NAVIGATION ARCHITECTURE FOR A SPACE MOBILE NETWORK

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The Tracking and Data Relay Satellite System (TDRSS) Augmentation Service for Satellites (TASS) is a proposed beacon service to provide a global, space-based GPS augmentation service based on the NASA Global Differential GPS (GDGPS) System. The TASS signal will be tied to the GPS time system and usable as an additional ranging and Doppler radiometric source. Additionally, it will provide data vital to autonomous navigation in the near Earth regime, including space weather information, TDRS ephemerides, Earth Orientation Parameters (EOP), and forward commanding capability. TASS benefits include enhancing situational awareness, enabling increased autonomy, and providing near real-time command access for user platforms. As NASA Headquarters' Space Communication and Navigation Office (SCaN) begins to move away from a centralized network architecture and towards a Space Mobile Network (SMN) that allows for user initiated services, autonomous navigation will be a key part of such a system. This paper explores how a TASS beacon service enables the Space Mobile Networking paradigm, what a typical user platform would require, and provides an in-depth analysis of several navigation scenarios and operations concepts.

INTRODUCTION

The Earth Regimes Network Evolution Study (ERNESt) proposed the development of a new near-Earth communication network consisting of a new generation of ground and space based communication assets.[1] This new network would abandon the current network architecture defined by the Apollo era Manned Space Flight Network (MSFN) and Space Shuttle era Space Network (SN) and transition to the architectural concepts that enable today's terrestrial wireless networks. ERNESt's Space Mobile Network (SMN) will provide a modern user experience that emulates some services provided by modern smart phones, particularly the automated delivery of communication services and always available positioning and navigation capability. The efficiency of the SMN relies on a significant reduction in centrally-managed, fully-scheduled services in the current networks in favor of a user-initiated, decentralized, delay-tolerant type of non-deterministic network topology. The proposed SMN architecture will be incompatible with the current metric tracking and ground based orbit determination practices. A continually available global beacon service that enables autonomous determination of user and network asset locations

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is a fundamental component of the communication and navigation capabilities envisioned in the SMN.

An initial operational capability of a beacon service can be realized today within the framework of the current SN via the Tracking and Data Relay Satellite System (TDRSS). The concept of a space-based beacon service has been explored since the 1980s, and an initial demonstration of the TDRSS Augmentation Service for Satellites (TASS) beacon concept was carried out in the mid-2000s.[2,3] TASS has evolved since that time and today, early demonstration of the beacon concept via TASS represents a crucial step towards enabling the Space Mobile Network. A recent effort to revitalize TASS is underway in order to exploit the opportunities provided by the increasing use of GPS and autonomous navigation (autonav) in space.

This paper provides an overview of the TASS beacon and its role within the SMN and user community. Supporting navigation analysis is presented for two user mission scenarios: an Earth observing spacecraft in low earth orbit (LEO), and a highly elliptical spacecraft in a lunar resonance orbit. These diverse flight scenarios indicate the breadth of applicability of the TASS beacon for upcoming users within the current network architecture and in the SMN.

TASS AS AN ENABLER FOR A SPACE COMMUNICATIONS AND NAVIGATION ARCHITECTURE USING SPACE MOBILE NETWORKING

Historically, space communications networks provided service to orbiting spacecraft from globally distributed ground terminals. TDRSS augments this architecture by providing continuous, around the clock communications to NASA's low earth-orbiting missions via geosynchronous relay satellites (Figure 1). In this current network paradigm, service scheduling typically requires days of notice before events. Additionally, some missions require service solely for the radiometric tracking data used for orbit determination, tying up network resources. The Space Mobile Network will minimize or eliminate manual scheduling by providing automated end-to-end, delay tolerant data delivery service. However, processing and routing of communications services onboard relays would break the time and frequency relationships between the relay satellite, user, and a common timescale. Insertion of unknown, possibly large, delays when using store-and-forward techniques are incompatible with the regular production of direct range observations for ground based orbit determination systems.
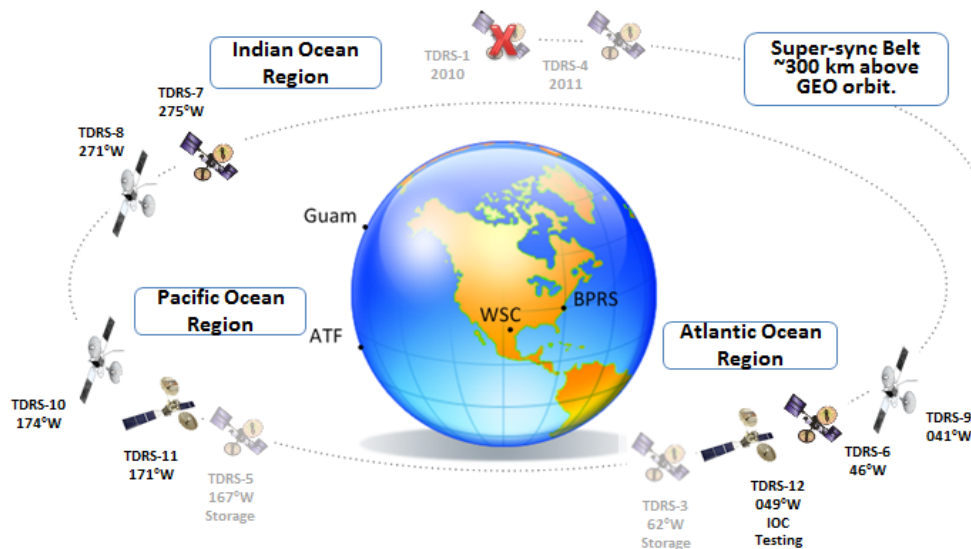

