TIME DISSEMINATION ALTERNATIVES FOR FUTURE NASA APPLICATIONS

Al Gifford
NASA Headquarters*
Fax: 202-3583520; E-mail: *al.gifford-1@nasa.gov*

Robert A. Nelson
Satellite Engineering Research Corporation
7701 Woodmont Avenue, Bethesda, MD 20814, USA
E-mail: *RobtNelson@aol.com*

Richard S. Orr
SATEL LLC
9700 Great Seneca Hwy, Rockville, MD 20850, USA
E-mail: *richard.orr@sa-tel.com*

A.J. Oria
Overlook Systems Technologies, Inc.**
E-mail: *aoria@overlooksys.com*

Beryl L. Brodsky
Overlook Systems Technologies, Inc.**
E-mail: *bbrodsky@overlooksys.com*

James J. Miller
NASA Headquarters*
E-mail: *jj.miller@nasa.gov*

Barbara Adde
NASA Headquarters*
E-mail: *barbara.adde@nasa.gov*

***300 E Street SW, Washington, DC 20546, USA**
****1950 Old Gallows Rd., Suite 400, Vienna, VA 22182, USA**

Abstract

This study describes an activity being undertaken by NASA. The Space Communication Architecture Working Group (SCAWG) was established to recommend the future architecture of NASA's communication, navigation, and timing systems through studies coordinated across all NASA Centers and Mission Directorates. The architecture will support both science missions and the Vision for Space Exploration (VSE), which calls for returning of humans to the Moon, expanding human presence to Mars, and exploring the solar system. Foreseeable NASA applications span a wide range of demands for time services. Four examples include: (1) event logging by human explorers; (2) networking of cooperative robots on a planetary surface (e.g., the Moon or Mars); (3) time transfer for navigation local to a planetary body; and (4) time synchronization for communication and science. Documented accuracies range from 1 s for event logging down to 10 ns for local navigation and communication. Accuracy requirements below 1 ns for science missions are anticipated. Required time corrections due to the change in relative range between a time source and user during the light-time measurement interval are described. In addition, corrections for relativistic effects on clocks in Earth orbit or the Mars and Moon environments are necessary. The time dissemination alternatives identified thus far are based on existing time dissemination technologies, including radiometric ranging, network time dissemination, and stand-alone time dissemination techniques. The paper presents concept descriptions of: (1) DSN two-way ranging utilized for time transfer; (2) scalable one-way, two-way time dissemination using relay satellites; and (3) a GPS augmentation system, consisting of pseudolites or beacons distributed on the surface of the Moon and elsewhere in the solar system.

INTRODUCTION

This paper describes an activity being undertaken by the National Aeronautics and Space Administration (NASA). The Space Communication Architecture Working Group (SCAWG) was established to recommend the future architecture of NASA's communication and position, navigation, and timing (PNT) systems through studies coordinated across all NASA Centers and Mission Directorates. The architecture will support both science missions and the Vision for Space Exploration (VSE), which calls for returning of humans to the Moon, expanding human presence to Mars, and exploring the solar system. The SCAWG activity has stimulated dialog among the technically cognizant individuals within NASA on a potential solar system wide architecture for timekeeping and time dissemination. This effort has created a process for selecting such an architecture. This paper identifies the main time architecture requirements and the salient features, discusses the tradespace of architectural alternatives, and postulates a few notional architecture implementations for time dissemination. Time scales and relativity effects in time transfer are reviewed because of their importance to the overall problem.

1. REQUIREMENTS AND SALIENT FEATURES

The requirements identified presently, although incomplete, range from coarse applications such as instrument and human event logging all the way to precision applications such as one-way radiometric ranging for navigation. However, future requirements outside this range may emerge. From this range of requirements, the salient features of the time dissemination architecture may be postulated. These include:

- The future time and frequency architecture will be an integral part of the space communication and navigation infrastructure, retaining the possibility of stand-alone dissemination systems.
- The architecture will be scalable to accommodate user requirements from Coarse (1 second to 1 millisecond), to Fine (1 millisecond to 1 microsecond), to Precision (1 microsecond to 1 nanosecond).
- Terrestrial time scales at nanosecond-level accuracies will be available to users to the extent required.
- The appropriate principles of general relativity will be applied as required for dissemination among systems on spacecraft and solar system objects.

