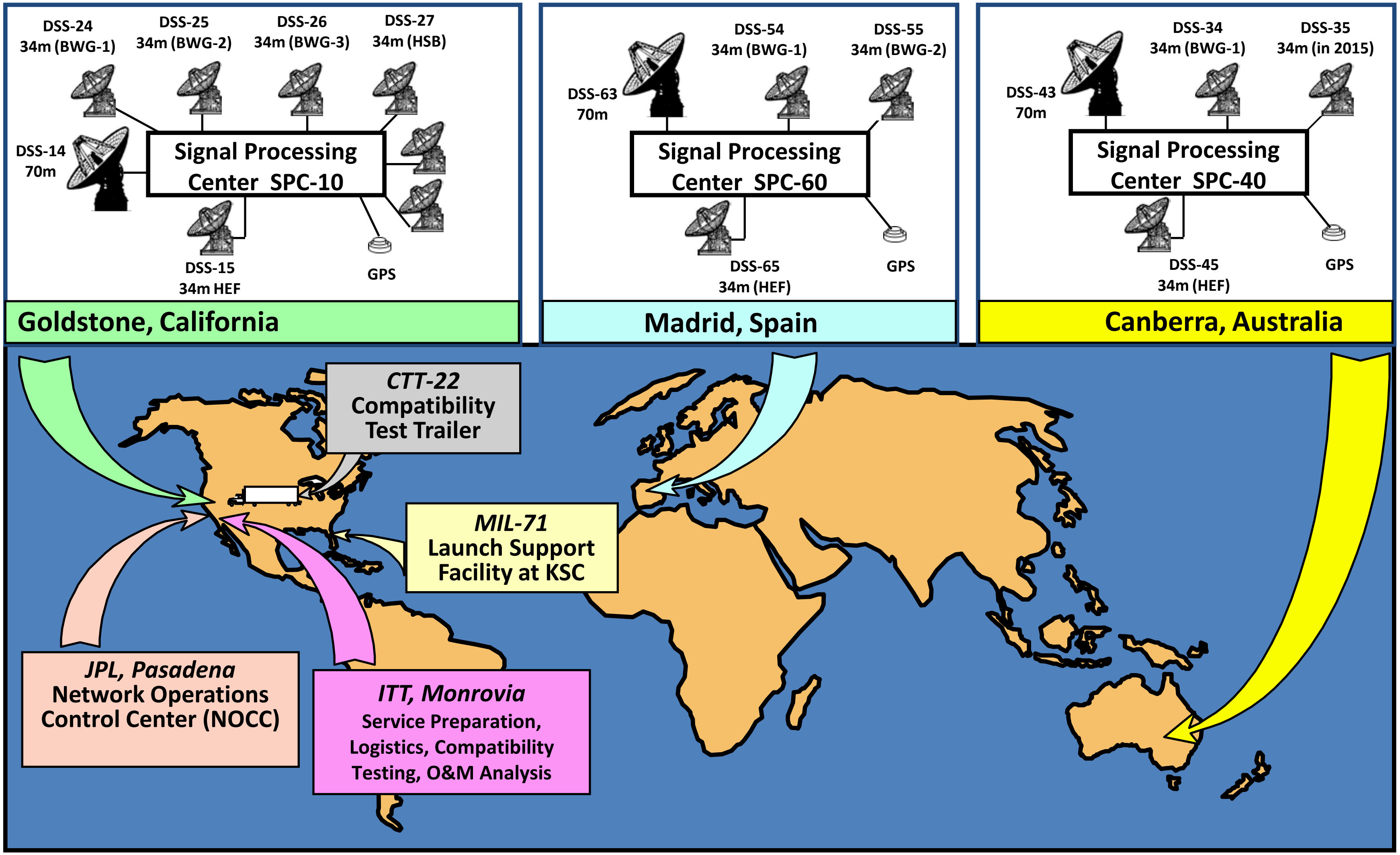
Deep Space Telemetry



Deep Space Angular Tracking

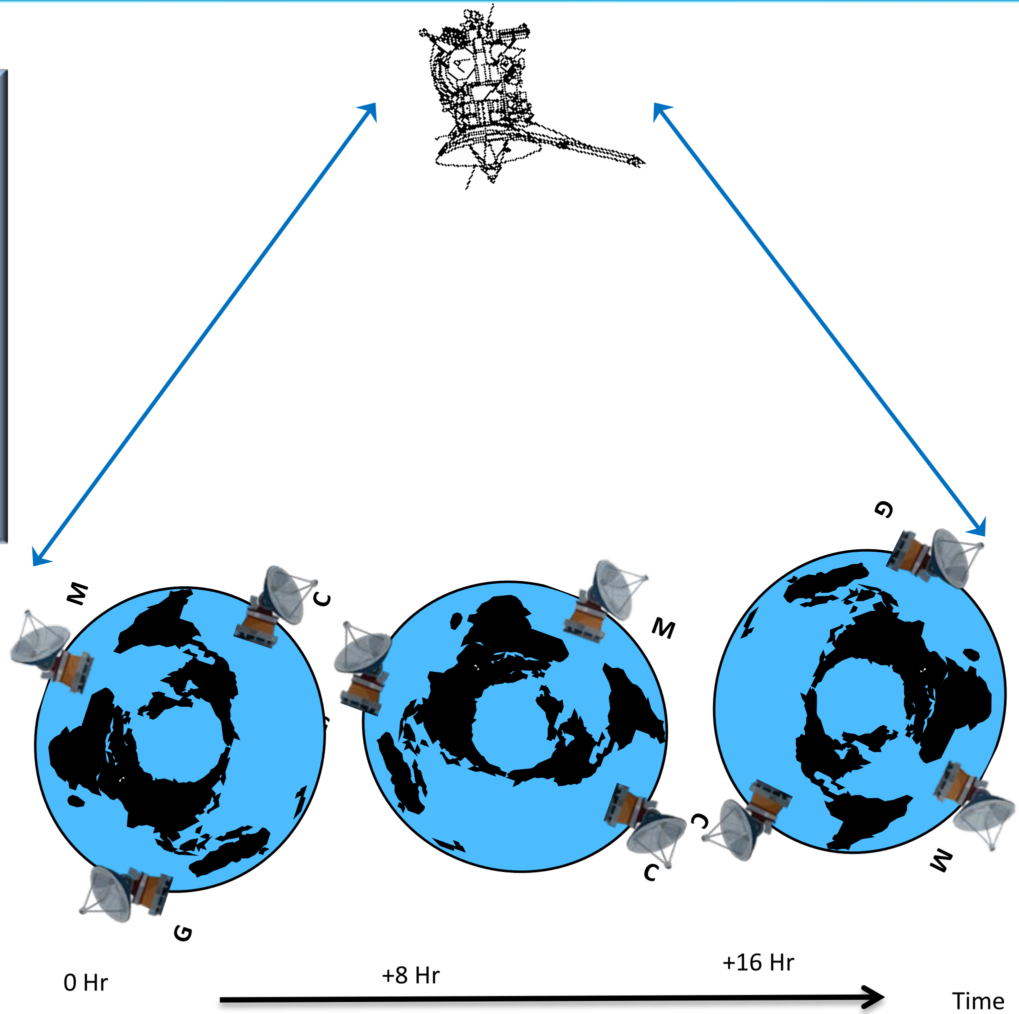


DSN Facilities



Continuous Tracking of a Deep Space Spacecraft

As the earth rotates, the spacecraft signal is picked up at one location and tracked from rise to set when the next location comes into view. Therefore, with 3 locations can continuously track the spacecraft.

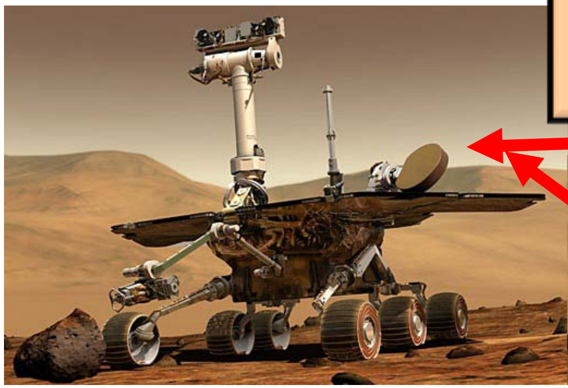


Early spacecraft did not have (much) storage, hence transmitted data continuously to the ground

When two stations can see the s/c at the same time, allows for **VLBI** – long distance between the antennas

Madrid Deep Space Communications Complex
Spain

Mars Relay Example



MER 0.3m Antenna
~55 dB_{ic} Gain

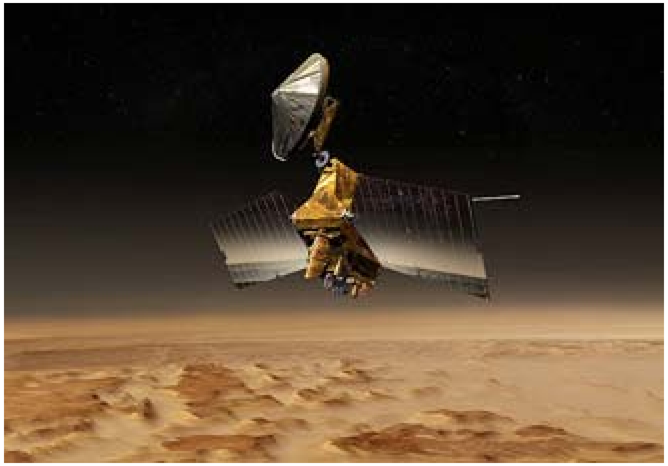
MGS 1.5m Antenna
~70 dB_{ic} Gain

Arriving on Mars in 2004, the Spirit and Opportunity Mars Exploration Rovers (MER) each had a high gain directional antenna capable of transmitting data either to the Mars Global Surveyor (MGS) satellite in Mars orbit (for relay back to Earth) or directly back to the 70m directional antennas of the DSN.

This flexibility was invaluable since in 2006, the Mars Global Surveyor satellite began to fail.

DSN 70m Antenna
~100 dB_{ic} Gain

International Mars Relay Spacecraft



NASA's Mars Reconnaissance Orbiter

Launched August 12, 2005, is on a search for evidence that water persisted on the surface of Mars for a long period of time. While other Mars missions have shown that water flowed across the surface in Mars' history, it remains a mystery whether water was ever around long enough to provide a habitat for life.

