NASA Architecture for Solar System Time Distribution

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Abstract— **The National Aeronautics and Space Administration (NASA) is developing an architecture for communication, navigation, and time distribution to support the future human exploration of space. Foreseeable applications span a wide range of demands for time services, including event logging by robotic and human explorers, networking of cooperative elements on a planetary surface, time transfer for navigation, and time synchronization and correlation for communication and science. This paper describes the key attributes of a flexible approach designed to meet those demands.**

I. Introduction

This paper describes efforts at NASA to develop an architecture for position, navigation, and time (PNT) systems to be used in the exploration of space [1, 2]. The architecture supports future science missions and the Vision for Space Exploration (VSE), which calls for returning humans to the Moon, expanding human presence to Mars, and going beyond.

The navigation architecture combines mission functions at the application level for determining position, planning trajectories, and executing maneuvers with infrastructure functions that provide tracking and timing data. It provides for radiometric tracking services that are available via space relays and ground terminals, along with communication services for all users. The navigation architecture supports conventional radiometric tracking services for all user spacecraft, utilizing the same links that are used for operational communications. In addition, the architecture relies on the capabilities of the Global Positioning System (GPS) for missions in LEO, MEO, and GEO that need high precision orbit determination or low cost continuous autonomous position determination, as well as a general source for time [3].

This paper describes an activity undertaken by NASA to recommend the future architecture of NASA's communication, navigation, and timing systems through studies coordinated across all NASA Centers and Mission Directorates.

II. Requirements and Salient Features

The requirements range from coarse applications, such as instrument and event logging, to precision applications, such as one-way radiometric ranging for navigation. From this range of requirements the salient features of the time dissemination architecture may be postulated:

- The future time and frequency architecture will be an integral part of the space communication and navigation infrastructure, retaining the possibility of standalone dissemination systems.
- The architecture will be scalable to accommodate user requirements, comprising Coarse (1 s – 1 ms), Fine (1 ms – 1 μs), and Precision (1 μs – 1 ns) resolutions.
- Terrestrial time scales at nanosecond-level accuracies will be available to users to the extent required.
- The principles of general relativity will be applied for time synchronization and dissemination among timing systems on spacecraft and solar system platforms.

III. Concepts for Solar System Wide Time Transfer

Time synchronization and dissemination may be accomplished through the systems used for radiometric navigation and tracking and communications channels (including network time dissemination). This Section discusses the tradespace of alternatives, either throughout the entire solar system or in a region of interest. A variety of alternatives are identified that will be considered by NASA in developing the time distribution architecture.

Historically, three vehicles have been used to disseminate time in our Earth environment: radionavigation systems, communication systems, and stand-alone time dissemination systems. Beyond the relative technical merits, there are also important issues of cost. The effectiveness for the number of users to be supported is another consideration.

All radionavigation techniques involve measurement of time and frequency. Radionavigation is accomplished through a network of ground stations and satellites that transmit signals used to determine the state vector of the user and to correct the user time base. Depending on the algorithms used, radiometric navigation systems are typically characterized as using one-way or two-way signals. In either case, the measurement of Time of Arrival (TOA), Time Difference of Arrival (TDOA), Frequency Difference of Arrival (FDOA), pseudorandom noise (PRN) correlation, Doppler shift, and Accumulated Delta Range (ADR) are fundamental to the navigation application. They are the natural observables for data required and time dissemination algorithms.

Network algorithms are additional alternatives for time dissemination that are under consideration. For example, the Network Time Protocol (NTP) and the IEEE Standard 1588 are candidates for implementation. These protocols are being studied at the NASA Goddard Space Flight Center [4]. Hardware-assisted techniques, which exploit the synchronous characteristic of the link level of communication systems, have been demonstrated and are also viable candidates [5].

A. Two-Way Radiometric Ranging (DSN)

The NASA Deep Space Network (DSN) utilizes a two-way radiometric ranging technique that can also provide time transfer. Although two-way radiometric ranging does not require access to a terrestrial time scale for range measurements from a single source, the DSN ground clocks are synchronized to UTC(NIST), a realization of Coordinated Universal Time (UTC), to permit the handoff of the return link to another DSN site.

