NASA’s communications capability is based on the premise that communications shall enable and not constrain missions. Communications must be robust to support the 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, access links, navigation and timing, reprogrammable communications systems, communications systems for EVAs, advanced antenna technology, transmit array concepts and communications in support of launch services including space based assets are very important to the future of exploration and science activities of the Agency. Emphasis is placed on size, weight and power improvements. Even greater emphasis is placed on these attributes as smaller spacecraft (e.g., micro and nano satellite) technology matures. Innovative solutions centered around operational issues associated with the communications capability are needed. Communications that enable the range safety data from sensitive instruments is imperative. These technologies are to be aligned with the Space Communications and Navigation Architecture as being developed by the Agency. A typical approach for flight hardware would include: Phase 1 - Research should identify and evaluate candidate telecommunications technology applications to demonstrate the technical feasibility and show a path towards a hardware/software demonstration. Plan a demonstration to validate the technologies/tools/processes. Bench or lab-level demonstrations showing concept viability is encouraged. Commercial applicability should be addressed. Phase 2 - Emphasis should be placed on developing and demonstrating the technology under simulated flight conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into space-worthy systems defining interfaces (both on the spacecraft and to candidate ground segments). When applicable, researchers should deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

Subtopics

O1.01 Coding, Modulation, and Compression

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

Power and spectrum efficient solutions are needed for both near-Earth and deep-space science and exploration applications. Channel coding efficiency from 50% to 87%, combined with good bit-error/burst-error correction property will provide solutions to multiple missions. A high-speed, digital receiver capable of demodulating coded modulations in addition to uncoded modulations is needed for future missions. In compression, implementation of a high-speed decoder for decoding a standard embedded bit-stream offering tunable lossy compression to lossless compression is desired. Proposals are sought in the following specific areas:
Compression

High-speed decoder capable of decoding coded bit stream conforming to CCSDS 122.0-B-1 Image Data Compression standard (www.ccsds.org) is solicited. The decoder has to provide over 640 Mbits/sec decoding for up to 16-bit image data coded in an embedded bit stream. The implementation technology shall point to potential space-use feasibility.

Coding

1. Special emphasis is placed on a channel coding design suitable for near-Earth missions, operating at least at over 80% coding rate with an error floor lower than Bit-Error-Rate (BER) of $10^{-10}$, and at least 8-bit burst-error correction property, with encoder/decoder complexity consistent with implementations at data rates close to 1 Gbps and power consumption smaller than a few watts. The new design when compared with current CCSDS Reed-Solomon (255,223) coder at BER of $10^{-5}$ shall have over 2dB Eb/No gain. The preferred code block frame length is from 4K to 16K bits. Proposed implementation technology shall point to potential space-use feasibility.

2. High-speed FPGA decoder for a set of 10 recently proposed low-density parity-check (LDPC) codes specified in a CCSDS Orange Book CCSDS 131.1-O-1 (www.ccsds.org). These codes include 9 codes, of rates 1/2, 2/3, and 4/5 and input blocklengths 1024, 4096, and 16384, and a rate 7/8 code of input blocklength 7136. The design should be capable of switching in real-time between decoders for any of the 10 codes, and have a throughput of at least 50 Mbps. There may be opportunities to use partial, stand-alone FPGA solutions developed by NASA.

High-Rate Receiver

High-rate receiver capable of decoding coded and un-coded modulation suite (8-PSK, GMSK, filtered OQPSK) specified by CCSDS 413.0-G-1 April 2003 (www.ccsds.org) and 16-PSK, 16-QAM, 16-APSK with processing throughput greater than 300 Mbits/sec is desired. A desirable feature for the receiver output is 7 bits/sample that can be used as input to channel decoding algorithms based on soft-decision decoding.
This call for proposals is meant to serve NASA's ever-evolving set of missions, which require precise tracking of spacecraft position and velocity in order to achieve mission success. The call seeks evolutionary improvements in modularity, sustainability, cost, and performance for current space navigation concepts that support the Vision for Space Exploration. This includes Projects Constellation, Mars Exploration Program, robotic servicing, and robotic Earth and space science missions. NASA also seeks disruptive navigation concepts that might not match the modularity, sustainability, cost, and/or performance of current technologies and their near-term evolution, but have convincingly demonstrable potential to overtake the evolution of current technologies within the future development of Project Constellation, and Earth and space science missions, in the 2015 - 2020 timeframes.

While the definition of “precise” depends upon the mission context, typical interplanetary scenarios have required Earth-based radiometric ranging accuracies of order 1-2m at 1 AU, Doppler to 0.03 mm/sec, and plane-of-sky angles to 2.5 nano-radians. While some legacy applications remain at 2.3 GHz, most current tracking is being done at 8.4 GHz. Forward looking demonstrations are being planned at 32 GHz. These radiometric techniques have been complimented by optical techniques which achieve ~1.5 micro-radian angular accuracy upon target approach. The accuracy of radio-based techniques is typically limited by one's ability to calibrate the path delay through intervening media (troposphere, ionosphere) and by the phase stability of electronics in both the spacecraft and ground systems. For both media and electronics, the stability goal is to achieve Allan standard deviations of $4 \times 10^{-15}$ at 100 seconds and $1.5 \times 10^{-15}$ at $10^3$ to $10^4$ seconds while maintaining, or improving upon, current levels of reliability.