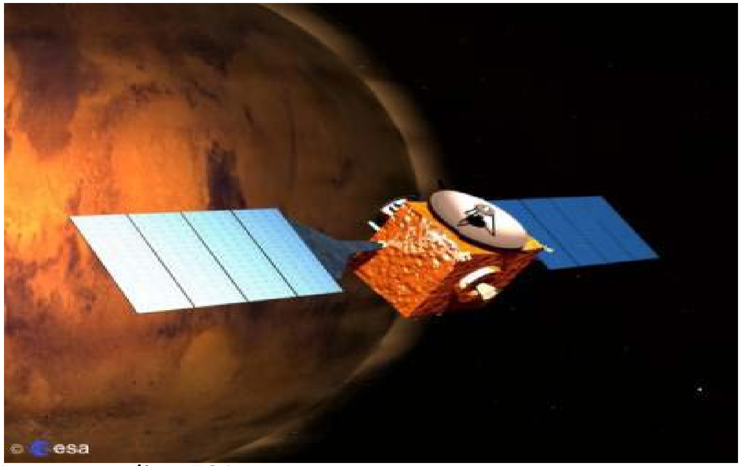


Image credits: ESA

ESA's Mars Express

Launched on June 2, 2003, ESA's Mars Express orbiter will play a key role in an international exploration program spanning the next two decades.

Both vehicles serve as internationally interoperable data relays.
MAVEN to be added soon!

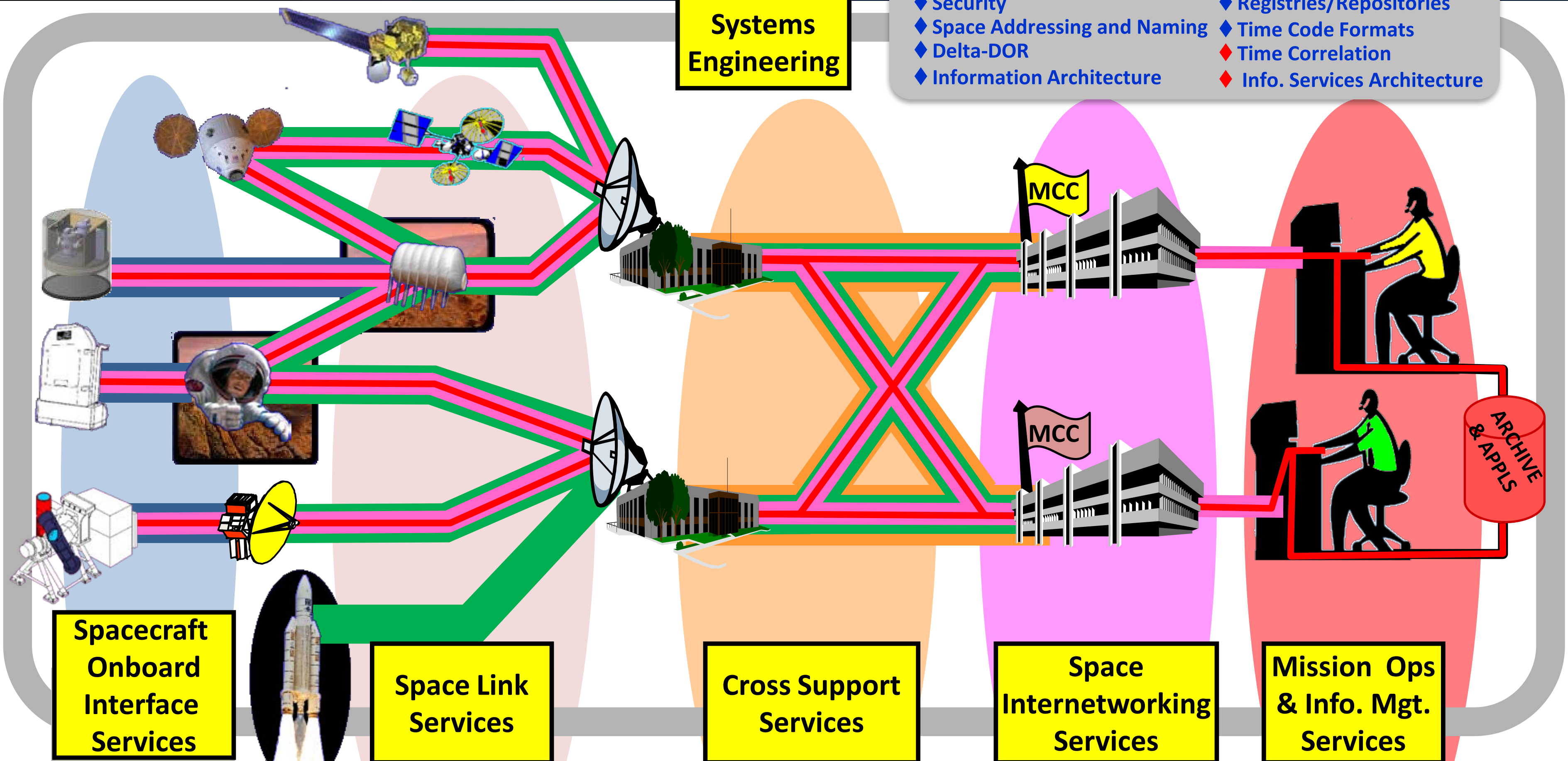
Enabling International Collaboration

SCaN represents NASA at international fora related to space communications and navigation issues. These include:

- Interoperability Plenary (IOP)
- Interagency Operations Advisory Group (IOAG)
- Space Frequency Coordination Group (SFCG)
- Consultative Committee for Space Data Systems (CCSDS)
- International Telecommunications Union (ITU)
- International Committee on Global Navigation Satellite Systems (ICG)
- Other foreign space agencies

End to End Architecture Standards Via CCSDS

- ♦ Systems Architecture
- ♦ Security
- ♦ Space Addressing and Naming
- ♦ Delta-DOR
- ♦ Information Architecture
- ♦ XML utilization
- ♦ Registries/Repositories
- ♦ Time Code Formats
- ♦ Time Correlation (red ♦)
- ♦ Info. Services Architecture (red ♦)



Spacecraft Onboard Interface Services
- ♦ Onboard Subnet. Services
- ♦ Onboard Application Services
- ♦ Wireless WG
- ♦ Plug-n-Play (red ♦)

Space Link Services
- ♦ RF & Modulation
- ♦ Space Link Coding & Sync.
- ♦ Multi/Hyper Data Compress.
- ♦ Space Link Protocols
- ♦ Ranging
- ♦ High Rate Uplink
- ♦ Space Link Security
- ♦ Planetary Surface Comm. (red ♦)
- ♦ Optical Modulation/Coding (red ♦)

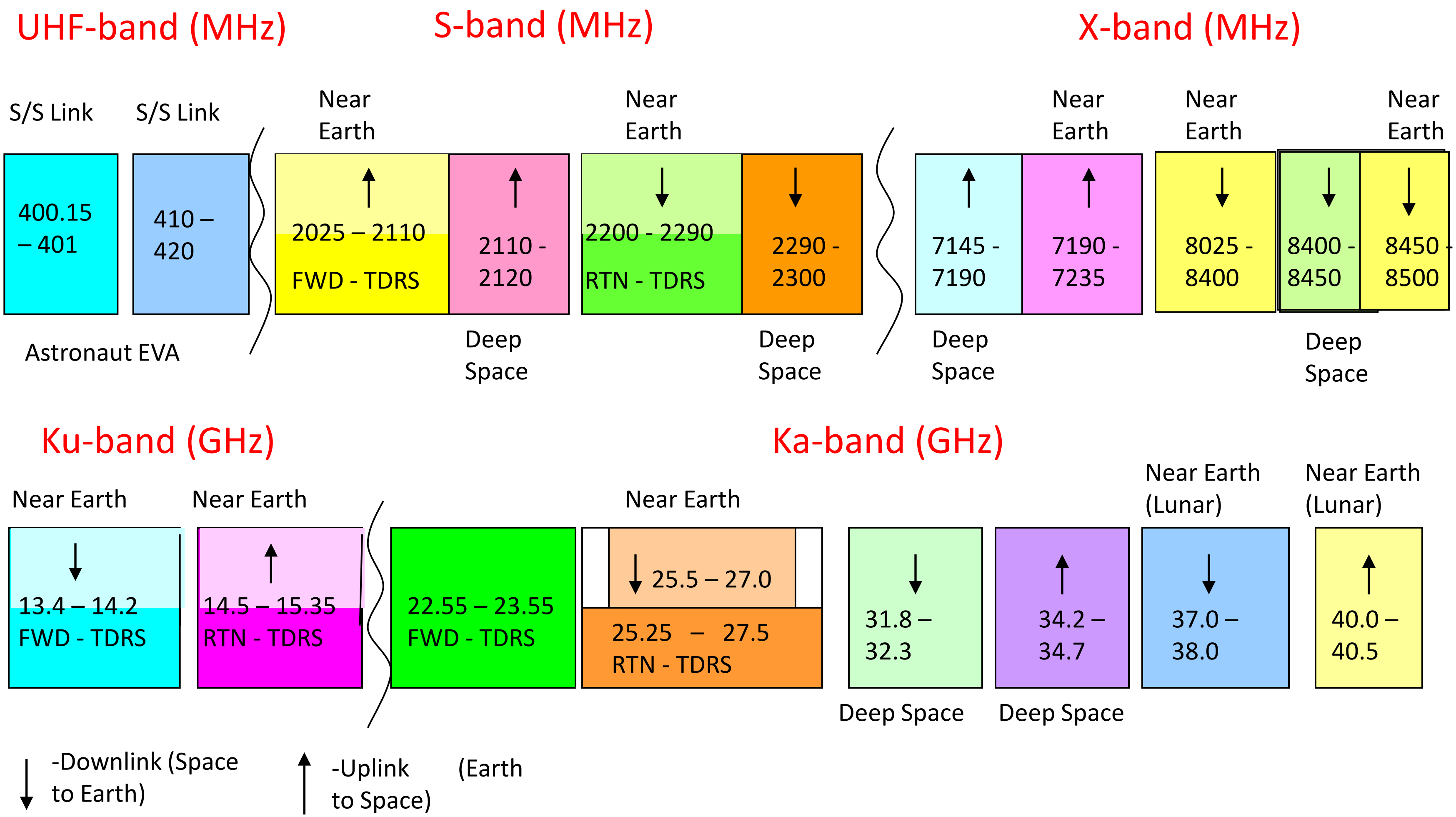
Cross Support Services
- ♦ CS Service Management
- ♦ CS Transfer Services
- ♦ Cross Support Architecture
- ♦ CCSDS Reference Architecture (red ♦)

