GENESIS AND DESIGN OF THE TRACKING, TELEMETRY, AND COMMAND SYSTEM FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

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ABSTRACT

The genesis and design of a unique Tracking, Telemetry, and Command (TT&C) System for the Navstar Global Positioning System (GPS) is described from the perspective of the System Architect/Engineer. Working from the diverse and sometimes conflicting mission requirements, derivative performance requirements for the TT&C System were generated. System design tradeoffs were performed in an effort to compromise conflicting requirements which affected the frequency domain, link budgets, antenna sizing, and modulation schemes. The characteristics of the resulting TT&C System included the following:

a. Primary uplinking to the satellite on a spread spectrum secure link at X-Band.

b. Use of a closed-loop uplink which takes advantage of existing onboard functions as references to achieve precise ground-space synchronization.

c. Incorporation of state-of-the-art error control techniques to achieve high net data throughputs with concurrently “zero error” data transfer from ground to space.

d. Hybrid frequency ground antennas to accommodate both the primary and backup command links, with compatible telemetry downlinks. A common S-Band frequency input within the satellite to both the primary wideband Pseudo Random Noise (PRN) correlation receiver and the backup Space Ground Link System (SGLS) receiver.

INTRODUCTION

A unique TT&C System is described from the perspective of the System Architect/ Engineer. The System Architect/Engineer is that species of Systems Engineer who interprets and helps define the mission and system requirements, develops the overall system design concept and interfaces, resolves conflicts, allocates functions between the space and ground segments, and monitors the system throughout its detailed design, development, and operational deployment phases.

The case at hand is the TT&C System for the operational Navstar GPS. Representative technical characteristics of this new design are described in the way that the system design and requirements evolved (their genesis), as opposed merely to reprinting the technical and functional requirements as they were finally depicted in the Request For Proposal (RFP).

THE SYSTEM ENGINEERING PROBLEM

The system engineering problem was to design a TT&C System for the operational Navstar GPS which could satisfy several constraints, including:

a. The CPS Mission timelines and operational scenarios.

b. Integrated control of the space vehicle housekeeping functions with mission payload management.

c. The GPS threat model.

d. TT&C compatibility with GPS Phase I test satellites.

e. Reduced ground antenna sizing to achieve lower unit cost, increased reliability, and transportability/mobility.

f. Adequate system definition to enable separate competitive procurements for the ground and space segments to a common interface, while at the same time soliciting industry ingenuity in detailed design implementation.

GPS Mission Constraints. The Navstar GPS is a space-based radio navigation and positioning system that will provide extremely accurate three dimensional position and velocity information plus system time both to authorized Department of Defense (DoD) users and for general civilian use worldwide. The system utilizes 24 satellites for broadcasting coded navigation messages continuously on two different radio frequencies at L-Band. Mission models and preliminary timelines were developed from the above mission summary, and these led to the development of specific derivative performance requirements for the satellite TT&C System. A few examples are cited below.

Sizing The Uplink Channel.

Uplink Net Data Throughput Rate. An uplink net throughput rate evolved, both for getting emergency commands into a satellite for "safing" or other critical functions and for the ability to upload the payload processor rapidly with up to 256,000 bits within a reasonable time. Since these requirements were replicated over the entire constellation of satellites, and because both mission payload support and TT&C passes could be required for each satellite more than once/day, the net throughput was established at a nominal 1-2 kbps. The system was also required to have the capability to vary the net data throughputs and transmission rates downward if necessary to accommodate noisy or jamming operational environments.

Uplink Undected Bit Error Rate (BER). The GPS user airplane, ship, or jeep is assured of three dimensional position accuracy to a few meters anywhere on the globe plus precise time information. These system accuracies require that each satellite be uploaded often enough to keep the prediction intervals reasonably short, and that the ephemeris and other broadcast data from each satellite be correct. The ground system, therefore, must not only calculate accurate ephemeris and clock predictions for each satellite, but these data must be uploaded "essentially error free" into the payload processor for subsequent broadcast to all users.