Figure 1. TDRSS Configuration (mid 2014)

Accurate predictive ephemerides for users and network assets is a pre-requisite for user signal acquisition by the network and autonomous scheduling of network resources to meet user demand access requests. The ability for such a scheme to work efficiently is predicated on the ability of all users to autonomously perform onboard orbit determination, such that when they make their user initiated service requests, they provide the network with accurate predictive ephemerides for use in acquisition and scheduling. Acquisition becomes a fundamental constraint to autonomous network scheduling; without dedicated, diverse, scheduled, deterministic tracking arcs that obey the user's needs for geometric observability of the orbit, users cannot perform orbit determination in this new architecture. One-way non-coherent metric tracking observations and the assumption of autonomous onboard navigation are more conducive to the SMN architecture and can be provided by a beacon service such as TASS.

For many users, GPS will provide a viable substitute for network-provided tracking data. Two classes of users exist for which GPS may not be viable: "disadvantaged" users such as CubeSats that cannot afford the size, weight, and power for an additional radio beyond that needed for communication, and users whose orbit never reaches low enough altitudes to access adequate GPS signals. Two-line elements (TLEs), which are parameters that coarsely describe a user orbit, may be used for LEO spacecraft, but are generally neither reliable enough nor accurate enough to support maneuvering spacecraft or those in higher orbits.[4] The tracking sources that feed most TLEs are often too coarse to detect maneuvers and do not predict accuracy in the along-track direction.

Architectural Assumptions

The baseline TASS system consists of a minimum of three geosynchronous longitudinal node locations that each provide a two-legged, one-way ranging signal synthesized from a common time reference system on the ground. Extrapolations to the next generation of services provide benefits worth exploring. A generalization of TASS to a near-omnidirectional beacon, e.g. as a payload on some future relay satellite, or higher powered Earth-based beacons, supports navigation for users in regimes beyond the reach of GPS.

User Initiated Service

The hailing paradigm is central to the concept of user initiated service and autonomous scheduling. Spacecraft will have the ability to alert the network when a high rate data link is required, e.g. when a science data recorder is full, by hailing via a low-rate telemetry, tracking and command channel. The hail not only alerts the network to the presence of a user and provides information regarding the user's request for service, but also provides the self-determined (via autonav) state information necessary for the network to provision and fulfill the user's request. In many cases, knowledge of the relay location will be necessary for the user to radiate the hail. The relay orbital data provided by the TASS beacon, in combination with the user's autonav capability, allows the hail to be radiated in the proper direction. User state information provided in the hail will be used by the automated scheduling system on the ground to compute visibility windows, a necessary first step in provisioning high rate service to the customer. Finally, the broadcast channel provided by the TASS beacon will pass notification to the spacecraft when their high rate link will be available.

TASS enables user autonav in the Earth regime by providing globally available radiometric observations. Space based relays combined with Earth based beacons could provide a standalone navigation capability in the near Earth domain. TASS provides a means to accomplish user navigation information for acquisition, the first step of the process required for decentralized SMN.

Global Dissemination of a Common Timescale

In a modernized communications network, high data rate communications, higher order modulations, and new methods of multiple access will require tighter synchronization and improved phase noise performance than what is present in today's network. Improved time synchronization by users will facilitate a transition from two-way coherent Doppler and delay observations to one-way techniques; this architectural trade is already being pursued by the Deep Space Network.[5] Additionally, the user initiated service concept will require the coordination, and hence synchronization, of many different network elements.

The improvement in communication techniques (data rate, multiple access) brought about by assuming synchronization to a common timescale, will enable more efficient use of network resources. Smaller inter-service windows and reduced acquisition times will allow for improved utilization of single access, high data rate relay and ground terminals. This will increase the network's ability to move data and service a large volume of customers.

