Recent Efforts in Advanced High Frequency Communications at the Glenn Research Center in Support of NASA Mission

By

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Abstract

This presentation will discuss research and technology development work at the NASA Glenn Research Center in advanced frequency communications in support of NASA's mission. An overview of the work conducted in-house and also in collaboration with academia, industry, and other government agencies (OGA) in areas such as antenna technology, power amplifiers, radio frequency (RF) wave propagation through Earth's atmosphere, ultra-sensitive receivers, among others, will be presented. In addition, the role of these and other related RF technologies in enabling the NASA next generation space communications architecture will be also discussed.

Outline

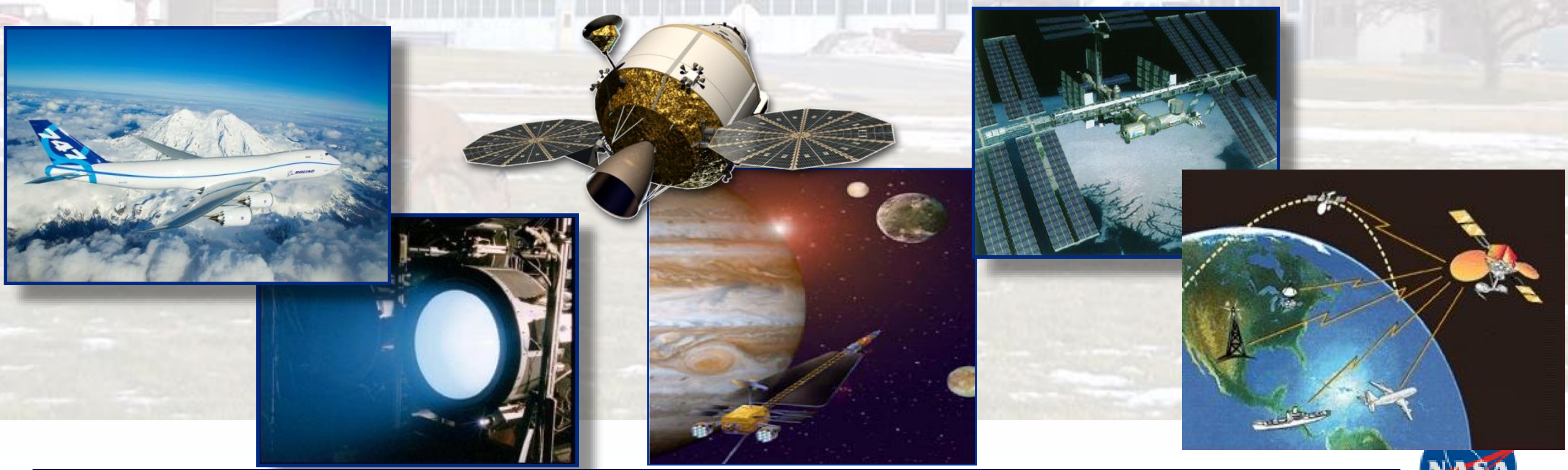
- NASA and Glenn Research Center Mission and Vision
- Brief Overview of NASA GRC
- Examples of Activities RF Communications
  - RF Propagation
  - Large Aperture Deployable Antennas
  - Phased Array Antennas: Ferroelectric Reflectarray Antenna
  - Power Amplifiers
  - Optical Communications
  - Low TRL Game Changing Technologies: SQIF
- Conclusions

Vision and Mission

- NASA Vision: To reach for new heights and reveal the unknown, so that what we do and learn will benefit all humankind

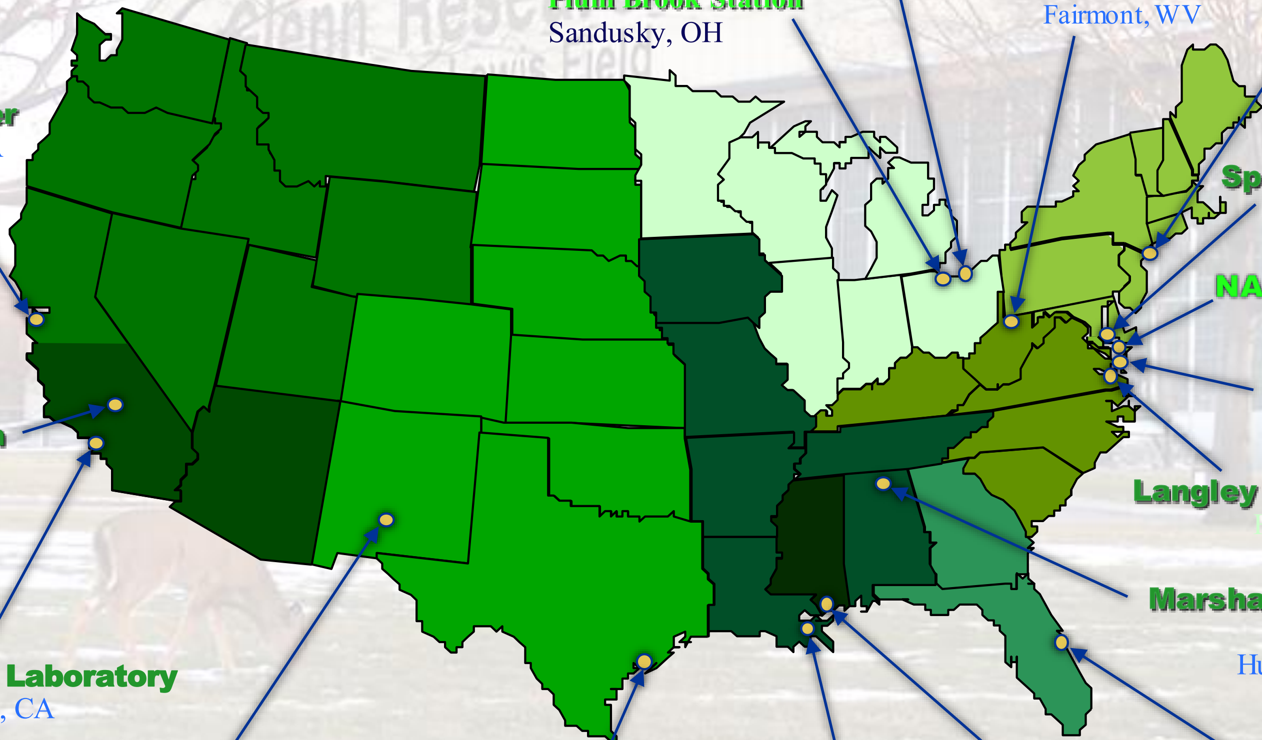
- NASA Mission: Drive advances in science, technology, and exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of the Earth

Glenn's Mission: We drive Research, Technology, and Systems to advance Aviation, enable Exploration of the Universe, and Improve Life on Earth



NASA Centers and Installations

Deep Space Network Facilities
- Goldstone, in CA Mojave Desert
- Near Madrid, Spain
- Near Canberra, Australia



Glenn Research Center Campuses

Lewis Field (Cleveland)

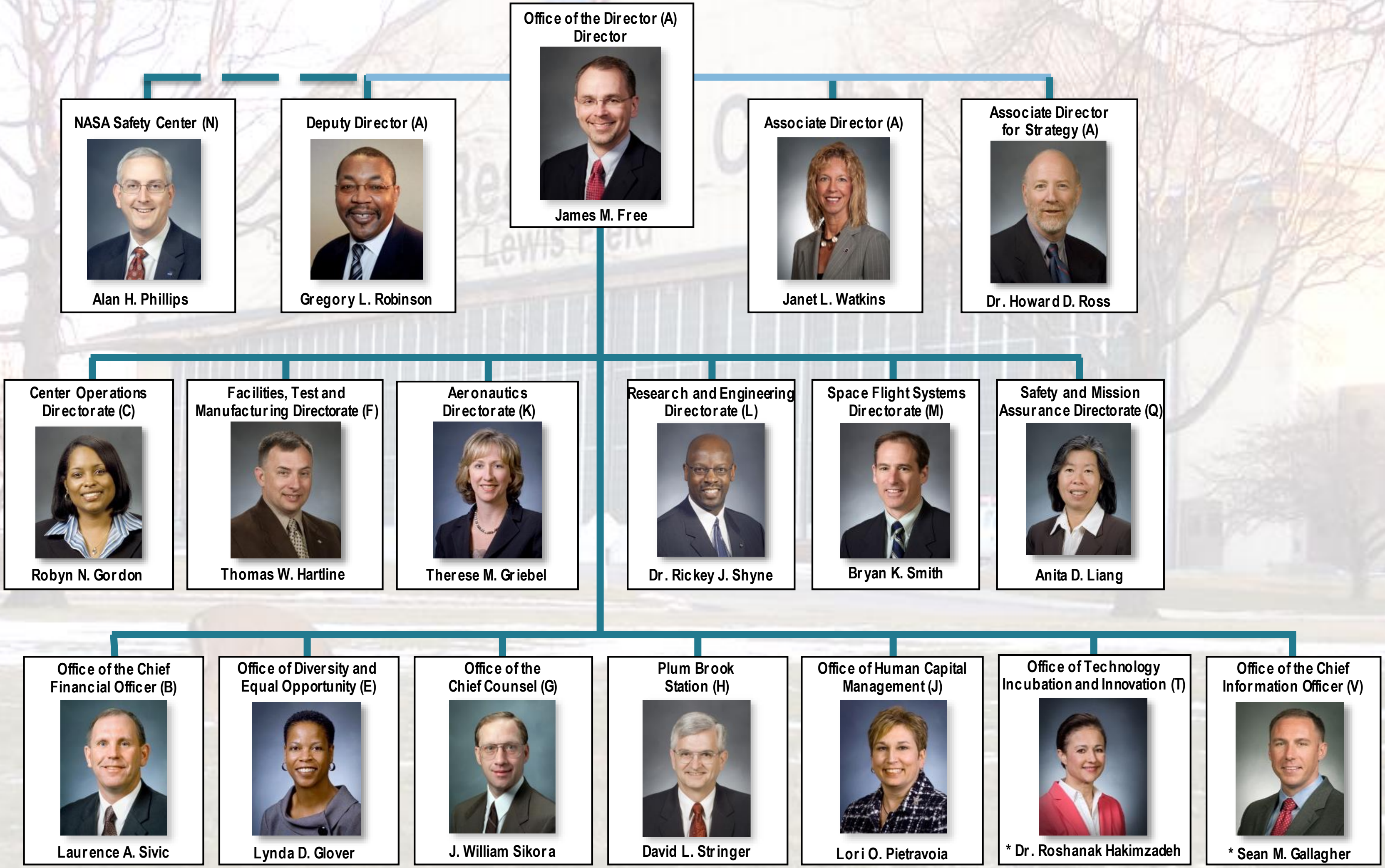
- 350 acres
- 1626 civil servants and 1511 contractors
- 66% of the workforce are scientists and engineers

Plum Brook Station (Sandusky)

- 6500 acres
- 11 civil servants and 102 contractors

as of 1/2013

NASA Glenn Research Center Senior Management



* Acting

Research & Engineering Directorate Leadership Team

Deputy Director of Research and Engineering (L)

Dr. Marla Pérez-Davis

Director of Research and Engineering (L)

Dr. Rickey J. Shyne

Associate Director of Research and Engineering (L)

Maria Babula

Chief Engineer Office (LA)

Richard T. Manella

Management Support and Integration Office (LB)

Kathy K. Needham

Communications and Intelligent Systems Division (LC)

*Dr. Mary V. Zeller

Power Division (LE)

Randall B. Furnas

Materials and Structures Division (LM)

Dr. Ajay K. Misra

Systems Engineering and Architecture Division (LS)

Derrick J. Cheston

Propulsion Division (LT)

