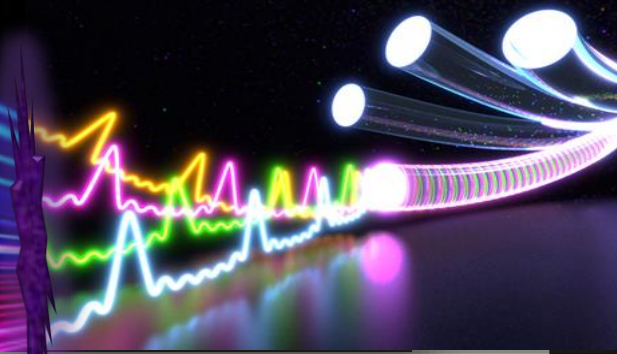


Communicating with Light:
A New Dawn in the Information Age

Presentation to the University of Toledo
Electrical Engineering and Computer Science Department
Graduate Seminar

Dr. Daniel Raible



Our Journey of Discovery

New Vistas, New Perspectives



E-ring formed from salt-water jets at the south pole of Enceladus

The Day the Earth Smiled
July 19, 2013

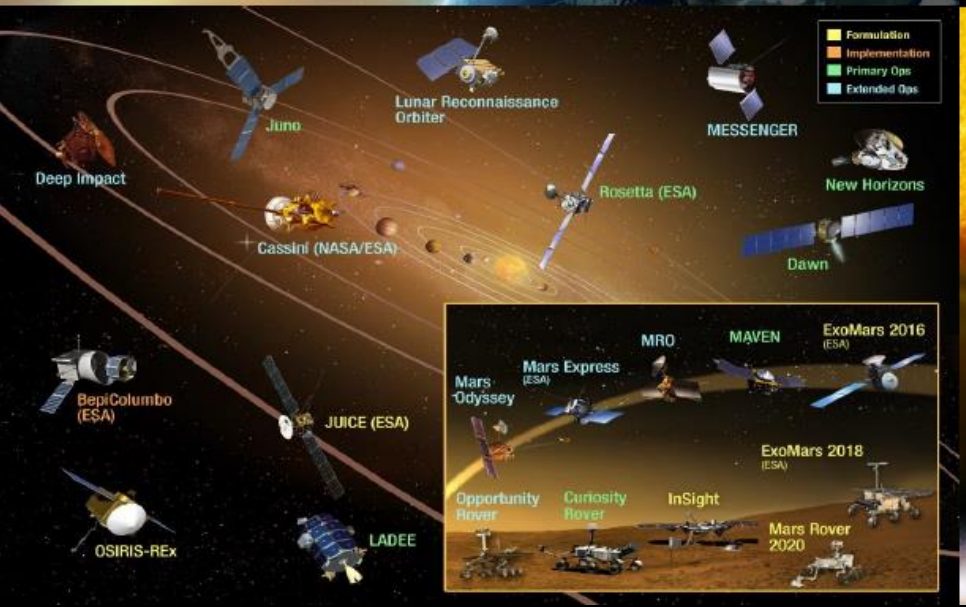
NASA seeks answers to profound questions using space data

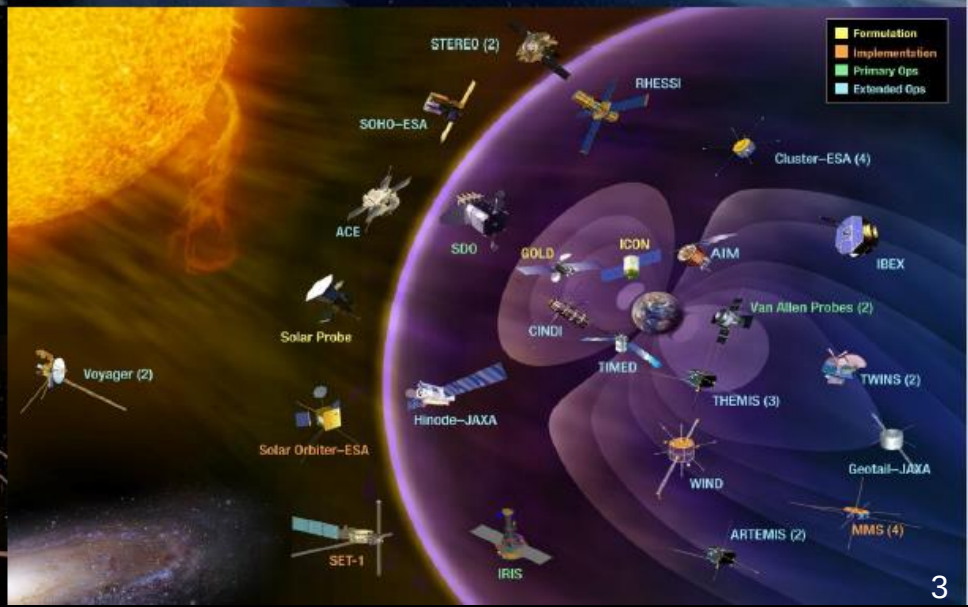
- How and why are Earth's climate and the environment changing?
- How and why does the Sun vary and affect Earth and the rest of the solar system?
- How do planets and life originate?
- How does the universe work, and what are its origin and destiny?
- Are we alone?

NASA's Networks Enable Today's Science Missions

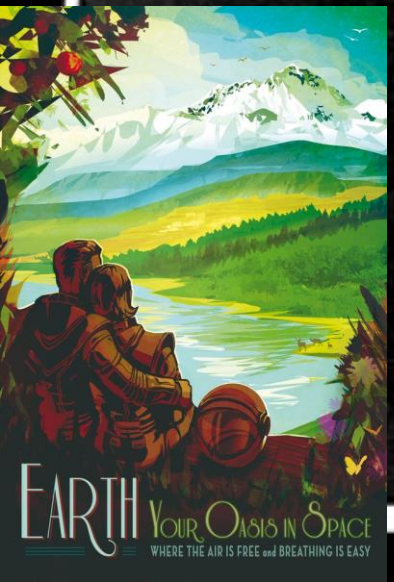




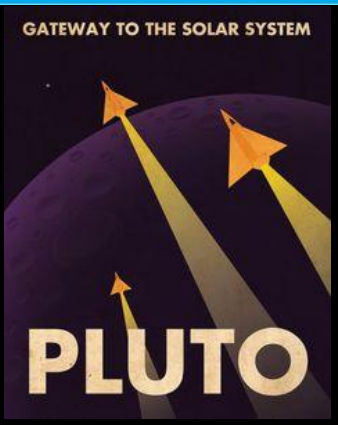


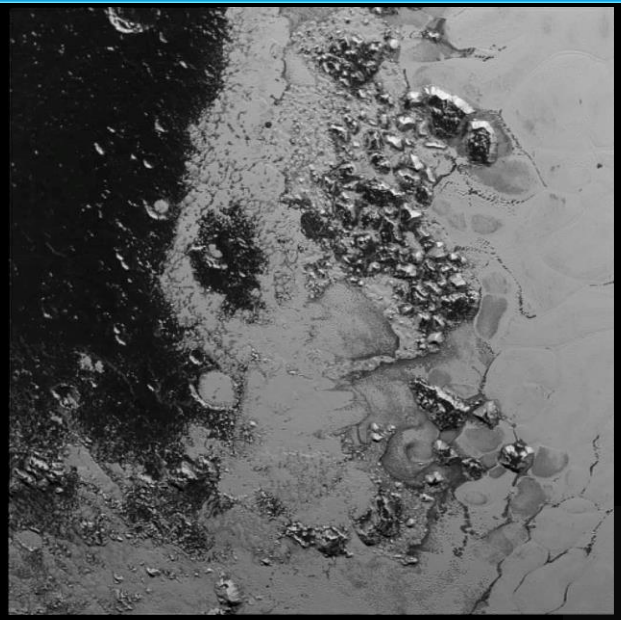


First Television Picture From Space
TIROS-1 Satellite April 1, 1960



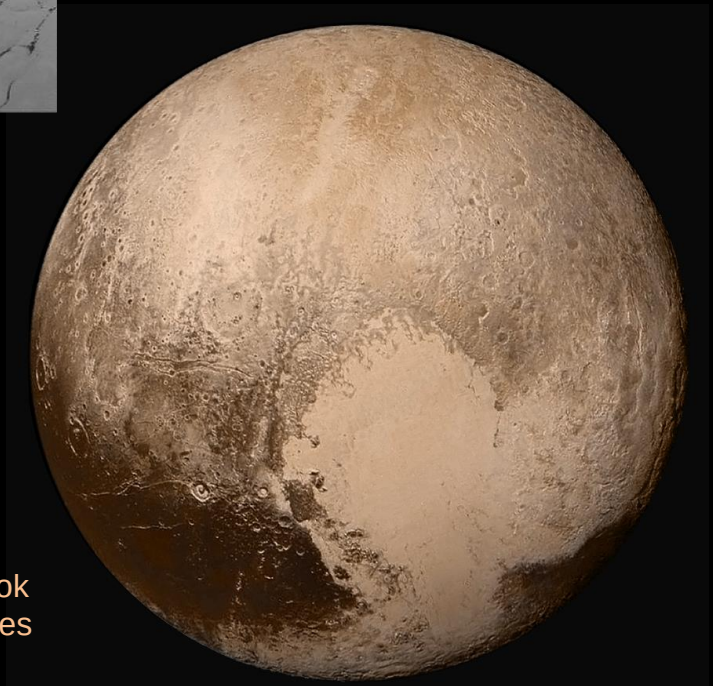
New Horizons at Pluto
July 23, 2015











At 2.0 kbps data rate from Pluto, it took over a year to transmit all of the images from the flyby back to Earth

Radiometric Data

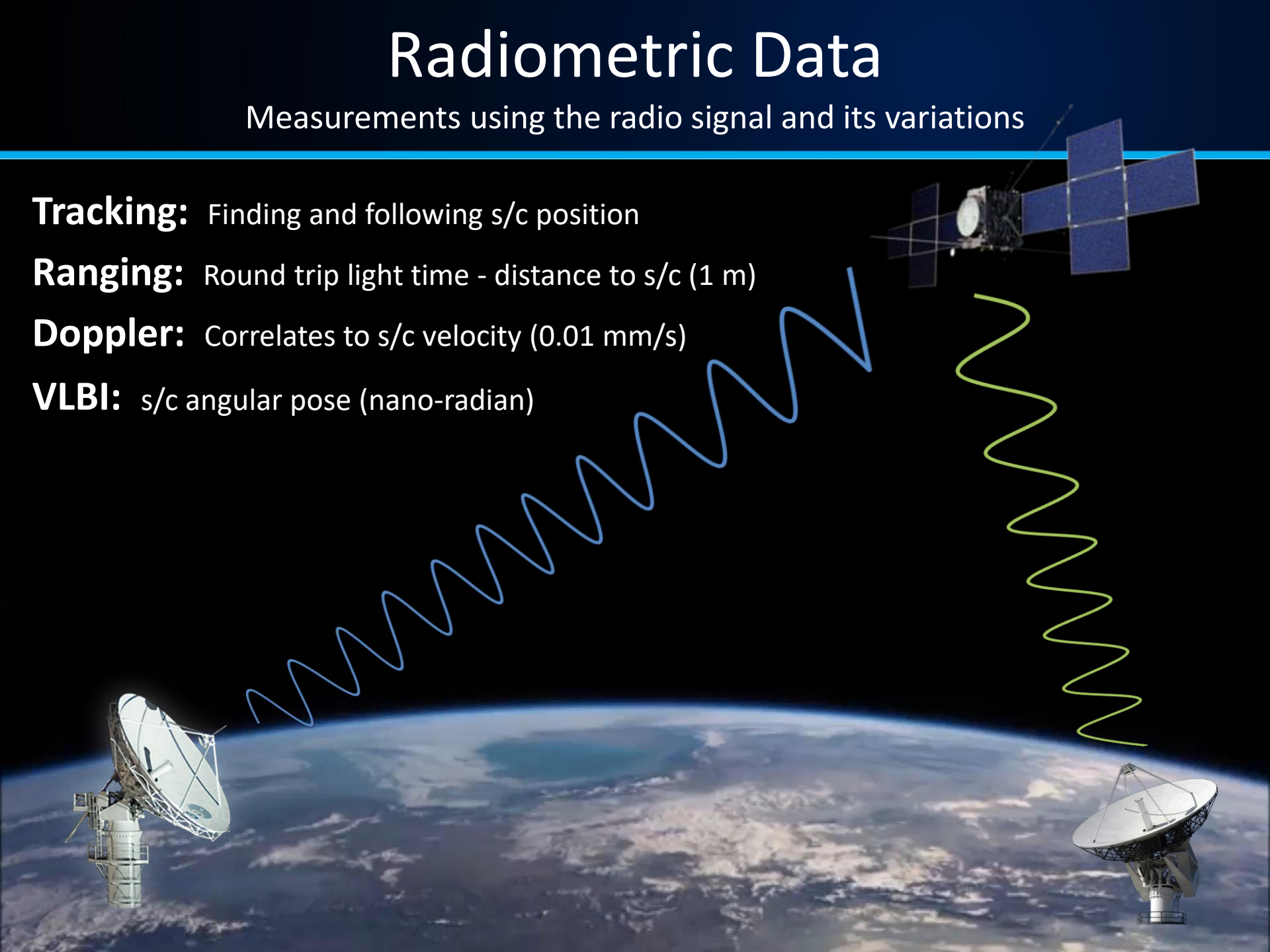
Measurements using the radio signal and its variations