A notional two-way high precision time service for the DSN can be implemented. By the addition of time-tagging hardware on the user platform, time synchronized to within 10 ns with respect to UTC could be achieved in the existing DSN infrastructure. In addition, the efficiency of the two-way ranging system could be enhanced by an atomic clock onboard the satellite of the type under development at the Jet Propulsion Laboratory (JPL). This technology, known as the Ultra Stable Ion Clock, has been included in the Gravity Mapping, Magnetometry, and Aeronomy (MAGNUM) proposal submitted to NASA on July 30, 2006 as the Mars Ultra-Stable Ion Clock (MUSIC). An onboard device of this type allows the one-way or two-way transmission to be initiated from the satellite, which could reduce the burden on the ground terminal. An early demonstration of two-way radiometric ranging initiated off the Earth's surface could be accomplished in combination with a one-way radiometric ranging demonstration of a GPS pseudolite as discussed below in Section D.

Dynamic two-way time transfer involves measurements between two platforms, where one or both platforms may be moving as shown in Figures 1a and 1b. In Figure 1a, a DSN station transmits a signal to the spacecraft. Upon receiving the signal, the satellite transmits another signal back to the DSN station. During this process the position of the DSN station has shifted due to Earth's rotation. In Figure 1b the transmission originates in the spacecraft and is sent to the DSN station. Upon receiving the signal, the DSN station transmits a signal to the spacecraft, which has shifted in space.

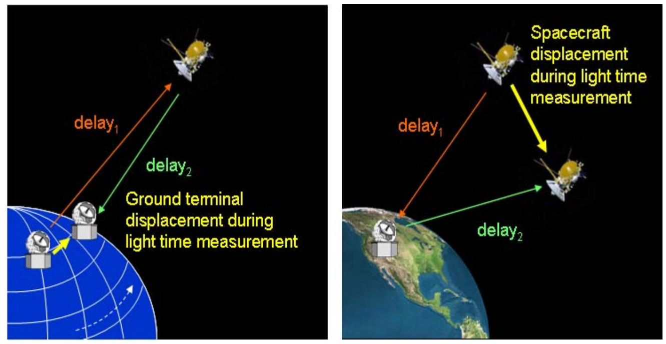

Figure 1. Dynamic time transfer examples with one moving platform. (a) Signal originates on Earth. (b) Signal originates in space.

These displacements during the light-time interval induce time delay components that must be taken into account in computing the range from the round-trip travel time.

B. Relay Satellites

The forward link of a two-way radiometric time transfer measurement could be utilized as a one-way ranging signal by multiple users. This one-way signal could be supplemented by a return on-demand signal that would complete a two-way time transfer measurement. The bandwidth requirement and user burden are significantly reduced in this type of architecture.

A relay satellite could be designed to support both one-way and two-way on-demand tracking and time transfer that would support user time requirements between 10 ns and 1 ms. Examples of such systems for Mars are shown for two aerostationary satellites in Figures 2a and 2b.

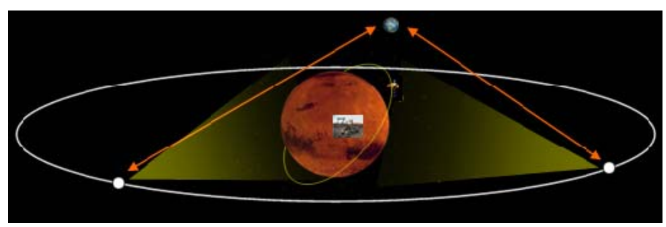

Figure 2a. Areostationary satellites in broadcast mode only.

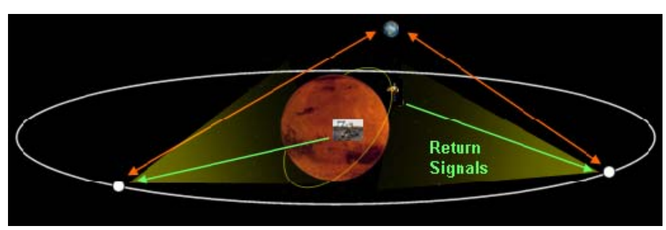

Figure 2b. Areostationary satellites with return signals.

An early demonstration of this capability could be accomplished on the Tracking and Data Relay Satellite System (TDRSS). (This time service is not currently being provided by TDRSS.) The NASA TDRSS Augmentation System for Satellites (TASS) could be modified such that the underlying PRN code of the forward link would be synchronized to UTC. This one-way broadcast service would provide millisecond level time to users on or near the Earth and a one-way ranging signal. When exercised, the on-demand return link could provide nanosecond level time recovery if the light-time effects were accounted for. Figure 3a depicts a demonstration with a one-way broadcast from TDRSS to a satellite and a surface vehicle. Figure 3b incorporates a return signal which is relayed by TDRSS back to the tracking station.

