CONTINGENCY SUPPORT SIMULATION FOR THE TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)[1]

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Abstract

In March 2006, the Tracking and Data Relay Satellite (TDRS)-3 experienced an unexpected thrusting event, which caused significant changes to its orbit. Recovery from this anomaly was protracted, raising concerns during the Independent Review Team (IRT) investigation of the anomaly regarding the contingency response readiness. The simulations and readiness exercises discussed in this paper were part of the response to the IRT concerns.

This paper explains the various levels of simulation needed to enhance the proficiency of the Flight Dynamics Facility (FDF) and supporting elements in recovery from a TDRS contingency situation. The main emergency to address is when a TDRS has experienced uncommanded, unreported, or misreported thrusting, causing a ground station to lose the ability to acquire the spacecraft, as happened in 2006. The following levels of simulation are proposed:

- Tests that would be performed by the individual support sites to verify that internal procedures and tools are in place and up to date
- Tabletop simulations that would involve all of the key support sites talking through their respective operating procedures to ensure that proper notifications are made and communications links are established
- Comprehensive simulations that would be infrequent, but realistic, involving data exchanges between ground sites and voice and electronic communications among the supporting elements

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1. Introduction

The National Aeronautics and Space Administration (NASA) Tracking and Data Relay Satellite System (TDRSS) enables communication with and tracking of Earth-orbiting spacecraft. The system is composed of nine spacecraft in low-inclination geosynchronous orbits positioned in assigned longitudinal slots around the Earth and the ground systems used to track and control them. A Tracking and Data Relay Satellite (TDRS) is controlled through the White Sands Complex (WSC) located in White Sands, New Mexico, under the direction of the Space Network (SN) Project of Code 452 at NASA's Goddard Space Flight Center (GSFC). The Flight Dynamics Facility (FDF) at GSFC is responsible for TDRS orbit determination (OD) and prediction.

This paper presents a definition of TDRS contingency, a discussion of the roles of the various groups in contingency recovery, and proposed levels and types of simulation and testing to assure contingency response proficiency. At this time, the only simulations that have been approved and conducted were group-only internal tests of the type described in Section 4.1using a TDRS-8 drift maneuver as a testing opportunity.

A major consideration for the controlling agencies is that the TDRS spacecraft health and service to users be maintained. Two recent anomalies, one in 2006 and one in 2007 are discussed to illustrate the types of problems that these agencies can face.

1.1 TDRS-3 Anomaly

On March 22, 2006, TDRS–3 had an Emergency Time Out (ETO) resulting in an attitude divergence leading to a protracted period of loss of service. The anomaly included significant thrusting for over 2 hours until near 0300 UTC and minor thrusting continuing for another 10 hours until approximately 1300 UTC, when the thrusting ended. The spacecraft was then drifting westward at a rate of 3 degrees per day. Table 1 is adapted from the timeline as reported by the FDF to the ETO review team,

Table 1. TDRS-3 2006 Anomaly

Date	Time (UTC)	Event
3/22	00	Loss of attitude control and loss of Earth reference
3/22	03	End of 90 percent of thrusting
3/22	13	End of last 10 percent of thrusting. Tracking data taken during this period were unusable due to thrusting.
3/22	14	TDRS-3 returned to normal mode, S-band tracking only
3/22	15	FDF provided solution based on premaneuver data
3/22	18	First pass of data received
3/23	01	Third and last pass of data received
3/23	0122	FDF reported being unable to generate a usable solution from the data.
3/23	17	The first posttumble United States Strategic Command (US STRATCOM) solution is received
3/23	20	FDF obtained a converged solution from three Canberra passes over a 7–hour arc using the US STRATCOM vector as initial conditions

Date	Time (UTC)	Event
3/23	21	FDF delivered a converged solution
3/24	00	Maneuver to stop drift
3/24	12	Maneuver to return the spacecraft to its box (to start drift back)
3/24	18	Resumption of Bilateration Ranging Transponder System (BRTS) events
3/28	02	Maneuver to slow drift
3/28	14	Maneuver to stop drift and stay in the box
3/28	19	TDRS-3 emergency terminated

The FDF found that the orbit change due to the thrusting was approximately 4380 kilometers in orbital position after 32 hours. The concern from the anomaly review team was that the FDF did not succeed in performing OD until approximately 31 hours after the return of the TDRS to normal mode. The investigation determined that the primary reason was the difficulty in acquiring sufficient usable tracking data to generate an orbit after such a large maneuver. The data received from the Canberra site were the only good data received by the time the first orbit update was attempted at 0100 UTC on March 23. However, the data covered only slightly more than a quarter of the orbit, not enough for a solution with data from a single station and with poorly known a priori elements. It was not until US STRATCOM provided a better initial state vector that the FDF was successful in processing the data and updating the TDRS-3 orbit at approximately 2100 UTC on March 23.

