R&E

COMMUNICATIONS AND INTELLIGENT SYSTEMS DIVISION (LC)

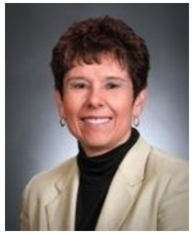
Ms. Dawn C. Emerson, Chief

Dr. Félix A. Miranda, Deputy Chief*

*Acting

Research and 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)

Dawn C. Emerson

Power Division (LE)

Randall B. Furnas

Materials and Structures Division (LM)

Dr. Ajay K. Misra

Systems Engineering and Architecture Division (LS)

Derrick J. Cheston

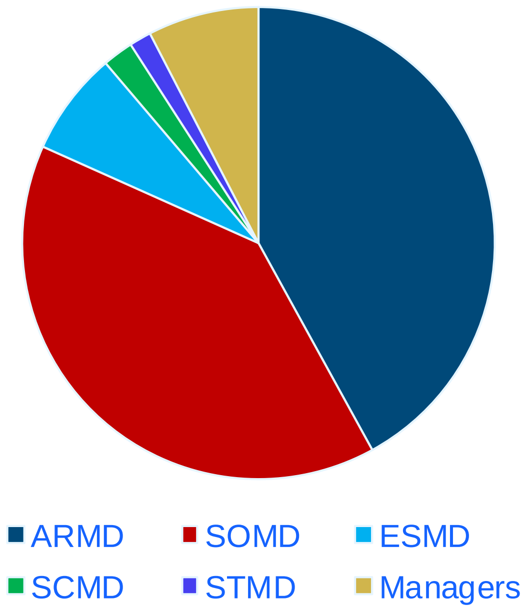
Propulsion Division (LT)

Dr. George R. Schmidt

Communications and Intelligent Systems Division (LC)

Provides expertise, plans, conducts and directs research and engineering development in the competency fields of advanced communications and intelligent systems technologies for application in current and future aeronautics and space systems.

LC Support to Mission Directorates



LC Competency Elements:

Space Communications (SpaceComm) & Aeronautical Communications (AeroComm)
Expertise:

- Networks & Architectures
- Information & Signal Processing
- Advanced High Frequency
- Optical Communications

Intelligent Systems – Cross-Cutting Competencies
Expertise:

- Optics and Photonics
- Smart Sensor Systems
- Instrumentation- Electronic
- Controls- Dynamic System Modeling and Controls

Communications and Intelligent Systems Division (LC)

123 FTE
58 WYE

Communications and Intelligent Systems Division (LC)
Dawn C. Emerson
Deputy: TBD, Dr. Félix A. Miranda- Acting

Communications ST: TBD

Architectures, Networks and Systems Integration Branch
LCA/Dave Buchanan, Denise Ponchak
27 FTE (1 Ph.D, 22 MS, 4 BS), 20 WYE

Intelligent Control and Autonomy Branch
LCC/Dr. Sanjay Garg
20 FTE (5 Ph.D, 10 MS, 2 BS), 11 WYE

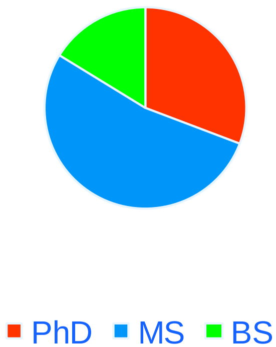
Advanced High Frequency Branch
LCF/Thomas Kacpura*
19 FTE (7 Ph.D, 9 MS, 3 BS), 4WYE

Information and Signal Processing Branch
LCI/Gene Fujikawa
18 FTE (4 Ph.D, 10 MS, 4 BS), 8 WYE

Optics and Photonics Branch
LCP/Dr. George Baaklini
20 FTE (9 Ph.D, 10 MS, 1 BS), 6 WYE

Smart Sensors and Electronics Systems Branch
LCS/Dr. Larry Matus
16 FTE (10 Ph.D, 4 MS, 2 BS), 8 WYE

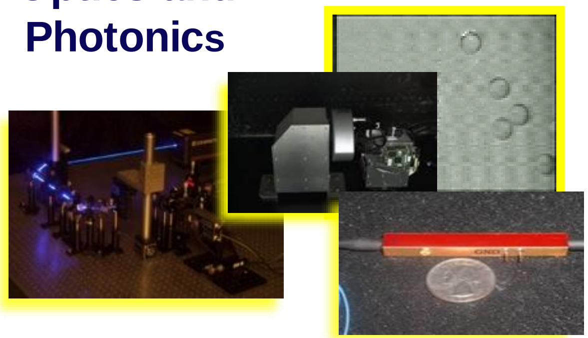
Education



*Acting

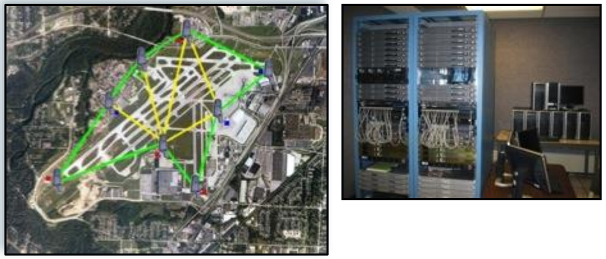
Communications and Intelligent Systems Division (LC)

Optics and Photonics



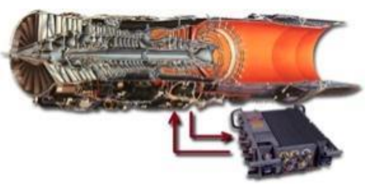
Optical Instrumentation
Optical Communications
Health Monitoring

Architectures, Networks and Systems Integration



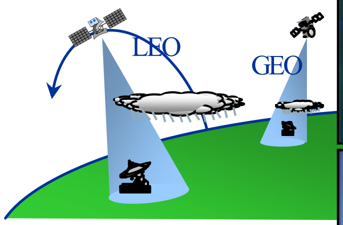
Communications Architectures
Modeling and Simulation/Tech Demos
Spectrum and Link Analysis

Intelligent Control and Autonomy



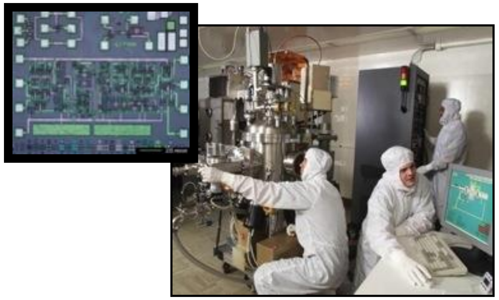
Intelligent Controls
Dynamic Modeling
Health Management