2. CONCEPTS FOR SOLAR SYSTEM WIDE TIME TRANSFER

Time dissemination may be accomplished through the systems used for radiometric navigation/tracking and communications (including network time dissemination). This section discusses the available trade space for time dissemination 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 dissemination architecture. Historically, we have used three vehicles to disseminate time our Earth environment: radionavigation systems, communication systems, and stand-alone time dissemination systems. Beyond the relative technical merits of the alternatives considered, there are also important issues of relative 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/or satellites that transmit signals used to determine the state vector of the user and to correct the user time base. According to the algorithms used, radiometric navigation systems are typically designated as one-way or two-way. In either case, the measurement of the 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 and, as such, are natural observables for data required and time dissemination algorithms.

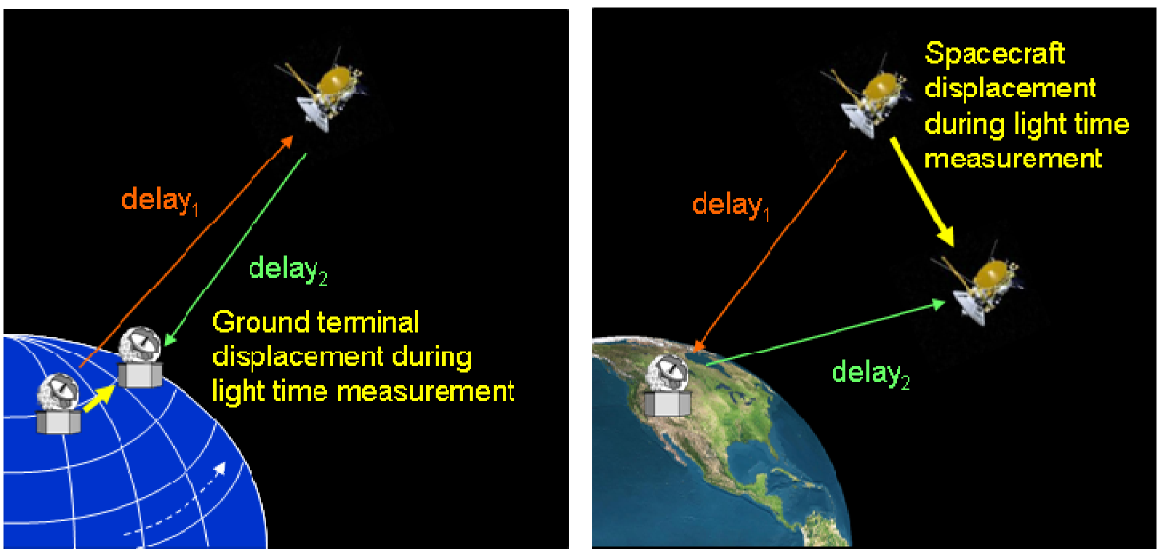
Network algorithms are another alternative for time dissemination that are under consideration. For example, Network Time Protocol (NTP) and the IEEE Standard 1588 are potential candidates for implementation. These protocols are under study at the NASA Goddard Space Flight Center **[1]**. Hardware-assisted techniques, which exploit the synchronous characteristic of the link level of communication systems, have been demonstrated and are also viable candidates **[2]**.

2.1. TIME TRANSFER USING 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 an external reference, UTC (NIST), to permit the handoff of the return link to another DSN site.

A notional two-way high precision time service for the DSN is this: by the addition of time-tagging hardware on the user platform, time synchronized to within 10 ns with respect to UTC could be implemented 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 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 30 July 2006 as Mars Ultra-Stable Ion Clock (MUSIC). An onboard device of this type allows the two-way (or one-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 in Section 3.3.

