Overview of the Advanced High Frequency Branch

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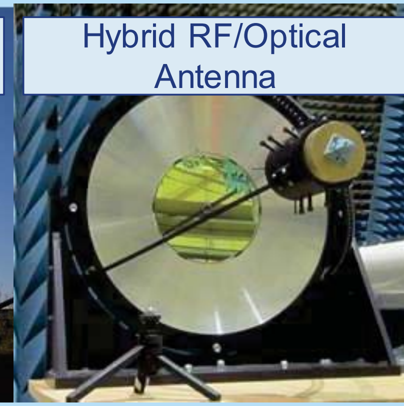
NASA Glenn Research Center

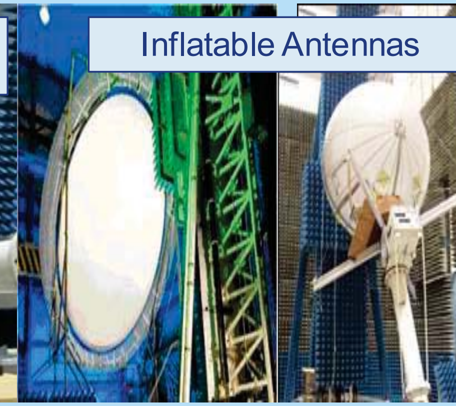
Advanced High Frequency Branch (LCF)

Branch Overview

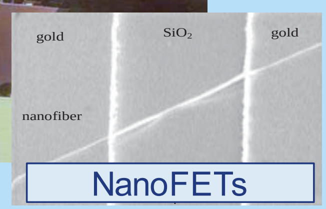
- Conducts research and technology development, integration, validation, and verification at frequencies extending up to the terahertz region in the areas of semiconductor devices and integrated circuits, antennas, power combiners, frequency and phase agile devices for phased arrays, and radio wave propagation through Earth's atmosphere, in support of NASA space missions and aeronautics applications.
- R&D is conducted in-house and also in collaboration with academia and industry to develop low mass, small size, high power and efficiency traveling-wave tube amplifiers, solid state power amplifiers; novel antenna technologies (e.g., wideband antennas, hybrid antennas (i.e., RF/Optical), ground stations, among others.
- The Branch supports development of advanced technologies such as superconducting quantum interference filter (SQIF) for ultra-sensitive receivers and Ka-band multi-access arrays for NASA's next generation space communications.
- Facilities include planar and cylindrical near-field, far-field and compact antenna ranges, cryogenic microwave and millimeter-wave device and circuit characterization laboratory, high power amplifier characterization laboratory, radio wave propagation laboratory, and clean room facilities.
- Semiconductor device modeling and high frequency circuit simulation, fabrication, and integration facilities are also available.
- Unique expertise and critical mass in Analog Electronics for technology integration in support of aerospace projects.


AlphaSat Propagation Terminal in Milan, Italy


Hybrid RF/Optical Antenna

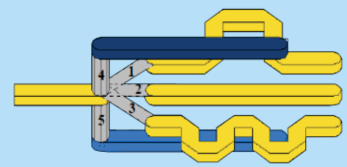

Inflatable Antennas

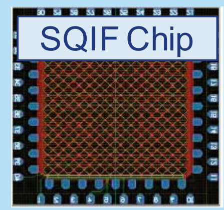

Semiconductor/Nanofabrication Clean Room Facility



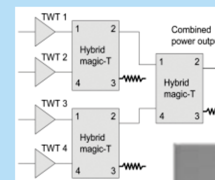
NanoFETs

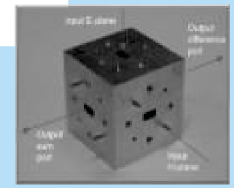
Nanoionic Switch



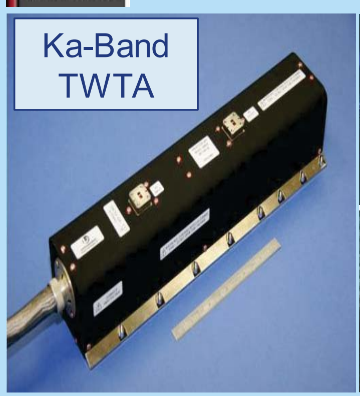

SQIF Chip

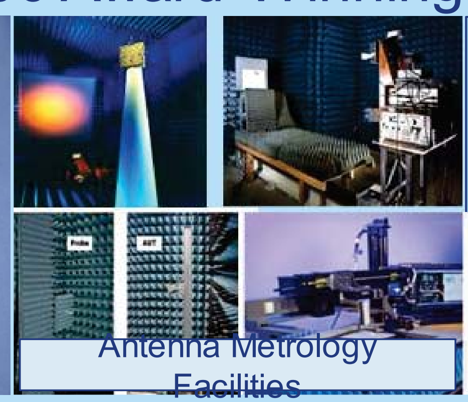
High Efficiency Power Combining TWTAs





R&D 100 Award Winning Technologies


Ka-Band TWTA


Antenna Metrology Facilities

Phased Array Systems

LCF – Telecommunications Competencies

The Branch develops and lead research in antenna and advanced high frequency systems design, analysis, integration and testing. The work encompasses antennas and related technologies for space, aeronautics and terrestrial terminals. NASA's HEOMD, SMD, and ARMD sponsor the work performed. Additional work has also been supported by Other Government Agencies (OGA) and Industry via Space Act Agreements (SAA). The Branch works cooperatively with other GRC Divisions, NASA Centers, industry and academia in studies of electromagnetic phenomena.