Various analytic methods were used to derive the equivalent numerical undetected BER which corresponds to the requirement to upload payload data "essentially error free". Reference 1, for example, assumed continuous uploading at 2 kbps, a maximum upload block size of 256,000 bits, and a 10^{-6} probability of having one or more undetected erroneous uploads in one day. The conclusion, consistent with other analytic approaches, was to establish an undetected BER requirement of 10^{-15}. Establishing this 10-15 requirement was, however, an iterative process which involved investigation of various error control schemes to ensure that it could be met by available and reliable technology.

The generation of a single performance requirement for the TT&C System has been described, but this is only the beginning of the Architectural process. To derive numeric requirements from the Mission Model which are impossible, uneconomical or impractical to implement is clearly not the appropriate System Engineering practice. Therefore, for this as well as all other critical requirements, strawman analyses and designs were developed to ensure that the requirements specified to the space and ground contractors were feasible to implement. In the case of the undetected BER, numerous analyses and reviews of hardware state-of-the-art were undertaken to ensure that reliable error correction and detection technology exists to do the job. For example, various block cyclic error detection codes and several BCH (n, k) error detecting codes were analyzed (References 1 and 2) and found to be capable of satisfying the requirement, assuming a typical average BER of 10^{-5} in a Gaussian noise channel. The analyses took into consideration the code lengths and efficiencies, since another TT&C System requirement to be met is to complete a mission upload within seven (7) minutes in the worst case jamming environment.

Interaction With Industry. The next stage of the design evolution was to permit industry to work detailed designs around the framework of the established design concept and interfaces. The ground TT&C RFP (Reference 3) required bidders to trade-off different error correction and detection techniques to fulfill the various performance requirements which have been discussed. Pursuant to the selection of the Contractors who would execute the final design, a detailed Interface Specification would be mutually coordinated under the auspices of the SAMSO Project Office and the Aerospace Corporation to assure a workable interface.

Compromising Conflicting Requirements. As the statement of the System Engineering problem implied, the design of a TT&C System to satisfy the complex GPS mission imposes somewhat conflicting design requirements. Thus a clear desire to develop reasonably small, inexpensive, reliable, and transportable ground antennas is antithetical to the development of a system which can be safe against various potential RF interference threats. In addition, since a requirement was imposed that the new TT&C System be compatible with the early test satellites, this appears to remove a degree of freedom when performing design tradeoffs. Few variables remain to be traded, namely: the frequency domain, effective radiated power (ERP), and some means of achieving processing gain. The following discussion will describe the requirement to protect the GPS mission, and then consider how the diverse requirements were addressed to reach a compromise system solution.

Need For GPS Mission Protection. Because of the vital nature of GPS in supporting both critical Department of Defense (DoD) Systems and civilian air and sea navigation, the operational GPS satellites must not be susceptible either to inadvertent or even willful or malicious interference. Specifically, unauthorized commanding or mission data uploading must not be possible. Further, it must not be possible to prevent the GPS TT&C System from performing these functions. As a consequence of the need to protect such a critical and costly resource, the GPS TT&C System had to accommodate the ability to secure all uplink command and payload data as well as downlink telemetry data. A powerful error control technique would be implemented to ensure and validate proper information transfer to the satellite. In addition, sufficient ERP and/or processing gain had to be provided to protect against potential jamming of the spacecraft receivers since there has been a marked rise in the sophistication and daring of renegade guerrillas who would be pleased to hamper the defense posture of sovereign nations and their civilian international and national air travel.

Uplink Frequency Selection. In response to the requirement to reduce aperture sizes both on the spacecraft and the ground if possible, various portions of the RF spectrum were investigated. Link budget analyses showed that even with the greater free space loss at higher frequencies, there was equal or better performance at several higher portions of the spectrum than in the lower part, while simultaneously reducing antenna and other hardware size. For example, X-Band performed essentially as well in power budget calculations as S-Band. S-Band (1.8 - 2.2 GHz) had been used in the GPS Phase I test satellites and is an extremely crowded part of the frequency domain, with many overlapping users both in the space-ground and terrestrial applications. Further, there is only a 5 MHz channel available at S-Band for uplinks, and this would not support any of the known techniques for achieving significant processing gain advantage in a jamming environment. At X-Band, however, the ground and space hardware size could be reduced substantially, and there was more spectrum available to support advanced modulation schemes (such as the spread spectrum technique eventually selected). Additionally it was found that both space and ground hardware had been developed for the X-Band region which was compatible with the requirements of the system, thereby minimizing development risk. Accordingly, X-Band was selected as the primary uplink frequency.

