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Report to Chairman, Subcommittee on Space Science and Applications, Committee on Science, Space and Technology, House of Representatives

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SPACE OPERATIONS

NASA's Communications Support for Earth Orbiting Spacecraft

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Information Management and
Technology Division

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The Honorable Bill Nelson
Chairman, Subcommittee on Space Science
and Applications
Committee on Science, Space,
and Technology
House of Representatives

Dear Mr. Chairman:

On November 7, 1988, your office requested that we review the National Aeronautics and Space Administration's (NASA) plans to provide emergency backup communications support for earth orbiting spacecraft after the planned closing of four ground stations. Such backup support is needed when spacecraft emergencies (malfunctions in on-board systems) occur and ground intervention is required. You also requested that we provide (1) information on the number of spacecraft emergencies that have occurred over the past few years and (2) information about the reliability of the space-based Tracking and Data Relay Satellite System (TDRSS) White Sands Ground Terminal.

Several concerns about NASA's plans to provide backup communications support for earth-orbiting spacecraft have been raised by officials at the Goddard Space Flight Center, which is responsible for individual spacecraft projects as well as the communications networks that support them. These officials expressed specific concerns in August 1988 about NASA's plan to close four of its ten existing ground stations once the space-based TDRSS system becomes fully operational. The Goddard officials foresaw that some of those stations might be needed to (1) help spacecraft in an emergency, and (2) support future small spacecraft missions in equatorial orbits as well as launches of expendable rockets. In January 1989, however, Goddard reported that, after further consultation with spacecraft project managers, their concerns about emergency support to resolve on-board malfunctions had been lessened, because spacecraft project managers had expressed the view that the probability of loss or damage to the spacecraft if the four stations were closed would be extremely low. Project officials said that they had not performed formal risk assessments on the impact of closing the four ground stations as requested by the Office of Space Operations. Rather, their assessment was based on their professional judgment. Further, Goddard officials said the issues concerning communications support for future small spacecraft missions in equatorial orbits as well as launches of expendable rockets had not been resolved.

During our work, project officials representing some future missions expressed concerns to us about NASA's position not to provide communications support for the transmission of scientific data from their missions, should they lose the use of TDRSS. According to the Associate Administrator for Space Operations, since 1975 NASA's decision has been to provide emergency backup support for the safety and proper functioning of the spacecraft only and not for the transmission of scientific data.

Based on data maintained by NASA between 1982 and 1987 (the latest available), the 11 to 23 earth orbiting spacecraft for which the Goddard Space Flight Center was responsible[1] experienced 316 malfunctions in on-board systems that required emergency intervention. According to Goddard records, most of these malfunctions, which averaged 2.2 per spacecraft per year, resulted in little or no permanent damage to the spacecraft.

The automated equipment and software at the White Sands ground terminal have had reliability problems. Numerous single points of failure in this equipment and software have led to temporary outages of the entire terminal, which processes all TDRSS communications. During an outage, spacecraft that normally use TDRSS must rely on ground stations for all communications support. NASA is solving the problem chiefly by constructing a second TDRSS ground terminal, which is scheduled to open in 1993 at a cost of $427 million.

Background

In 1983, NASA began implementing its space-based TDRSS, which allows earth orbiting user spacecraft to relay their communications through special TDRSS satellites to a single ground station in White Sands, New Mexico. Until 1983, NASA relied chiefly on a worldwide network of ground stations, called the Ground Spaceflight Tracking and Data Network (Ground Network), to provide all communications, including emergency backup support, for earth orbiting spacecraft. Spacecraft communications support, whether from the Ground Network or through TDRSS, includes (1) sending commands to operate the spacecraft and

[1] According to NASA officials, Goddard is responsible for most earth-orbiting NASA spacecraft missions.

maintain its safety and proper functioning, (2) receiving data for tracking the exact position of the spacecraft, and (3) receiving scientific data collected by the spacecraft's instruments. Such support is essential for achieving scientific objectives and for executing critical commands that ensure a safe and successful mission.

TDRSS is a significant technological improvement over the Ground Network because it (1) allows many earth orbiting spacecraft to be in contact with the ground much longer during normal operations and (2) can handle higher data transmission rates. Low-earth orbiting spacecraft — those at altitudes of up to several hundred miles — "see" only a small portion of the earth's surface at any one time. If no ground station is in the spacecraft's view, communication with the earth is not possible. However, TDRSS satellites are in high earth orbit and can "see" earth-orbiting spacecraft below them for much longer periods. Spacecraft need special communications equipment to use TDRSS. As of March 1989, five NASA spacecraft, plus the space shuttle, have been equipped to use TDRSS.

NASA's Emergency Backup Communications Plans

Part of the justification for TDRSS was that it would allow NASA to close most of its older ground stations. Accordingly, NASA has been phasing out most of the stations in the old Ground Network as TDRSS was being deployed. Thirteen Ground Network stations were closed between 1980 and 1985. Four additional stations, at Guam; Hawaii; Ascension Island; and Santiago, Chile, are scheduled to close by September 30, 1989. This move is expected to save annual operating costs of close to $7 million per station. NASA's closure plan is contingent upon TDRSS becoming fully operational, which depends on the successful on-orbit testing of the Tracking and Data Relay Satellite-4 (TDRS-4) spacecraft launched on March 13, 1989. NASA plans to accomplish this testing by the end of June 1989.

After closing these four additional stations, NASA will provide backup communications support for spacecraft emergencies from special substations at three Deep Space Network sites located at Goldstone, California; Canberra, Australia; and Madrid, Spain; and from three other ground stations located at Bermuda, Merritt Island, Florida and the Wallops Flight Facility in Virginia. NASA believes that these six stations will provide enough global coverage to accommodate emergency backup communications needs for earth orbiting spacecraft. Based on NASA cost estimates, these closures can be expected to save about $28 million in operating costs in fiscal year 1990.

