The Space Communication and Navigation Technology Area supports all NASA space missions with the development of new capabilities and services that make our missions possible. Communication links are the lifelines to our spacecraft that provide the command, telemetry, and science data transfers as well as navigation support. Advancement in communication and navigation technology will allow future missions to implement new and more capable science instruments, greatly enhance human missions beyond Earth orbit, and enable entirely new mission concepts. NASA's communication and navigation capability is based on the premise that communications shall enable and not constrain missions. Today our communication and navigation capabilities, using Radio Frequency technology, can support our spacecraft to the fringes of the solar system and beyond. As we move into the future, we are challenged to increase current data rates: 300 Mbps in LEO to about 6 Mbps at Mars to support the anticipated numerous missions for space science, Earth science and exploration of the universe. Technologies such as optical communications, RF including antennas and ground based Earth stations, surface networks, cognitive networks, access links, reprogrammable communications systems, advanced antenna technology, transmit array concepts, and communications in support of launch services are very important to the future of exploration and science activities of the Agency. Additionally, innovative, relevant research in the areas of positioning, navigation, and timing (PNT) are desirable. NASA's Space Communication and Navigation (SCaN) Office considers the three elements of PNT to represent distinct, constituent capabilities:

- **Positioning**, by which we mean accurate and precise determination of an asset's location and orientation referenced to a coordinate system.

- **Navigation**, by which we mean determining an asset's current and/or desired absolute or relative position and velocity state, and applying corrections to course, orientation, and velocity to attain achieve the desired state.

- **Timing**, by which we mean an assets acquiring from a standard, maintaining within user-defined parameters, and transferring where required, an accurate and precise representation of time, minimize the impact of latency on overall system performance.

This year, the following technology areas are being solicited to meet increasing data throughput and accuracy needs: Optical communications, RF communications, experiments involving reprogrammable communications systems, flight dynamics and breakthrough or high impact communication technologies. Emphasis is placed on size, weight and power improvements. Innovative solutions centered on operational issues are needed in all of the aforementioned areas. All technologies developed under this topic area to be aligned with the Architecture Definition Document and technical direction as established by the NASA SCaN Office. For more details, see [http://ti.arc.nasa.gov/tech/asr/intelligent-robotics/haughton-field/](http://ti.arc.nasa.gov/tech/asr/intelligent-robotics/haughton-field/).
Subtopics

H9.01 Long Range Optical Communications

Lead Center: JPL
Participating Center(s): GRC, GSFC

This subtopic seeks innovative technologies for long range Optical Telecommunications supporting the needs of space missions. Proposals are sought in the following areas:

Systems and technologies relating to acquisition, tracking and sub-micro-radian pointing of the optical communications beam under typical deep-space ranges (to 40 AU) and spacecraft micro-vibration environments.

- **Isolation platforms** - Compact, lightweight, space-qualifiable vibration isolation platforms for payloads massing between 3 and 50 kg that require less than 15 W of power and mass less than 3 kg that will attenuate an integrated angular disturbance of 150 micro-radians to less than 0.5 micro-radians (1-sigma), from

- **Laser Transmitters** - Space-qualifiable, >20% DC-to-optical (wall-plug) efficiency, 0.2 to 16 nanosecond pulse-width 1550-nm laser transmitter for pulse-position modulated data with from 16 to 320 slots per symbol, less than 35 picosecond pulse rise and fall times, near transform limited spectral width, single polarization output with at least 20 dB polarization extinction ratio, amplitude extinction ratio greater than 38 dB, average power of 5 to 20 Watt, massing less than 500 grams per Watt. Also of interest for the laser transmitter are: robust and compact packaging with radiation tolerant electronics inherent in the design, and high speed electrical interface to support output of pulse position modulation encoding of sub nanosecond pulses and inputs such as Spacewire, Firewire or Gigabit Ethernet. Detailed description of approaches to achieve the stated efficiency is a must.