Advanced High Frequency



Antennas/Propagation
RF Systems and Components
3-D Electromagnetic Modeling

Smart Sensors and Electronics Systems



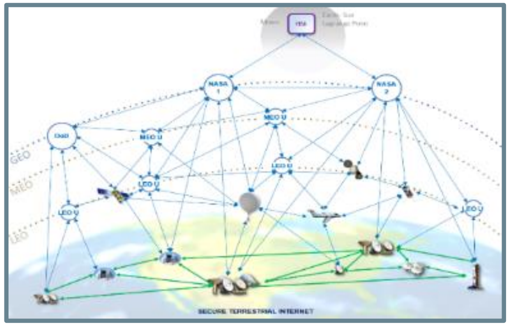
Thin Film Physical Sensors
High Temp/Harsh Environment Focus
Wireless Technologies

Information and Signal Processing

Radio Systems – SDRs, Cognitive
Bandwidth and Power-Efficiency
Waveform Development

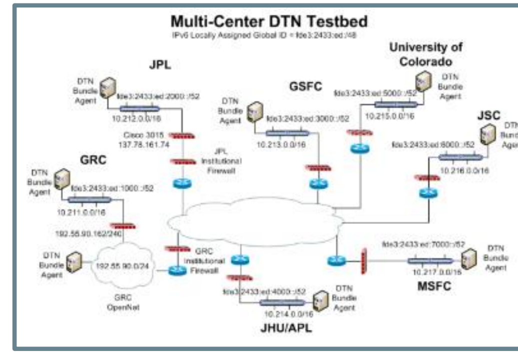
Additional Information
LC Branches

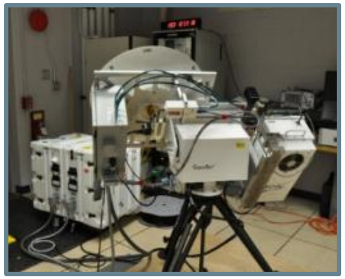
Architectures, Networks and Systems Integration Branch (LCA)

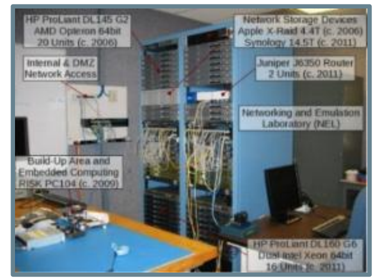


Communications Systems

- Systems engineering of future SCaN Integrated Network Architecture.
- Requirements decomposition, systems definition, development, hardware and software build up, test and delivery of Space Network compatibility test unit including TDRS signal simulator.

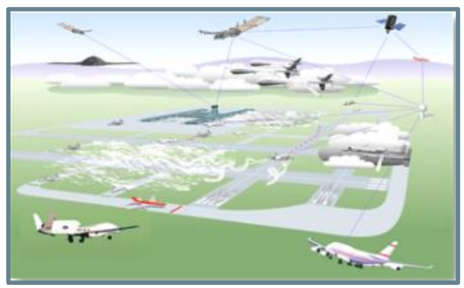


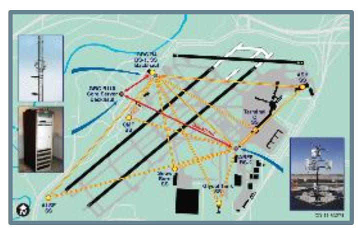




Aeronautical Communications

- Includes air-to-air, air-to-ground, and ground-based mobile wireless communications, information networking, navigation and surveillance research, technology development, testing and demonstration, advanced concepts and architectures development, and national and international technology standards development.





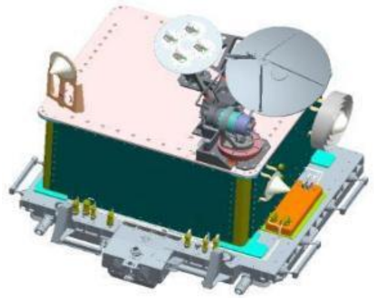
Network Research

- Development of network components, design of network layers and networked systems architectures. Emphasis is on secure wireless mobility, protocol characterization and development, requirements definition, and flight software/hardware component assessment. Also includes "virtual" mission operations.

Information and Signal Processing Branch (LCI)

LCI Overview

Conducts research and technology development of information and signal processing methods and approaches of digital communications systems for aerospace applications. Emphasis on software-defined and cognitive radios; open SDR architectures and waveform development; position, navigation and timing methods; spectrum and power efficient techniques; reconfigurable microelectronic devices



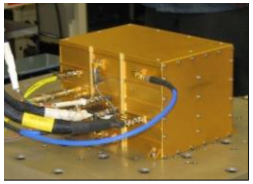
SCaN Testbed

Focus Areas

- Software-Defined and Cognitive Radios
  - Space Telecommunications Radio System (STRS)
  - STRS-compliant Hardware and Software
  - SDR Waveform Development
  - Digital Core for RF/Optical Terminal
- High Speed Signal Processing
  - Computer Modeling and Simulation Tools
  - Wireless and Microelectronic Devices for Communications
- Advanced Exploration Systems
  - Integrated Audio/Microphone Arraying
  - EVA Radio Development
  - Surface Navigation
- SCaN Testbed Flight Radio Experiments and Demonstrations
  - GPS Navigation and Timing
  - Ka-Band, Bandwidth-Efficient, High Rate Waveform
  - S- and Ka-Band IP Networking and Routing
  - Adaptive Modulation and Coding for Cognitive Radio

Facilities/Labs

- Software-Defined and Cognitive Radio Technology Development Laboratory
- Digital Systems and Signal Processing Lab
- EVA Radio and Integrated Audio Lab
- SCaN Testbed on ISS Available for Experimenters



Software Defined Radios

Extra-Vehicular Activity (EVA) Radio

AES/EVA Integrated Audio

iROC Flexible Digital Core

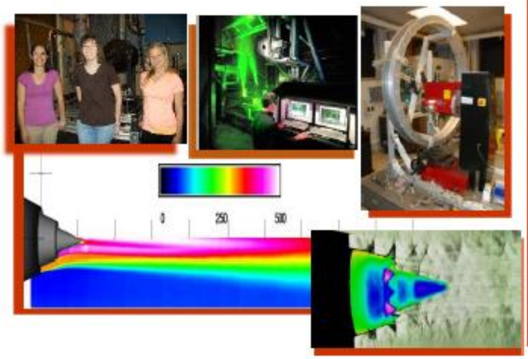
Advanced High Frequency Branch (LCF)

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.

Optics and Photonics Branch (LCP)

Optical Instrumentation



http://www.grc.nasa.gov/WWW/Optinstr/

- Our data and instrumentation help designers understand the fundamental physics of new systems, validate aeronautics computational and life models, and improve space optical communications for human and robotic explorations.
- Our data leads to improved designs, validation and verification of systems performances, increased communications, safety and security and reduced design cycle times for many of the core technologies developed at Glenn and across NASA.