Dynamic two-way time transfer involves calculation between two platforms where one, or both, may be moving (Figure 1a and 1b). In Figure 1a, a DSN station transmits a signal to the spacecraft and, 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 and, upon receiving the signal, it transmits another signal back to the spacecraft. During this process, the position of the spacecraft in space has shifted. These displacements during the light-time measurement interval induce delays components that must be taken into account in computing range from the round-trip travel time.



(a) (b)

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

2.2. One- and Two-Way Ranging and Time Transfer using 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- 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 in Figures 2a and 2b.

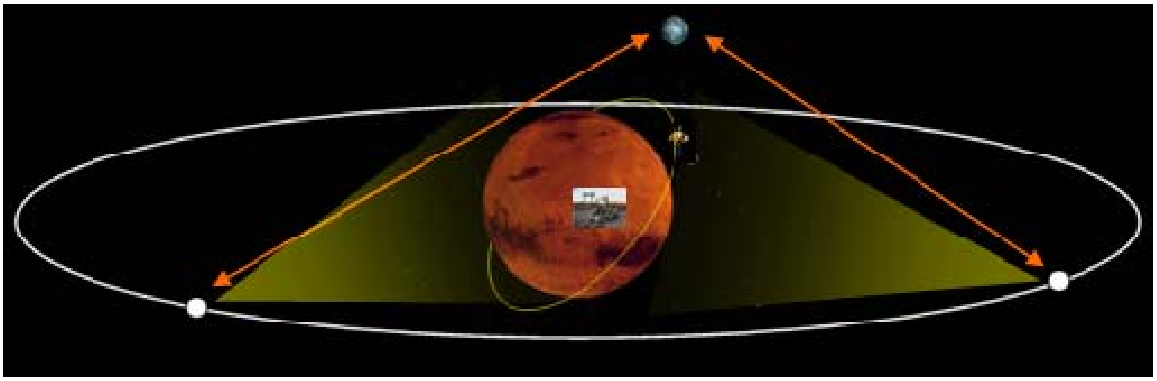


Figure 2a. Areostationary satellite/s in broadcast mode only.

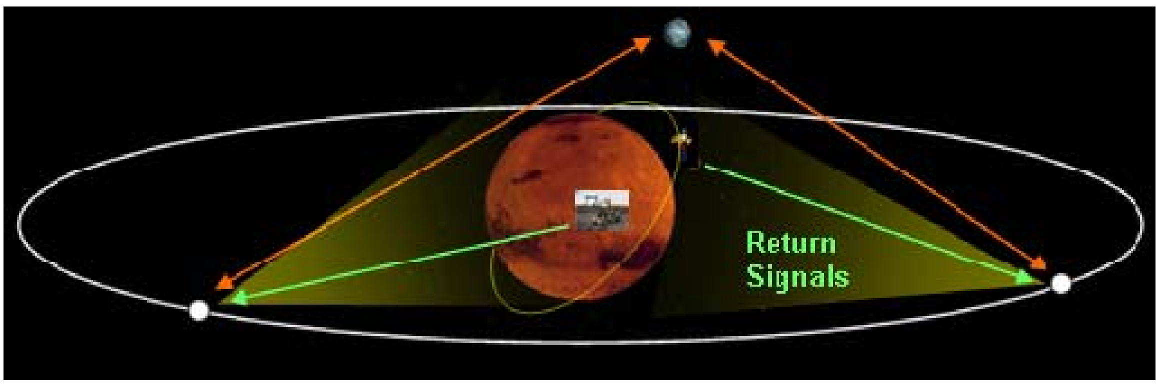


Figure 2b. Areostationary satellite/s with return signals.

An early demonstration of this capability could be accomplished on the Tracking and Data Relay Satellite System (TDRSS)[1]. 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 (see Section 4.3). 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.

[1] Note: This time service is not currently being provided by TDRSS.

