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

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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
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

- **1950s**: Baseline (First Deep Space mission)
- **1960s**: 3.7-m X-Band Antenna (S/C), Reduced Antenna Tolerances (G), Interpolated, Improved Coding (S/C)
- **1970s**: Reduced Microwave Noise (G), Improved Coding (G & S/C), 20-W S-Band TWT, Block Coding (G & S/C)
- **1980s**: Reduced Transponder Noise (S/C), Reduced Maser (G), Improved Antenna (G)
- **1990s**: 70-m Antenna (G), Video Data Compression (G & S/C)
- **2000s**: Reduced Microwave Noise (G), Advanced Coding and Compression (G & S/C)
- **2010s**: 105m Spacecraft Antenna (S/C), DSN Array - Phase 1 (G), 100W Ka-Band Transmitter (S/C), Kepler
- **2020s**: MRO, TPF

**Data Rate (bps)**
- 1.0 × 10^-6
- 1.0 × 10^-4
- 1.0 × 10^-2
- 1.0 × 10^0
- 1.0 × 10^2
- 1.0 × 10^4
- 1.0 × 10^6
- 1.0 × 10^8
- 1.0 × 10^10
- 1.0 × 10^12

**Year**
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030
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

- Alaska Satellite Facility
  - Fairbanks, Alaska

- Partner Station
  - Gilmore Creek, Alaska

- USN Alaska
  - Poker Flat & North Pole, 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, Marianna Islands

- USN Hawaii
  - South Point, Hawaii

- White Sands Ground Station
  - 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

- Canberra Complex
  - Canberra, Australia

- Satellite Applications Center
  - Hartebeesthoek, Africa
Examples Advanced High Frequency Technologies & Capabilities

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

Physics 101

Absorption

Scattering
Problem Statement
Next Generation Deep Space Network (DSN)

Single Large Aperture Antenna

Smaller Aperture Antenna Array
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.

GRC/GSFC data collection in Guam is providing short baseline site diversity data for practical implementation of Ka-band in tropical environments.

GRC/GSFC data collection in White Sands is providing availability measurements for RF Space-Ground Links.

GRC/GSFC data collection in Svalbard is providing critical characterization of Ka-band performance at low elevation angle polar sites for NEN upgrades.

GRC/JPL data collection in Goldstone is providing characterization of turbulence effects for the practical implementation of Ka-band uplink arrays for DSN upgrades.

GRC/GSFC data collection in Madrid is providing availability data for Ka-band Ka-band Uplink Array (Next Gen.)

Guam (SN)  White Sands Complex (SN)  Alaska (NEN)  Svalbard (NEN)  Canberra (DSN)  Goldstone (DSN)  Madrid (DSN)
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.
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

**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

350 x 12 m DSN Array

1 x 34 m DSN

Corresponding Ka SC Power:
- 183 W
- 550 W
- 2444 W

Large Aperture Deployable Antennas

**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**

**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

**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

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

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

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

National Aeronautics and Space Administration
John H. 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)

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

Stowed Configuration

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

**Practical Phase Shifters: 2003-2004**
Novel phased array concept based on quasi-optical feed and low-loss ferroelectric phase shifters refined. 50 wafers of Ba0.8Sr0.5TiO3 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 (Ba0.8Sr0.5TiO3)], 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.
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 & CoNNeCT 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

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

Photograph of Fabricated Three-Way Combiner Showing Split Block Construction

Schematic Showing Port Configuration
Optical Communications

Near Earth Domain

Deep Space Domain
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

Doubly curved graphite skin/aluminum core mirror coupons

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

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

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

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

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