Dr. George R. Schmidt

*Acting

Glenn Core Competencies

Air-Breathing Propulsion

In-Space Propulsion and Cryogenic Fluids Management

Physical Sciences and Biomedical Technologies in Space

Communications Technology and Development

Power, Energy Storage and Conversion

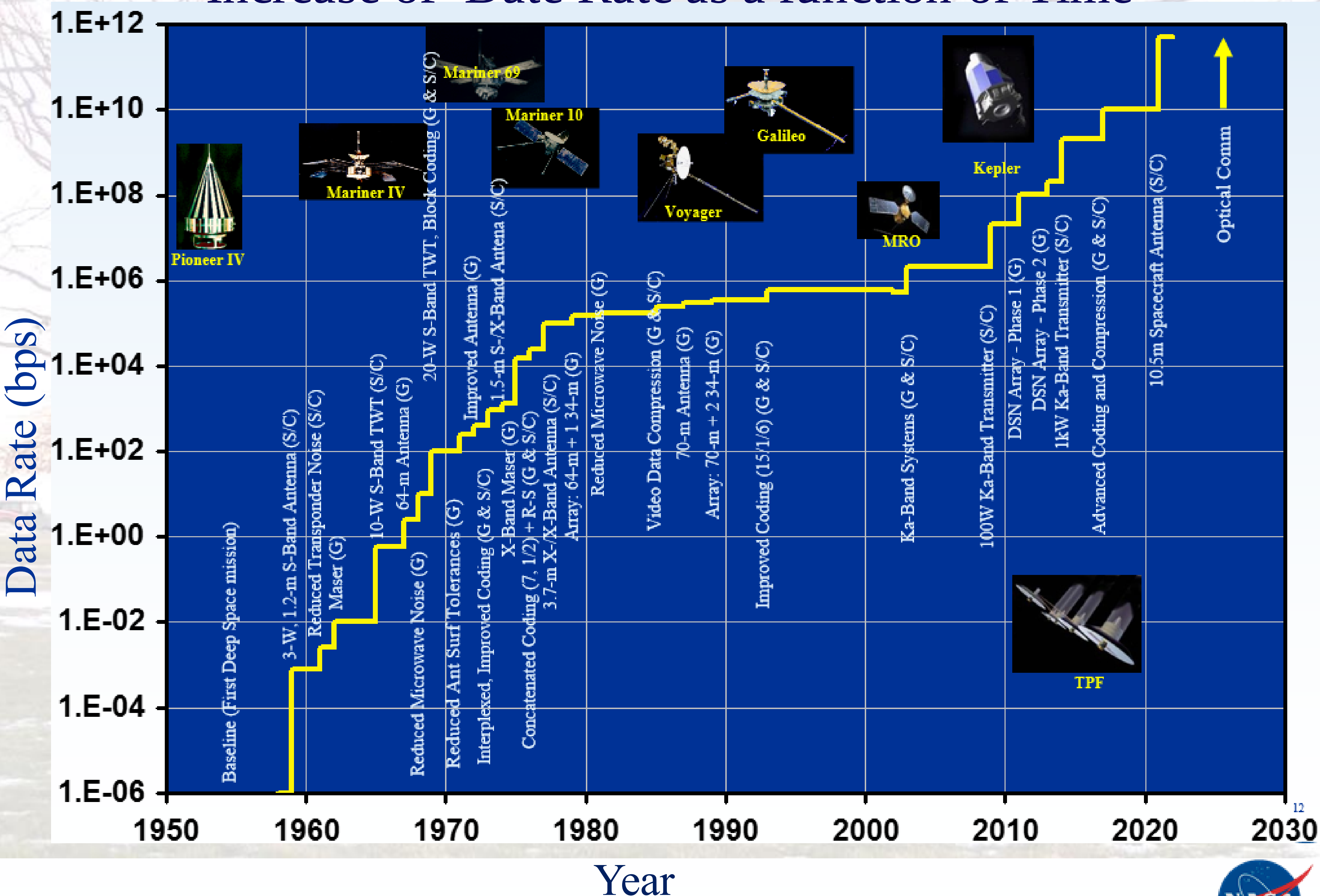
Materials and Structures for Extreme Environments

Importance of Communication

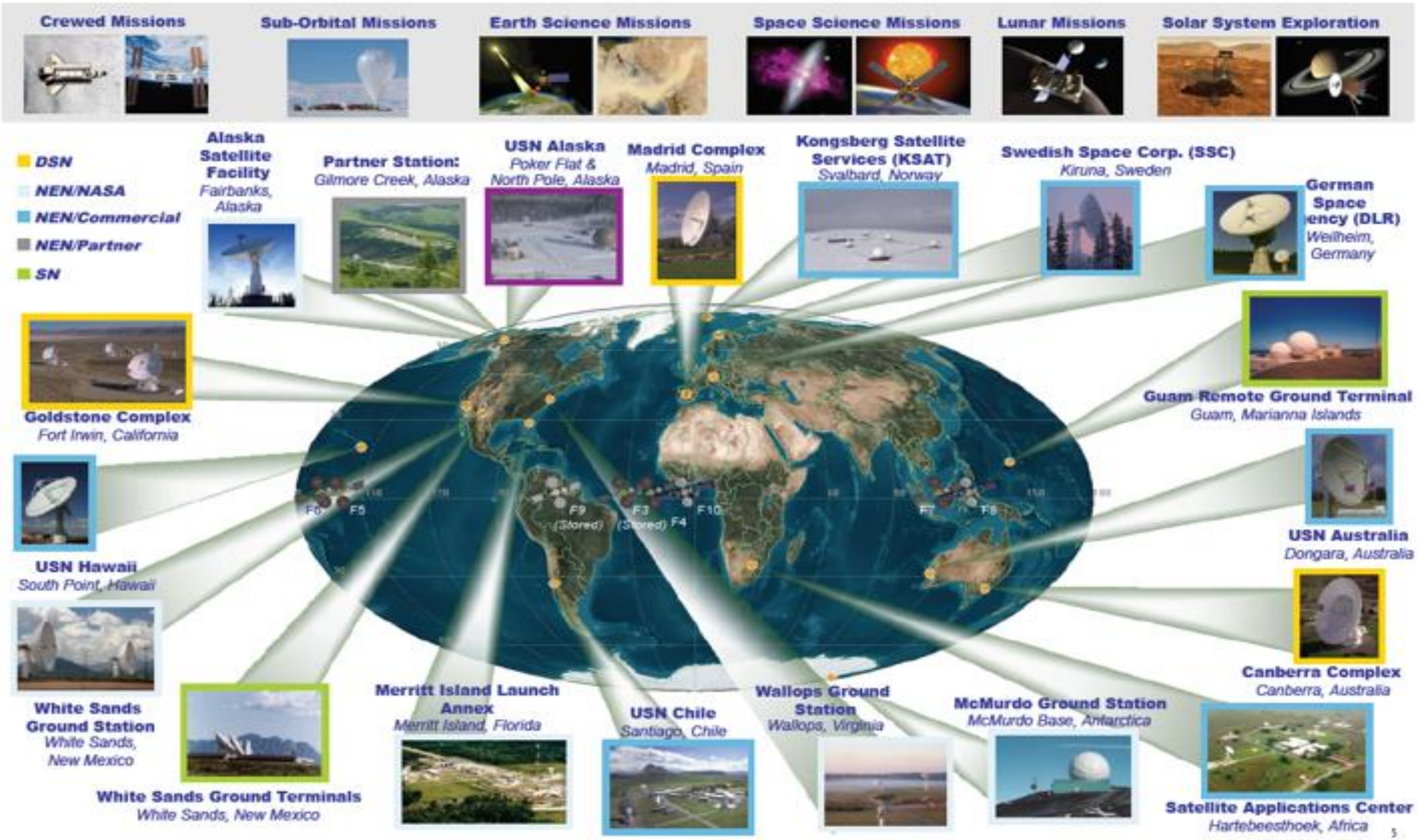
Enable Communications with:

- Humans in the space environment
- Spacecraft
- Planetary Surface (e.g., Rovers)

Increase of Date Rate as a function of Time



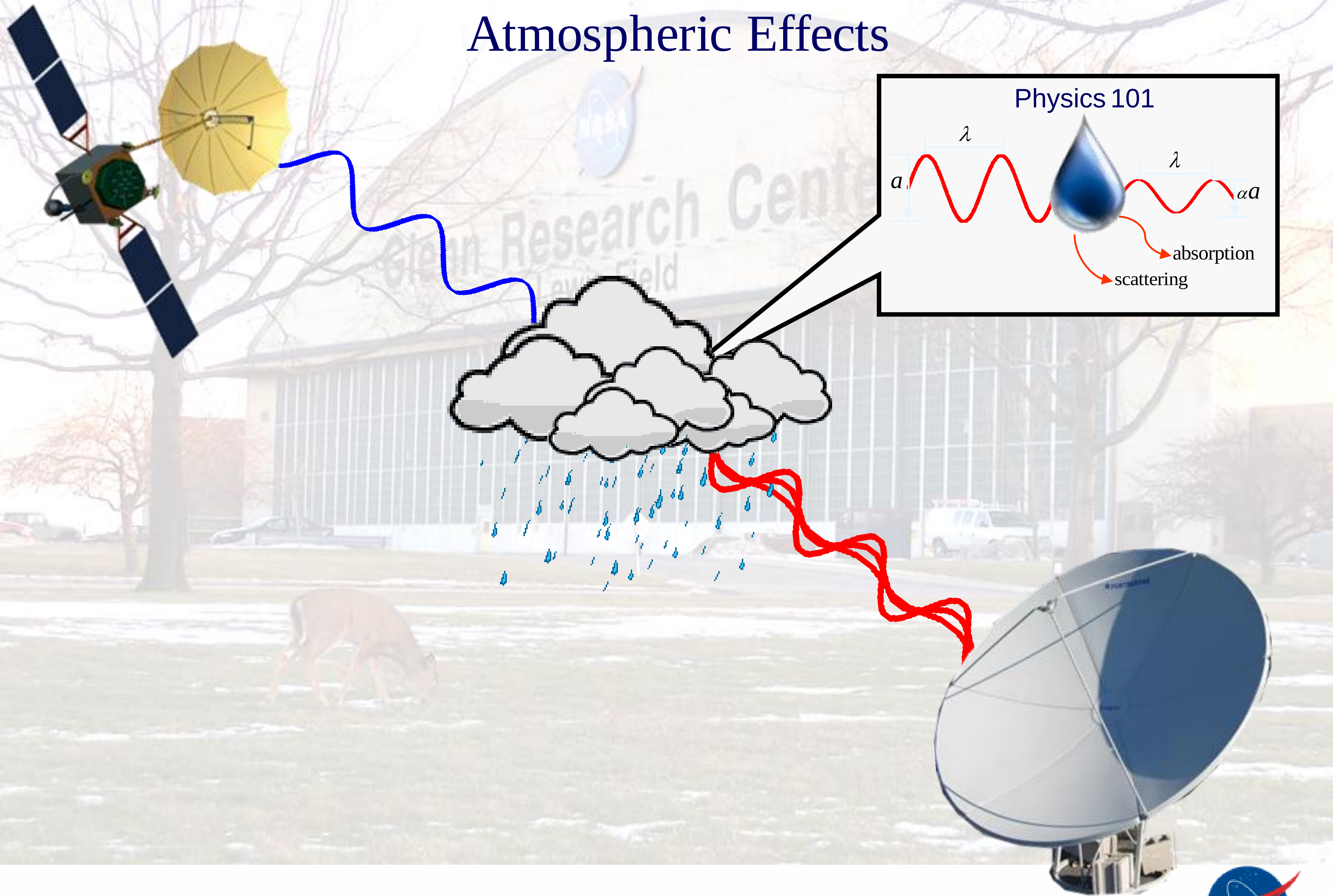
Space Communication and Navigation Operational Network



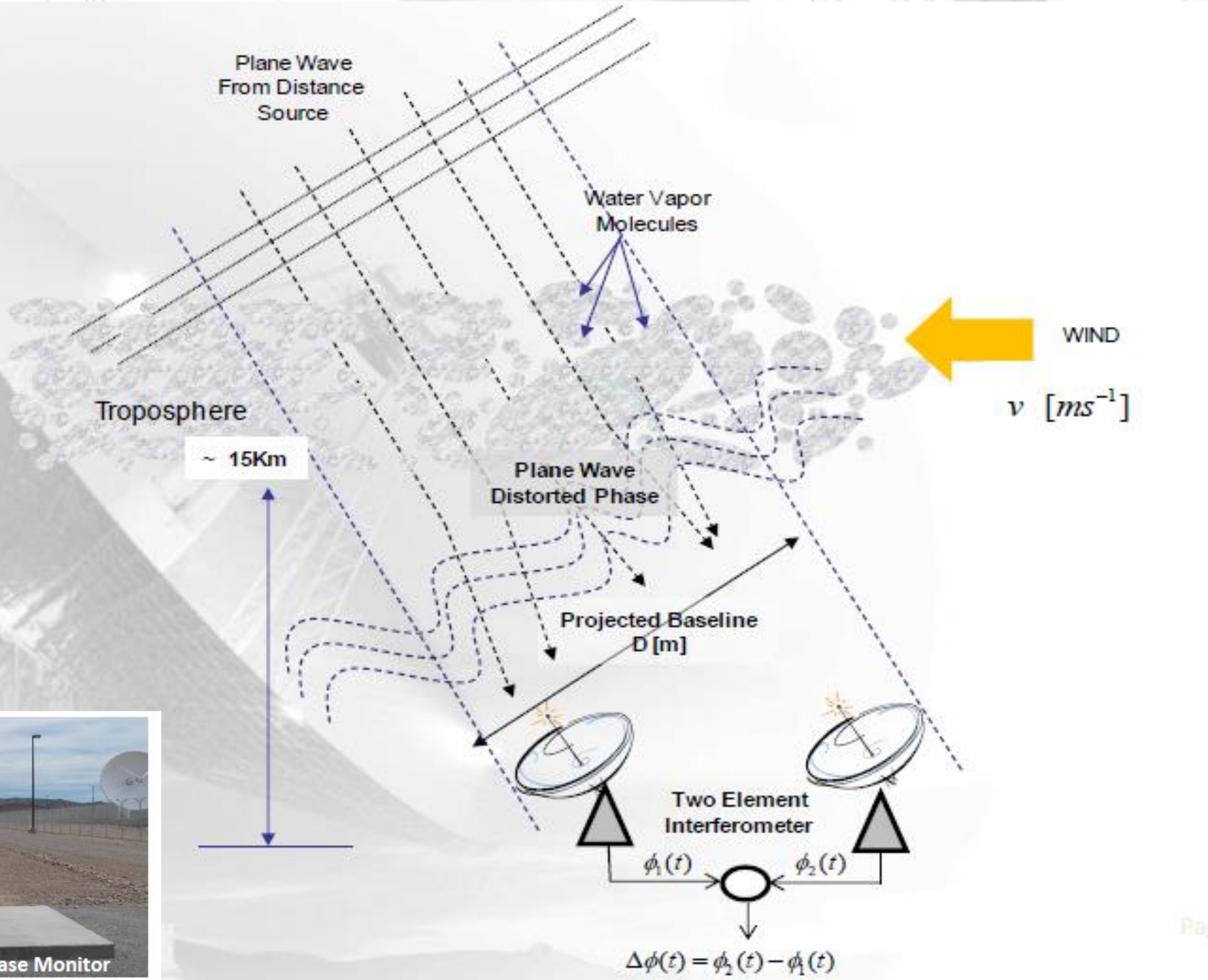
Examples Advanced High Frequency Technologies & Capabilities