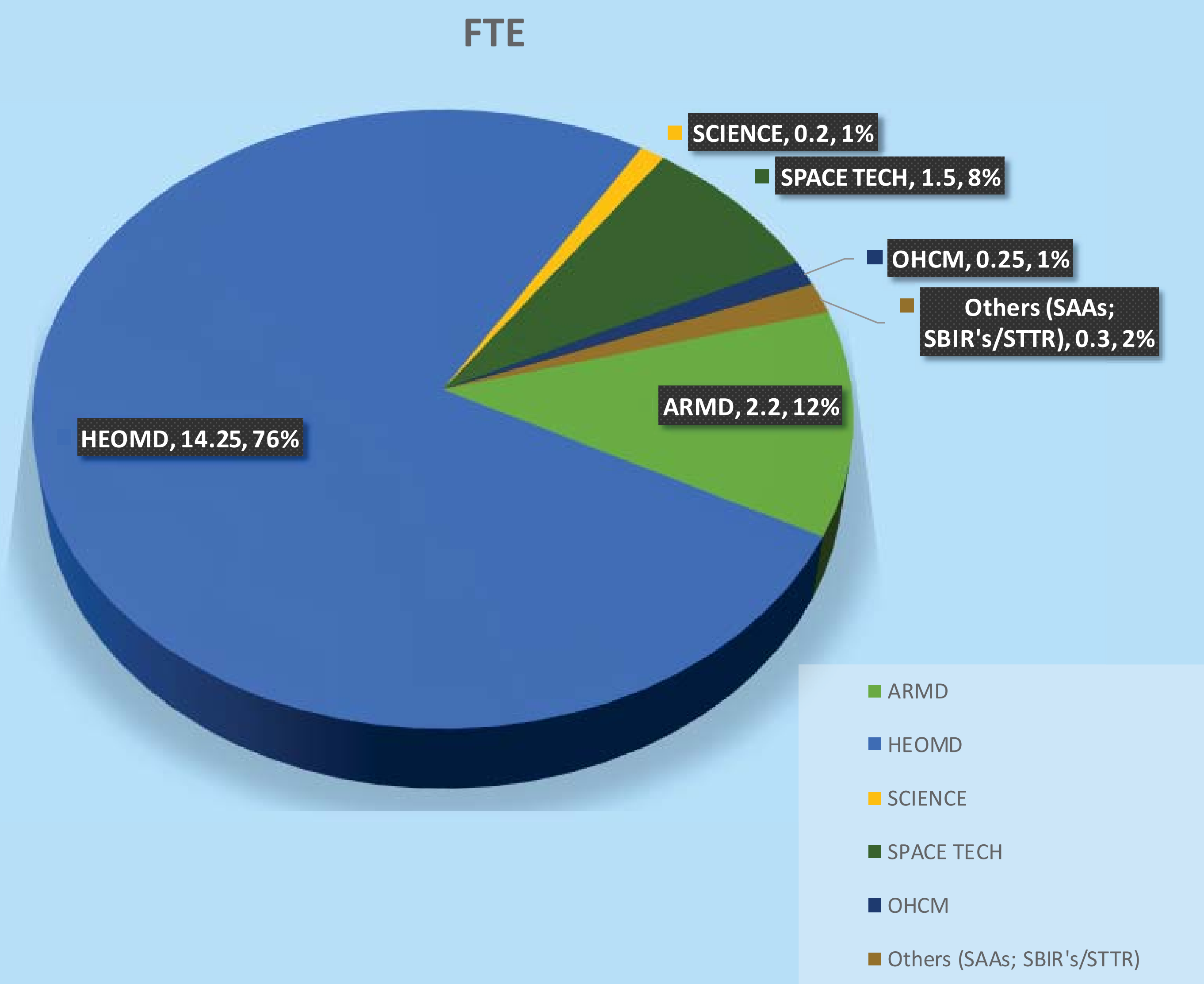
<u>Antenna and Microwave Systems:</u> Performs design, simulation/analysis, fabrication, and testing of antenna systems, subsystem, components and techniques for advanced communication systems. The advances in antenna technology produced by the Branch are used in both NASA, OGA, and commercial applications. The Branch develops, maintains, and operate diverse microwave laboratories, antenna ranges and facilities for the study and measurement of the aforementioned systems.

<u>RF (Ka-, V-,W-band) & Optical Propagation:</u> Work encompasses the development , optimization, deployment and long term data collection and monitoring of single or distributed ground based antennas and radiometric technology to improve the statistical understanding of atmospheric effects (e.g., Attenuation, Phase Stability, etc.) at Ka- and mmWave frequencies at current and potential future NASA operational sites (e.g. Goldstone, White Sands, Svalbard, Guam, etc.). The data analysis and related statistical information will determine the extent to which a particular site is capable of supporting large aperture and widely distributed antenna systems for future NASA's Ka-Band and/or higher frequency communication links. Theoretical and simulation work is also performed on optical propagation through atmospheric media from space to ground for optimization of link margins of optically-enable communication links.

<u>RF and Optical Communications</u>: Encompasses the design, simulation and testing verifications of RF and optical communications concepts in controlled laboratory environment. This work is traditionally performed at low TRL either in the antenna ranges (Bldg. 7) or microwave components and systems laboratories (bldg. 77) for concept validation via "bench-top" demonstration.

<u>Cryo-Electronics:</u> Encompasses the evaluation of innovative microwave materials, devices, and circuit technologies at low temperatures (~20K) in support of the Communications, Instrumentation and Controls Division's effort to develop next generation communications systems for Space Exploration (e.g., SQIF). Existing facilities have been used to evaluate space qualified cryogenic receiver components, superconducting phased array antennas, tunable thin-film ferroelectric based oscillators, filters and phase shifters, ferroelectric/semiconductor heterostructures, SiGe low noise amplifiers, InP HEMT low noise amplifiers, among others.

Current Customers (LCF)



Branch Personnel

Name	Title	Degree	Primary Competency/skills
Cauley, Mike	Research Electronics Engineer	MS EE	Communications Networks and Engineering/Antenna Technology/analog electronics
Downey, James	Research Electronics Engineer	Ph.D. EE	Microwave Systems/analog electronics
Force, Dale	Electronics Engineer	MS EE; MS Phys	Electron Device Technology
Hoder, Douglas	Electronics Engineer	MS EE	Communications Networks and Engineering/analog electronics
Manning, Robert	Electronics Engineer	Ph.D. EE	Microwave Systems/Theoretical RF and Optical Propagation
Miranda, Félix	Supervisory Electronics Engineer	Ph.D. Phys	Technical Work and Team Management/Microwave circuits, antenna technology, ferroelectrics, Superconductivity
Morse, Jacquelynne	Electronics Engineer	BS EE	Microwave Systems/RF Propagation
Nessel, James	Electronics Engineer	MS EE	Microwave Systems/RF & mmWave Propagation
Piasecki, Marie	Electronics Engineer	MS EE	Microwave Systems
Roberts, Anthony	Electronics Engineer	BS Phys	Communications Networks and Engineering
Romanofsky, Robert	Electronics Engineer	Ph.D. EE	Microwave Systems/Electromagnetics/antenna technology/superconductivity
Schoenholz, Bryan	Electronics Engineer	BS EE	Communications Networks and Engineering/analog electronics
Simons, Rainee	Physicist	Ph.D. EE	Electron device Technology/Microwave Systems/Electromagnetics/antenna technology
Theofylaktos, Noulie	Electronics Engineer	MS EE	Communications Networks and Engineering
Vyhnalek, Brian	Electronics Engineer	MS EE; MS Phys	Electromagnetics/superconductivity/RF Propagation
Welch, Bryan	Electronics Engineer	MS EE	Communications Networks and Engineering/analog electronics
Wilson, Jeffrey	Physicist	Ph.D. Phys	Electron Device Technology/Quantum Communications
Zaman, Afroz	Electronics Engineer	Ph.D. EE	Microwave Systems/Antenna Technology
Zemba, Michael	Electronics Engineer	MS EE	Microwave Systems/RF Propagation