Space Internetworking Services
- ♦ Space Packet Protocol
- ♦ Asynch Messaging
- ♦ IP-over-CCSDS Links
- ♦ Motion Imagery & Apps
- ♦ Delay Tolerant Networking
- ♦ Voice

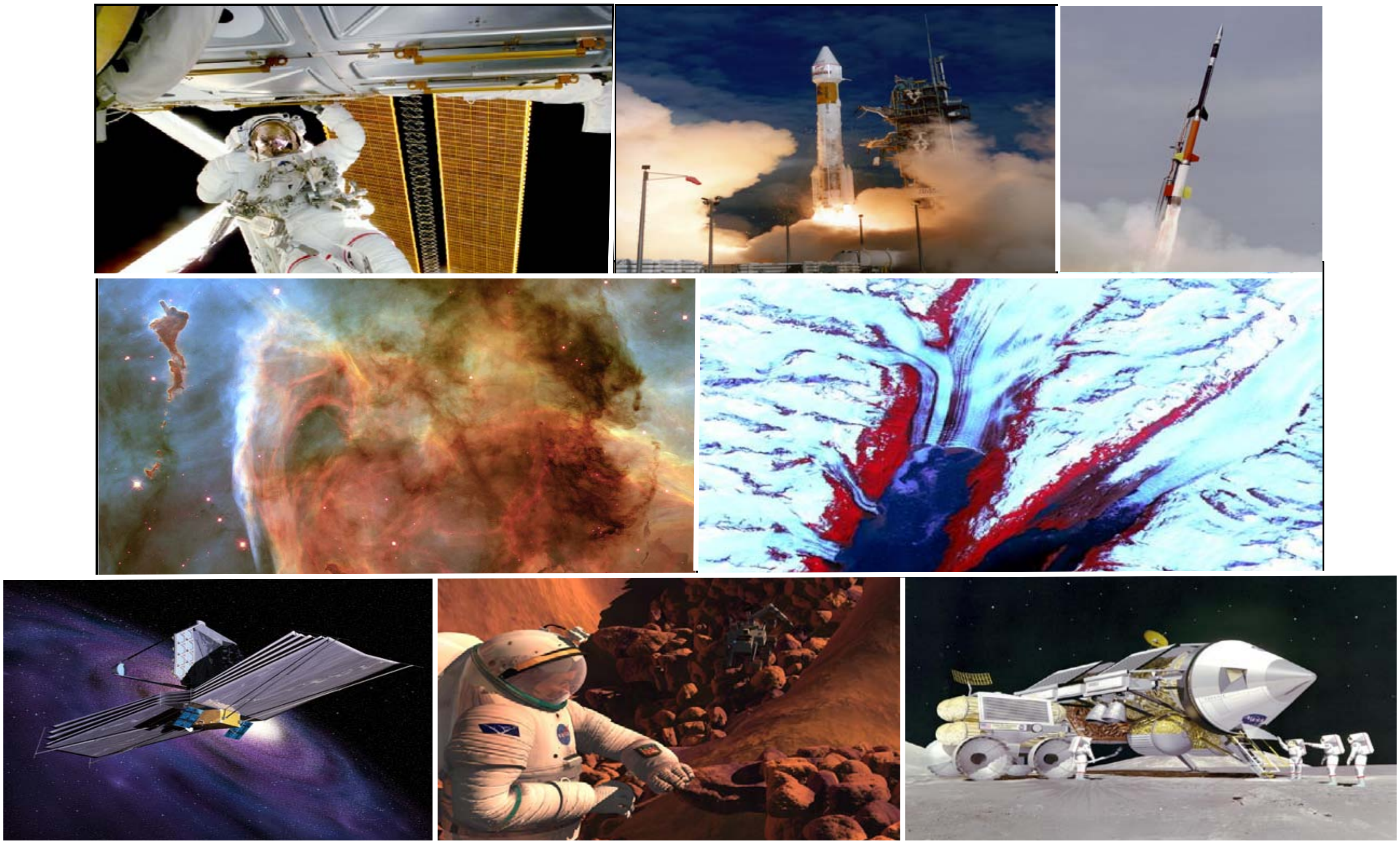
Mission Ops & Info. Mgt. Services
- ♦ Data Archive Ingestion
- ♦ Navigation
- ♦ Info. Pack. & Registries
- ♦ Spacecraft Monitor & Control
- ♦ Digital Repository Audit/Certification

♦ = Studies

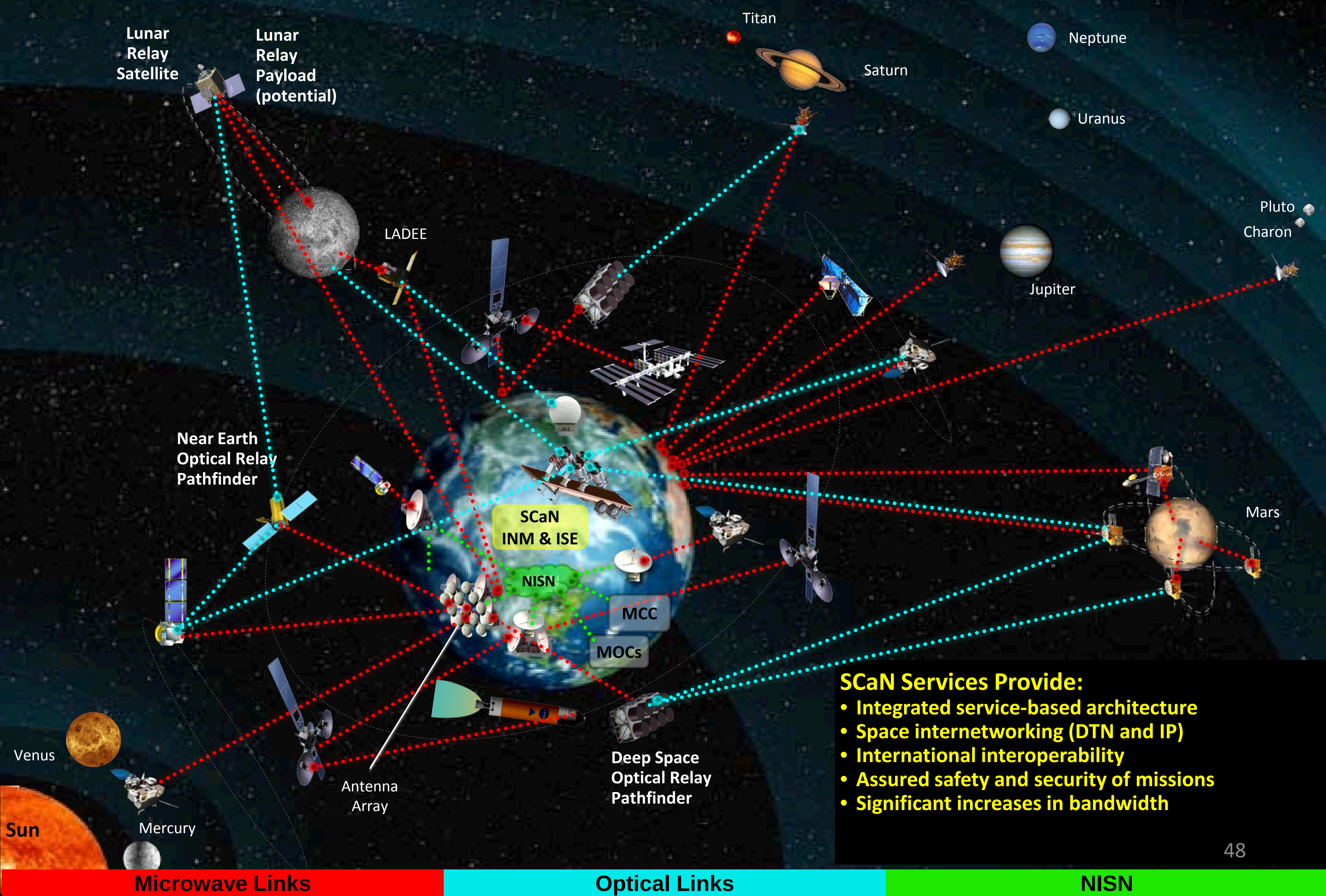
NASA's Most Frequently Used Bands for Communication



Future SCaN Networks Missions



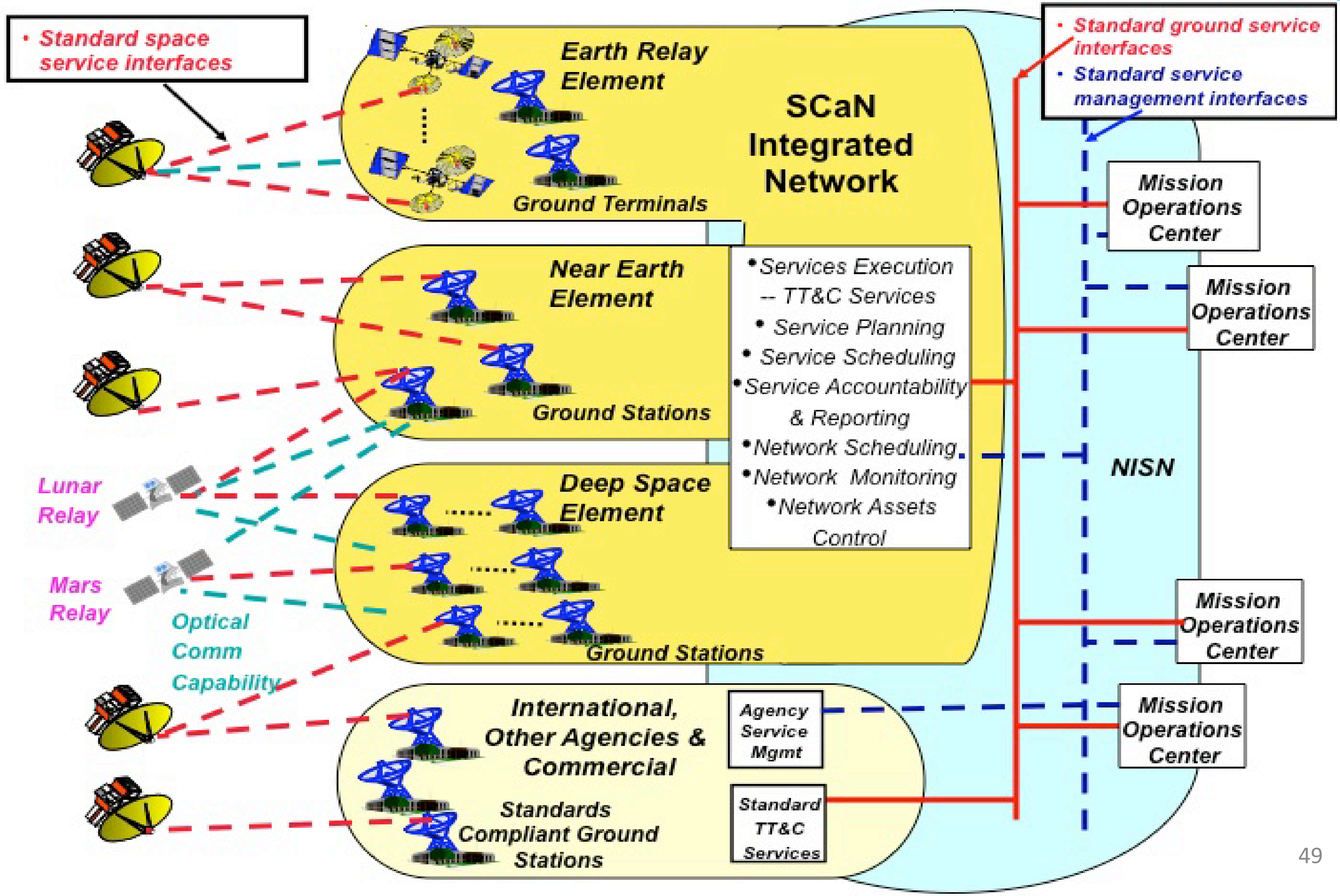
SCaN Notional Integrated Communication Architecture