RF Propagation

Atmospheric Effects

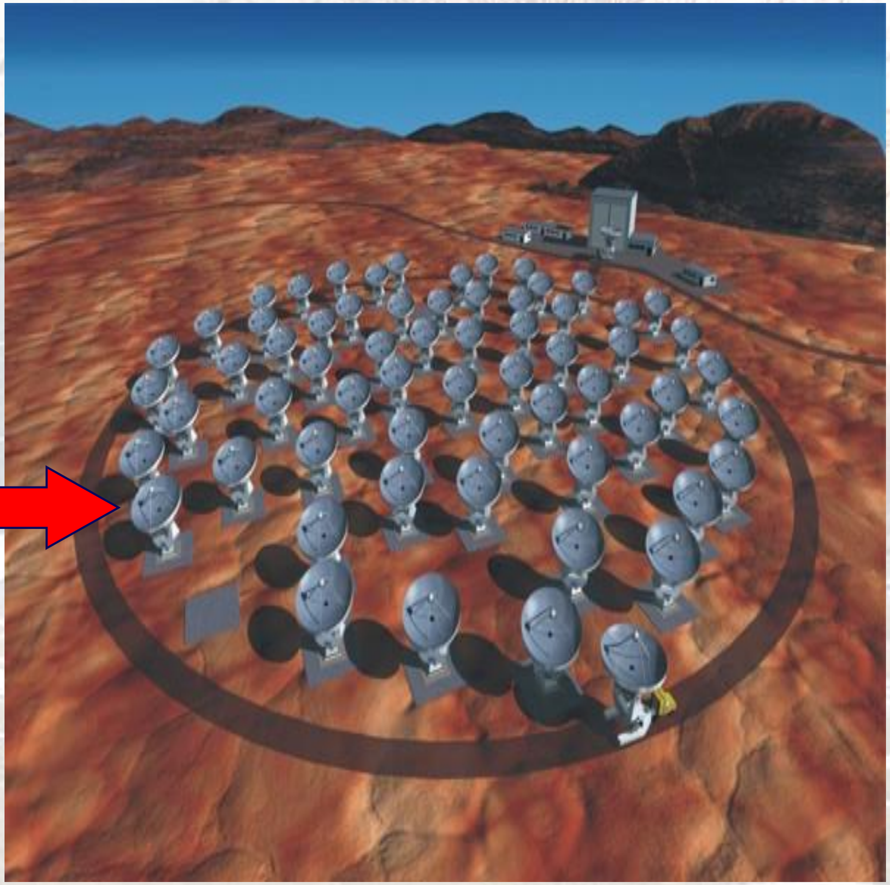


Problem Statement



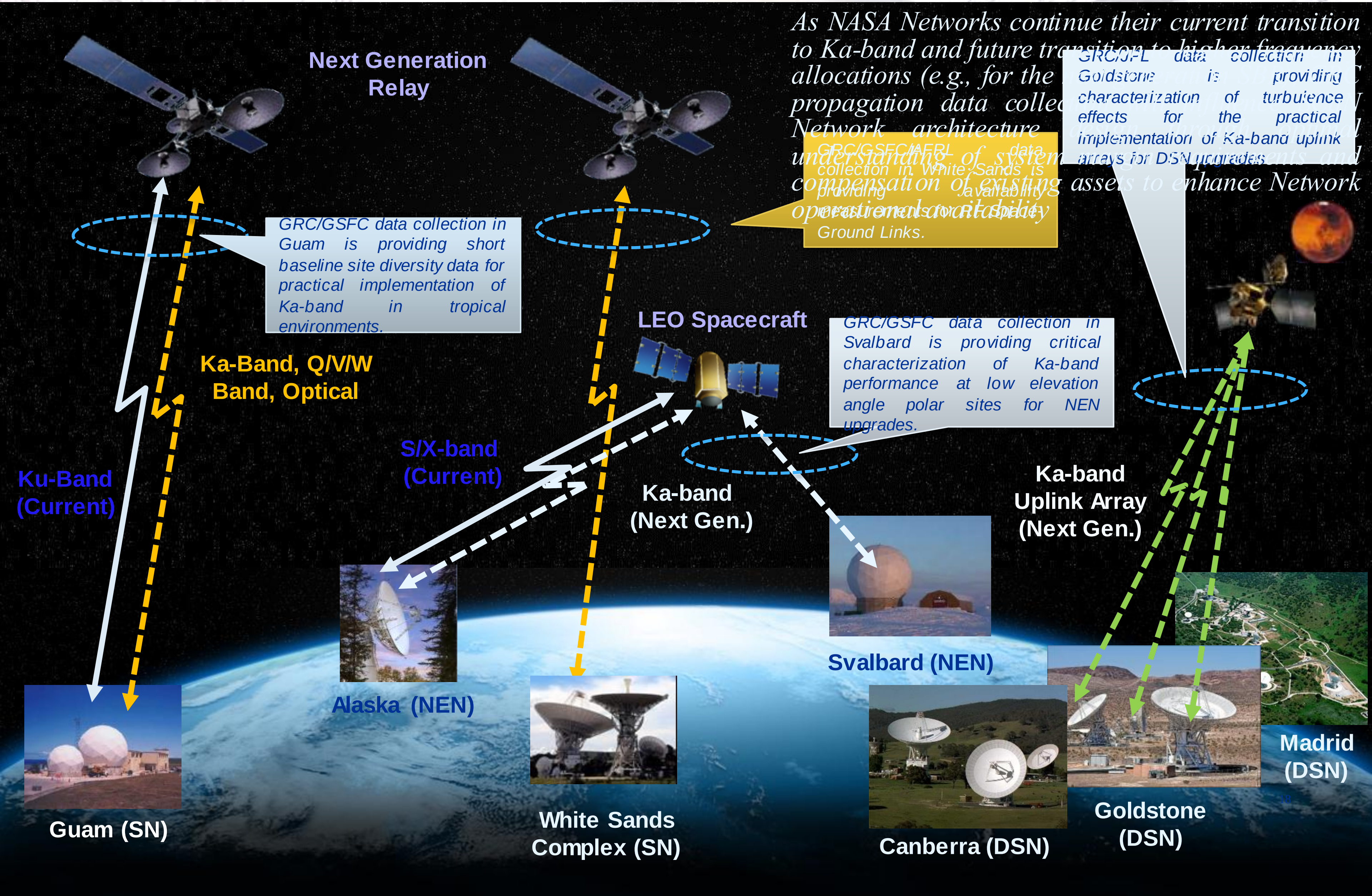
Next Generation Deep Space Network (DSN)

Single Large Aperture Antenna



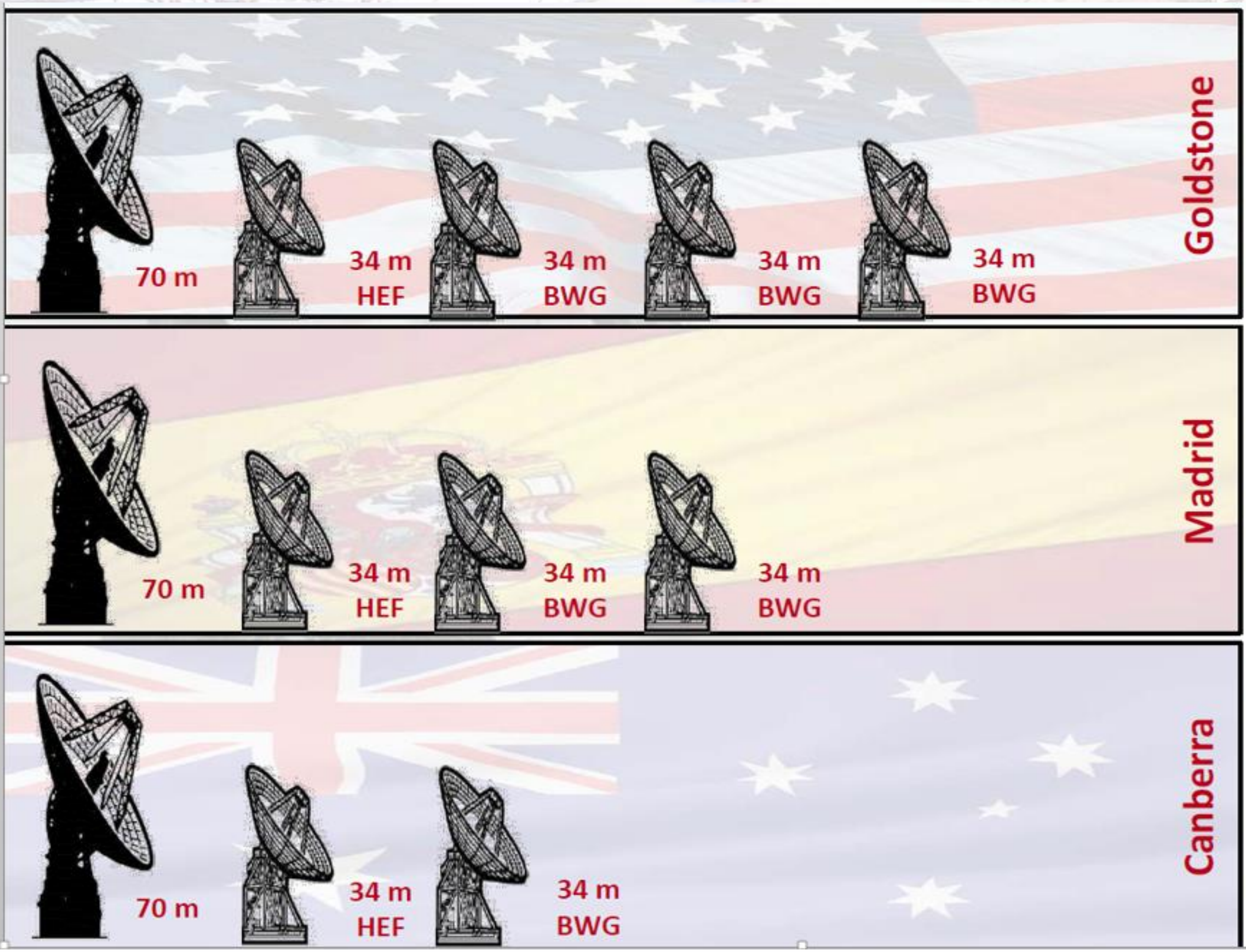
Smaller Aperture Antenna Array

Propagation Studies Relevance and Impact



Deep Space Network (DSN)