Space navigation technology concepts should support launch and return to Earth, including range safety, early orbit operations, in-space assembly, cis-lunar and interplanetary transit, libration point transit and orbit, lunar and planetary approach and orbit, ascent and descent from lunar and planetary surfaces, including precision landing, automated rendezvous and docking, and formation flying spacecraft forming synthetic apertures for science imaging and interferometry. Surface navigation technology concepts should support communications and navigation surface networks involving rovers and/or astronauts on a lunar and/or other planetary environment.

NASA considers applicability to multiple operational regimes through modularity and/or missionization of common components a key element in its exploration strategy. Space navigation systems must produce accurate long-term trajectory predictions as well as definitive epoch solutions. Surface navigation systems must produce accurate dead-reckoning over long traverses. Where applicable, proposed concepts should be interoperable with and/or leverage the resources of NASA’s space communications architecture. All navigation systems should be compatible, where applicable, to continuous or near-continuous trajectory perturbations generated by onboard spacecraft systems. All concepts must show some significant advantages over current techniques in at least one of the following areas: accuracy, cost, reliability, modularity, sustainability, or for onboard systems, mass, power, and volume.

Innovative technologies are sought in the following areas:
Highly phase-stable RF ground systems are critical to high accuracy radiometric tracking. Present systems rely upon analog transmission over 0.5 to 10 km distances of a broadband (100 - 600 MHz) spectrum. Transmission induced phase errors could be greatly reduced by developing highly phase stable digital sampling and time tagging systems that can be placed near (~10m) to the RF feedhorn without measurably degrading the RF signal capture with spurious tones and noise. Phase stability goals are given above. The sampler should Nyquist sample the 100 - 600 MHz band with at least 8-bit resolution and be capable of digitally transmitting the resulting samples over fiber optic lines;

The VLBI parameter estimation software used to build the radiometric reference frames used for precise tracking relies on a Square Root Information Filter that makes use of Householder transformation techniques. These solutions often take several days of CPU time on a modern workstation. Block matrix techniques have the potential to optimize the interaction of the CPU and cache memory thereby greatly reducing the CPU time needed for solutions. The goal is a factor of three improvement in total solution time for problems with 7 million data points and 500,000 parameters, which include at least 5000 parameters that are active over the entire data set;

Microwave radiometry of atmospheric emission lines (22 GHz H$_2$O, 60 GHz O$_2$) has been successful in demonstrating 1 mm level calibration of tropospheric path delay. However, the usefulness of this technique has been limited by the large mass and size of the instrument packages. Identifying/developing low mass, low cost implementations of this technique without significantly sacrificing accuracy would greatly enhance precise tracking;

Develop low mass, (Less than 1 kg) low cost onboard radio frequency standards for generating highly phase-stable onboard radio signals which achieve Allan standard deviations of $1 \times 10^{-15}$ at 1000 seconds and drift of less than $10^{-15}$/day;

Develop innovative tracking technologies using new wavelengths (X-ray, Infra-red, etc.), such as systems using celestial and planetary emissions and reflections (not limited to the visible spectrum) that can produce three-dimensional absolute and relative position and velocity in regions where Earth-based GPS measurements are not available. The technologies can exploit either ground based or on-board techniques;

Develop innovative technologies for improving the state-of-the-art in terms of cost and performance in making spacecraft-to-spacecraft measurements, such as omni-directional range and bearing sensors and robotic-vision-based systems;

Develop innovative navigation algorithms and software supporting analysis, design, and mission operations that will reduce operations costs and support multiple systems in simultaneous, tightly-coupled, non-quiescent operations, such as robotic servicing, formation flying, or surface mobility.

Systems and technologies for providing an EVA crewmember with real-time navigation and position information while traversing on foot or on a rover. This system will be especially useful when the suited crewmember is traversing on foot and cannot rely on the rover system and markers for walk-back navigation.

Develop a highly integrated Ultra Wide Band (UWB) communications and tracking solution to reduce costs and provide robust performance, multipath immunity, long range one-way tracking, high precision short range tracking, high (broadband) capacity, and a transmit-only tag tracking system. RFID tags using UWB technology have been shown to provide sub-inch accuracy for close-in tracking. This precision tracking can be used to allow astronauts and robonauts to work in close proximity with reduced risk of collisions. The same UWB equipment can be used for long range tracking/wideband communications and the precise tracking at close ranges. Because of its mitigation properties, this impulse radio technology is well-suited for surface mobile area networks and reliable for simultaneous target tracking and high data rate communications in and around lunar craters. Commercial applications include precise tracking of moving oil-drill equipment, medical imaging, automobile collision-avoidance and surveillance through walls.
O1.03 Communication for Space-Based Range
Lead Center: GSFC
Participating Center(s): AFRC, GRC, KSC

Metric tracking of launch vehicles for range safety purposes is currently based on redundant radars, telemetry receivers, and uplink command transmitters at the launch site with additional assets deployed downrange in order to maintain line-of-sight communications with the vehicle as it passes over the horizon to orbital insertion.

The vision of space-based range architecture is to assure public safety, cut the costs of launch operations, enable multiple simultaneous launch operations, decrease response time, and improve geographic and temporal flexibility by reducing, or eliminating, these assets. In order to achieve this, a number of advancements in tracking and telemetry are required. Some of NASA’s needs are:

**GPS/IMU Metric Tracking and Autonomous Systems**

Realization of a space-based range requires development of GPS receivers that incorporate:

- Low power consumption;
- Low mass/volume;
- Compliance with range safety standards;
- Flexible tracking loop programmability;
- Programmable output formats; and
- Operability in high G environments.

Other highly desirable GPS specific characteristics include open architecture supported by development software and the capability of being incorporated onto circuit boards designed for multiple functions.