1.2 TDRS-5 Anomaly

At 0420 UTC on July 10, 2007, TDRS-5 experienced what appeared to be a halt of the Attitude Control System (ACS) Control Processor Electronics (CPE), causing a loss of attitude control. This resulted in a loss of K-band command and telemetry with a subsequent ETO and loss of user support capability. The spacecraft then autonomously configured to S-band command and telemetry. Table 2 shows the steps as the spacecraft control was reestablished, and TDRS-5 was brought back to operational support.

Table 2. TDRS–5 2007 Anomaly

Date	Time (UTC)	Event
7/10		
	0420	ACS CPE Halt and loss of Earth reference
	0420	ETO, customer support transferred to TDRS-6
	0801	Sun Acquisition Mode
	1800	Earth Acquisition
	1854	Normal Mode
	2054	K-band Acquisition
	2114	Resumption of TT&C data, no S-band TT&C data received
	2130	Resumption of BRTS events

Date	Time (UTC)	Event
	2238	Complete payload activation
	2326	First updated solution with 1 hour of BRTS data
7/11		
	0115	Second updated solution with 3.5 hours of BRTS data, no significant improvement in OD
	0843	Resume routine customer support

The FDF found that the orbit changes were 3 kilometers along track/day and a drift rate of 0.005 degrees/day. Compared with the earlier TDRS-3 anomaly, the loss of control was for a shorter period, and there was no long-duration thrusting, so the change to the orbit was much less severe. Also, TDRS-5 is located such that there were more tracking options available. The circumstances of this anomaly did not take the spacecraft out of view of the BRTS, so reacquisition in K-band and restoration of BRTS tracking was done more rapidly than when recovering from the TDRS-3 anomaly.

2. Definition of Contingency

A TDRS contingency occurs whenever a TDRS is in a condition such that its attitude and/or orbit cannot be predicted or controlled within the limits needed for operational customer support or for maintaining its location within the geosynchronous orbit (Reference 1). This can occur when a TDRS tumbles, has divergent attitude, or has uncontrolled thrusting. WSC will declare a TDRS emergency when such an event occurs.

This contingency definition is limited to TDRS tracking and control and does not include collision avoidance, although an important part of managing a contingency includes providing predicted ephemerides for use in analyzing the potential for close approaches.

During such contingencies, the TDRS operational modes progress from loss of Earth lock to normal operations as control of the spacecraft is reestablished. These modes are outlined in Table 3.

Table 3. TDRS Operational Modes

Mode	Status
Tumble (attitude divergence) and loss of Earth lock	No tracking, limited commanding, no user support for operational spacecraft. Tracking and orbit support cannot be performed as long as the spacecraft is tumbling and/or under self-thrusting.
Sun Acquisition	Attitude under control, intermittent commanding there may or may not be sufficient tracking for OD.
Earth Acquisition	S-band tracking and full commanding. Orbit prediction accuracy may not be sufficient for operational support.
Normal Operations	K-band tracking, BRTS events, full commanding and operational support. A TDRS could be in normal operations mode but still be under contingency support.

The desire is to minimize the amount of time any given TDRS spends in a mode outside of normal operations because that impacts the SN ability to service its users.

3. Response Guidelines

The response to a TDRS contingency is based on the TDRS status (whether the spacecraft is operational or nonoperational), and whether the spacecraft location is in the East, West, or Zone of Exclusion (ZOE) slot (see Figure 1 and Table 4). The first concern when a spacecraft anomaly occurs is the health of the spacecraft. The various support entities are notified and their recovery and emergency procedures are initiated. Support from additional tracking facilities is requested if the TDRS has drifted out of view of its primary supporting antenna. The various support entities coordinate their responses and act in concert when resolving issues for the SN service users. This becomes more important if an anomaly is not resolved quickly and the service interruption becomes protracted.