TASS CONCEPT OF OPERATIONS

TASS was envisioned to provide continuously available global coverage of data dissemination for spacecraft to enhance their autonomy, flexibility, and navigation performance. The current TASS architecture consists of the Data Message sources, the ground and space segment assets used to transmit the TASS signal to the orbiting user community, and the user receiving equipment. The data and commands to be incorporated into the TASS message are received at the ground station and formatted into a bit stream. This data message is provided to the service transmitter and modulated, along with a pseudo-random noise (PN) code, for transmission on the ground-to-space uplink signal to the Tracking and Data Relay Satellites. The TASS beacon will be broadcast from each of the three geo-synchronous longitude nodes via the S-band Multiple Access Forward (MAF) system using a broadened conical beam with a 10.5 degrees half-cone angle – enough to cover the Earth disk plus 1400 km altitude, giving global coverage, including limited coverage over the poles (Figure 2). As orbiting users fly through the TASS service volume, their onboard equipment receives the signal, produces navigation measurements, demodulates the data, and consumes the message portions of interest. While an initial operational capability can by realized within the current SN, the TASS architecture is designed to be flexible and has the potential to broadcast on alternate frequencies, from different relay orbital locations, from ground-based transmitters foregoing the relay, with broader coverage, and with additional data content.

Figure 2. TASS Beacon and GPS Service Volumes

The PN code epoch is synchronous with GPS time, which is directly traceable to Universal Time Coordinated (UTC), the time system used by the current networks. To provide for time transfer, the TASS signal is modulated at a specific fixed carrier frequency and the PN code chipping rate is coherently derived from the uplink carrier frequency. Each TASS signal will be transmitted at the same fixed frequency, but uses a unique PN code assigned to that beacon

transmission node source. The continuity and global coverage of the TASS signal allows any number of orbiting users to simultaneously interrogate the signal as needed. The location of each participating relay satellite or ground-based transmitter is also included in the data message. The interrogating user can then derive pseudorange, Doppler, and time from the TASS signal.

User Equipment

There are several possible options for user equipment to receive the TASS signal. A single or dual frequency user of GPS for onboard navigation may choose to also fly an S-band transponder modified to acquire and track the TASS PN code and generate range and Doppler measurements. Such a user may decode and apply the GPS differential corrections to increase the accuracy and integrity of the GPS measurements. This data would then be used by onboard navigation flight software running in the spacecraft flight computer or embedded in the receiver processor to produce precise orbit determination solutions. In the future, user equipment concepts integrating TDRSS transponder and GPS receiver functions within a single enclosure could provide a more seamless integration of TASS signals.

Another class of users might have only a communications network transponder or transceiver, especially if they are constrained by size, weight, or power or do not require precision orbit determination. The receive portion of that communications unit would be configured to track the TASS signal then produce pseudorange and Doppler measurements from the signal for use in onboard navigation applications. The receiver would also demodulate the TASS messages to utilize relay ephemeris, Earth orientation parameters (EOP), or other message parameters useful for autonomous operations and SMN functionality. The receiver could be designed to alternate between tracking the TASS signal and tracking the traditional user unique Multiple Access or Single Access network service, or it could include multiple channels to receive the TASS signal while simultaneously supporting normal scheduled or hailed services.

Data Message

As currently designed, using link parameters based on the 2nd and 3rd generation TDRS MAF capabilities, the TDRS satellites can transmit a TASS message bandwidth of at least 1024 bits per second. The TASS ground equipment creates a unique data stream for each broadcasting relay that includes both data that is common to all broadcasts, as well as unique information identifying the relay spacecraft and user commands for broadcast to a selected beacon coverage zone. The TDRS/relay ephemeris and network system health/integrity/status messages cycle through information for all of the active beacon transmission nodes, not just the information relevant to the relay spacecraft or ground element broadcasting the TASS signal. This allows users autonomy in acquiring pertinent signals from any transmitting relay in the fleet and timely onboard acquisition and navigation system updates of the relay orbital state.

The message also includes integrity alerts about the TASS signal itself, alerting the user to potential operational impacts, a measure of delay from the TASS signal production through the ground terminal to the antenna, and a range code epoch. The message is designed to be modular to allow for future changes in message types and broadcast intervals.

The real-time data used to construct the operational broadcast beacon message originates from several different sources. GPS differential corrections and GPS integrity data will be provided by the Jet Propulsion Laboratory. TDRS/relay ephemeris and maneuver notices will originate from the Goddard Space Flight Center (GSFC) Flight Dynamics Facility. EOP, ionosphere map data, and Space Environment data will come from the Space Weather Laboratory's Community Coordinated Modeling Center at GSFC. Network system (e.g. TDRSS) health/integrity and status will originate from the network ground terminal, currently White Sands Complex. Low-rate user

commands will originate at the user Mission Operations Center (MOC) and flow either directly to the TASS Data Integration box or via an indirect route through the network ground terminal for integration into the broadcast beacon data stream.

