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MODELING AND ANALYSIS OF SELECTED SPACE STATION COMMUNICATIONS AND TRACKING SUBSYSTEMS

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ABSTRACT

The Communications and Tracking System on board Space Station Freedom (SSF) provides space-to-ground, space-to-space, audio, and video communications, as well as tracking data reception and processing services. Each major category of service is provided by a communications subsystem which is controlled and monitored by software. Among these subsystems, the Assembly/Contingency Subsystem (ACS) and the Space-to-Ground Subsystem (SGS) provide communications with the ground via the Tracking and Data Relay Satellite (TDRS) System. The ACS is effectively SSF's command link, while the SGS is primarily intended as the data link for SSF payloads.

The research activities of this project focused on the ACS and SGS antenna management algorithms identified in the Flight System Software Requirements (FSSR) documentation, including:

- Software modeling and evaluation of antenna management (positioning) algorithms.
- Analysis and investigation of selected variables and parameters of these antenna management algorithms, i.e., descriptions and definitions of ranges, scopes, and dimensions.

In a related activity, to assist those responsible for monitoring the development of this flight system software, a brief summary of software metrics concepts, terms, measures, and uses was prepared.

The results of these research activities can be summarized as follows:

1) A software prototype of the ACS antenna control algorithms was developed to capture the basic positioning requirements of the ACS. This model was exercised repeatedly with input files of representative (expected) TDRS data and random TDRS data. The bias and translation algorithms for converting TDRS data to ACS coordinates appear to be correct, although considerable uncertainty is created by inconsistent and/or erroneous data values, ranges, and dimensions in the FSSR; moreover, not all such uncertainties have been resolved.

2) A very brief exploration of the SGS antenna management (positioning) algorithms was completed. SGS-peculiar functions were encoded and combined with basic ACS-related functions to allow a quick look at the SGS. This model was exercised using a limited sample of input files. At first look, the algorithms appear correct, but the SGS system description suffers from inconsistencies and uncertainties similar to those found for the ACS.

3) A considerable amount of the research period was devoted to investigation, discussion, and resolution of characteristics of selected ACS or SGS variables and parameters.

4) A brief written introduction to software metrics was prepared.

INTRODUCTION

The Communications and Tracking System (C&TS) planned for Space Station Freedom (SSF) will provide space-to-ground, space-to-space, audio and video communications, as well as tracking data reception and processing and other services necessary to support the space station mission. [1] [2] Each major category of service, identified in Figure 1, is provided by a dedicated C&TS subsystem.

Among these C&TS subsystems, the Assembly/Contingency Subsystem (ACS) provides space-to-ground communications via S-band Single Access Tracking and Data Relay Satellite System (TDRSS) services; Figure 2 identifies the major ACS hardware components. The ACS interfaces with on-board audio and on-board data systems and carries audio and/or data signals. The ACS is capable of data rates up to 192 kbps in the high data rate mode, the normal mode of operations planned; the actual rate is determined by the mix of audio versus data present in the signal. In the low data rate mode, a rate of 12 kbps is possible. There are two identical sets of ACS hardware elements planned as shown in Figure 2, with software control of which particular set (called a 'string') is in service; included in these redundant hardware sets are steerable high rate S-band horn antennas. The low data rate mode will use an omni-directional antenna and is essentially a backup system to the steerable antennas. The primary function of the ACS is to provide the command link between ground stations and the SSF.

The Space-to-Ground (SGS) subsystem also provides space-to-ground return link communications via Ku-band Single Access TDRSS services; Figure 3 identifies its major hardware components. The SGS interfaces with on-board audio, on-board video, and payload data systems. The primary function of the SGS is to provide the data link between ground stations and the SSF payloads.