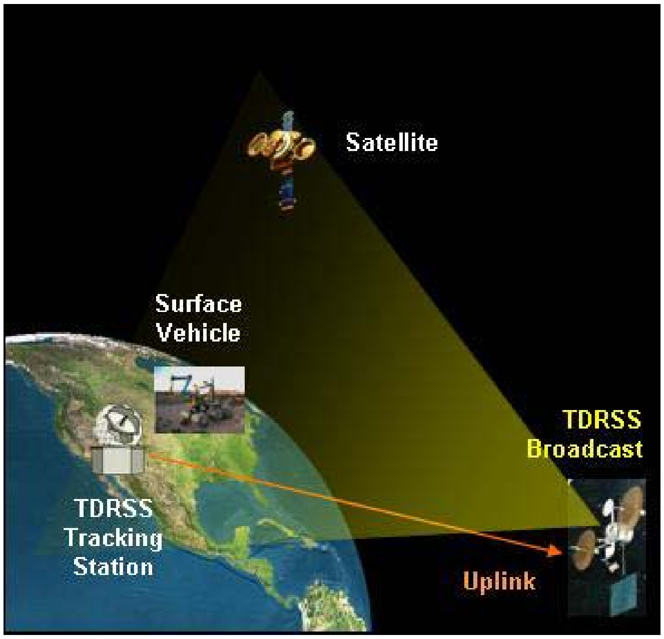

Figure 3a. TDRSS demo in broadcast mode only.

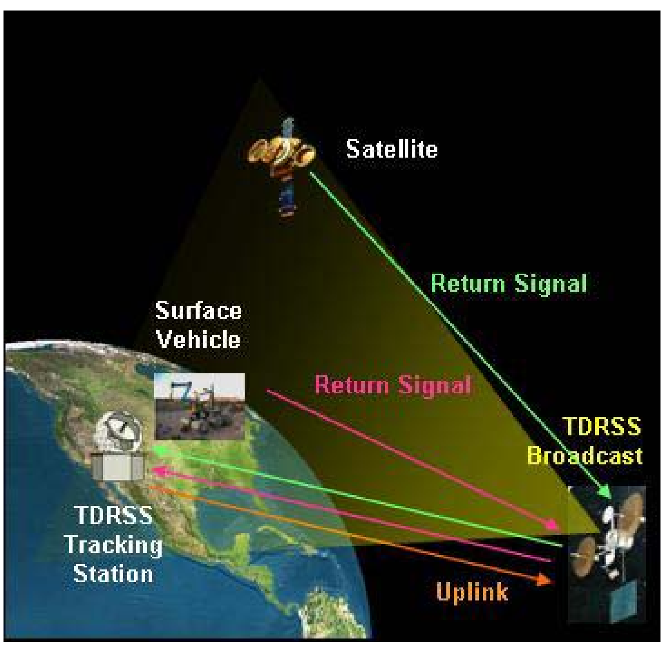

Figure 3b. TDRSS demo with return signals.

C. Combined One-Way and Two-Way Tracking Techniques

A number of signal alternatives for communications and navigation in lunar vicinity are under current consideration. Among these, some architectures favor the combined use of radiometric observables developed from one-way and two-way signal exchanges. For example, during the era of human exploration, a Lunar Network may be in place consisting of one to three lunar relay satellites (LRS) and a number of functionally identical Lunar Communication Terminals (LCT) located on the surface near outposts or sortie sites. The LCTs may be regarded as beacon signal sources that supplement the capabilities provided by the relay satellites. A user on the lunar surface or on a trajectory close to it (ascent, descent, or low orbit) may receive multiple, simultaneous signals from network assets (LRS or LCT). These contain communication both in broadcast mode (*e.g.*, LRS navigation messages) and directed to individual users, as well as the results of prior radiometric measurements made within the network, and they form a basis from which new observables can be derived.

The user terminal may receive and track input signals in an all-in-view manner but respond to each of these sequentially, *i.e.*, only one at a time. If the inputs are wideband signals with narrow and unambiguous autocorrelation mainlobes, such as pseudonoise, code-division multiple access (PN/CDMA) waveforms, they can be turned around coherently to preserve delay and Doppler shift contents that provide measurable two-way radiometrics upon receipt at one or more network assets. From signals that are not transponded the user terminal may extract similar one-way radiometrics. The ensemble of data thus collected may be communicated to a single point—the user terminal or a network asset—to determine a navigation and timing solution, typically with a Kalman filter that is collecting data over time.

