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Key Issues for Navigation and Time Dissemination in NASA's Space Exploration Program

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Abstract

The renewed emphasis on robotic and human missions within National Aeronautics and Space Administration's (NASA) space exploration program warrants a detailed consideration of how the positions of objects in space will be determined and tracked, whether they be spacecraft, human explorers, robots, surface vehicles, or science instrumentation. The Navigation Team within the NASA Space Communications Architecture Working Group (SCAWG) has addressed several key technical issues in this area and the principal findings are reported here.

For navigation in the vicinity of the Moon, a variety of satellite constellations have been investigated that provide global or regional surface position determination and timing services analogous to those offered by the Global Positioning System (GPS) at Earth. For full and continuous coverage of the lunar surface, a constellation of six satellites in circular polar orbits, distributed in two planes, is recommended for both communications and navigation. A constellation of eight satellites can provide enhanced global coverage with potentially higher reliability, while fewer than six satellites in circular or elliptical orbits can provide regional coverage. In the vicinity of Mars there are options for satellite constellations not available at the Moon due to the gravitational perturbations from Earth, such as two satellites in an areostationary orbit.

Alternative methods of radiometric navigation are considered, including one-way and two way signals, as well as autonomous navigation. One-way signals similar to those used by the GPS, supplemented by a stable clock and a terrain database in the receiver, could achieve real time position and time determination with only two satellites simultaneously visible. Ranging signals from satellites can be supplemented by surface pseudolites at surveyed positions. Two-way signals could be accommodated over a communications channel. The use of a software radio capable of receiving all available signal sources, such as the GPS, pseudolites, and communication channels, is discussed. Methods of time transfer and dissemination are also considered in this paper.

Introduction

In late 2003, the National Aeronautics and Space Administration (NASA) established the Space Communications Architecture Working Group (SCAWG) to lead analyses coordinated across all NASA Centers and Mission Directorates and recommend the future architecture of NASA's communication systems. In January 2004, the President of the United States announced the Vision for Space Exploration (VSE) calling for returning humans to the Moon, expanding human presence to Mars and beyond, and exploring the solar system.

The charter of the Working Group was expanded to address architectures for navigation and time dissemination and directed to develop an integrated Communication and Navigation (C&N) Capability Roadmap as part of an agency initiative to define the strategies and plans for implementing the VSE. The SCAWG has provided the focal point for C&N architecture studies and recommendations with a unified perspective.

The SCAWG established the Navigation Team to investigate alternatives for space navigation as an initial phase in determining a long range navigation architecture for the Earth, Moon, and Mars. Since its formation in October 2004, the Navigation Team has undertaken to study these issues in depth.

Overview of the Navigation and Time Architecture

The navigation architecture combines mission application level functions for determining position, planning trajectories, and executing maneuvers with infrastructure functions that provide tracking and timing data supporting those mission level applications. The Navigation architecture provides for radiometric tracking services that are available via space relays and ground terminals along with communication services for all users. In addition, the navigation architecture makes available GPS capabilities for those user missions in Earth orbit to Geostationary Orbit (GEO) needing either high precision orbit determination or low cost, continuous, autonomous position determination. The navigation architecture relies on techniques and methods already established. However, the architecture extends the existing navigation services throughout the overall communication architecture. Tracking services are extended to provide new methods of two-way measurements that are originated by user spacecraft. As an evolution from the current capabilities for disseminating time, the architecture features a single, standard time scale for NASA space applications across the solar system that is interoperable with the existing Earth-based infrastructure, comprising the GPS, the Ground-based Earth, Near-Earth Relay (NER), Lunar Relay and Mars Relay Elements.

Top Level Requirements

Navigation services begin in the pre-launch phase and continue through final landing and recovery of human missions or sample return missions, supporting all required operations in the process. Services required for missions include: radiometric data; delta-differential one-way ranging (ΔDOR); orbit determination; trajectory analysis; maneuver planning and design; natural body ephemeris; modeling and calibration of tracking; gravity modeling; cartography; navigation ancillary data; and time dissemination and synchronization. Table 1 depicts the key navigation performance requirements.