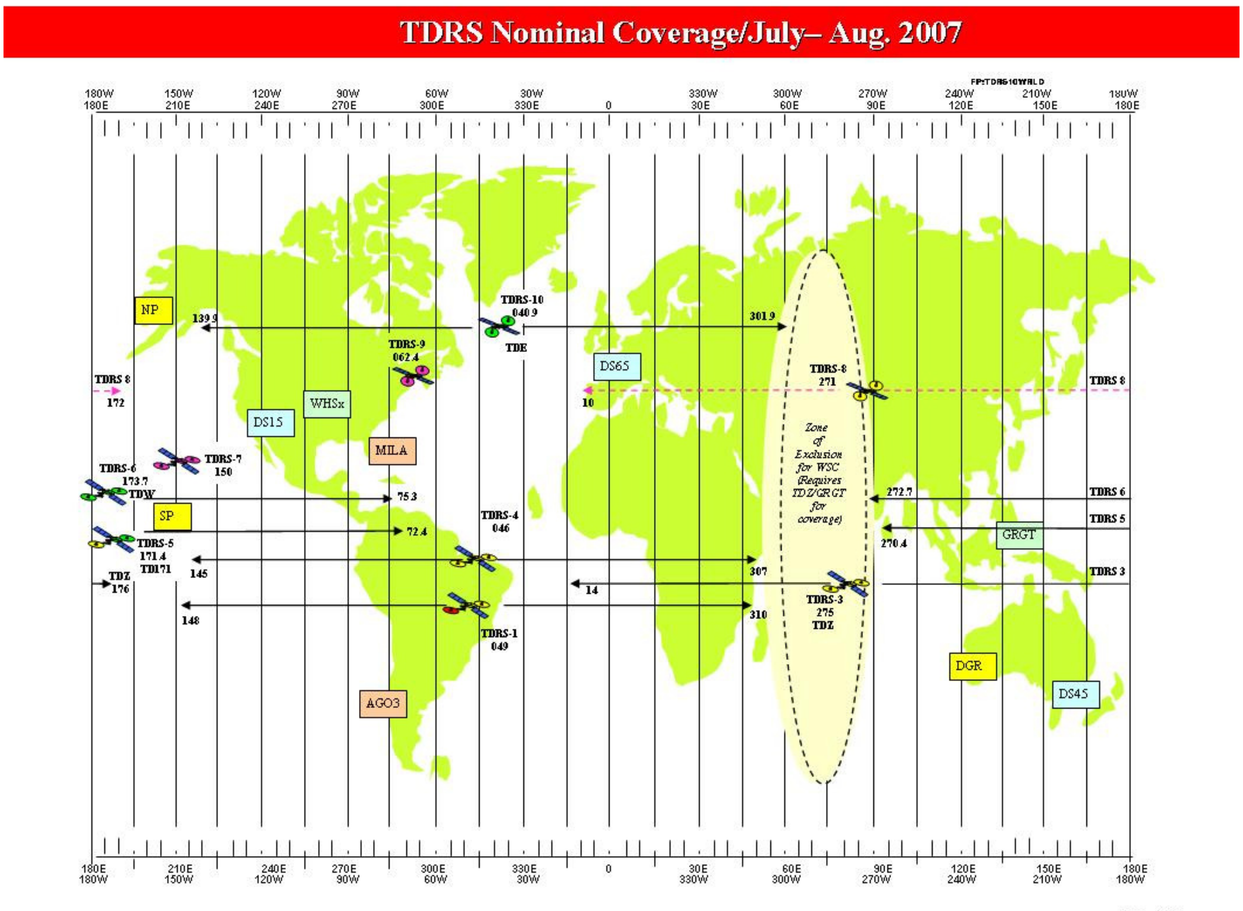

Figure 1. TDRS Visibility and S-band Trackers [2]

[2] Adapted from a chart of typical SN coverage at the equator distributed by Fred Pifer, July 2007.

Successful resolution must include, at a minimum, the abilities to acquire and track the TDRS, to provide valid tracking data to the FDF, and to generate good solutions and provide acquisition data. Determining the source of the anomaly or achieving the return of the TDRS to operational support is not necessary to declare the contingency resolved.

