TDRSS Augmentation System for Satellites

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In 2015, NASA Goddard Space Flight Center (GSFC) reinvigorated the development of the TDRSS Augmentation Service for Satellites (TASS). TASS is a global, space-based, communications and navigation service for users of Global Navigation Satellite Systems (GNSS) and the Tracking and Data Relay Satellite System (TDRSS). TASS leverages the existing TDRSS to provide an S-band beacon radio navigation and messaging source to users at orbital altitudes 1400 km and below.

I. Introduction

The Tracking and Data Relay Satellite System (TDRSS) is a contemporary of the Space Shuttle and Global Positioning Service (GPS) programs. Initially designed in the 1970's to support the communication and navigation requirements of the Space Shuttle, TDRSS addressed shortcoming of previous ground based tracking and data networks by providing continuous service coverage for users in low Earth orbit. TDRSS offers a less capable multiple access (MA) service provided by an electronically steered phased array and a more capable single access (SA) service provided by two 5 meter steerable antennas. Early in the TDRSS program engineers realized that the TDRS MA payload could be manipulated to create a wide-angle beam that could deliver a navigation and communications beacon with global coverage. The concept of a beacon service delivered by TDRSS underwent intermittent study and development from the mid 1980's through present day[1].

Over the intervening three decades the TDRSS program has continued to expand and evolve: seven 1st generation satellites were built and launched through 1995 (including the loss of TDRS-B on the Challenger in 1986), three 2nd generation satellites with improved EIRP, G/T, expanded field-of-view, and a new Ka-band single access service were launched in the early 2000's, and three 3rd generation satellites were built between 2012 and 2015, two of which are operational today (TDRS-M is in storage awaiting launch). The Space Network (SN) ground segment expanded in concert with the TDRSS constellation. The Second TDRSS Ground Terminal (STGT) was added near the original White Sands Ground Terminal (WSGT) outside Las Cruces, NM. Eventually the Guam Remote Ground Terminal (GRGT) was built in 1998 to support TDRS located over the Indian Ocean, and another ground terminal in Blossom Point, MD was declared operational in 2015. Currently the Space Network operates four 1st, three 2nd, and two 3rd generation TDRS, seven of which are operational at any given time. The Space Network Ground Sustainment (SGSS) project is executing a complete overhaul of the aging, heterogeneous equipment that composes the Space Network ground segment. The completion of the new SGSS ground system is expected in 2018.

The Earth Regimes Network Evolution Study (ERNESt) proposed the development of a new near-Earth communication network architecture[15]. 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 and transition to the architectural concepts that enable today's terrestrial wireless networks. ERNESt's Space Mobile Network (SMN) is expected to 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 SMN efficiency relies on a significant reduction in centrally-managed, fully scheduled services from the current deterministic network topology in favor of a user-initiated, decentralized, delay-tolerant type of non-deterministic network toplogy. The concept of a continually available global beacon service that provides one-way non-coherent metric tracking observations and related ancillary data, coupled with autonomous navigation onboard the user provides a means for users to navigate initially, and continually, to obtain communication services from the

SMN. A space-relay beacon service is a fundamental component of the communication and navigation capabilities envisioned in the SMN.

With the evolution of the Space Network, a feasible path to fielding an initial operational capability (IOC) of a communication and navigation beacon service provided by TDRSS is now available to NASA. As the capabilities of the Space Network have grown so have the scope and capabilities of the TASS beacon. The TASS beacon concept now includes providing a GPS compatible radiometric source, GPS global differential corrections, space weather information, SN constellation health, SN constellation ephemeris, and most significantly, an allocation for opportunistic user forward commands. The significant growth in scope and capability of TASS over time warrants a new name, the Next Generation Broadcast Service (NGBS).

II. Next Generation Broadcast Service Description

NGBS will deliver both one-way radiometric (Doppler and pseudorange) and forward data transport services to users. Portions of the overall forward data volume will be allocated for fixed message types while the remaining data volume will be available for user forward command data. The NGBS signal format is shown in Figure 1:

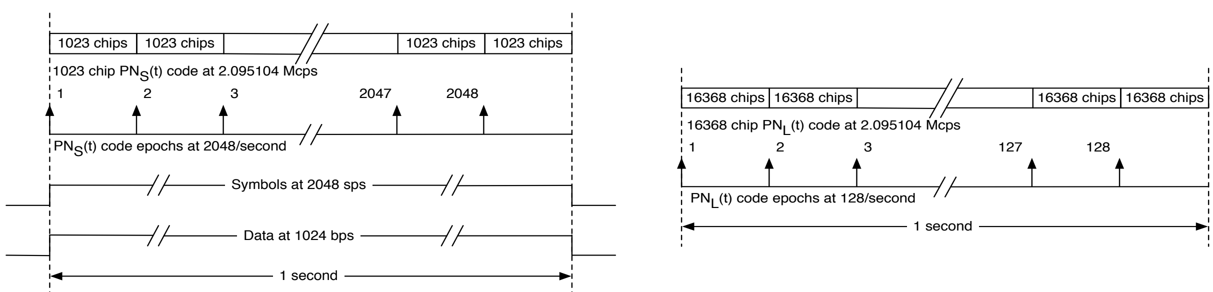

Figure 1: NGBS Command (Left) and Range (Right) Signal Format

Forward Doppler and ranging observations will be made possible by a spread-spectrum code-division multiple access (CDMA) signal format on an S-band carrier. The NGBS signal will reside within the 2106.4±3 MHz spectrum currently allocated for the Space Network's multiple access forward (MAF) service. Given re-use of the MAF spectrum the NGBS signal must be compliant with the authorized broadcasts from the Space Network and not interfere with existing Space Network operations. In order to facilitate one-way forward ranging, the beacon's data message and data symbol, PN code epoch, and carrier establish a coherent 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 NGBS beacon consists of in-phase and quadrature carrier components. Each carrier component is bi-phase shift key (BPSK) 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 1024 bps data message is encoded by the Consultative Committee for Space Data Systems (CCSDS) low-density parity-check (LDPC) rate ½ k=1024 forward error correcting code[2] resulting in a modulated symbol rate of 2048 sps. 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. The $PN_L(t)$ code is a 16368 chip sequence modulated at the same 2.095104 Mcps rate as the $PN_S(t)$ code. The 128 $PN_L(t)$ epochs are aligned with the beginning and end of each second. Selection of 2105.579520 MHz for the NGBS RF carrier, which is an integer multiple of the chipping rate (1023x2048x1005), provides a rational time base from the NGBS signal that resides 826730 Hz below the nominal MAF RF carrier frequency, although still within the 2106.4±3 MHz spectrum allocation.

The NGBS 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 NGBS $PN_L(t)$ 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 NGBS $PN_L(t)$ 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. Final code selection will identify six of the forward command link and range channel codes to allow for up to six TDRS to broadcast the NGBS beacon simultaneously.

The relevant data NGBS data message types and their salient features are described Table 1:

Table 1. NGBS Messages

NGBS Message	Significance
Forward Commanding	Missions benefit from the ability to send commands either impromptu, at specific geo-spatial locations, or at specific times. The forward 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.
TDRS Ephemerides	High accuracy relay orbit knowledge provided by NGBS improves user orbit estimation, provides a means of identifying relay direction for user antenna pointing and improves relay pointing error for high frequency services. NGBS signals received by globally 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 Earth orientation parameters (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 low Earth orbit (LEO) user, which is one of the largest sources of inaccuracy in orbit knowledge[12,13]. NGBS 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.
Space Weather	Disseminating the broadly used Space Weather alerts to the orbiting community who 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.

The NGBS messages provide a diverse set of data that can be applied autonomously enhance user operations. Dissemination of commonly, regularly requested data will reduce the need for scheduled network contacts, allowing more network time to be dedicated for science data return and improving overall network efficiency. NGBS messages improve the reliability and accuracy of onboard navigation significantly reducing or eliminating the need for centralized ground-based orbit determination.

The truly novel capability offered by NGBS is opportunistic, or on-demand, forward commanding. The Space Network currently offers an on-demand return data transport service called Demand Access Service (DAS). DAS is available on 1st and 3rd generation TDRS which employ ground-based beam forming for the multiple access return (MAR) service. DAS users can radiate at any time and their data is delivered promptly via IP to the user mission operations center (MOC). The DAS service bypasses the normal multiple week advanced scheduling process employed by SN operations. NGBS, with an allocation for forward data commands, will provide a similar capability for a forward data transport service. A NGBS/DAS user will be able, for the first time, to arbitrarily "ping" their satellite at any time. On-demand two-way data transport services is a powerful capability yet to be explored by the space operations community.

The NGBS signal also provides benefits beyond user navigation and operations. The signal structure enables time transfer and synchronization which are also services offered by the current Space Network. Novel science applications related to GNSS enabled reflectometry are also enabled by the global presence of a well-characterized signal as seen in Table 2:

Table 2. Other NGBS Benefits

NGBS 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. NGBS reduces the need for users to request "tracking-only" network 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 Applications	The global and continuous beacon 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[14], enhances the science return from radio occultation and reflectometry, augmenting climatology analysis.

III. NGBS Architecture

The NGBS will be delivered through three architectural elements, the ground segment, space segment, and user segment. The three elements acting in concert will deliver services to NGBS users in low Earth orbit.

The NGBS ground system will rely on the capabilities offered by the SGSS architecture[11]. SGSS's significant change to the Space Network ground system (SNGS) is the replacement of analog based signal distribution and transport by an IP based digital intermediate frequency (IF) signal distribution network. The SGSS Front End (FE) subsystem performs a wideband sampling of the entire 650 MHz TDRS space-to-ground (SGL) Ku-band downlink provided by the main mission antenna (MMA). The SGSS FE digitally channelizes the sampled 650 MHz SGL downlink spectrum into the various TDRSS service bands. Digital IF channels are multicast over a 10GbE network and modems demodulate user data by subscribing to the proper digital IF multicast address.