SCaN Services Provide:

- Integrated service-based architecture
- Space internetworking (DTN and IP)
- International interoperability
- Assured safety and security of missions
- Significant increases in bandwidth

SCaN Integrated Network Service Architecture



Goals of the SCaN Technology Program

- Support the SCaN Vision of the Future as Described in the SCaN Architecture Definition Document

- Enable Future NASA Missions with New Communication and Navigation Technology that Enhances their Science Return

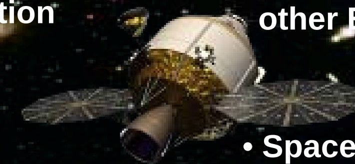
SCaN Communications and Navigation Technology Themes

- Optical Communications
- Antenna Arraying Technology – Receive and Transmit
- Advanced Antenna Technology
- Advanced Networking Technology
- Spacecraft RF Transmitter/Receiver Technology
- Software Defined Radio
- Spacecraft Antenna Technology
- Spectrum Efficient Technology
- Ka-band Atmospheric Calibration
- Position, Navigation, and Time
- Space-Based Range Technology
- Uplink Arraying

CoNNeCT Provides Broad Relevancy to NASA Programs and Missions

- Ka/S band System for Lunar Relay

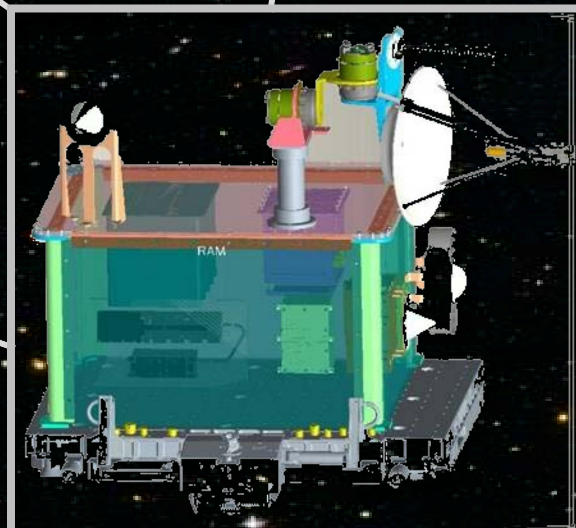
- GPS L1, L2c, L5 development and validation
- GPS TASS validation



- S band rates for CEV ops testing
- Orion radio prototypes
- Potential SDRs for other Ex applications

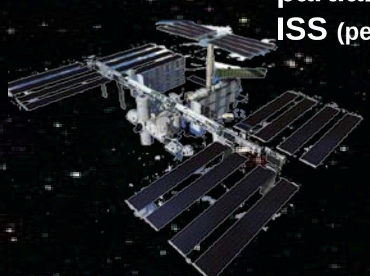
- Space based networking, including DTN

- SDRs for Fifth Gen TDRSS User Transponder
- Ka/S System for TDRSS K, L function, performance validation



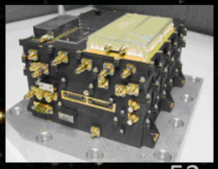
- Potential SDRs for Space Based Range

- Potential SDRs for lunar landers, rovers, EVA



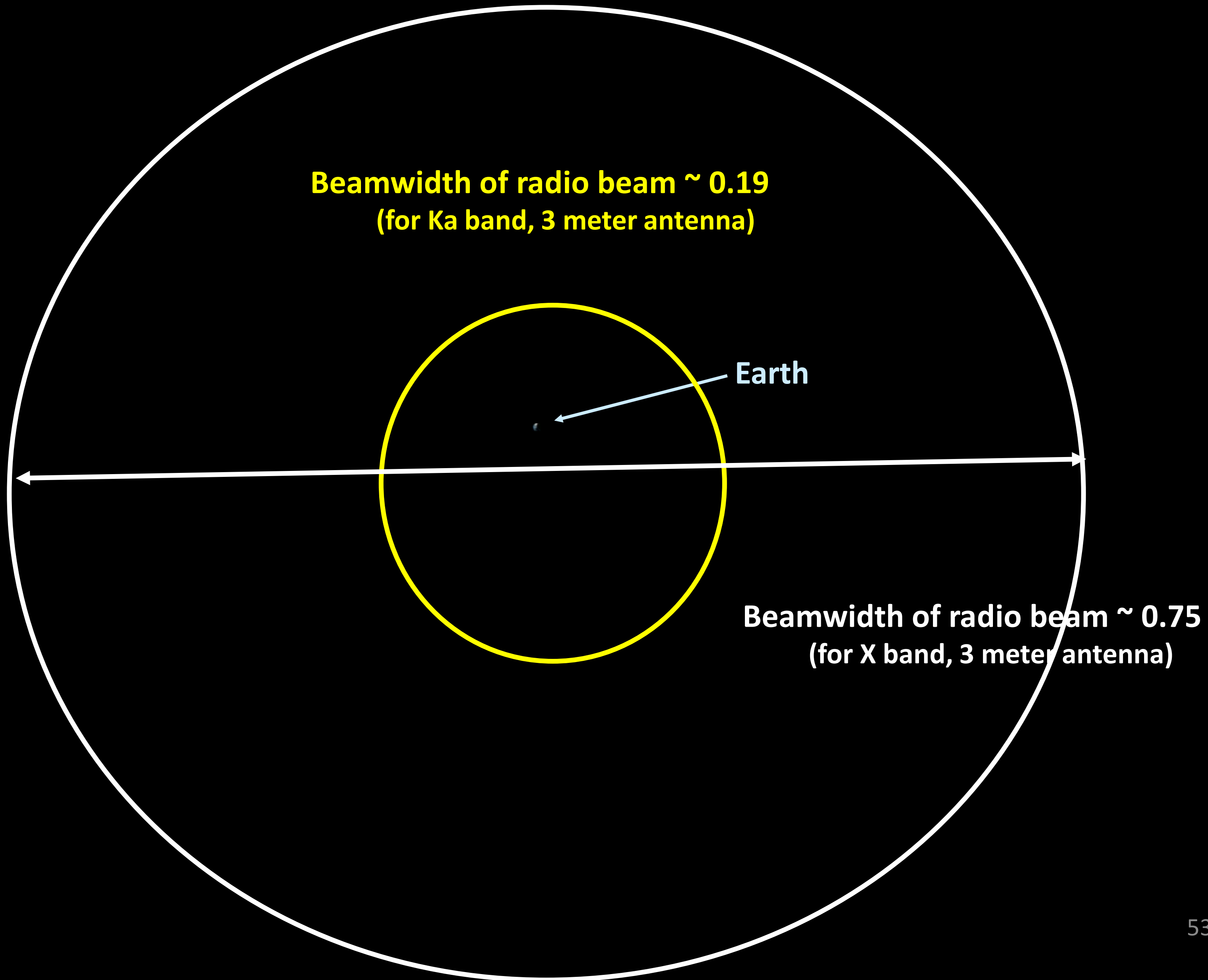
- Ka System HRDL partial backup for ISS (pending CR)

Connect Payload with Ka, S, L band, and JPL Electra, GD Starlite, and Harris SDRs