Concerns About the Closure Plan

The station closure plan was reviewed and approved within NASA in 1985. Then, in June 1988 as the planned station closings were drawing near, the Office of Space Operations, which has overall responsibility for NASA communications, asked Goddard Space Flight Center to review the plan. In August 1988, concerns were raised by officials at Goddard, which is responsible for most earth orbiting spacecraft as well as their support networks, that the plan might endanger future missions, including the Hubble Space Telescope, Upper Atmosphere Research Satellite, and Cosmic Background Explorer. Project officials estimate the development costs of these three future missions at $1.5 billion, $679 million, and $150 million, respectively. Goddard officials felt that in an emergency these spacecraft would need to rely on support from ground stations in order to recover from on-board systems emergencies such as component failures or other malfunctions of on-board systems.

According to Goddard officials, in certain emergencies, a spacecraft can lose the ability to communicate through TDRSS. Therefore, spacecraft operators must use ground stations to try to return the spacecraft to normal operations. TDRSS communications generally require that a spacecraft carefully point a specialized antenna at the precise position in the sky where the TDRSS satellite is located. However, during emergencies, a spacecraft may lose control of its precise orientation in space or may adopt a position such that the specialized antenna is not pointing properly. Ground stations must then be used to communicate with the spacecraft by sending powerful signals to the spacecraft's backup omnidirectional antenna. Some currently operational satellites, including the Earth Radiation Budget Satellite and Landsat-4, have had such emergencies.

Goddard officials were concerned that fewer stations might mean unacceptably long gaps between the periods when spacecraft would be in view of a ground station. For example, a gap of 14.8 hours was predicted for the Hubble Space Telescope, even though the spacecraft had a specified maximum allowable gap of 9 hours.[2] In general, longer gaps result in fewer opportunities to transmit and receive emergency communications, thus raising the potential risk of spacecraft degradation or loss. Goddard recommended to the Office of Space Operations that two of the four stations scheduled to close — the Hawaii and Ascension Island stations — be kept open on a one-shift, 5-day per week level to

[2] According to Goddard, damage to a specific instrument would occur if commands were not relayed to it within a 9 hour period.

fill these gaps. (The stations would be on call for emergency backup support 24 hours per day.)

In a December 1988 letter, the Office of Space Operations asked Goddard to study this emergency support issue. Specifically, the Office (1) was concerned because NASA had not budgeted money for operating the Hawaii and Ascension Island stations in fiscal year 1990 and (2) was uncertain whether alternatives for providing the necessary support had been thoroughly considered. Goddard had estimated that it would cost $10.6 million to keep the Hawaii and Ascension Island stations open during fiscal year 1990 on a single-shift, five-day-per-week basis. An additional $9 million would be needed to perform essential equipment upgrades to keep the stations operating. The Office asked Goddard to (1) assess the risk to individual spacecraft projects of closing the ground stations and (2) provide a funding plan to keep Hawaii and Ascension Island open within the planned fiscal year 1990 budget if Goddard still believed that keeping the stations open was necessary.

On January 30, 1989, about five months after raising their initial concern, Goddard reported in a follow-up letter to the Office of Space Operations that they were planning to proceed with the closing of all four Ground Network stations because their concerns about future missions had been lessened. Project managers for the Cosmic Background Explorer, Gamma Ray Observatory, Upper Atmosphere Research Satellite, and Hubble Space Telescope believed that, based on their knowledge of these spacecraft, the probability of loss or damage to the spacecraft if the four stations were closed would be extremely low.

First, according to the Hubble Space Telescope and Upper Atmosphere Research Satellite project managers, the "unacceptable gaps" in coverage identified in August 1988 generally would occur only if two malfunctions happened simultaneously. A failure in the primary TDRSS communications system would have to occur, causing the spacecraft to rely on ground stations for support. Then an unrelated on-board malfunction would probably have to occur, requiring quick access and resolution. They believed that if no on-board malfunction occurred, the spacecraft could survive a long coverage gap without permanent loss of any capability.

Second, the project managers for the future Cosmic Background Explorer, Gamma Ray Observatory, Upper Atmosphere Research Satellite, and Hubble Space Telescope projects believed that the planned safehold modes[3] for their missions would be sophisticated enough to protect the spacecraft during relatively long periods without contact with the ground, even if the spacecraft were tumbling. They said that commands to wake up the spacecraft and diagnose problems could be transmitted when the spacecraft was over one of the six remaining ground stations.

Project officials said that their position that the probability of loss or damage to the spacecraft if the four stations were closed would be extremely low was based on their professional judgment. They said their position was not based on the risk assessments they were asked to perform by the Office of Space Operations, which were not done. Therefore, we believe that NASA needs formal assurance that earth-orbiting spacecraft missions will not be exposed to unreasonable risks after the four ground stations are closed. NASA can gain this assurance through an assessment of risks, as the Office of Space Operations requested that Goddard perform.

Other Communications Support Issues Related to Ground Stations

In discussions and correspondence with the Office of Space Operations during 1988, Goddard officials identified two other reasons for retaining the Hawaii and Ascension Island stations besides support for spacecraft emergencies. First, certain future earth orbiting spacecraft, known as Small Explorer class missions, will rely on ground stations for all communications support, including resolution of emergencies, because they will be too small to warrant the increased project expense and additional weight of installing TDRSS equipment and using TDRSS. Although some of these missions could be serviced by the station at Wallops Island, Virginia, other missions flying in equatorial orbits would not be in view of any ground stations. Goddard's January 1989 letter noted that the issue of support for future small spacecraft remained unresolved.