TABLE 1.—KEY NAVIGATION PERFORMANCE REQUIREMENTS

Capability needed (3-sigma)	3-D position	3-D velocity
Surface operations	30 m	To Be Determined (TBD)
Global surface operations	30 m	TBD
Relay spacecraft	10 m (1-sigma); 100 m (1-sigma) predicted	TBD
Non-precision landings	5 km at landing	
Lunar Surface Access Module (LSAM) Landings	1 km (unaided) and 100 m (aided)	
Precision landings	100 m at landing	
Robotic Lunar Exploration Program (RLEP) Landing	50 m with short latency (post processing)	
Surface rendezvous	10 m at landing	TBD
Ascent (surface location)	10 m at liftoff	Not a driver
Rendezvous (at relative navigation initiation)	500 m (relative)	10 cm/s (relative)
Docking and berthing (assuming inertial navigation available as backup)	1 km	50 cm/s
In-space servicing (assuming inertial navigation available as backup)	1 km	50 cm/s
Constellations1	100 m (absolute)	10 cm/s
Formation flying1—coarse	10 m (relative)	3 cm/s
Formation flying1—precision	3 m (relative)	3 mm/s
Formation flying1—very high precision	3 cm (relative)	0.03 mm/s
Libration point station keeping	50 km	2 cm/s
Fly-bys, Impulsive transits	TBD	TBD
Fly-bys, Low-thrust transits	TBD	TBD
1 A constellation, i.e., a cluster of spacecraft, requires absolute position and velocity knowledge with respect to Earth. Constellations that require formation flying, i.e., maintaining precise offsets between spacecraft, have requirements for position and velocity relative to each other.		

Navigation Method Alternatives

Navigation alternatives studies included one-way, two-way, and autonomous navigation techniques, supported by a set of analyses defining a combined communications and navigation architecture that provides navigation support beyond the Earth. The one-way navigation concept explores the possibility of using a one-way navigation signal similar to GPS. This concept is a synergistic approach that could provide seamless navigation, positioning, and timing, in the Earth-Moon system that utilizes and extends existing infrastructure. The two-way navigation concept could also be interoperable with GPS during transit between the Earth and the Moon.

The navigation architecture includes an option for autonomous navigation. The autonomous system for in-space vehicles utilizes only periodic updates from external radiometric sources. The autonomous component for lunar surface operations could consist of a traverse vehicle wheel odometer, gyro and attitude initialization sensor, lunar feature map, map “benchmark” point, and video camera. Table 2 depicts the navigation data types and missions phases.

The proposed navigation alternatives should be integrated in a way that maximizes performance for a given user mission. For instance, although a vehicle autonomous navigation system could determine and provide all required navigation data for intervals of time, past experience indicates its performance may be inadequate unless supplemented with planned vehicle position and velocity vector initializations via radiometric tracking solutions. The regions of navigation in the Earth-Moon environment are shown graphically in figure 1.

TABLE 2.—NAVIGATION DATA TYPES AND MISSION PHASES

Mission phases	Navigation data types
Launch/Ascent/ Entry/Low Earth Orbit (LEO)	Launch/Ascent supported by angles-only tracking
	Space-based range using GPS and Near Earth Relay (NER)
	Entry/LEO supported by Earth-based range/Doppler and GPS pseudo-range
LEO to GEO altitudes	Earth-based range/Doppler
	NER range/Doppler
	GPS pseudo-range and data message
Beyond GEO altitude to Cislunar Space up to Earth-Moon La-grange point (L1)	Earth-based range/Doppler
	GPS pseudo-range and data message
Lunar vicinity navigation	Earth-based range/Doppler can meet needs for all orbiting users
	Lunar-orbiting range/Doppler can meet needs for other orbiting users
	Lunar-orbiting range/Doppler is adequate for surface users given a certain latency with user burden constraints
Mars vicinity	Earth-based range/Doppler can meet needs for all orbiting users
	Mars-orbiting range/Doppler can meet needs for other orbiting users
	Mars-orbiting range/Doppler is adequate for surface users given a certain latency with user burden constraints
	Mars-orbiting range/Doppler is required for precision approach and landing
Deep space navigation	Earth-based range/Doppler and Very Long Baseline Interferometry (VLBI) data types