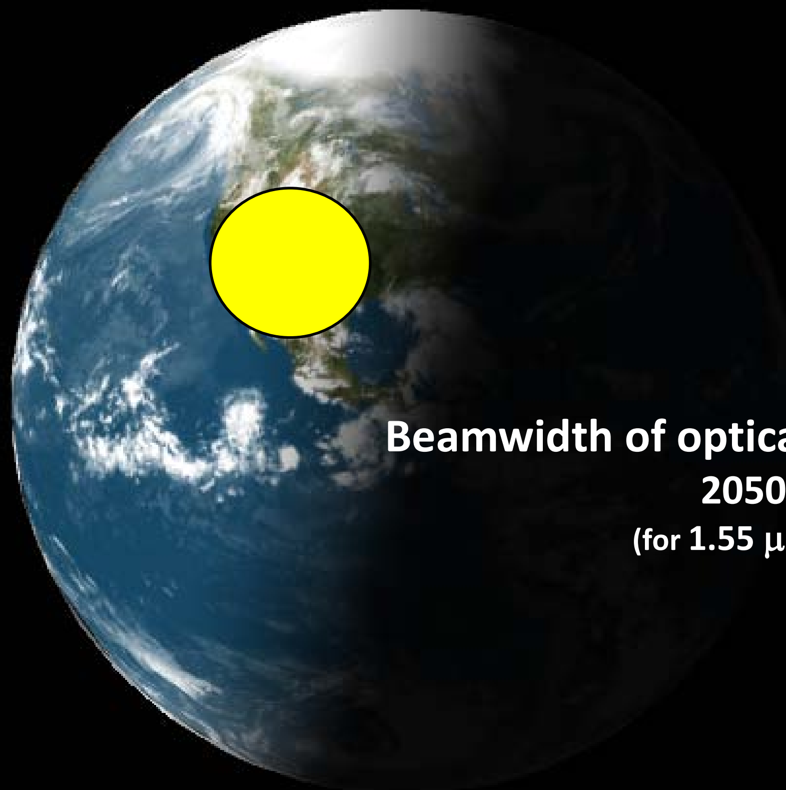


- SDR/STRS technology advancement to TRL-7

Beamwidth Example: Radio from Mars



Beamwidth Example: Optical from Mars



Beamwidth of optical beam ~ 0.00029

2050 Km

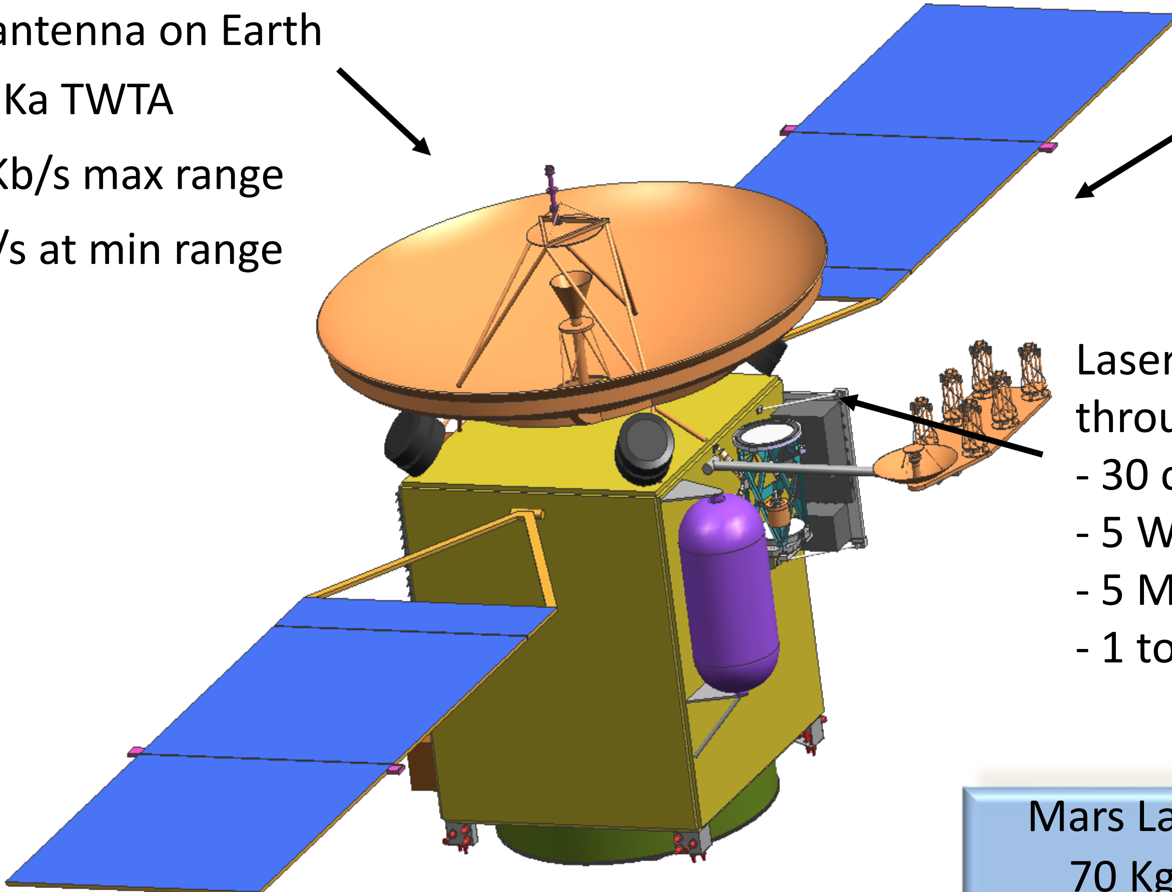
(for 1.55 μm, 0.3 meter)

A much larger percentage of transmitted energy goes into the receiver

MARS Laser Communication Demo on the 2009 Mars Telecom Orbiter Mission Concept

3m antenna for RF link
34 M antenna on Earth
- 35W Ka TWTA
- 350 Kb/s max range
- 4Mb/s at min range

Gimbaled UHF & X-Band antennas for uplinks from Mars



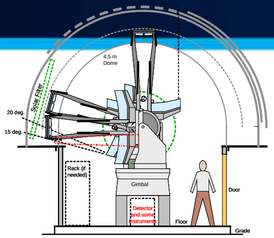
Lasercom terminal looks through hole in antenna
- 30 cm flight aperture
- 5 Watt laser
- 5 M ground aperture
- 1 to 50 Mb/s link

Mars Lasercom Terminal
70 Kg and 150 Watts

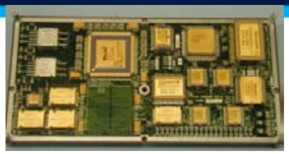
Optical Communications Technology

Objective

- **Develop optical technologies for 10-1200 Megabit per second data links to meet NASA SCaN requirements for 2020 IOC**
  - Low mass and high efficiency implementations are required for deep space optical link scenarios
  - Identify, develop, and validate high ROI ground and flight technologies
  - Create the necessary technical infrastructure to test and validate industry and NASA developed optical communications flight components prior to flight

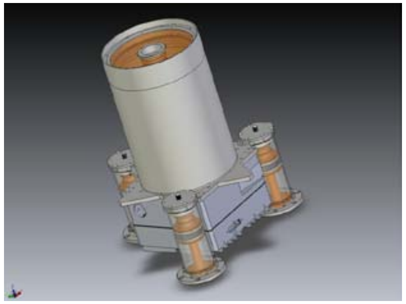


Ground Aperture

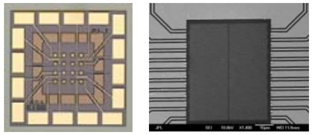


Optical Transceiver Flight Processor

PPM Laser Transmitter

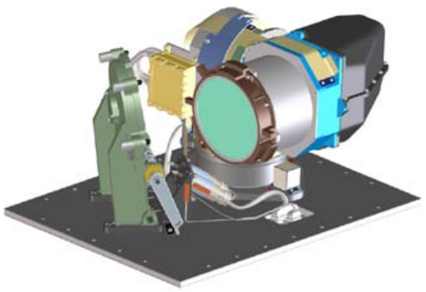


Deep Space Optical Transceiver



Single Photon Detectors

Scalable Receiver/Decoder



Near Earth Ground Terminal

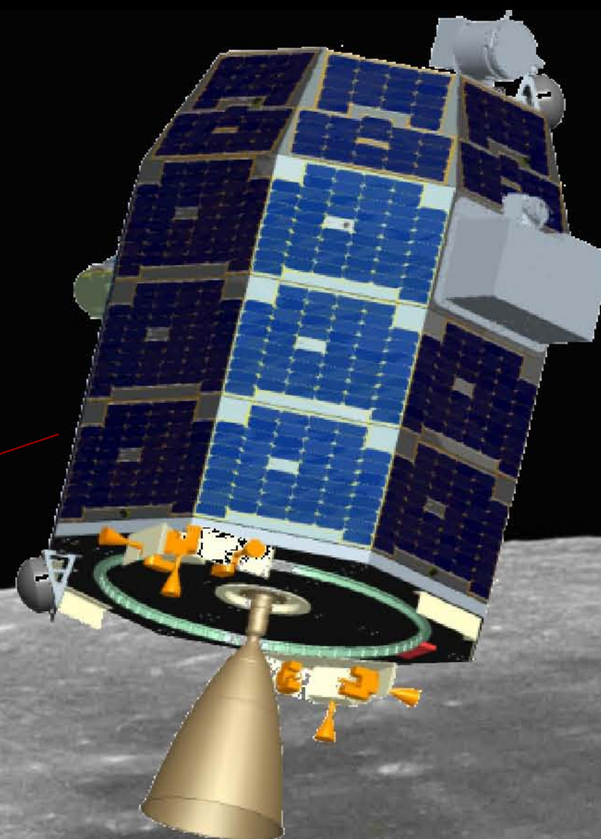
Near Earth Flight Terminal

<u>Some Example Key Challenges:</u>

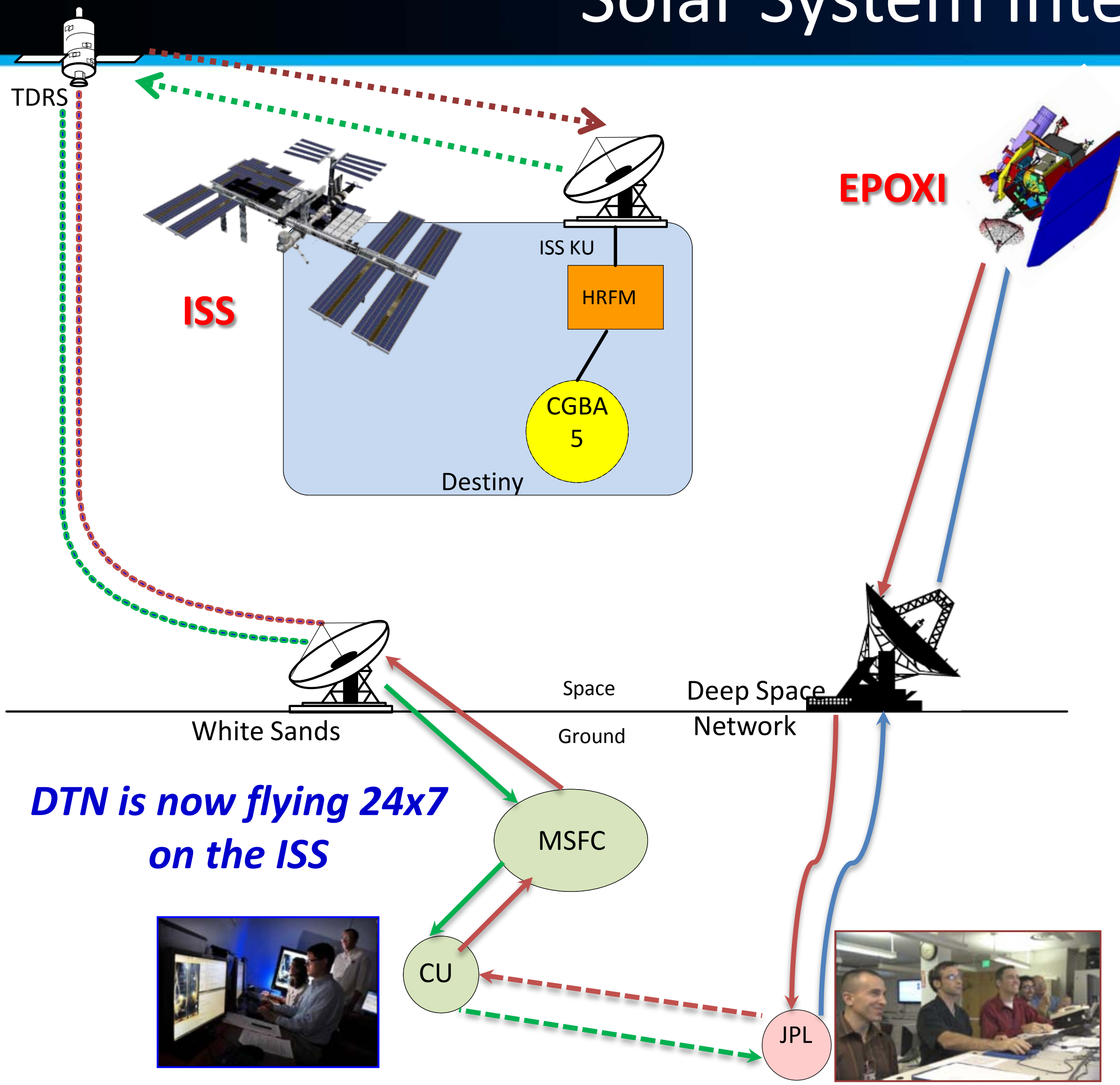
- Sub-Hertz vibration isolator; flight photon counting detector arrays
- Lightweight flight optics; integrated flight photon counting detector arrays with read-out integrated circuit
- Beaconless tracking solutions; high power uplink laser transmitter
- Detector jitter mitigation; efficient narrowband optical filter