Photonics and Health Monitoring

Flow/Noise Diagnostics
- Particle imaging Velocimetry (PIV)
- Background Oriented Schlieren
- Rayleigh Scattering
- PIV Tomography
- Combustion diagnostics
- Raman Diagnostics (Species, T)
- Plasma generation

Surface Diagnostics
- Temperature Sensitive Paint
- Pressure Sensitive Paint
- Stress Sensitive Film

Engine Icing
- Light Extinction Tomography
- Light Extinction Probes
- Raman Spectroscopy
- Impedance Sensor

Optical Communications

Free Space Communications
- Optical Teletennas
- Beaconless Pointing Systems
- High Data Rate for Deep Space & Near Earth

Secure Quantum Communications
- Quantum Entanglement
- Pulsed photon Pairs
- Quantum Illumination
- Quantum Key Distributions

Mobile and Remote Sensing
- On-Orbit Solar Cell Characterization MISSE 5-8; TACSAT- 4;
- Hyperspectral Imaging
- Mobile Sensing Platforms

Communications
- Communications over power lines
- Communications Interface Boards
- High Data Rate

Health Monitoring
- Microwave Blade Tip Clearance
- Self diagnostic Accelerometer
- Fiber optics sensors
- Morphology dependent resonance
- Phosphor Thermography
- Capacitance & piezo patches sensors
- Wireless and wired techniques

Smart Sensors and Electronics Systems Branch (LCS)

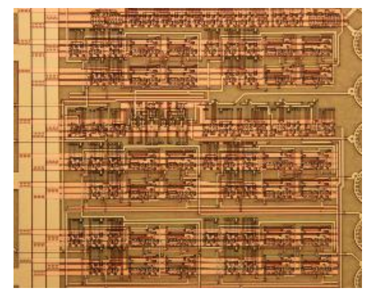
Description

Conducts research and development of adaptable instrumentation to enable intelligent measurement systems for ongoing and future aerospace propulsion and space exploration programs. Emphasis is on smart sensors and electronics systems for diagnostic engine health monitoring, controls, safety, security, surveillance, and biomedical applications; often for high temperature/harsh environments.

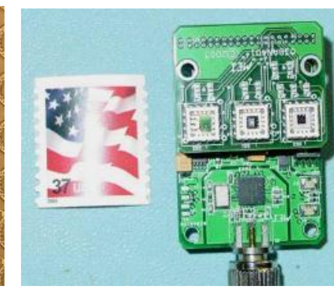
Microsystems Fabrication Facility

Facilities/Labs

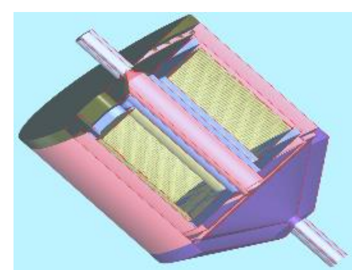
- Microsystems Fabrication Facilities
  - Class 100 Clean Room
  - Class 1000 Clean Room
- Chemical vapor deposition laboratories
- Chemical sensor testing laboratories
- Harsh environment laboratories
  - Nanostructure fabrication and analysis
  - Sensor and electronic device test and evaluation



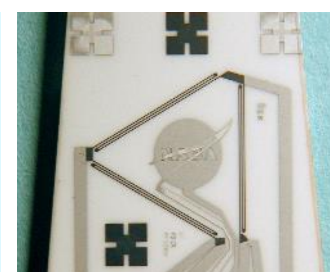
SiC Signal Processing



Chemical Gas Sensors



MEMS Fuel Actuation



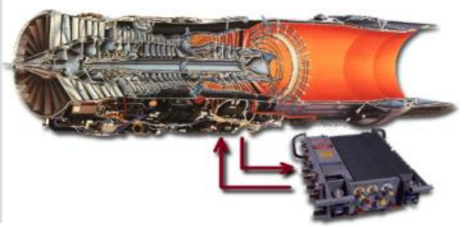
Thin Film Physical Sensors

Focus Areas

- Silicon Carbide (SiC) - based electronic devices
  - Sensors and electronics for high temp (600°C) use
  - Wireless sensor technologies, integrated circuits, and packaging
- Micro-Electro-Mechanical Systems (MEMS)
  - Pressure, acceleration, fuel actuation, and deep etching
- Chemical gas species sensors
  - Leak detection, emission, fire and environmental, and human health monitoring
- Microfabricated thin-film physical sensors
  - Temperature, strain, heat flux, flow, and radiation measurements
- Harsh environment nanotechnology
  - Nano-based processing using microfabrication techniques
  - Smart memory alloys and ultra low power devices

Intelligent Control and Autonomy Branch (LCC)

Propulsion Controls



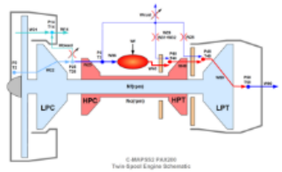
Active Combustion Control
Control of Thermo-acoustic Instability
High Bandwidth Fuel Actuation

Advanced Control Architecture
Distributed Engine Control
Hardware-in-the-loop Test-bed

Intelligent Engine Control
Enhanced Engine Response for Emergency Operations
Robust Engine Control
Model-Based Engine Control
V&V of Advanced Controls

High Speed Propulsion
Aero-Propulso-Servo Elasticity for Supersonic Propulsion System
Mode Transition Management for Air-Breathing Hypersonic Propulsion

Health Management



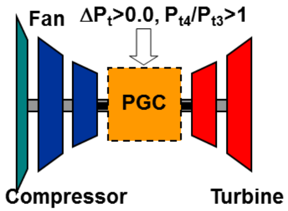
Propulsion & Power Systems
Gas Path Health Management
Sensor Selection
Sensor Data Qualification
Fault Modeling and Diagnostics
Model-Based Engine Simulation for Engine Test, Calibration and Performance Analyses

Current NASA Programs

Aeronautics Research Mission
Advanced Air Vehicle
Airspace Operations and Safety
Transformative Aeronautics Concepts

Human Exploration and Operations Mission
Space Launch System
SCAN
Orion

Advanced Propulsion Concepts



Unsteady Propulsion
Pulse Detonation Engine
Pressure Gain Combustion

Communications

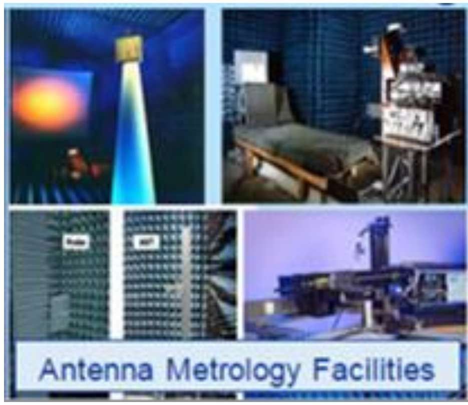
Integrated Radio and Optical Comm
Spacecraft Attitude Estimation
Spacecraft Structural Dynamics