Table 4. Ground Tracking Sites

Ground Network Sites	**Antenna(s)**	**Approximate TDRS Visibility**
Merritt Island, Florida	MILA	West, East
Santiago, Chile	AGO3	East
Deep Space Network Sites		
Goldstone, California	DS15/DS26/DS27	West
Canberra, Australia	DS45/DS46	West, ZOE
Madrid, Spain	DS65/DS66	East, ZOE
Universal Space Network Sites		
Hawaii	South Point (SP)	West
Alaska	North Pole (NP)	West
Perth, Australia	Dongara (DGR)	West, ZOE

3.1 Responses

Each organizational entity involved in TDRS support has its own set of operational procedures that define in detail the steps to be taken during a TDRS emergency. Table 5 presents the responses expected to various TDRS contingencies.

Table 5. TDRS Contingency Mode Responses

Mode	**SN/WSC/FDF**	**Action**
Tumble (attitude divergence) and loss of Earth lock	SN	Coordinate response Contact users
	WSC	Declare spacecraft emergency Assess health of satellite Transition to S-band Take Random Access Memory (RAM) dumps, if possible Recycle onboard processors, if needed Enable gyros, catalyst bed heaters, and thrusters Configure for Sun mode
Tumble with thrusting	FDF	Attempt to propagate trajectory OD is unlikely to generate usable results
Tumble without thrusting	FDF	Propagate trajectory Attempt OD

Mode	SN/WSC/FDF	Action
Sun Mode	WSC	Orient solar arrays to Sun Induce spin about Sun line
	FDF	Attempt OD Generate acquisition data
	SN	Monitor responses and continue coordination
Earth Acquisition	WSC	Attempt Earth acquisition at each opportunity (twice a day in Sun Mode) Maneuver TDRS to retain/resume assigned slot
	FDF	Continue OD efforts Generate acquisition data
	SN	Continue coordination and user contact
Transition to K-band	WSC	Configure payload for user support Declare end of emergency
	FDF	Perform normal post-maneuver support
	SN	Continue coordination
Contingency Resolved	WSC	Track the TDRS Provide valid tracking data to FDF
	FDF	Generate good solutions Provide acquisition data
	SN	Postcontingency evaluation

During a contingency situation, the expectation is that ranging would be performed by any assets available for support. The FDF would attempt OD when data becomes available. There may be some limitations in the data that would reduce their effectiveness for orbit support, such as short data arcs, dropouts from spacecraft spin, or a lack of calibration of the tracking station equipment. If the FDF experiences continued difficulty in generating a solution, the coordination meetings would be the forum to discuss requesting assistance from US STRATCOM or additional measures to improve station tracking.

3.2 Ground Station Availability

TDRS tracking of a BRTS transponder requires a K-band space–to–ground link. Once a TDRS transitions to S-band up during an emergency, it no longer has BRTS lock. When significant out–of–plane thrusting has occurred and BRTS events are not promptly resumed, additional tracking support is requested. Table 4 lists the relevant ground sites and their approximate visibility. The identification of some of the antennas at the sites is given, but this list is not complete. These sites and the current TDRS locations are shown in Figure 1. As this figure shows, the visibility from ground S-band trackers for ZOE TDRSs is quite limited.

3.3 Contingency Support Coordination

During contingency support activities, it is important that correct information be disseminated across the relevant agencies, that the customers be kept informed, and that difficulties identified in resolving the contingency be addressed. It is also important that consistent information be provided to all of the groups and that SN customers have a single source for this information.

Once a contingency is declared, representatives from WSC, the FDF, and the SN prepare for teleconferences (telecons) or meetings to begin 8 hours after the declaration of the contingency. The nominal schedule for the meetings is at the 8–hour, 12–hour, 16–hour, and 24–hour points, with modifications to that schedule as deemed necessary. The meetings continue until the contingency is determined to be resolved.

The representatives include:

- WSC – Operations
- FDF – FDF Operations Director, Flight Dynamics Support Services (FDSS) Operations Manager
- SN – SN System Manager (SSM), SN Conjunction Assessment Point of Contact (POC)
- FDF–Liaison to United States Strategic Command (US STRATCOM)

Analysts and customer representatives can be invited as necessary.