Signal Structure

The TASS signal must be compliant with the authorized broadcasts from the SN, and not interfere with existing SN operations. As such, the signal structure was designed to work within the current SN on an S-band MAF carrier. Updates to the parameters that define the TASS signal elements can be determined to match alternate frequency bands if needed. In order to facilitate one-way forward ranging, the beacon's data message and coherent data symbol, PN code epoch, and carrier establish a rational time base traceable to a specified time standard. The week, second of week, and clock correction parameters will allow the PN epoch transmission time to be corrected to centimeter level precision.

The TASS beacon consists of in-phase and quadrature carrier components. Each carrier component is bi-phase shift key modulated by a separate bit train. The in-phase bit train is the modulo-2 sum of the short 1023 chip PN code, $PN_s(t)$, and the 1024 bps data message, while the quadrature bit train is modulated by the long PN code, $PN_L(t)$, only. The $PN_S(t)$ sequence is modulated onto the carrier at a rate of 2.095104×10^6 (1023x2048) chips per second. The chipping rate enforces synchronicity of $PN_S(t)$ code epochs with each symbol edge. The 2048 $PN_S(t)$ epochs occur in 1 second, and are aligned with the beginning and end of each second (Figure 3). The $PN_L(t)$ code is a 16368 chip sequence modulated at the same 2.095104 Mcps rate as the $PN_S(t)$ code (Figure 4). The 128 $PN_L(t)$ epochs are aligned with the beginning and end of each second.

The TASS PN codes will be derived from the family of codes described in the Space Network Interoperable PN (SNIP) Code Libraries. The SNIP library contains codes for use by NASA, ESA, and JAXA, as well as unallocated codes. $PN_s(t)$ will be allocated from the family of 1023 chip Gold forward command link codes. The TASS $PN_L(t)$ code modulated onto the dataless quadrature channel will be derived from the maximal length forward range channel codes. The nominal forward range codes are produced by an 18-stage shift register and are 262143 chips in length. The TASS $PN_L(t)$ codes will be balanced 16368 sequence contained within the larger code. Study is currently underway to finalize $PN_s(t)$ and $PN_L(t)$ code selection.
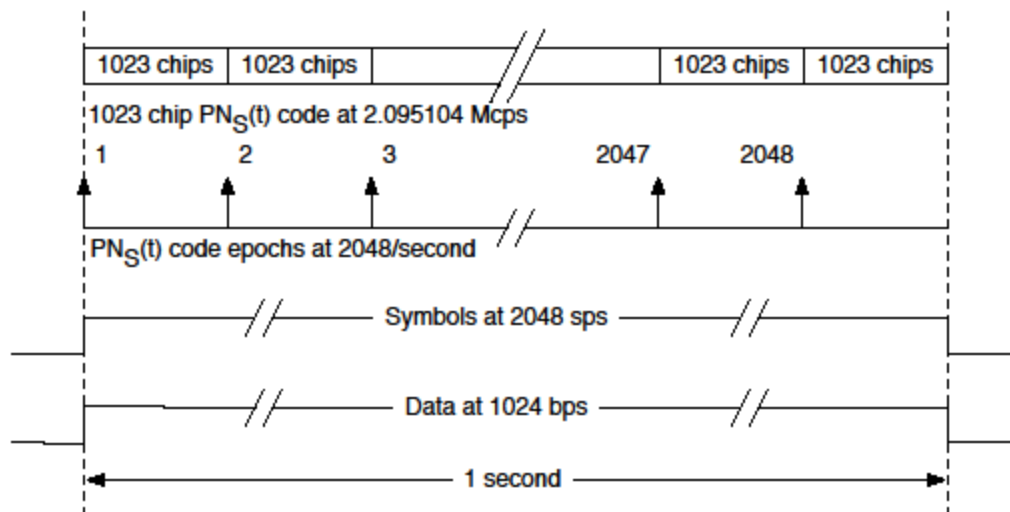

Figure 3. Inphase Component

The in-phase and quadrature signal components modulate a carrier; for the current SN, it is an RF carrier that lies within the frequency allocation for the TDRS MAF service. The nominal center frequency of the MAF service is 2106.406250 MHz and the channel is allocated 6 MHz of spectral bandwidth. Selection of 2105.579520 MHz for the TASS RF carrier, which is an integer multiple of the chipping rate (1023x2048x1005), provides a rational time base from the TASS signal that resides 826730 Hz below the nominal MAF RF carrier frequency.
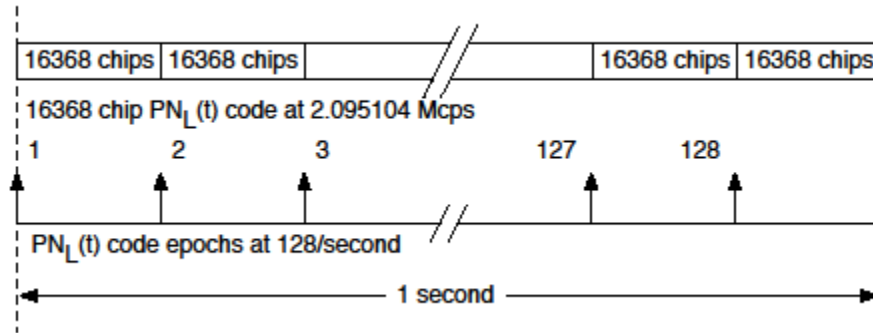