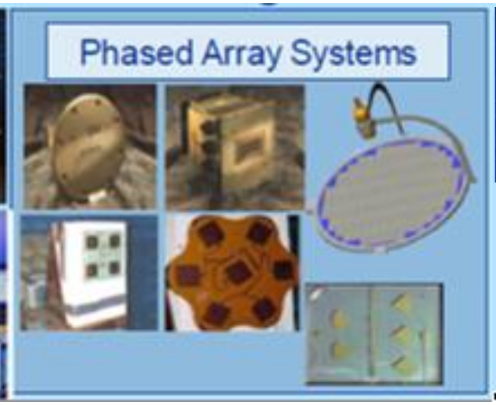
Software Tools

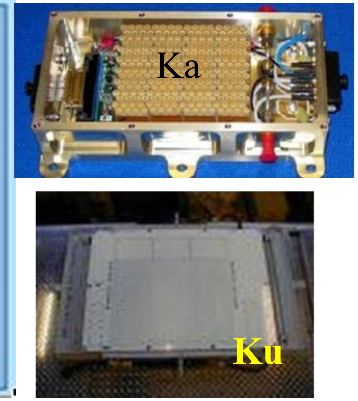
Engine Modeling & Control
C-MAPSS (Commercial Modula Aero Propulsion System Simulation)
C-MAPSS40k (40,000 lb Thrust Engine)
T-MATS (Tool for Modeling and Analysis of Thermodynamic Systems)
Combustion Instability Simulation

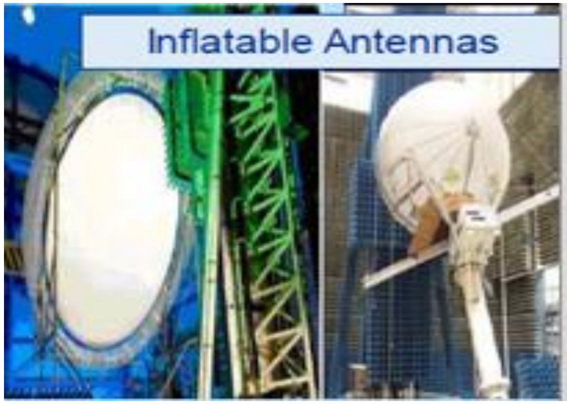
Areas for Potential Collaboration Including Technology Needs

Advanced RF Antenna and Optical Technologies

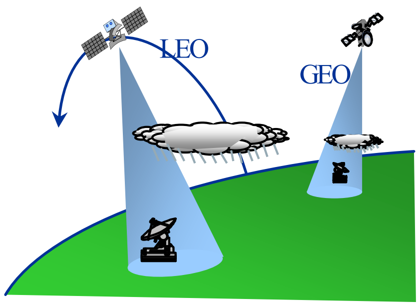


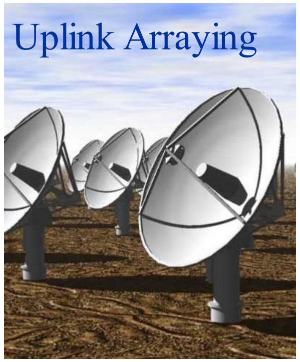






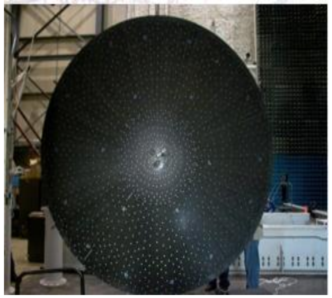
Antennas/Propagation



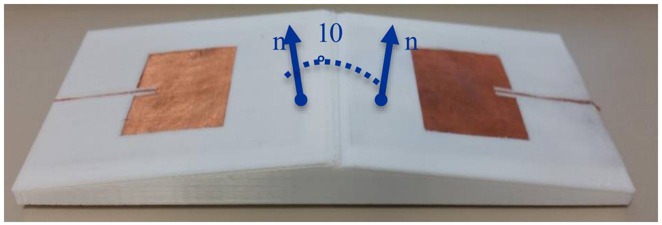


Mesh Antennas

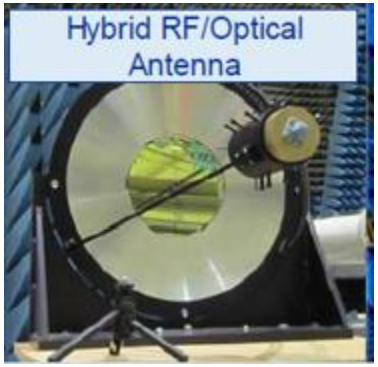
Shape Memory Polymers Antennas



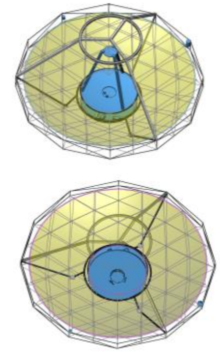
3-D Printed Antennas for Cubesats



SCaN Testbed Ground Station



Teletenna Concept



Advanced RF Antenna and Optical Technologies

Technology Needs

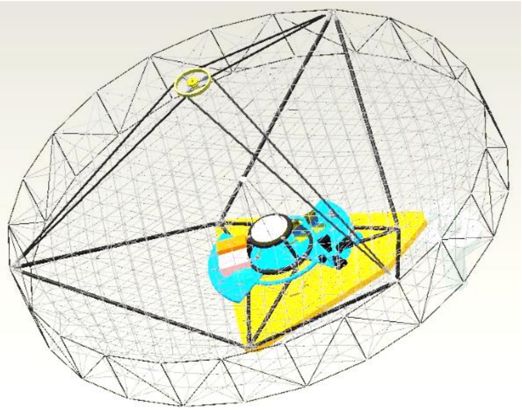
- Flight and ground antennas providing larger effective apertures than those currently in operation, with high efficiency but lower mass per unit area and accurate pointing.
- Novel materials, design, and manufacturing methods that enable lower mass, greater efficiency, and greater control of fields across the antenna aperture.
- Game-changing advances in component technologies that could enable significant advances in antenna array performance and enable alternate, higher-performance architectures
- Ka-band multiple-access phased arrays for NASA's Next Generation Communication and Navigation Architecture Systems (i.e., TDRSS follow-on relay and user terminals)
- High-performance electronically-steered antennas required for a dedicated communications relay spacecraft with multiple simultaneous connections, advanced multifunction antennas to support science missions that utilize a multifunction antenna to both communicate and conduct science.
- Antennas that are reconfigurable in frequency, polarization, and radiation pattern that reduce the number of antennas needed to meet the communication requirements
- Arrays of optical telescopes as an option to building large monolithic telescopes
- Light weight precision mirror technologies for space applications
- Novel high efficiency single photon counting detector systems

Example of Optical Technology Need: Novel Optical Communications Architectures

Goal: Develop futuristic deep-space optical communications terminals for space and ground systems

Objective: Investigate hybrid microwave and optical teletenna systems for deep space communications and explore alternative to single monolithic earth-based terminals.