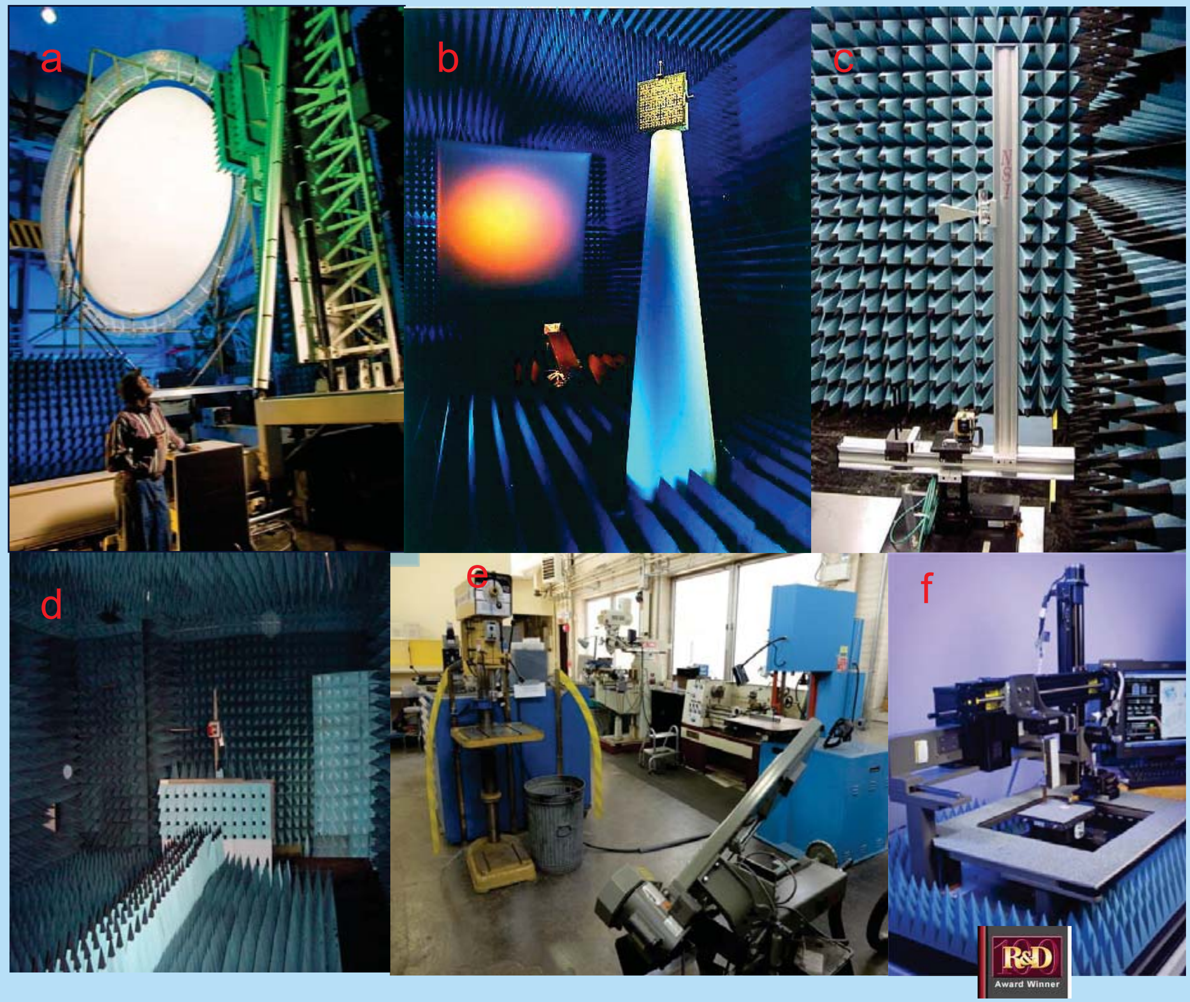
Branch Personnel

Contractors/Contract		Title	Name	Primary Competency
Harbath, Peter	ZIN	SSC	BS EE	RF propagation Instrumentation
Lambert, Kevin	Vantage	SSC	Ph.D. EE	Antenna Technology& Metrology
Mueller, Carl	ANALEX	SSC	Ph.D. Mat. Sci	Microwave Circuits, Antennas
Turner, LeTisha	SGT	Branch Support Assistant		Branch Support Assistant

Antenna Ranges

The Microwave System Laboratory (MSL) houses five RF antenna measurement ranges which are available for use by Glenn staff and their industrial and academic associates. The ranges support the work being done at the center in the research and development of communication systems. Although used primarily to observe and characterize the performance of microwave antennas, the ranges can be used for communication system studies and to study other types of electromagnetic phenomena such as scattering.
Examples of measurements which have been performed at the facility include:

- Satellite communication antennas for space and ground segment terminals
- Aeronautical terminal antennas
- Phased array antennas, reflectarray antennas
- Large aperture inflatable antennas
- Electromagnetic scattering
- Multibeam antennas
- Mobile antennas
- Bit Error Rate performance of scanning antennas
- Miniaturized antennas
- Electromagnetic scattering of antenna structures & materials



(a) Near Field Range Antenna; (b) Compact Range Antenna; (c) Cylindrical Near Field Range; (d) far Field Range; (e) Machine Shop (f) Antenna Near Field Probe Station Scanner

Beach Ball Antenna – The Road From Idea to Deployment

Prototype Inflatable Radome Antenna System at GRC

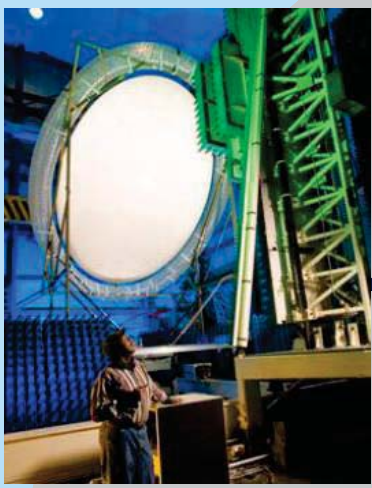
In The Field: 2009-2010

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.

2011 2011 2010

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.

Ferroelectric Reflectarray Antenna– The Road From Idea to Deployment

Modified 615 Element Scanning Ferroelectric Reflectarray: 2005-2009

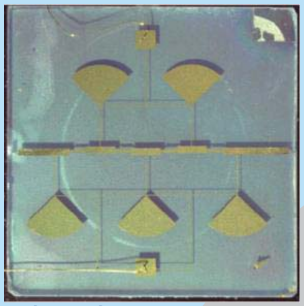
Prototype antenna with practical low-power controller assembled and installed in NASA GRC far-field range for testing. Low-cost, high-efficiency alternative to conventional phased arrays

2010

MISSE-8 ISS Space Exp.; STS-134 ,05/16/ 2011

Cellular Reflectarray: 2010

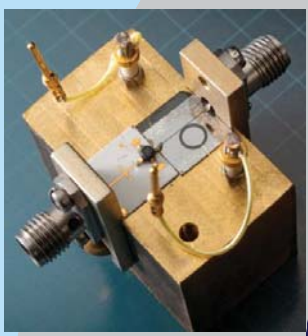
Derivative attracts attention for commercial next generation DirecTV, etc. applications



Thin film ferroelectric phase shifter on Magnesium Oxide

Practical Phase Shifters : 2003-2004

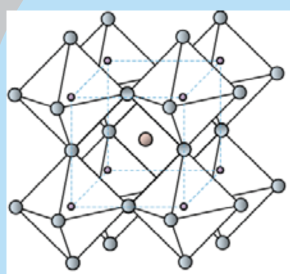
Novel phased array concept based on quasi-optical feed and low-loss ferroelectric phase shifters refined. 50 wafers of $Ba_{0.5}Sr_{0.5}TiO_3$ on lanthanum aluminate processed to yield over 1000 ferroelectric K-band phase shifters. Radiation tests show devices inherently rad hard in addition to other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



First Ku-Band tunable Oscillator based on thin ferroelectric films

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

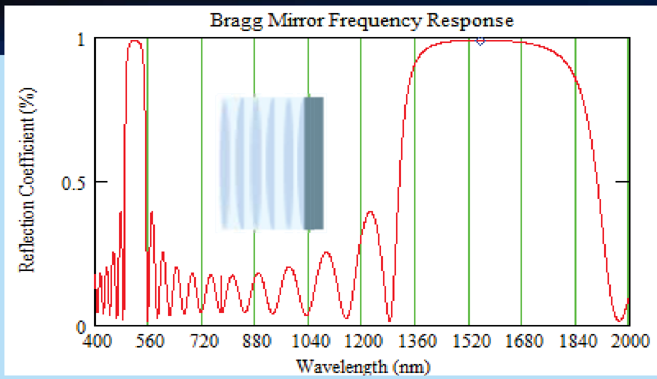


Parent crystal: Strontium Titanate

Seedling Idea: 1995-1999

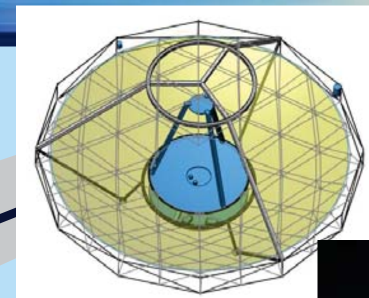
Basic experiments with strontium titanate at cryogenic temperatures suggest loss tangent of ferroelectric films may be manageable for microwave applications