Figure 4. Quadrature Component

The TASS messages are provided in frames with byte-aligned frame elements that contain the message type, transmit relay, message time, the 896-bit message payload, and a cyclic redundancy check code. Currently, the payload messages spread across four types of message frames, where each frame type contains one or more of the TASS data types. It takes 10 seconds to broadcast the four frame types, although this can easily be expanded to accommodate future data offerings. The TASS Data Message Study white paper defines the signal and message structure in greater detail.[6]

Service Offerings and Benefits

The TASS beacon signal and data message offer elements to augment spacecraft onboard autonomous navigation and relieve ground operations of efforts needed to provision and upload data regularly. While some ground operations build in automation, the speed and update frequency of the data provided by TASS remove the burden of developing the ground automation and/or local operating procedures, while simultaneously improving mission performance. At the highest level, the TASS signal allows users to navigate accurately, to protect them from impactful space environment events in a timely manner, and to flow commands on a demand-access basis without relying on or waiting for scheduled uplink services. Table 1 and Table 2 respectively delineate the benefits of TASS in navigation and other arenas.

Table 1. TASS Features That Aid or Enable Navigation

FEATURE	SIGNIFICANCE
Signal Structure	Correlated PN chipping rate, frequency selection, and message framing provide means for measuring pseudorange and Doppler, and determining time. Useful as independent standalone observation inputs to orbit estimation or supplements to GPS observations. TASS reduces need for user to request "tracking-only" network services.
TDRS Ephemerides	High accuracy relay orbit knowledge provided by TASS improves user orbit estimation, provides a means of identifying relay direction for user antenna pointing and improves relay pointing error for high frequency services. TASS signal received by worldwide distributed receivers provide metric tracking observations of the relay that improve ephemeris accuracy and reduce the time to recover after a maneuver.
TDRS Maneuver Window	A user applies the TDRS maneuver window knowledge to edit tracking measurements from a maneuvering TDRS or accommodates the maneuver in their orbit estimation process. Reduces ground intervention for uploading TDRS maneuver windows.
Earth Orientation Parameters	Users require updated EOP to perform coordinate system transformations. The frequency of EOP updates relate directly to the navigation solution accuracy of the user platform.
Total Electron Content	The Total Electron Content (TEC) allows users to correct for disturbances in transit time and frequency change introduced as the reference signal traverses the ionosphere. TEC provides information for Earth observing science instruments.
Kp Geomagnetic Index	The Kp index directly impacts the drag force on a LEO user, which is one of the largest sources of inaccuracy in orbit knowledge.[7, 8] TASS includes a timely update of the 3-hour Kp index to aid definitive and predictive orbit estimation.
GPS Differential Corrections	GPS differential corrections enable precise, real-time navigation for a variety of applications including Earth science, formation flying, and atmospheric sensing.
GPS and TDRS Integrity	Integrity information on the networks that source tracking data, alerts users to potentially degraded measurements that may affect navigation performance.

Table 2. Additional Benefits of TASS Beacon

FEATURE	SIGNIFICANCE
Forward Commanding	Missions benefit from the ability to send commands either impromptu, at specific geospatial locations, or at specific times. The forwarding commanding allows users to respond to near-real time alerts or dynamic events, coordinate and correlate science observations, provision limited or lights out operations, or inform the user platform of the need to hail for communication services in the SMN. Combined with Demand Access return services, users achieve communication without the burden of scheduling services.
Time Transfer	The signal's rational time base referenced to UTC offers a method independent of GPS to disseminate time and maintain synchronization across the network and user community necessary for the decentralized SMN. Precise synchronization will facilitate the transition from two-way to one-way radiometric techniques.
Direct Science Application	The global and continuous TASS presence provides a signal of opportunity available for Earth remote sensing. The smaller wavelength of the S-band signal, aided by the low phase noise implementation[8,9] enhances the science return from radio occultation and reflectometry, augmenting climatology analysis.
Space Weather	TASS provides a means to disseminate the broadly used Space Weather alerts to the orbiting community which can then take action to protect humans or sensitive instruments. Alerts include event type, directionality, force, and time of impact for appropriate segregation by the user community.