Tracking: Finding and following s/c position

Ranging: Round trip light time - distance to s/c (1 m)

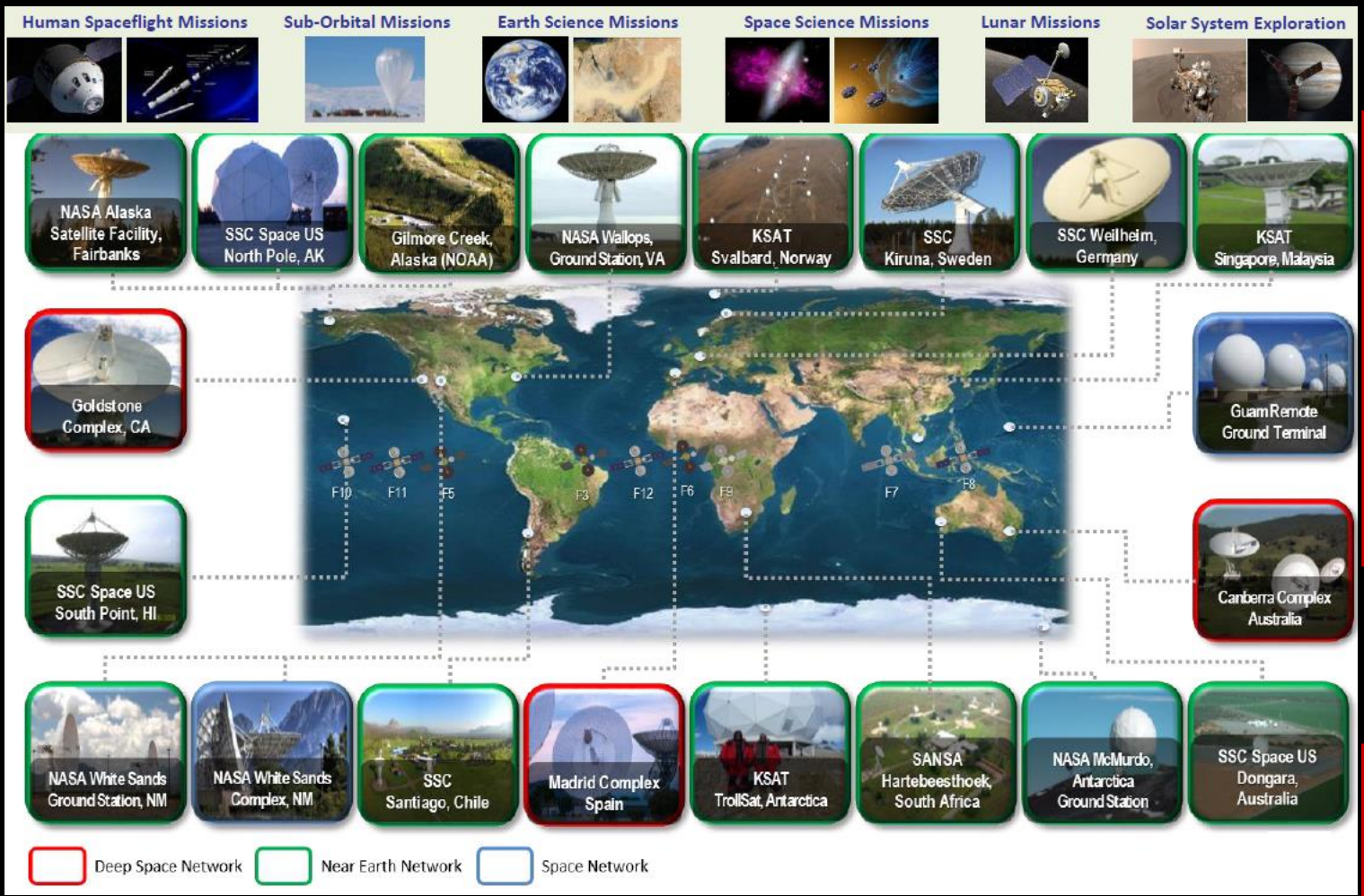
Doppler: Correlates to s/c velocity (0.01 mm/s)

VLBI: s/c angular pose (nano-radian)



Space Communications and Navigation Networks Across the Globe to Support the Missions

What We Built



SCaN 3D Demo



http://www.nasa.gov/multimedia/3d_resources/spacecomm.html

NetworKing Game



http://www.nasa.gov/multimedia/3d_resources/scan.html

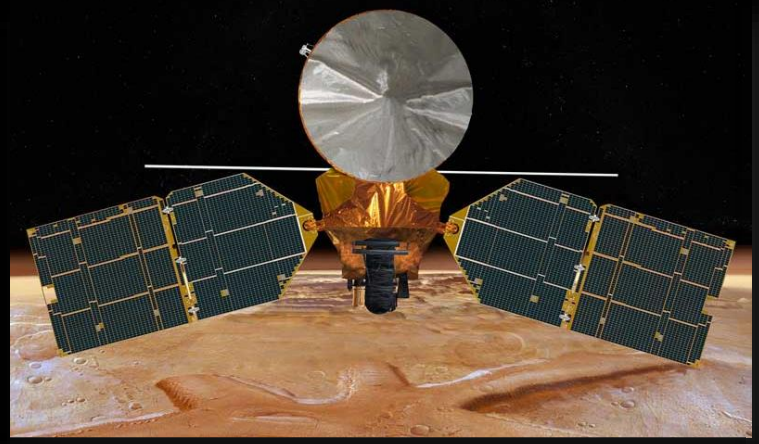
A network to communicate with all of the spacecraft

…*some* of the time…

Link Performance Examples

Communications is a Bottleneck for Space Data Return

State of Practice



MRO: 300 kbps - 4 Mbps 8 – 54 min

data rate round-trip light time



Surface Communications Data Services

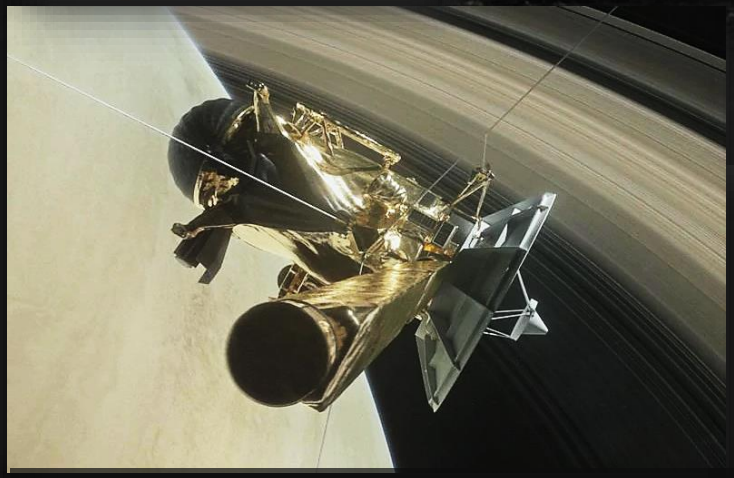
• Audio*	8-64 kbps/channel (at least 4 channels)
• TT&C*	< 100 kbps
• SDTV Video	6 Mbps
• HDTV Video	19 Mbps
• Biomedical Control*	70 kbps
• Biomedical Monitoring*	122 kbps

**Must be Reliable Links*





Hubble: 4 kbps ~0.36 s



Cassini: 40 - 164 kbps 2.2 – 3.0 hr



STEREO: 427 - 750 kbps ~21.2 min



Requirements: Communications Data to Serve the Missions Spans Many Purposes, Rates and Quality of Services

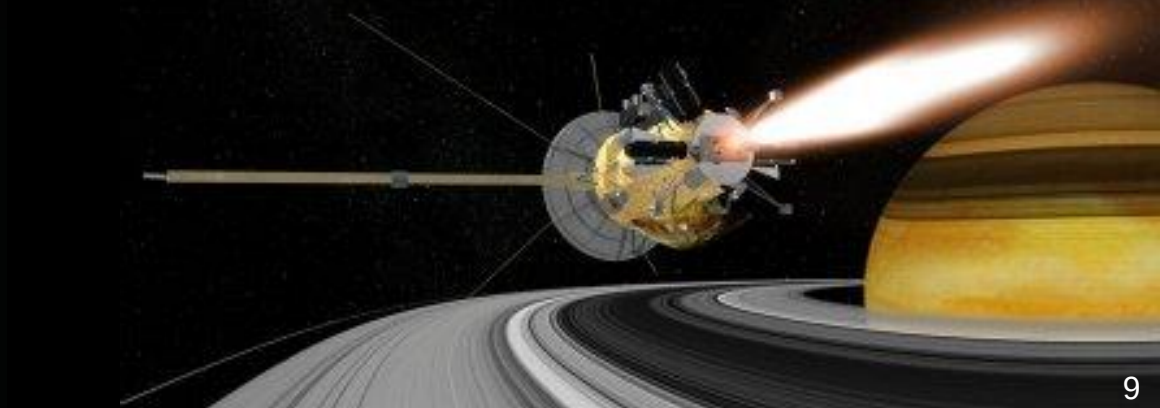


Different types of data, with different requirements (BER, bandwidth, latency, security, custody, etc.)

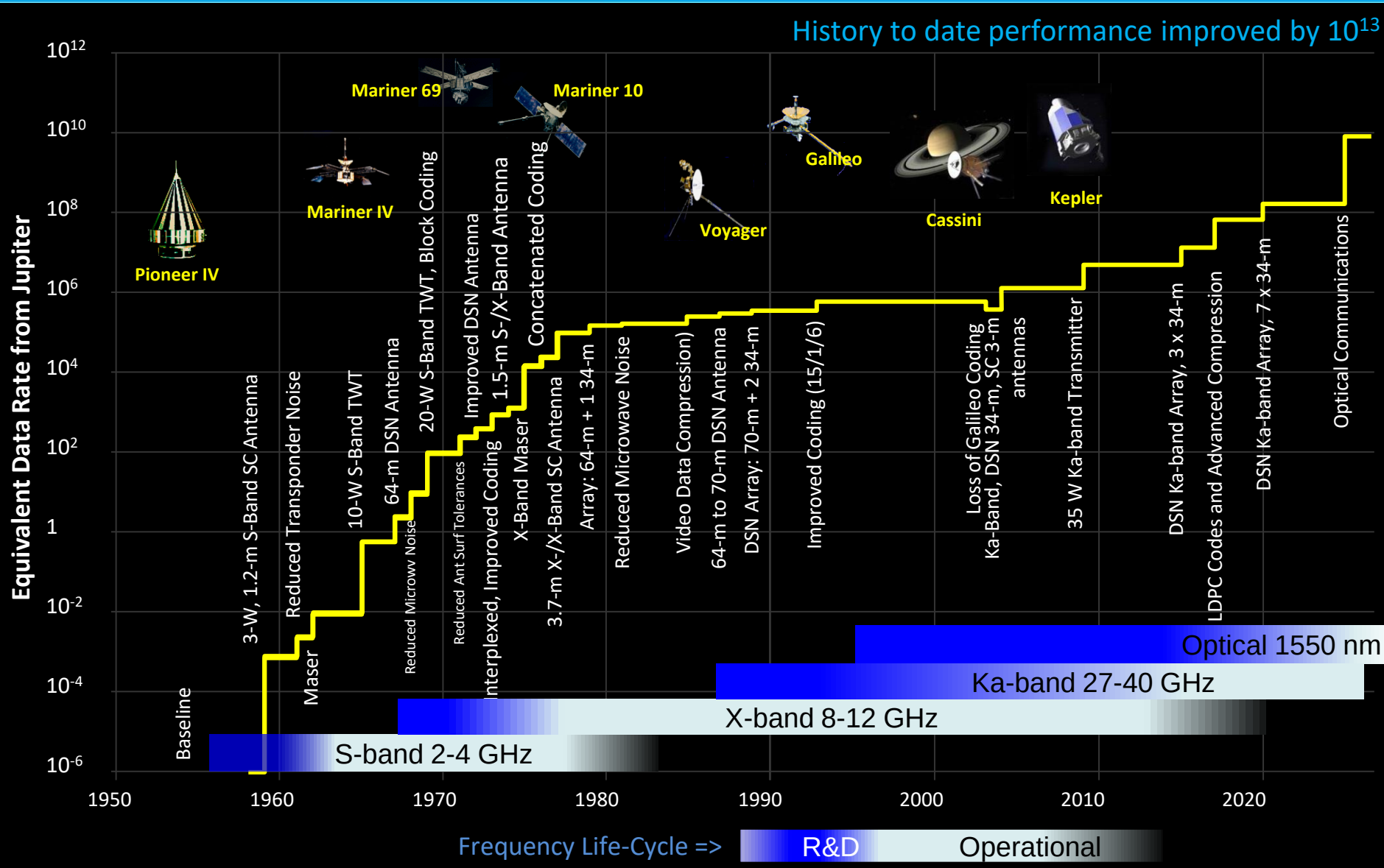
- Tracking, telemetry and control (TT&C)
- Scientific data from instrumentation
- Pictures (high-resolution, stereoscopic, hyper-spectral)
- Video (composite of images)
- Biometric, voice, text messages to/from astronauts
- Asymmetric versus balanced forward & return links
- Networks versus PtP links of spacecraft, relays, surface assets

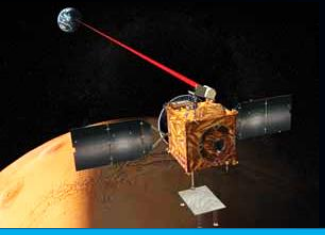
What do missions want?