- **Photon counting near-infrared detectors arrays for ground receivers** - Hexagonal close packed kilo-pixel arrays sensitive to 1000 to 1650 nm wavelength range with single photon detection efficiencies greater than 60% and single photon detection jitters less than 40 picoseconds 1-sigma, active diameter greater than 15 microns/pixel, and 1 dB saturation rates of at least 10 mega-photons (detected) per pixel and dark count rates of less than 1 MHz/square-mm.

- **Photon counting near-infrared detectors arrays for flight receivers** - For the 1000 to 1600 nm wavelength range with single photon detection efficiencies greater than 40% and 1dB saturation rates of at least 1 mega-photons/pixel and operational temperatures above 220K and dark count rates of

- **Ground-based telescope assembly** - Telescope/photon-buckets with primary mirror diameter ~2.5 meter, f-number of ~1.1 and Cassegrain focus to be used as optical communication receiver/transmitter optics at 1000-1600nm. Produce a maximum image spot size of ~20 micro-radian, and field-of-view will be ~50 micro-radian. Telescope shall be positioned with a two-axis gimbal capable of 0.25 milli-radian pointing. Desired manufacturing cost for combined telescope, gimbal and dome in quantity (tens) is ~$3 M each.

Research should be conducted to convincingly prove technical feasibility during Phase I - ideally through hardware development, with clear pathways to demonstrating and delivering functional hardware, meeting all objectives and specifications, in Phase II.

**Phase I Deliverables** - Phase I deliverables shall include a final report describing design studies and analyses,
system, sensor, or instrumentation concepts, prospective material formulations, testing, etc. Prototype systems, components, sensors, instruments or materials can be developed in Phase I as well. The designs or concepts should have commercialization potential. For Phase II consideration, the final report should include a detailed path towards Phase II hardware proof-of-concept system or component or material manufacturing and testing as applicable. The technology concept at the end of Phase I should be at a TRL of 4.

Phase II Deliverables - Phase II deliverables shall consist of working proof-of-concept systems, tested material formulations with samples, tested component, sensor, or instrumentation hardware, etc. which have been successfully demonstrated in a relevant environment and delivered to NASA for testing and verification. The technology at the end of Phase II should be at a TRL of 5-6.

Potential NASA Customers include:

- Deep Space Planetary Missions.
- Deep Space Optical Terminal (DOT) Project.
- Space Communications and Navigation (SCaN) Program.

H9.02 Long Range Space RF Communications

Lead Center: JPL
Participating Center(s): ARC, GRC, GSFC

This subtopic seeks to develop innovative long-range RF telecommunications technologies supporting the needs of space missions.

In the future, spacecraft with increasingly capable instruments producing large quantities of data will be visiting the Moon and the planets. These spacecraft will also support long term missions, such as to the outer planets, or extended missions with new objectives. They will possess reconfigurable avionics and communication subsystems and will be designed to require less intervention from earth during periods of low activity. The communication needs of these missions motivate higher data rate capabilities on the uplink and downlink as well as more reliable RF and timing subsystems. Innovative long-range telecommunications technologies that maximize power efficiency, reliability, receiver capability, transmitted power and data rate, while minimizing size, mass and DC power consumption are required. The current state-of-the-art in long-range RF space telecommunications is 6 Mbps from Mars using microwave communications systems (X-Band and Ka-Band) with output power levels in the low tens of Watts and DC-to-RF efficiencies in the range of 10-25%.

Technologies of interest:
This subtopic seeks innovative technologies in the following areas:

- Ultra-small, light-weight, low-cost, low-power, modular deep-space transceivers, transponders and components, incorporating MMICs, MEMs and Bi-CMOS circuits.

- MMIC modulators with drivers to provide a wide range of linear phase modulation (greater than 2.5 rad), high-data rate (10 - 200 Mbps) BPSK/QPSK modulation at X-band (8.4 GHz), and Ka-band (26 GHz, 32 GHz and 38 GHz).