This project focused on software modeling and analysis of the ACS and the SGS subsystems, with emphasis being given the ACS due to its critical role as the SSF's command link. There are, however, strong similarities between the ACS and SGS, such that the findings related to the ACS have general applicability to the SGS as well. The basic purpose of the research was to explore, via a software modeling frame of reference, the ACS and SGS subsystems as currently described by the C&TS Flight System Software Requirements (FSSR) documents. [3] [4] This exploration, in turn, had as its goals the identification, description, and, where possible, resolution of inconsistencies or anomalies found in the FSSR descriptions of these two subsystems and their requirements. The research was further limited to evaluation of the ACS High Gain Antenna Management and the SGS Antenna Management subcapabilities which deal basically with antenna positioning functions to maintain communications via the TDRSS. The specific research activities included:

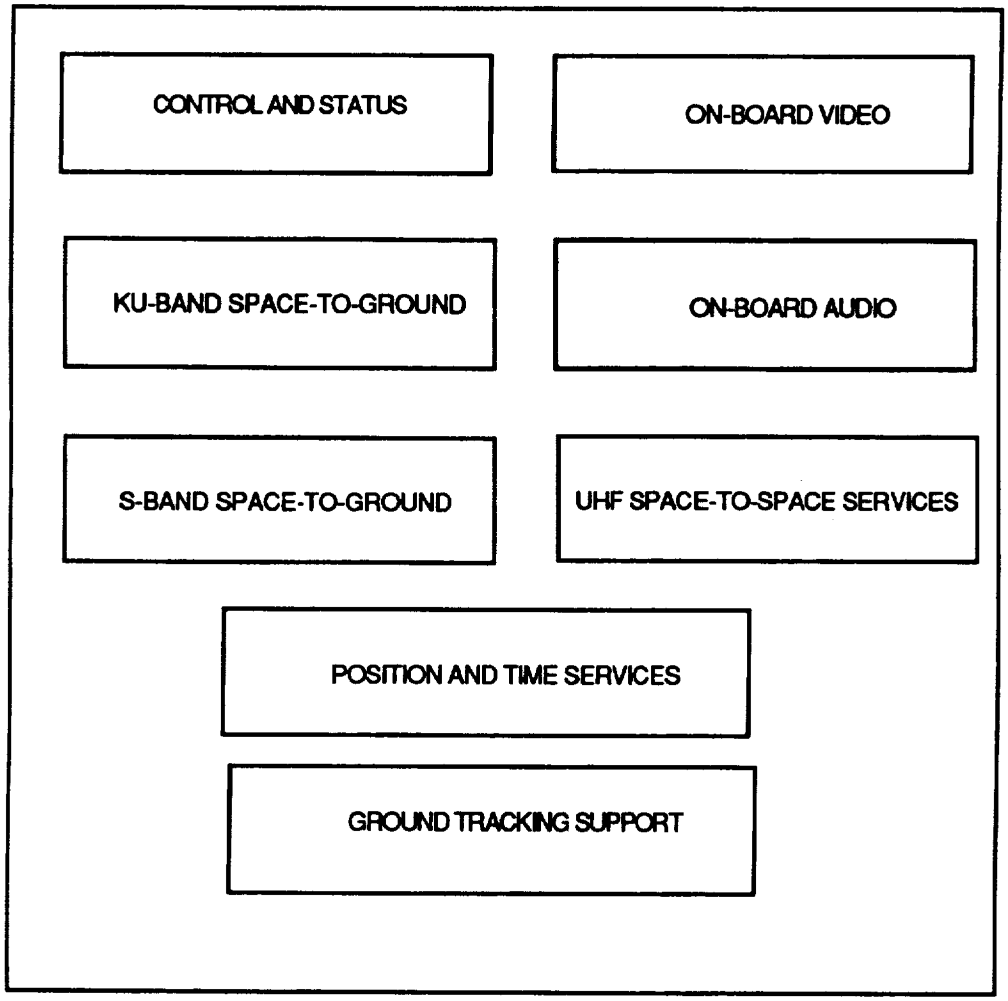