NAVIGATION ANALYSIS

TASS fulfils a key need in the SMN by giving users the ability to perform onboard, autonomous navigation. TASS-based navigation performance was examined for two categories of users: those already supported by the current network, and those only supported by a future, augmented TASS service. A LEO user in a polar orbit was used as an example of the former case. This represents a likely first step in the development toward the SMN; the current network supports this orbit regime, but many current LEO users do not navigate autonomously and the demand for network services from SmallSat users is expected to continue to grow. A user in a lunar resonance orbit, such as that planned for the Transiting Exoplanet Survey Satellite (TESS), was used as an example of the latter case. Such a user operates at an altitude not supported by the current TDRSS network but would benefit from a beacon service in a future network architecture. This analysis is primarily intended to assess beacon visibility for the two user cases, so the measurement settings and modeling fidelity were relaxed. Two-body equations of motion without drag or solar radiation pressure were used. Measurement noise was given a covariance of 1 m^2 for pseudorange and 1 cm^2/s^2 for Doppler. The initial state covariance was set to 100 km^2 and 1 cm^2/s^2 for the position and velocity components of the state respectively.

Methodology

For both user categories described above, linear covariance analysis of a sequential estimator was performed in order to quantify the performance of TASS-based navigation. A mission simulation and analysis tool developed by engineers at Goddard Space Flight Center, Orbit Determination Toolbox, was used to conduct the analysis.[10] An extended Kalman filter was used to sequentially estimate the user state,

$$x = \begin{bmatrix} x^T & \dot{x}^T & ct_{b,r} & c\dot{t}_{b,r} \end{bmatrix}^T, \tag{1}$$

where x represents the user spacecraft position, $\dot{x}$ the user velocity, c the speed of light, $t_{b,r}$ the receiver clock bias and $\dot{t}_{b,r}$ the receiver clock drift. In order to simplify notation, time dependency is suppressed throughout this paper when there is no risk of ambiguity. The state was estimated from measurements

$$y_i = h_i(x_i, t_i) + v_i, \tag{2}$$

where h_i is a nonlinear function of the user state at measurement time t_i, and v_i is the measurement noise, a zero mean Gaussian white noise process with covariance R_i. The *a priori* state estimate was updated according to the Kalman gain matrix K_i:

$$\hat{x}_i^+ = \hat{x}_i^- + K_i r_i^-, \tag{3}$$

Here the superscript + indicates an *a posteriori* estimate, i.e., an estimate after a measurement update. The measurement innovation is defined as the difference between the true and estimated measurements $r_i^- = y_i - \hat{y}_i$.

The state estimate was propagated between measurement updates according to a model of user dynamics

$$\frac{d}{dt}x(t) = f(x(t), t) + w(t). \tag{4}$$

Here f is a nonlinear function of the user state and $w(t)$ is a Gaussian white noise process with zero mean and covariance $Q(t)$. This dynamics model was integrated over the time interval be-

tween measurement updates in order to provide the next *a priori* state estimate. In addition to propagating and updating the state estimate, a metric of state estimate quality was propagated and updated in the form of the state covariance. This technique is described in detail in Reference 11.

In both user cases, three TDRS were selected as sample disseminators of the TASS beacon (TDRS 8, 11 and 12). The "global beam" of the TDRS-based TASS beacon will be formed by manipulation of the electronically steered array. This antenna was assumed to be oriented toward the earth (i.e., nadir-pointing). Visibility was assessed along the line-of-sight between the user and each TASS beacon disseminator, first by considering earth blockage and then by comparing a calculated link budget to the receiver's acquisition and tracking thresholds.

Received carrier-to-noise spectral density was calculated

$$C/N_0 = P_T + A_d + G_T + G_R - (T_s + k + Nf),$$ (5)

where P_T is the transmitted power, A_d the free space path loss, G_T and G_R the gains of the transmit and receive antennas, respectively, T_S the system noise temperature, k Boltzmann's constant, and Nf the noise figure of the receiver and low noise amplifier (LNA). In both cases the user antenna was modeled as isotropic, the system noise temperature was set to that of a space-pointing antenna (290 K) and the noise figure of the LNA was 2 dB. Beyond these common features, the two user cases were treated differently.

LEO User Case

Earth-observing science missions are an example of LEO users supported by the current network. The circular orbit used for this analysis had an altitude of 702 km and an inclination of approximately 98 degrees. The in-phase channel of the transmitted TASS signal, was modeled to have an effective isotropically radiated power (EIRP) of 36 dBW at boresight, rolling off to 30.5 dBW at a 10.5 deg cone angle. In order to demodulate the 1024 bps message, a minimum E_b/N_0 of 31.8 dB-Hz is required (1.7 dB + $10\log_{10}1024$). The receiver threshold was set at 35 dB-Hz, allowing a 3 dB margin. Figure 5 shows the covariance analysis results of one orbit of the LEO case when pseudorange and Doppler are measured from the three TDRS beacons.