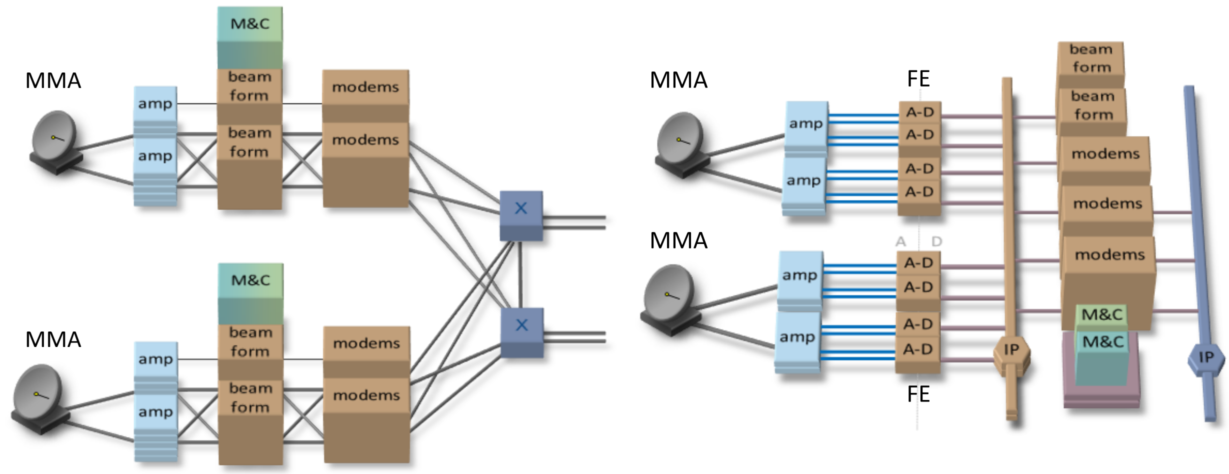

Figure 2. Current SNGS Architecture (Left) and Future SGSS Architecture (Right)

In the forward direction the SGSS FE digitally combines the digitized IF streams corresponding to the S-band SA, MA, and K-band SA forward service channels into the complete SGL Ku-band uplink spectrum. Critically, SGSS will also enable a dual MAF capability built into the 2^{nd} and 3^{rd} generation TDRS satellites not supported by the current ground system. The digital IF architecture greatly reduces delay variability attributable to the ground system by establishing a single digital-to-analog conversion point and precise time reference near the antenna pedestal resulting in improved forward ranging performance.

Deployment of NGBS will require the installation of hardware that generates modulated digital IF steams for ingestion by the SGSS FE, uplink to the TDRS, and broadcast by the MAF array on the TDRS. The SGSS digital bearer plane will allow for these chassis to be installed at only two locations, STGT and GRGT. Two levels of data processing will be required to form the specific data message broadcast by each NGBS beacon.

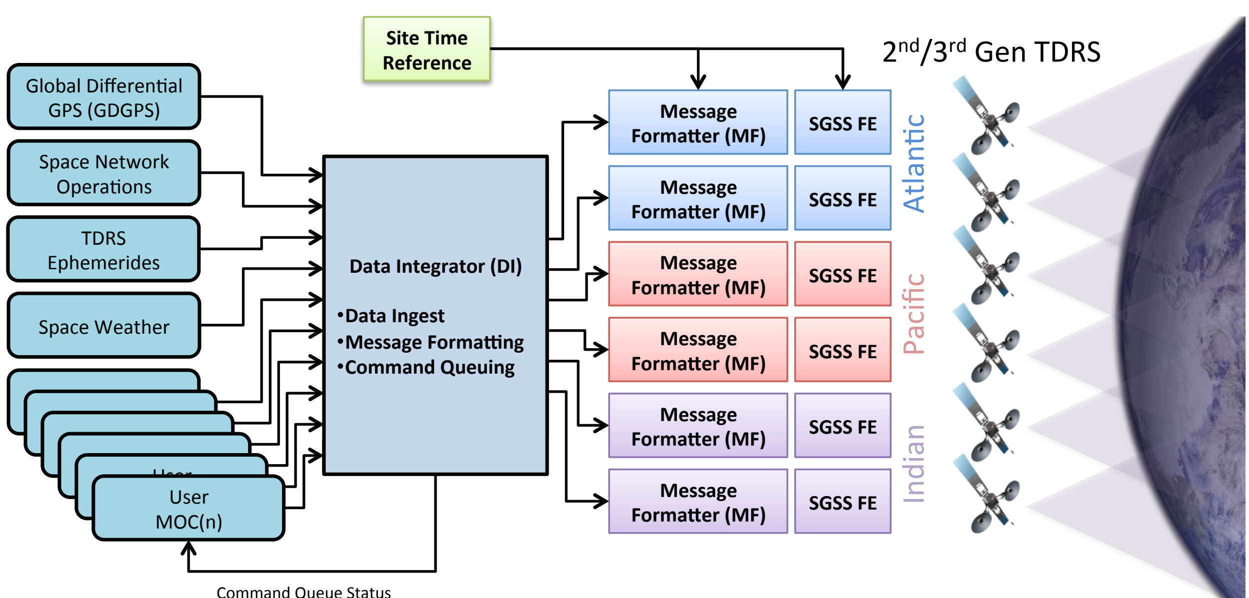

Figure 3. NGBS System Architecture

Initial data processing will be performed by the data integrator (DI) system. The data integrator will maintain connectivity with the data sources necessary to populate NGBS messages. The DI will process incoming xml, ASCII text, or otherwise machine-readable data formats and convert them to the bitwise sequence broadcast by the NGBS beacons. The DI will also process incoming user forward command data and place this in a queue. The DI will provide forward command message queue status for each NGBS beacon. Users will be able to place forward commands in the message queue on a per beacon or system wide basis. Currently a first-in-first-out (FIFO) queue prioritization scheme is baselined but more complex queuing schemes may be employed in the final system.

The message formatting (MF) system will perform all remaining data processing necessary to generate the final bit sequence by attaching necessary time tags and frame counts to each frame based on the site time reference, perform LDPC rate ½ encoding, and attaching a 64 bit frame synchronization marker. The MF will also perform data modulation, spread spectrum modulation, and ultimately generate the digital IF sent to the SGSS FE subsystem for modulation on the MAF uplink carrier.