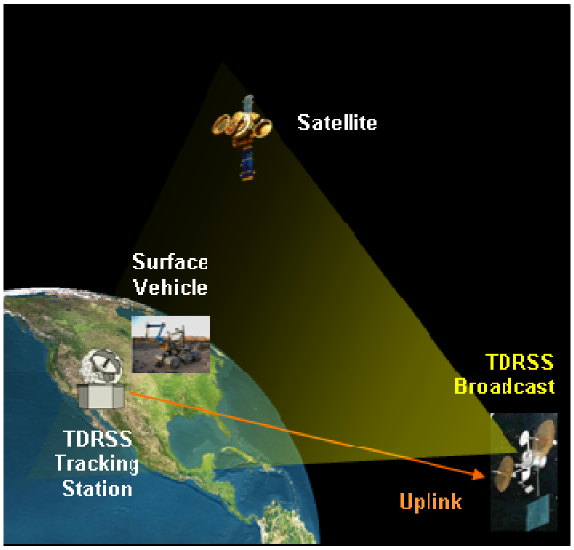


Figure 3a. TDRSS demo in broadcast mode only.

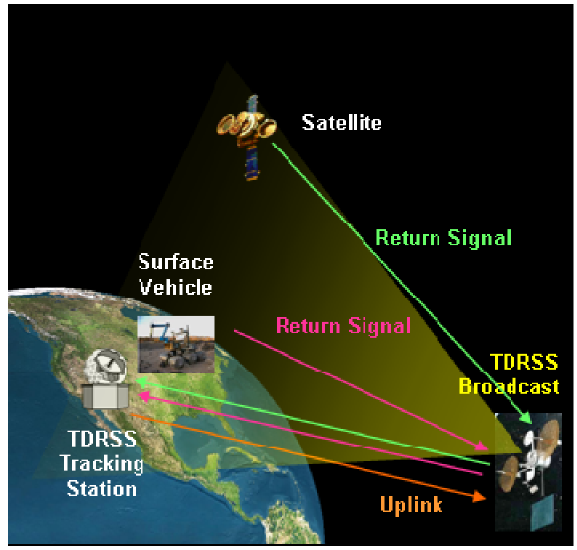


Figure 3b. TDRSS demo with return signals.

2.3. Lunar Beacon/s 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 dedicated, nominal 24-satellite navigation constellation providing the minimum of four navigation satellites in view required to determine position and time of moving platform anywhere in the Service Volume. To measure time at known positions, only one GPS satellite is required. In dynamic applications where instantaneous position is known through the Doppler of two-way communications, a single GPS satellite (or pseudolite) can provide UTC or GPS Time. The expense, however, in deploying enough radiometric sources to provide four-fold coverage near the Moon or Mars, or on their surface, forces one to consider reducing the number of radiometric sources required through 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, 300 km position uncertainty represents a 1 ms time uncertainty. If the relative range to the beacon is known, high precision time transfer to the 10 ns level can be achieved with just one beacon in sight. Obviously, the time service could be embedded in the navigation as a function of the implemented 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 pseudorandom noise (PRN) signal similar in structure, if not frequency, to those transmitted by GPS satellites. Measurement types available from a pseudolite include pseudorange and accumulated delta range (ADR), also known as integrated Doppler measurements.

One example of a notional one-way radiometric navigation and timing architecture is the extension of GPS services through the Solar System 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. Though the IIF payload would broadcast civil signals only (L1, L2C, and L5) and be operated by NASA, similar signals could potentially be broadcast on other frequencies as well.