Figure 1.- Communications and Tracking Functions

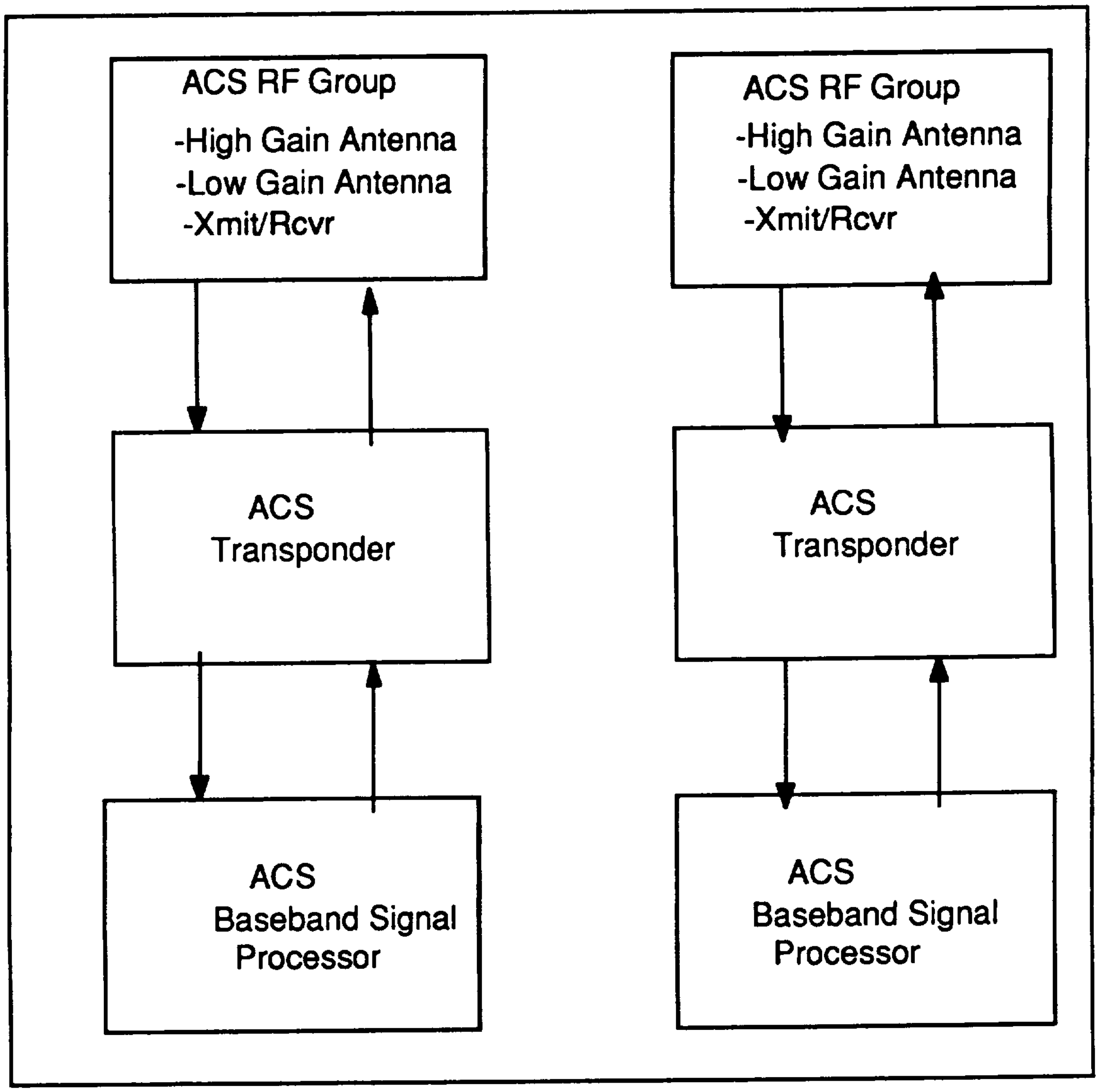

Figure 2.- Assembly/Contingency Subsystem Hardware

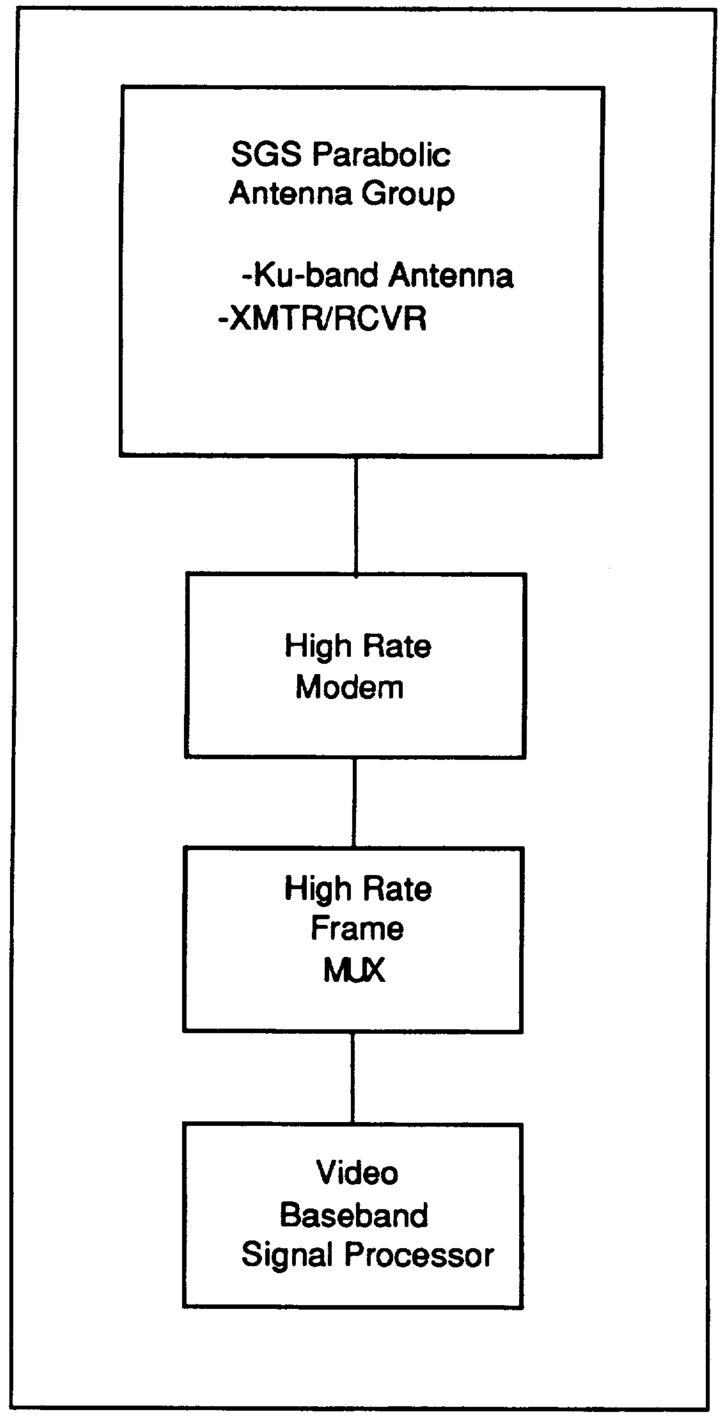

Figure 3.- SGS Hardware Schematic

- Software modeling and evaluation of antenna management (positioning) algorithms.
- Analysis and investigation of selected variables and parameters of these antenna management algorithms, i.e., descriptions and definitions of ranges, scopes, and dimensions.

In a related activity, to assist those responsible for monitoring the development of this flight system software, a brief summary of software metrics concepts, terms, measures, and uses was prepared.

DISCUSSION

ACS Modeling and Analysis

The discussions which follow require the following definitions:

- Rectangular coordinates - coordinates expressed in terms of an x-, y-, and z-component. For example, the TDRSS vectors provided as inputs to the ACS High Gain Antenna Management (ACAM) are given in this coordinate reference. In terms of SSF normal flight mode, defined as "...having the Space Station transverse boom perpendicular to the orbital plane..." [5], the definitions of the x-, y-, and z-axes are as follow:
  - ±X-axis - in the direction of travel (and the velocity vector);
  - ±Y-axis - out the starboard (right) side of the transverse boom;
  - ±Z-axis - towards the center of the earth.
- Spherical coordinates - coordinates expressed in terms of two angles. For the ACS, these two angles are theta and phi, representing the elevation and azimuth position of the TDRS satellite with respect to the SSF, defined as:
  - Elevation - rotation measured with respect to the -Z-axis, with 0 degrees Elevation set at the -Z-axis, and positive elevation measured as motion towards the +X-axis.
  - Azimuth - rotation measured with respect to the +X-axis , with 0 degrees azimuth set at the +X-axis, and positive azimuth measured as motion towards the +Y-axis.
- Unit vector - a vector whose magnitude is equal to unity. For example, the TDRSS pointing vector is a unit vector whose components represent the direction of the TDRSS satellite with respect to the SSF.