Challenge: Minimizing hybrid system mass; implementing precision beaconless pointing; realizing vibration isolation to support micro-radian beam pointing; minimizing ground array cost relative to single monolithic telescope.

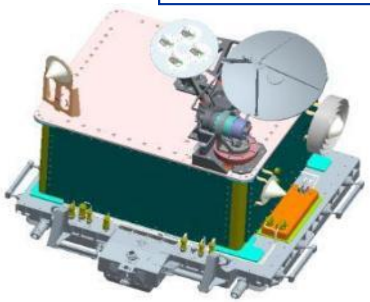


Benefit: Enhancing data rate from Mars to Earth from the current 6 Mbps to over 250 Mbps and minimizing the capital investment needed to support the ground infrastructure to enable that link.

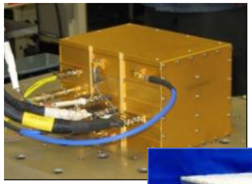
State of Art Technology Readiness Level (TRL): 3 **Technology Performance Goal TRL: 6**

Cognitive Radio and Signal Processing Technologies

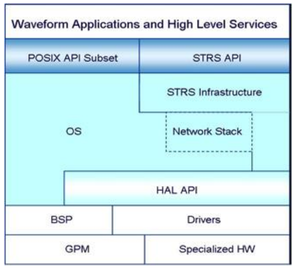
SCaN Testbed



Software Defined/Cognitive Radios



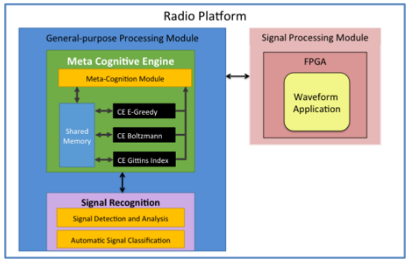

AES/EVA Radio/Integrated Audio



Space Telecommunication Radio System (STRS) Architecture

Combined Communications/Imaging

iROC Flexible Digital Core

Cognitive Engine Algorithms

Cognitive Radio and Signal Processing Technologies

Goal

To improve the state of the user platform (spacecraft/aircraft) to maximize data return, enable substantial efficiencies, or adapt to unplanned scenarios through the use of cognitive systems. Cognitive systems and autonomy have the potential to improve system performance, increase data volume return, improve data transmission efficiency, and reduce user burden to improve science return from NASA missions. Cognitive systems will sense, detect, adapt, and learn from its environment to improve the communications/navigation capabilities of the user platforms.

Technology Needs

- Cognitive engine (algorithm) and component development to demonstrate new capability in sensing and adapting to the radio/mission environment
- Introduce changes in physical layer (PHY) data rate, modulation, and coding, media access control layer (MAC) for new protocols and cognitive engines to negotiate changes between nodes and throughout the network, learning opportunities and techniques, and networking and application layers (and across layers) to adjust to signal conditions, efficiently using links for telemetry, video, adaptive and intelligent routing, etc.

Cognitive Radio and Signal Processing Technologies

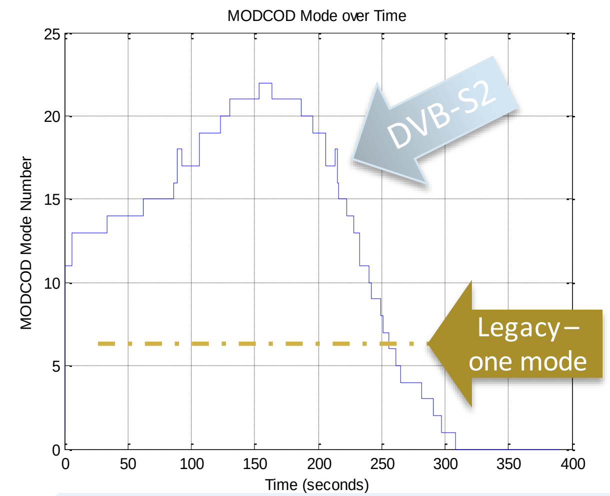
Technology Needs

- System wide distributed intelligence of cognitive and intelligent applications - system wide effects on decisions made by one or more communication/navigation elements, how to handle unexpected or undesired decisions
- Flexible data rate, modulation, or frequencies between nodes of satellites, utilizing space and ground network stations and multiple access techniques that optimize connectivity and throughput while minimizing onboard data storage and interference
- Signal processing platforms, adaptive front ends for RF or optical communications with cognitive or intelligent applications to provide needed capability while minimizing on-board resources and cost.
- Precise autonomous navigation and pointing techniques to minimize pointing loss and to coordinate multiple autonomous activities with cognitive radio systems that can continuously maximize data return via both multiple beam GEO relays and direct to ground links.

Example of Cognitive Technology Needs: Adaptive Coding and Modulation DVB-S2

Previous approaches for Space Applications
- NASA networks are fixed coding & modulation
- Worst case link margin used to guarantee nominal operations,, leading to overdesigned systems, and non-optimal utilization
- Increasing capability requires proportionally larger systems

New Method:
- Coding and modulation (data rate) can be varied based on link conditions, applicable to all space networks (SN, DSN, NEN)
- Leverage existing standards (e.g. DVB-S2, CCSDS AOS OCF)
- Apply cognitive systems to sense, detect, classify, learn, and adapt to time-varying communication environment.



Legacy Mode (OQPSK, Conv&RS, 5 MSym) - average throughput of **3 Mbps**
DVB-S2 Mode (5 MSym) – average throughput of **9 Mbps**

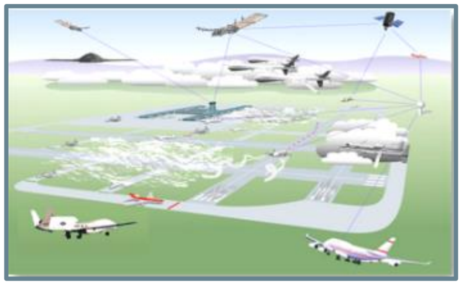
Benefits:
- Increased data volume return and efficient use of communication link and spectrum
- Communications more robust and resilient to unpredicted conditions (e.g. interference)
- Enables increased autonomy