Second, Goddard officials also said that the Ascension Island station would be needed to provide support for launches of expendable rockets such as the Delta, Titan, and Ariane. The ground station at Ascension Island was most heavily used for that purpose in the past and would still be required in the future. According to officials of the Office of Space Operations, NASA is negotiating with the Air Force to continue providing launch support from Ascension Island; however, plans have not yet been finalized.

[3]NASA spacecraft generally have "safe-hold" modes of operation designed to protect the spacecraft when it cannot communicate with the earth.

Appendix I details NASA's plans for emergency communications support for earth-orbiting spacecraft and for station closings. It also gives information on the need for ground station support for Small Explorer missions in equatorial orbits and launches of expendable rockets.

Concerns About Transmission of Scientific Data From Degraded Missions

During a spacecraft emergency such as a loss of proper orbital orientation or a failure within a central on-board computer, NASA's primary concern is regaining control of the spacecraft. Collection of scientific data is suspended until normal communications can resume. But, according to project officials, a failure in the on-board communications system may permanently prevent a spacecraft from using TDRSS without preventing on-board instruments from continuing to conduct scientific work. Such a mission would need continuing, long term communications coverage from ground stations to transmit its scientific results. The Solar Maximum Mission had this problem in 1986 when its TDRSS antenna froze in place and could no longer be pointed at the TDRSS satellites. Ground stations enabled it to transmit its scientific data back to earth. Project officials representing some future missions, including the Hubble Space Telescope and Upper Atmosphere Research Satellite, expressed concerns to us about NASA's position not to provide communications support for the transmission of scientific data from their missions, should they lose the use of TDRSS.

According to the Associate Administrator for Space Operations, since 1975 NASA's decision has been to provide emergency backup support for the safety and proper functioning of the spacecraft only and not for the transmission of scientific data. Instead, some future missions — the Hubble Space Telescope and Gamma Ray Observatory — will be serviced by space shuttle missions. For example, we were told that TDRSS communications problems on the Hubble Space Telescope could be fixed when the telescope is serviced on orbit, or the spacecraft could be returned to earth for repair and later launch. According to the Associate Administrator, other missions that are not designed for on orbit servicing may not be able to continue science operations if their TDRSS communications system fails. We asked the Office of Space Operations for documentation of this decision; however, the Office was unable to provide any.

Frequency of Spacecraft Emergencies in the Recent Past

Based on data maintained by NASA between July 1982 and December 1987 (the latest year for which data are available), earth orbiting spacecraft for which the Goddard Space Flight Center was responsible experienced 316 on-board system malfunctions that required emergency intervention.[4] With 11 to 23 spacecraft active during any given year, malfunctions per spacecraft averaged 2.2 per year. During this five and a half year period, 3 spacecraft experienced only 1 malfunction each; the TDRS-1 satellite experienced the highest number of malfunctions, 51; and the Nimbus-7 spacecraft had the second highest number, 35. According to Goddard's records, most of the malfunctions resulted in little or no permanent damage to the spacecraft, and Goddard did not maintain records on the type or amount of ground-based communications necessary to resolve the problems or the specific ground stations that were used. More information about past spacecraft emergencies is contained in Appendix I.

Reliability of the TDRSS White Sands Ground Terminal

All transmissions through TDRSS, whether from earth to the TDRSS satellites or vice versa, pass through the White Sands Ground Terminal, located at White Sands, New Mexico. For this reason, the White Sands Ground Terminal is critical to the operational reliability of earth orbiting spacecraft that use TDRSS. NASA has encountered problems with the reliability of the automated equipment and software at the White Sands terminal. Numerous system outages, lasting from a few minutes to several hours or more, have occurred since the White Sands terminal began operating in 1983. When such a system outage occurred, earth orbiting spacecraft relied on available NASA ground stations, including those scheduled for closure, for all communications.

NASA is in the process of constructing a Second TDRSS Ground Terminal at White Sands in large part because of concerns about the reliability of the original terminal. The new terminal is scheduled to be completed in 1993. Appendix II contains additional information on the reliability of the TDRSS White Sands Ground Terminal.

Conclusions

Although Goddard has stated that its concerns about backup communications support for spacecraft emergencies have been lessened, no assessments of the risks to individual spacecraft missions from closing

[4]Malfunctions for a total of 26 spacecraft are included in this figure. Those 26 spacecraft included 4 TDRSS users, 21 non-TDRSS users, and the TDRS-1 satellite itself, which experienced 51 of the 316 malfunctions.

the ground stations have been performed, as requested by NASA's Office of Space Operations. Significant financial investments are being made for NASA spacecraft, which dwarf the costs of operating the ground stations. For example, the Upper Atmosphere Research Satellite is expected to cost $679 million to develop, the Cosmic Background Explorer $150 million, and the Hubble Space Telescope $1.5 billion, whereas the cost of keeping ground stations open is about $7 million per station per year. Therefore, we believe that NASA needs assurance that earth-orbiting spacecraft missions will not be exposed to unreasonable risks due to the closing of the ground stations. To gain this assurance, specific data about the risks to individual spacecraft missions needs to be compiled and documented. This data can then facilitate a formal assessment of risks, as was requested by the Office of Space Operations.

Also, NASA has yet to resolve how to provide communications support for launches of expendable rockets. Although NASA is negotiating with the Air Force to continue providing launch support for expendable vehicles from the Ascension Island station, plans have not yet been finalized. Finally, NASA has not yet determined exactly how communications support will be provided for future Small Explorer class missions flying in orbits close to the equator.

Recommendations

We recommend that the NASA Administrator ensure that (1) appropriate risk analyses are performed and documented for present and future earth-orbiting spacecraft missions before the four ground stations located at Guam, Hawaii, Santiago, and Ascension Island are closed, (2) plans for support for launches of expendable vehicles are finalized before the Ascension Island station is closed, and (3) a plan is developed to provide support for Small Explorer missions in equatorial orbits.