Integrated Radio Optical Communications "Teletenna"

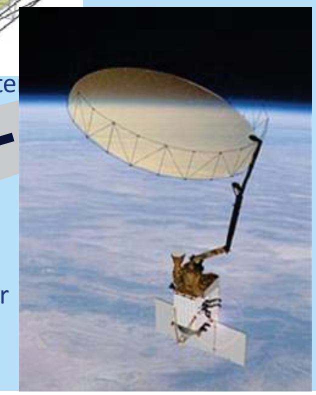


GRC developed microwave transparent Bragg optical sub-reflector

doubly curved graphite skin/aluminum core mirror coupons

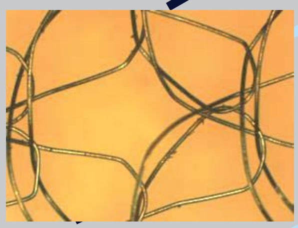


Integrated Teletenna Syste



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

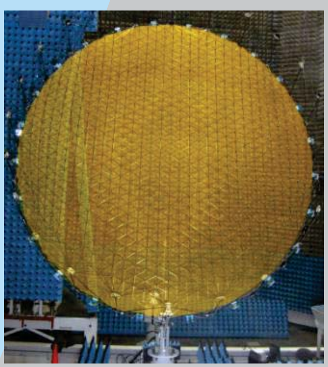
GRC/MicroEngineered Metals process developed to achieve <30 Å surface finish



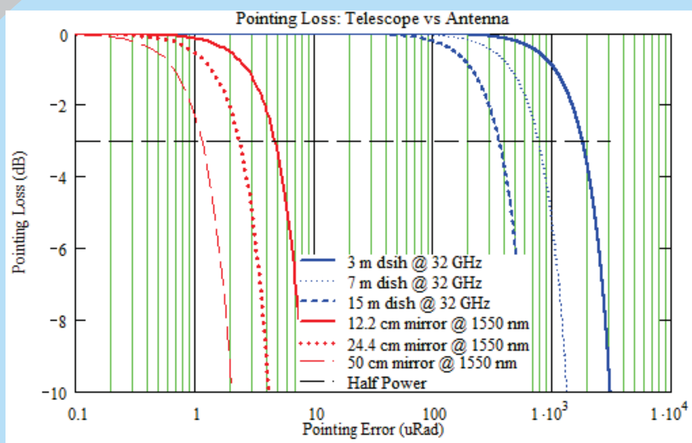
Knitted gold plated molybdenum mesh >98% reflective at Ka-band.

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

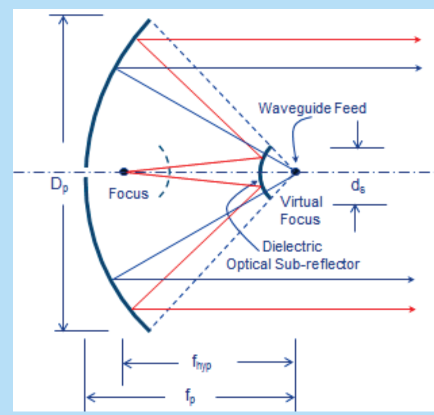
Teletenna material options and associated mass



Northrop Grumman 5.2 m Astromesh Reflector Characterized at GRC in 2008

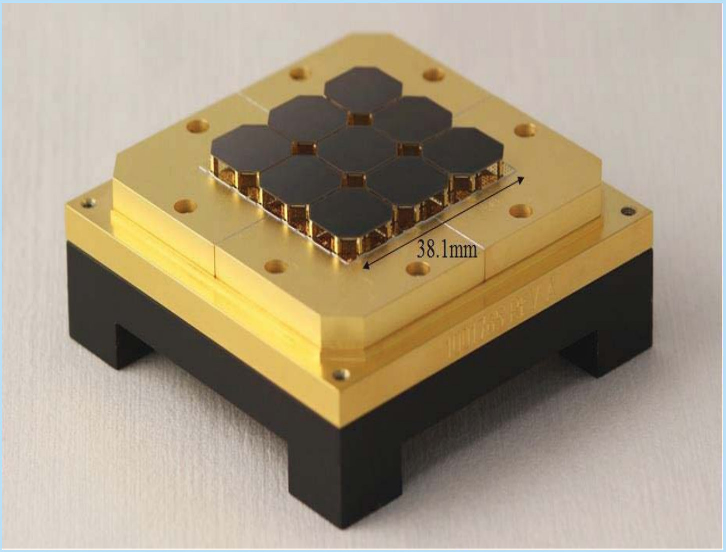


Telescope and Antenna Beam-widths/Pointing Loss

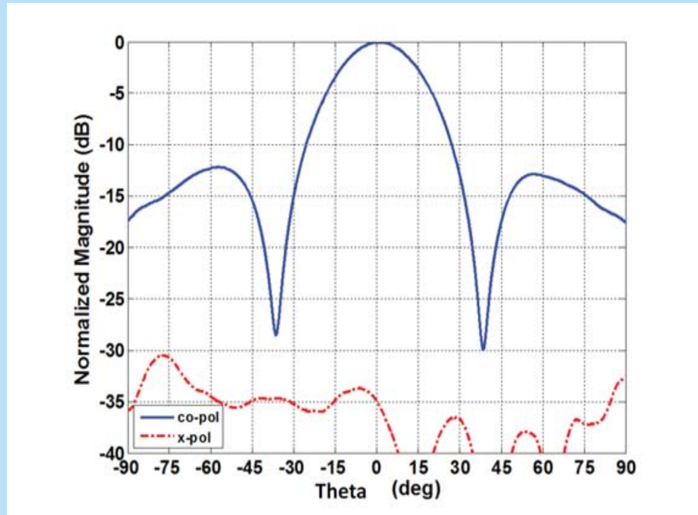


Hybrid Cassegrain/Prime Focus Telescope & antenna concept

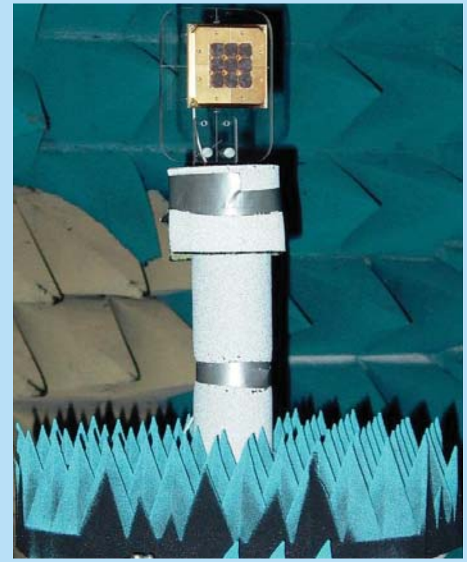
Ultra-wide Band Antennas



Photograph of the final 8 – 40 GHz WISM antenna feed. The outer dimensions of the antenna are 71.1mm by 71.1mm, although the PolyStrata® portion is 38.1mm on a side.