The ACAM subcapability includes the following functions related to antenna pointing, an updating activity to be performed once every five seconds to maintain TDRSS contact:

- Accept TDRSS (also referred to by using only the first four initials - TDRS) pointing and rate of change vectors, provided as inputs from the Guidance, Navigation and Control/Propulsion (GN&C/P) System, in rectangular coordinates having x-, y-, and z-components.
- Apply a static bias correction to these TDRSS vectors to compensate for the actual boresight alignment of the S-band horn antennas.

- Convert the resultant vectors from rectangular (x,y,z) coordinates to spherical coordinates (theta, phi) corresponding to the antenna gimbal movements in elevation and azimuth.

- Adjust the resultant antenna gimbal parameters (elevation, elevation rate, azimuth, azimuth rate) so as not to exceed specified software or hardware limits for each.

- Provide the final results for S-band antenna gimbal angles and rates as outputs to be used by the Antenna Controller module to actually drive the gimbal motors to effect motion.

The C&TS FSSR describes algorithms, antenna limits, static bias corrections, and other values required to carry out the ACAM computations. These specifics were used to construct an object-oriented software model using Turbo C++ (Turbo C++ is a registered trademark of Borland International, Inc.). Inputs to the model, representing TDRSS rectangular pointing and rate vectors, were created by one of two methods: (i) using random number generation techniques to derive both unit pointing and constrained rate vectors; or (ii) combining specific unit pointing vector values supplied by a NASA contractor (Lockheed Engineering Services Corporation) with constrained rate vectors derived from modeling work done by a second NASA contractor (Spar Aerospace Limited). [6][7] The Turbo C++ model's intermediate and final results were captured for analysis and verification of inputs and outputs produced by the ACAM process; Table 1 contains an example of model outputs.

The model described above was exercised repeatedly during the research period. A significant number of constants, variables, and parameters specified in the C&TS FSSR were found to have questionable values, ranges, or limits. Consequently, much of the research activity was devoted to investigation of these items, with the following results.

1) The ACS Static Bias Correction - Default Values given in [4], Table 3.2.3-29a, were identified as being 180 degrees out of phase; i.e., the Gamma correction value specified (z-axis rotation) as -PI/4 (-45 degrees) should be given as +3PI/4 (+135 degrees). This error resulted from a choice of coordinate system used in a subcontractor drawing/documentation.

2) The 'Data Type, Units, and Range' characteristics of the 'TDRS n Line-of-Sight' unit vector specified in [3], Table 3.2.3-30, titled 'ACS High Gain Antenna Management Capability Inputs from External systems', were found to be inconsistent. Specifically, the identification of '-1.0E7 to +1.0E7 rad' as the range of values for this unitless pointing vector was both logically and mathematically incorrect; the correct range is given as '-1.0 to +1.0'. And, given this error, the specifications of Accuracy and Precision characteristics are also inconsistently given, both in size and dimensional units.

TABLE 1.- SAMPLE ACS MODEL OUTPUTS

TDRS Raw Data

Position Vector	Rate Vector
X: 0.856803	X: -0.000061
Y: 0.156809	Y: -0.000183
Z: 0.491223	Z: 0.000153

TDRS Biased Data

Position Vector	Rate Vector
X: -0.494970	X: -0.000086
Y: -0.716732	Y: 0.000173
Z: 0.491223	Z: 0.000153

ACS_Gimbal Angle and Rates -- Calculated

Theta (in radians):	2.084290	Elevation (in degrees):	119.420993
Theta-prime (in radians):	0.000175	Elev'n rate (in degrees):	0.010038
Phi (in radians):	-2.175181	Azimuth (in degrees):	-124.628716
Phi-prime (in radians)	-0.000194	Azimuth rate (in degrees):	-0.011126

ACS_Gimbal Angle and Rates -- Clipped

Theta (in radians):	2.084290	Elevation (in degrees):	119.420993
Theta-prime (in radians):	0.000175	Elev'n rate (in degrees):	0.010038
Phi (in radians):	-2.175181	Azimuth (in degrees):	-124.628716
Phi-prime (in radians)	-0.000194	Azimuth rate (in degrees):	-0.011126

3) The 'Data Type, Units, and Range' characteristics of the 'TDRS n Line-of-Sight Rate' vectors specified in Table 3.2.3-30 of [3] were determined to be in error. The components of these vectors represent instantaneous velocities along the three axes and thus require that negative magnitudes be included.