An initial operational capability of the NGBS architecture will require at least three space based beacons in geosynchronous orbit to provide global coverage. NGBS beacons will be broadcast by 2nd and 3rd generation TDRS.

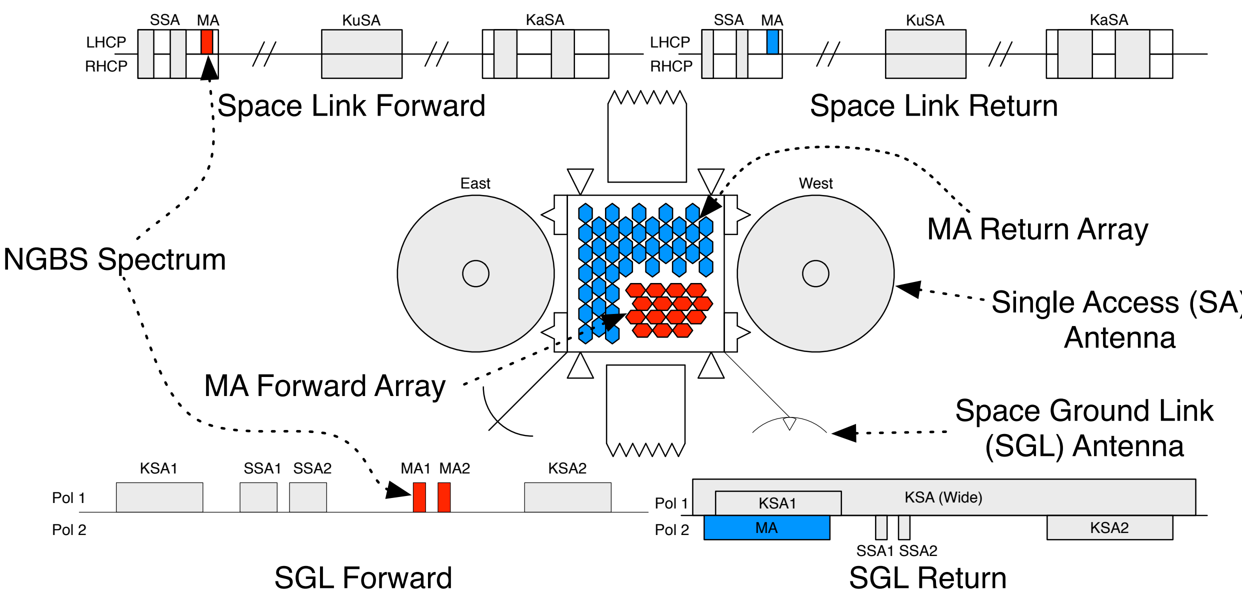

Figure 4. Conceptual 2nd/3rd Gen TDRS Diagram and Frequency Plan

The TDRS SGL antenna receives the Ku band SGL forward uplink generated by the SGSS FE and radiated by the SGSS MMA. Within the TDRS the MAF channel is segmented and down converted to the 2106.4 MHz MAF center frequency by the payload. All mixing frequencies within the TDRS payload are coherently derived from the TDRS command uplink and therefore coherent to the master ground system timing system. The 2nd and 3rd generation TDRS employ a 15-element phased array to provide the MAF service to users. The 15-element array is functionally split into two arrays of 7 and 8 elements each. The MAF signal is fed into a network of application specific integrated circuits (ASIC) that perform the necessary phase and amplitude shifts to form a beam in the direction of the user. Each ASIC supplies the shifted MAF signal to filters and amplifiers before radiation by each individual MA antenna element. Operationally the TDRS is configured to use 12 of 15 MAF antenna elements, NGBS will configure the satellite in a 4-element configuration to broaden the MAF beam and achieve global coverage while maintaining a nadir pointing vector and requisite power levels.

The baseline NGBS user element will be comprised of an integrated GPS receiver, Space Network compatible transponder, NGBS receiver, and an extended Kalman filter.