Lunar Lasercom Space Terminal (LLST)

- Lunar Lasercom Space Terminal (LLST) to fly on Lunar Atmosphere and Dust Environment Explorer (LADEE)
- Launch Readiness Date: Mar 2013 from Wallops Flight Facility, VA on Minotaur V
  - 1 month transfer
  - 1 month commissioning
    - 250 km orbit
    - LLCD operation (up to 16 hours)
    - S/C and Science payloads checkout
  - 3 months science
    - 50 km orbit
    - 3 science payloads
      - Neutral Mass Spectrometer
      - UV Spectrometer
      - Lunar Dust Experiment



DTN and IP - Enablers of the Solar System Internet



October 2008: "DINET-I"

First fully automatic DTN flight test on Deep Impact/EPOXI in deep space

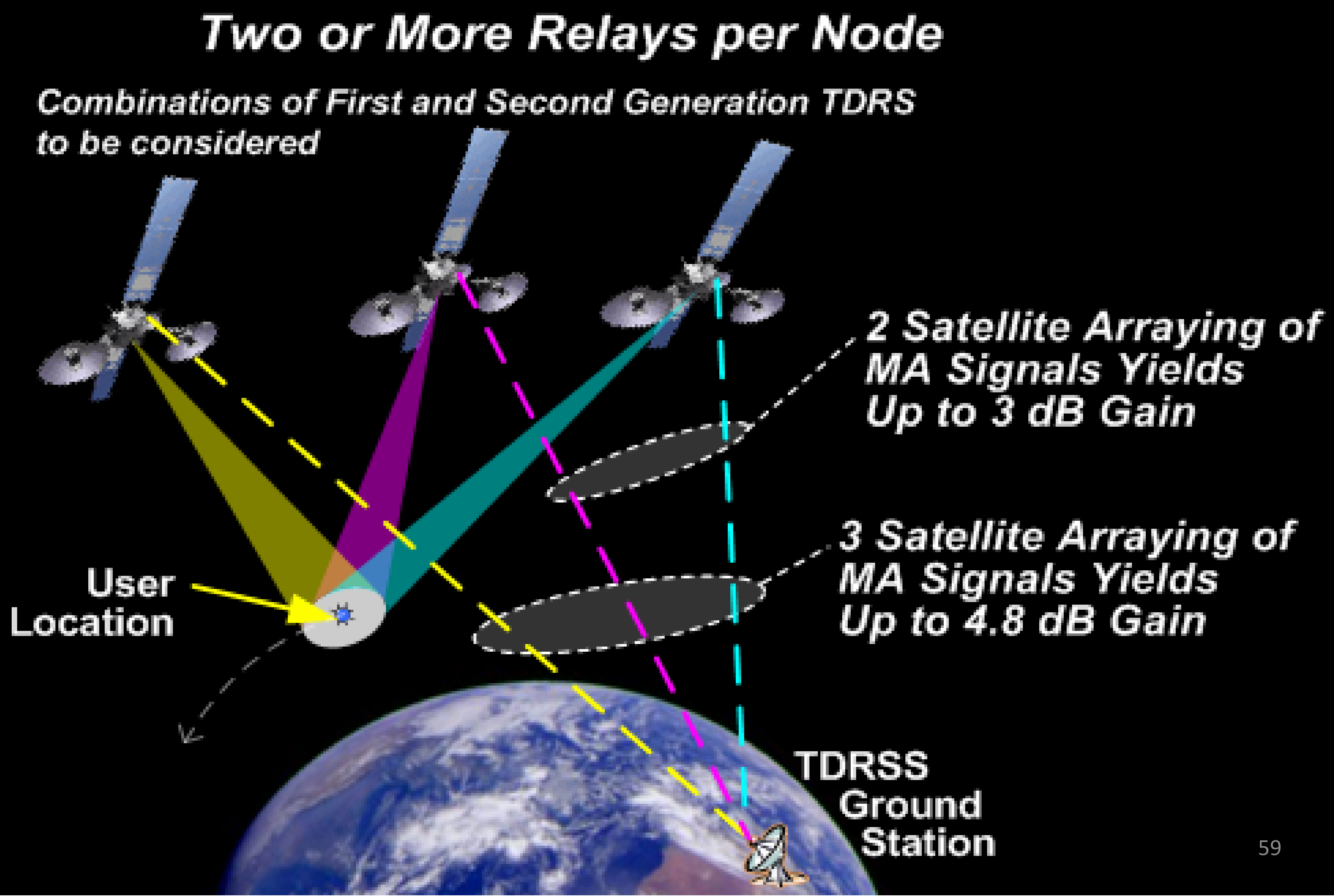
- Operated over signal propagation delays of 49 to 81 seconds; end-to-end latencies on the order of days were tolerated.
- Station handovers and transient failures in DSN uplink service were handled automatically and invisibly.
- Moved 292 images (about 14.5 MB) through the network.
- No data loss and no data corruption anywhere in the network, despite several transient unanticipated lapses in service at Deep Space Network (DSN) stations during tracking passes

End of 2010: DINET-II

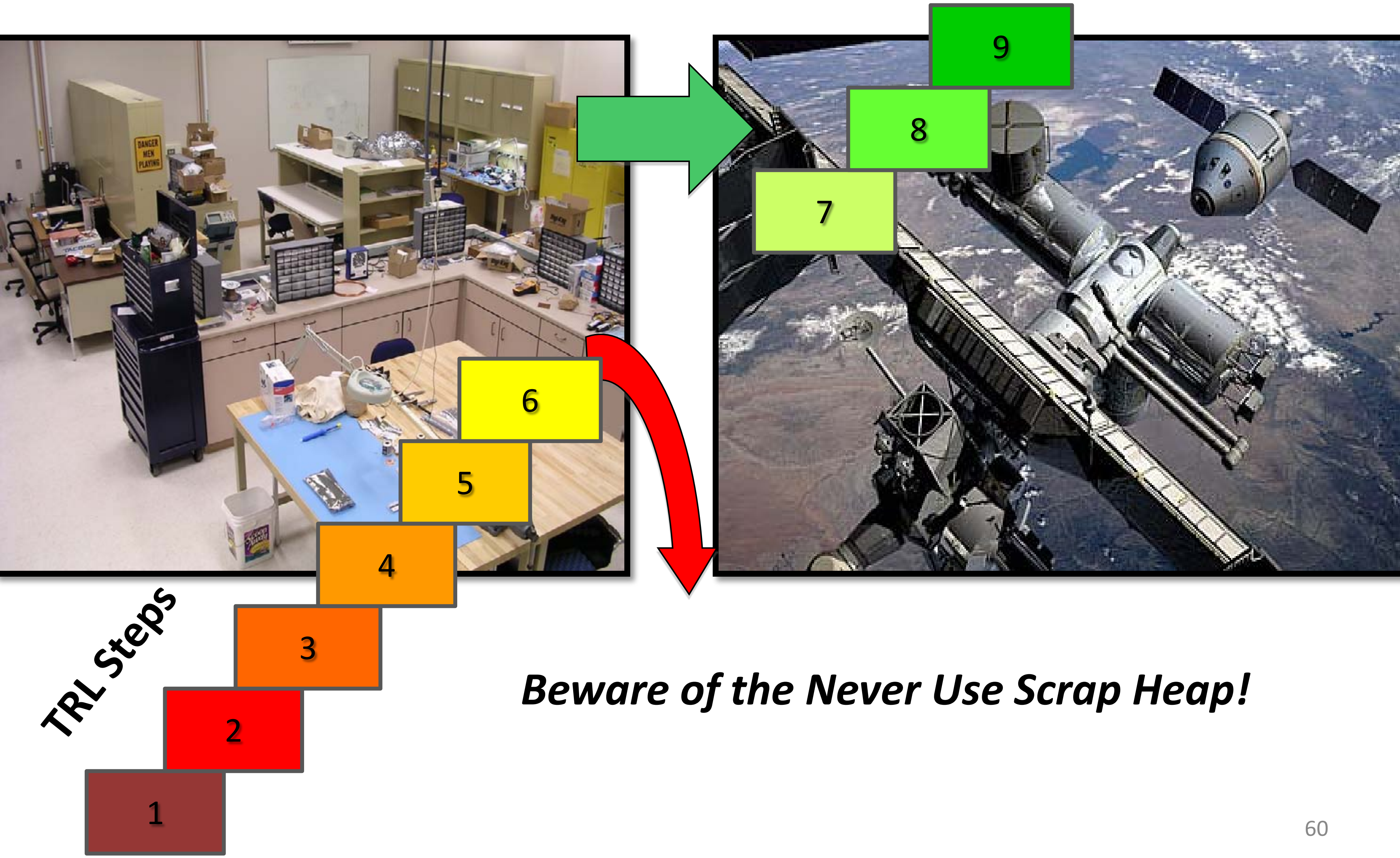
Flight validation on EPOXI in deep space in <u>flight configuration</u>

- Validate additional DTN functionality (security, DTN-enabled CFDP, multiple priority levels)
- Flow Bundles to DTN nodes outside of JPL (to the ISS)

TDRS Satellite Arraying Will Enhance Link Performance



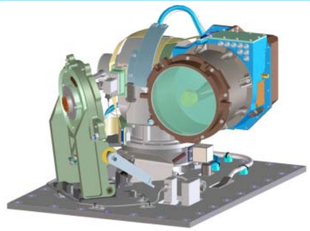
The Transition From Ground-Based TRL 6 to Space Ops
TRL 7 is a Major Step



Beware of the Never Use Scrap Heap!