Tactical grade inexpensive expendable IMUs are needed which can function on spin-stabilized rockets (up to 7 rps) and reliably function during sudden jerk and acceleration associated with launch and engine firings and can be coupled with GPS receivers.
Also needed are approaches to processing and merging the independent outputs of GPS and Inertial Navigation Sensors and combining them with rule-based systems for autonomous navigation and termination decision making.

**Space-Based Telemetry**

Small, lightweight, low cost transceivers capable of establishing satellite communications links for telemetry and control during the launch and assent stages of flight are required to provide unbroken communications throughout the launch phase. These may enable use of the NASA TDRSS, or commercial communications satellite constellations. These transceivers are needed for use on suborbital and orbital platforms as well as for launch operations. While the communications support for launch vehicle operations may require continuous support for short durations in the order of less than 30 minutes other applications will be on platforms which require support for the duration the mission which could last for more than a month. Additionally it is highly desirable to limit the user burden to provide adequate EIRP and G/T for providing acceptable link margins between the constellation and the transceiver. Hence use of communications constellations in lower than GEO will be advantageous.

 Techniques for multiplexing narrow bandwidth channels to permit increased bit rates and improved algorithms for ensuring smooth transition of support between communications satellites are also needed.

**GPS Attitude Determination for Launch Vehicles**

Investigate using inexpensive arrays of GPS antennas and receivers on small, expendable launch vehicles to determine the attitude angles and their rates of change as an alternative to traditional inertial measurement units.

The system should be contained entirely on the vehicle and not rely on ground-based processing. The attitude accuracy should be comparable to gyroscope-based systems and should be free of drift and gimble lock. The system must be able to maintain attitude output during periods of high dynamics and erratic flight. The attitude must be determined at a rate of least 10 Hz with minimal processing delay and must be output in a format compatible with vehicle telemetry systems.

Integrated small, low mass, low power consumption transceiver/sensor packages are needed which can provide bidirectional communication interfaces between flight platforms such as weather balloons via the internet for the purpose of measurement of wind profiles, and atmospheric weather parameters such as temperature, humidity and ozone levels.
O1.04 Antenna Technology

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

NASA seeks advanced antenna systems for use in spacecraft and planetary surface vehicles used in science, exploration systems, and space operations missions. Future human and robotic missions to the Moon and Mars will have stringent communication requirements. Highly robust communication networks will be established on-surface as part of a long-term, evolutionary mission set. Such networks will grow to consist of a large number of communication links that connect the various network nodes. Some of these nodes must also maintain continuous high data rate communication links between the surface and orbiting relays or directly to the Earth. Great demands will be placed on these communication systems to assure mission safety, robustness in harsh environments, and high reliability for long duration missions with diverse human and robotic elements.

Areas of interest include very large aperture, lightweight spacecraft antenna systems, including high-gain deployable antenna architectures, multi-frequency and dual polarized antennas, self-orienting systems, phased array antennas, adaptive beam correction and pointing control, reconfigurable antennas, novel concepts, and antennas that can adapt to failed components without compromising performance and operability (e.g., smart antennas that include structural health monitoring and active control). Antenna systems for novel navigation concepts (e.g., pulsar beacons) as well as integrated communications and navigation architectures are desirable.

Large inflatable membrane antennas to significantly reduce stowage volume, provide high deployment reliability, and significantly reduced mass density (i.e.,

High efficiency, miniature antennas with smaller than lambda square aperture size, to provide astronauts and robotics communications for surface to surface and surface to orbit for lunar, Mars, and planetary exploration missions are highly desirable. Recent new antenna research and development has shown that it is possible to design and build aperture antennas with smaller than the minimum effective aperture apertures size of dipoles. This new class of antennas can provide higher antenna gains (> 2.5 dBi) than the dipole antenna in much smaller aperture size (}

There is also interest in space-to-surface links at 25.5 GHz and 37 GHz. The size of reflector antennas is limited by the accuracy of the reflector surface that can be achieved and maintained on-orbit. Development of special materials and structural techniques to control their environment, etc., reduces environmentally induced surface
errors and increases the maximum useable reflector size. Distortions caused by thermal gradients are inherently a large scale phenomenon. The reflector surface is usually sufficiently accurate over substantially large local areas but these areas are not on the same desired parabolic surface. An array of feed elements can be designed to illuminate the reflector with a distorted spherical wave. This distortion can be used to compensate for large scale surface error introduced by thermal gradients, gravitational and other forces, as well as manufacturing. Topics of interest include but are not limited to: Compensating Feed System for an Antenna Reflector Surface With Large Scale Distortions; Techniques for the remote Measurement of Satellite Antenna Profile Errors; Determination of Orbiting S/C Antenna Distortion by Ground-Based Measurements; Measuring and Compensating Antenna Thermal Distortions; Reflector Measurements and Corrections using arrays; and Reflector Distortion Measurement and Compensation Using Array Feeds.

NASA is interested in low cost phased array antennas for suborbital vehicles such as sounding rockets, balloons, UAV's, and expendable vehicles. The frequencies of interest are S-band, Ku-band, and Ka-band. The arrays are required to be aerodynamic in shape for the sounding rockets, UAV's, and expendable platforms. The balloon vehicles primarily communicate with TDRS and can tolerate a wide range of mechanical dimensions.