- High DC-to-RF-efficiency (> 60%), low mass Solid-State Power Amplifiers (SSPAs), of both medium output power (10 W-50 W) and high-output power (150 W-1 KW), using power combining and/or wide band-gap semiconductors at X-band (8.4 GHz) and Ka-band (26 GHz, 32 GHz and 38 GHz).

- Utilization of nano-materials and/or other novel materials and techniques for improving the power efficiency or reducing the mass and cost of reliable vacuum electronics amplifier components (e.g., TWTAs and Klystrons).

- Ultra low-noise amplifiers (MMICs or hybrid, uncooled) for RF front-ends (High dynamic range (> 65 dB), data rate receivers (> 20 Mbps) supporting BPSK/QPSK modulations.

- MEMS-based integrated RF subsystems that reduce the size and mass of space transceivers and transponders. Frequencies of interest include UHF, X- and Ka-Band. Of particular interest is Ka-band from 25.5 - 27 GHz and 31.5 - 34 GHz.

- Novel approaches to mitigate RF component susceptibility to radiation and EMI effects.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

**Phase I Deliverables** - Feasibility study, including simulations and measurements, proving the proposed approach to develop a given product (TRL 3-4). Verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

**Phase II Deliverables** - Working engineering model of proposed product, along with full report of development and measurements, including populated verification matrix from Phase I (TRL 5-6). Opportunities and plans should also be identified and summarized for potential commercialization.

Potential NASA Customers include:

- Deep Space Planetary Missions such as Mars 2018, Mars Sample Return, Jupiter Outer Planet Missions.

- Human Space Exploration Missions such as missions to Asteroids, Mars or various Earth-Moon Libration Waypoints.
H9.03 CoNNeCT Experiments

Lead Center: GRC

Participating Center(s): JPL

NASA has developed an on-orbit, reprogrammable, software defined radio-based (SDR) testbed facility aboard the International Space Station (ISS), to conduct a suite of experiments to advance technologies, reduce risk, and enable future mission capabilities. The Communications, Navigation, and Networking reConfigurable Testbed (CoNNeCT) Project provides SBIR recipients and through other mechanisms NASA, large business, other Government agencies, and academic partners the opportunity to develop and field communications, navigation, and networking technologies in the laboratory and space environment based on reconfigurable, software defined radio platforms. Each SDR is compliant with the Space Telecommunications Radio System (STRS) Architecture, NASA’s common architecture for SDRs. The Testbed is installed on the truss of ISS and communicates with both NASA’s Space Network via Tracking Data Relay Satellite System (TDRSS) at S-band and Ka-band and direct to/from ground systems at S-band. One SDR is capable of receiving L-band at the GPS frequencies of L1, L2, and L5.

NASA seeks innovative software applications and experiments to run aboard the Testbed to demonstrate and enable future mission capability using the reconfigurable features of the software defined radios. Experiment software/firmware can run in the flight SDRs, the flight avionics computer, and on a corresponding ground SDR at the Space Network, White Sands Complex. Unique experimenter ground hardware equipment may also be used. Experimenters will be provided with appropriate documentation (e.g., flight SDR, avionics, ground SDR) to aid their experiment application development, and may be provided access to the ground-based and flight SDRs to prepare and conduct their experiment. Access to the ground and flight system will be provided on a best effort basis and will be based on their relative priority with other approved experiments. Please note that selection for award does not guarantee flight opportunities on the ISS.

Desired capabilities include, but are not limited to, the examples below:

- Demonstration of mission applicability of SDR.
- Aspects of reconfiguration:
  - Unique/efficient use of processor, FPGA, DSP resources.
  - Inter-process communications.
- Spectrum efficient technologies.
- Space internetworking:
  - Disruption Tolerant Networking.
- Position, navigation and timing (PNT) technology.
- Technologies/waveforms for formation flying.
• High data rate communications.
• Uplink antenna arraying technologies.
• Multi-access communication.
• RF sensing applications (science emulation).
• Cognitive applications.