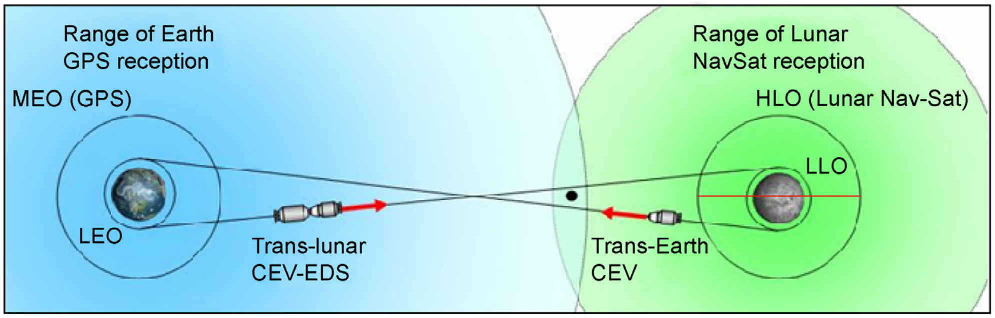


Figure 1.—Earth-Moon regions of navigation.

Tracking Infrastructure

The navigation architecture provides integrated Doppler and range tracking at both ground terminals (at Earth, Moon, and Mars) and orbiting relays (at Moon and Mars) supporting the formation and measurement of radiometric data. The architecture supports both one-way and two-way radiometric measurements. The flexible architecture allows these measurements to be made using many signaling schemes. The techniques implemented in the navigation architecture are illustrated in figure 2.