Antenna pointing techniques and technologies for Ka-band spacecraft antennas that can provide spacecraft knowledge with sub-milliradian precision (e.g.,

NASA is designing arrays of ground-based antennas to serve the telecommunications needs of future space exploration. Medium-size (12m class) antennas have been selected for receiving, and arrays of hundreds of them are expected to be required. Applications include communication with distant spacecraft; radar studies of solar system objects; radio astronomy; and perhaps other scientific uses. A significant challenge is the implementation of an array for transmitting (uplinking), which may or may not use the same antennas that are used for receiving. The uplink frequency will be in the 7.1 - 8.6 GHz range (X-band) in the near term, and may be in the 31.5 - 33.0 GHz band (Ka-Band) in the future; it will likely carry digital modulation at rates from 10 kbps to 30 Mbps. An EIRP of at least 500 GW is required, and some applications contemplate an EIRP as high as 10 TW. It is also desirable to support as many as ten simultaneously-operating deep-space missions from one complex on Earth, and to have at least three geographically separated complexes so communication is possible with a given spacecraft at any time of the day. The major challenges in the uplink array design are:

- Minimizing the life-cycle cost of an array that produces a given EIRP by selecting the optimum combination of antenna size, transmitter power, and number of antennas. This becomes much more difficult if the option of using the same antenna for both uplink and downlink is considered.

- Identifying/developing low-cost, highly reliable, easily serviceable components for key systems. This could include highly integrated RF and digital signal processing electronics, including mixed-signal ASICs. It could also include low-cost, high-volume antenna manufacturing techniques. (For the receiving array, another key component is a cryogenic refrigerator for the 15 - 25K temperature range.) Also, low-cost transmitters, including medium-power of the order of 100's of watts amplifiers, are desirable.

- Phase calibration techniques are required to ensure coherent addition of the signals from individual antennas at the spacecraft. It is important to understand whether space-based techniques are required or
ground-based techniques are adequate. In general, a target spacecraft in deep space cannot be used for calibration because of the long round-trip communication delay.

- Design of ultra phase-stable electronics to maintain the relative phase among antennas. These will minimize the need for continuous, extensive and/or disruptive calibrations.

- Understanding the effect of the medium (primarily the Earth’s troposphere) on the coherence of the signals at the target spacecraft. Generally, turbulence in the medium tends to disrupt the coherence in a way that is time-dependent and site-dependent. A quantitative understanding of this is needed.

- Techniques for integrating a very low-noise, cryogenically-cooled receiver with a medium power (1W to 200W) transmitter. If transmitters and receivers are combined on the same antenna, the performance of each should be compromised as little as possible, and the low cost and high reliability should be maintained.

Research should be conducted to demonstrate technical feasibility during Phase 1 and it should show a path toward a Phase 2 hardware demonstration that will, when appropriate, deliver a demonstration unit for testing at the completion of the Phase 2 contract.

O1.05 Reconfigurable/Reprogrammable Communication Systems

Lead Center: GRC

Participating Center(s): GSFC, JPL, JSC

NASA seeks novel approaches in reconfigurable, reprogrammable communication systems to enable the Vision for Space Exploration, Science, and Space Operations. Exploration of the Moon and Mars will require advancements in communication systems to manage the demands of the harsh space environment on space electronics, maintain flexibility and adaptability to changing needs and requirements, and provide flexibility and survivability due to increased mission durations. NASA missions can have vastly different transceiver requirements and available resources depending on the science objective, operating environment, and spacecraft resources. For example, deep space missions are often power constrained; operating over large distances, and subsequently have lower data transmission rates when compared to near-Earth or near planetary satellites. These requirements and resource limitations are known prior to launch; therefore, the scalability feature can be used to maximize transceiver efficiency while minimizing resources consumed. Larger platforms such as vehicles or relay spacecraft may provide more resources but may also be expected to perform more complex functions or support multiple and simultaneous communication links to a diverse set of assets.

This subtopic seeks advancements in reconfigurable transceiver and component technology, providing flexible, reconfigurable capability while minimizing on-board resources and cost. The use of open standards within the software radio development is desirable while minimizing potential increased resources and inefficiencies. Topics of interest include the development of software defined radios or radio subsystems which demonstrate reconfigurability, flexibility, reduced power consumption of digital signal processing systems, increased performance and bandwidth, reduced software qualification cost, and error detection and mitigation techniques. Complex reconfigurable systems will provide multiple channel and simultaneous waveforms. Areas of interest can be divided as follows:
Signal Waveforms and On-Orbit Reconfiguration

Multiple waveforms and multiple channel support strive to reduce radio count to reduce power consumption of the overall communication system. Tradeoffs in radio count and radio complexity are considered in the analysis. Reconfiguration for software and firmware upgrades shall provide access control, authentication, and data integrity checks for the reconfiguration process. Partial reconfigurable logic allows simultaneous operation and upload of new waveforms or functions. Upon operator or automated load detection failure, capability to provide access back to a known, reliable operational state is needed. An automated restore capability ensures the system can revert to a baseline configuration, thereby avoiding permanent communications loss do to an errant reconfiguration process. Approaches should minimize size and power consumption for deep space transceivers incorporating fault tolerant, reprogrammable digital signal processing devices.

Implementations demonstrating the concept function, and benefits of dynamic or distributed on-board processing architectures to provide maximum reconfigurability and processing capacity are sought. A common processing system capacity for communications, science, and health monitoring is envisioned.

Demonstration of adaptive modulation and waveform recognition techniques are desired to provide capability to reconfigure to the waveform identified based on an on-board library or enable new waveform upload to the on-board library from the ground.

Software Architecture, Implementation, Modeling and Verification

Development and demonstration of low overhead, low complexity hardware and software architectures to enable software component or design reuse, or common testing standards that demonstrates cost or time savings. Emphasis on the application of open standards architecture to facilitate interoperability among different vendors to minimize the operational impact of upgrading hardware and software components.

