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

By

Dr. Félix A. Miranda
Chief, Advanced High Frequency Branch
NASA Glenn Research Center
Cleveland, OH 44135
Tel. 216-433-6589
E-mail: Felix.A.Miranda@nasa.gov

Pennsylvania State University
State College, PA
March 19, 2015
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
Deep Space Network Facilities
- Goldstone, in CA Mojave Desert
- Near Madrid, Spain
- Near Canberra, Australia

Glenn Research Center
Lewis Field
Cleveland, OH

Goddard Institute for Space Studies
Greenbelt, MD

Jet Propulsion Laboratory
Pasadena, CA

Ames Research Center
Mountain View, CA

Armstrong Flight Research Center
Edwards, CA

Houston, Texas

White Sands Test Facility
White Sands, NM

Johnson Space Center
Houston, Texas

Michoud Assembly Facility
New Orleans, LA

Kennedy Space Center
Cape Canaveral, FL

Langley Research Center
Hampton, VA

Marshall Space Flight Center
Huntsville, AL

Stennis Space Center
Stennis Space Center, MS

Goddard Space Flight Center
Greenbelt, MD

Stennis Space Center, MS

NASA Headquarters
Washington, D.C.

Wallops Flight Facility
Wallops Island, VA

Independent Verification and Validation Facility
Fairmont, WV

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

Glenn Research Center
Plum Brook Station
Sandusky, OH

NASA Centers and Installations
Glenn Research Center Campuses

Lewis Field (Cleveland)
- 350 acres
- 1626 civil servants and 1511 contractors
- 66% of the workforce are scientists and engineers

as of 1/2013

Plum Brook Station (Sandusky)
- 6500 acres
- 11 civil servants and 102 contractors
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 Data Rate as a function of Time

Year

Data Rate (bps)

1.0E+12
1.0E+10
1.0E+08
1.0E+06
1.0E+04
1.0E+02
1.0E+00
1.0E-02
1.0E-04
1.0E-06


Baseline (First Deep Space mission)
3-W, 1.3-m S-Band Antenna (S/C)
Reduced Transponder Noise (S/C)
Maser (G)
Reduced Microwave Noise (G)
Interpolated Improved Coding (S/C)
Reduced Ant Antenna Tolerances (G)
64-m Antenna (G)
29-W S-Band TWT, Block Coding (G & S/C)
64-m Antenna (G)
29-W S-Band TWT, Block Coding (S/C)
1.5-m S-Band Antenna (S/C)
29-W S-Band TWT, Block Coding (G & S/C)
Reduced Microwave Noise (G)
Improved Antenna (G)
1.5-m S-Band Antenna (S/C)
29-W S-Band TWT, Block Coding (S/C)
Reduced Microwave Noise (G)
Improved Antenna (G)
70-m Antenna (G)
Redundant Antenna (G)
70-m + 2.34-m (G)
Video Data Compression (G & S/C)
Video Data Compression (G & S/C)
Advanced Coding and Compression (G & S/C)
Advanced Coding and Compression (G & S/C)
Advanced Coding and Compression (G & S/C)
Advanced Coding and Compression (G & S/C)
105-m Spacecraft Antenna (S/C)
100-W Ka-Band Transmitter (S/C)
100 W Ka-Band Transmitter (S/C)
DSN Array - Phase 1 (G)
Kepler
MRO
Galileo
Voyager
Mariner 10
Mariner 09
Pioneer IV
Space Communication and Navigation Operational Network

- Crewed Missions
- Sub-Orbital Missions
- Earth Science Missions
- Space Science Missions
- Lunar Missions
- Solar System Exploration

- DSN
- NEN/NASA
- NEN/Commercial
- NEN/Partner
- SN

Goldstone Complex
Fort Irwin, California

Alaska Satellite Facility
Fairbanks, Alaska

Partner Station:
Poker Flat & North Pole, Alaska

USN Alaska

Madrid Complex
Madrid, Spain

Kongsberg Satellite Services (KSAT)
Svalbard, Norway

Swedish Space Corp. (SSC)
Kiruna, Sweden

German Space Agency (DLR)
Weilheim, Germany

Guam Remote Ground Terminal
Guam, Mariana Islands

USN Australia
Dongara, Australia

Canberra Complex
Canberra, Australia

Satellite Applications Center
Hartebeeshoek, Africa

White Sands Ground Station
White Sands, New Mexico

White Sands Ground Terminals
White Sands, New Mexico

Merritt Island Launch Annex
Merritt Island, Florida

USN Chile
Santiago, Chile

Wallops Ground Station
Wallops, Virginia

McMurdo Ground Station
McMurdo Base, Antarctica
Examples Advanced High Frequency Technologies & Capabilities