Program Officials' Views

We discussed the contents of this report with the Associate Administrator for Space Operations and other officials from the Office of Space Operations and the Goddard Space Flight Center. They agreed that the substance of the report was fairly and accurately represented. The Associate Administrator stressed that the decision regarding closure of the ground stations was not driven by budgetary pressures; funds would have been obtained to retain the ground stations if it were determined that continued operation was necessary.

Officials from the Office of Space Operations also told us that the issue of support for launches of expendable vehicles was being addressed primarily through negotiations with the Air Force to take over and operate the Ascension Island station. Although this solution had not yet been finalized, they said the Ascension Island station would not be closed until some means of continuing support from that location had been finalized. The officials said they could not make decisions about support facilities for future Small Explorer missions in equatorial orbits in the absence of specific support requirements, which are not yet defined for these missions. They said that as these requirements are defined, they will be dealt with on a case-by-case basis.

In developing the information for this report, we reviewed official documentation of NASA's backup communications plans, conducted technical discussions with NASA network managers and flight project operations directors, and analyzed past spacecraft emergencies and on-board system malfunctions. We did not independently assess the impact of the station closings on individual projects. While we did not obtain official agency comments on a draft of this report, we discussed its contents with responsible officials in the Office of Space Operations and included their views where applicable. More details on our objectives, scope and methodology are discussed in appendix III.

As arranged with your office, unless you publicly release its contents earlier, we plan no distribution of this report until 30 days after the date of this letter. At that time, we will send copies to other appropriate congressional committees; the Administrator, NASA; and other interested parties upon request.

This work was performed under the direction of Samuel W. Bowlin, Director for Defense and Aeronautics Mission Systems. Other major contributors are listed in appendix IV.

Sincerely yours,

Ralph V. Carlone

Ralph V. Carlone
Assistant Comptroller General

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Abbreviations

GAO	General Accounting Office
NASA	National Aeronautics and Space Administration
TDRSS	Tracking and Data Relay Satellite System
TDRS-4	Tracking and Data Relay Satellite-4

NASA's Plans for Providing Emergency and Other Communications Support for Earth Orbiting Spacecraft

Background

NASA has always relied primarily on ground stations to provide communications, including emergency support, for its spacecraft. Originally, three separate networks were built, supporting (1) unmanned satellites in earth orbit, (2) spacecraft flying beyond earth orbit, and (3) manned spaceflight missions. On completion of the Apollo lunar landing program in 1972, the networks supporting unmanned earth-orbiting satellites and manned spaceflight missions were combined into the Spaceflight Tracking and Data Network. In 1983, the deployment of the first Tracking and Data Relay Satellite System (TDRSS) satellite provided the network with new capabilities for greater orbital coverage and higher data transmission rates. Since the introduction of TDRSS, the older ground station network is referred to as the Ground Spaceflight Tracking and Data Network (Ground Network) to distinguish it from the TDRSS.

NASA currently has three communications systems to meet the needs of NASA flight missions. These are the Ground Network, which supports earth orbital missions; the Deep Space Network, which primarily supports planetary and interplanetary flight missions; and the Space Network, including the TDRSS, which will provide most low earth orbital mission support when it becomes fully operational. The functions of TDRSS and the Ground Network overlap to a large extent, and TDRSS will take over the bulk of the Ground Network functions after it becomes fully operational.

The TDRSS will use a set of two active and one spare satellites. The two active satellites will be located at 41 degrees West Longitude, over the Atlantic Ocean off the coast of Brazil, and at 171 degrees West Longitude, over the Pacific Ocean southwest of the Hawaiian Islands. The spare is to be located between the two active satellites. The first TDRSS satellite, called TDRS-1, was launched in April 1983. A second TDRSS satellite, TDRS-2, was destroyed in the Challenger accident in January 1986. TDRS-3 was successfully launched in September 1988, followed by TDRS-4 on March 13, 1989. TDRS-4 will take the place of TDRS-1, which will become an on-orbit spare. After the new configuration is tested in orbit, the TDRSS network will be considered fully operational. This is expected to occur by the end of June 1989.

TDRSS represents a significant technological improvement over Ground Network because it allows low earth orbiting spacecraft to be in contact with the ground for much longer periods of time during normal operations than the Ground Network. Also, TDRSS is able to accommodate higher data rates and more efficiently transmit large volumes of data than the Ground Network. For example, at its highest transmission rate of 300 million bits per second, the new system can reportedly transfer in a single second the contents of a 20-volume encyclopedia with 1,200 pages in each volume and 2,000 words on each page. Ground Network stations, on the other hand, can handle transmissions at speeds no greater than 1.5 million bits per second.

Ground Network stations can provide low-earth orbiting spacecraft with communications coverage for only about 15 percent of the time it takes to orbit the earth. This is because low-earth orbiting spacecraft — those at altitudes of up to only a few hundred miles — "see" only a small portion of the earth's surface at any one time. If no ground station happens to be in the spacecraft's view, communication with the earth is not possible. TDRSS, on the other hand, provides coverage for about 85 percent of an average spacecraft's orbit and could provide continuous coverage for satellites flying higher than 720 miles. This is because TDRSS satellites fly in a high earth orbit (approximately 22,300 miles) that keeps them permanently in view of both the ground terminal at White Sands and most of the surface of the earth. Using TDRSS, spacecraft with the proper on-board equipment can relay their communications through the TDRSS satellites to the White Sands terminal.