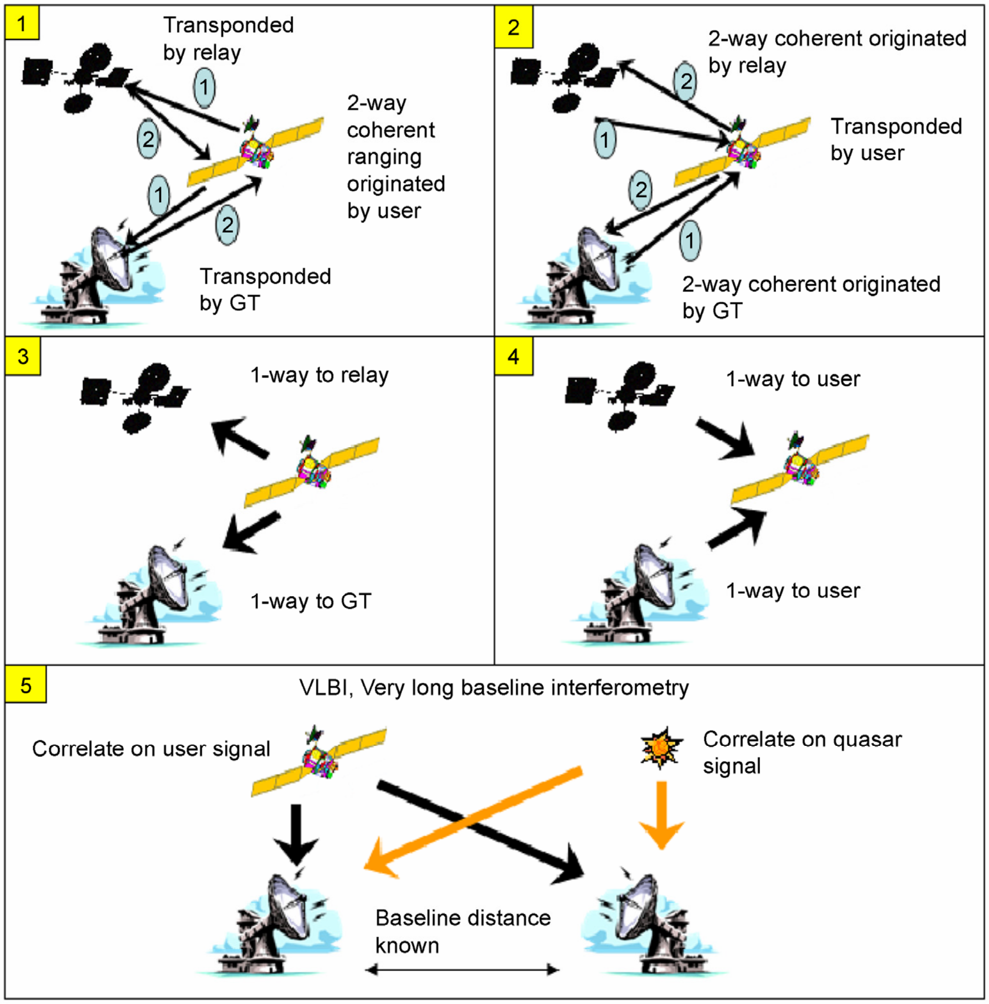


Figure 2.—One way and two way radiometric tracking architecture (GT: Ground terminal).

Utilization of GPS

Many missions are able to satisfy their navigation requirements using the radiometric capabilities that are built into the communications provided by the four elements of the Space Communication Architecture. Missions may decide to use GPS, either in addition to or in place of communications channel tracking. For these missions, use of GPS is recommended as the primary alternative for space vehicle navigation in Earth vicinity as far as GEO. GPS may also be used for navigation during launch (under the Space-Based Range (SBR) concept) and re-entry flight phases. Beyond GEO altitude GPS is recommended as a supplemental means of navigation to improve the performance of other methods, including ground-tracking, two-way communications channel tracking, autonomous navigation, and celestial navigation.

Navigation up to GEO altitude has been shown to be feasible by analysis and hardware-in-the-loop tests. Advantages of using the GPS include precision, real-time state determination, autonomy, robustness, independence from terrestrial infrastructure, and cost effectiveness. Navigation beyond GEO requires GPS receiver architectures specialized to this application as a supplemental means of navigation. Key features of such receivers include: enhanced acquisition and tracking algorithms; integrated, extended Kalman filters; clock models; and Ultra-Stable Oscillators (USO). Navigation Transmitters on the Moon.

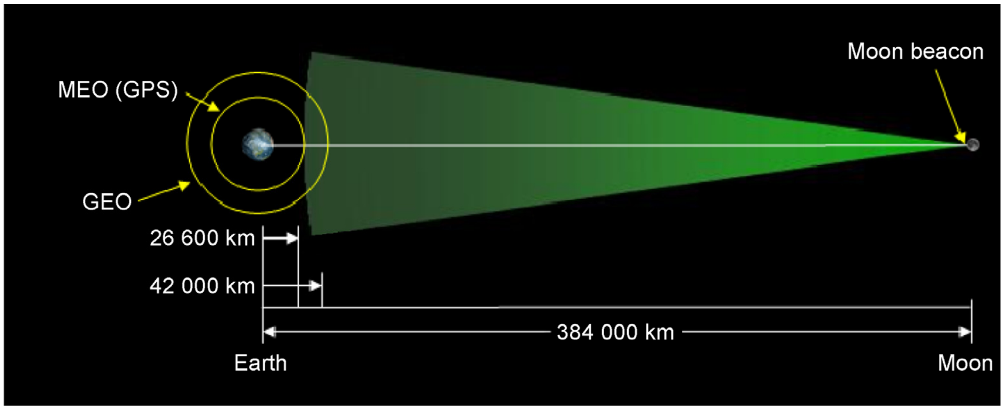


Figure 3.—Geometry of a navigation augmentation by a transmitter on the moon.

The GPS navigation paradigm can be extended to the lunar vicinity by placing radiometric transmitters at surveyed points on the Moon's surface. These transmitters can provide signal structures having the characteristics of both pseudorandom noise (PRN) signals for range measurements and continuous beacon signals for Doppler shift measurements. The transmitters could be co-located with corner cube laser reflectors for continuous tracking from the Earth. The geometry is illustrated in figure 3.

A GPS payload could be operated as a pseudolite providing navigation and timing services in the Earth-Moon environment. The Moon transmitter could be synchronized to GPS time via a communications link. A hardware assisted network time transfer technique could be implemented providing 3 ns time synchronization to the internal GPS system time. A Moon transmitter could provide a test bed for the eventual evolution of a Solar System wide navigation system. The Crew Exploration Vehicle (CEV) and other manned/unmanned vehicles would be able to navigate seamlessly between the Earth and the Moon.