- AlphaSat Propagation Terminal in Milan, Italy
- Hybrid RF/Optical Antenna
- Inflatable Antennas
- Ka-Band 180 W Space TWTA
- Semiconductor/Nanofabrication Clean Room Facility
- Antenna Metrology Facilities
- SQIF Chip
- High Efficiency Power Combining TWTAs
- Phased Array Systems
- 5.5 m NGSA
- NASA Propagation Terminal
RF Propagation
Atmospheric Effects

Physics 101

absorption
scattering
Problem Statement

Plane Wave From Distance Source

Water Vapor Molecules

Troposphere

~ 15Km

Plane Wave Distorted Phase

Projected Baseline \( D \) [m]

WIND

\[ v \left[ ms^{-1} \right] \]

GRC Product: Atmospheric Phase Monitor

\[ \Delta \phi(t) = \phi_2(t) - \phi_1(t) \]
Next Generation Deep Space Network (DSN)

Single Large Aperture Antenna

Smaller Aperture Antenna Array

Glenn Research Center at Lewis Field
As NASA Networks continue their current transition to Ka-band and future transition to higher frequency allocations (e.g., for the next generation SBR), GRC propagation data collection will influence SCaN Network architecture design through optimal understanding of system margin requirements and compensation of existing assets to enhance network operational availability.
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

Goldstone

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.
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

- Phase measurements implemented in array loss predictions
- Q-band Radiometer
- mmWave Propagation
- Evolution of GRC Propagation Terminals

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

- Guam (SN)
- Svalbard (NEN)
- White Sands, NM (SN)
- Goldstone, CA (DSN)

**Real-Time Compensation: 2012–2016**
SCaN funded effort to integrate real-time compensation techniques into NASA network operations

**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

**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

*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.

*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.

*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.

*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:** $\lambda/2$
- **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

---

Glenn Research Center at Lewis Field
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)

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

Stowed Configuration

Surface metrology based on laser radar scan. RMS error=0.014”
Reflectarray Array Antenna
Low Cost, High Efficiency Ferroelectric Reflectarray

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.

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
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.

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

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

**Practical Phase Shifters: 2003-2004**
Novel phased array concept based on quasi-optical feed and low-loss ferroelectric phase shifters refined. 50 wafers of $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ 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 ($\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$)), including oscillators, filters, antenna elements, etc., that rival or even outperform their semiconductor counterparts at frequencies up to Ka-band.

**Seedling Idea: 1995-1999**
Basic experiments with strontium titanate at cryogenic temperatures suggest loss tangent of ferroelectric films may be manageable for microwave applications.

First Ku-Band tunable Oscillator based on thin ferroelectric films

Parent crystal: Strontium Titanate

Thin film ferroelectric phase shifter on Magnesium Oxide
Traveling Wave Tube Power Amplifiers
High Power & Efficiency Space Traveling-Wave Tube Amplifiers (TWTAs) - A Huge Agency Success Story

Lunar & ISS Missions: 2007-2011
- Delivered K-band 40 W space TWTAs to the Lunar Reconnaissance Orbiter & CoNeCT missions

- 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

- 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

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

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

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

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

Photograph of Fabricated Three-Way Combiner Showing Split Block Construction

Schematic Showing Port Configuration
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

"We are driving advances in new, high payoff space technologies like laser communications...thus seeding innovation that will expand our capabilities" – NASA Administrator Charlie Bolden on the Fiscal Year 2013 Budget Rollout

Optimizing component integration of an RF/optical communication system
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”
Integrated Radio Optical Communications— "Teletenna Concept"

GRC developed microwave transparent Bragg optical sub-reflector

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

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

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

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

Teletenna material options and associated mass

<table>
<thead>
<tr>
<th>3 m Radio Antenna Material</th>
<th>25 cm Optical Mirror Material</th>
<th>Total Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite (16.7 kg)</td>
<td>Beryllium (0.5 kg)</td>
<td>17.2</td>
</tr>
<tr>
<td>Composite (16.7 kg)</td>
<td>Composite (0.1 kg)</td>
<td>16.8</td>
</tr>
<tr>
<td>Mesh (7.5 kg)</td>
<td>Composite (0.1 kg)</td>
<td>7.6</td>
</tr>
</tbody>
</table>

doubly curved graphite skin/aluminum core mirror coupons
Low TRL Game Changing Technologies
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 $\sim kT \approx 10^{-22}$ 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 $\geq 1$Gbps 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.