- Uninterrupted data from anywhere in the solar system, more pictures, faster video, 3D, IMAX, telepresence, etc.
- High peak data rates to support human exploration
- QoS provisions for priority, latency, error rate, security



Deep Space Communications Data Rate Evolution



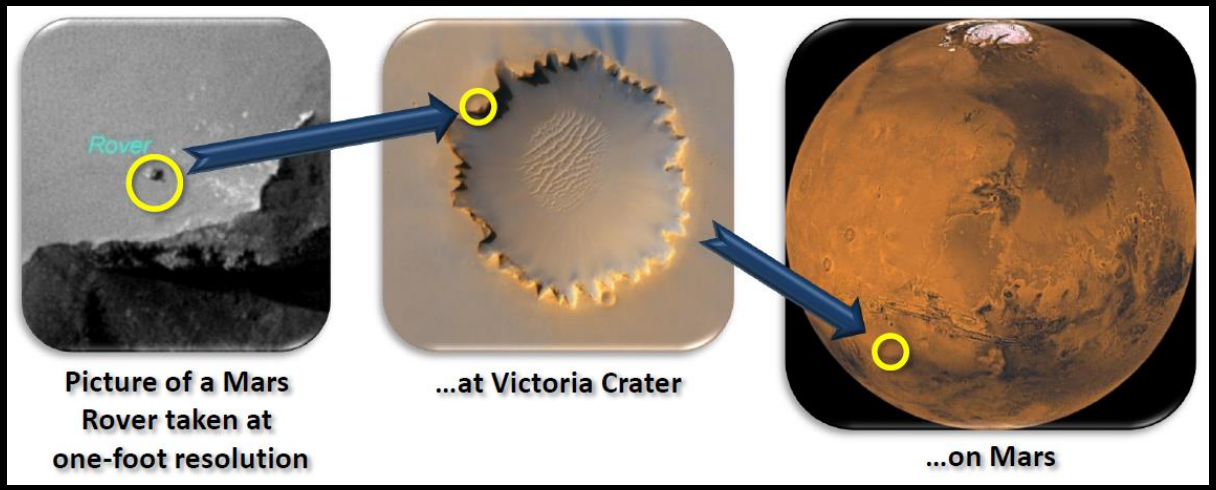


Something New:
Free-Space Optical Communications (FSOC)

Goal: Don't let communications capability constrain data on our missions



- Motivated by present mission needs and RF limitations
  - Up to 20-fold increase in data rate, enables increased data collection
  - Optical spectrum unbounded/unregulated, over RF spectrum congestion
- Lower transceiver size, weight and power (SWaP) over existing RF solutions
  - Weight: expensive to launch, ~50% savings in mass (could be reallocated to instruments)
  - Power: expensive in space, ~65% savings in power (increased mission capability / life)
- Component technology is here now
- Can transmit while maintaining radio silence during sensitive scientific measurements



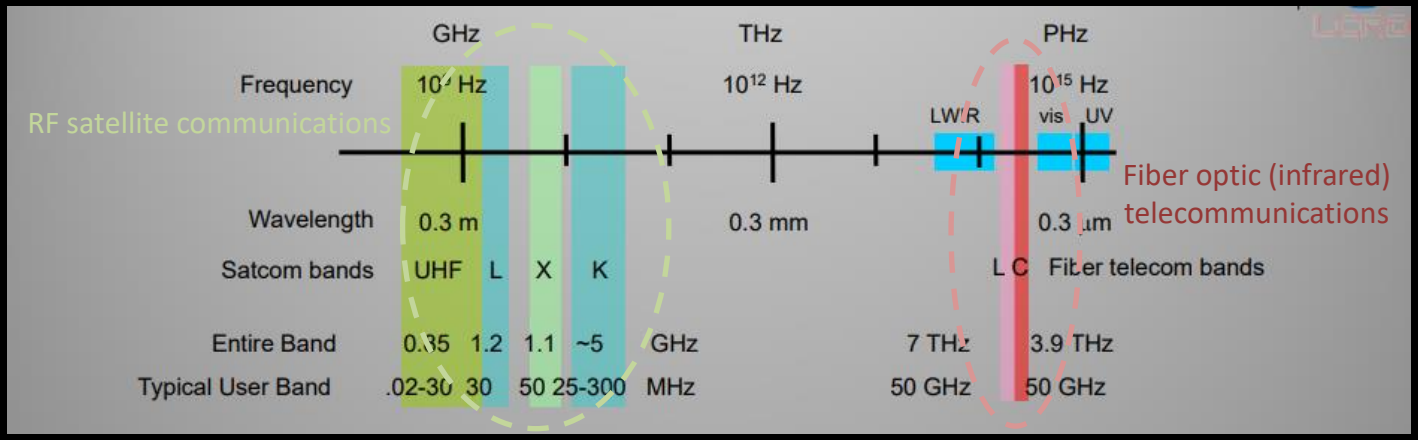
To transmit a 30 cm resolution "Google Map" of the entire Martian surface (at 1 bit/pixel):

Current Ka-band RF system would take 2 years

Optical communications can do it in 9 weeks!

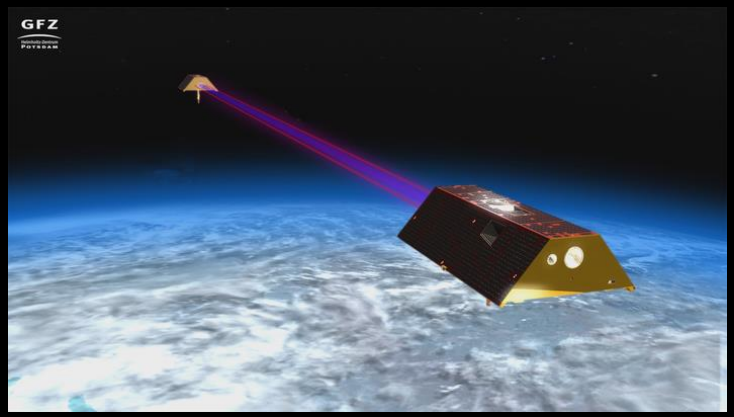
Benefits of Optical Communications

Enables space missions to return 10-100 times more data, for 1% of the antenna area of RF systems, while utilizing less mass, power and unregulated spectrum



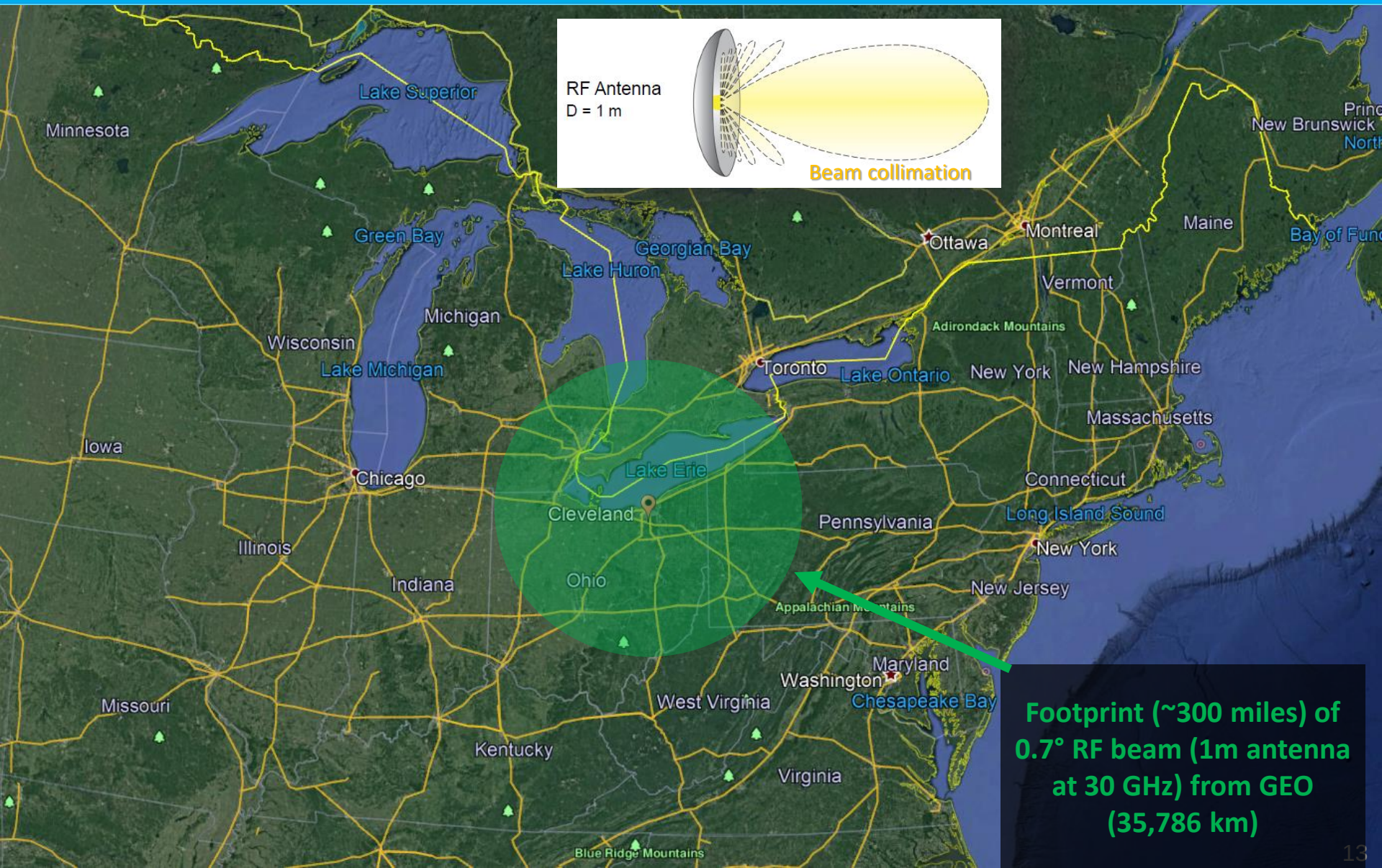
Laser systems on spacecraft allow centimeter and picosecond-class optimetric measurements to enable precision altimetry, formation flying and LIDAR imaging





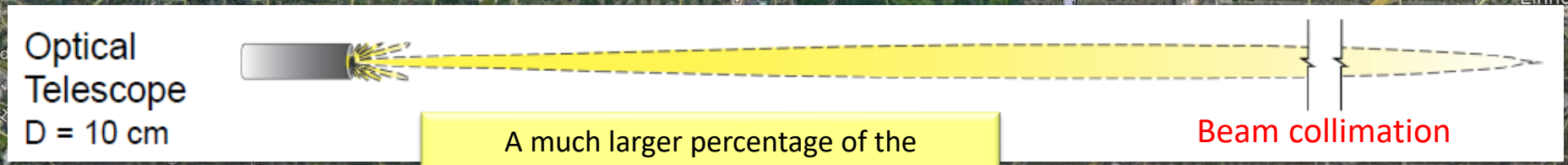
RF Beam from a Satellite in Geosynchronous Equatorial Orbit (GEO)

Electromagnetic beamwidth is ruled by the diffraction limit



Optical Beam from Geosynchronous Equatorial Orbit (GEO)

Benefits and Challenges



A much larger percentage of the transmitted energy goes into the receiver

Footprint (~600 meter) of 15 μradian optical beam (0.8 millidegree from 4" aperture at 1.55 μm) from GEO



Clouds and mist can interrupt a laser

- \+ Great for privacy (physical security), can add QKD for additional layer
- \+ Higher received energy density = higher data rates (increased SNR)
- -- …but comes at the cost of very challenging pointing control

How Small an Angle is a Micro (μ) radian?