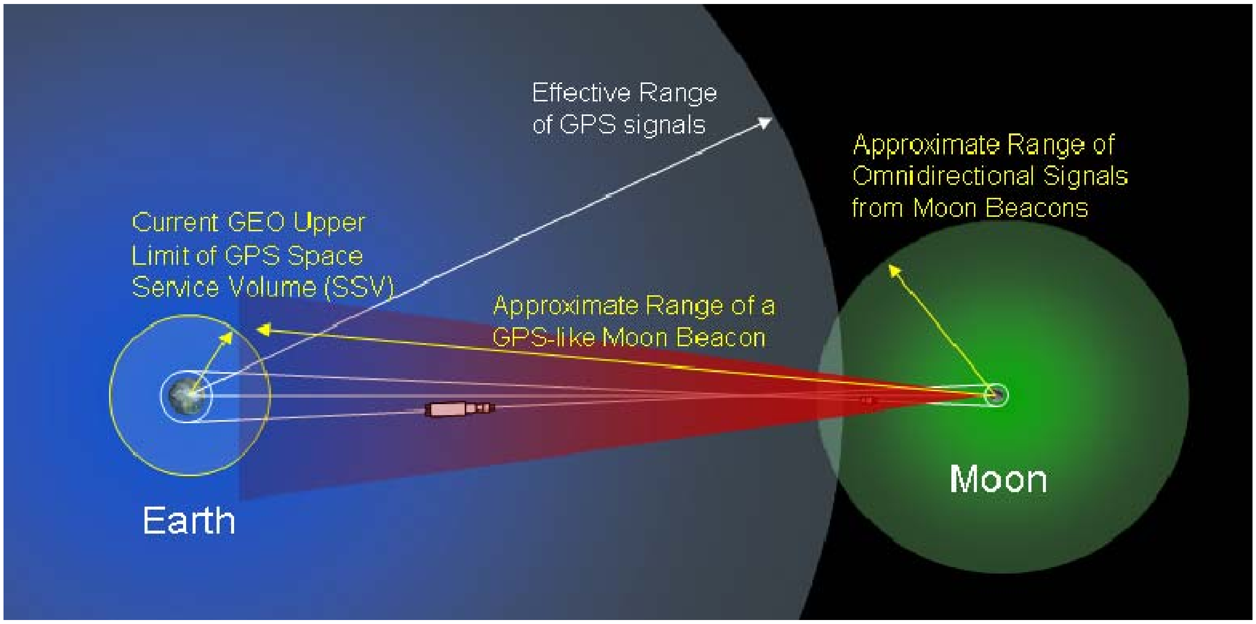


Figure 4. Notional GPS extension for cislunar navigation and timing.

3. TIME SCALES AND RELATIVISTIC TRANSFORMATIONS

3.1. 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. Atomic clocks are highly accurate, precise, and stable, properties which render them amenable to scientific application. There now exists a unique opportunity to began the development of an internationally recognized solar system time scale that would be a natural extension of UTC (Coordinated Universal Time). Definition of the epoch of a solar system time scale and the practical means to acquire the time scale from one or more laboratory or satellite realizations are subjects for discussion at the international level.

3.2. RELATIVISTIC TRANSFORMATIONS

Transformations between clocks operating at the Moon or Mars will become an essential activity for conducting future missions at these bodies. Accurate time transfer requires consideration of relativistic effects that make clocks operate differently at Mars and the Moon from clocks at Earth. The analysis shows that the secular rates at Mars and the Moon differ by an order of magnitude and the periodic effects at Mars have amplitude differences of about 10 milliseconds relative to the Earth if uncorrected for relativistic effects.

As discussed at another paper presented in this conference **[3]**, 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: (a) 1.7 ms at the Earth orbital period (365.2422 d); (b) 11.4 ms at the Mars orbital period (686.9297 d). Therefore, in the transfer of time between a clock on Mars and a clock on the Earth, there are both secular and periodic effects that are of the order 1 to 10 milliseconds.

3.3. SIGNAL PROPAGATION TIME CORRECTION FOR RECEIVER MOTION

If a signal is transmitted from a satellite at coordinate time t_T to a moving receiver at coordinate time t_R, the coordinate time elapsed over the path length in the Earth-Centered Inertial (ECI) frame is

$$\text{(1)} \qquad \Delta t = \frac{\rho}{c} = \frac{1}{c}\,|\,\mathbf{r}_R(t_R) - \mathbf{r}_T(t_T)\,| = \frac{1}{c}\,|\,\Delta\mathbf{r} + \mathbf{v}_R\ (t_R - t_T)\,| \approx \frac{1}{c}\,|\,\Delta\mathbf{r}\,| + \frac{1}{c^2}\,\Delta\mathbf{r}\cdot\mathbf{v}_R$$