For one-way radiometric data to be useful, the end terminals must share a common time scale that is maintained by accurate and long-term stable clocks. Within the network the time source might be an atomic clock whose discrepancies with a governing time scale are disseminated in navigation messages to users. For the users there are various choices, such as an ultra-stable oscillator that is periodically disciplined by a lunar network asset.

D. Lunar Beacons for GPS Augmentation

In one-way navigation, a ground station, beacon, or satellite transmits a ranging signal that includes a navigation message stating the current beacon's position and its clock offset to the navigation system's time base. The GPS, a one-way navigation system, is a nominal 24-satellite constellation providing a minimum of four satellites simultaneously in view to determine position and time for a moving platform anywhere within the Service Volume. To measure time at a known position, only one GPS satellite is required. In dynamic applications where instantaneous position is known through the Doppler shift of two-way communications, a single GPS satellite (or pseudolite) can provide UTC or GPS Time. However, the cost of deploying enough radiometric sources to provide four-fold coverage near or on the surface of the Moon or Mars forces one to consider reducing the required number of radiometric sources by placing solution constraints on the user end, such as accurate maps, precision clocks (or time synchronization by other means), or increased latency time. Although one-way navigation systems on the Moon or Mars do not require access to terrestrial time sources to support the local navigation mission, such systems could provide a cost-effective means to support user requirements for access to terrestrial time scales.

Beacons on the Moon could be used to provide a scalable time service. The scalability of the time service is limited by the position uncertainty of the user platform. For example, a position uncertainty of 300 km corresponds to a time uncertainty of 1 ms. If the relative range to the beacon is known, high precision time transfer at the 10 ns level can be achieved with just one beacon in sight.

Obviously, the time service could be embedded in the navigation service as a function of the option. A system of beacons on the Moon could provide time services over an appreciable volume of cislunar space while aiding in the determination of the user's state vector during various mission phases. A particular case of a beacon is a pseudolite, which transmits a PRN signal similar in structure, if not frequency, to those transmitted by GPS satellites. Measurement types available from a pseudolite include pseudorange and ADR.

One example of a notional one-way radiometric navigation and timing architecture is the extension of GPS services throughout the solar system, as shown in Figure 4. Local planetary radionavigation satellites and beacons would be coherent with GPS time to the 10 ns level and would provide terrestrial time references (*e.g.*, UTC) to users. An early technology validation might include the placement of a GPS Block IIF payload on the surface of the Moon to supplement near Earth-Lunar time transfer and navigation. Although the IIF payload would broadcast by only civil signals (L1, L2C, and L5) and would be operated by NASA, similar signals could be broadcast on other frequencies as well.

Originally motivated by the problem of GPS reception inside buildings on earth or in other situations that would greatly attenuate GPS signal-to-noise ratio (*e.g.*, jamming), many researchers have addressed development of weak-signal GPS algorithms and receivers [6]. NASA itself has contributed heavily in this area, having developed and tested a fully spaceflight-qualified GPS receiver (*Navigator*) for high earth orbit (HEO) missions [7]. If successful, this new technology will enable applications unforeseen even a few years ago, including the potential of GPS for time transfer and navigation in lunar vicinity.

Weak-signal GPS receivers leverage many techniques to maximize the information derivable from the received signals: novel satellite selection strategies; increased signal-to-noise ratio from coherent integration time extended beyond the GPS navigation message bit boundaries; DFT processing for rapid, parallel Doppler search; code and carrier tracking loops tailored to anticipated dynamics; directional, high-gain antennas (in applications distant from earth); and onboard navigation filters to process dynamic solutions when there is an insufficient number of visible GPS sources to prosecute instantaneous point solutions.

GPS data derived in this manner could be used to transfer GPS Time from Earth to the lunar vicinity, or, in combination with other lunar-local radiometric observables, to generate autonomous orbit determination for the LRS.