Experimenters using ground or flight systems will be required to meet certain pre-conditions for flight including:

• Provide software/firmware deliverables (software/firmware source, executables, and models) suitable for flight.
• Document development and build environment and tools for waveform/applications.
• Provide appropriate documentation (e.g., experimenter requirements, waveform/software user's guide, ICD's) throughout the development and code delivery process.
• Software/firmware deliverables compliant to the Space Telecommunications Radio System (STRS) Architecture, Release 1.02.1 and submitted to waveform repository for reuse by other users.
• Verification of performance on ground based system prior to operation on the flight system.

Methods and tools for the development of software/firmware components that is portable across multiple platforms and standards-based approaches are preferred.

Documentation for both the CoNNeCT system and STRS Architecture may be found at the following link:

(http://spaceflightsystems.grc.nasa.gov/SpaceOps/CoNNeCT/)

These documents will provide an overview of the CoNNeCT flight and ground systems, ground development and test facilities, and experiment flow. Documentation providing additional detail on the flight SDRs, hardware suite, development tools, and interfaces will be made available to successful SBIR award recipients. Note that certain documentation available to SBIR award recipients is restricted by export controls and available to U.S. citizens only.

For all above technologies, Phase I will provide experimenters time to develop and advance waveform/application architectures and designs along with detailed experiment plans. The subtopic will seek to leverage more mature waveform developments to reduce development risk in subsequent phases, due to the timeframe of the on-orbit Testbed. The experiment plan will show a path toward Phase II software/firmware completion, ground verification process, and delivering a software/firmware and documentation package for NASA space demonstration aboard the flight SDR. Phase II will allow experimenters to complete the waveform development and demonstrate technical feasibility and basic operation of key algorithms on CoNNeCT ground-based SDR platforms and conduct their flight system experiment. Opportunities and plans should also be identified and summarized for potential
commercialization.

Phase I Deliverables:

- Waveform/application architecture and detailed design document, including plan/approach for STRS compliance.
- Experiment Reference Design Mission Concept of Operations.
- Experiment Plan (according to provided template).
- Demonstrate simulation or model of key waveform/application functions.
- Plan and approach for Commercialization of the technology (part of final report).
- Feasibility study, including simulations and measurements, proving the proposed approach to develop a given product. Early software/firmware application source and binary code and documentation. Source/binary code will be run on engineering models and/or SDR breadboards (at TRL-3-4).

Phase II Deliverables:

- Applicable Experiment Documents (e.g., requirements, design, management plans).
- Simulation or model of waveform application.
- Demonstration of waveform/application in the laboratory on CoNNeCT breadboards and engineering models.
- Results of implementing the Commercialization Plan outlined in Phase I.
- Software/firmware application source and binary code and documentation (waveform contribution to STRS Repository for reuse by others). Source/binary code will be run on engineering models and/or demonstrated on-orbit in flight system (at TRL-5-7) SDRs.

Potential NASA Customers include:

- Deep Space Planetary Missions.
- Extra Vehicular Activity Office.
- Space Communications and Navigation (SCaN) Program.
NASA’s current Position, Navigation, and Timing (PNT) state-of-the-art relies on both ground-based and space-based radiometric tracking, laser ranging, and optical navigation techniques. Post-processed GPS position determination performance accuracy is at the cm-level at Near-Earth distances and at meter-level at High-Earth Orbit distances; while autonomous real-time GPS performance, such as provided by GPS-Enhanced Onboard Navigation System (GEONS) can achieve accuracy performance of 20 meters. For missions at Mars, Deep Space Network navigation services provide performance accuracy of 1km, while optical navigation methodologies obtain performance accuracy of 10s of km at this distance.