SCaN Technologies Trying to Take the TRL 7 Leap

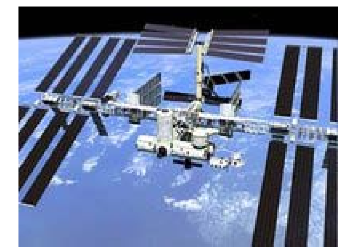
- Optical Communication



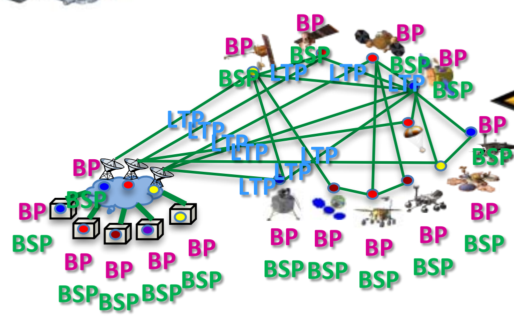
LADEE

- Software Defined Radios

ISS

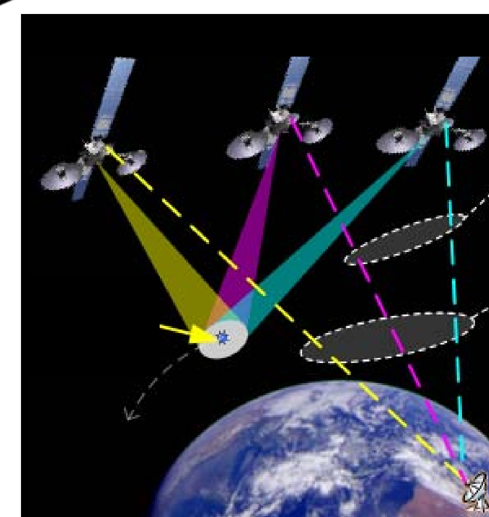


- Disruptive Tolerant Networking



TDRSS

- TDRSS Antenna Combining



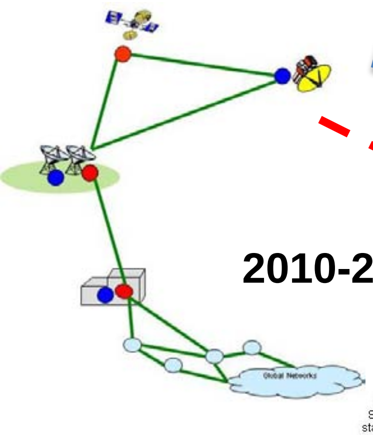
DTN – Vint Cerf

Phase-I of Space DTN Development

Phase-II DTN

Classical Point-to-Point

AUTOMATION of data transfer for simple one-hop missions or disrupted channels



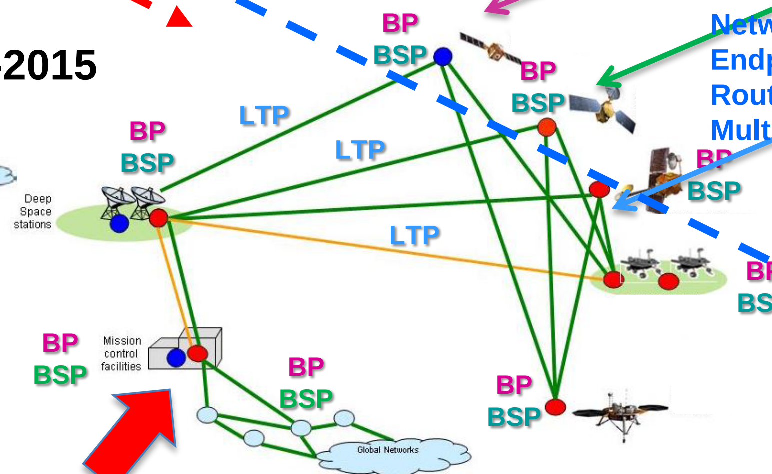
2010-2015

DTN Applications to support SSI user operations
Quality of Service (QoS) to support diversity
Network Management for monitor and control of the SSI
Security implemented end-end at multiple levels
Security Key Management for automated protection
Network Time distribution for synchronizing protocols
Endpoint Naming conventions for SSI address resolution
Routing end-end based on naming and late binding
Multiple Access to allow efficient resource sharing

Bundle Protocol (BP) in each node provides *routing and store/forward*

Bundle Security Protocol (BSP) in each node provides *authentication*

Licklider Transport Protocol (LTP) between nodes provides *hop-by-hop reliability*

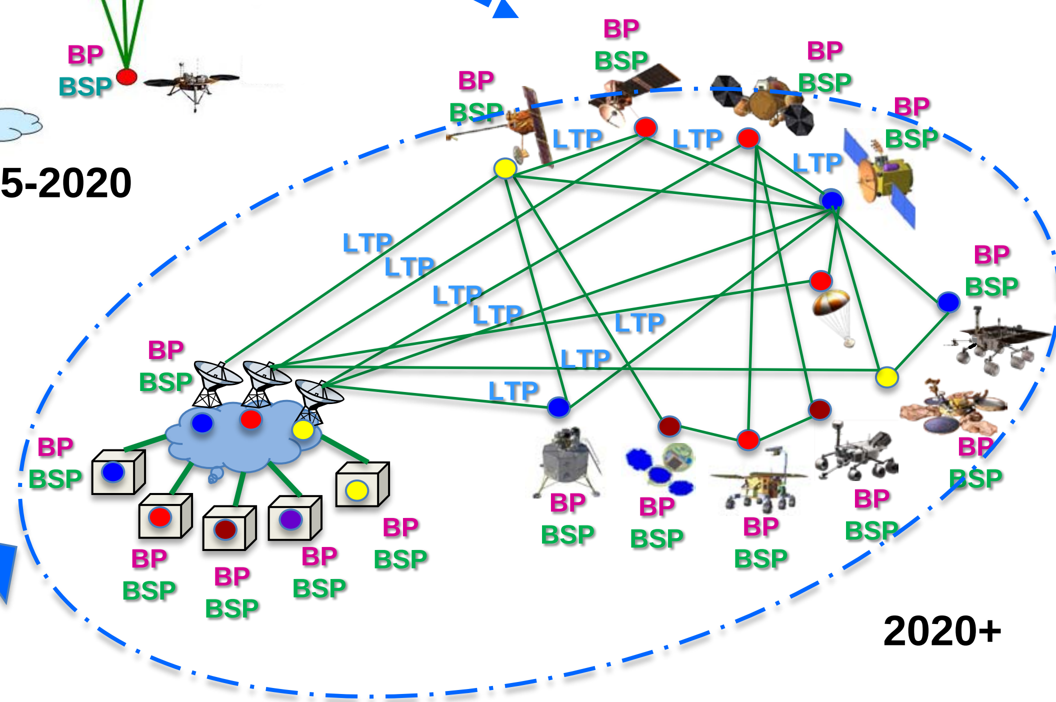


DTN 2011: Basic relay and free-flyer automation

AUTOMATION of data transfer for emerging multi-hop missions

2015-2020

DTN 2016: Solar System Internet



FULLY AUTOMATED end-to-end operations of the Solar System Internet

2020+

Daily Debrief

Final Key Thoughts

- Communications and Navigation networks are critical needs for any space mission
  - Space Agency capabilities can be:
    - Mission enabling or
    - mission roadblocks
- NASA has created future architecture plans to ensure SCaN is Mission Enabling
- Space Communications is increasingly Global in scope
  - International coordination is essential in many areas
  - European involvement through ESA, INTA and their partner companies is an opportunity for engineering students to seriously consider