In Figure 5 (a), the Root Sum Square (RSS) error for the position components of the user state is shown to converge. Periods of TDRS visibility are plotted as horizontal lines corresponding to each beacon. Figure 5 (b) shows the position estimate error along the velocity, normal and bi-normal directions, as well as the corresponding 3σ formal error bounds. Despite measurement outages and only occasional instances of more than one visible satellite, the RSS error profile indicates that a beacon from 3 separate geo-longitude nodes would adequately support a user in a LEO polar orbit. Recall that the filter convergence indicates only sufficient beacon visibility for the user – the solution convergence to an RSS position error of less than five meters is not indicative of expected performance.
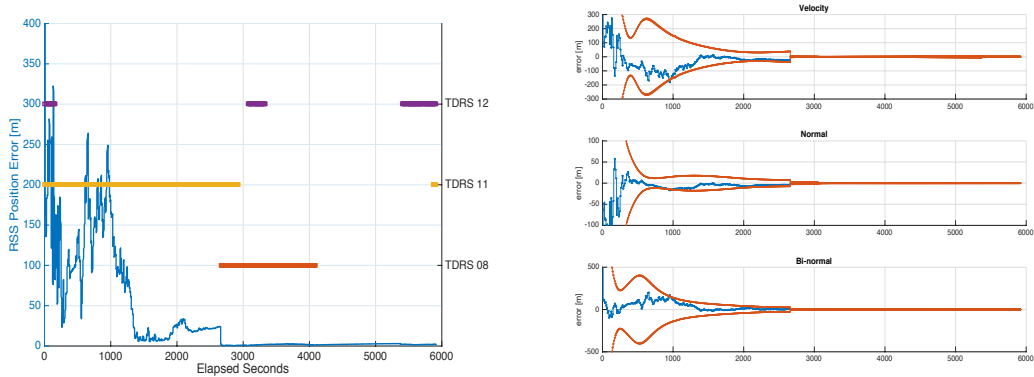
(a) RSS Position Error and Visibility   (b) True and Formal 3σ Position Errors

Figure 5. LEO User Navigation Performance for TASS Pseudorange and Doppler Beacon.

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TESS-like User Case

The TESS mission is in a lunar resonance orbit with an initial inclination of 20 degrees, an eccentricity of 0.55 and a semi-major axis of 242,293 km. The TASS beacon, as broadcast by the existing TDRSS network, does not support users at this altitude, and conventional on-board navigation is difficult. This scenario demonstrates the expanded set of users that the SMN, and TASS specifically, could support with augmentations to the existing network. For this study, ground station disseminators were added to supplement the TDRS-based beacons, although other types of network augmentation are possible. The ground station sites are given in Table 3 and were selected from existing Near Earth Network (NEN) sites. The transmit antennas were modeled as zenith-pointing, conical beams, and three different beamwidth half-angles were considered: 30°, 55° and 80°. The transmit EIRP was 72 dBW, consistent with NEN station performance.

Table 3. Ground-Based Beacon Locations

Code	Location	Latitude	Longitude	Height (m)
ASFS	ASF Poker Flat, AK	64 51 31.7109	212 08 30.5687	205.409
MC1S	McMurdo, Antarctica	-77 50 20.8662	166 40 01.4964	153.000
WAPS	Wallops Island, VA	37 55 29.7320	284 31 24.5190	-20.100
WS1S	White Sands, NM	32 32 26.7178	253 23 16.4417	1456.545