Methods (i.e., Hardware Abstraction Layers) that enable portability among reconfigurable logic hardware devices among different vendors, different device families and types of digital processing technologies.

As the use of software and firmware increases with more flexible and portable software defined radio technologies, methods are sought to reduce the complexity and cost to space qualify and verify software operation for use in space yet maintain or increase on-orbit reliability.
Techniques to ensure reliable software execution and failure detection and self-correction.

One promise of software defined radios is software and design reuse maintained in a common repository. The cost or ability to reuse software depends on implementation, development practices, code complexity and other circumstances. This subtopic seeks the development and demonstration of software tools or tool chain methodologies to enable both design and software code reuse.

The Space Telecommunications Radio System (STRS) architecture incorporates the development of an open architecture for NASA Software Defined Radios for space. The STRS standard includes software/firmware and hardware compliance rules that must be followed to comply with the standard. A tools suite that autonomously implements accurate and repeatable tests is required to verify infrastructure, waveform, and hardware STRS compliance. The tool suite must be extendable as the STRS architecture expands to incorporate additional requirements. Innovative solutions are sought under this solicitation to develop the requirements, top level design objectives, and top level design of the compliance tools. The recommended solutions must not incorporate proprietary products or solutions.

Fault Tolerance

The use of reconfigurable logic devices in software defined radios is expected to increase in the future to provide reconfigurability and on-orbit flexibility for waveforms and applications. As the densities of these devices continue to increase and feature size decreases, the susceptibility of the electronics to single event effects also increases. Novel approaches to mitigate single event effects caused by charged particles are sought that reduces power consumption and complexity compared to traditional approaches (i.e., voting schemes and constant updates (scrubbing)).

Techniques and implementations to provide a core waveform capability within the software defined radio in the event of failure or disruption of the primary waveform and/or system hardware. Communication loss should be detected and core or "gold" waveform automatically executed to provide control access to the diagnostic system and over-the-air reload operational waveform and control software.

Radio Architectures
Innovative solutions to provide software defined radio implementations to reduce power consumption and mass. Solutions should promote modularity and common, open interfaces.

Software defined radio implementations that enable future hardware scalability among different mission classes (e.g., low rate deep space to moderate or high rate near planetary, or relay spacecraft). Operational characteristics range from 1's to 10's Mbps at UHF and S-band frequency bands up to 10's to 100's Mbps at X, and Ka-band frequency bands.

**Component Technology**

Advancements in analog-to-digital converters or digital-to-analog converters to increase sampling and resolution capabilities while reducing power consumption.

Novel techniques to advance memory densities, reduce power consumption, and improve performance in harsh environments.

Advancements in reconfigurable logic technology including processing advancements, radiation hardened commercial technology and advancements in advanced computing such as polymorphous computing.

**O1.06 Miniaturized Digital EVA Radio**

**Lead Center: JSC**

**Participating Center(s): GRC**

With NASA now planning future sustained manned lunar outpost missions, the need is paramount for a reliable, robust, lightweight, and compact EVA software radio capable of achieving enhanced performance and efficiency on any of the following frequency bands of interest: UHF (401 - 402 Mhz, 25khz bandwidth), S-band (2.4 - 2.483 GHz), and Ka-band (22.55 - 23.55 GHz). Assume multi-point RF communications and simultaneous links to suit/vehicles at 10 km range and RF contingency voices at UHF half-duplex.
Due to menacing dust storms, frequency agility will be necessary during periods of disruptions. The programmable radio must support multiple bandwidths and data transmissions of telemetry, voice, and high-rate video. Assume bi-directional link and 20 Mbps maximum data rate. Solutions should include adaptive techniques to accommodate changing propagation and interference.

Small volume and low mass are always sought for human missions to enhance astronaut mobility on planetary surface. Operational scenarios dictate that EVA radios transmit audio, telemetry, and high-rate video to surface rovers, lander, and habitats, and other astronauts. Proposers must address EVA radio relay communications to surmount obscurations or poor line-of-sight to any surface nodes described above.

Pioneering astronauts exploring the surface of the Moon will also require a network enabling not only communications but precision relative navigation to keep these explorers abreast of their position relative to each other and lunar assets out to a maximum of 10 km.

NASA needs systems and technologies to provide an EVA crewmember with real-time navigation and position information while traversing on foot or in a rover. This system will be apt when the suited crewmember is traversing on foot and cannot rely on the rover system and markers for walk-back navigation. Because EVA radio is battery operated, power consumption should be minimized.

This solicitation seeks to develop a highly integrated multi-band multi-mode EVA adaptive intelligent programmable radio, a network that enables navigation between mobile and fixed communicating nodes, and required middleware technologies. Assume a stand-alone overlay or perhaps an embedded layer in a pre-existing, CDMA, OCDMA, ODFM, VOFDM or TDMA packet communication environment. In addition, EVA radio must dynamically and adaptively conserve power consumption on the fly packet-by-packet while maintaining interoperability among nodes.

Both communication and navigation functions of the network must assure 3D tracking and navigation accuracy, a BER of $10^{-8}$ or better, and graceful degradation. As a minimum, the proposed communications network concept must be capable of stand alone operation, independent of any other communication or navigation asset, and be capable of delivering high data rate or variable data rate digital communication ranging from voice to imagery transmissions while continually delivering bearing and pseudo-ranges between nodes within the network.