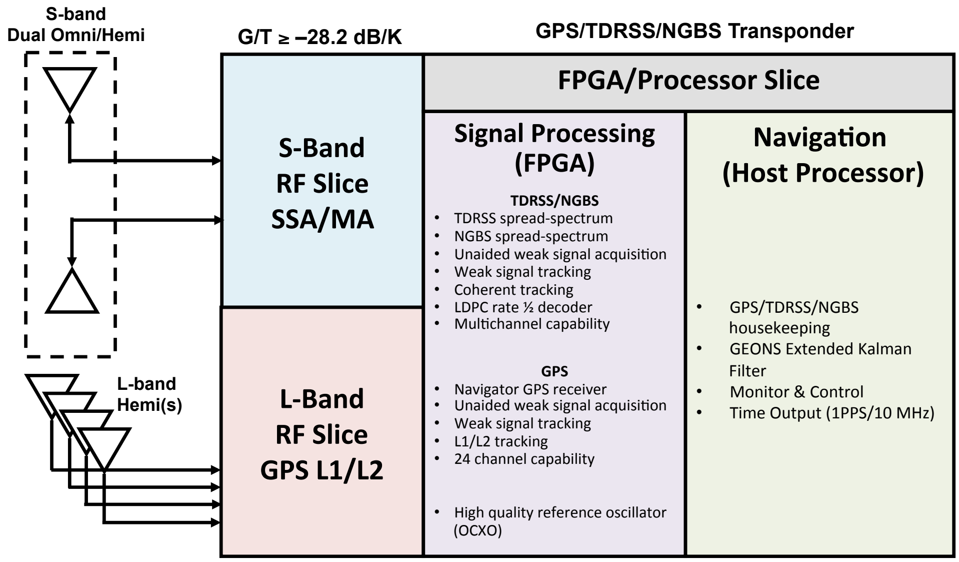

Figure 5. User Element

The GPS receiver is NASA's Navigator GPS receiver. Navigator includes a proven weak signal tracking fast acquisition capability used to enable formation-flying missions such as Magnetospheric Multiscale (MMS) and also operation in high-dynamics environments (EFT-1)[3]. Navigator, or commercialized versions of the receiver, has flown on five missions through 2015, with two more planned in 2016. Navigator also includes the GPS Enhanced On-board Navigation System (GEONS), a flight heritage extended Kalman filter[4]. Navigator is currently GPS L1 capable only although an L2 capable version is under development and is expected to reach technology readiness level (TRL) 6 by the end of 2016.

The addition of an S-band receive and transmit RF front end will allow for both a TDRSS compatible transponder and also a NGBS receiver. Although previous technology development projects such as the Low Power Transceiver (LPT) have combined a GPS receiver and a TDRSS transponder[5] they have not resulted in widespread use operationally or commercially. By adding the TDRSS transponder and NGBS receiver to a successful TRL9 GPS receiver project greatly increases the chances of successful technology infusion and commercialization are greatly increased.

Although the block diagram above represents a fully integrated GPS, TDRSS, and NGBS receiver, a stand-alone NGBS user has access to a basic navigation capability. Disadvantage users such as cubesats could fly a NGBS receiver only and still be provided a basic stand-alone navigation capability[6] without the additional cost, power, and mass penalties that accompany a radio with both L and S band front ends.

IV. Initial Operational Capability

An initial operational capability of the NGBS is feasible with the completion of the SGSS project in late 2018 and the launch and commissioning of TDRS-M (TDRS-13) in 2017. With these architectural components in place an initial three-beacon NGBS service would be globally accessible for users below a 1400 km altitude.

The 15-element array MAF array on 2nd and 3rd generation TDRS is functionally split into two arrays of 7 and 8 elements each. The 12-element operational configuration the MAF array produces a beam pattern with a 5 deg 3 dB beamwidth and >42 dBW of effective isotropic radiated power (EIRP) at a 10.5 deg raster angle. The operational MAF configuration is asymmetric, resulting in a narrower azimuth vs elevation pattern, as seen in Figure 6. By employing a 4 MA element configuration the MAF 3 dB beamwidth will be expanded from 5 to 16 deg and the pattern will be symmetrical. The NGBS beacon will be pointed to spacecraft nadir at all times and will provide at least 36 dBW EIRP at boresight and greater than 30.5 dBW EIRP at a 10.5 deg offset angle, corresponding to a 1400 km orbital altitude. Although four 1st generation TDRS are still operational, the satellites offer a lower achievable MAF EIRP and have been excluded from the NGBS IOC architecture.

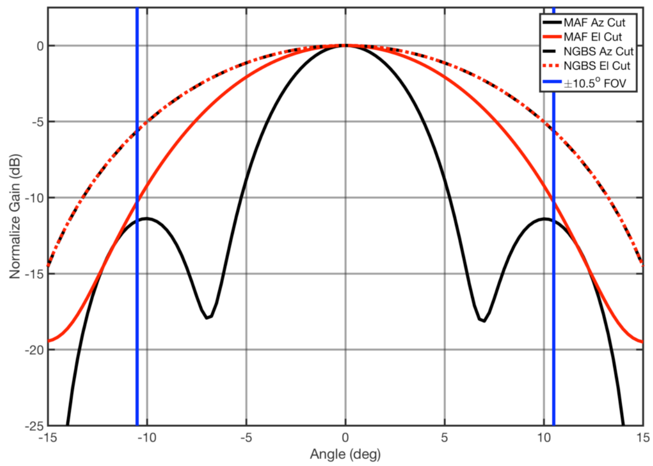

Figure 6. MAF and NGBS Antenna Patterns

With the defined beacon antenna pattern shown in Fig 6 and the signal format described in Sec II a 1024 bps data rate is achievable to a user terminal with a -28.2 dB/K G/T, roughly corresponding to a receiver with a -3 dB gain isotropic antenna. Initial coverage analysis performed in Systems Tool Kit (STK) shows that 100% coverage in LEO is expected for the minimum 3 beacon constellation, as shown in Figure 7:

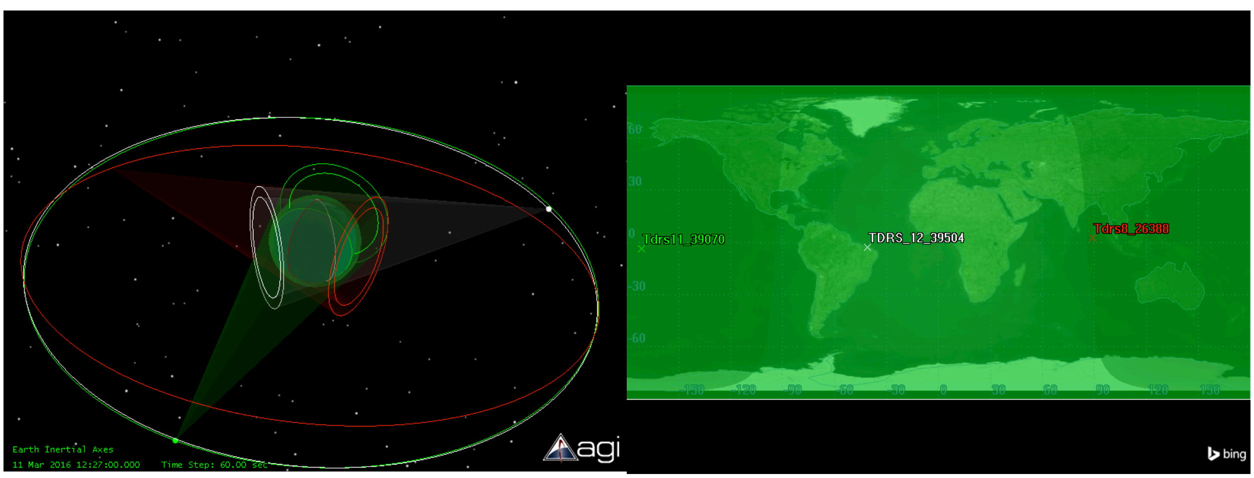

Figure 7: STK Simulation (Left) and Predicted NBGS Coverage (Right)

An initial operational capability of NGBS will offer a service with significant value while also giving NASA critical experience in designing and operating a service that provides a continuous signal presence in space. Significant work remains to develop an NGBS system concept of operations, derive system requirements, and design the ground and user elements. By adapting the MAF payload on the current 2nd and 3rd generation TDRS to fulfill the NGBS space element the overall cost and risk of developing an NGBS IOC is low. Further study is required to formally document potential impacts to overall Space Network MAF service availability and reliability and to make a final decision on the use of operational TDRS for an NGBS IOC. Implementing and operating the service will provide invaluable experience to NASA and will inform the design of a fully operational capability that follows.

V. Fully Operational Capability

Further refinements to the concepts of operation and requirements are an expected output from the work performed to establish an initial operational capability of the NGBS. As the Space Communication and Navigation (SCaN) architecture evolves so will the user and network needs that form the basis of the NGBS.

The NGBS and an evolution of the current Space Network DAS service are expected to provide the highly reliable, omnipresent physical link necessary to deliver a control plane to the overall Near-earth network environment. NBGS and DAS will allow for the dissemination of state information for both network providers and users to allow for autonomous service request, provisioning, and fulfillment. To allow the SMN architectural concept to exist beyond users in LEO the NGBS service volume will need to be expanded. Three strategies can be employed to achieve a greater NGBS service volume.

The first is the design of a specific NGBS payload for the 4^{th} generation of TDRS. Conceptual design and costing studies are already underway to determine the capabilities expected to be deployed on a 4^{th} generation TDRS. Instead of manipulating the current MAF payload to produce a wide-angle beam with global coverage the NBGS beacon would be broadcast via a high powered amplifier coupled with one or more Earth shaped antennas that move gain to the angular region beyond the Earth's limb. Much like the use of GPS sidelobes to enable high altitude GPS this payload design would compensate for the additional free space path loss encountered by users interrogating the NGBS beacon beyond the Earth's limb.

Second is the incorporation of NGBS ground based beacons to illuminate targets at very high altitudes. Users in Lagrange, lunar, or lunar resonant orbits could be provided access to the NGBS beacon on a continual or periodic basis by the use of ground based antenna systems to radiate the beam when and where necessary. Providing such a service would allow extension of the effective NGBS service volume and associated SMN concepts without requiring 100% coverage at a given altitude. In extreme visions of future SCaN architectures a MEO based satellite constellation could be employed as NGBS repeaters to further enhance the NGBS service volume, provide a greater system total daily volume, and to increase the available link margin to users.

Finally the concept of optical multiple access (OMA) technology is under study by NASA as a potential replacement for the current MAR service offered by the SN. This technology could be applied for a forward data transport service as well to enable a NGBS beacon at optical frequencies.

VI. Current Progress

The past 18 months have seen a reinvigoration of the engineering efforts necessary to reach an initial operational capability of NGBS. Work has progressed on all three NGBS architectural elements.

An initial NGBS signal structure and data message format has been created and studied. An exhaustive dynamic link analysis using conservative user G/T and NGBS EIRP values show that the NBGS link is robust at 1024 bps and exhibits greater than 3 dB of link margin for any orbit below 1400 km.

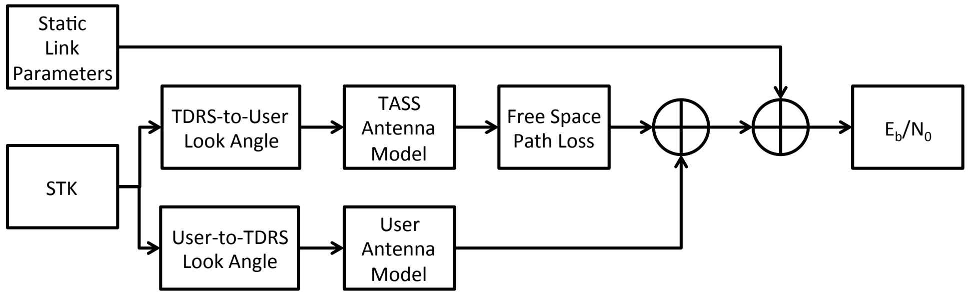

Figure 8. Link and Coverage Analysis Process

The dynamic link analysis employed a combination of modeling in STK and Matlab. STK propagated both user and TDRS vectors and computed user-to-TDRS and TDRS-to-user look angles. The STK computed look angles at each time step were blended with the NGBS antenna model, user antenna model, and static link parameters to compute an instantaneous link budget and ultimately a received E_b/N_0. The resulting time history of E_b/N_0 was processed to derive availability and outage duration statistics:

Table 3. Dynamic Link Analysis Summary

	NGBS Configuration	3 Beacon	5 Beacon	3 Beacon	5 Beacon
Orbit	User Antenna Model	% Availability		Outage Duration (Minutes) 90% Bound	
ISS	GPM	98.46	99.80	0.45	0.45
ISS	-3 dB ISO	100.00	100.00	0.00	0.00
ISS	MMS	99.97	99.97	0.00	0.00
ISS	LADEE	100.00	100.00	0.00	0.00
SSO LEO	GPM	92.16	97.94	0.67	0.45
SSO LEO	-3 dB ISO	100.00	100.00	0.00	0.00
SSO LEO	MMS	100.00	100.00	0.00	0.00
SSO LEO	LADEE	100.00	100.00	0.00	0.00

The dynamic link analysis employed different combinations of user orbit, user antenna model, and NGBS constellation. The two representative user orbits explored in the analysis were the International Space Station (ISS) and also a LEO sun synchronous orbit (SSO LEO). A -3 dB isotropic antenna that provided a reference to the static link budget, and three antenna patterns were simulated from recent NASA missions; Global Precipitation Measurement (GPM), MMS, and also Lunar Atmosphere and Dust Environment Explorer (LADEE). Two different constellations were simulated, the nominal 3 satellite constellation with one NGBS beacon located in each of the Indian, Pacific, and Atlantic orbit slots, and a 5 satellite configuration with two satellites each in the Pacific and Atlantic regions with a single beacon in the Indian region. The link analysis showed little to no outages over the user orbit. The GPM antenna model only showed outages because of the passively coupled omni antenna design employed by the mission, which results in deep interferences fringes in the composite antenna pattern. The dynamic link analysis confirmed earlier lower fidelity STK coverage studies.

With this robust link the option to increase the NBGS data rate to 2048 bps is a possibility. At the time of the signal design the CCSDS LDPC rate ½ return data transport codes offered the greatest coding gain improvement over traditional convolutional rate ½ coding. A new CCSDS standard specifying shorter block LDPC codes designed for forward data transport is now in draft[8]. The next iteration of the signal design will incorporate the draft short block length LDPC codes into the solution space. The explicit goal is increasing the data rate to 2048 bps. The additional data volume will be allocated for forward user commands, not to the messages already defined in the NGBS message structure.

The combined GPS/TDRSS/NGBS terminal is under development. The next evolution of the Navigator GPS receiver has already been implemented in the SpaceCube 2.0 hardware platform[9]. A L1/L2 GPS front-end slice has been incorporated with a Xilinx Virtex-5 FPGA slice to deliver a complete L1/L2 receiver. The dual frequency GPS receiver is now undergoing environmental qualification at Goddard Space Flight Center. A TDRSS compatible (2025-2118 MHz Rx, 2200 – 2300 Tx) front-end slice schematic is complete and awaits layout and card fabrication. After fabrication and integration of the S-band RF front end with the SpaceCube 2.0 platform the entire unit will be requalified to achieve a TRL6 for the combined NGBS user terminal.

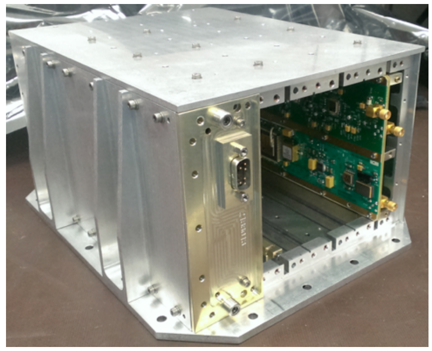

Figure 9. Navigator GPS Implemented in the SpaceCube 2.0 Engineering Unit

The signal processing for the TDRSS transponder is derived from the Glenn-Goddard transceiver (GGT) waveform delivered to the SCaN Testbed project and flown on the Jet Propulsion Laboratory (JPL) Radio hardware platform[10]. The waveform revision under development addresses some of the low C/N_0 sensitivity issues incumbent to the initial design while adding the requisite LDPC rate ½ decoding capability to receive and process the NGBS signal. The base functionality of the waveform will allow for an initial demonstration of the NGBS in space. Later revisions will incorporate a circular correlation based weak signal, fast acquisition capability to give the NGBS receiver similar acquisition and tracking performance as the Navigator L1/L2 GPS receiver.

Initial parametric studies have shown that acquisition of the command channel or direct acquisition of the range channel can be accomplished using less than 1 second of total coherent and noncoherent integration time at C/N_0 values of 30 dB-Hz. To demodulate the desired 2048 bps data rate at a 10^{-5} bit error rate (BER) and assuming 1.5 dB of implementation loss the received C/N_0 input must greater than 37 dB-Hz. Studies will inform the final circular correlation acquisition approach to search over the code space of the command or range channel and a Doppler search space of ±65 kHz commensurate with LEO dynamics and the 2106.4 MHz S-band carrier.

