This product is part of the RAND Corporation monograph series. RAND monographs present major research findings that address the challenges facing the public and private sectors. All RAND monographs undergo rigorous peer review to ensure high standards for research quality and objectivity.

Sustaining Air Force Space Systems

A Model for the Global Positioning System

Don Snyder • Patrick Mills • Katherine Comanor • Charles Robert Roll, Jr.

Prepared for the United States Air Force

Approved for public release, distribution unlimited

RAND PROJECT AIR FORCE

The research described in this report was sponsored by the United States Air Force under Contract F49642-01-C-0003 and FA7014-06-C-0001. Further information may be obtained from the Strategic Planning Division, Directorate of Plans, Hq USAF.

Library of Congress Cataloging-in-Publication Data

Sustaining Air Force space systems : a model for the Global Positioning System / Don Snyder ... [et al.].
p. cm.
Includes bibliographical references.
ISBN 978-0-8330-4044-2 (pbk. : alk. paper)
1. Astronautics, Military—United States—Equipment and supplies. 2. Global Positioning System. 3. United States. Air Force—Procurement. 4. United States. Air Force Space Command—Planning. I. Snyder, Don, 1962– II. Rand Corporation.

UG1523.S87 2007
358'.88—dc22

2007001853

Published 2007 by the RAND Corporation
1776 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
1200 South Hayes Street, Arlington, VA 22202-5050
4570 Fifth Avenue, Suite 600, Pittsburgh, PA 15213-2665
RAND URL: http://www.rand.org/
To order RAND documents or to obtain additional information, contact
Distribution Services: Telephone: (310) 451-7002;
Fax: (310) 451-6915; Email: order@rand.org

Summary

Aging systems and systems operating longer than their anticipated life span, sometimes because of program slips in follow-on systems, have intensified the need for understanding how maintenance and sustainment affect the performance of space systems. In this monograph, we develop a pilot framework for analyzing these and related questions in the ground segment of the Global Positioning System and recommend steps for implementing this framework. In doing so, we address the issue of modeling approach and how to define appropriate metrics of performance. We develop the guidelines for metrics and analytic methods as generally as possible so that they will be useful for other space systems.

Much of the spirit of the current metrics used to monitor the maintenance of the ground segments of space systems follows that of metrics used for aircraft. But, space systems have some attributes that differ significantly from those of aircraft systems, and these attributes suggest that the metrics for maintenance and sustainment for space systems be reconsidered. From a modeling perspective, the central difference is that space systems are highly integrated systems in near constant operation, not fleets of aircraft, any one of which can perform the specified mission. This difference leads to three challenges for the analyst.

First, the logical metric used in the aircraft realm—the fraction of the fleet that can perform the stated mission—is not applicable in the space realm. Space command systems function as an integrated whole, and the whole must meet operational mission goals at all times.

What is needed for space systems is either a measure or measures that reflect the overall system performance, even when the system is operating nominally. The metric should also be sensitive to sustainment perturbations. We call a measure of performance that has these qualities a *sentinel metric*. A further constraint on performance-metric selection is that the users of space systems are often diverse, spanning the various military services, other governmental organizations, and, even occasionally, the civilian sector. Each of these users may require different capabilities and levels of performance to satisfy their own mission requirements.

Second, for the ground segments of most space systems, what makes components break—and a related matter, what modifications make components more reliable—are not as well understood as cause-and-effect linkages are in the aircraft domain. Flying hours drive some engine maintenance in jets, but what preventative maintenance efforts lead a software-dominated system to be more reliable? When does maintenance intervention in software introduce bugs that lower system reliability in the short term, and when should such intervention be avoided?

Third, even when causal linkages are understood, since space systems are operated as single entities and not as sets of individual capabilities, there are many fewer identical components and failures from which to collect statistically meaningful data. If the statistical distributions of underlying data, such as the time between failures and the time to restore function, are not well constrained, the fidelity of the predictive estimates of performance diminishes.

For a pilot study, we examine the Global Positioning System (GPS) and how a model might be developed to explore how programming[1] investments and trade-offs in maintenance and sustainment for the ground segment of this system might be analyzed. The GPS is a satellite-based system that provides accurate spatial location and timing data for civilian and military users. It is composed of three segments:

---

1 Unless otherwise indicated, we use the terms *programming* and *programmer* to refer to the activities and individuals involved in the building of the Air Force Program Objective Memorandum (POM), not to computer code.

the user segment, receivers that GPS users employ to locate themselves and determine time; the space segment, the satellite constellation; and the ground control segment, which will be the focus of this study. The ground segment has three subsystems: monitoring stations, the Master Control Station, and ground antennas. One of the main functions of the ground segment is to monitor and maintain the accuracy of the overall system. The monitoring stations check on the status of the satellites, the Master Control Station makes decisions on updates to the satellites, and the ground antennas transmit those updates to the satellites (see pp. 7–12).

The starting point for modeling the effect of sustainment activities on operational performance is the selection of a measure of performance. The qualities of the measure of performance determine the scope of the decisions that can be made using the model, and they dictate the minimum level of granularity of the data-collection and analysis efforts. For the GPS program, regardless of the user, the appropriate sentinel measures of performance are measures of the variance over time of the accuracy of the user's location and time estimates. These broad metrics are appropriate for programming decisions, and they may differ from metrics used to determine operational priorities.