Time Synchronization and Dissemination

The time synchronization and dissemination architecture uses a uniform time scale, a unit interval of one second as defined in the International System of Units (SI), and time dissemination traceable to an internationally recognized terrestrial time scale (e.g., Coordinate Universal Time (UTC) modulo 1 second to remove issues associated with leap seconds). This single time scale for system-wide NASA space exploration applications is interoperable with the existing Earth-based infrastructure and GPS, as well as internationally recognized atomic time scales used for civil and scientific timekeeping.

The time and frequency dissemination architecture is based on five essential ingredients: (1) clocks; (2) timescales; (3) mathematical algorithms; (4) fabrication and calibration of hardware interfaces; and (5) a communication link. The dissemination and transfer of time between remote clocks and spacecraft time registration hardware requires recognition of the appropriate principles of theoretical physics, including general relativity.

The basic elements of a common NASA timescale will be: (1) clocks, (2) measurements of the proper time differences among clocks, (3) relativistic transformations of the local clock readings, (4) formation of the timescale using transformed clock observations, (5) dissemination of individual clock offsets to the common timescale, and (6) synchronization of individual clocks to the common timescale. It is necessary to distinguish between the formal definition of the timescale and a particular realization of the timescale as given by an individual laboratory. Time comparisons may be made via dedicated terrestrial links, satellites, communications links, networks, or the GPS.

Allocation of Navigation Functions between Missions and Infrastructure

The Navigation Architecture allocates functions between user missions and the SCA which provides the common infrastructure. The infrastructure in each of the four elements—Ground-based Earth Element (GEE), Near Earth Relay (NER), Lunar Relay (LR), and Mars Relay (MR)—provides a combination of physical navigation aids (e.g., radiometric tracking signals and time transfer) as well as navigation services (e.g., support for orbit determination, trajectory analysis, maneuver planning and design; natural body ephemeris; modeling and calibration of tracking; gravity modeling; and navigation ancillary data) that assist programs in designing and operating their missions. This provides users with a high degree of flexibility in determining whether to maximize reliance on infrastructure-provided capabilities or develop unique capabilities to meet mission requirements.

Navigation functionality may be concentrated at a single point or may be distributed among infrastructure elements, depending upon the policy for use of navigation-related information. The location of the control authority governing decisions concerning future vehicle trajectories is one example of a factor playing into this aspect of architecture. The navigation infrastructure supports traditional performance of navigation on the ground, but also supports performance of navigation on board vehicles as we move towards increasing vehicle autonomy.

Software Defined Radios

The use of Software Defined Radio (SDR) technology is allowed in the Navigation Architecture providing an option for integrating autonomous navigation sensor data and radiometric data. One approach uses an SDR, a common clock, and a navigation computer to provide a flexible and robust strategy for autonomous navigation capable of performing two-way and one-way integrated Doppler and range that can be integrated in real-time (or near real-time) and disseminating position, velocity, and time for onboard guidance as well as downlinked telemetry.

Analysis of Satellite Constellations for Lunar Navigation

If one could save on the number of satellites, it might make sense to bias the coverage towards the hemisphere in which the coverage zone lies and sacrifice some coverage in the opposite hemisphere. This observation takes us to the polar coverage problem, since the equatorial regions are handled by an equatorial orbit. In developing lunar South Pole constellation alternatives, it has been shown that one pole can be covered from a single inclined elliptical orbit of two or three satellites, and that the inclination can be chosen to achieve a “frozen” orbit that makes minimal maintenance demands over a multi-year period. If it were desired to switch this orbit to cover the opposite pole, the satellites could be repositioned within the orbit to do so, at a delta velocity (ΔV) cost quantified subsequently.

Given a two-satellite configuration that can continually cover a pole of choice, the addition of a three-satellite configuration in circular equatorial orbit results in a five-satellite configuration that provides continuous coverage over the lunar surface excepting one polar region, as shown conceptually in figure 4. The constellation can be reconfigured to cover the other pole by modifying the orbits of the two polar satellites.