Future NASA missions will require precision landing, rendezvous, formation flying, cooperative robotics, proximity operations, and coordinated platform operations. As such, the need for increased precision in absolute and relative navigation solutions increases. As operations occur further from Earth and more complex navigational maneuvers are performed, it will be necessary to reduce the reliance on Earth-based systems for real-time decisions. Investments in technologies to implement autonomous on-board navigation and maneuvering will permit a reduction in dependence on ground-based tracking, ranging, trajectory/orbit/attitude determination, and maneuver planning and support functions. Therefore, the early focus for NASA will be to improve PNT through increasing real-time PNT accuracy and precision, as well as achieving this performance in autonomously on-board the spacecraft.

Technologies and software should support a broad range of spaceflight customers. Technologies and software specifically focused on a particular mission’s or mission set’s needs are the subject of other solicitations by the relevant sponsoring organizations and should not be submitted in response to this solicitation. In the context of this solicitation, flight dynamics technologies and software are algorithms and software that may be used in ground support facilities, or onboard a spacecraft, so as to provide PNT services that reduce the need for ground tracking and ground navigation support. Flight dynamics technologies and software also provide critical support to pre-flight mission design, planning, and analysis activities.

This solicitation is primarily focused on NASA’s flight dynamics software and technology needs in the following focused areas:

- Next generation of multi-purpose ground-based and on-board autonomous navigation filtering techniques, such as adaptive filtering where measurements are selectively weighted, or filters that monitor state noise and measurement noise processes.
- Algorithms for real-time multi-platform relative navigation (relative position, velocity, attitude/pose).
- Algorithms which process clock measurements and estimate and/or propagate the timekeeping model (which generates the time and frequency signal output) and timekeeping system architectures in which outputs of an ensemble of clocks are weighed and software filtered to synthesize an optimized time estimate.
- Sensor measurement models and processing algorithms for next generation sensors, including (but not limited to): optical navigation sensors (high resolution flash LIDAR, visible cameras, infrared cameras), radar sensors, radiometrics, fine guidance sensors, laser rangefinders, high volume/high speed FPGA-based electronics for LIDAR.
- Algorithms for real-time vision processing, path planning and optimization, constraint handling, integrated system health management, fault management (FDIR), event sequencing, optimal resource allocations, collaborative sensor fusion, sensor image motion compensation and processing, pattern
recognition/matching, hazard search and detection, feature location and mapping, high performance inertial and celestial sensor models, accurate and fast converging vehicle state estimation filters and adaptive flight control systems.

- Applications of advanced dynamical theories to space mission design and analysis for ground-based and on-board autonomous algorithms, especially in the context of unstable orbital trajectories in the vicinity of small bodies, libration points, and Near-Earth objects.

- Autonomous navigational planning, detection, and filter optimization, as well as attitude control systems for autonomous platform orientation, using sensor measurement fault detection & management and/or fault-tolerant filtering algorithms.

- Addition of novel estimation techniques and/or orbit determination capabilities to existing NASA mission design software that is either freely available via NASA Open Source Agreements, or that is licensed by the proposer.

Proposals that leverage state-of-the-art capabilities already developed by NASA are especially encouraged, such as:

  

- General Mission Analysis Tool (http://sourceforge.net/projects/gmat/)

- GPS-Inferred Positioning System and Orbit Analysis Simulation Software:
  
  - (http://gipsy.jpl.nasa.gov/orms/goa/)

- Optimal Trajectories by Implicit Simulation (http://otis.grc.nasa.gov)

Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

Phase I Deliverables - Phase I research should be conducted to demonstrate technical feasibility (to reach TRL 3), with preliminary software being delivered for NASA testing at the end of the Phase I contract, as well as show a plan towards Phase II integration. Phase I Deliverables include:


- Preliminary Software at end of Phase I contract.

- Final Phase I Technical Feasibility Report with a Phase II Integration Path.