The associated TDRS Line-of-Sight unit vectors contain <u>dimensionless</u> (unitless) values representing the relative <u>position</u>, not range, of the TDRS and the SSF. Thus, use of 'rad/sec' with respect to changes in these unitless vectors, given in rectangular coordinates, is logically inconsistent. Moreover, this inconsistency can be confirmed by examining the TDRSS rate vector mathematical formulations found in [8]. The dimensional units for this input parameter are correctly given as sec^{-1}.

The Range <u>magnitude</u> given as 0..0.1 (rad/sec) is also believed to be incorrect; the origin of this range value could not be identified. However, review of SSF subcontractor system documentation and discussion with several subcontractor representatives suggests a more representative range for the components of this rate vector would be -2.0E-4 to +2.0E-4 sec^{-1}, calculated given SSF and TDRSS nominal orbits and attitudes.

4) There appears to be a general inconsistency, or at least an opportunity for confusion, with respect to the number of TDRSS satellites. In [3], Table 3.2.3-30, for example, one finds reference to 'TDRS One ' through 'TDRS Six'. In Table 3.2.3-25, one finds reference to 'TDRS Occultation 1' through 'TDRS Occultation 4'. And in other parts of the C&TS FSSR, there are references to TDRS-East and TDRS-West. It would be useful to reconcile these differences for the reader of the FSSR.

5) The values specified as 'Azimuth' and 'Elevation' in Table 3.2.3-30, inputs which define the ACS antenna 'park' position, appear to be consistent with the electrical and software limits given earlier in the ACAM section. However, comparing these values to the 'ACRFG TDRS Pointing Vectors Control' values given in Table 3.2.3-68-7C.1, there are (unresolved) inconsistencies for these parameters.

6) Table 3.2.3-68-7.C1 also gives ranges for 'TDRS Azimuth Angular Velocity' and 'TDRS Elevation Angular Velocity' which appear to be in error. In [7], velocity constraints are given as 9 degrees per second for azimuth and elevation, values significantly larger than the -0.10 to +0.10 degree/sec specified in this table. Similarly, then, there is reason to question the associated Precision attributes shown for the angular velocity entries of Table 3.2.3-68-7C.1.

SGS Modeling and Analysis

The discussions which follow require the following definitions:

- Elevation (pitch) - rotation measured with respect to the -Z axis (about the y-axis), with 0 degrees elevation set at the -Z axis, and positive elevation measured as motion towards the +X axis.
- Cross-elevation (roll; or azimuth) - rotation measured with respect to the -Z axis, with 0 degrees azimuth set at the +X axis, and positive azimuth measured as motion towards the +Y axis.

The SGS Antenna Management (SGAM) capability includes the following functions related to antenna pointing, an updating activity to be performed at least once per second.

- Accept TDRSS pointing and rate of change vectors, provided as inputs from the GN&C/P system, in rectangular coordinates.
- Convert the TDRSS vectors from rectangular to spherical coordinates (alpha, beta) corresponding to the SGS antenna parameters of pitch and roll (or elevation and cross-elevation; or elevation and azimuth). This translation between coordinate systems directly incorporates static bias correction to compensate for antenna alignment.
- Adjust the resultant antenna parameters (elevation, elevation rate, azimuth, azimuth rate) so as not to exceed specified software or hardware limits.

- Provide the final results for KU-band antenna angles and rates as outputs to be used for actual antenna positioning.

The C&TS FSSR describes algorithms, antenna limits, and other specifics required to carry out SGAM computations. The Turbo C++ model used for the ACS (ACAM) evaluation, described earlier, was modified and adapted to develop an equivalent SGS (SGAM) model. Input were identical to those used for ACS modeling; an example of model outputs is shown in Table 2.