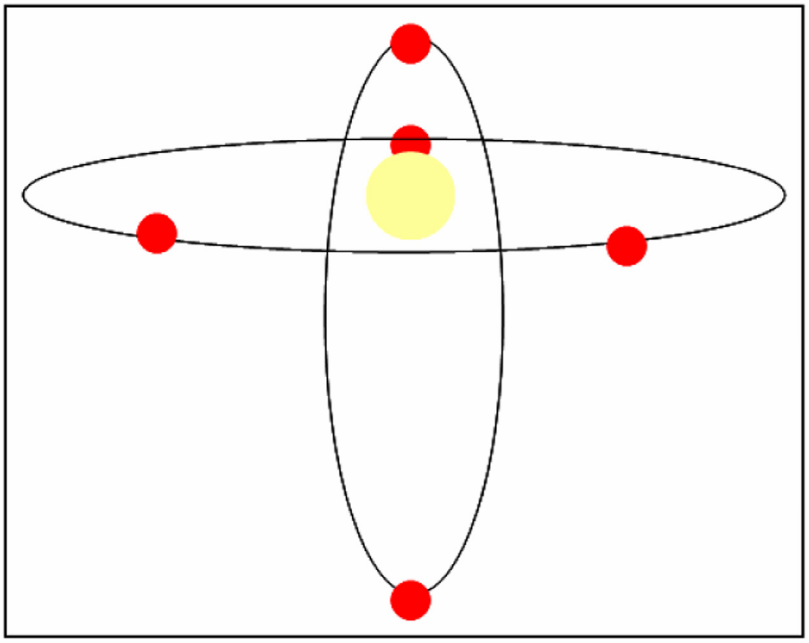


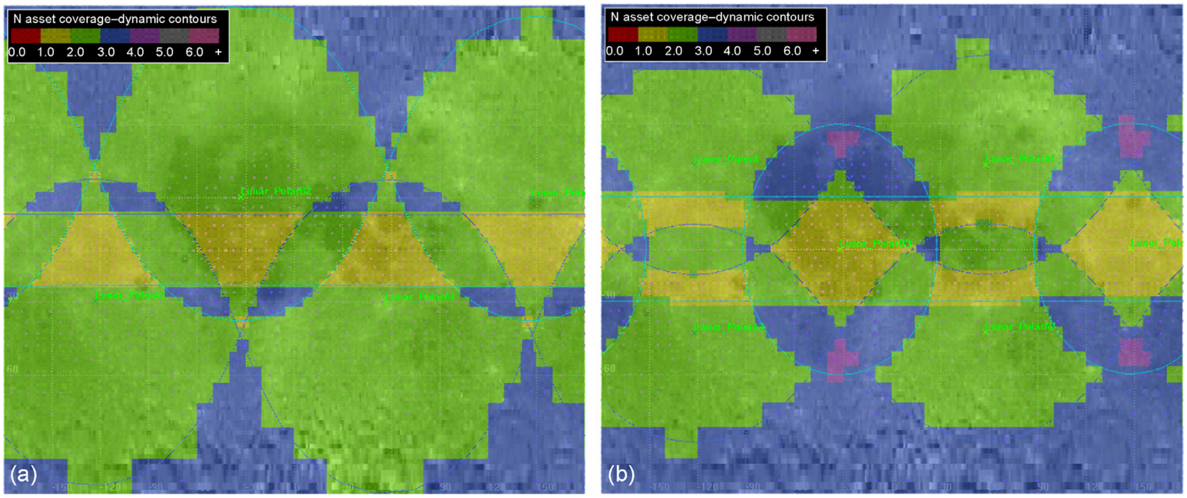
Figure 4.—Five satellite constellation configured for south pole emphasis.

To provide the greatest flexibility with a more robust constellation design, a constellation of satellites might be considered that would provide continuous, full coverage of the lunar surface. The properties of polar constellations with two planes and six satellites or eight satellites are given in table 3.