8.7 mradians



Apparent Sun or Moon size from Earth

290 μradians



Limit of human visual acuity, a penny at 4 km

145 μradians



Jupiter from Earth

Jupiter and four moons
from amateur telescope

4.8 μradians

Neptune from Earth

Neptune and Triton
from amateur telescope

485 nradians

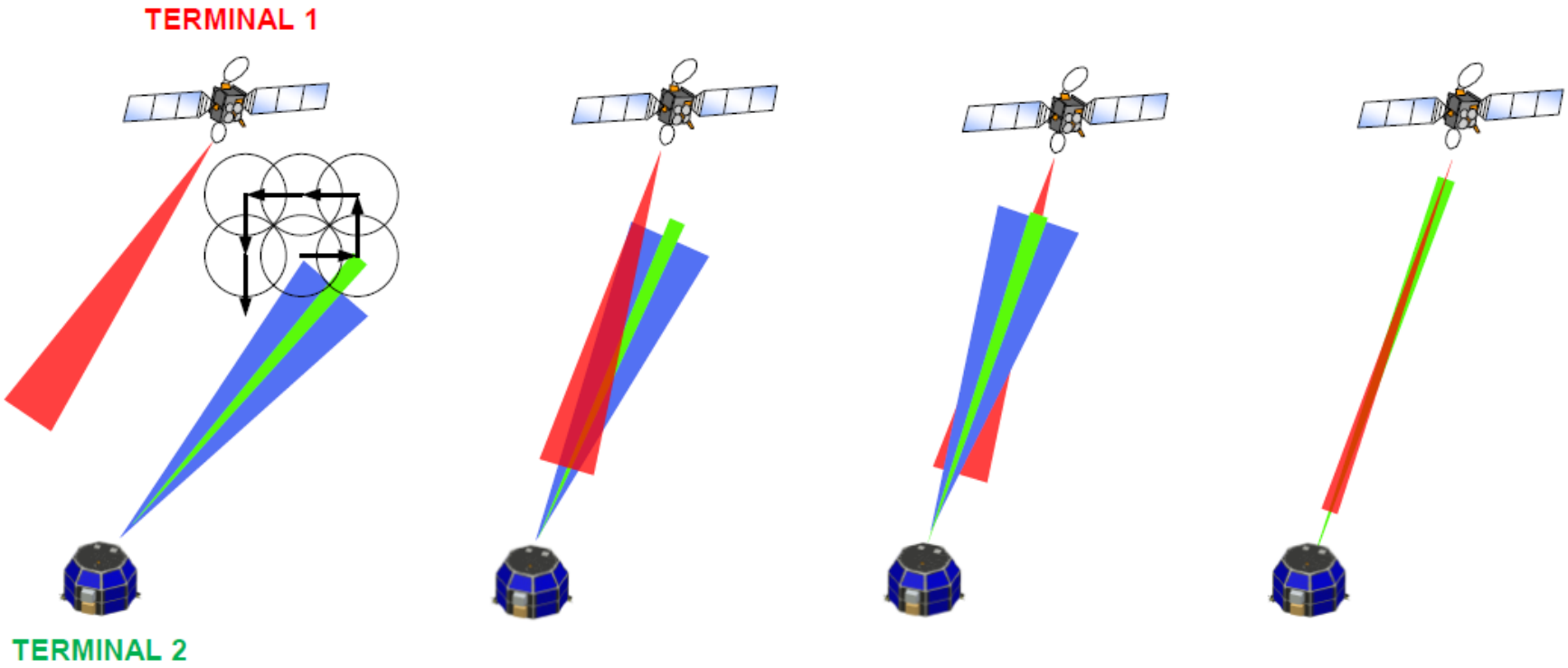


Pluto from Earth

Pluto, Charon, Nix and Hydra
from Hubble Space Telescope

Pointing, Acquiring and Tracking (PAT) the Optical Beam

Using a Beacon to Accomplish µradian Performance



Terminal 2 scans forward link beacon (raster, spiral, etc.)

Terminal 1 acquires forward link beacon, pulls in to course-track

Terminal 2 acquires return link beacon, pulls in to course track

Terminals 1 and 2 reduce beamwidths, begin fine-tracking

Optical Communications Technologies
and Design Drivers

Laser fiber amplifiers



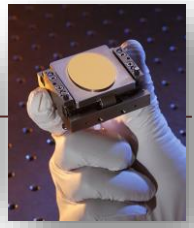
- Efficiency
- Power vs data rate
- Extinction ratio
- Pulse repetition frequency
- Reliability

Optical modems



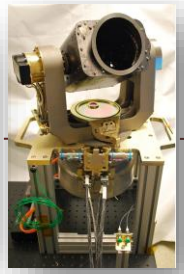
- Power efficiency
- Low mass
- Processing
- Configurability

Fine-pointing mirrors



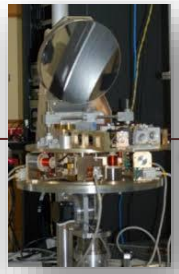
- Bandwidth
- Reaction
- Performance
- Reliability

Transmit optics



- Low mass
- Aperture size
- Field of view
- Xmit-rcv isolation
- Duplex operation
- Thermal effects
- Optics contamination

Platform



- Vibration environment (S/C jitter)
- Deadband cycle
- Earth exposure time

Space



- Radiation
- Space loss
- Galactic noise

Atmosphere



- Visibility
- Cloud cover
- Attenuation
- Elevation angle
- Sun angle
- Solar loading
- Turbulence
- Scattering

Earth



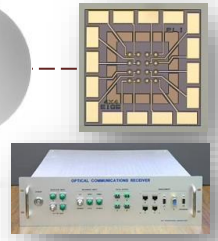
- Reflectance
- Albedo variations
- Crescent size
- Motion

Receiver optics



- Aperture size
- Array?
- Field of view
- Xmit-rcv isolation
- Duplex operation
- Thermal effects
- Optics contamination
- Multiple sites for weather

Focal plane array & receiver



- Type
- Array size
- Pixel size
- Noise
- Spectral band
- Field of view
- Dynamic range
- Sensitivity
- Readout rate
- Update rate
- Processing power
- Stray sun light
- Scattered transmit light
- Reliability
- SPE & SEP angles
- Acquisition time

Payload Stabilization

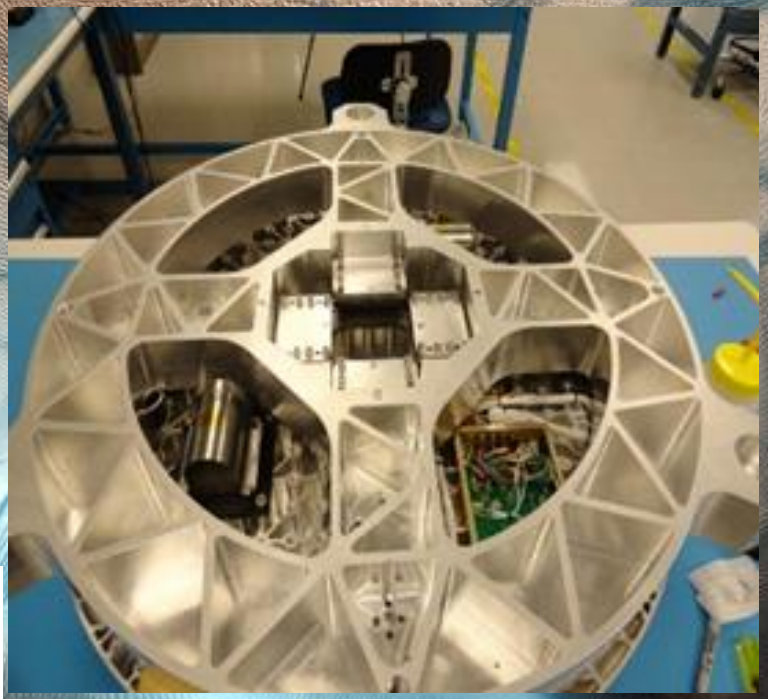


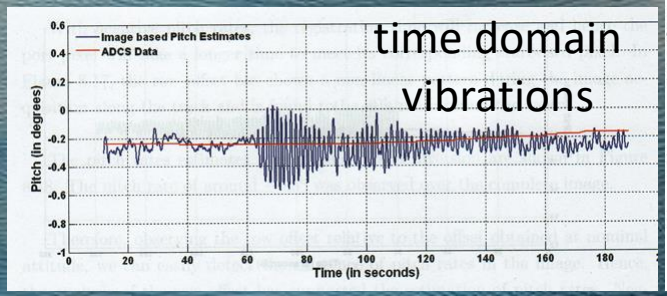


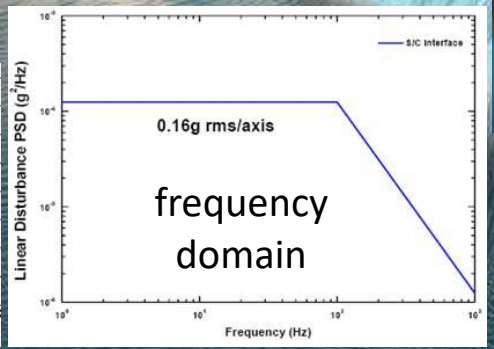
ATA Applied Technology Associates — Sensing ways to make the world better™

MRO (Mars Reconnaissance Orbiter)

HiRISE (High Resolution Imaging Science Experiment)







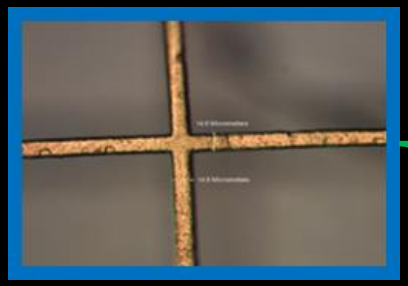
Active/passive isolation platform developed to offer greater than 50 dB vibration reduction in the 0.1 Hz – 500 Hz band for deep-space craft

Optical / RF Teletenna

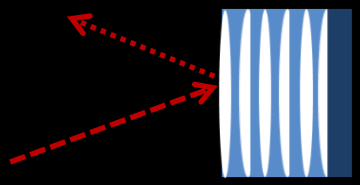
(telescope + antenna)

Co-boresighted 1550 nm Optical / 32 GHz RF Communication Beam

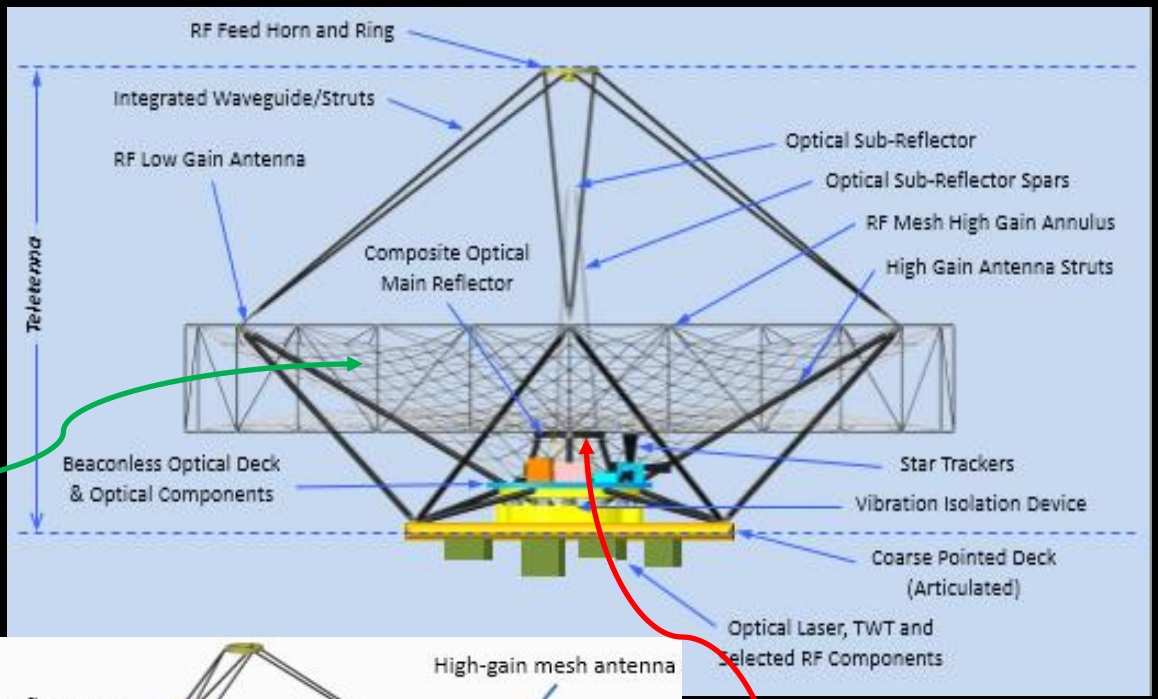
- Roughly half the mass of the MRO 3 m antenna
- RF section thermally and mechanically isolated from optics
- Custom integrated strut/waveguide to rf feed offers reduced mass and an 8% power savings
- Bragg Mirror Optical Sub-reflector is transparent at RF 32 GHz