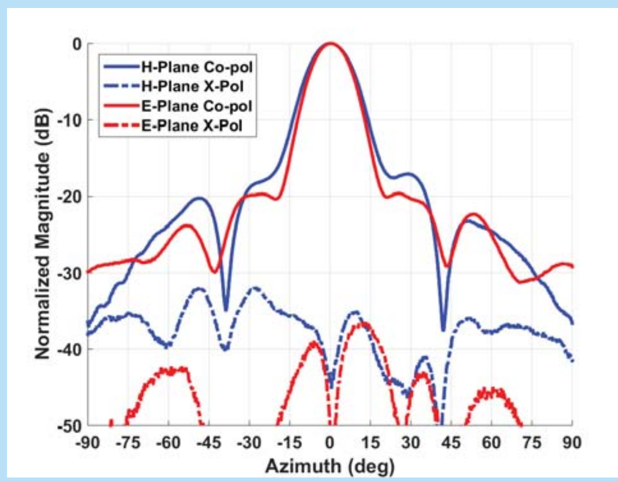


Measured co-polarized and cross-polarized performance at 9.75 GHz at an azimuth angle of 0 degrees for the X-band vertically-Polarized portion of the array.



WISM Feed mounted in the NASA GRC Far-Field Range

Ref: "A Microfabricated 8-40 GHz Dual-Polarized Reflector Feed," by Kenneth Vanhille, Tim Durham, William Stacy, David Karasiewicz, Aaron Caba, Christopher Trent, Kevin Lambert, and Félix Miranda; Proceedings of the 2014 Antenna Applications Symposium, Robert Allerton Park, Monticello, IL, Sept. 23-25, 2014.



WISM Feed principal plane patterns at 36.5 GHz.

This work is being performed as part of a collaborative effort led by Harris Corporation for the development of a "Wideband Instrument for Snow Measurement (WISM)."

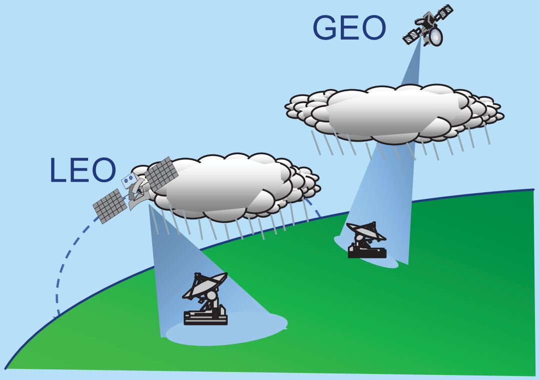
The work is supported by grant NNX11AF27G under the Instrument Incubator Program of the Earth Science Technology Office of the National Aeronautics and Space Administration.

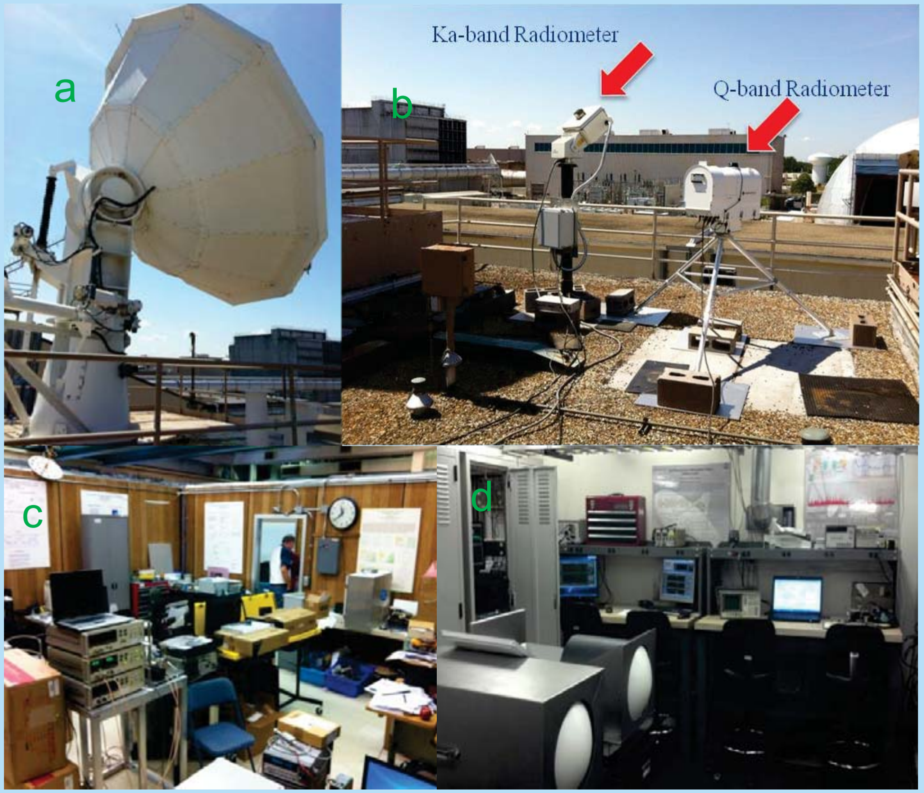
Infrastructure Support Capabilities

RF Propagation Research Laboratory

Laboratory Objectives

- Evaluate GEO and LEO propagation links and validate models that will enable NASA, DoD and commercial communication system designers to optimize spacecraft power requirements and reduce cost.
- Fabricate, characterize, and perform systems operation verification of in-house and/or commercially available instruments such as radiometers, beacon receivers, and interferometers.
- Develop digital receiver techniques and radiometry sensing techniques for characterizing radio frequency waves at Ka-band and millimeter waves (e.g., Q/V/W bands).





(a) 5.5 Meter Diameter Beam Waveguide Antenna on top of Bldg. 55 (b) K-band and Q-band radiometers collecting Data in roof of bldg 55; (c) &(d) RF Propagation assembly, component test, and station monitoring areas in bldg. 55

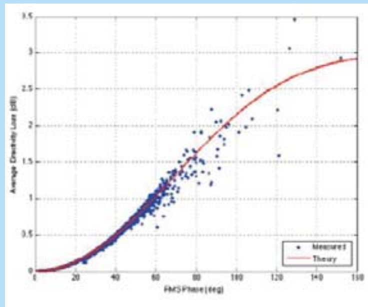
RF Propagation – The Road From Idea to Deployment

mm-wave Propagation Studies: 2012-Future

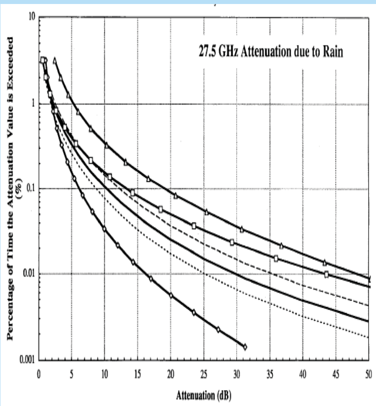
GRC undertakes expansion of mm-wave frontier via propagation activities in the Q/V/W bands

Q-band Radiometer

mmWave Propagation



Phase measurements implemented in array loss predictions



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

Svalbard (NEN)

Guam (SN)

White Sands, NM (SN)

Goldstone, CA (DSN)

Evolution of GRC Propagation Terminals

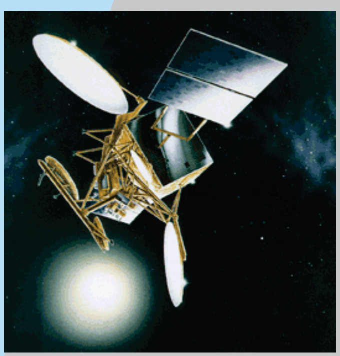
Real-Time Compensation: 2012-2016

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

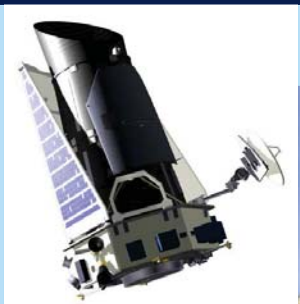
Atmospheric Attenuation Studies: 1993 – 2002

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.