The data integrator and message formatter subsystems exist in prototype in a lab environment. Currently the DI and MF are integrated in a single chassis. As the NGBS concept evolves and the SGSS implementation matures the specific hardware targets will be finalized but the software should remain largely unchanged. The current chassis will support initial live sky demonstrations with a single TDRS and thus must be compatible with the legacy Space Network ground system architecture.

As part of the link budget and signal design activity live-sky tests with 2nd and 3rd generation TDRS are underway to understand margin available in the system. The 2nd and 3rd generation TDRS offer some additional EIRP capability beyond the 42 dBW specified in the Space Network User's Guide (SNUG). A test will be run on a 2nd generation TDRS to quantify any additional MAF EIRP capability above the operational set point. A test of the 3rd generation spacecraft to quantify MAF EIRP headroom is unnecessary given the availability of commissioning test data from 2013 and 2014. A live-sky test of the 4-element MAF configuration will be executed on TDRS-12 in June of 2016. Three simultaneous observers located at STGT, Glenn Research Center (GRC), and the SCaN Testbed aboard the International Space Station (ISS) will verify both the peak EIRP achievable in this configuration as well as the beam pattern predicted by a mathematical model. A design iteration of the signal format and link budget will be performed incorporating the results of the live-sky testing in order to determine the feasibility of establishing a 2048 bps data rate as the NGBS baseline. The results of this signal design iteration may result in changes to the chipping rate, data rate, and carrier frequency but the signal will remain in the 2106.4±3 MHz MAF spectrum allocation.

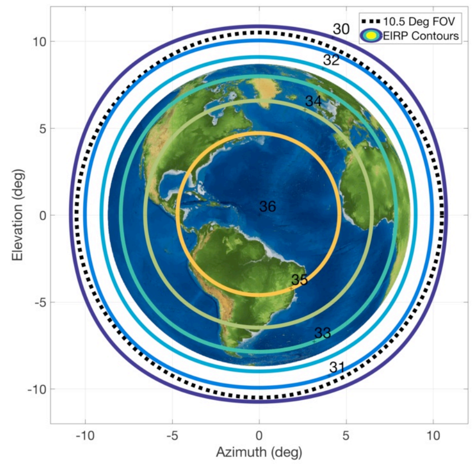

Figure 10. Predicted 4-Element MAF EIRP Contours

VII. Conclusion

The history of the TASS, now NGBS, is a testimonial to the slow pace of development and technology advancement in the risk adverse space industry. Although the capability and capacity to field a beacon service has existed since the advent of the TDRSS program the opportunity to field a comprehensive service that enhances user operations, navigation, and communications will only be available after the completion of SGSS and the launch of TDRS-M. The low risk NGBS will augment use of GNSS in space by increasing GNSS reliability and accuracy while also providing additional radiometric signal diversity for LEO spacecraft. The NGBS data messaging design provides important data that enhances user operations, navigation, and timing. NGBS, paired with Space Network's DAS, offer a truly novel on-demand data transport service that mirrors the user experience offered by terrestrial wireless networks. Work has started on all three NGBS architectural elements to establish a path towards an initial operational capability before 2020. A fully operational capability offered by future 4th generation TDRS, ground based NGBS beacons, or other assets will offer an enhanced suite of services with an expanded service volume.

Appendix
Acronym List

ASIC	Application Specific Integrated Circuit	**LPT**	Low Power Transceiver
BER	Bit Error Rate	**MA**	Multiple Access
BPSK	Bi-Phase Shift Key	**MAF**	Multiple Access Forward
CCSDS	Consultative Committee for Space Data Systems	**MAR**	Multiple Access Return
CDMA	Code Division Multiple Access	**MF**	Message Formatter
DAS	Demand Access Service	**MMA**	Main Mission Antenna
DI	Data Integrator	**MMS**	Magnetospheric Multiscale
EIRP	Effective Isotropic Radiated Power	**MOC**	Mission Operations Center
EOP	Earth Orientation Parameters	**MSFN**	Manned Space Flight Network
ERNESt	Earth Regimes Network Evolution Study	**NGBS**	Next Generation Broadcast Service
FE	Front End	**OMA**	Optical Multiple Access
FIFO	First-In-First-Out	**SA**	Single Access
GDGPS	Global Differential GPS	**SCaN**	Space Communication and Navigation
GEONS	GPS Enhanced Onboard Navigation System	**SGL**	Space-To-Ground
GGT	Glenn-Goddard Transceiver	**SGSS**	Space Network Ground Sustainment
GNSS	Global Navigation Satellite Systems	**SMN**	Space Mobile Network
GPM	Global Precipitation Measurement	**SN**	Space Network
GPS	Global Positioning Service	**SNGS**	Space Network Ground System
GRC	Glenn Research Center	**SNIP**	Space Network Interoperable PN
GRGT	Guam Remote Ground Terminal	**SNUG**	Space Network Users Guide
GSFC	Goddard Space Flight Center	**SSO**	Sun Synchronous Orbit
IF	Intermediate Frequency	**STGT**	Second TDRSS Ground Terminal
IOC	Initial Operational Capability	**STK**	Systems Tool Kit
ISS	International Space Station	**TASS**	TDRSS Augmentation Service for Satellites
JPL	Jet Propulsion Laboratory	**TDRSS**	Tracking and Data Relay Satellite System
LADEE	Lunar Atmosphere and Dust Environment Explorer	**TEC**	Total Electron Content
LDPC	Low Density Parity Check	**TRL**	Technology Readiness Level
LEO	Low Earth Orbit	**WSGT**	White Sands Ground Terminal

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