TABLE 2.- SAMPLE SGS MODEL OUTPUTS

TDRS Raw Data

Position Vector	Rate Vector
X: 0.856803	X: -0.000061
Y: 0.156809	Y: -0.000183
Z: 0.491223	Z: 0.000153

SGS_Gimbal Angle and Rates -- Calculated

Alpha (in radians):	-1.050225	Elevation (in degrees):	-60.173452
Alpha-prime (in radians):	0.000163	Elev'n rate (in degrees):	0.009324
Beta (in radians):	0.157459	Azimuth (in degrees):	9.021721
Beta-prime (in radians)	-0.000036	Azimuth rate (in degrees):	-0.002088

SGS_Gimbal Angle and Rates -- Clipped

Alpha (in radians):	-1.050225	Elevation (in degrees):	-60.173452
Alpha-prime (in radians):	0.000163	Elev'n rate (in degrees):	0.009324
Beta (in radians):	0.157459	Azimuth (in degrees):	9.021721
Beta-prime (in radians)	-0.000036	Azimuth rate (in degrees):	-0.002088

The SGS model was exercised a limited number of times due to the research emphasis placed on the more critical ACS system. Nonetheless, this limited SGS modeling and analysis highlighted inconsistencies similar to those found for the ACS. Specifically, the following areas were identified.

1) Specification and definition of 'TDRS n Line of Sight' and 'TDRS n Line of sight Rate' vectors found in [4], Table 3.2.4-38 titled 'SGS Antenna Management Capability Inputs from External Systems', included inconsistencies similar to those discovered for the ACS's ACAM subcapability.

X-, y-, and z-components of the TDRS Line of Sight vectors are erroneously characterized as meters, with an erroneous range of -1E7 to +1E7 meters. These components are unitless and lie between -1.0 and +1.0.

X-, y-, and z-components of the TDRS Line of Sight Rate vectors are erroneously specified in terms of radians per second. The 'Range' value given, -0.1 .. +0.01 radians per second, obviously has the wrong dimensions; the correct magnitude of this range is unknown.

The 'TDRS Line of Sight Rate Vector' issues discussed in the ACS Modeling and Analysis section apply equally to the SGS system.

2) The specification and description of 'SGS Antenna Management Capability Outputs to External Systems', given in Table 3.2.4-40 of [4], merit further analysis and exploration. It appears there are inconsistencies in this table of SGS parameters similar in number and scope to those found in the corresponding ACS (ACAM) table.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Software modeling and evaluation of ACS and SGS antenna management (positioning) algorithms have revealed numerous discrepancies in the documentation and description of their capabilities and requirements.

A significant number of the characteristics of the ACS and SGS subsystems, i.e., constants, variables, and parameters, appear to be logically or mathematically inconsistent. The utility of the software modeling research activity itself derived from the identification of such uncertainties, and the opportunity to resolve some of them.

There still exists almost universal misunderstanding, or at least disagreement, surrounding the definition and description of the TDRSS Line-of-Sight Rate Vectors, so much so in fact, that these rate vectors, their interpretation, composition, and use deserve continued research and evaluation. These rate vectors play significant roles in the actual gimbal motor drive algorithms [9], so they need to be well understood, a condition that certainly is not true at this moment.

Recommendations

Complete and detailed mathematical analysis of the ACS, then the SGS, antenna management (positioning) algorithms should be completed to establish a solid foundation for the description of these subsystems and their capabilities in the C&TS FSSR.

Software modeling of the ACS and SGS subsystems should continue and should incorporate orbital equations and other mathematical information from which TDRSS Line-of-Sight and TDRSS Line-of-Sight Rate vectors can be numerically produced, thus replicated. Software modeling should continue to be viewed as a vehicle for asking -- and answering -- questions related to the ACS and SGS subsystem components and functional requirements.

Contract should require a common coordinate reference system be used by all participants for all documents and contract submissions.

Contracts should require documentation, derivation, and/or direct references for each parameter (e.g., range; dimensional units; magnitudes) used in the description and characterization of system capabilities such as ACAM and SGAM.

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