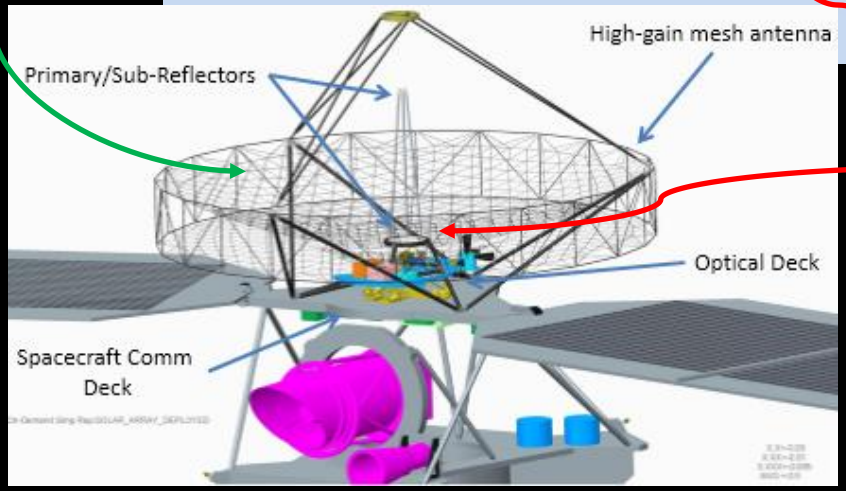


- 3 meter - Low density mesh RF annulus
- Knitted gold plated molybdenum mesh >98% reflective at Ka-band
- Wire diameter is about 30 µm



Optical sub-reflector
11 alternating layers of rutile and silica







Composite mirror for 25 cm optical main reflector

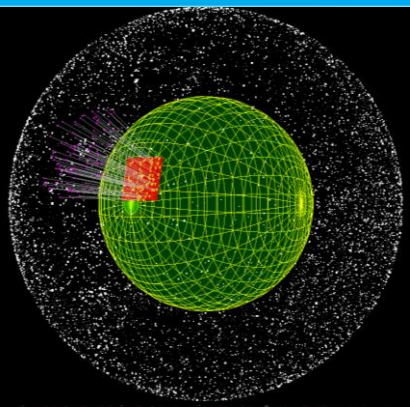
Determining Spacecraft Attitude (μradian) Through Advanced Celestial (optical) Navigation



Micro Star Tracker

- Provides increased spacecraft autonomy with extensibility to other deep space missions
- Relies on spacecraft state estimate with attitude knowledge obtained via star tracker networks and/or interferometric means
- Component technology has developed to the point of beaconless consideration
- Established experimental test bed using multi-camera concept and virtual star-fields

Ursa Major

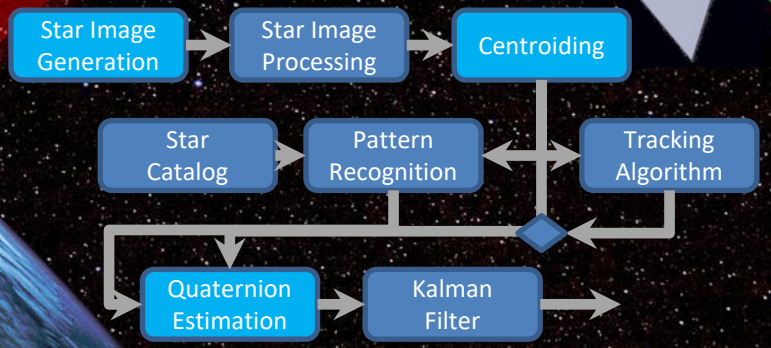


Star Field Visualization & Analysis Tool

Star Tracker Equipped Craft

Taurus

Ground Terminal



Optical Transmitter Architecture

Master Oscillator Power Amplifier (MOPA)

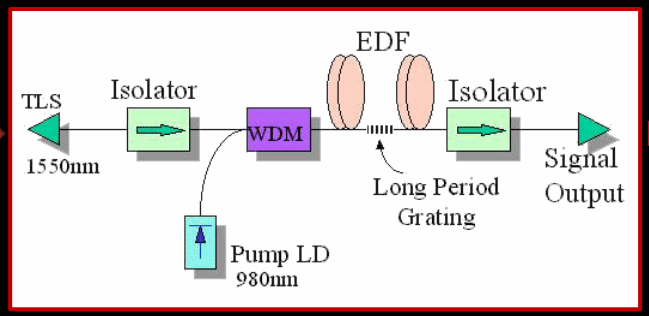
Distributed Feedback (DFB) Master Laser



Electro-Optic (EO) Modulator



High Power Erbium-Doped Fiber Amplifier (EDFA)



Fiber to Free Space Interface



High Speed Data Driver



Pump Lasers

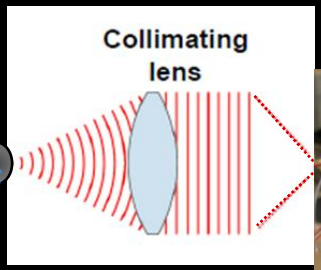
- In 1990's EDFA technology shifted to 1550nm
- High power EDFA as transmit amplifiers
- Low power EDFA as low-noise receiver amplifiers

Coupling Light from Fiber to Free Space

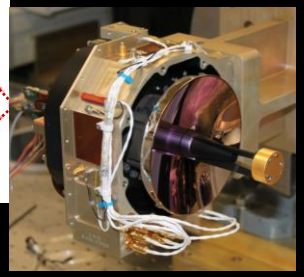


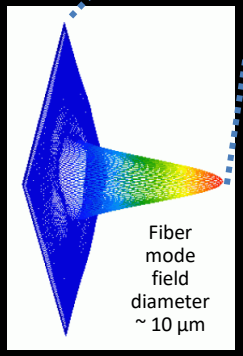
Fiber Transmitter



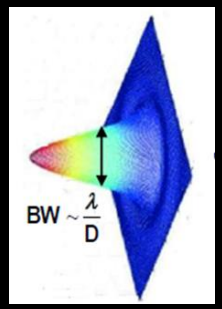


Transmitting Telescope





D





Far-field receiver

Far field pattern is 2-D spatial Fourier transform of transmitted signal field in telescope aperture

- Telescope is the transmit “antenna”
- Expands a ~10 µm beam from fiber to much larger diameter D to produce antenna gain
- High gain -> narrow beamwidth
- Telescope pointing accuracy is critical!

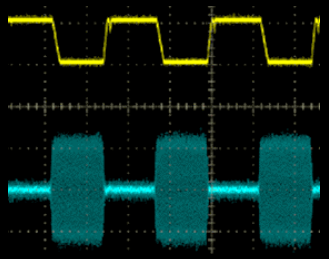
Antenna gain $G \approx \left(\frac{\pi D}{\lambda}\right)^2$

Far-field beamwidth $BW \approx \frac{\lambda}{D}$

Modulating Properties of Light
to Impart Information

AM radio station example: Operating at a frequency of 500 kHz and using 5kHz of bandwidth yields a spectral efficiency of 1 %. Upscaling to optical frequencies we should have a channel bandwidth of around 2 THz, and you might expect Tb/s data rates for a single optical wavelength…

But, modern electronics are not fast enough to modulate light very well, so performance is generally limited to between 10-100 Gb/s.

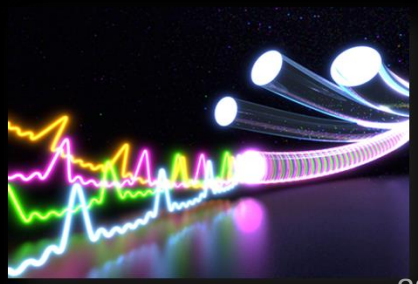


Modulating light intensity: The simplest version uses on-off keying (OOK). This may be combined temporally to create a very efficient technique (next slide). Dividing the light into multiple brightnesses to send more bits is challenging, because after the light has travelled some distance losses have taken their toll, so is generally avoided.

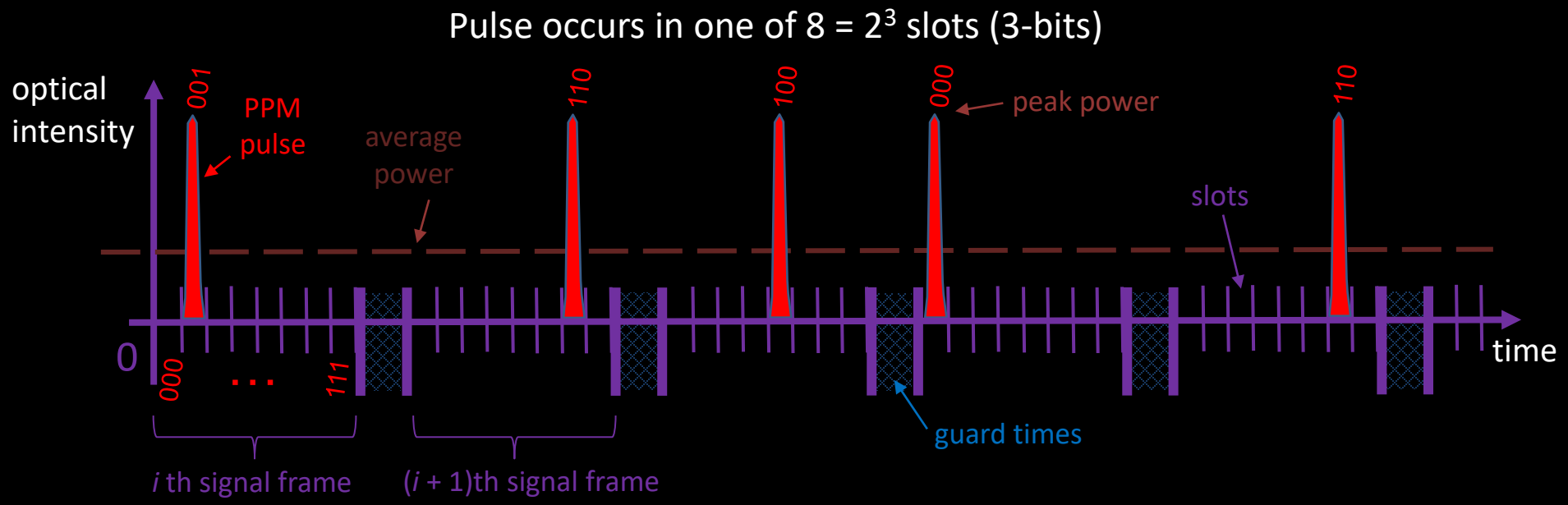


Modulating light phase: Fiber-coupled electro-optic phase modulators are utilized to enable higher Gb/s rates with Differential Phase Shift Keying (DPSK). Atmospheric effects on phase generally require adaptive optics (AO) at the ground terminals for wavefront correction.

Going toward the future: Dense Wavelength Division Multiplexing (DWDM) technology from the terrestrial telecommunications industry may be leveraged to realize many modulated FSOC channels across the link.

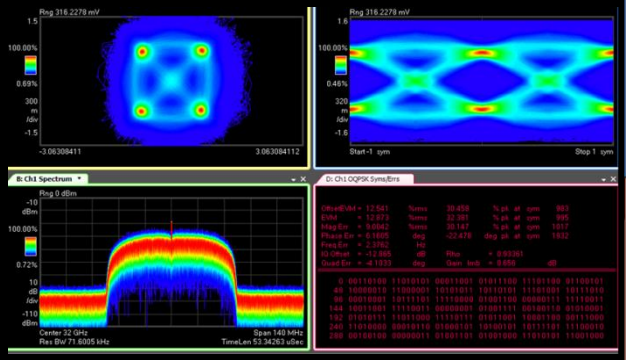


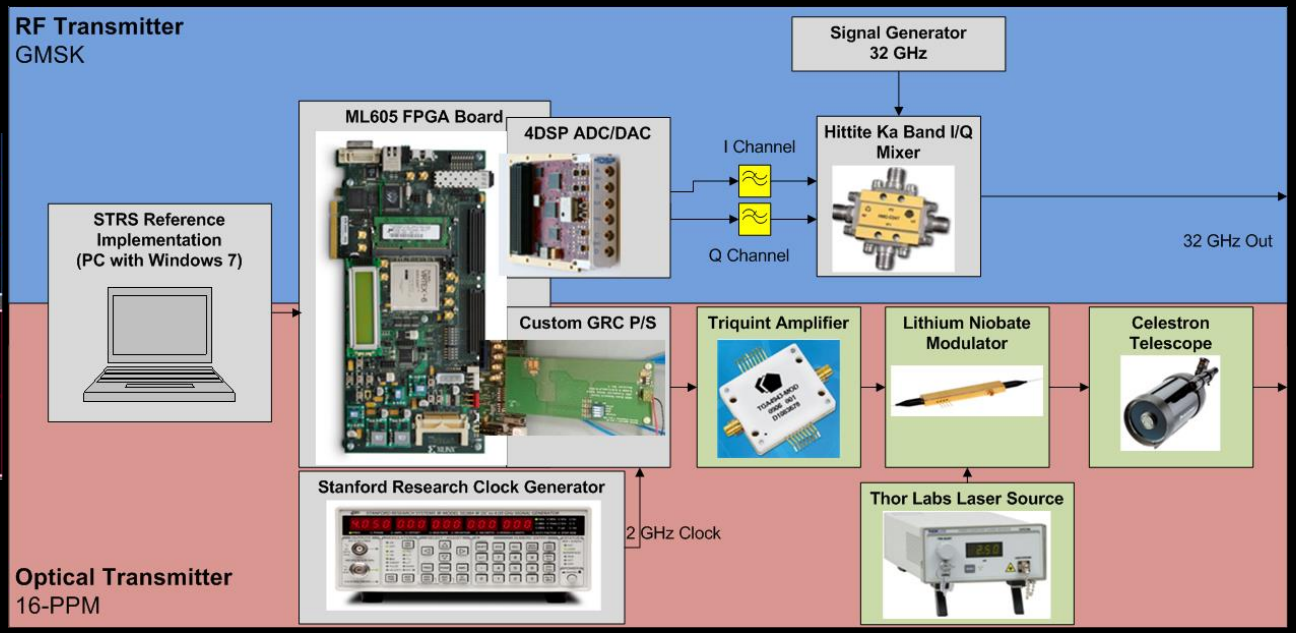
Efficient Signaling Example:
8-ary Pulse Position Modulation (PPM)