The Role of the Ground Stations in Resolving Spacecraft Emergencies

In certain emergency situations, on-board system malfunctions will prevent a spacecraft that normally communicates through TDRSS from doing so. Therefore, spacecraft operators must use ground stations to try to return the spacecraft to normal operations. TDRSS communications generally require that a spacecraft carefully point a specialized antenna at the precise position in the sky where the TDRSS satellite is located. However, during emergencies, a spacecraft may lose control of its precise orientation in space or may adopt a position such that the specialized antenna is not pointing properly. In such cases, ground stations must be used to communicate with the spacecraft by sending powerful signals to the spacecraft's backup omnidirectional antenna.

According to a spacecraft project manager, most modern spacecraft are complex electromechanical systems that are likely to experience some component failures or other malfunctions during their active life. A malfunction can often be corrected by commands to work around the problem or switch to some backup system. Malfunctions in a spacecraft's on-board computer, communications equipment, or attitude control system can jeopardize the future of the mission if not promptly addressed. Furthermore, such malfunctions may prevent the spacecraft from using TDRSS for communications, if that is the system the spacecraft normally uses. In such emergency cases, ground stations must be used to diagnose and resolve the problem.

For ground stations to be able to assist low-earth orbiting spacecraft in emergencies, they must be located within a current or upcoming track of the malfunctioning spacecraft's orbit. Otherwise, the ground stations cannot "see" the spacecraft, which is hidden by the curvature of the earth. Eventually, most spacecraft will fly over many points on the globe; however, it may take many hours for a spacecraft to fly over any given location. According to the ground networks director, the more ground stations that are scattered across the globe, the better the chances that some of those stations will be located in the spacecraft's current or upcoming track. In some cases, particularly for spacecraft flying in an orbit close to the equator, ground stations located in a much higher or lower latitude may never be visible to the spacecraft.

Past Malfunctions in Earth Orbiting Spacecraft

Based on data maintained by NASA between July 1982 and December 1987 (the latest available data), earth orbiting spacecraft for which the Goddard Space Flight Center was responsible experienced 316 on-board system malfunctions that required emergency intervention.[1] With 11 to 23 spacecraft active during any given year, malfunctions per spacecraft averaged 2.2 per year. During this five and a half year period, 3 spacecraft experienced 1 malfunction each; the TDRS-1 spacecraft experienced the highest number of malfunctions, 51; and the Nimbus-7 spacecraft had the second highest number, 35. According to Goddard's records, malfunctions occur in many spacecraft subsystems, including 1) attitude control and stabilization, 2) power, 3) propulsion, 4) structure/mechanical, 5) telemetry and data handling, 6) thermal, 7) timing, control and command, and 8) payload instrument. Goddard classified the severity of the malfunctions by their final impact on continuing spacecraft operations. Table I.1 shows Goddard's classification of the number and severity of earth orbiting spacecraft malfunctions during the period from July 1982 through December 1987.

[1] Malfunctions for a total of 26 spacecraft are included in this figure. Those 26 spacecraft included 4 TDRSS users, 21 non-TDRSS users, and the TDRS-1 satellite itself, which experienced 51 of the 316 malfunctions.

Table I.1: Number and Severity of Spacecraft Malfunctions, July 1982 Through December 1987

Degree of Impact on Operations	Number of malfunctions
Negligible (0 - 5 percent loss)	162
Minor (5 - 33 percent loss)	131
Substantial (33 - 66 percent loss)	17
Major (66 - 95 percent loss)	4
Catastrophic (95 - 100 percent loss)	2[a]
Total	**316**

[a]The Geostationary Operational Environmental Satellite-1 spacecraft was deactivated after a failure in February 1985, and the National Oceanic and Atmospheric Administration-8 spacecraft failed in December 1985.

Goddard's classification of the severity of spacecraft malfunctions only takes into account the malfunction's final impact on the spacecraft. According to a Goddard spacecraft project manager, many of the malfunctions that have occurred on earth orbiting spacecraft could have been more serious if ground stations were not available to allow spacecraft operators to resolve the problem. However, Goddard does not maintain records indicating the type and/or amount of communications support that was required to resolve these problems or the ground stations that were used. Following are examples provided by flight project officials in which rapid ground-based communications were used in resolving spacecraft malfunctions.

Earth Radiation Budget Satellite

In July 1987, the Earth Radiation Budget Satellite lost attitude control while operators were attempting to turn the spacecraft so that its solar panels would continue to face the sun. The spacecraft began to spin, or tumble, in orbit. Because of the tumble, stabilizing commands could not be transmitted through TDRSS, since the spacecraft's specialized antenna needs to be pointed directly at the TDRSS satellite to form a communications link. But ground stations could transmit strong signals to the spacecraft's emergency omnidirectional antenna, which does not require pointing to transmit and receive signals. The spacecraft was visible to several ground stations, including Merritt Island, Hawaii, Guam, Santiago, and the three Deep Space Network sites during the emergency (see Figure I.1 for locations). Coverage from these stations was used first to diagnose the problem and then to send up commands to fix it. As a result, the spacecraft was recovered with no permanent loss of capability.

Landsat-4

The Landsat-4 spacecraft experienced a similar loss of attitude control in April 1985 when an on-board earth sensor began transmitting erroneous information. Landsat-4 also began to tumble, prohibiting use of its TDRSS antenna. According to the Landsat operations director, ground stations at Hawaii, Guam, Ascension Island, Merritt Island, Bermuda, Madrid, and Canberra were used to diagnose the problem and transmit commands to deactivate the erroneous sensor. The operations director said that the availability of ground stations offering wide global coverage was crucial to resolving this problem.