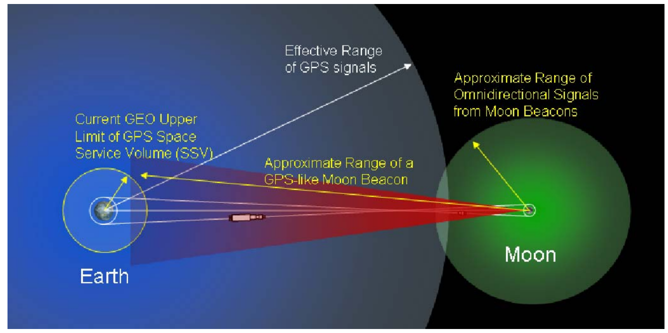

Figure 4. Notional GPS extension for cislunar navigation and timing.

IV. Time Scales and Relativistic Transformations

A. Time Scales

Multiple time scales exist and are in simultaneous use because the reckoning of time has progressed from a system based upon the rotation of the Earth to one defined by atomic state transitions. Today UTC is the internationally recognized scale of civil time based on atomic clocks [8].

There now exists a unique opportunity to begin the development of an internationally recognized solar system time scale that would be a natural extension of UTC but would be uniform without leap second steps. The choice of a suitable epoch and the establishment of a practical means to disseminate realizations of the time scale via laboratories and satellites are subjects for discussion at the international level.

B. Relativistic Transformations

Transformations between clocks operating on Mars and the Moon will become an essential activity for conducting future solar system missions. Accurate time transfer requires consideration of relativistic effects that make clocks operate differently at Mars and the Moon from clocks at Earth. These effects must be taken into account for time synchronization and dissemination.

The difference in the readings of a clock on the surface of Mars and a clock on the surface of the Earth has both secular and periodic terms. The net secular drift is 0.49 ms/d. The amplitudes of the periodic variations are 1.7 ms at the Earth orbital period (365.2422 d) and 11.4 ms at the Mars orbital period (686.9297 d). The relativistic effects for a clock on the Moon are about an order of magnitude less [9].

C. Signal Propagation Time Correction for Receiver Motion

It is also necessary to account for the motion of the receiver during the signal propagation time [10]. A notional example is illustrated in Figure 5. In the case of a receiver at rest on the Earth, an observer in an Earth-Centered Inertial (ECI) frame sees that the receiver has moved due to the Earth's rotation and applies a velocity correction, but an observer in the Earth-Centered Earth-Fixed (ECEF) frame regards the receiver as stationary and applies a Sagnac correction. Which mathematical approach is taken is determined by convenience.

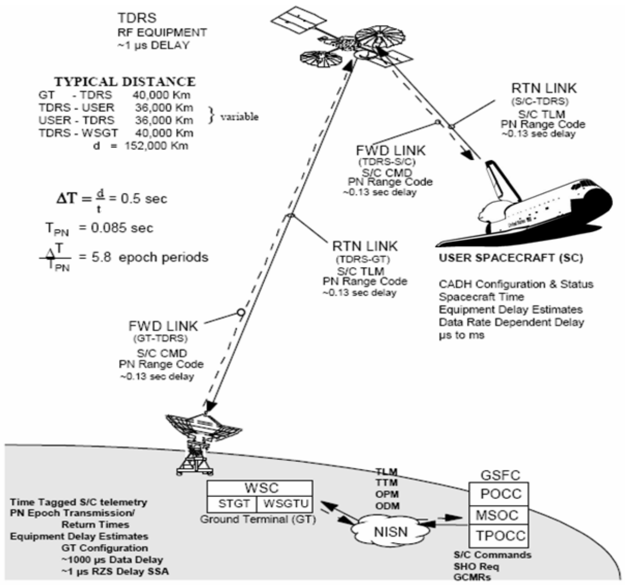

Figure 5. Receiver motion during signal propagation.

IV. CONCLUSIONS

Over the next 25 years NASA foresees its involvement in numerous activities whose proper functioning will depend upon accurate knowledge of time in diverse solar system locations. NASA is studying candidate architectures for a scalable time dissemination service meeting these future needs. This paper has indicated a few methods by which the goals might be accomplished, including examples for the Earth vicinity as well as for the Moon and Mars. Important issues relevant to time scales and corrections for various physical phenomena in processing observables that provide time-related data have been highlighted.

It has shown that, whereas the potential for radiometric-based time transfer is well understood, use of network time transfer protocols in the space environment is an approach that requires further study and definition. A continuous timescale, without leap seconds, should be defined for precision space navigation and other real-time operational applications. Finally, accurate time transfer requires attention to platform dynamics and the effects of general relativity.

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