High Power Microwave Amplifier Laboratory

The High Power Microwave Amplifier Laboratory houses the facilities to characterize space travelling-wave tube amplifiers (TWTAs) and solid-state power amplifiers at K-band, Ka-band, Q-band, and, and E-band frequencies. The facility includes high voltage power supplies, network analyzer, frequency synthesizer, spectrum analyzer, power meters, tunable microwave source, and miscellaneous waveguide components. The above test equipment and waveguide hardware can be configured to characterize microwave devices and circuits in terms of their two-port scattering parameters. In addition, it also allows us to acquire RF parameters such as power output, phase, and frequency.

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



200 Watt TWTA

LRO TWTA

SCaN Testbed TWTA

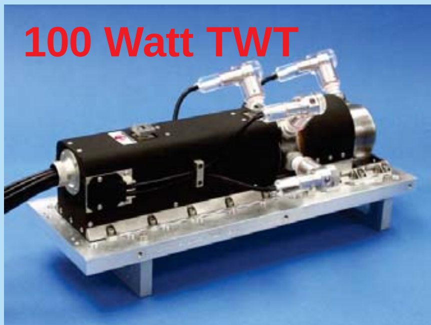
High Throughput TWTA

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*

100 Watt TWT



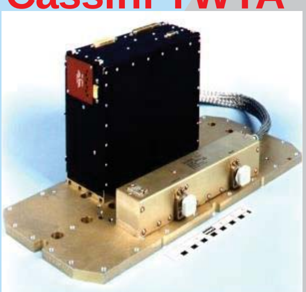
Jupiter Mission – Higher FoM: 2004-2006

- *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

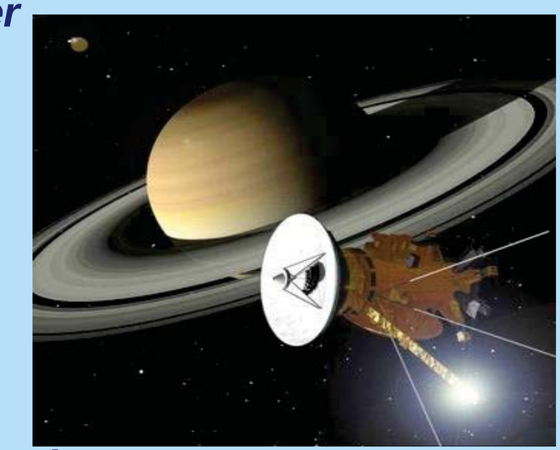
- *Demonstrated a Ka-Band space TWT, output power 100 W, efficiency 60 %, mass 2.3 kg. Output power 10X higher than the Cassini TWT and FoM is 43*

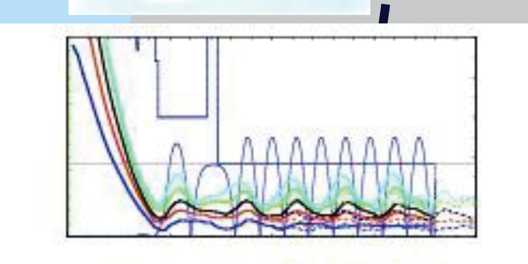
Cassini TWTA



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*

Infrastructure Support Capabilities

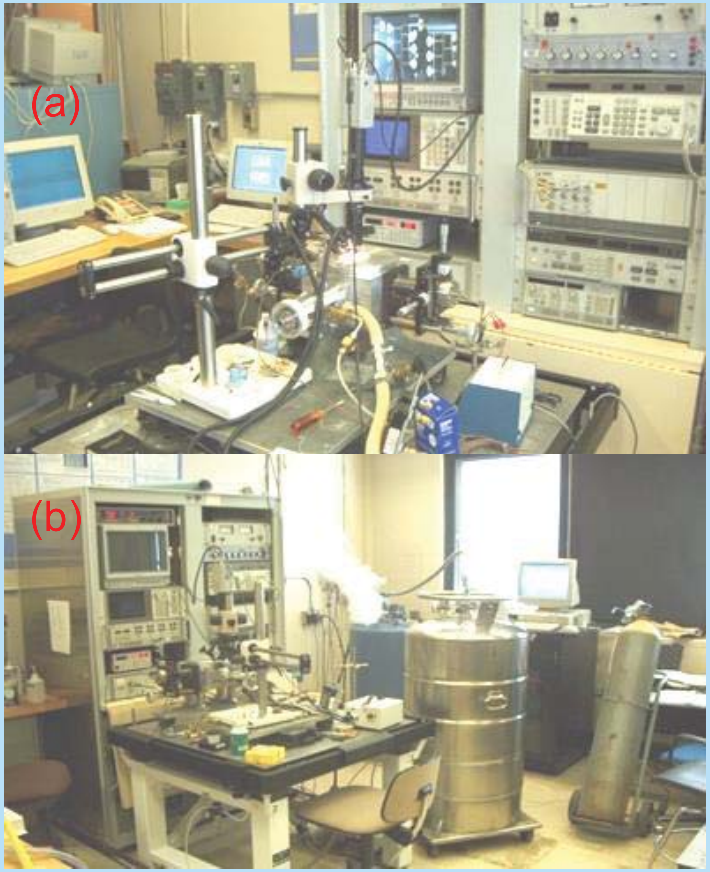
Cryogenic Microwave Electronics Laboratory

Description:

The Cryogenic Microwave Electronics Laboratory is used to evaluate innovative microwave materials, devices, and circuit technologies in support of the Communications and Intelligent Systems Division's effort to develop next generation communications systems for Space Exploration such as SQiF. The facility has been used to evaluate space qualified cryogenic receiver components, superconducting phased array antennas, tunable thin-film ferroelectric based oscillators, filters and phase shifters, ferroelectric/semiconductor heterostructures, SiGe low noise amplifiers, InP HEMT low noise amplifiers, and more.