TABLE 3.—POLAR ORBIT CONSTELLATIONS (SHOWN FOR 4 REPRESENTATIVE ORBIT RADIUS SETS)

Parameter	Polar 6/2/1				Polar 8/2/1			
Number of satellites	6				8			
Number of planes	2				2			
Satellites per plane	3				4			
Phasing between planes	60°				45°			
Inclination	90°				90°			
Central angle	69.3°				60°			
Elevation angle at Edge of Coverage	0.0°	4.2°	6.3°	9.3°	0.0°	10.9°	13.9°	16.1°
Half cone angle	20.7°	16.6°	14.4°	11.4°	30.0°	19.1°	16.1°	13.9°
Orbit radius (km)	4917	6085	6946	8685	3476	5216	6084	6951
Orbit radius/Lunar radius	2.83	3.50	4.00	5.00	2.00	3.00	3.50	4.00
Period of revolution (hour)	8.59	11.83	14.43	17.27	5.11	9.39	13.02	14.45

A comparison of the levels of surface coverage provided by the polar 6 satellite and polar 8 satellite lunar constellations is illustrated in figure 5. Continuous, 100 percent lunar global coverage can be achieved with 6 satellites. An enhanced level of coverage can be achieved with a constellation of 8 satellites. A constellation of 8 satellites would provide a measure of redundancy to maintain a minimum of 6 satellites for full. There is a potential tradeoff between a constellation of 8 single-string satellites and a constellation of 6 dual-string satellites with greater reliability.



Measured as the minimum number of satellites providing coverage over 1 m

Figure 5.—Comparison of coverage level for polar constellations. (a) 6/2/1. (b) 8/2/1.

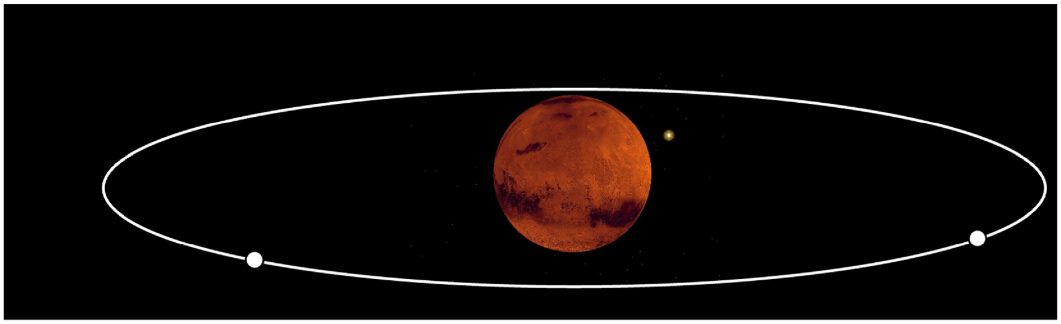


Figure 6.—Two satellites in areostationary orbit.

Analysis of Satellite Constellations for Mars Navigation

For the vicinity of Mars there are options for constellation not available for lunar exploration. Two satellites in orbit about Mars in areostationary orbit could provide both communications and navigation capability, as shown schematically in figure 6. A receiver supplemented by a stable clock and a terrain database could achieve real time position and time determination. The areostationary orbit is the Mars equivalent of a geostationary orbit, where the period of revolution of the satellite and the period of rotation of the planet are equal. The radius of an areostationary orbit is 20,427 km.

Two areostationary satellites could provide ranging data to fixed or mobile receivers on the surface of Mars either by means of a pseudorandom noise code or a two-way communications channel. If the ranging measurements were supplemented by a database of terrain elevations—coupled with timing data using a stable clock, such as an USO, a cesium atomic clock, or rubidium atomic clock—then real time precise position determination could be achieved.

Conclusions

This paper has summarized a variety of key issues for navigation and time dissemination in NASA's space exploration program. The navigation architecture supports conventional radiometric tracking services for all user spacecraft, utilizing the same links as are used for operational communications. In addition, the navigation architecture relies on GPS capabilities for those user missions in LEO to GEO needing high precision orbit determination or low cost continuous autonomous position determination. The architecture also supports time distribution that is related to a common time reference.

Plans are underway at NASA for a return of human missions to the Moon in the timeframe of 2018. Additional programs are being planned for the human exploration of Mars around 2030. The technical investigations identified in this paper are first steps towards the realization of these ambitious goals.

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