With ever-increasing versatility of the emerging programmable radios, NASA also needs a more potent approach to
energy conservation - one that matches the QoS requirement, channel condition, and the interference environment to the most energy efficient operating point of the EVA radio. This requires an intelligent and/or cognitive middleware to draw QoS information from the application, plus channel and interference information from the PHY. Thus, the middleware identifies the unique PHY and MAC combinations that results in minimal energy operation.

As the number of modes delivered on the QoS increases, choosing the mode with the least energy profile must lead to substantial energy savings and battery life extension. The evolutionary use of Software Defined Radios and the emergence of technologies such as multi-antenna have resulted in radio systems that can easily support 1000s of unique modes. Coupled with the presence of heavy interference like dust storms and channel impairments, the minimal energy mode of operation must be identified. Proposed solutions must achieve energy consumption of 5x to 10x reduction in total power consumption, depending upon the richness of and diversity of modes available on the target radio. All software must be portable to any radio platform.

Phase 1 Deliverables:

Propose a robust multi-band miniaturized frequency-agile EVA software defined radio suitable for applications and bands. Address all technical MEMS challenges, pitfalls, and tradeoffs of EVA radio size, weight, power as well as reliability, complexity, and performance. Solutions should encompass a notional architecture, functional requirements, and building block concepts, demonstrating a reliable and simultaneous voice, telemetry, and video transmission as well as reconfigurability across multiple applications and frequency bands. Special interests include single-chip design/packaging and RF MEMs technologies to realize compact radios under 5 lbs.

Develop suitable communication and navigation 3D tracking network system and algorithms capable of demonstrating the feasibility of the approach. Integrated communication and navigation solutions must include tracking, locating, identifying tagging assets with multiple routes over an operational range of 10 km - even if they descend in craters. Based on a minimum of three nodes, simulate the performance of the proposed integrated communications and navigation network architecture and conduct sensitivity analysis for the selected implementation strategy.

Develop the required middleware to properly characterize it in simulation. Achieve minimal power consumption by proper mode selection and perform demonstrated with five unique radio models including EVA. Conduct trades and identify the right set of required parameters for the ideal radio for such middleware. Quantify performance in terms of energy savings and the ability of the middleware to maximize connectivity and throughput in a mobile ad hoc network.
Phase 2 Deliverables:

Develop a EVA multi-band compact, lightweight, reconfigurable radio hardware prototype unit with multi-functional capabilities described in above.

Further enhance the concepts investigated in Phase 1 and demonstrate the feasibility of the approach on an actual platform.

Fabricate and test a prototype with a minimum of 3 nodes using an active multi-node integrated communication and navigation network. Simulate and refine navigation and/or power software algorithms for real time robust operations and characterize system performance in compliance with the design goals outlined in Phase 1.

O1.07 Transformational Communications Technology

Lead Center: GRC
Participating Center(s): JSC

NASA seeks revolutionary, highly innovative, "transformational" communications technologies that have the potential to enable order of magnitude performance improvements for exploration systems, science, and space operations mission applications. The promise of high-performance, multi-functional, nano-structured materials has led to intense interest in developing them for near-term applications for human spaceflight and exploration. These materials, notably single wall carbon nano-tubes, exhibit extraordinary mechanical, electrical, and thermal properties at the nano-scale and possess exceptionally high surface area. The development of ultra-capacitors and nano-scale communication devices and systems including FET arrays, nano-antennas, nano-transceivers are of interest for nano-space applications.

Phase 1 must convincingly show the proposed technology will have performance better than the equivalent legacy technology. For example, for a fixed-SAW oscillator part replacement, specific objectives include low power consumption (10 dBm), low spurious output (harmonics attenuated by 30 dBc), low-voltage operation (
Research interests focus on, but are not limited to, the following areas:

- Innovative methods of using X-ray or radio pulsar signals for precise navigation or positioning of spacecraft.
- Small, low mass, reliable detectors, improvements in position accuracy, digital signal processing advances for time of arrival, drift estimation, and position estimation.
- Development of nano-scale communication devices and systems (e.g., FET arrays, nano-antennas, nano-transceivers, etc.), which can enable nano-spacecraft applications.
- Quantum entanglement or other innovative breakthroughs in quantum information physics to specifically address curious effects and critical unknowns relevant to revolutionary improvements in communicating data, information or knowledge between independent entities across space-time are sought.
- Methods and techniques to demonstrate extremely novel means of effectively packaging, storing, encrypting, and/or transferring information or knowledge.
- Breakthrough power-efficiency in communications brought about through the use of natural phenomenon (e.g., soliton pulse/wave/energy propagation).
- RF Micro Electro-Mechanical Systems (MEMS) devices. Besides low spatial volume, lightweight, and low-power consumption, these devices are also attractive to operate as high Q components and perform frequency selectivity - namely, agile pre-selectors, multi-couplers, and diplexers. Selectivity, or Q, for band pass filters currently comes at an unacceptably high penalty in size and mass. For example, most high rejection diplexers for space-based radios are almost as enormous as the modern radio package itself. To build and design high performance, tightly coupled, low volume space radios, compact selectivity-determining devices are a critical enabler. Most high Q filters above 400MHz, such as inter-digital filters and others involving resonant cavities, are wholly mechanical assemblies which can be "folded" in their design and lend themselves to micro machining techniques.
- Other rich areas of investigation may lie within the area between MEMS and Micro-Machined devices, including electromechanically tuned filters, 3D micro machined RF resonators, filter configurations consisting of cantilevered structures, as well as carbon nano-tube waveguides. Develop, apply and demonstrate advantages of RF MEMS circuitry that proliferate the implementation of next-generation lightweight communications systems (e.g., extravehicular activity (EVA) radios).