Capabilities:

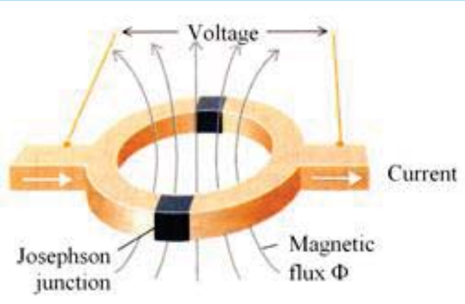
- S-parameters from 100 MHz to 40 GHz at temperatures from 30 K to 300 K (room temperature to 67 GHz)
- Noise parameters up to 40 GHz at temperatures from 30 K to 300 K
- Magneto-resistance
- Hall and Van der Pauw measurements (plus mobility spectra)
    - Shubnikov deHass
    - Resistance to 10^{11} Ohm
- Antenna Far Field Patterns up to 10 cm apertures cooled to 30 K
- 3D measurements at nanometer scale using phase-shift interferometry
- AFM/STM

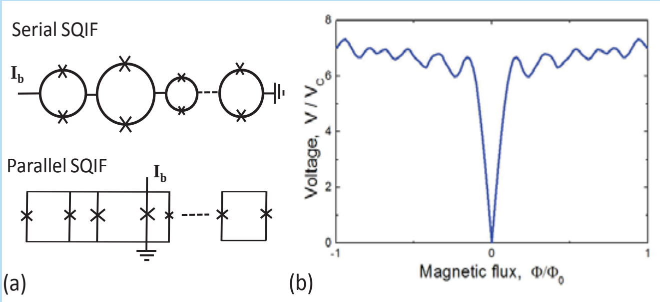


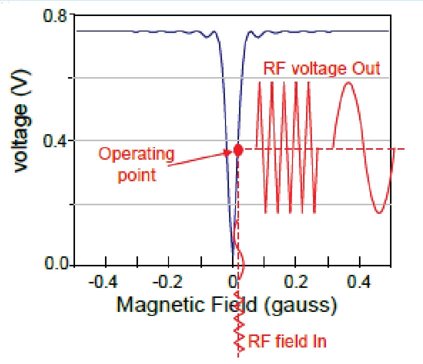
(a) 40 GHz Cryogenic On-Wafer Probe Station; (b) 2.5 K, 9 T Hall system

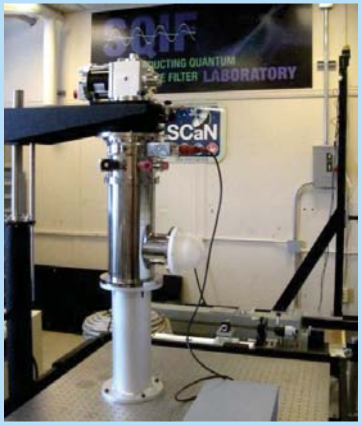
Superconducting Quantum Interference Filter (SQIF) Receiver

- Use <u>magnetic</u> instead of <u>electric</u> field detection to take advantage of highly sensitive Superconducting Quantum Interference Device (SQUID) arrays.
- 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 is ~ kT$\approx 10^{-22}$ J.



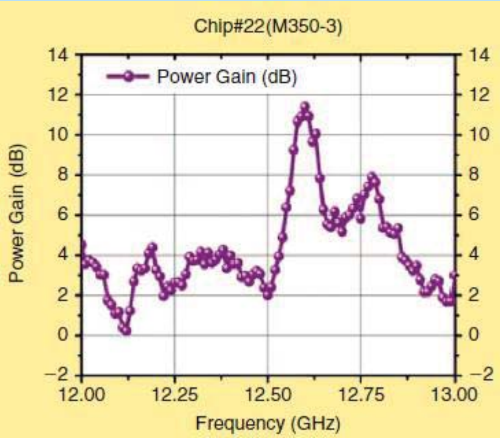






Custom 3.3 K Refrigerator with Vibration Isolation Bellows, Horizontal Cold Finger, Beryllia Heat Shield and X-Band Radome

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

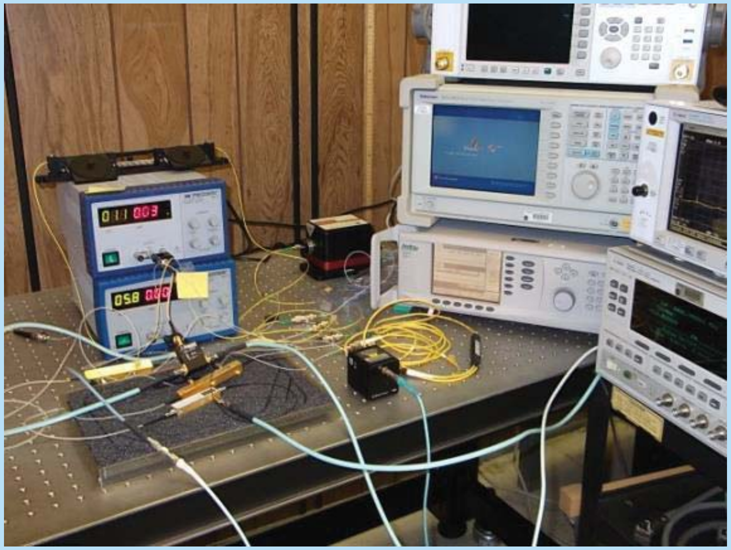


First reported X-band SQIF performance…

The Microwave/Teraherz/Lightwave Device & Circuit Integration Lab (B. 55)

Provides Support to: OCT; STMD (CIF)

The facility Includes a tunable diode laser (1150 μm) and power supply, a multi-wavelength analyzer module/controller, digital communications analyzer and bit error rate analyzer, signal generator, DC regulated power supply for diode lasers, there optical tables, a RF probe station, and an oven. The above test equipment along with miscellaneous fiber optic components and hardware can be configured to test hybrid RF/photonic integrated circuits, semiconductor photodetectors, and photonic integrated circuits.



The Lab was supported by the following programs in the past:

- GRC 2013 Center Innovation Fund (CIF) Proposal entitled "Design of Tunable Terahertz Receiver Based on Quantum Cascade Laser." PI: Dr. Hung D. Nguyen
- GRC 2012 Center Innovation Fund (CIF) Proposal entitled "Optical Transmitter for Selective RF High-Frequency Bands." PI: Dr. Hung D. Nguyen
- GRC 2011 Center Innovation Fund (CIF) Proposal entitled "Optical Communication Transmitter Terminal for Selective RF High-Frequency Band." PI: Dr. Hung D. Nguyen
- GRC IR&D, FY2003-2005 Proposal entitled "Gb/s Chip-to-Chip Optical Interconnect for Satellite Transceivers," PI: Dr. Rainee N. Simons

The above CIF proposal efforts have resulted in the following Patent Applications:

- LEW 19072-1-1: A Non-Provisional Utility Patent Application entitled "Optical Tunable-Based Transmitter for Multiple Radio Frequency Bands," was filed. Inventors are : Dr. Hung D. Nguyen, Dr. Rainee N. Simons, Edwin G. Wintucky, and Dr. Jon C. Freeman
- LEW 19197-1: A Provisional Utility Application entitled "Multi-Frequency Teraherz Quantum Cascade Laser Source," was filed. Inventors are : Dr. Hung D. Nguyen, Dr. Rainee N. Simons, and Edwin G. Wintucky

Transatlantic Earth Station Laboratory (TESLA)

The Transatlantic Earth Station Laboratory (TESLA) was originally designed to support transatlantic satellite communications experiments into Europe and Northern Africa. Over the years the laboratory grew to include many high speed computer networks and satellite stations including a C-band ground station which provided a 24x7 satellite connection into Chile. Today the facility is largely inactive except for supporting UAS (Unmanned Aircraft System) flight experiments with the GRC S-3 and T-34 research aircraft.

The 8.1-meter TESLA ground station has supported the following activities over the years:

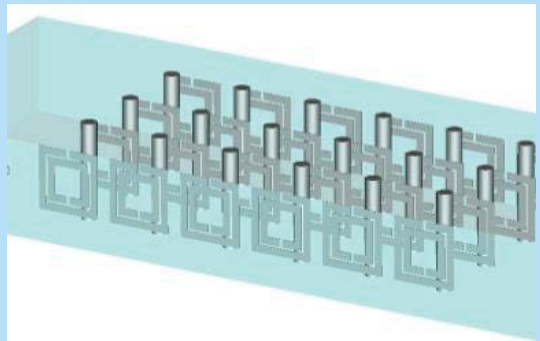
- STS-99 - Near real-time delivery of Shuttle Radar Topography Mission (SRTM) science data from STS-99 to DLR (German Aero Space Center).
- Desert-RATS (Desert Research and Technology Studies) – Two way communications to NASA research camps located in highly remote areas in Arizona.
- AATT (Advanced Air Transportation Technology) – Supported NASA 727 and DC-9 flight experiments of the Boeing developed Ku-band conformal phased array antenna. (This antenna design is used in the commercial ConneXion by Boeing system.)
- Several annual ARC-GRC Emergency Preparedness Tests.