4. Simulations and Tests

The purpose for performing simulations and tests is to assist in preparing support personnel for their role in a contingency, to monitor the ability of various support entities to respond quickly in a contingency, and to determine where there are insufficiencies that need to be addressed. This section addresses proposed simulations and tests as well as what has been done to date.

The intention is that proficiency simulations will occur at least annually using one of the simulations listed in Table 6, that is, one of the proposed levels will be selected for a given time period. Before a simulation, the type, number of participants, initiation time, success criteria, proposed duration, and funding will be specified and approved by the SN Project. A Simulation Coordinator will be appointed to set up the simulation, gain concurrence from the participants, initiate the simulation, and track and record the progress. Following the simulation, a report will be prepared with the lessons learned and action items for distribution to the SN Project and the simulation participants.

Table 6. Proficiency Simulation Options

Simulation	Action	Participant(s)
Tests	Verify that support procedures and tools are ready and personnel are trained. Test that tools used in recovery operations execute properly. Success criteria: proper and timely computations and notifications	Each entity separately

Simulation	Action	Participant(s)
Tabletop	Entities step through operating procedures to check that proper communications are established and notifications sent and received. No exchange of data and solutions Performing a simulation after hours adds realism Success criteria: Notifications received and responded to within a given time	SN, WSC, FDF and possibly selected GN/DSN sites
Comprehensive	Realistic Exchange data and solutions Success criteria: Correct and timely message traffic	SN, WSC, FDF and one or more GN/DSN sites

4.1 Tests

Tests are performed by each supporting element separately and do not require coordination among the groups. It is assumed that each element does internal testing on its own schedule, as each element is expected to maintain proficiency to be prepared to perform support.

The FDF recently tested a potential response to a contingency by performing orbit support using TDRS-8 data from its recent repositioning. The simulation presumed no a priori knowledge of a maneuver with receipt of acceptable tracking data immediately after the maneuver. The OD was performed with tracking data before and after the maneuver. No outside facilities were involved in this simulation other than the routine provision of TDRS data.

The initial TDRS-8 drift stop maneuver, which ended at 0505 UTC on March 27, 2007, was used for this analysis. The maneuver was not modeled in the input vector or in the Goddard Trajectory Determination System (GTDS) Differential Correction (DC) Program input to simulate an unreported thrusting by a TDRS. The tracking data arc between this maneuver and the next maneuver was approximately 11 hours long and was composed solely of TT&C data from the Space Network Expansion (SNE) ground terminal. The data were in 5-minute segments of approximately four segments per hour from 0600 to 1650 UTC on March 27.

Using data immediately before the maneuver produced orbit solutions that converged but only used the data before the maneuver. This solution did not model the maneuver and was not acceptable as a source of information on the postburn TDRS orbit. Various techniques to force the solution to use the postmaneuver data were tried, but none were successful. This included constraining the solution to the input plane, moving the epoch to force a better solution, applying a fixed solar radiation pressure coefficient instead of estimating the value, and opening up the edit criterion.

Two points worthy of emphasis are that this maneuver had a rather large Delta-V, slowing the orbital velocity of the spacecraft by approximately 300 km/day and that the data arc was a short one of approximately 11 hours. The maneuver window was from 0500 to 0600 UTC on March 27, 2007.

The conclusions reached are

- Over a short arc with no maneuver modeling, the FDF would be unable to generate a reliable orbit based on TT&C data from one station after a large maneuver
- Future simulations to determine how large an unmodeled maneuver can be tolerated can be done by processing other past maneuvers of different sizes.

4.2 Tabletop Simulation

This section describes a proposed tabletop simulation exercise, which is currently under discussion. No time frame has been established for performing this simulation.

In a tabletop simulation, each of the participants sits around a table or in a teleconference with their respective procedures. The Simulation Coordinator has a situation scripted with expected responses. The success or failure of the simulation depends on how well the responses during the simulation match the expected responses, and how well the various procedures match what each participant expects from the others. A variation on this would be that the actual time when the exercise is to be performed is not released in advance and part of the simulation is to see how long it takes the various participants to respond. At the end of the simulated responses, there should be a Q&A or what-if period, a time for the participants to ask each other what they would have done if the parameters had been changed. This provides a forum for developing procedures to further account for various scenarios. The updated procedures can then be tested at the next internal test or tabletop simulation.