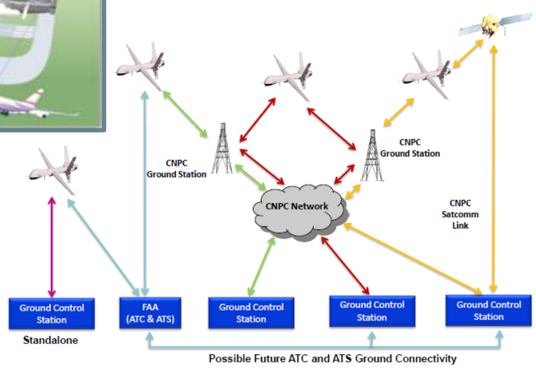
Return on Investment
- **3X** data throughput increase
- Access time per user services/infrastructure
- Reduced SWaP, operations complexity, and cost
- Increased system contingency management capability

Technology Infusion Plan
- Collaboration with SN on DVB-S2 for operations
- Applications will go into STRS repository for mission reuse
- Foundation for cognitive/intelligent systems

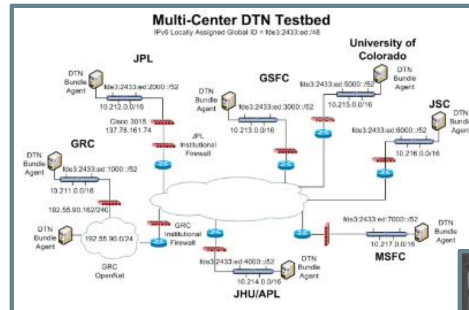
Network Architecture Research and Trade Studies

Aeronautics-based (National Airspace System) Architectures

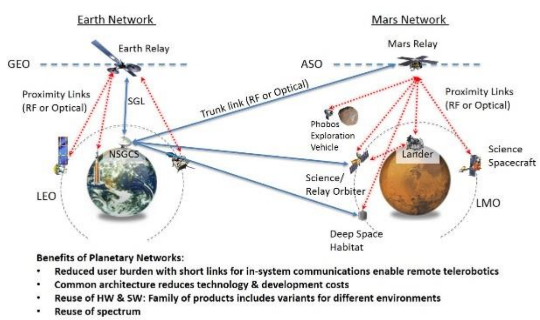


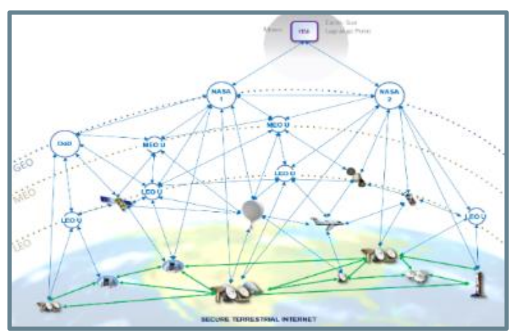


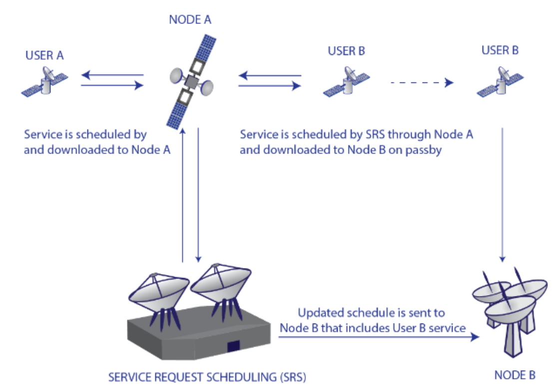
Network/Protocol Emulation Labs



Space-based Communications Architectures







Secure Network Architecture Research and Trade Studies

Collaboration Areas and Technology Needs

- DTN – Delay Tolerant Networking
  - Determine the viability of DTN and or other networking protocols that address network management challenges for highly delayed or disruptive networks and that allow data transfer rates up to 100 Gbps.
- Cognitive Networks
  - Perform research to apply a cognitive process to wireless networks. The cognitive network covers all the layers of the OSI model.
- Information-centric Security
  - Develop and demonstrate an advanced, information centric system that provides secure command and control services with an emphasis on security of the information itself, rather than a link, network, or application.
- Network Centric UAS Aircraft Operations
  - Automate and streamline the conventional operations through the development of network centric operations.
- Highly Integrated CNS Systems and Operations
  - Develop safety critical command and control communications to enable routine access to all segments of the National Airspace System (NAS) for all unmanned aircraft classes.

Example of Network Centric UAS Aircraft Operations

Goal: Automate and streamline conventional operations through the development of network centric operations.

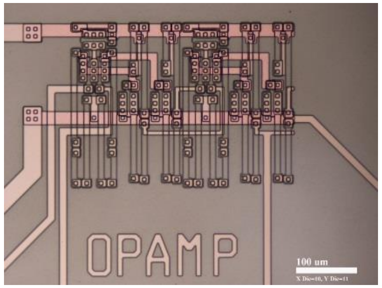
Objective: NASA GRC and a whole host of commercial, DoD, and civilian government partners have developed experimental virtual mission operations concepts. Introduction of these concepts into active flight missions is the next step. Experience is needed network centric security protocols, network protocols, software, and virtual operations development.

Challenge: Current systems are limited in their ability to replace expensive, FTE driven operations with autonomous, cognitive, machine-to-machine operations. Definition, development, and integration of secure, network centric systems will require significant changes in organizational thinking and operations

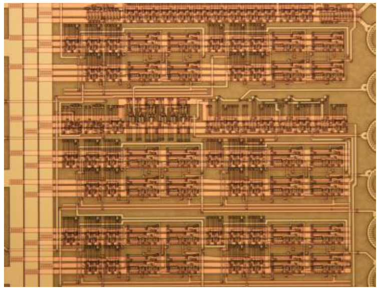
Benefit: Dramatic reductions in FTE costs with corresponding improvements in operational responsiveness

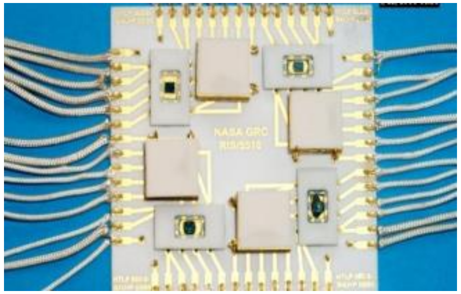
Smart Sensors and Electronics Systems Technologies

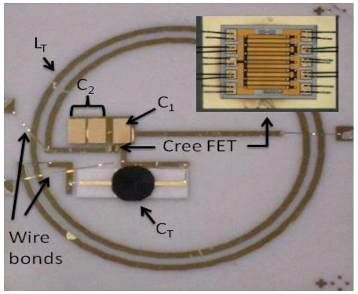
Silicon Carbide (SiC) – Based Electronic Devices for High Temperature (500 °C)