Other Ground Station Intervention

In addition to loss of attitude control, other problems such as a malfunction in the on-board computer or an irregularity in the power supply can cause a spacecraft to go into a dormant or "safe hold" mode, requiring ground station intervention to recover. The safe hold mode generally shuts down scientific experiments, but it protects on-board power sources and other systems so that the spacecraft can wait for relatively long periods of time, until ground stations are able to issue commands to revive the spacecraft and diagnose any remaining problems. Older missions, such as Landsat-4 and Landsat-5, are susceptible to occasional on-board computer malfunctions when cosmic rays striking the spacecraft cause the computer's memory to be altered. The alterations have the potential to activate erroneous commands. Resolution of the problem involves transmitting the contents of the computer's memory to the ground, analyzing it for errors, and then reloading corrected software into the computer via transmission from ground stations.

NASA's Ground Station Closure Plan

The current network of NASA ground stations, shown in Table I.2, provides backup communications support to TDRSS-oriented spacecraft when they experience emergencies that prohibit TDRSS communications.

Table I.2: Status of NASA Ground Stations as of March 1989

Ground Network Stations	
Ascension Island	to be closed 9/89
Santiago	to be closed 6/89
Guam	to be closed 6/89
Kaui, Hawaii	to be closed 9/89
Bermuda	open indefinitely
Merritt Island, Florida	open indefinitely
Dakar, Senegal	to be closed 1991[a]
Deep Space Network Stations	
Goldstone, California	open indefinitely
Madrid	open indefinitely
Canberra	open indefinitely
Other	
Wallops Island, Virginia	open indefinitely

[a]This special purpose station is designed to support orbital insertion of the space shuttle. The Office of Space Flight negotiated with the Office of Space Operations to keep this station open until 1991 as a backup in case of an outage of the TDRSS White Sands Ground Terminal.

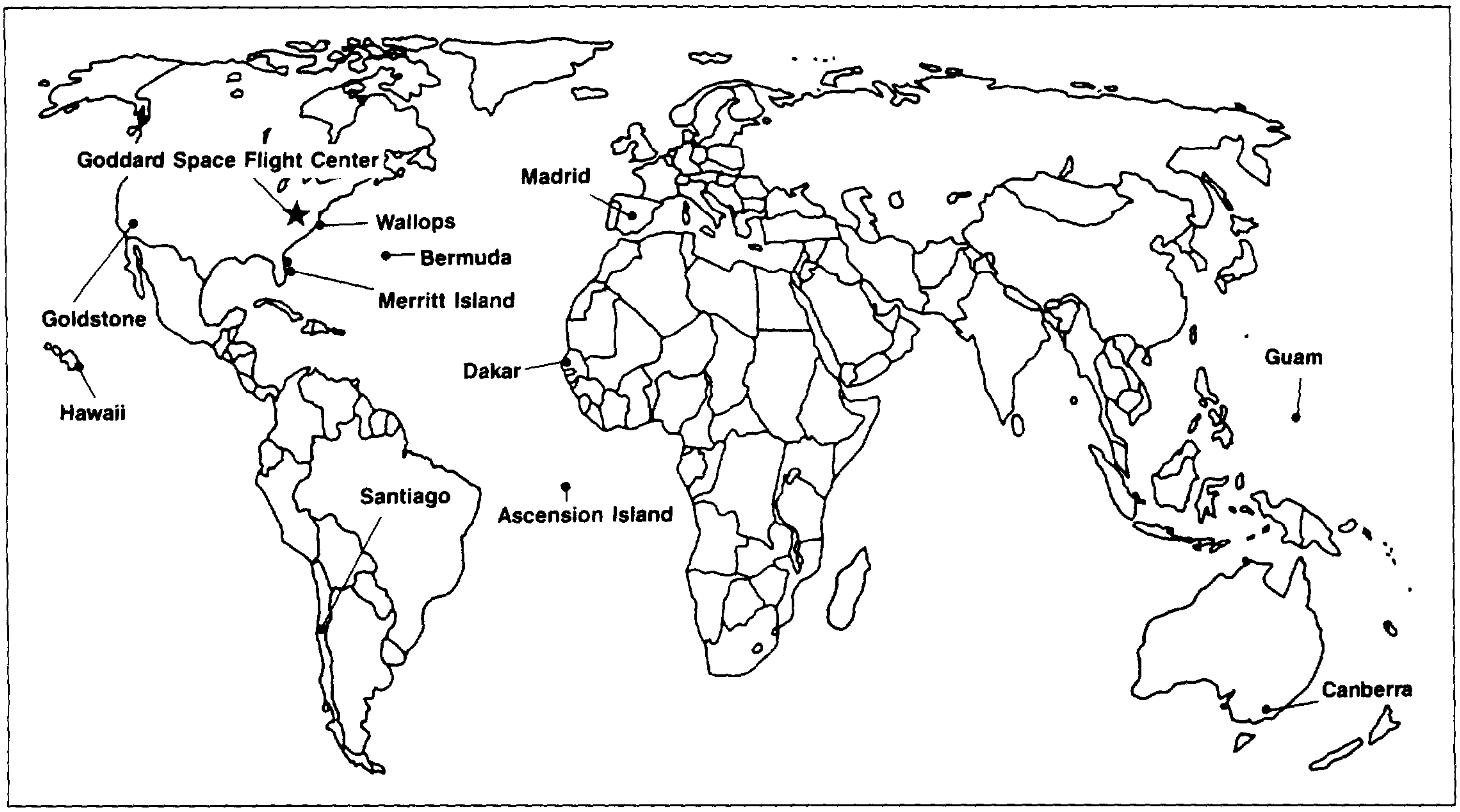
NASA has been planning to close most of its ground stations once TDRSS becomes fully operational. Thirteen Ground Network stations were closed between 1980 and 1985[2]. Four of the remaining Ground Network stations, located at Guam, Hawaii, Ascension Island, and Santiago are scheduled to be closed by September 30, 1989. NASA's plan to close them is contingent upon successful on-orbit testing of the TDRSS satellite launched by the space shuttle Discovery on March 13, 1989. On-orbit testing is expected to be completed by the end of June 1989.