O1.08 Long Range Optical Telecommunications

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-microradian pointing of the optical communications beam under typical deep-space ranges (to 40 AU) and spacecraft micro-vibration environments.

• Uncooled photon counting imagers with >1024 x 1024 formats, ultra low dark count rates and 400 - 2000 nm sensitivity.

• Ultra-low (0.7).

• Nutating fiber pointing mechanisms with high precision (3 kHz).

• Compact, lightweight, low power, broad bandwidth (0 - 3 kHz) disturbance rejection and/or isolation platforms.

• Space-qualifiable, > 20% wall plug efficiency, lightweight, 20-500 psec pulse-width (10 to > 100 MHz PRF), tunable (± 0.1 nm) pulsed 1064-nm or 1550-nm laser transmitter fiber MOPA sources with >1 kW of peak power per pulse (over the entire pulse-repetition rate), with Stimulated Brillouin Scattering (SBS) suppression and > 10 W of average power, near transform limited spectral width, and

• > 2-m diameter, 90% transmission.

• > 2-m diameter f/1.1 primary mirror and Cassegrain focus of ~f/6 optical communication receiver telescopes. Maximum RMS surface figure error of 1-wave at 1000 nm wavelength. Telescope is positioned with a 2-axis gimbal capable of 0.25 mrad pointing. Combined telescope and gimbal shall be manufacturable in quantity (tens) for

• Daytime atmospheric compensation techniques capable of removing all significant atmospheric turbulence distortions (tilt and higher-order components) on an uplink laser beam; and/or for a 2-m diameter downlink receiver telescope. Also of interest are technologies to compensate for the static and dynamic (gravity sag and thermal) aberrations of 2-m diameter telescopes with a surface figure of 10's of waves.

• Ground-based, relatively low-cost diode-pumped laser technology capable of reaching 100 kW average power levels in a TEM$_{00}$ mode, for uplink to spacecraft.

• Photon counting Si, InGaAs, and HgCdTe detectors and arrays for the 1000 to 1600 nm wavelength range with single photon detection efficiencies > 60% and output jitters less than 20 psec, active areas > 20 microns/pixel, and 1 dB saturation rates of at least 100 megaphotons (detected) per pixel and dark count rates of 2.

• Radiation hard (100 Mrad level) photon counting detectors and arrays for the 1000 to 1600 nm wavelength range with single photon detection efficiencies > 40% and 1 dB saturation rates of at least 30 megaphotons/pixel and operational temperatures above 220 K and dark count rates of

• Single-photon-sensitive, high-bandwidth (1 GHz), linear mode, high gain (> 1000), low-noise

Research should be conducted to convincingly prove technical feasibility during Phase 1, with clear pathways to demonstrating and delivering functional hardware, meeting all objectives and specifications, in Phase 2.
O1.09 Long Range Space RF Telecommunications

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

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

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

- MMIC modulators with drivers to provide large linear phase modulation (above 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-efficiency (> 60%) 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 techniques and/or wide-bandgap semiconductor devices at X-band (8.4 GHz) and Ka-band (26 GHz, 32 GHz and 38 GHz);

- Epitaxial GaN films with threading dislocations less than 1e6 per cm2 for use in wide band-gap semiconductor devices at X- and Ka-Band;

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

- Long lifetime, radiation hard SSPAs, modulators and MMICs for 26 GHz Ka-band (lunar communication);

- TWTAs operating at higher millimeter wave frequencies (e.g., W-Band) and at data rates of 10 Gbps or higher;

- Ultra low-noise amplifiers (MMICs or hybrid) for RF front-ends (MEMS-based RF switches and photonic control devices needed for use in reconfigurable antennas, phase shifters, amplifiers, oscillators, and in-flight reconfigurable filters. Frequencies of interest include VHF, UHF, L-, S-, X-, Ka-, V-band (60 GHz) and W-band (94 GHz). Of particular interest is Ka-band from 25.5 - 27 GHz and 31.5 - 34 GHz.

O1.10 Surface Networks and Orbit Access Links

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

Surface Networks

Exploration of lunar and planetary surfaces will require short-range (~ 25 km), bi-directional, and robust multiple point links to provide on-demand, disruption-tolerant, and autonomous interconnection among surface-based assets. Some of the nodes will be fixed, such as base stations and relays to orbital assets, and some will be moving, such as rovers and humans. The ability to meet the demanding environment presented by lunar and planetary surfaces will encompass the development and integration of a number of communication and networking
technologies and protocols, including:

- Low power, space-rated Application-Specific Integrated Circuits (ASICs) and Field Programmable Gate Arrays (FPGAs) for wireless network products: short range (Fixed, long range (Integrated tracking, timing, and navigation services which will determine locations of human and robotic assets on the lunar surface, providing them to relevant entities;
- Self-healing, ad hoc, disruption tolerant network protocols for intelligent, autonomous link management and reliability;
- Non-line-of-sight communication between stationary and moving assets, outside or inside lunar craters;
- Autonomous surface navigation and hazard avoidance systems for robotic and fixed assets;
- Analog voice-only radio service to the lunar outpost and the lunar relay satellite at the highest network priority for HF, UHF, or S-band.