The activities in Table 7 are in roughly chronological order, but they are expected to overlap one another. The simulation clock need not run in real time. That is, the Simulation Coordinator may elect to declare that a specific time has passed, say 8 hours of data collection, and advance the clock.

Table 7. Simulation of Response to Losing Contact with TDRS–West (TDW)

Simulation Coordinator	Participant	Expected Action	Response/Time Duration
Give specific time and conditions for TDW loss of contact			Simulation Start (S)
	WSC Operations Supervisor	Declare TDRS emergency	S + 15 min
	WSC Operations Supervisor	Contact SSM, SN Project	S + 15 min
Define data available on TDW health to WSC; TDW in Tumble			S + 30 min
	WSC Operations	Report spacecraft health	S + 1 hr

Simulation Coordinator	Participant	Expected Action	Response/Time Duration
	SSM, SN Project	Contact FDF Operations Director, SN Conjunction Assessment POC	S + 1 hr
	FDF Operations Director	Contact FDSS Operations Director and US STRATCOM POC	S + 2 hr
	SSM, SN Project	Distribute schedule and number for telecons/meetings	S + 2 hr
	FDSS Operations Director	Contact FDSS Operations Manager	S + 2 hr
Declare TDW in Sun Mode			S + 2 hr
	FDSS Operations Director or Manager	Contact FDF Orbit Analyst and FDF Operations Analyst	S + 2 hr
Declare TDW in Earth Acquisition Mode (S-band)			
Define tracking data available to FDF (TT&C)			S + 12 hr
	FDF Orbit Analyst	Report on evaluation of available tracking data and suitability for OD, whether or not additional tracking is needed. Request tracking coverage.	S + 14 hr
Define BRTS tracking available to FDF (K-band)			S + 16 hr
	FDF Orbit Analyst	Report OD results	S + 17 hr
	SN, WSC, FDF	Report status via telecon	S + 18 hr
Define objects orbiting near TDW			S + 18 hr
	US STRATCOM	Report conjunction assessment results	S + 19 hr
	All	Q&A/What-if period	S + 20 hr

4.3 Comprehensive Simulations

Comprehensive simulations of TDRSS contingency support require considerable planning and preparation to assure that the exercise is worthwhile. The SN, the FDF, and WSC would decide the objective of a simulation, the schedule and timeline, how the simulation is going to be conducted and monitored, and what measures of success are expected. It would be desirable to complete one or more successful tabletop simulations before attempting a comprehensive simulation to incorporate the lessons learned.

The type of simulation envisioned is one in which a circumstance arises when a station from Table 4 is asked to provide tracking support for a TDRS during an emergency. The steps in the simulation would include:

- Making the request for support
- Providing the station with acquisition data
- Configuring the station to perform the tracking
- Performing the tracking
- Providing the data to the FDF
- Processing the data within the FDF to generate a solution
- Distributing ephemeris and acquisition data based on the new solution

Measures of success of the simulation would be the timeliness of the communications, the validity of the tracking data, and the ability of the FDF to use the data to generate a new solution.

Part of developing the simulation would be to decide how realistic a scenario would be used. For example, the simulation presented above could include tracking a spacecraft and providing the data to the FDF, but it could also be one of recording data from previous tracking to provide to the FDF at the scheduled time. The simulation would need to be developed in a way that would not impact normal operations. Care would need to be taken to ensure that the simulation exercise is not confused with ongoing routine operations.

5. Conclusions

The ability to respond quickly and appropriately to a TDRS anomaly is important for maintaining the TDRS spacecraft health and providing continued service to users, as TDRS anomalies continue to be experienced about once a year. Simulating a TDRS emergency provides an opportunity to prepare for contingencies and to determine any future actions that are needed to improve responses. The goal is to mitigate the risk that a future severe TDRS anomaly will take as long to resolve as did the TDRS-3 anomaly in March 2006.

WSC, the FDF, and the SN routinely perform internal tests, but they have not, as yet, held a coordinated TDRS contingency simulation. The challenge is to develop a simulation program that fits within the time and budget constraints. Performing appropriate simulations and tests would provide assurance that the emergency support procedures at the various support sites are sufficiently detailed and that personnel are well trained in their use.

6. References

1. 452-ICD-SN/FDF, *The Interface Control Document Between the Space Network and the Flight Dynamics Facility,* Appendix E, June 2007