The Bermuda and Merritt Island stations, scheduled to remain open indefinitely, are permanent facilities that support launches of the space shuttle. According to NASA officials, the Dakar station, currently in caretaker status, is a temporary station used as backup communications support during insertion of the shuttle into earth orbit. The Dakar station is scheduled to be closed in September 1990.

NASA's primary reason for closing the ground stations is that they are no longer needed for routine communications services for low earth orbiting spacecraft. Also, closing the stations saves the expense of operating

[2]The stations, in order of closing, were located at Winkfield, England; Rosman, North Carolina; Honeysuckle Creek, Australia; Madrid (Cebreros), Spain; the Pioneer site at Goldstone, California; Quito, Ecuador; Tula Peak, New Mexico; Buckhorn, California; Fairbanks, Alaska; Botswana; Orroral Valley, Australia; Madrid (Fresnedillas), Spain; and Greenbelt, Maryland.

Figure I.1: NASA Controlled Ground Stations



and maintaining them and providing expensive communications links to these sites around the world. Currently, these costs amount to approximately \$4 - 7 million per station. After the four Ground Network stations are closed, NASA plans to provide emergency backup communications support from the 26-meter antenna substations at the three sites of the Deep Space Network, located at Goldstone, California; Canberra, Australia; and Madrid, Spain; as well as from the Bermuda and Merritt Island, Florida Ground Network stations and the ground station at Wallops Island, Virginia. The Wallops station will also support several specific spacecraft missions, including International Ultraviolet Explorer, Cosmic Background Explorer, Nimbus-7, and Interplanetary Monitoring Platform-8.

NASA believes that these stations will provide sufficient global coverage to accommodate emergency backup communications needs for earth orbiting spacecraft. Based on cost estimates provided by Goddard, closure of the four stations can be expected to save NASA close to $28 million in operating costs in fiscal year 1990. Fiscal year 1989 and 1990 costs for each of the stations planned to be closed, as estimated by Goddard, are shown in Table I.3. The Office of Space Operations confirmed that these estimates are valid approximations of the costs of keeping the stations open at their current operating levels.

Table I.3: Estimated Operating Costs of Ground Stations Slated to Be Closed

Dollars in millions

	Fiscal years	
Station to be closed	**1989**	**1990**
Ascension Island	$7.29	$7.58
Santiago, Chile	7.33	7.62
Guam	7.10	7.38
Kaui, Hawaii	4.96	5.16
Total	**$26.68**	**$27.74**

Concerns Raised About the Closure Plan

The plan to close the Ground Network stations at Guam, Hawaii, Ascension Island, and Santiago was reviewed and approved within NASA in 1985. However, the station closures were delayed for more than three years due to the moratorium on shuttle flights after the Challenger accident, since TDRSS satellites can only be launched from the space shuttle.

In June 1988, as the closure decision was again drawing near, NASA's Office of Space Operations, which has overall responsibility for NASA communications, asked for a current assessment of the station closure plan from the Goddard Space Flight Center, which manages all of NASA's earth-orbiting spacecraft missions as well as the communications networks that support them. At that time, Goddard raised concerns about the closure plan. In an August 1988 response to the Office of Space Operations request, the Director of the Goddard Space Flight Center stated that continued availability of the Ground Network stations at Kaui, Hawaii and Ascension Island would be required to provide emergency support for earth orbiting spacecraft. Goddard recommended that these two stations be kept open indefinitely on a reduced operating schedule to accommodate the safety and proper functioning of several specific missions. The Goddard recommendation was based chiefly on the concern that the six remaining ground stations would not offer enough coverage to provide for the safety and proper functioning of certain satellites.

Specifically, Goddard presented data showing that the remaining sites would not provide sufficient ground station coverage for the Hubble Space Telescope, Upper Atmosphere Research Satellite, Cosmic Background Explorer, and other missions. The adequacy of coverage was expressed in terms of the length of the gaps that would occur between times that a spacecraft would be in view of one of the six remaining ground stations. For example, Goddard calculated that the maximum allowable communications gap for safety and proper functioning of the Upper Atmosphere Research Satellite, which, according to a project official, is expected to cost $679 million to develop, would be six hours. In other words, the spacecraft could survive for six hours between the time it lost contact with one ground station and the time it came into view of another. During that time, the spacecraft's safe hold mode would protect on-board power sources and other systems until ground stations were able to issue commands to revive the spacecraft and diagnose any problems. However, Goddard predicted a possible gap, after the Ground Network station closures, of 9.6 hours. Goddard felt that if TDRSS communications were unavailable and a spacecraft malfunction occurred during that gap, spacecraft problems could result, due to the inability of operators to access the spacecraft within six hours.

In another example, the Hubble Space Telescope, which cost $1.5 billion to develop, according to a project official, had a maximum allowable gap of 9 hours and a predicted gap of 14.8 hours if the stations were closed. Permanent damage to one of the spacecraft's instruments could result if it malfunctioned and was not serviced by ground operators within 9 hours. Coverage gaps were also identified for the Cosmic Background Explorer, which cost $150 million, and the Earth Radiation Budget Satellite, costing $44 million, according to project officials. According to Goddard documents, keeping the Hawaii and Ascension Island stations open would reduce these maximum gaps to very close to or less than the specified maximum allowable gaps. This is because the stations would break up large gaps in global coverage over the Pacific and Atlantic Oceans.