Downlink Telemetry Frequency. The selection of the frequency to be used for satellite downlink telemetry was based on different considerations. Satellites potentially may become unstable, so that an earth-fixed directional telemetry antenna may not then be pointing earthward. If this should happen, an omnidirectional telemetry antenna is required to effect recovery commands and readouts from the spacecraft. However, any attempt to reduce ground aperture size is contrary to this requirement and requires either a directional (high gain) satellite antenna, more power, or both. Various tradeoffs were accomplished to ascertain the relationship of the amount of gain of the satellite telemetry antenna to the ground antenna size. Figure 1 is indicative of these studies. Figure 1 shows that the ornnidirectional antenna under the assumed conditions required a 32 foot diameter ground antenna; that a medium gain antenna of 6 dB would close the link into a 16 foot antenna; and that a directional, earth coverage antenna with average gain of nearly 13 dB worked into an 8 foot dish. The telemetry link was subsequently specified based on the operational GPS requirement to transmit 64 kbps telemetry, and unless larger transmitters were used, the link would require the equivalent of a 9-turn helix to meet the gain of the earth coverage antenna. As a consequence, the satellite specification was written to require that two telemetry data rates should be provided, 64 kbps and 500 bps. Further, it was required that if the satellite lost earth lock, two automatic switch functions must take place: a switch from the earth coverage directional S-Band antenna to a backup omni at S-Band, and a switch from the 64 kbps down to 500 bps, a factor of 128 (21 dB) to make up for the loss of the high gain antenna in the link.

X-Band for the downlink telemetry was considered less desirable than S-Band owing to the greater design problems and physical space problems on the satellite of achieving omnidirectional transmission at the higher frequency.

Design of Closed-Loop Uplink. The rationale for selecting X-Band as the command and payload data uplink frequency has been discussed. It has been indicated that various functions which already existed in the payload came to influence the required bandwidth of the X-Band uplink channel and the modulation technique to be employed. The GPS satellite payload incorporates an atomic frequency standard such as rubidium or cesium with extremely good long-term frequency stability, on the order of 10^{-12} to 10^{-13} . Further, the payload uses a PRN code generator to generate the 10.23 mbps code with which user receivers correlate to determine the range, range rate, and code state for purposes of navigation. Based upon these and other considerations, such as the need to achieve processing gain against potential RF interference, it was decided to implement a closed-loop system as the best way to satisfy the accuracy, timing, and mission protective requirements imposed on the GPS TT&C System (see Figure 2).

The ground TT&C computer, under either schedule or operator control, will provide either satellite commands or payload data for transmission on the uplink. The uplink format will be dependent upon this selection. This source command or payload data will be encoded for error correction/detection and may be interleaved as necessary for burst error protection. Overhead and control data is added into the format to enable the satellite properly to interpret the received information. The ground TT&C System incorporates a GPS PRN type receiver to track the satellite PRN navigation signal on L-Band. This received signal is advanced and then adjusted in phase and frequency so that when it is turned around and transmitted back up to the satellite, it will arrive there in synchronism with the satellite onboard PRN reference (within + 150 nanoseconds). Before uplinking the PRN signal, however, it is passed through a security device and modulo-2 added to the encoded command or payload data. Thus, command or payload data at a nominal 1-2 kbps (or less) will be modulo-2 added to a secure PRN wavetrain and transmitted at a 10.23 mbps symbol rate to the satellite on X-Band by use of Phase Shift Key (PSK) modulation.

The satellite TT&C System also incorporates a simplified PRN receiver, since most of the PRN tracking function has been transferred to the ground so as to achieve maximum simplicity and reliability in the satellite.