Deep Space Network (DSN) Enhancement Project



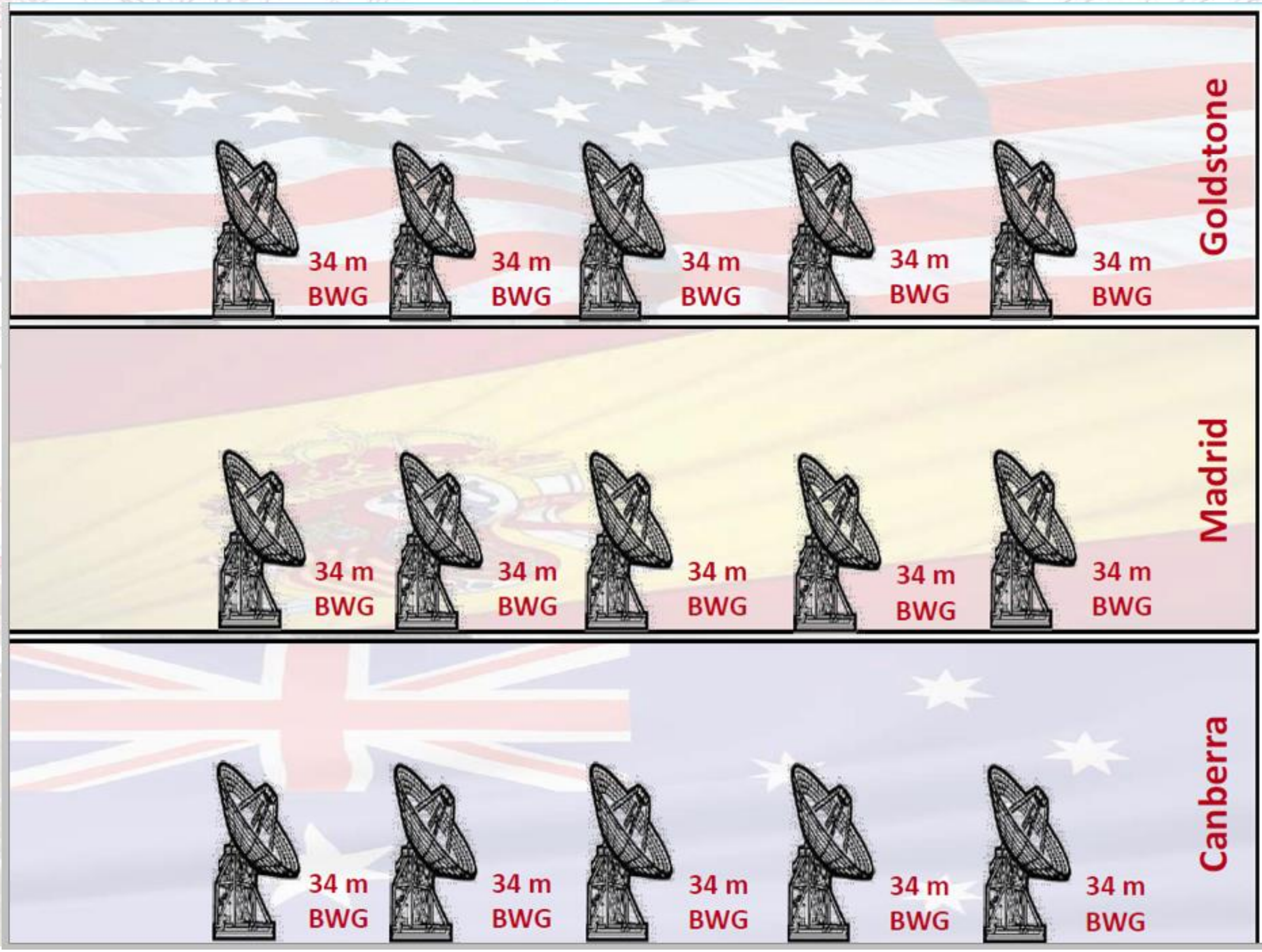
DSN Configuration: Today

Each ground station has:

- one 70m antenna
- one 34m High Efficiency antenna (HEF)
- one or more Beam Wave Guide (BWG) antennas.

- HEF antennas were built in the 1980's and were the first to support X-band uplink.
- BWG antennas were built in the 1990's and route energy between the reflector and a room below ground which allows for many feeds and amplifiers at multiple frequencies to be illuminated selectively by a mirror.

Deep Space Network (DSN) Enhancement Project



DSN Configuration: 2025

By 2025, the 70 meter antennas at all three locations will be decommissioned and replenished with 34 meter BWG antennas that will be arrayed.

All systems will be upgraded to have X-band uplink capabilities and both X- and Ka-band downlink capabilities.

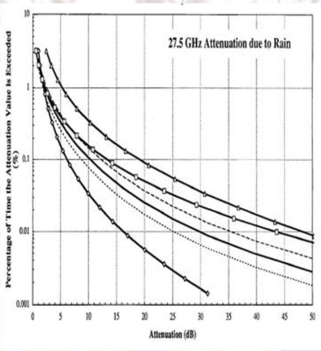
Current NASA Network Characterization Sites

In the post-ACTS era, NASA propagation activities have primarily focused on site characterization of NASA operational networks throughout the world.

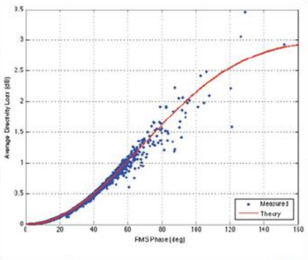
RF Propagation – The Road From Idea to Deployment

mm-wave Propagation Studies: 2012-Future

GRC undertakes expansion of mm-wave frontier via propagation activities in the Q/V/W bands



ACTS Propagation Data instrumental in development of ITU-R attenuation models



Phase measurements implemented in array loss predictions

Q-band Radiometer

mmWave Propagation

Svalbard (NEN)

Guam (SN)

White Sands, NM (SN)

Goldstone, CA (DSN)

Evolution of GRC Propagation Terminals

Real-Time Compensation: 2012-2016

SCaN funded effort to integrate real-time compensation techniques into NASA network operations

ACTS Propagation Terminal

Atmospheric Phase Studies: 2004 – Present

Characterization of atmospheric phase noise is studied to identify suitable sites for Uplink Arraying Solution to large aperture 70-m class antenna issues with Deep Space Network. GRC, in collaboration with JPL and GSFC, leads the characterization of atmospheric-induced phase fluctuations for future ground-based arraying architecture

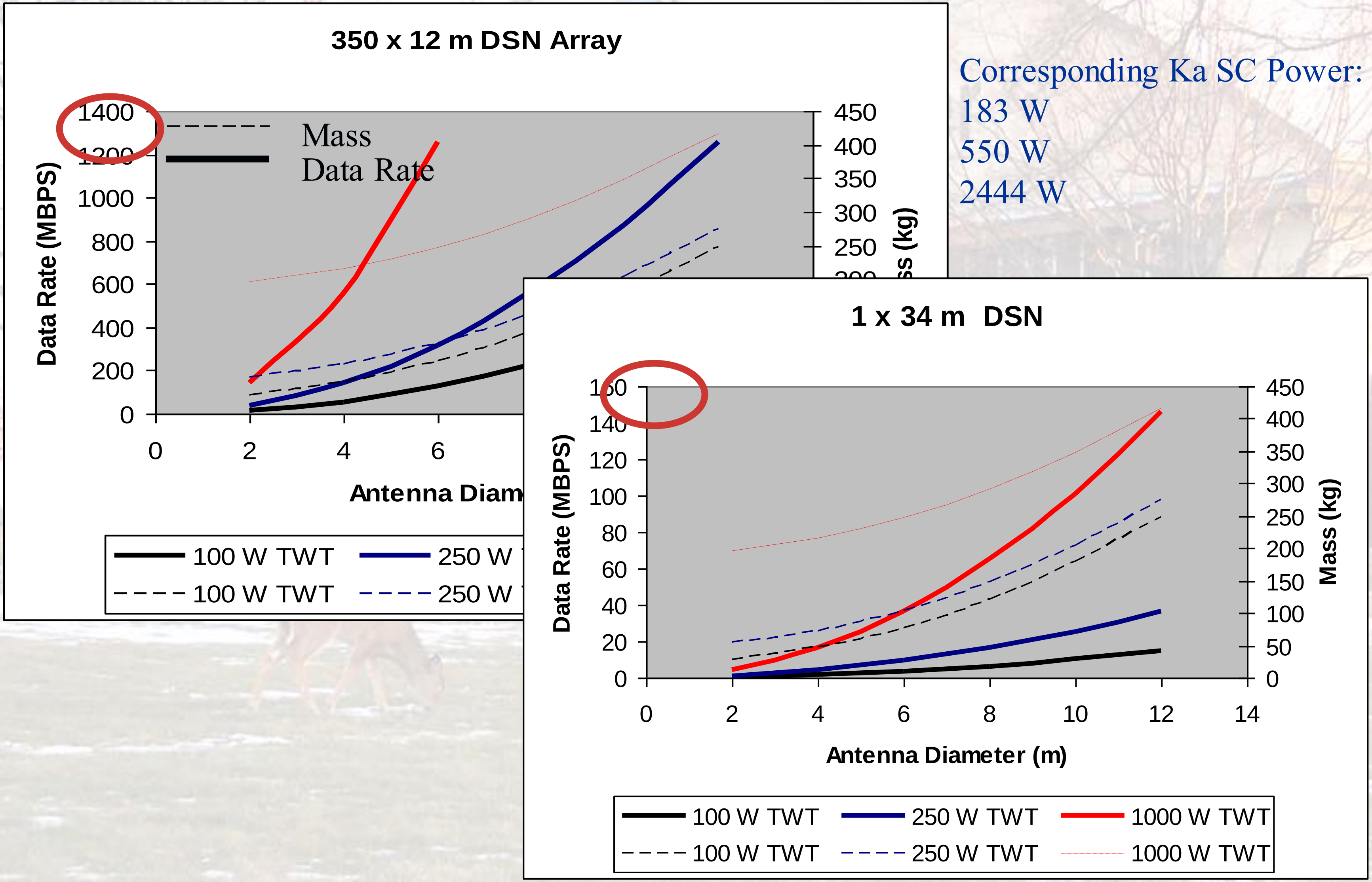
ACTS Satellite

Atmospheric Attenuation Studies: 1993 – 2002

Propagation studies were undertaken by NASA to determine the effects of atmospheric components (e.g., gaseous absorption, clouds, rain, etc.) on the performance of space communication links operating in the Ka-band. Sites throughout the Continental US and Puerto Rico were characterized.

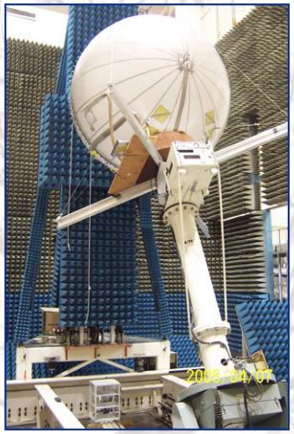
Large Aperture Deployable Antennas

Rationale For Large Deployable Antenna Task



Corresponding Ka SC Power:
183 W
550 W
2444 W

Large Aperture Deployable Antennas



Prototype Inflatable Radome Antenna System at GRC

In The Field: 2009-2010

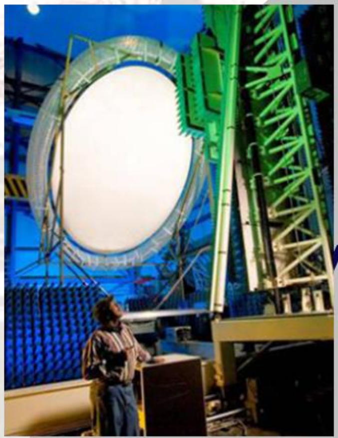
Popular Science's – Invention of the Year 2007, listed as one of the "Inc. 500: The Hottest Products" of 2009. GATR continues to field units which enable high-bandwidth Internet, phone and data access for deployments and projects in Afghanistan, South Africa, South America, Haiti, Korea, as well as assisting hurricane disaster recovery here on our own soil.

GPS GND Terminals: 2014

2011 2011 2010 2013

First Practical System: 2008

Through the help of NASA Glenn, the SCAN project, a reimbursable Space Act Agreement, material refinements through Air Force Research Laboratory (AFRL) and the Space and Missile Defense Command (SMDC), GATR Technologies markets World's first FCC certified inflatable antenna



4m x 6m parabolic membrane reflector derived from solar concentrator in GRC near-field

Fundamental Research: 2004-2007

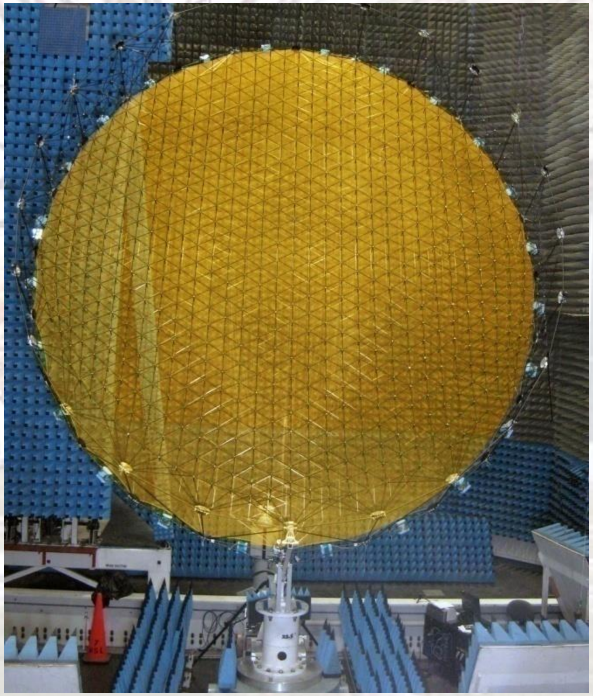
Designed and fabricated a 4x6m off-axis inflatable thin film antenna with a rigidized support torus. Characterized the antenna in the NASA GRC Near Field Range at X-band and Ka-band. Antenna exhibited excellent performance at X-band. Ka-band surface errors are understood.