where ρ is the geometric path length, $\Delta\mathbf{r} \equiv \mathbf{r}_R(t_T) - \mathbf{r}_T(t_T)$ is the difference between the position of the receiver and the satellite at the coordinate time of transmission t_T, and $\mathbf{v}_R$ is the velocity of the receiver in the ECI frame. If the receiver has position $\mathbf{R}$ and velocity $\mathbf{v}'_R$ relative to the rotating geoid, $\Delta\mathbf{r} = \mathbf{R}(t_T) - \mathbf{r}_T(t_T)$, and $\mathbf{v}_R = \mathbf{v}'_R + \boldsymbol{\omega}\times\mathbf{R}$. Then the signal propagation time correction for receiver motion becomes the sum of two terms,

$$\text{(2)} \qquad \Delta t_{\mathrm{v}} = \Delta\mathbf{r}\cdot\mathbf{v}'_R / c^2 + \boldsymbol{\omega}\cdot[\mathbf{r}_T(t_T)\times\mathbf{R}(t_T)]/c^2 = |\,\Delta\mathbf{r}\,|\ v'_R\ \cos\theta / c^2 + 2\,\omega\,A/c^2$$

where $|\,\Delta\mathbf{r}\,|$ is the range, θ is the angle between the receiver velocity and the line joining the satellite and the receiver, and A is the area of the triangle with vertices at the satellite, receiver, and center of the Earth projected onto the equatorial plane at the coordinate time of transmission t_T. In the Earth's rotating frame of reference, the first term is a range rate, or integrated Doppler shift, and the second term is the Sagnac effect.

The Sagnac effect is given by

$$\text{(3)} \qquad \Delta t_{\text{Sagnac}} = \frac{2\,\omega\,A}{c^2} = \boldsymbol{\omega}\cdot(\mathbf{r}_A\times\mathbf{r}_B) = \frac{\omega}{c^2}\left(x_A\,y_B - y_A\,x_B\right)$$

where A is the perpendicular projection of the area formed by the center of rotation and the endpoints of the light path with endpoints at (x_A, y_A) and (x_B, y_B).

In the case of a receiver at rest on the Earth, an observer in the 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.[2]

Which mathematical approach is taken is determined by convenience. For example, for the system illustrated in Figure 1a the approach of Eq. (2) might be appropriate. For the system illustrated in Figure 1b, Eq. (1) would be convenient.

[2] The term "Sagnac effect" is part of the vocabulary of only the observer in the rotating reference frame. The corresponding correction applied by the inertial observer should be called a "velocity correction."

4. SUMMARY AND FUTURE WORK

Over the next 25 years, NASA foresees involvement in numerous activities whose proper functioning will depend upon sufficiently accurate knowledge of time in diverse solar system locations. Through the SCAWG, NASA is studying candidate architectures for a scalable time dissemination service meeting these future needs. The paper has indicated a few methods by which this goal might be accomplished, including examples for the Earth vicinity, as well as 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.

This paper 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 relativistic effects.

Future work items expected to be accomplished include the following tasks:

- Increase the involvement of NASA in the U.S. and international timing metrology communities.
- Continue the SCAWG effort to collect mission timing requirements to help prioritize future time work.
- Develop additional architectural candidates using internal and external expertise in network time dissemination protocols and carry out the architecture alternative analysis.
- Perform continued studies in the area of Position, Navigation, and Time (PNT) to select technologies consistent with cost, mass, volume, performance, and other constraints.
- Address potential U.S. shortfalls in precision clock availability.
- Identify near-term technology demonstrations to support a baseline PNT architecture.
- Document a Concept of Operations (CONOPS) that would serve as the basis for the specification, development, and implementation of Space Communications Architecture (SCA).

5. REFERENCES

[1] J. Rash, R. Parise, K. Hogie, E. Criscuolo, J. Langston, C. Jackson, H. Price, 2000, *"Internet Access to Spacecraft,"* 14th Annual/USU Conference on Small Satellites, August 2000.

[2] T. Celano, 2002, *"Ku Band (SATCOM) and L-Band (Line-of-Sight) relay tests"* (briefing), Timing Solutions, Boulder, Colorado, 20-21 November 2002.

[3] R. A. Nelson and T. Ely, 2007, *"Relativistic Transformations for Time Synchronization and Dissemination in the Solar System,"* in Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 305-318.