Onboard the satellite, the TT&C System obtains a reference PRN navigation signal from the payload which is the identical signal being broadcast and tracked by the ground TT&C

L-Band receiver. This signal is passed through a spaceborne security device identical to the one on the ground and input to a modulo-2 adder. The other input to the satellite modulo-2 adder is the output of the satellite PRN correlation receiver which has demodulated the wideband X-Band signal from the ground. The output of the spaceborne modulo-2 adder will be the identical encoded command or payload data that originated in the ground TT&C computer. This results from the self cancellation characteristic of successive modulo-2 additions.

The product of the modulo-2 addition on the satellite is then error checked/corrected, de-interleaved as necessary, and routed either to the command decoder for execution, or to the payload processor for storage.

Backup Command Links. At least two important system considerations led to the addition of a backup S-Band command uplink in the TT&C System. First, the primary X-Band uplink system is synchronized to the satellite onboard reference. Thus, if the operational frequency standard on the satellite should fail completely or if the satellite should tumble, it would not be possible for the TT&C System to track the L-Band PRN downlink and in turn synchronize the uplink to the onboard PRN reference. Satellite components do fail, and there are planned to be at least three atomic frequency standards on each satellite. However, some sort of backup command link would be necessary to command the redundancy switchover. Secondly, it was stated that there was a requirement for the system to be compatible with any residual Phase I test satellites still functioning in orbit at the time of deployment of the operational TT&C System. Those test satellites employ a rather standard Military S-Band SGLS command link. So it was decided that both critical functions could be accommodated by the use of an S-Band, SGLS uplink as a backup to the primary X-Band channel. This S-Band link is a ternary system (1, 0, and S bits) which FSK modulates each of the ternary states onto separate subcarriers at 1 kbps. These subcarriers are subsequently phase modulated onto the SGLS composite baseband signal, and radiated at 1.8 GHz to the satellite. The return downlink telemetry will biphase modulate a subcarrier on an S-Band 2.2 GHz downlink carrier.

A final alternate uplink capability became available at essentially no cost when it was discovered that the S-Band ternary data, when upconverted to X-Band and transmitted in the Standard narrowband SGLS ternary format, could be received by the satellite. Preliminary design analyses of the satellite had shown that it was advantageous to have the PRN wideband receiver and the SGLS ternary receiver operate off a common intermediate frequency. Therefore, all X-Band signals received at the satellite would automatically be downconverted to some intermediate S-Band frequency which was the same frequency expected by both types of receiver. To prevent confusion or one link from jamming the other, priority logic was added in the satellite so that a valid X-Band PRN uplink signal would always be selected.

CONCLUSION

A difficult System Engineering problem; namely, to design a TT&C System capable of supporting the diverse mission and technical requirements of the Navstar GPS has been addressed. The evolution of the specific performance requirements and system trade-offs as well as the means to compromise conflicting system requirements has been represented. The resulting design is a multiple frequency (See Table I) TT&C System with considerable operational flexibility and redundancy. The performance and technical characteristics of the GPS TT&C System are described as they ultimately evolved from the perspective of the System Architect/Engineer so that greater insight could be gained into the genesis of those specifications which are finally imposed upon industry.