(a) 80° ground antenna beamwidth

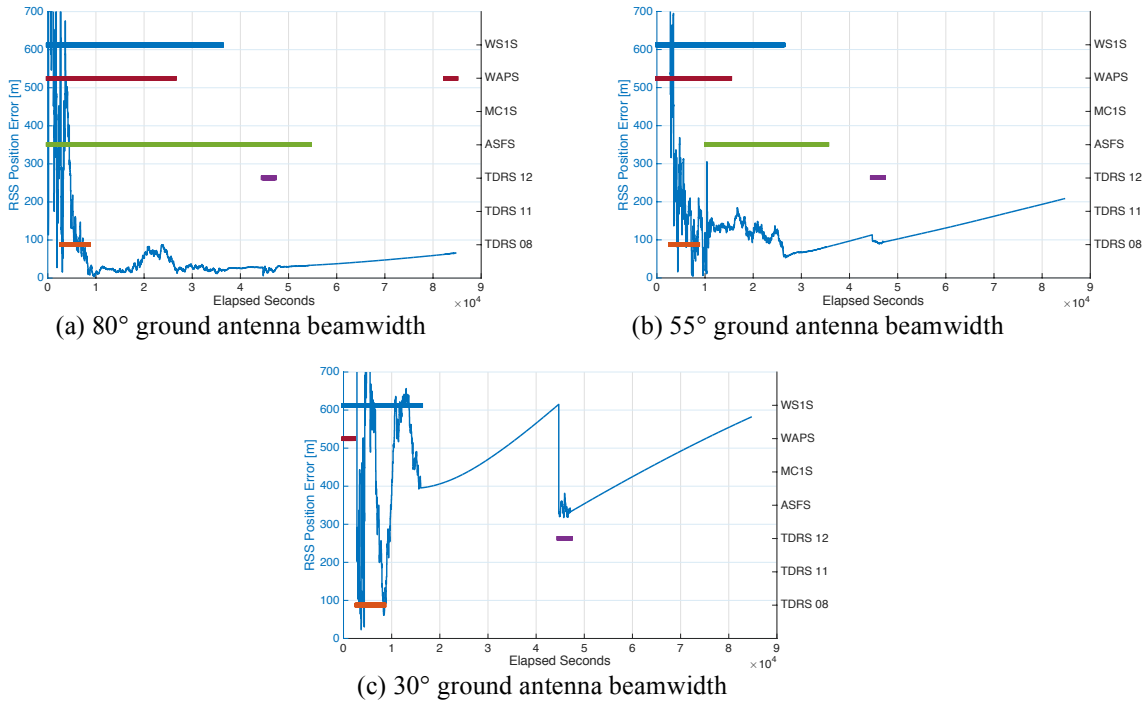(b) 55° ground antenna beamwidth

(c) 30° ground antenna beamwidth

Figure 6. TESS-like User RSS Position Error and Visibility for TASS Pseudorange and Doppler

The beacon signals arriving at the TESS-like user from the TDRS will be weaker, so receiver operation is different than in the LEO user case. The dataless pilot quadrature channel must be tracked in order to take advantage of longer integration times. The quadrature channel is 10 dB weaker than the in-phase channel, or 26 dB EIRP at boresight. Using a one second integration

time and true phase lock loop (rather than the 20 ms integration and Costas loop assumed in the LEO case) the receiver threshold can be set at 5 dB-Hz. In order to navigate using the TASS beacon, however, a user needs knowledge of the relay satellite positions. This information is assumed to come from demodulating the data message from at least one ground station beacon per period of TDRS orbit data applicability. Therefore, the receiver threshold must be set at 35 dB-Hz when tracking ground station beacons in order to demodulate the data message. The system noise temperature is set to that of an Earth-pointing antenna (300 K).

Figure 6 shows the RSS position errors for each of the three ground antenna beamwidths when using pseudorange and Doppler measurements. The simulation was run for 1/14th of a TESS orbit (one day). TDRS visibility shown in Figure 6 is intermittent and brief, but there are numerous instances of simultaneous measurements. TESS requires only 6 km 3σ orbit knowledge accuracy per axis and the RSS profiles indicate that the TASS beacon configuration studied here could adequately support a user in a lunar resonance orbit during the portion of the orbit demonstrated, but covariance analysis should be performed over several revolutions in order to provide a conclusive assessment. It is clear that a ground beacon EIRP of 72 dBW is sufficient, but beamwidths below 55° significantly degrade performance. Further analysis is necessary to perform a trade between the ground-based beacon's EIRP, field of view, and field of regard.

Although the three TDRS beacon configuration is sufficient for LEO users, expansion of the beacon service is essential for high-altitude users. The addition of ground station beacons is demonstrated here, but other modifications are possible, such as placing zenith-facing antennas on the TDRS or adding beacons in other orbits. Future studies will add Monte-Carlo simulations and run both users through multiple revolutions.

CONCLUSIONS

The next several years will provide an important opportunity for NASA to take steps to significantly depart from the current SCaN network, itself derived from systems envisioned, engineered, and deployed over 30 years ago. This transformation is essential for NASA to improve the services and experience provided to SCaN users while also addressing yearly operations and maintenance costs that weigh heavily on the current networks. The continued development and fielding of an operational TASS beacon will provide immediate near-term benefits to the NASA user community, while also providing an environment in which to demonstrate concepts necessary to realize the architecture envisioned by the Space Mobile Network such as beacon concepts, hailing, timing, and navigation capabilities.

TASS has clear benefits to both the user and network in areas of communications, timing, relay operations, user operations, and navigation. These benefits can be realized by the installation of hardware in the existing SN's ground segment and the use of relays already in orbit. The launch of TDRS-M and fielding of the SN Ground Segment Sustainment project will provide additional MAF resources available for the development and deployment of TASS without reducing the overall capability of the SN. Work is already underway to build on the initial TASS demonstration. This work will develop the necessary TASS ground hardware and software, verify the ability of the 2nd and 3rd generation TDRS satellites to provide global coverage via signals transmitted from the MAF antenna, and to develop a combined GPS receiver and TASS/TDRSS transponder to receive, process, and exploit the TASS signal. This work will allow for users in the near term to plan for and adopt the TASS service as part of their mission proposal and eventual flight operations.

Development of TASS presents a rare low risk/high reward opportunity and is a crucial step towards delivering a beacon service to enable the Space Mobile Network envisioned for the future.

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