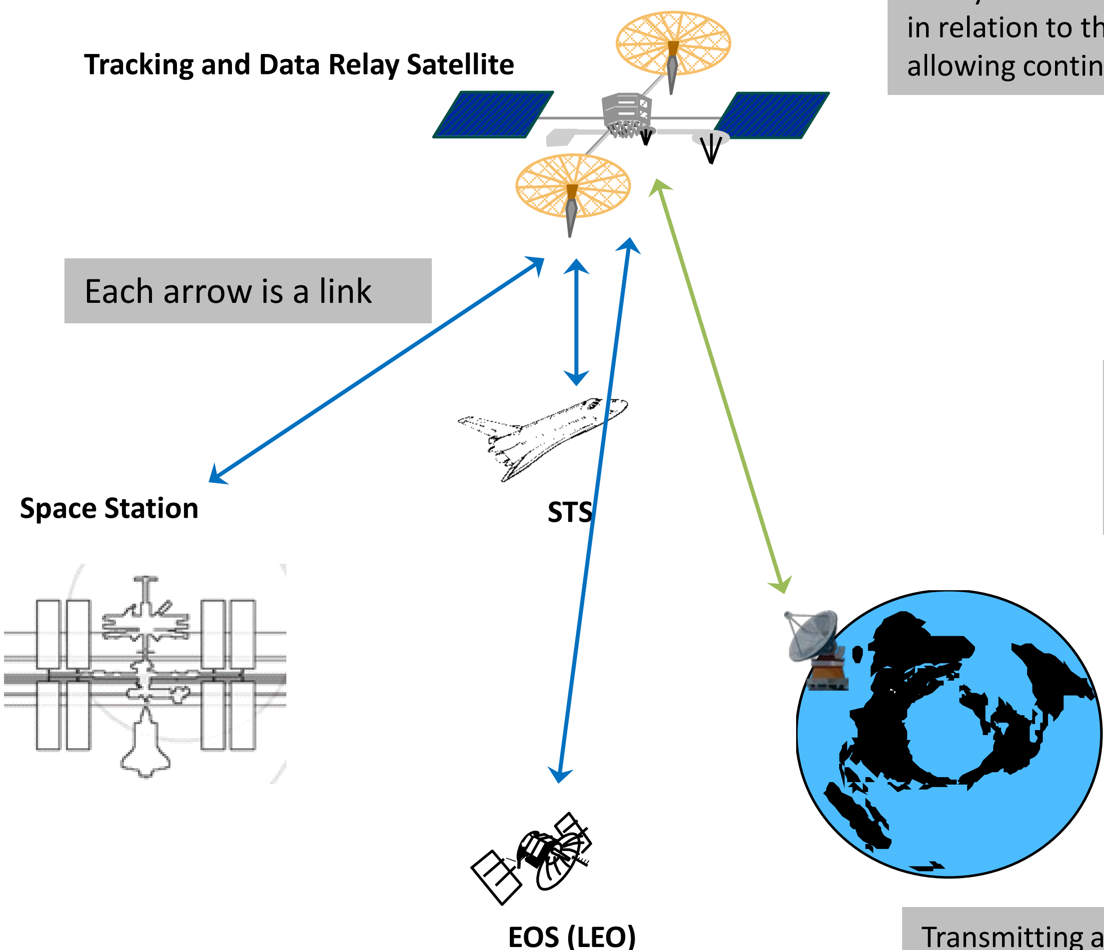
Acronyms

BPSK	Binary Phase Shift Keying
DTN	Delay and/or Disruption Tolerant Networking
DSN	Deep Space Network
ESA	European Space Agency
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
ISP	Integrated Service Portal
ISS	International Space Station
ISTP	International Solar Terrestrial Physics
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
QPSK	Quadrature Phase Shift Keying
NASA	National Aeronautics and Space Administration
NEN	Near Earth Network
PN	Pseudorandom
SN	Space Network
SCaN	Space Communications & Navigation
SOHO	Solar Helio-physics Observatory
SSI	Solar System Internetworking
TDRS	Tracking and Data Relay Satellite

BACKUP

Continuous View Relay

Geosynchronous satellite – maintains its position in relation to the receiving antenna on earth allowing continuous contact

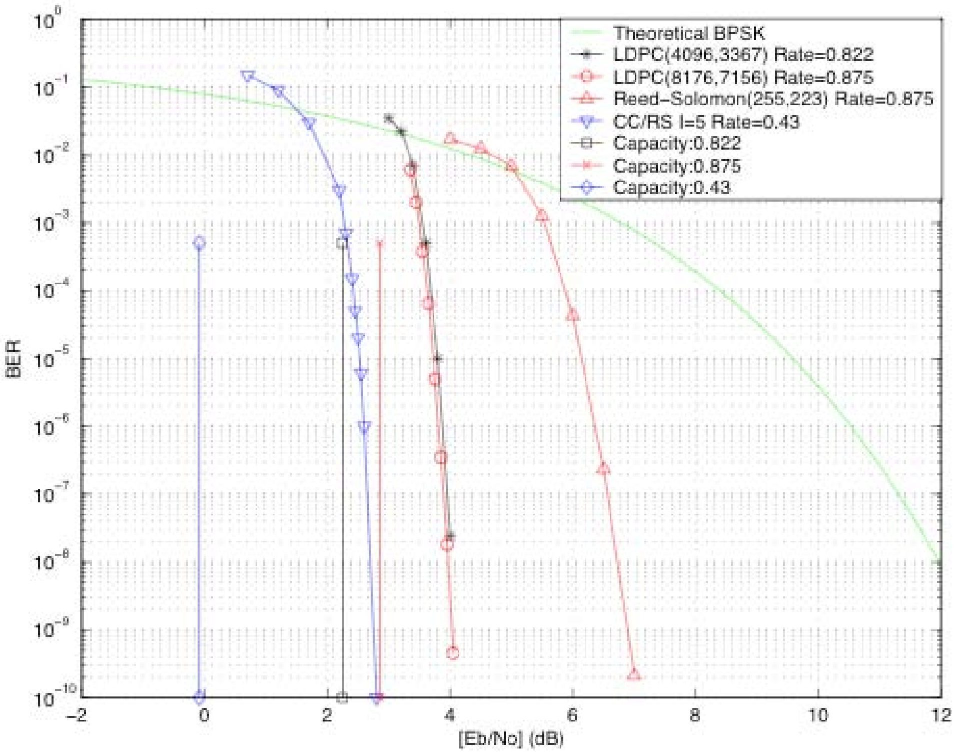


Bent Pipe or Repeating satellite. No processing done on the data in the satellite
Other examples are the TV and voice communication satellites

Transmitting antenna and receiving antenna have to be in **'view'** based on **time**! In reality it is the location in the sky at the receiving antenna, due to the fact that both the spacecraft and the earth move

EG-LDPCC Performance

- Euclidean Geometry Low Density Parity Check Codes (EG-LDPCC) are linear block codes that can achieve near-capacity performance. This was shown in 1995 almost 35 years after their discovery.

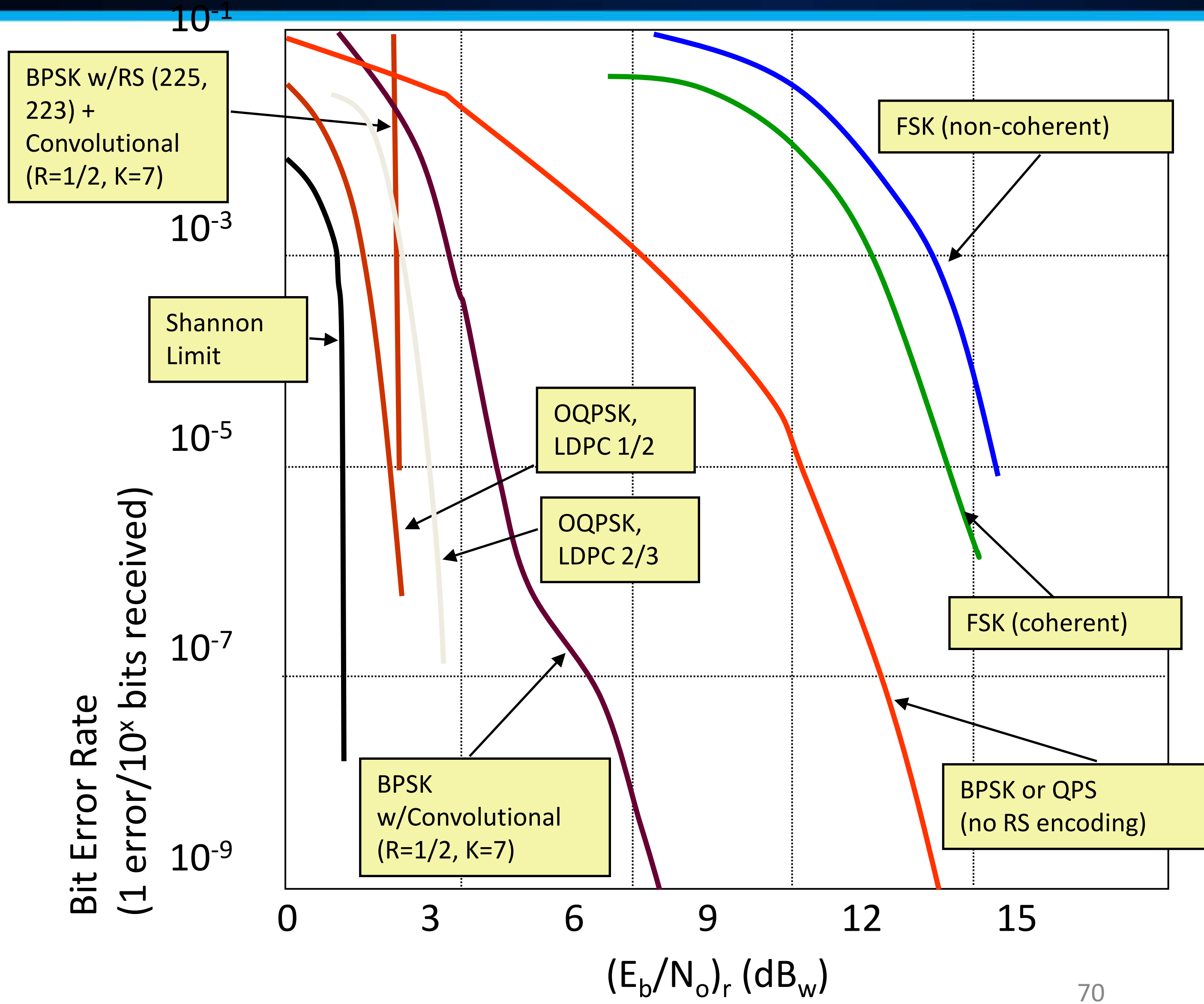


Link Budget Analysis – $(E_b/N_0)_r$ Evaluation

This graph shows the relationship between BER, SNR, encoding and modulation

-

Using this graph – you can determine the Required Signal-to-Noise Ratio for a specific link



Future Downlink Possibilities

	Data Rate Today		Data Rate ~2020		Data Rate ~2030	
Spacecraft Capabilities	3m Antenna X-Band 100 W Xmitter		3m Antenna Ka-Band 180 W Xmitter		5m Antenna Ka-band 200 W Xmitter	
DSN Antennas	1 x 34m	3 x 34m	1 x 34m	Equiv to 3 x 34m	1 x 34m	Equiv to 7 x 34m
Mars (0.6 AU)	20 Mbps	60 Mbps	400 Mbps	*1.2 Gbps	*1.3 Gbps	*9.3 Gbps
Mars (2.6 AU)	1 Mbps	3 Mbps	21 Mbps	64 Mbps	71 Mbps	*500 Mbps
Jupiter	250 Kbps	750 Kbps	5 Mbps	15 Mbps	16 Mbps	115 Mbps
Saturn	71 Kbps	213 Kbps	1.4 Mbps	4 Mbps	4.7 Mbps	33 Mbps
Neptune	8 Kbps	24 Kbps	160 Kbps	470 Kbps	520 Kbps	3.7 Mbps

* Reference spacecraft is MRO-class (power and antenna), Rate 1/6 Turbo Coding, 3 dB margin, 90% weather, and 20° DSN antenna elevation

** Performance will likely be 2 to three times lower due to need for bandwidth-efficient modulation to remain in allocated spectrum