ACKNOWLEDGMENTS

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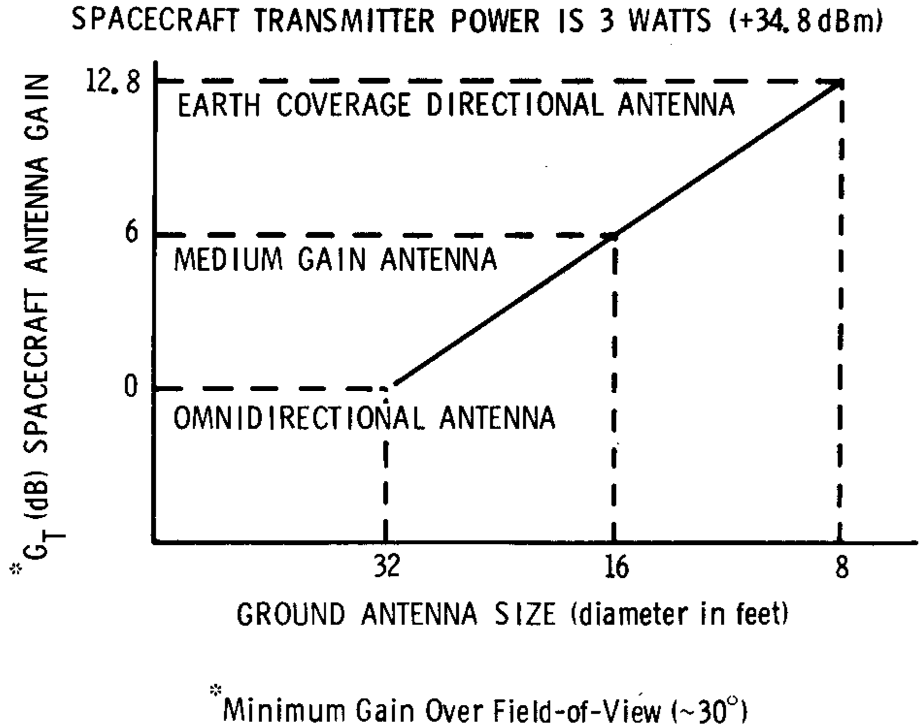

FIGURE 1. DOWNLINK CONSIDERATIONS FOR S-BAND TELEMETRY LINK

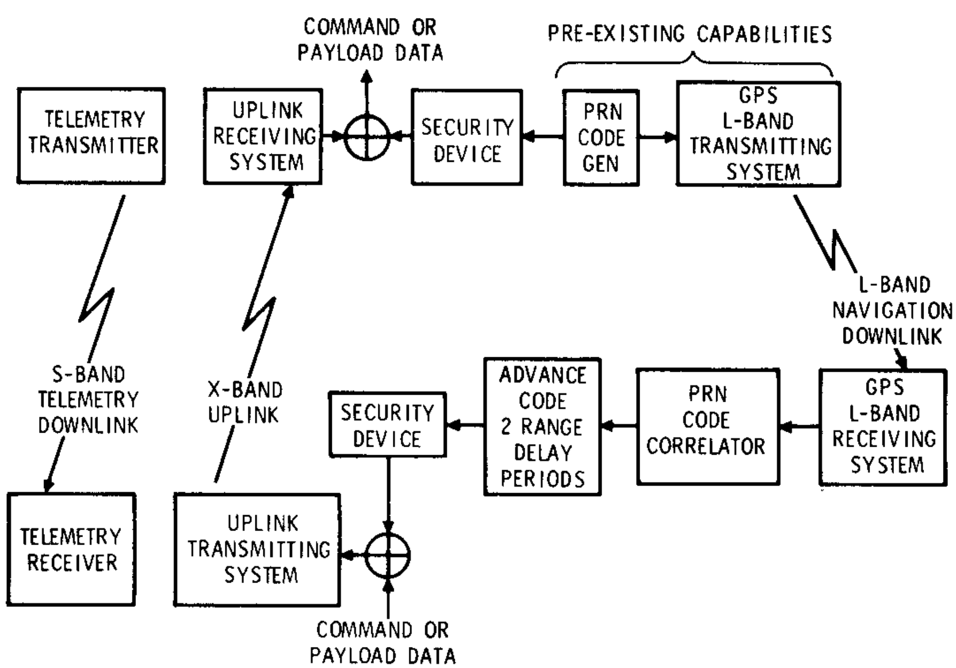

FIGURE 2. GPS CLOSED LOOP TT&C SYSTEM

Table I: TT&C RF Links

Function	Frequency	Channel Bandwidth	Modulation
Primary Uplink	X-Band	20 MHz	Spread Spectrum PSK
Backup Command:			
	S-Band	5 MHz	FSK/PM
	X-Band	5 MHz	FSK/PM (SGLS Ternary)
Telemetry Downlink	S-Band	128 KHz	SGLS PCM (BPSK)