In addition, to meet the stringent demands of continuous interoperable communications, human exploration needs to develop delay and tolerant networking (DTN) protocols that exploit persistent storage on mobile and stationary nodes to ensure timely and reliable delivery of data even when no stable end-to-end paths exist. Many networks straddle a continuum of disruption, from an almost-always connected network where a contemporaneous end-to-end path does exist, to highly intermittently connected networks where such a path seldom exists. More than disruption tolerant, solutions must exploit stability when it exists to nearly approximate the performance of conventional Mobile Ad hoc NETwork (MANET) protocols. Proposals should address the following areas:

- Technical challenges posed by the design considerations enumerated above and assess tradeoffs of disruption, load, storage, topology, and delivery ratio;
- Demonstrate adaptive DTN routing via simulations;
- Develop proof-of-concept nodes complete with the networking algorithms developed as part of the funded work;
- Demonstrate unique communications in networks that suffer from severe disruptions and delays with adaptive routing developed in Phase 1;
- Develop a prototype convergence layer adapter plug-in for an Extra-Vehicular Activity (EVA) radio.

**Orbit Access Links**

Lunar and planetary surface networks will need to seamlessly interface with communications access terminals and orbiting relays that can provide autonomous and disruption tolerant connectivity to Earth-based assets. The access link communications system will encompass the development and integration of a number of communications and networking technologies and protocols such as:
- Autonomously reconfigurable receivers capable of automatic link configuration and management;
- Microwave ranging hardware built into the communication system for rendezvous and collision avoidance;
- Ad hoc, long-range spacecraft-to-spacecraft network protocols to initialize links on demand such that each node can route data through to another node.

The effort will leverage on the following technologies addressed under other SBIR subtopics:

- Antennas for surface and orbital access communications required for the aforementioned goals shall be developed under subtopic O1.04.
- Radios for surface and orbital communications required for the aforementioned goals shall be developed under subtopic O1.06.
- Optical transceivers required for the aforementioned goals shall be developed under subtopic O1.08.
- Any high rate, low power, efficient amplifiers or transponders required for the aforementioned goals shall be developed under subtopic O1.09.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward Phase 2 hardware demonstration that will, when appropriate, deliver a demonstration unit for testing at the completion of the Phase 2 contract.

O1.11 Software for Space Communications Infrastructure Operations

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

The current infrastructure for NASA Space Communications provides services for near-Earth spacecraft and deep-space planetary missions. The infrastructure assets include the Deep Space Network (DSN), the Ground Network (GN), and the Space Network (SN). Recent planning for the Vision for Space Exploration (VSE) for human exploration to the Moon and beyond as well as maintaining vibrant space and Earth science programs resulted in a new concept of the communications architecture. The future communications architecture will evolve from the present legacy assets and with the addition of new assets (e.g., new large scale arrays under consideration, for further information see Space Communications Architecture Working Group report - link below).
New technology is sought to improve resource optimization and the user interface of planning and scheduling tools. The software created should have a commercialization approach with the new modules fitting into an existing or in-development planning and scheduling tool. Proposals are sought in the following three areas:

**Intelligent Assistants**

In order to automate the user's provision of requirements and refinement of the schedule, "intelligent assistant" software should manage the user interface. Assistants should streamline access and modification of requirement and schedule information. By modeling the user, this software can adjust the level of autonomy by determining what decisions should be made by the user or the automated system. Assistants should try to minimize user involvement without making decisions the user would prefer to make. The assistants should adapt to the user by learning their control preferences. This technology should apply to local/centralized and collaborative scheduling.

In a conflict-aware scheduling system (especially in a collaborative scheduling environment), conflicts are prevalent. With the concept of one big schedule from the beginning of time, real time, to the end of time, resolving conflicts become a difficult task especially since resolving conflicts in a local sense may affect the global schedule. Therefore, an intelligent assistant may provide decision support to the system or the users to assist conflict resolution. This may involve a set of rules combining with certain local/global optimization to generate a list of options for the system or users to choose from.

**Resource Optimization**

The goal of schedule optimization is to produce allocations that yield the best objectives. These may include maximizing DSN utilization, minimizing loss of desired tracking time, and optimizing project satisfaction. Each project may have their own definition of satisfaction such as maximal science data returned, maximal tracking time, best allocation of the day/week, etc. The difficulty is that we may not satisfy all of these objectives during the optimization process. Obviously, optimal solution for one objective may produce worse results for the other objectives. One possible solution is to map all of these objectives to an overall system goal. This mapping is normally non-linear. Technology needs to be developed for this non-linear mapping for scoring in addition to regular optimization approaches.

**Multiple Agents**

In an environment where all system variables can be controlled by a single controller, an optimal solution for the objective function can be achieved by finding the right set of variables. In a collaborative environment with multiple decision makers where each decision maker can only control a subset of the variables, modeling and optimization
become a very complex issue. In the proposed collaborative scheduling approach, there are many users/agents that will control their own allocations with interaction with the others. How we model their interactions and define system policy so the interaction can achieve the overall system goal is an important topic. The approach for multiple decision-maker collaboration has been studied in the area of Game Theory. The applications cover many areas including economics and engineering. The major solutions include Pareto, Nash, and Stackelberg. There are many new research areas including incentive control, collaborative control, Ordinal Games, etc.

Note that intelligent assistants and multiple agents represent different points on the spectrum of automation. Current operations utilize primarily manual collaborative scheduling, intelligent assistants would enhance users ability to participate in this process and intelligent agents could more automate individual customers scheduling. Ideally, proposed intelligent assistants and distributed agents would also be able to represent customers who do not wish to expose their general preferences and constraints. A start for reference material on this subtopic may be found at the following:

http://ai.jpl.nasa.gov in the publications area;


The proposal should explicitly include an operations scenario of before and after the inclusion of the new technology.