0.3 meter prototype Membrane reflector

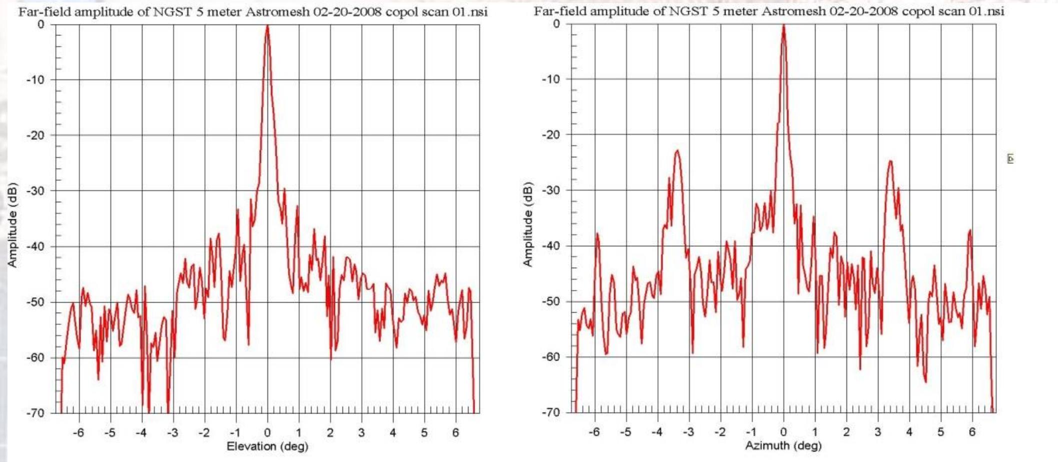
Seedling Idea: 2004

Circa 2004 need for large aperture deployable antenna identified for JIMO and Mars Areostationary relay platform. Antenna technology adapted from 1998 Phase II SBIR solar concentrator project.

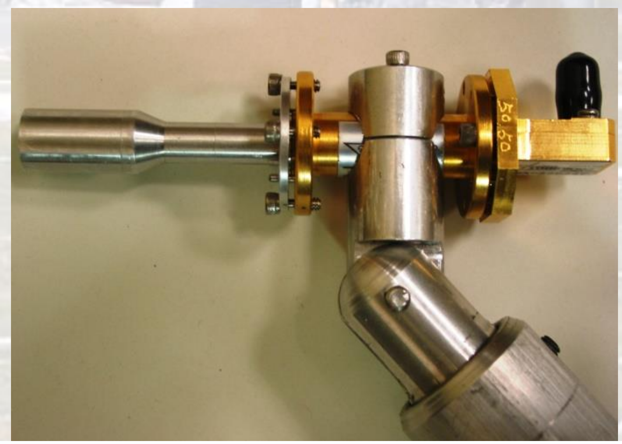
NGST 5m Astromesh Reflector Evaluated at 32, 38 and 49 GHz as well as laser radar surface accuracy mapping



NGST 5 m “Astromesh” Reflector in NASA GRC Near-Field Range

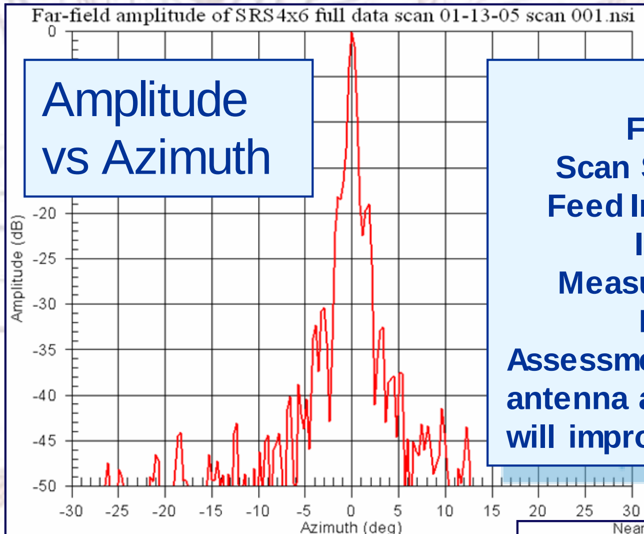


Far Field Elevation and Azimuth pattern at 33 GHz (Directivity = 62.8 dB)



GRC Dual-band feed horn assembly

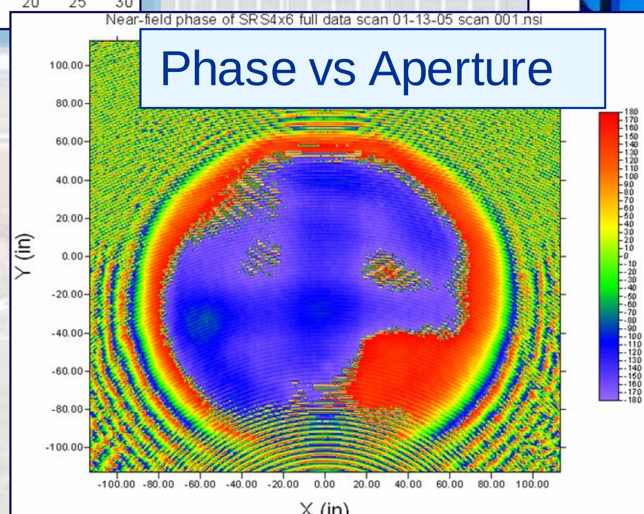
4x6m Antenna RF Characterization



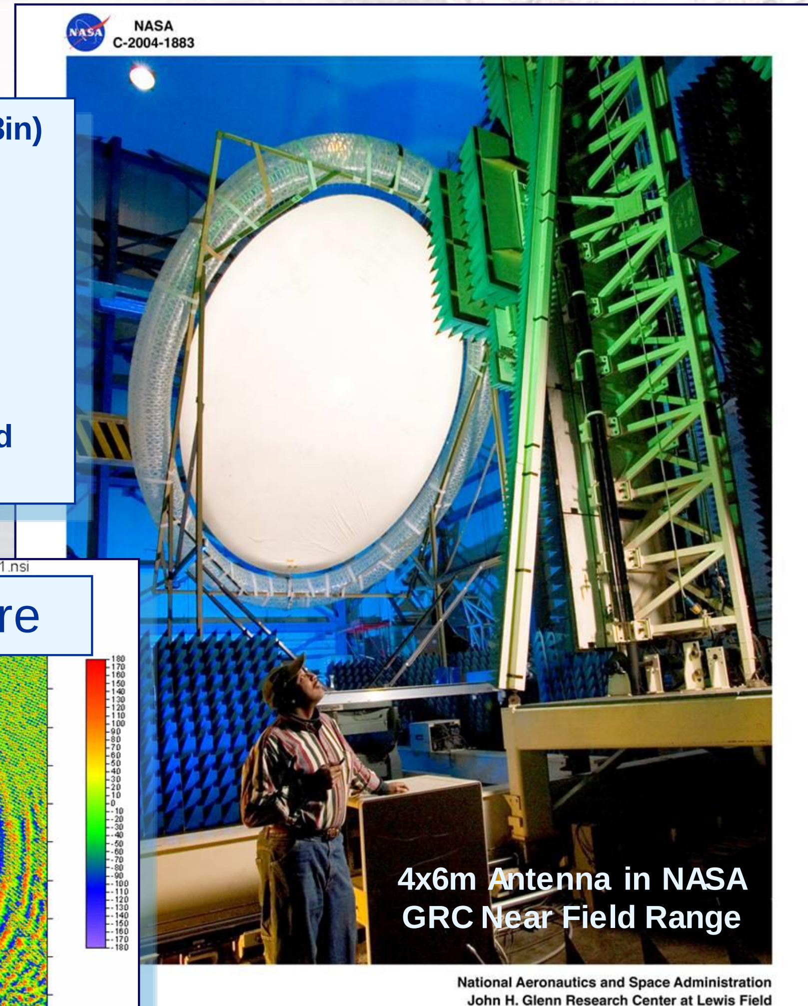
Amplitude vs Azimuth

Aperture: 4.17m (164.08in)
Frequency: 8.4GHz
Scan Step Size: λ/2
Feed Inclination: 5°
Ideal Gain: 51.3dB
Measured Gain: 49.3dB
Efficiency: 63.33%
Assessment: Performs well as antenna at X-band. Optimized feed will improve performance.

Design Specs
- 4x6m off-axis parabolic antenna
- Inflatable
- CP-1 Polymer
- RF coating
- Rigidized support torus
- Characterized in NASA GRC Near Field Range



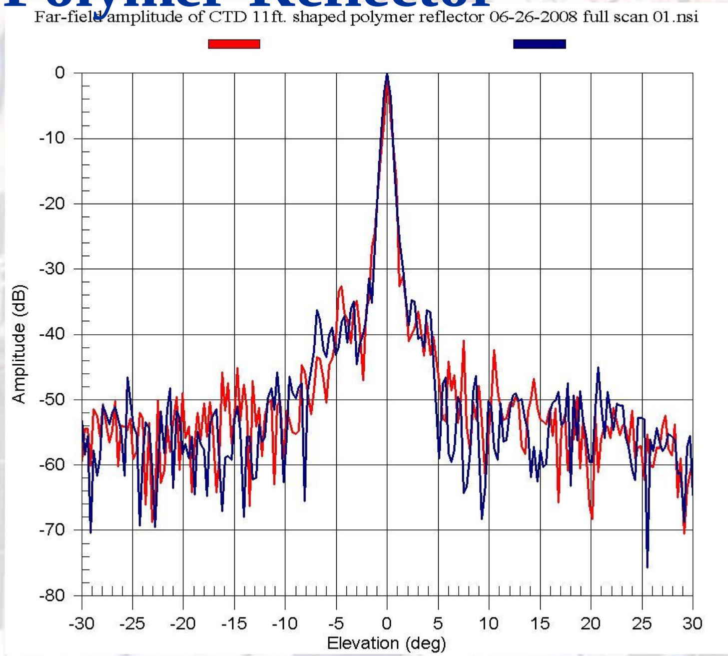
Phase vs Aperture



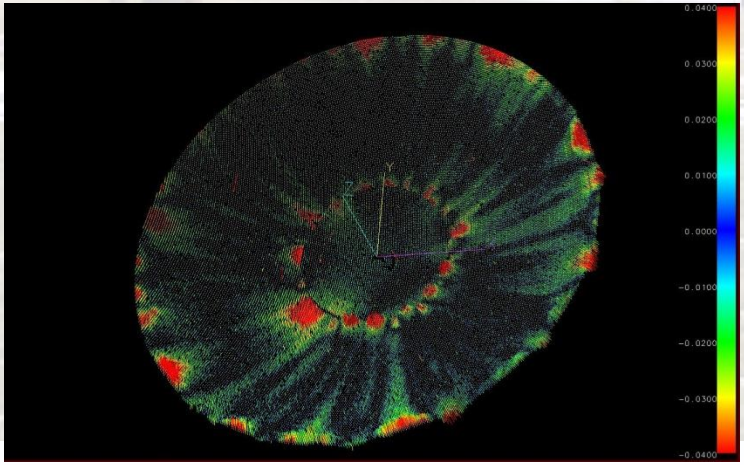
4x6m Antenna in NASA GRC Near Field Range

Composite Technology Development
Shape Memory Polymer Reflector

3.2 m Shape memory Polymer Composite Reflector

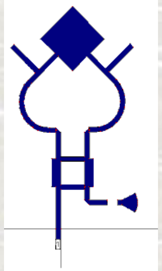


Far-field pattern at 20 GHz. Directivity = 50.3 dB
(aperture was severely under-illuminated)



Surface metrology based on laser radar scan. RMS error=0.014”

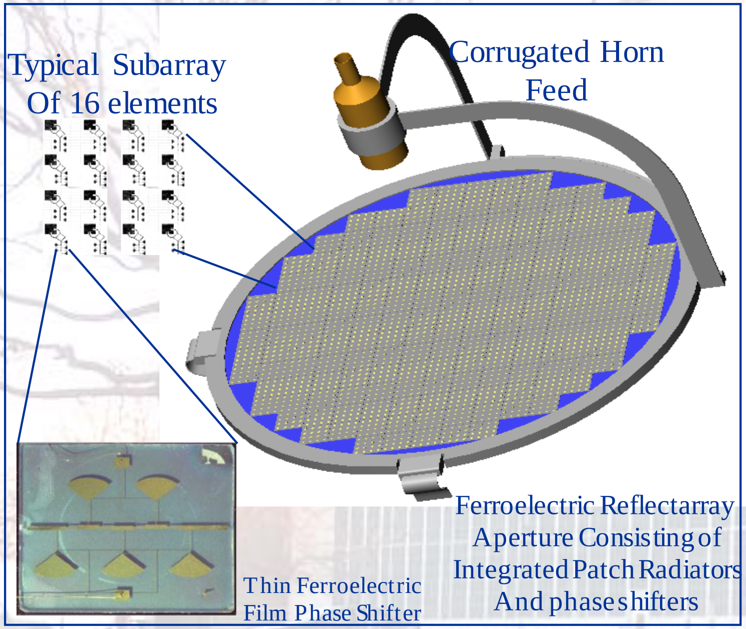
Stowed Configuration



Initial 20 GHz Microstrip Patch Feed
(length is 0.620”)

Reflectarray Array Antenna

Low Cost, High Efficiency Ferroelectric Reflectarray



Preliminary Validation Concept:

- Fly full scale reflectarray in near-Earth orbit for 6 months and downlink pseudo-random GBPS signal to tracking Earth terminal to characterize array performance.