- PPM signal format allows highly efficient modulation optimal for deep space (low power)
- Results in multiple bits per single photon when used with cryogenic nanowire detectors and photon counters
- Irradiance fluctuations (scintillation) induced by atmospheric turbulence tend to be averaged out
- Very powerful Error Correction Coding (ECC) implicitly deduces when a pulse is missed or when noise fills in incorrect pulses
- Laser source pulse repetition frequency (PRF) and detector recovery time limits rate

RF / Optical Software Defined Radio (SDR)



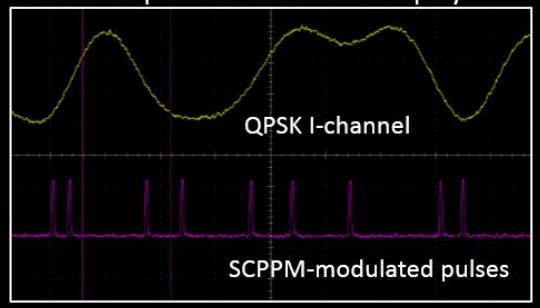


Reconfigurable hybrid RF & optical SDR

- Flexibility to reuse architecture across missions
- Reconfigurable performance during flight (modulation, error correction, encryption, etc.)
- Waveforms compliant with Space Telecomm Radio System (STRS) standards
- Commercialization through Harris Corp.



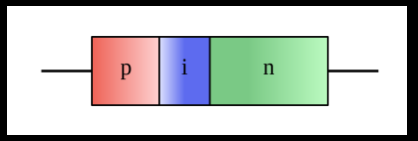
Oscilloscope Dual Waveform Display



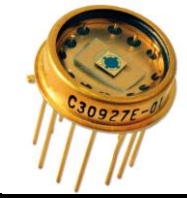
- Verified simultaneous operation of RF baseband generation and SCPPM signaling
- Platform can be used for future development of RF/Optical waveforms

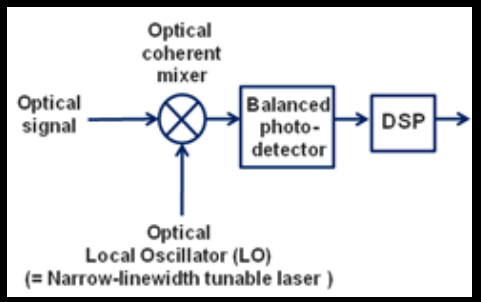
Optical Receiver Types

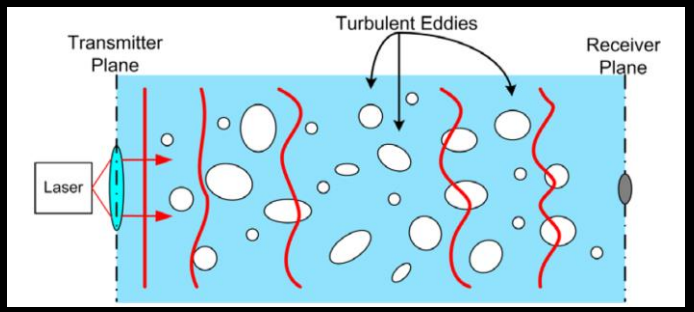
- Direct detection
  - PIN diodes — low gain, can have very high bandwidth
  - APD's — can have high gain, adds noise, medium bandwidth
  - Photon-counters — low noise, high gain detection of single photons
- Optical pre-amplifier
  - Fiber or semiconductor
  - Provides gain so can follow with high-speed PIN diode
  - Adds noise, so requires optical matches filters
- Coherent
  - Combine incoming beam with local oscillator beam
  - Detect sum on a PIN diode – difference frequency is seen as amplitude modulation
  - Quite sensitive, but complex to implement
- In general, preamps and coherent techniques require single-mode receivers
- Turbulent links support either:
  - Direct detection, or
  - Adaptive optics to create single mode beams

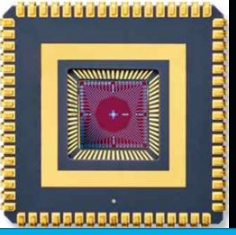


Avalanche Photodiode (APD)

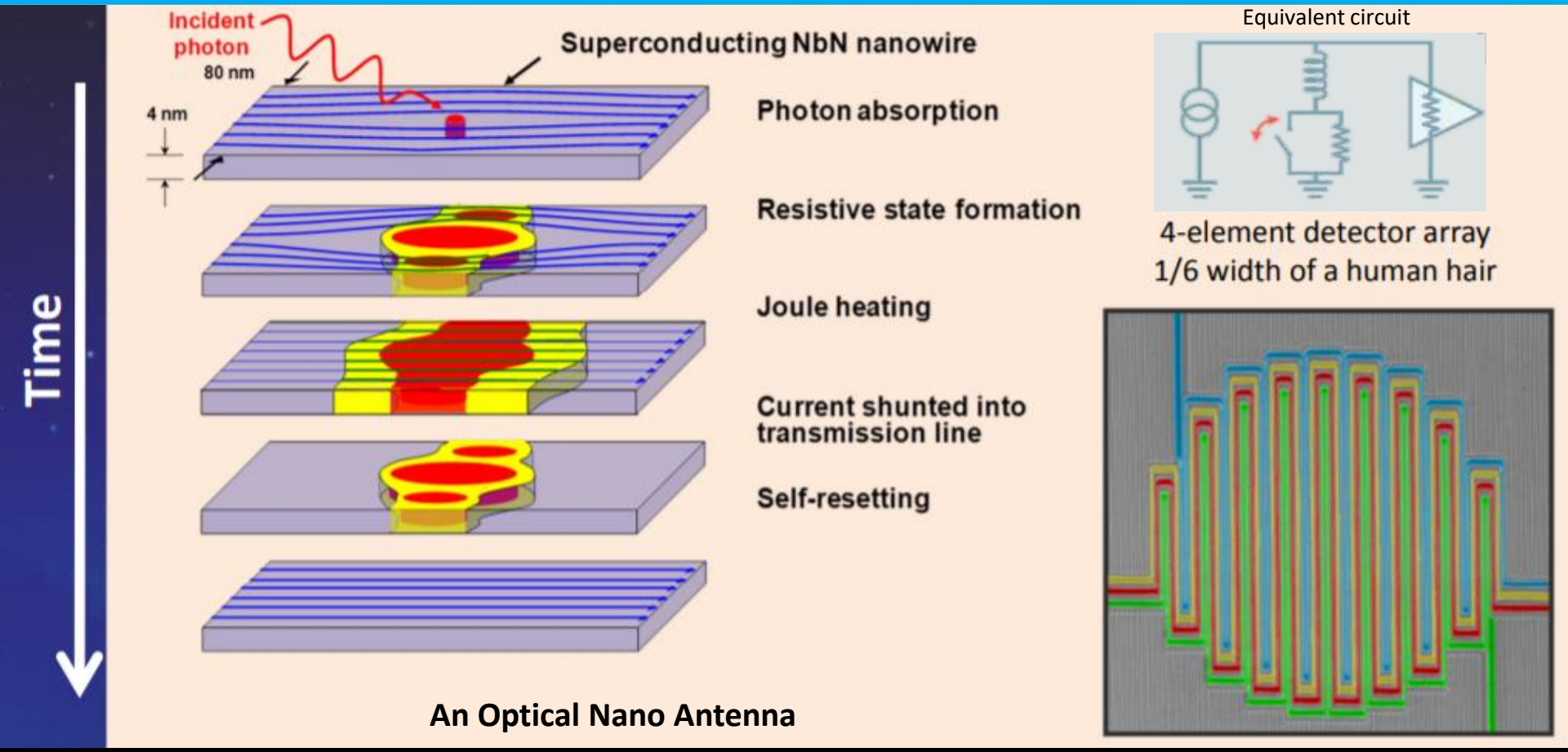








Superconducting Nanowire Single Photon Detector (SNSPD) Technology



Equivalent circuit

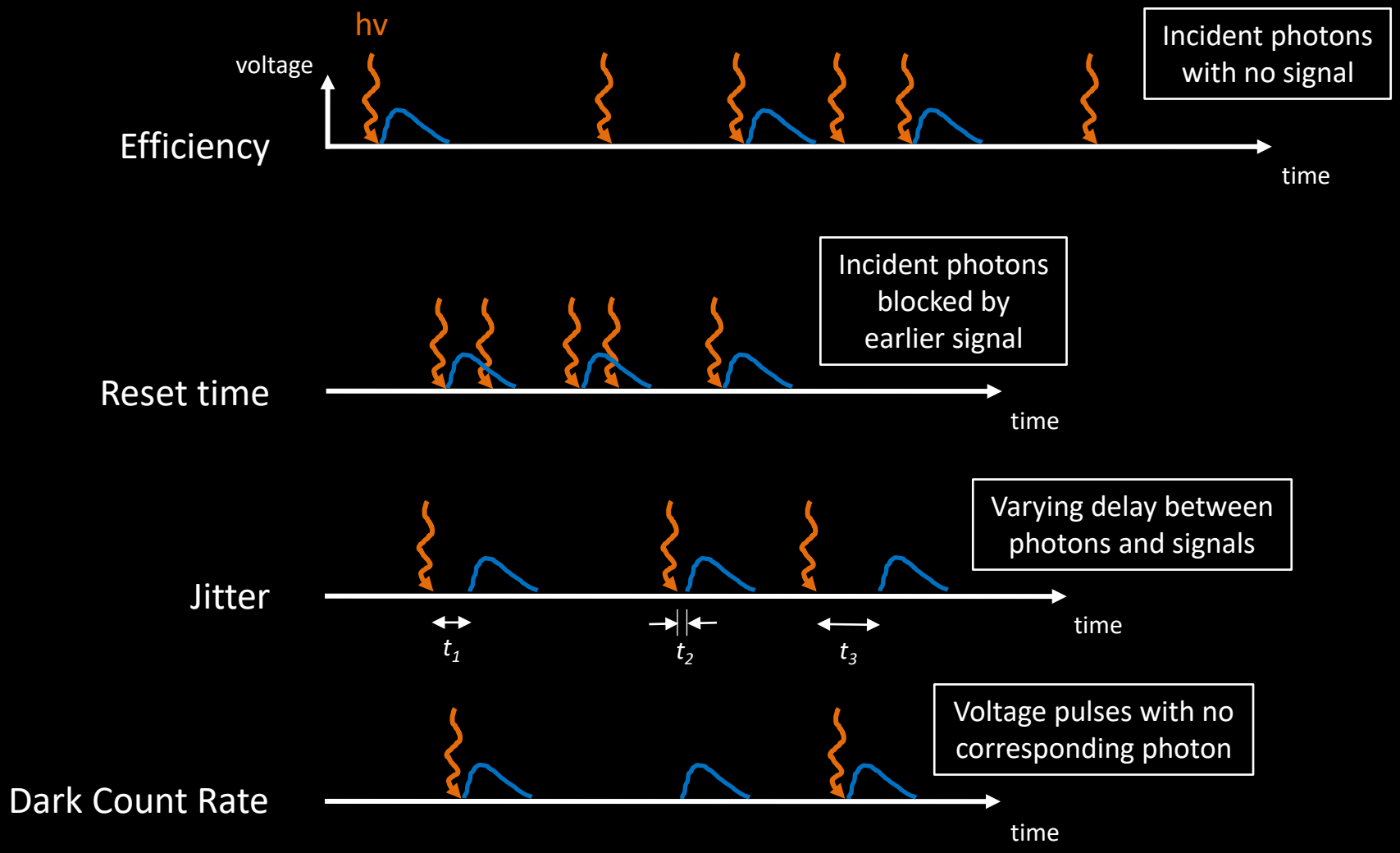
4-element detector array
1/6 width of a human hair

Cryogenic (1 - 4K) nanowire photon counting detectors

- The most sensitive instrument available for time-correlated (<80ps) single-photon detection, UV to mid-IR
- Extremely photon efficiency (~78% @ 1550nm) and thus ideal for long haul deep space communications
- Enables multiple bits of information per photon