Phase II Deliverables - Phase II efforts should build on Phase I research towards a Phase II software demonstration and delivering a software package for NASA testing at the completion of the Phase II contract (to reach TRL 5). Also, prototype software should be delivered to NASA at the end of the first year of the contract, to be reviewed and iterated upon towards the development of the final software demonstration and delivery. Phase II
efforts should also include development of proper documentation, which includes a thorough Algorithm Specification document. Phase II Deliverables include:

- Prototype Software at end of first year of Phase II contract.
- Final Phase II Technical Report.
- Algorithm Specification at end of Phase II contract.
- Delivery of software package at end of Phase II contract.
- Demonstration of software package at end of Phase II contract.

Potential NASA Customers include:

- Space Communications and Navigation (SCaN) Program

H9.05 Game Changing Technologies

Lead Center: GRC
Participating Center(s): ARC, GSFC, JPL

NASA seeks revolutionary, highly innovative, game changing communications technologies that have the potential to enable order of magnitude performance improvements for space operations, exploration systems, and/or science mission applications. As NASA moves towards an integrated network architecture, infusion of critical, enabling technologies will be key to meeting user needs and offering standardized services. Emphasis for this subtopic is on the mid - (3-8 yrs.), and far-term (>8 yrs.) with focused research in the following areas:

Develop novel techniques for size, weight, and power (SWAP) of communications systems by addressing digital processing and logic implementation tradeoffs, dynamic power management, hardware and software partitioning. Address reliability, robustness, and radiation tolerance for missions beyond low Earth orbit. Investigate and demonstrate unique, innovative electronic or optical technologies to alleviate demanding mission requirements (at least 10X improvement over state-of-the-art) in areas such as chip speed, compression, encoding/decoding, etc. Communication systems optimized for energy efficiency (information bits per unit energy) will be increasingly important for low energy communication systems.

Small spacecraft, due to their limited surface area, are typically power constrained, limiting small spacecraft communications systems to low bandwidth architectures. Technologies and architectures that can exploit commercial or other terrestrial communication infrastructures to enable novel small satellite (e.g., CubeSat) missions are desired. Identify advanced solutions for higher density integration techniques and packaging. Address how existing communications architectures can be adapted and utilized to provide higher bandwidth communications capabilities with better performance and at lower cost for spacecraft to ground, and spacecraft to spacecraft applications.
Novel approaches to addressing extremely high bandwidth, high data rate signaling using RF, mm-wave (Ka- to W-band), and/or optical (1550 nm) links.) Purely optical links are subject to atmospheric interference (clouds, rain, snow, fog, etc.) and can restrict operations for Earth-based optical terminals, so hybrid RF/optical systems are intriguing. Technologies that address flexible, scalable digital/optical core processing topologies to support both RF and optical communications in a single dual-feed terminal, such as: programmable modulation/coding, multi-rate clocking and data recovery, system-on-a-chip integration, memory management, multi-processor architectures, etc. are sought to mitigate risk of such a system.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II demonstration with delivery of a demonstration unit or package for NASA testing at the completion of the Phase II contract.

Opportunities and plans should also be identified and summarized for potential commercialization.

*Phase I Deliverables* - Phase I deliverables shall include a final report describing design studies and analyses, system, sensor, or instrumentation concepts, prospective formulations, testing, etc. Prototype systems, components, sensors, instruments or materials can be developed in Phase I as well. The designs or concepts should have commercialization potential. For Phase II consideration, the final report should include a detailed path towards Phase II proof-of-concept system or component or testing as applicable. The technology concept at the end of Phase I should be at a TRL range of 2-3.

*Phase II Deliverables* - Phase II deliverables shall consist of working proof-of-concept systems, samples, component, sensor, or instrumentation hardware, etc. which have been successfully demonstrated in a relevant environment and delivered to NASA for testing and verification. The technology at the end of Phase II should be at a TRL range of 3-4.

Potential NASA Customers include:

- Deep Space Planetary Missions.
- Extra Vehicular Activity Office.
- Space Suit Communications.
- Space Communications and Navigation (SCaN) Program.