SiC Op-Amp Integrated Circuit


SiC IC Signal Processing

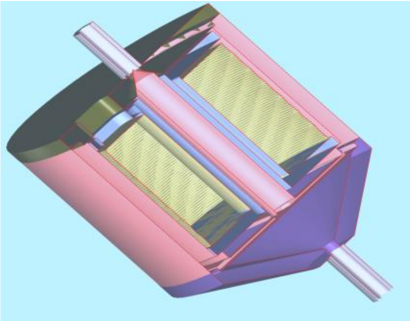

SiC Hi Temp Breadboard Package



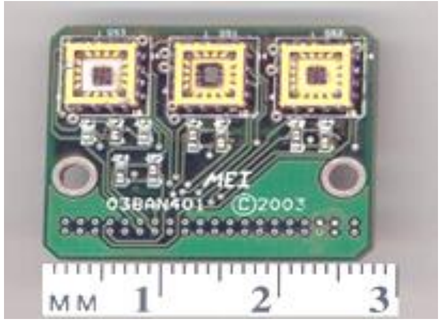
SiC Wireless Sensors

Silicon Carbide (SiC) – MEMS Based Devices

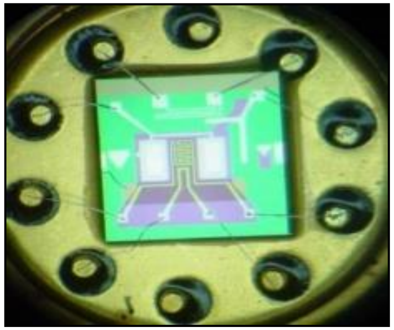

Packaged Pressure Sensors


MEMS Fuel Actuation

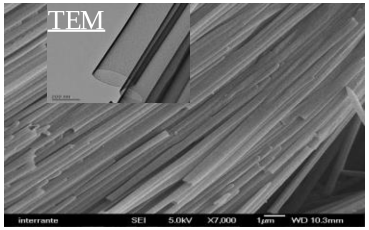
Chemical Gas Sensors



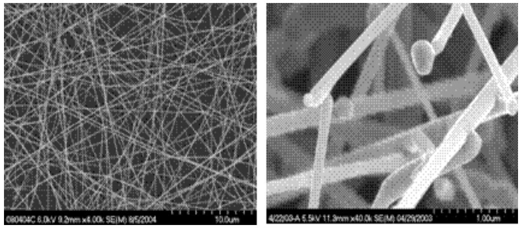
Packaged Gas Sensors


Hydrogen Sensor

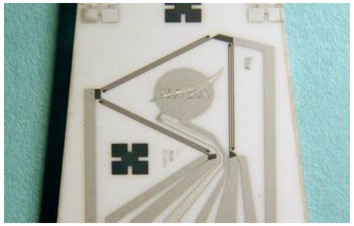
Harsh Environment Nanotechnology

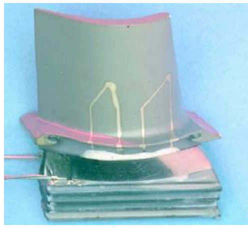


CVD SiC Nanotubes


Nanorod Structures

Thin Film Physical Sensors


Ceramic Strain Sensor

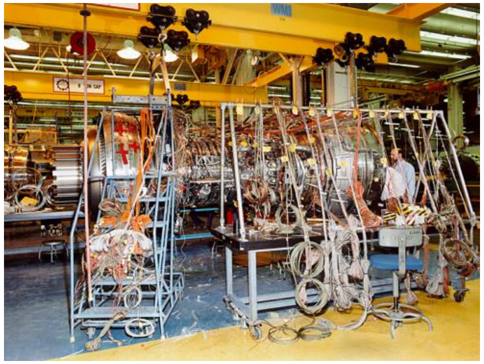

Thermocouple on complex shape

Smart Sensors and Electronics Systems Technologies

Technology Needs

- High temperature integrated circuit (IC) packaging technology that is manufacturable and cost effective.
- High temperature circuit components, e.g., capacitors, inductors, and resistors.
- Long-term, high temperature IC Mean Time to Failure (MTTF) and temperature cycling testing; failure analysis.
- System level modeling and simulation of MEMS-based sensors and actuator, e.g., fuel injectors.
- Embedding sensors and electronics into aerospace materials for health monitoring.
- Thin film thermo-electric materials for use in sensing applications (temperature, strain, heat flux) in high temperature corrosive environments, temperatures >1000 °C.
- High temperature thermo-electric materials for powering sensors and electronic devices in harsh environments (500 °C energy harvesting).
- Development of processes to control nano structure fabrication (non carbon nanotubes).
- Room temperature microfabricated sensor for the detection of carbon dioxide (CO_2).
- Platforms to test high temperature and harsh environment sensors for applications in gas turbines and aircraft engines.

Example of Smart Sensor Technology Need



Goal: Develop engines and turbines that are more efficient, quieter and less polluting than current systems.

Objective: Integrate sensors into the materials that comprise an engine or turbine and have those sensors obtain their power from the environment and transmit the data to a receiver without wires.

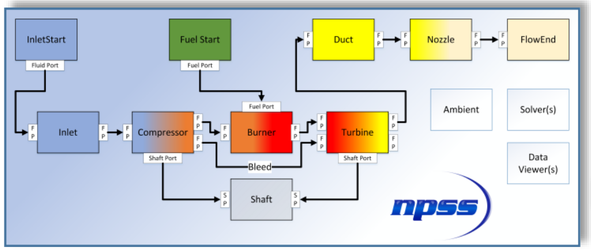
Challenge: Integrating a sensor and its electronics with a wireless transmitter and a power harvesting circuit within a small package that can be built into metal and ceramic components that comprise an engine or turbine.

Benefit: Distributed Integrated Intelligence in harsh environments – enables cognitive decision making, real time optimization of propulsion system: Improved efficiency, fuel reduction, less environmental impact.