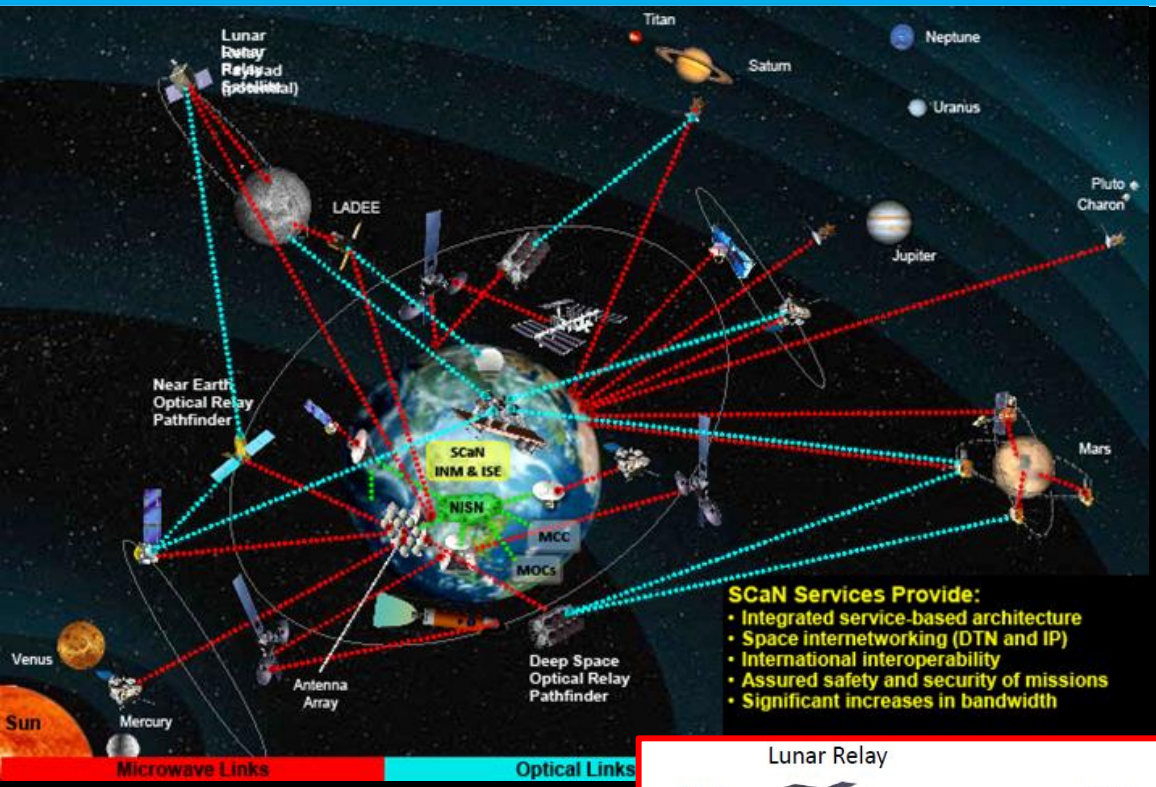
Characteristics of Photon Detectors

h = Planck's constant
v = Frequency of photon



SCaN Architectures

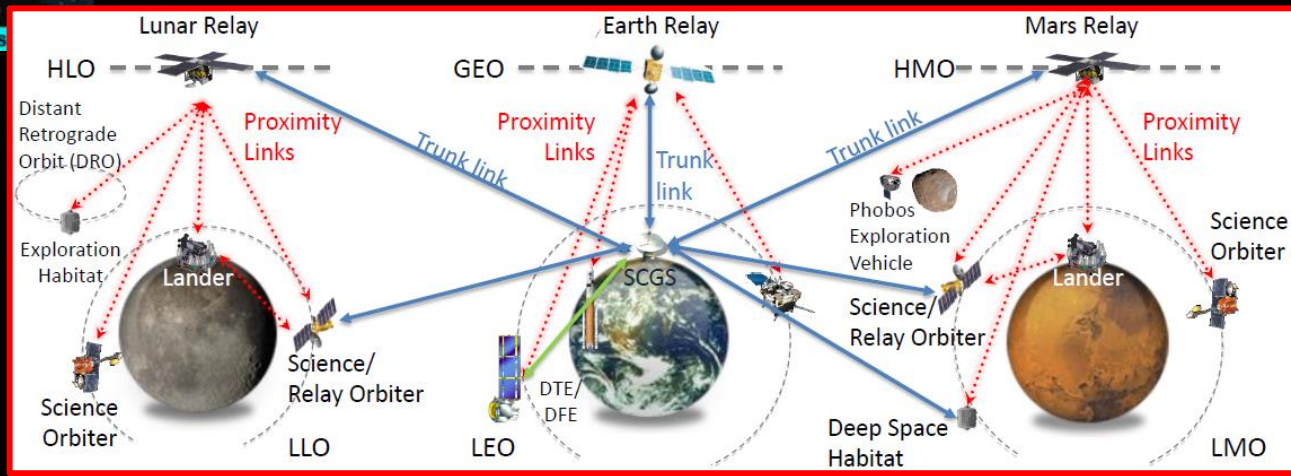
Migrating to Flexibility, Scalability and Affordability



Goals for Planetary Networks

- Reduced mission burden with short links for in-system communications, enables in-system telerobotics
- Common architecture reduces technology and development costs
- Reuse of hardware and software: family of products includes variants for different environments
- Reuse of spectrum

Network Topology Transformation



Delay/Disruption/Disconnection Tolerant Networking (DTN)

Buffers data until a transmit opportunity arises,
Where an end-to-end path may not be available

***S**tore,*
***C**arry,*
***F**orward…*

Space communication naturally exhibits several networking challenges

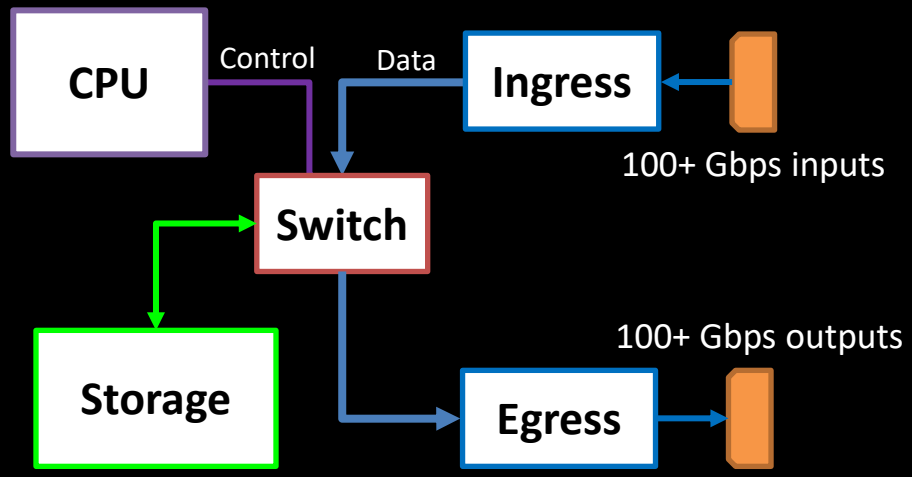
- Disconnection (*interruptions in service, can be unscheduled*)
- Buffering (*levies storage requirements on s/c*)
- Latency (*negates ACK - based protocols*)
- Security (*imparts requirements on transceivers*)

DTN approach organizes systems

- Multiple link (RF + optical) management, routing
- Ameliorates forward/return link & bus asymmetry
- Graceful optical and RF link handoffs
- Interoperability, reactive fragmentation and storage

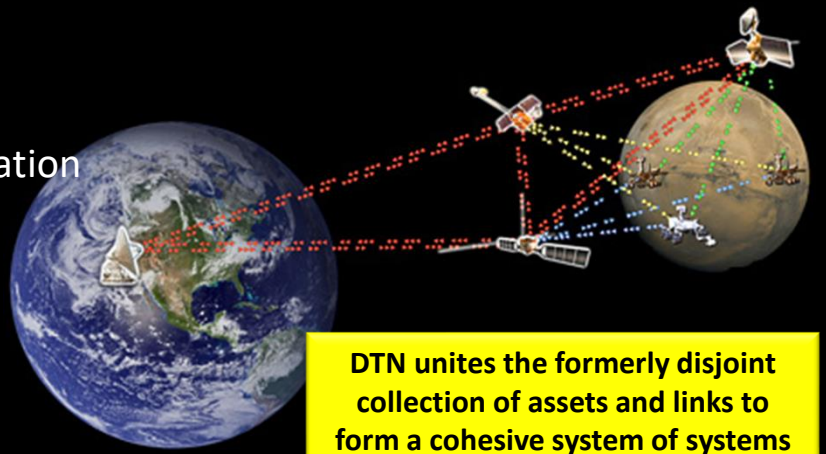
System provides functionality at two levels

- Control Plane
- Data Plane



Development Goals

- Ensure DTN is not the communications bottleneck
- Open architecture: RFC 5050 bundle protocol (BP) specification Consultative Committee for Space Data Systems (CCSDS)
- Offload burden from CPU (separate control / data plane)
  - **1 Gb/s now, 100 Gb/s later**
- **Commercialization on Harris backplane 'slice'**



DTN unites the formerly disjoint collection of assets and links to form a cohesive system of systems

Cognitive Communications

One of the Highest Priority Tech Developments

Space comm may be thought of as a multivariable optimization problem

…best suited to computations

TECHNOLOGY OBJECTIVES

- Increase the **efficiency, autonomy, and reliability** of space communication capability
- Develop innovative software, hardware, and algorithms that leverage modern advances in artificial intelligence and machine learning technology for communications
- Benefit science missions by reducing operational constraints and increasing data return

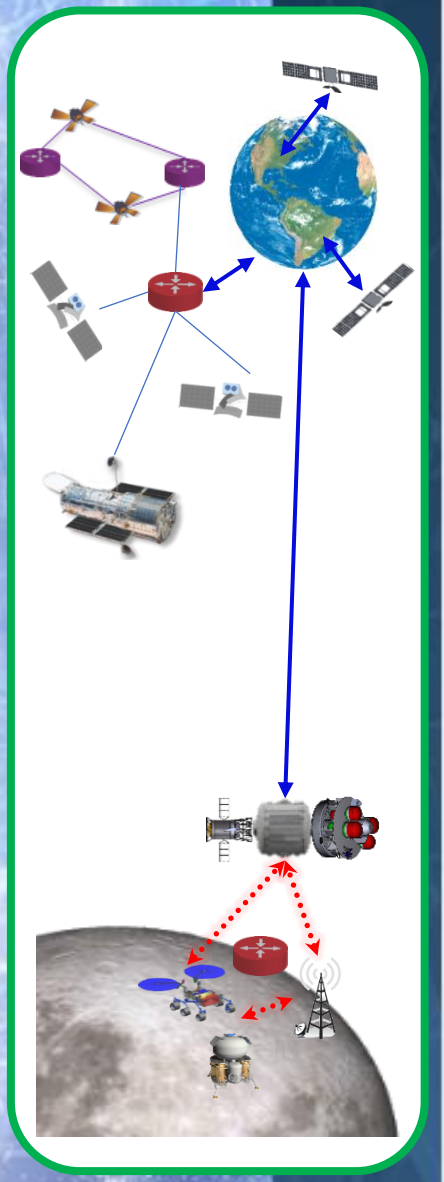
EXAMPLES OF COGNITIVE CAPABILITIES

- Real-time adaptive use of bandwidth while sensing and avoiding interference
- **Dynamic routing** between ground stations and space relays based on latency needs
- Ability to downlink data across multiple ground/space assets with automatic reassembly
- Delay-tolerant data storage, processing, and routing on-board a communications relay
- Machine-to-machine communication service requests on any available network

SUCCESSFUL OUTCOMES

- Seamless mission communication across many commercial and government networks
- Responsive service scheduling, enhancing data return and mission capability

Increased autonomy is necessary for a scalable and secure architecture – to not be beholden to unwieldy ground commanding



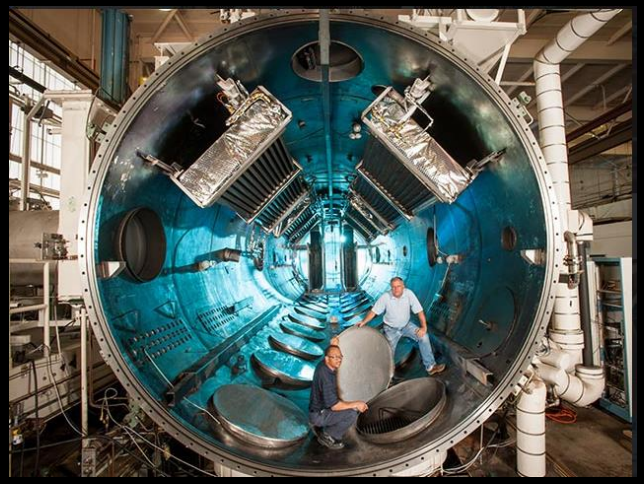
Facilities for Final Testing of Space Experiments