We examine the effect of the reliability of one subsystem of the GPS ground segment, the ground antennas, on the variance over time of the accuracy of a user's location estimate. Specifically, we examine a proxy for this measure: What is the approximate difference in where the satellites are relative to where they appear to be to a user (called the *estimated range deviation* [ERD]), averaged over the satellite constellation. Three types of service disruptions of ground antennas affect this measure: unscheduled maintenance, scheduled maintenance, and interruptions in the communications links connecting the ground antennas to the Master Control Station.

Scheduled maintenance includes all maintenance activities that are done on a regular basis, along with installation of system-component upgrades. *Unscheduled maintenance* includes hardware breaks, electronic component failures, and software crashes. Failures in communications links between the subsystem and the Master Control Station fall under the purview of, and are maintained by, the Defense Information Systems Agency (DISA), which is outside the control of Air Force Space Command. Nevertheless, these outages need to be quantitatively understood and included as part of the model so that the limits of Air Force actions on the system performance are understood.

Each subsystem is composed of a multitude of parts, and each part will have times between breaks that can be described by some probability density function. Once broken, each component requires some time before its function is restored that is also described by some probability density function. This time is the sum of the time to repair the component and any time that it takes to get that component and the maintenance personnel to the site.

The system can be modeled by collecting and analyzing the failure rates and restoration times of each of the components. However, such an analysis alone will not capture the full behavior of the system. Evaluating the performance of a system requires a systemwide view that incorporates not only the performance of the components but how they mutually interact, how they communicate with one another, redundancies, and the overall command and control of the system. For this reason, evaluating how maintenance and sustainment efforts affect space system performance should start with a systemwide view and work down to individual maintenance and sustainment activities (a top-down approach) (see pp. 12–19).

Using a top-down approach does not invalidate the need for an understanding of component-level failures. Rather, the systemwide, operational view places the components in context and reveals a priority for data collection and analysis. That is, a systemwide view indicates which subsystems or components are most problematic and, hence, are deserving of the highest level of attention in failure and repair data-collection and analysis. Once the key problems are identified, whether they are components failing, communications-link failures, lack of redundancy, or other issues, data for costs to remediate the problems can be estimated by examining their service-interruption modes in detail. This detail ties dollars invested to overall system performance as measured by the user's needs.

A complete, predictive analysis of maintenance and sustainment efforts for space systems then unfolds in the following steps. First, the operational objectives of the users are quantified in a way that reflects the long-term behavior of the system that is likely to be affected by programmatic decisions. These *operational* objectives then define the metrics for *maintenance and sustainment*. A predictive model based on a systemwide view links the maintenance and sustainment efforts to the operational metrics. This predictive model then reveals critical problem areas, which can be explored in greater detail. Once the critical areas are identified, additional analysis at the component level then links the remedies with costs, indicating how investments in resources affect operational performance.

For these reasons, in this monograph we start with a top-down approach to modeling the GPS (see pp. 12–19, 21–24). This approach puts the perspective of the user in the forefront, thereby placing the user's priorities in a position to motivate the maintenance and sustainment metrics. Although the scope of this study limited us from linking this work to component-level analysis and, hence, directly to costs, the approach explored in this monograph complements ongoing component-level analysis being done by Air Force Space Command (AFSPC/A4S). Linking the analysis presented here with ongoing work at AFSPC can present a complete, predictive model of space systems that reveals how dollars allocated in the budget affect the overall space system in terms of operational (not maintenance) performance.

Preliminary results indicate that, when ground antennas' reliability is considered in isolation, significant operational-performance deterioration will occur when the mean time between failures of ground antennas is less than 15 hours (given 5 hours for mean time to restore function) and when the mean time to restore function exceeds about 20 hours (given 50 hours for mean time between failures). Adding an antenna adds redundancy to a redundant system, providing little additional accuracy unless maintenance is quite poor. If system performance is to remain nominal, losing an antenna requires exemplary maintenance on the remaining antennas. (See pp. 24–35.)

The logical steps for implementing the framework developed in this report are as follows:

- Expand the model to include the reliability of the monitoring stations and that of the Master Control Station (and its backup facility). (See pp. 37–38.)
- Collect comprehensive data on when each of the subsystems is not functioning well enough to perform its assigned mission. This collection effort should include instances when the software crashes and needs to be reset, as well as such factors as failures of the communications links, even if these factors lie outside the control of AFSPC, and any other times (of which we are unaware) that a subsystem is operationally unavailable. This data-collection effort should be prioritized by system-level analysis of how maintenance affects the various users' requirements. (See pp. 38–39.)
- Extend the study to targeted components, to include the relationship of dollars invested into sustainment to the probability distributions of break rates and time to restore function. Key issues are, What causes breakages of mechanical components? Failures of electrical components? and Changes in software reliability? Specifically, are system failures correlated with service cycles, duration of use, or other factors? And what are the consequences of deferring scheduled maintenance on these systems to future break rates and break types? (See p. 39.)
- Expand the analysis to include other ways of increasing system performance, including improving the quality of the GPS algorithms, introducing more-advanced technologies, and providing cross-link capability among the satellites. (See pp. 39–40.)
- Expand the analysis to examine how fast the performance of the system degrades in response to an abrupt decrease in maintenance performance (i.e., the relaxation times of the GPS to perturbations in mean time between critical failures and mean time to restore function). (See pp. 31–32, 40.)
- Expand the analysis to embrace other space systems. (See pp. 40–41.)