NASA Glenn Research Centers 8.1-meter TESLA antenna

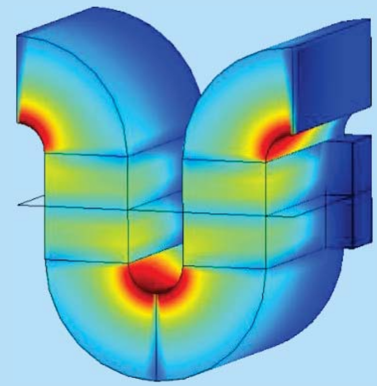
Modeling Capabilities

Modeling Tools:

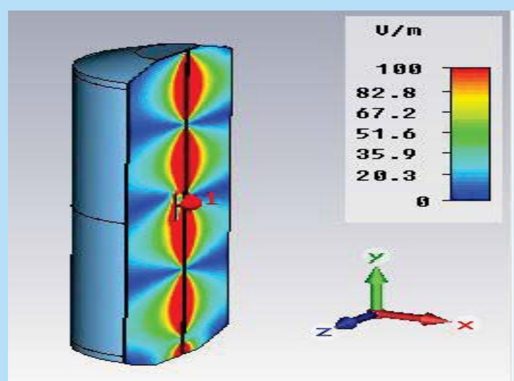
- NASA Coupled-Cavity Traveling-Wave Tube (TWT) Code to design microwave coupled-cavity and terahertz folded-waveguide TWT circuits.
- TWA3 to design helix TWT circuits.
- COMSOL Multiphysics to model electromagnetic metamaterials, antennas, SQIF thermal characteristics.
- Microwave Studio to model electromagnetic metamaterials, antennas, RF mass gauging for fuel tanks.
- Visualyse to model RF interference for AeroMACS and UAS.
- OptiSystem to model quantum key distribution and optical communication systems.
- HFSS; IE3D; Sonnet; etc. for microwave devices modeling and simulation



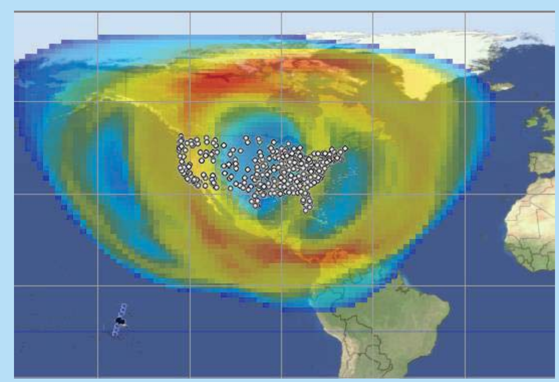
Left-handed metamaterial (Microwave Studio)



Current density in folded waveguide (COMSOL)



E-field in fuel tank for RF mass gauging (Microwave Studio)



RF power density from AeroMACS ground stations (Visualyse)

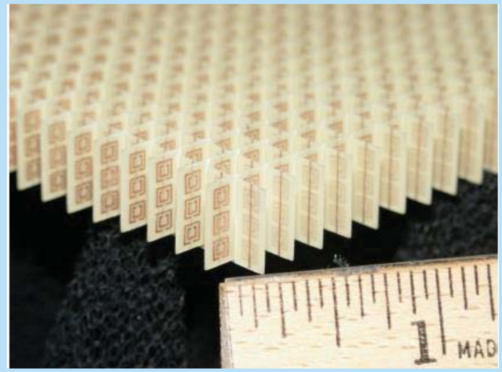
Metamaterials

- Experimentally demonstrated variable focal length left-handed metamaterial lens (Wilson and Schwartz, Appl. Phys. Letters, 2005).

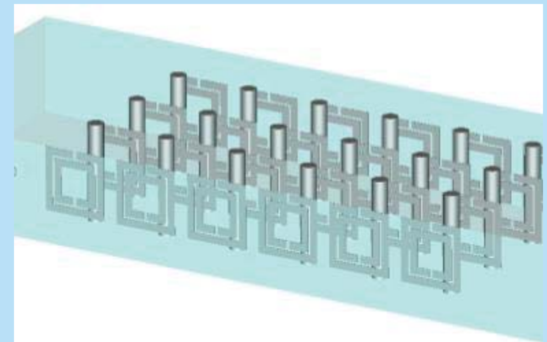
- Developed computational models of metamaterials in Microwave Studio and COMSOL Multiphysics.

- Computationally investigated metamaterials in walls of folded waveguide terahertz traveling-wave tubes (Starinshak and Wilson, NASA TP, 2008).

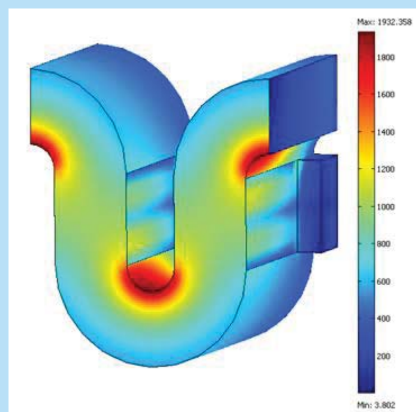
- Collaborating with University of Delaware on NASA EPSCoR project "Subwavelength Structures Based on Metamaterials and Spintronic Devices for Microwave Detection and Imaging".



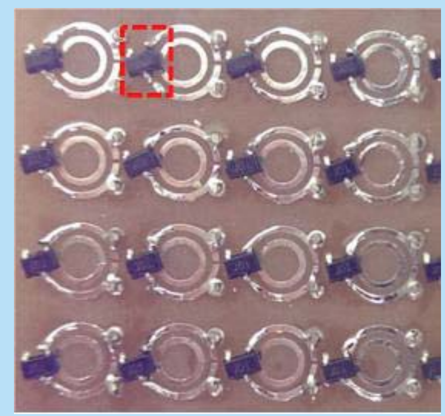
Metamaterial for variable focal length lens.



Microwave Studio model of metamaterial.



Current density in metamaterial THz TWT (COMSOL).



Metamaterial array (Univ. Delaware)

Current External Collaborations

- Air Force Research Laboratory- RF Propagation and mm-Wave Communications
- ESA/ASI—RF propagation; Svalbard; Alphasat
- Northrop Grumman Corporation– Deployable Mesh Reflectors
- Harris Corporation – Ultra wideband Antennas for Earth Science
- Army Research Laboratory—Clandestine Tag, Track, and Locate Low Signature Antennas
- SPAWAR/Hypres—SQIF
- ManTech– Large deployable antennas/cube Sats/phased arrays
- Applied Technology Associates – Vibration Isolation Systems for Optical Communications
- Vanguard Space Technologies – Light weight Composite Mirrors
- Configurable Space Microsystems Innovations and Applications Center (COSMIAC) @ UNM—CubeSats; Additive Manufacturing
- Numerous Universities (OSU, U. Delaware, UTEP, U-Utah, UPR, ASU, USF, etc.)