Technology Description:

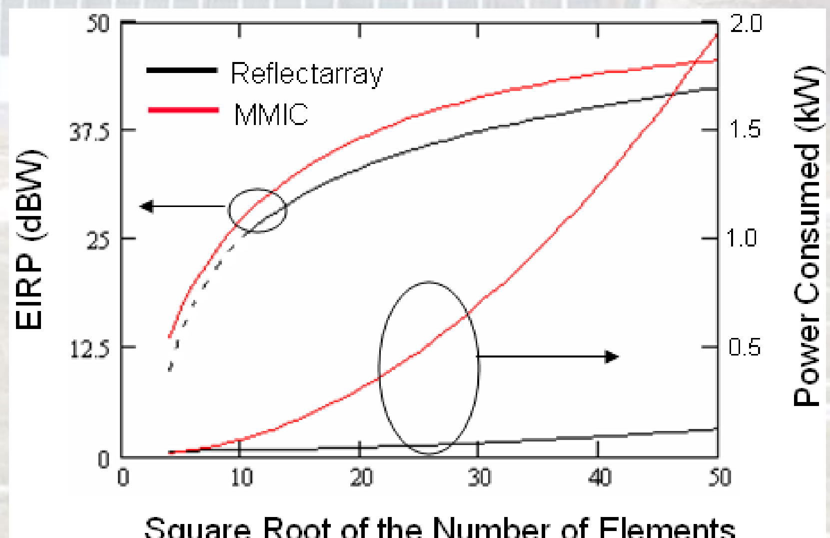
- Alternative to gimbaled parabolic reflector, offset fed reflector, or GaAs MMIC phased array
- Vibration-free wide angle beam steering (>±30°)
- High EIRP due to quasi-optical beam forming, no manifold loss
- Efficiency (>25%) intermediate between reflector and MMIC direct radiating array, cost about 10X lower than MMIC array.
- TRL at demonstration: 4

Potential Missions:

- Laser Interferometer Space Antenna (LISA)
- Space Interferometry Mission (SIM)
- Advanced Radio Interferometry between Space and Earth (ARISE)
- Pluto-Kuiper Express (PKE)

Flight Validation Rationale:

- Fundamental change in scanning array design and fabrication requires flight validation to demonstrate flight worthiness. Procedures for operating and deploying the reflectarray depart from existing practice.
- Dust accumulation, atomic oxygen, radiation effects and possible plasma effects are difficult to predict and simulate.



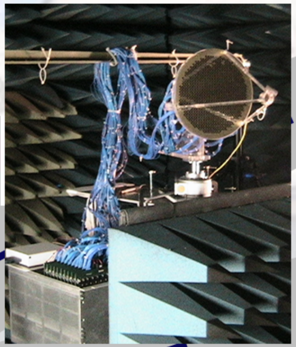
Ferroelectric Reflectarray Antenna—The Road from Idea To Deployment

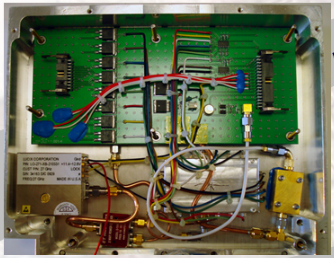
Modified 615 Element Scanning Ferroelectric Reflectarray: 2005-2009

Prototype antenna with practical low-power controller assembled and installed in NASA GRC far-field range for testing. Low-cost, high-efficiency alternative to conventional phased arrays

R&D 100 Award Winner

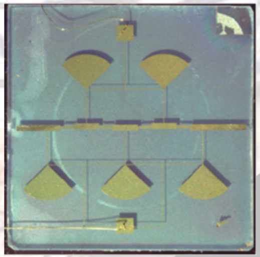
2010





MISSE-8 ISS Space Exp.; STS-134 ,05/16/ 2011. Returned to Earth 07/2014

Cellular Reflectarray: 2010 *Derivative attracts attention for commercial next generation DirecTV, etc. applications*



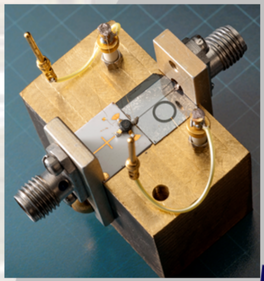
Thin film ferroelectric phase shifter on Magnesium Oxide

Practical Phase Shifters : 2003-2004

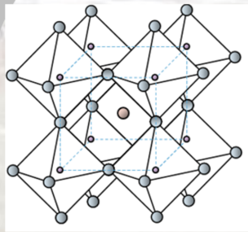
Novel phased array concept based on quasi-optical feed and low-loss ferroelectric phase shifters refined. 50 wafers of $Ba_{0.5}Sr_{0.5}TiO_3$ on lanthanum aluminate processed to yield over 1000 ferroelectric K-band phase shifters. Radiation tests show devices inherently rad hard in addition to other advantages over GaAs

Fundamental Research: 2000-2003

Agile microwave circuits are developed [using room temperature Barium Strontium Titanate ($Ba_{0.5}Sr_{0.5}TiO_3$)], including oscillators, filters, antenna elements, etc., that rival or even outperform their semiconductor counterparts at frequencies up to Ka-band



First Ku-Band tunable Oscillator based on thin ferroelectric films

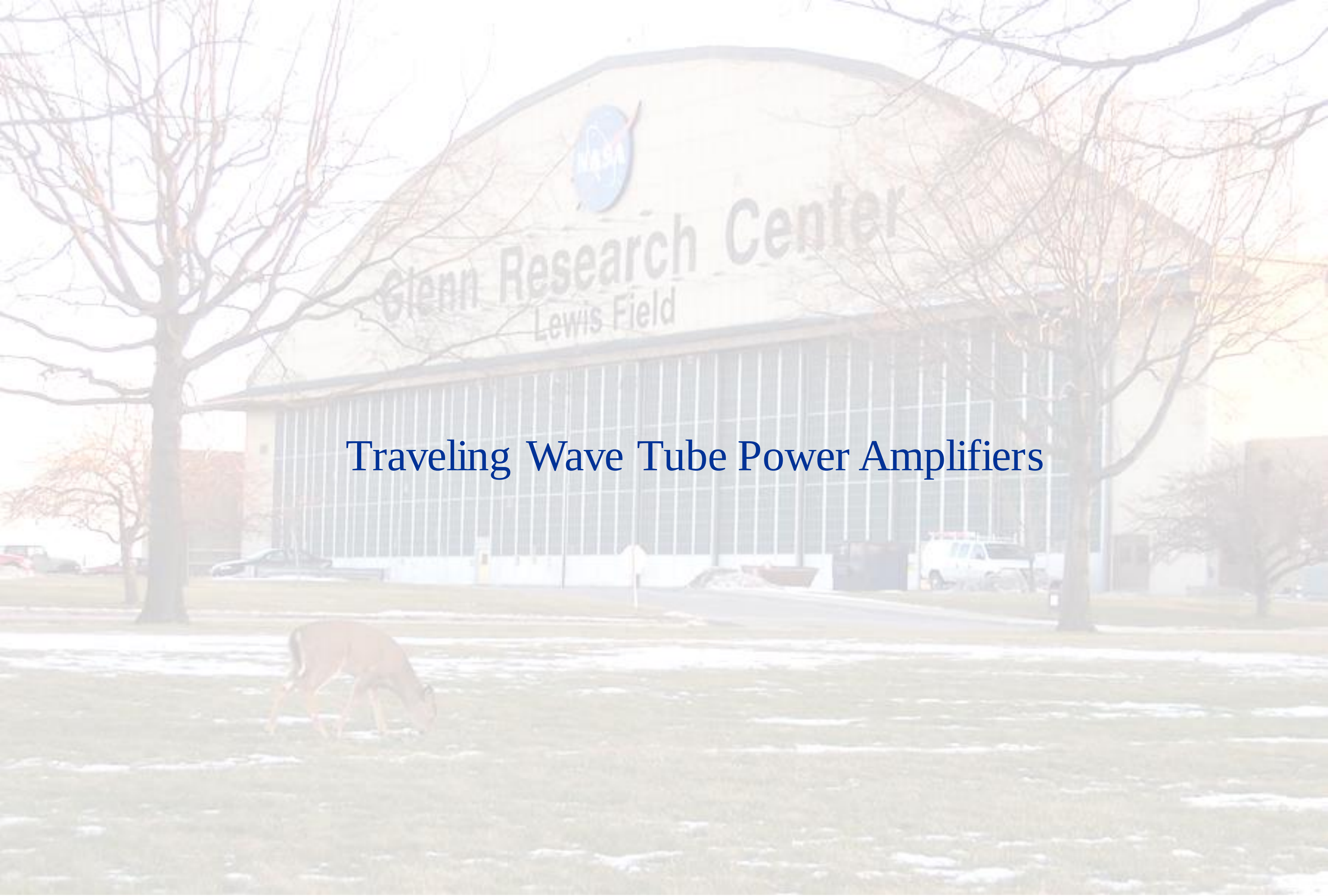


Parent crystal: Strontium Titanate

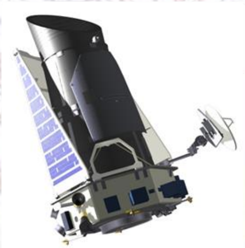
Seedling Idea: 1995-1999

Basic experiments with strontium titanate at cryogenic temperatures suggest loss tangent of ferroelectric films may be manageable for microwave applications

Traveling Wave Tube Power Amplifiers



High Power & Efficiency Space Traveling-Wave Tube Amplifiers (TWTAs) - A Huge Agency Success Story



LRO TWTA

SCaN Testbed TWTA

High Throughput

Q - V- & W-band TWTAs & Gbps Data Rates: 2012 & beyond

Lunar & ISS Missions: 2007-2011

- *Delivered K-band 40 W space TWTAs to the Lunar Reconnaissance Orbiter & CoNNeCT missions*

Jupiter Mission – Higher FoM: 2004-2006

- *Space qualified a Ka-Band TWT, output power 200 W, efficiency 62 %, mass 1.5 kg. Output power 20X higher than Cassini TWT and FoM is 133*

Mars Mission – Higher Power & Efficiency: 2001-2003

- *Demonstrated a Ka-Band space TWT, output power 100 W, efficiency 60 %, mass 2.3 kg. Output power 10X higher than the Cassini TWT and FoM is 43*

Cassini Mission: 1996-2000

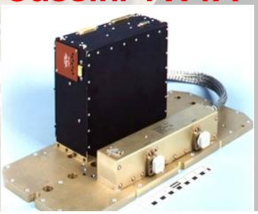
- *Delivered a Ka-Band space TWT, output power 10 W, efficiency 41 %, mass 0.750 kg. Figure of Merit (FoM) is power/mass = 13*