State of Art Technology Readiness Level (TRL): 3

Technology Performance Goal TRL: 6

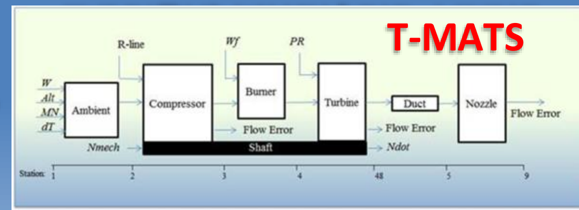
Control, Simulation, & Embedded HW Technologies



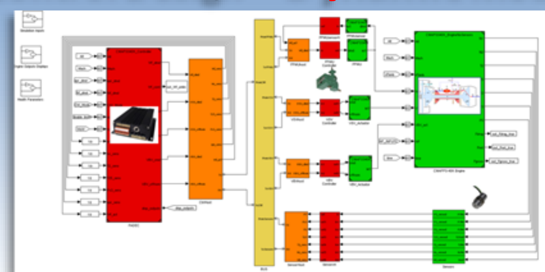
Engine Design – Steady State Model

Iterative Process

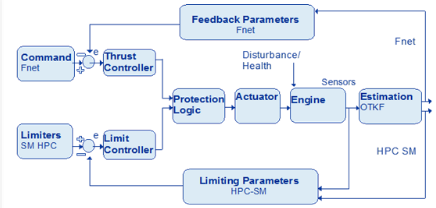
Design/Analysis Tools

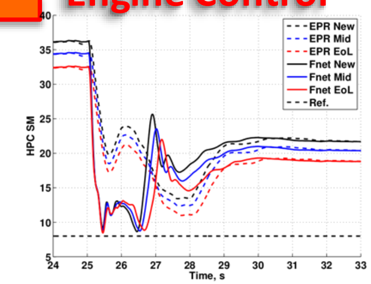


Control Design – Dynamic Model

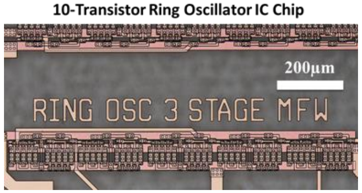


Model Based Engine Control

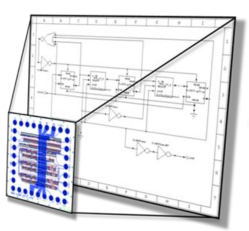




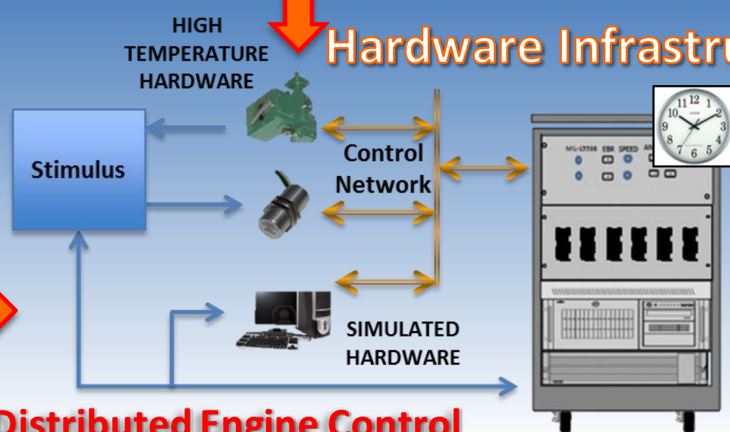
10-Transistor Ring Oscillator IC Chip



NASA High Temperature Silicon Carbide Electronics



Hardware Infrastructure



Distributed Engine Control

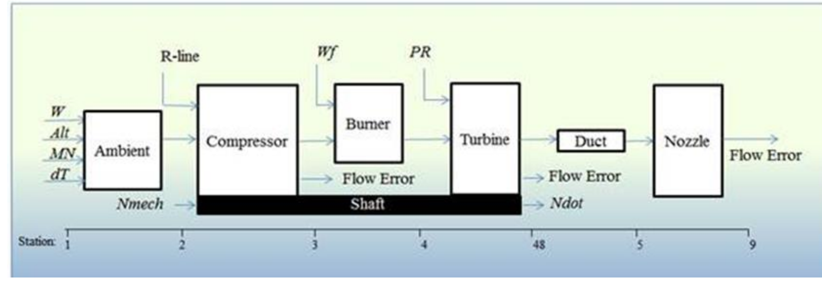
Control, Simulation, & Embedded HW Technologies

Technology Needs

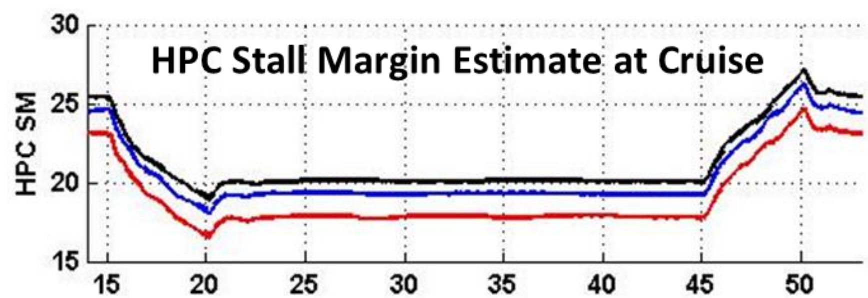
- Improved understanding of the information contained in the engine gas path related to system performance and safety.
- Improved sensing of spatial and temporal information in the engine gas path to extract information.
- Improved high temperature electronics to enable close coupling of the transducer to signal processing and digital data reduction functions.
- High speed, secure, reliable, local area networks in a high temperature environment to ensure deterministic distributed data flow and stable system control.
- Access to sufficient on-board computational resources to collect and process wide bandwidth system sensory data, process multivariable control algorithms, and evaluate control output relative to real-time model-based dynamic system simulation.
- Improved computational efficiency of complex multivariable control algorithms.
- Improved convergence and accuracy of real-time, on-board, dynamic engine system simulation.
- Improved modeling of engine system deterioration.
- Improved responsiveness and accuracy of engine system actuators.
- Improved fidelity of engine system simulation tools to enable quantitative evaluation of engine control architecture and engine system relative to constraints, performance and safety impact.
- More rapid control design process to enable timely input that impacts engine design process.

Example of Engine Control Technology Need: Control System Impact on Engine Design

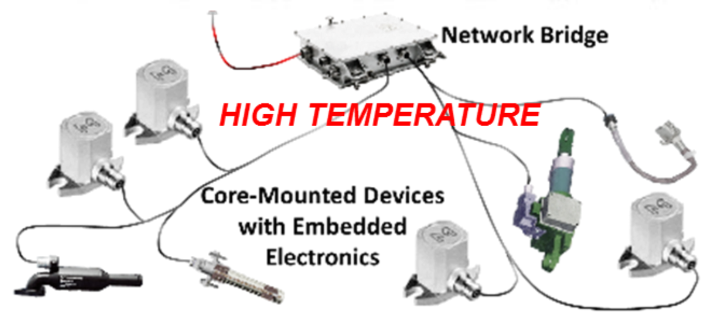
Goal: Demonstrate the capability of the control system to trade mechanical engine design margin for safe engine system performance improvement.



Objective: Investigate model-based control algorithms to precisely estimate system stability margin and performance characteristics in order to safely take advantage of unused engine capability.



Challenge: Coordinate a multidisciplinary investigation that couples steady-state engine design with dynamic control modeling and evaluates the outcome in terms of control hardware capabilities and architecture.



Benefit: Safely improve engine responsiveness and reduce fuel burn while developing design tools that have the capability to

State of Art Technology Readiness Level (TRL): 2 **Technology Performance Goal TRL: 5**