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 $4\times10^{-15}$ at 100 seconds and $1.5\times10^{-15}$ 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-
• 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.