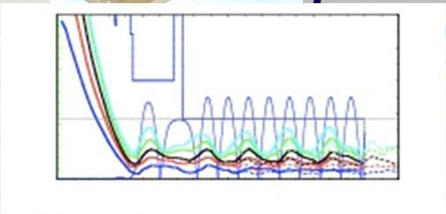
Modeling & Simulations: 1980-1995

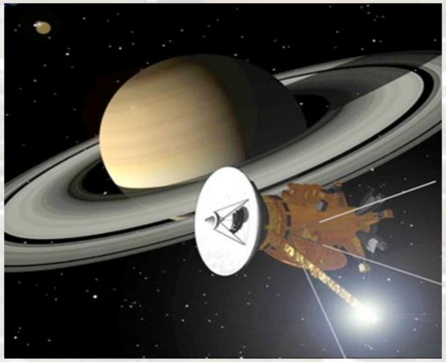
- *Basic design studies on traveling-wave tube (TWT) slow wave interaction circuits, collector circuit, focusing structure, electron gun and cathode*

100 Watt TWT

Cassini TWTA



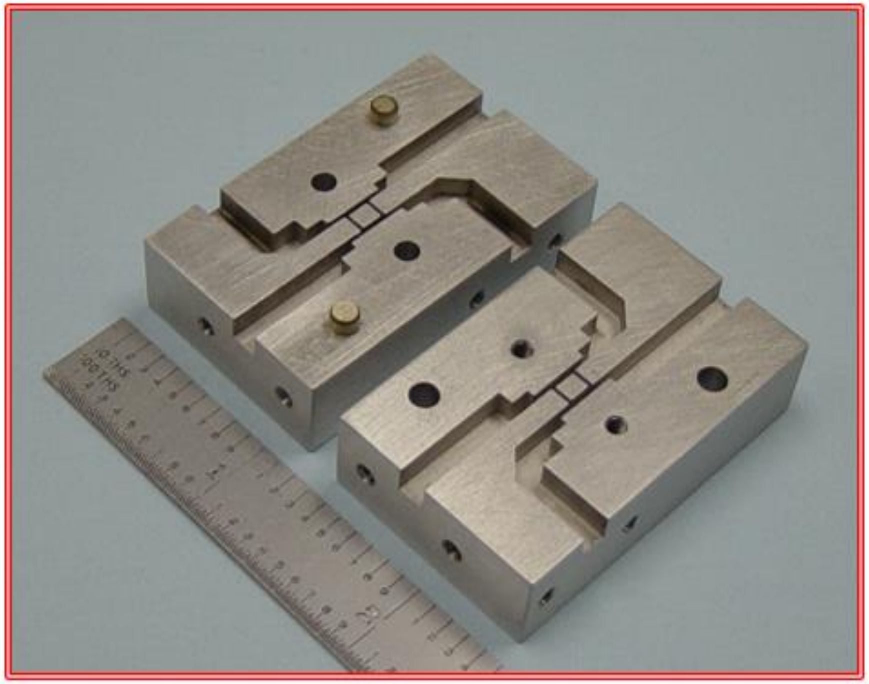




Hybrid Power Combiner for Ka-Band SSPA

Experimental Set-Up for Demonstrating Power Combining

2:1 Ka-Band Branch-Line Hybrid Power Combiner

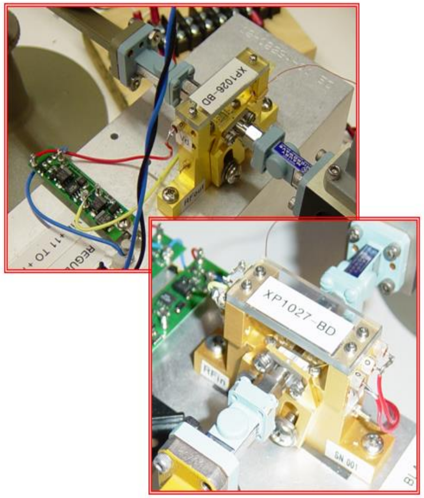


Power combining efficiency is as high as 92% across the 31.8 to 32.3 GHz DSN band

Hybrid Power Combiner for Ka-Band SSPA

Magic-Tee Power Combiner for Ka-Band SSPA

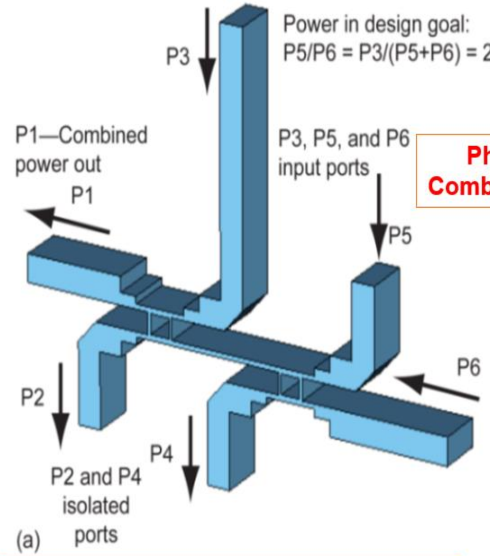
0.5 W & 1.0 W GaAs pHEMT MMIC Power Amplifier in Test Fixtures



2:1 Ka-Band Magic-Tee Power Combiner

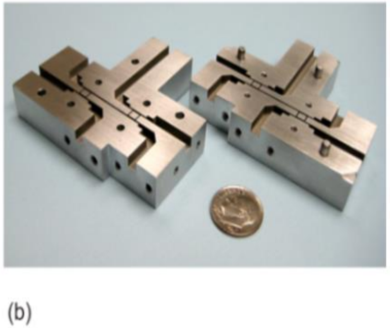
Power combining efficiency is as high as 90% across the 31.8 to 32.3 GHz DSN band

Three-Way Branch-Line Serial Combiner for Ka-Band SSPA



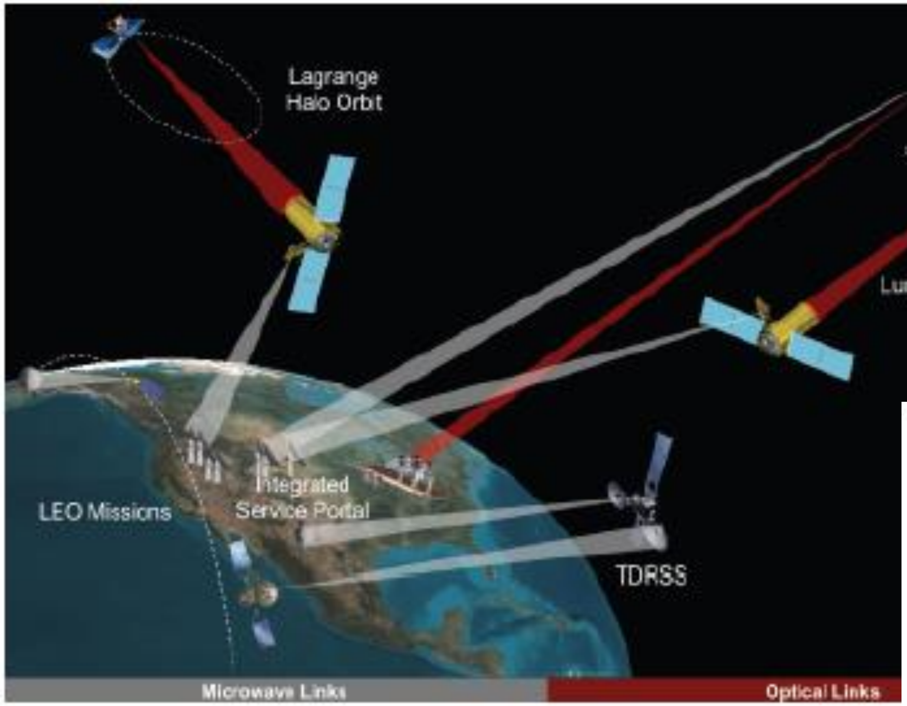
Schematic Showing Port Configuration

Photograph of Fabricated Three-Way Combiner Showing Split Block Construction

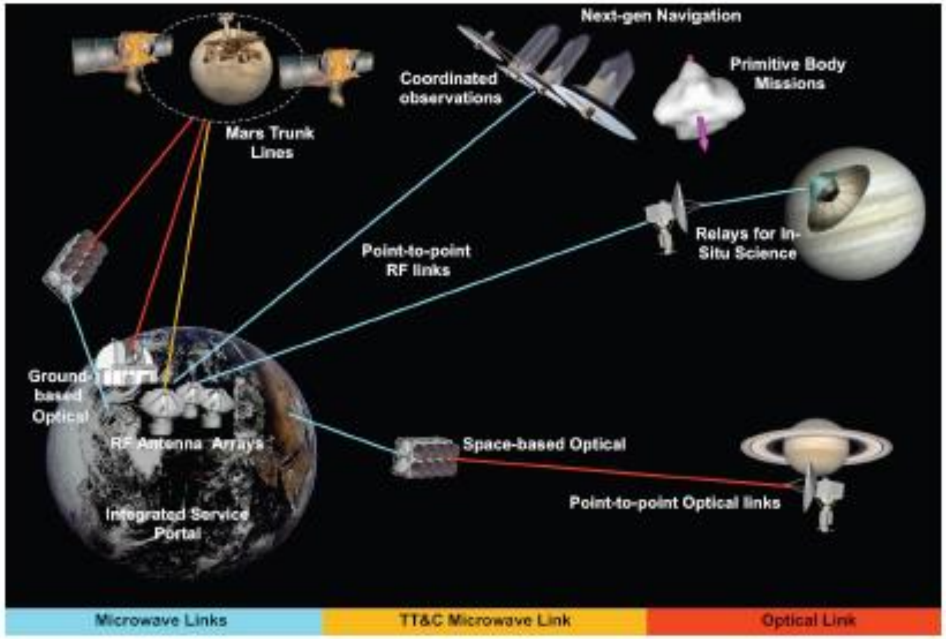


Optical Communications

Optical Communications



Near Earth Domain

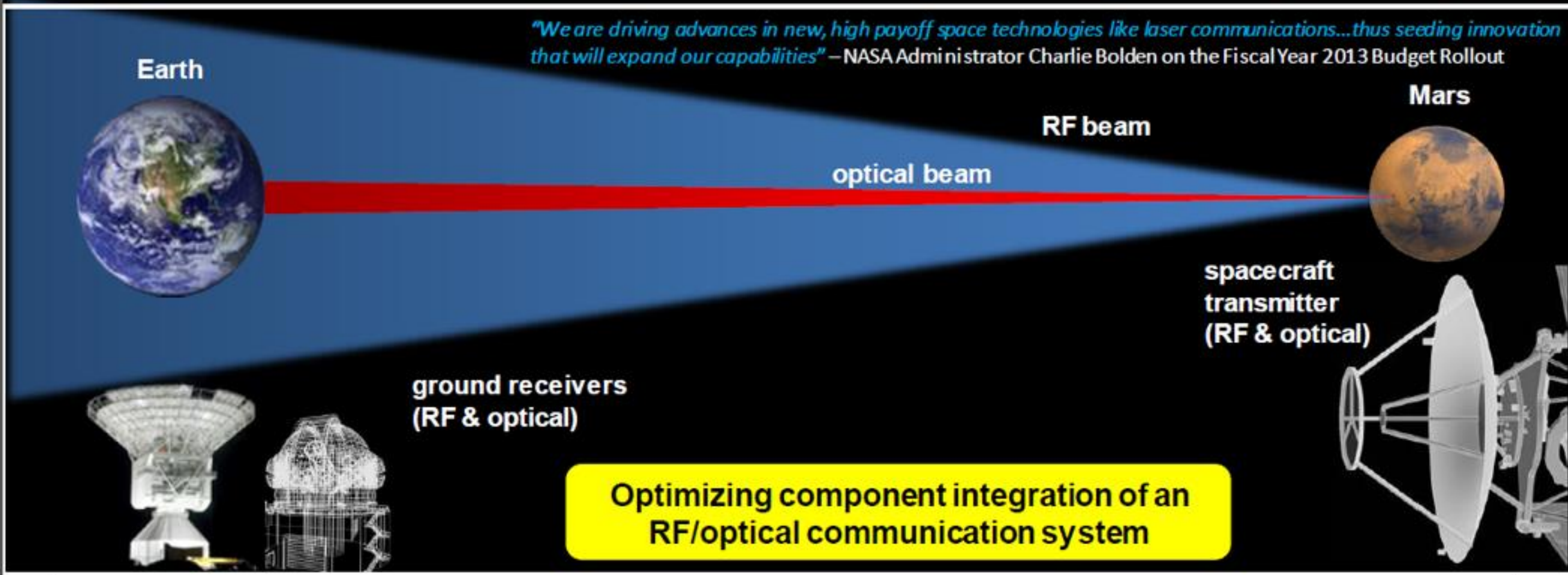


Deep Space Domain

SCaN Integrated Radio and Optical Communications

The integrated RF/optical approach:

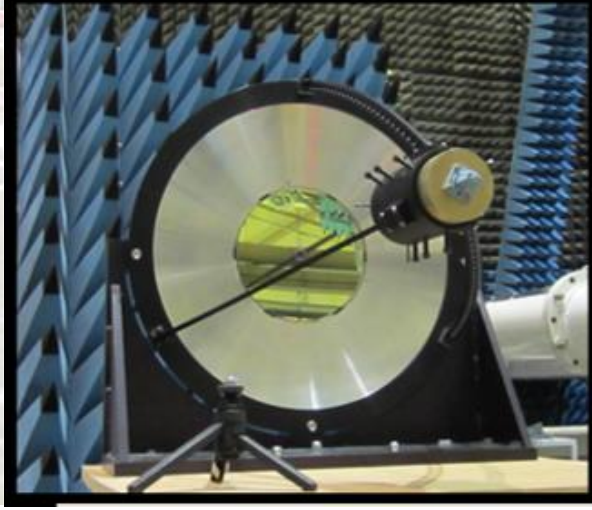
- Accelerates Gbps networked communication service through realizing a secure dual-band deep space trunk line, will not limit deep space science mission data return
- Offers an evolutionary approach to develop the operational readiness of optical communications technology for SCaN's integrated network architecture, while utilizing RF infrastructure to provide availability and redundancy



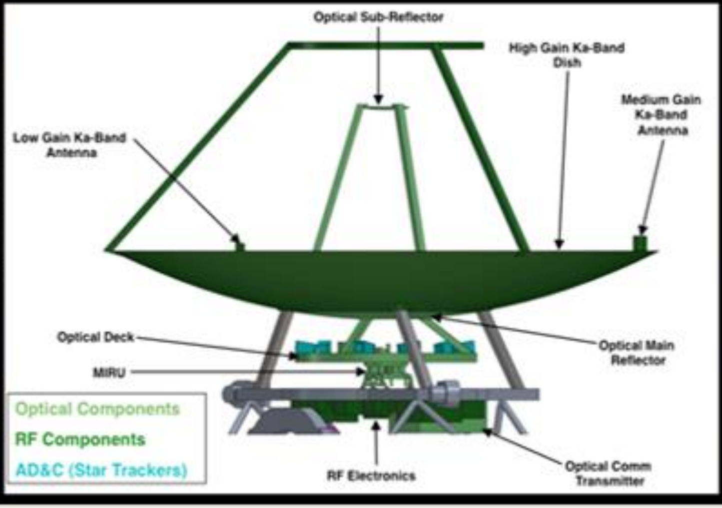
iROC Pointing, Acquisition and Tracking and the Hybrid RF/Optical Aperture are Highly Coupled

- Alternative concept to historical methodology relying on closed-loop tracking on Earth ground station beacon, resulting in increased spacecraft autonomy and extensibility to other deep space missions
- Relies on spacecraft state estimate, attitude knowledge obtained via star trackers
- Preliminary results show sufficient accuracy when solving attitude from estimates from each star tracker, as a function of number of star trackers and time-integrated measurements – technology has developed to the point of beacon consideration
- Derive test bed equipment using multi-camera concept and "star-field"

Prototype Teletenna

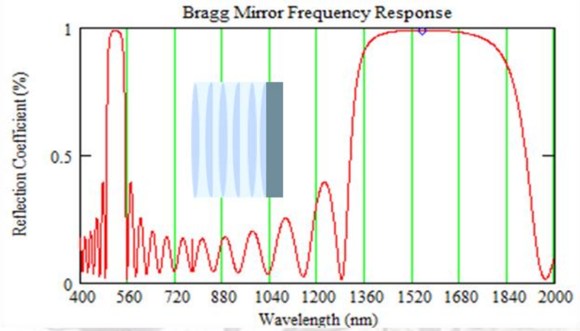


Telescope + Antenna = Teletenna

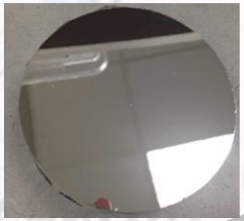


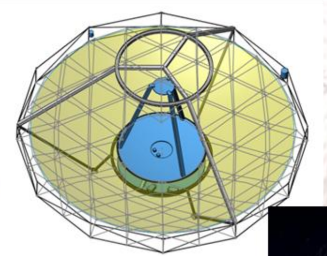
Beaconless Pointing Test- In Work

Integrated Radio Optical Communications— "Teletenna Concept"



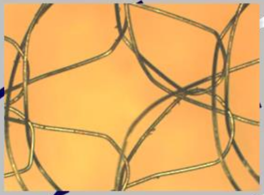
GRC developed microwave transparent Bragg optical sub-reflector


doubly curved graphite skin/aluminum core mirror coupons


Integrated Teletenna System

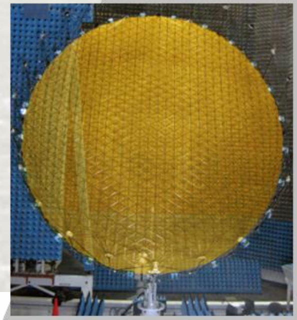

Large Deployable Mesh Antennas for Deep-Space Communications (NGST SMAP shown)

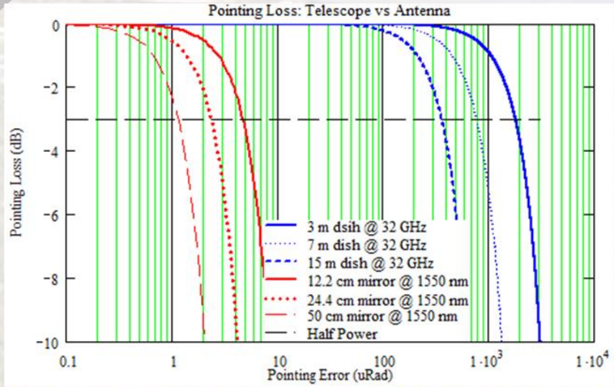
GRC/MicroEngineered Metals process developed to achieve <30 Å surface finish


Knitted gold plated molybdenum mesh >98% reflective at Ka-band.

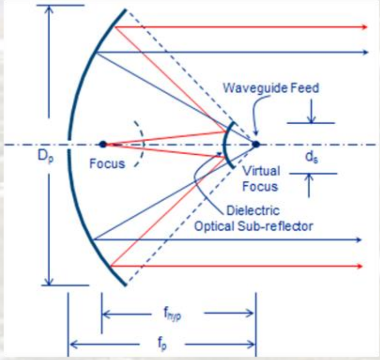
3 m Radio Antenna Material	25 cm Optical Mirror Material	Total Mass (kg)
Composite (16.7 kg)	Beryllium (0.5 kg)	17.2
Composite (16.7 kg)	Composite (0.1 kg)	16.8
Mesh (7.5 kg)	Composite (0.1 kg)	7.6

Teletenna material options and associated mass


Northrop Grumman 5.2 m Astromesh Reflector Characterized at GRC in 2008



Telescope and Antenna Beam-widths/Pointing Loss



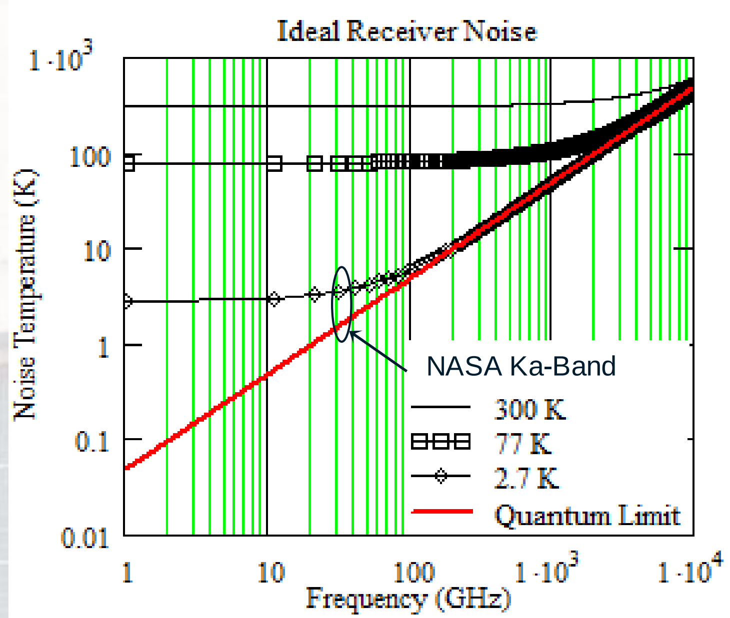
Hybrid Cassegrain/Prime Focus Telescope & antenna concept

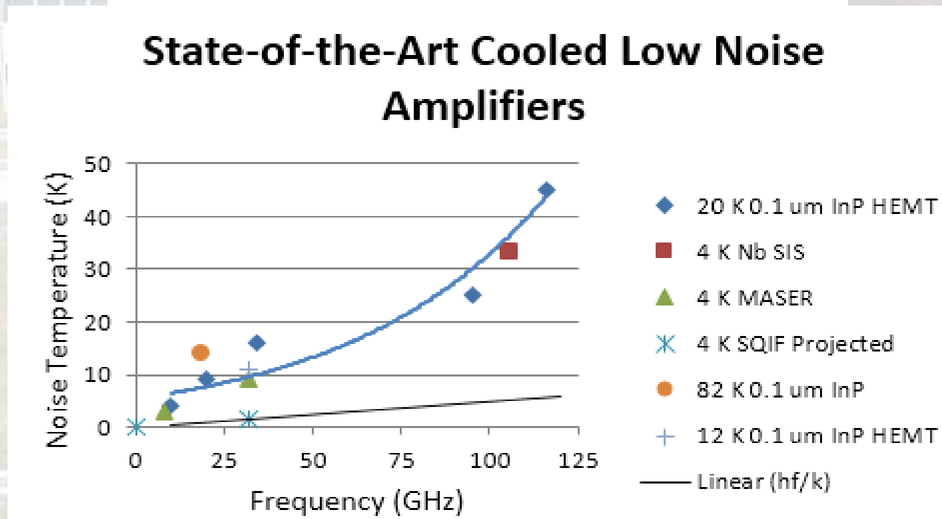
Low TRL Game Changing Technologies

SQIF

Superconducting Quantum Interference Filter-Based Microwave Receivers

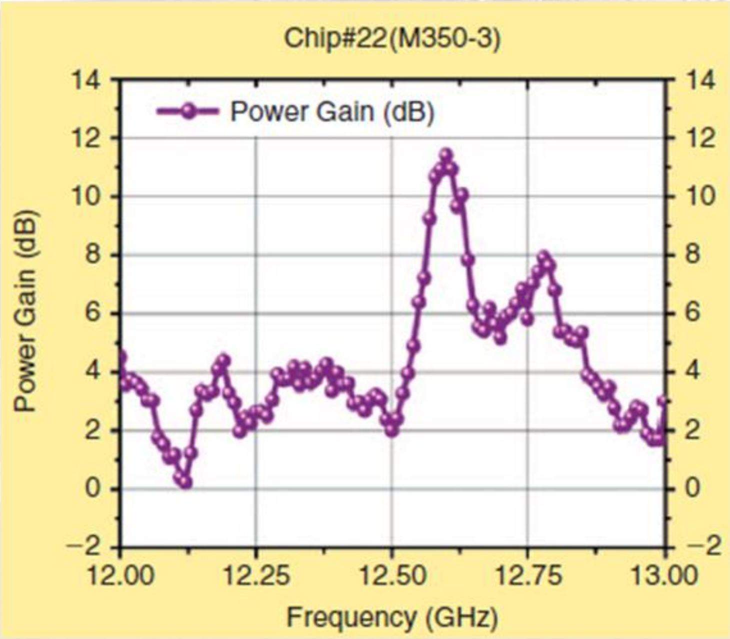
- Use magnetic instead of electric field detection to take advantage of highly sensitive Superconducting Quantum Interference Device (SQUID) arrays.
    - Proven and being used in medical and physics research, geology, etc.
- SQUIDs have a typical energy sensitivity per unit bandwidth of about 10^6 h or $\approx 10^{-28}$ J.
- Conventional semiconductor electric field detection threshold of ~ $kT \approx 10^{-22}$ J.





Quantum Sensitivity: Superconducting Quantum Interference Filter-Based Microwave Receivers

Focused Issue Featured Article: *Quantum Sensitivity: Superconducting Quantum Interference Filter-Based Microwave Receivers*



First reported X-band SQIF performance…

Summary

By 2030, deep space data rates of $\geq$ 1Gbps are desired. Choosing the proper communications technologies for future NASA exploration missions will rely on:

-- Data rate requirements, available frequencies, available space and power, and desired asset-specific services. Likewise, efficiency, mass, and cost will drive decisions.

-- Viable technologies should be scalable and flexible for evolving communications architecture.