Electromagnetic Interference (EMI) Laboratory



Structural Dynamics – Vibration Testing



Space Environments: Thermal and Vacuum Chamber



Reverberant Acoustic Test Facility

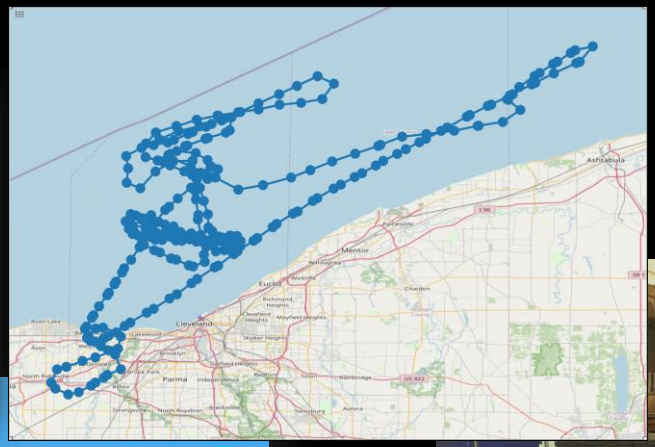


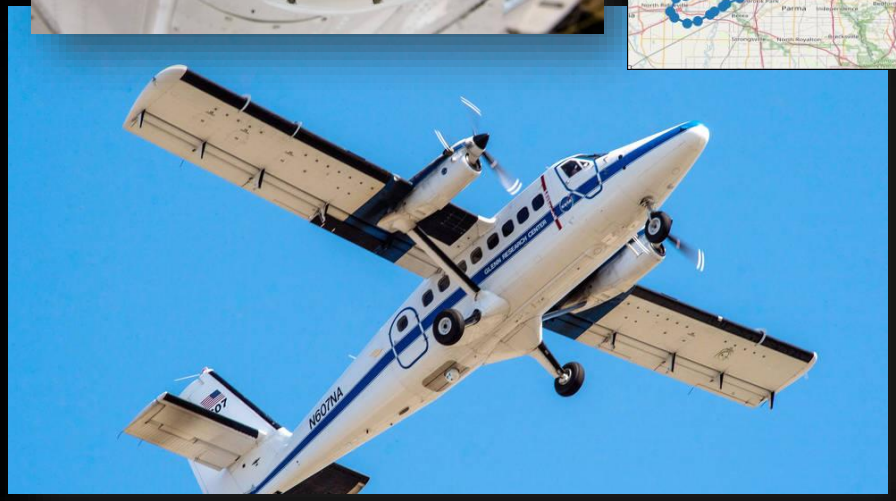
Lunar Laser Communications Demonstration (LLCD) 2013

- LLCD flew on Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft
- 250 km lunar orbit
- 3 month science mission

Aircraft Flight Demonstration 2019 - 2021







NASA Twin Otter Aircraft with Laser Terminal

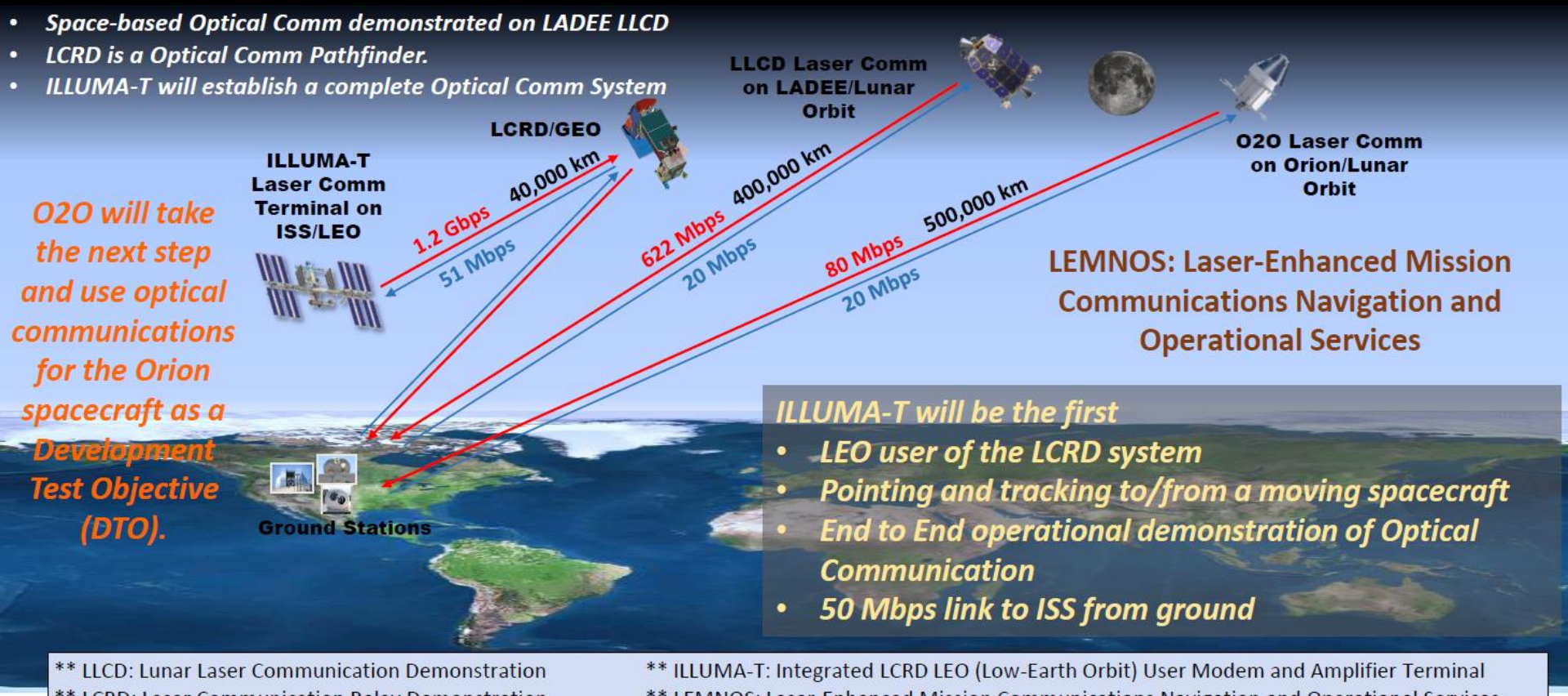


Laser Ground Terminal near GRC hangar

- Successfully conducted laser communications flight testing on GRC aircraft
- Supported link testing for quantum communications
- Achieved near-Gbps rates to/from ground terminal
- Exchanged TB of hyperspectral data over multiple days
- Communicated across obscuration interruptions such as landing gear, trees, etc.

Upcoming: Optical Communications Technology Demonstration Plan

- *Space-based Optical Comm demonstrated on LADEE LLCD*
- *LCRD is a Optical Comm Pathfinder.*
- *ILLUMA-T will establish a complete Optical Comm System*



O2O will take the next step and use optical communications for the Orion spacecraft as a Development Test Objective (DTO).

LEMNOS: Laser-Enhanced Mission Communications Navigation and Operational Services

ILLUMA-T will be the first

- *LEO user of the LCRD system*
- *Pointing and tracking to/from a moving spacecraft*
- *End to End operational demonstration of Optical Communication*
- *50 Mbps link to ISS from ground*

** LLCD: Lunar Laser Communication Demonstration
** LCRD: Laser Communication Relay Demonstration
** O2O: Orion EM2 Optical Communications Terminal
** ILLUMA-T: Integrated LCRD LEO (Low-Earth Orbit) User Modem and Amplifier Terminal
** LEMNOS: Laser-Enhanced Mission Communications Navigation and Operational Services

Upcoming: Discovery Mission 14 “Psyche”

Arizona State University

- Asteroid belt mission to the M-type 16 Psyche (252 km diameter), believed to be the exposed iron core of early protoplanet likely the remnant of violent collision stripping off outer crust
- Goal to understanding the processes of solar system formation; not possible on existing planetary bodies due to geologic activity
- Primary payload instruments: multispectral imager, magnetometer and gamma-ray & neutron spectrometer, radio gravity experiment
- 20 month duration, focusing on studies of the asteroid's gravity, composition and topography
- Solar electric propulsion system with Hall-effect thruster
- Will demonstrate Deep Space Optical Communications (DSOC)





Prototype DSOC payload

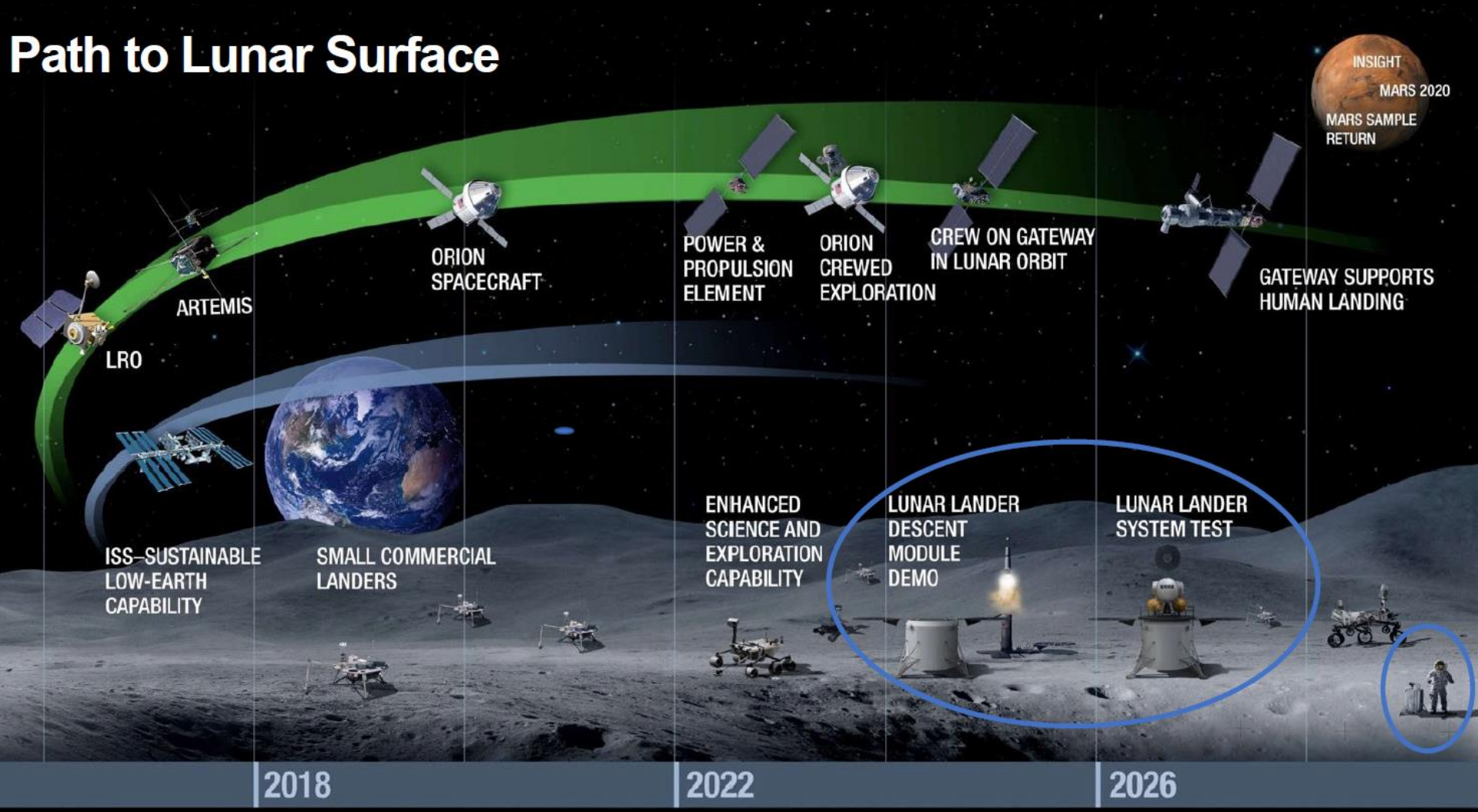


What will this heterogeneous network look like?

Human and Robotic Space Exploration

Where We Are Going

The path will depend heavily on both COTS systems and commercially provided services, so interoperability is paramount



How will a mixture of gov, commercial, academic & international assets protect from each other?

Ways to Participate

- Small Business Innovation Research Program
  - H9.01 - Long Range Optical Telecommunications
  - H9.03 - Flight Dynamics and Navigation Technology
  - H9.05 - Transformational Communications Technology
  - H9.07 - Cognitive Communications subtopic
  - H6.22 - Neuromorphic Processing subtopic
- NASA Contracting and Agreement Mechanisms
  - Space Act Agreement – Non-Reimbursable (no transfer of funds)
  - Space Act Agreement – Reimbursable (NASA receives funding)
  - Cooperative Agreement – 50/50 cost share for joint research
  - Contract – Payment for R&D activities
- Academic Collaborations
  - Faculty fellowships
  - Intern programs (LERCIP, USRP, GSRP)
  - Postdoctoral research
- Informal Discussions
  - Technical Workshops, e.g. Cognitive Communications for Aerospace Applications
  - Communications Division – Distinguished Technical Lecture Series
  - Project-level discussions

NASA Internships https://intern.nasa.gov/

- Internships are available from high school to graduate level
- Most interns receive a stipend award
- Interns are selected and placed for fall, spring and summer sessions
- Applications may be made to specific projects at Center locations, or Agencywide





Thank you for your kind attention!