The Goddard associate chief for ground networks told us that the data they used was based on the findings of a special task force that was convened by the Office of Space Operations in September 1987 and made up of representatives from Goddard, the Jet Propulsion Laboratory, and the Ames Research Center. That task force, which was chartered to determine the feasibility of developing low-cost, modularized ground stations, concluded in December 1987 that NASA's station closure plan was flawed because of coverage gaps that threatened the safety and proper functioning of low earth orbiting spacecraft. The task force recommended retaining capability at Guam and Ascension Island, using a new low-cost ground station architecture. According to an Office representative, the Office of Space Operations chose not to act directly on the task force's findings. Instead, as discussed above, in June 1988 the Office asked Goddard to provide a current assessment of the station closure plan.

Two additional concerns regarding closure of the Hawaii and Ascension Island stations were raised by Goddard during meetings with the Office of Space Operations. Specifically, Small Explorer class spacecraft, for which TDRSS communications are not feasible, would require ground station support on a routine basis. Also, the Ascension Island station would be needed to provide support for launches of expendable vehicles.

The Office of Space Operations asked Goddard in November 1988 to study further the emergency support issue. The Office was concerned that money had not been budgeted for operating the Hawaii and Ascension Island stations in fiscal year 1990 and questioned whether alternatives for providing the necessary support had been thoroughly considered. In further correspondence with Goddard in December 1988, the Office of Space Operations requested that Goddard perform risk assessments of the effect of closing the ground stations on individual spacecraft projects and that they develop a plan for providing for the continued funding of the two stations in fiscal year 1990 if they still felt that retaining the stations was necessary. Goddard had estimated that it would cost $10.6 million to keep the Hawaii and Ascension Island stations open during fiscal year 1990 on a reduced single-shift, five-day-per-week schedule, plus an additional $9 million to perform essential equipment upgrades to keep the stations operating.

In January 1989 Goddard reported to the Office of Space Operations that their concerns had been lessened. Project managers for certain future missions, including the Cosmic Background Explorer, Gamma Ray Observatory, Upper Atmosphere Research Satellite, and Hubble Space Telescope, expressed the belief that, based on their knowledge of the spacecraft, the probability of loss or damage to the spacecraft due to the lack of the closed stations would be extremely low for several reasons.

First, according to the Hubble Space Telescope and Upper Atmosphere Research Satellite project managers, the "unacceptable gaps" in coverage identified in August 1988 generally would occur only if two malfunctions happened simultaneously. First a failure in the primary TDRSS communications system would have to occur, causing the spacecraft to rely on ground stations for support. Second, an unrelated malfunction would probably have to occur on-board the user spacecraft that would require quick access and resolution. They believed that if no on-board malfunction occurred, the userspacecraft could survive a long coverage gap without permanent loss of any capabilities.

Second, the project managers for the future Cosmic Background Explorer, Gamma Ray Observatory, Upper Atmosphere Research Satellite, and Hubble Space Telescope projects believed that the planned safehold modes for their missions would be sophisticated enough to protect the spacecraft during relatively long periods without contact with the ground, even if the spacecraft were tumbling. They said that commands to "wake up" the spacecraft and diagnose problems could be transmitted when the spacecraft was over one of the six remaining ground stations.

These officials said that this opinion was based on their professional judgment about the survivability of their spacecraft rather than the risk assessments they were asked to perform but had not done. Goddard officials said the support requirements of the four spacecraft currently using TDRSS (Earth Radiation Budget Satellite, Landsat-4, Landsat-5, and Solar Mesosphere Explorer) were not taken into account in preparing the January 1989 position because all four have already outlived their designed lifetimes. Since their concerns had been lessened, Goddard reported that they were planning to proceed with the closing of all four of the Ground Network stations. However, Goddard noted that the issue of support for future small spacecraft and launches of expendable vehicles remained unresolved.

Ground Station Support for Small Explorers and Launches of Expendable Vehicles

Goddard officials told us that some type of ground station support will be needed in the future for spacecraft that are not designed to use TDRSS. Certain earth orbiting spacecraft, known as Small Explorer class missions, will rely on ground stations for all of their communications support, including resolution of emergencies, because they will be too small to warrant the expense and weight of installing equipment for using TDRSS. A NASA "announcement of opportunity" [3] for its Small Explorer class missions instructs planners for such missions to assume they will only be able to communicate with their spacecraft for one or two passes per day while the spacecraft is over Wallops Island, Virginia. In the January 1989 response to the Office of Space Operations, Goddard pointed out that certain types of missions, flying in orbits close to the equator, will not be able to make use of the Wallops Island station. Goddard noted that when equatorial spacecraft become part of the complement, support from additional locations will be required. Officials from the Office of Space Operations said they would address support requirements for these future missions once their specific requirements are defined.

Also, some type of ground station support will be needed to provide communications support for launches of expendable vehicles, such as the Titan, Delta and Ariane rockets. The Bermuda and Merritt Island Ground Network stations, which NASA plans to retain indefinitely, provide this kind of support for launches of the space shuttle. However, Goddard pointed out that launches of several NASA missions in 1990 and 1991 as well as future NASA medium launch vehicles will also require communications support to monitor the performance of these launch vehicles. In addition, launches of approximately 28 Department of Defense, commercial, and foreign vehicles annually will require real time communications support. Goddard has stated that the Ascension Island location, where one of the stations scheduled to be closed is located, was most heavily used for this type of support, and that support from this geographic location will still be required in the future. As of January 1989, Goddard reported that it was not clear how such support would be provided once the NASA Ascension Island station was closed.

When asked how NASA planned to provide this support, officials from the Office of Space Operations told us they were addressing the problem

[3] The announcement of opportunity was a request for basic research proposals to conduct space science investigations within the context of the Explorer program.

primarily through negotiations with the Air Force to take over and operate the Ascension Island station. However, as of March 1989, this solution had not yet been finalized.

Concerns About Transmission of Scientific Data From Degraded Missions

NASA officials said that during a spacecraft emergency such as a loss of attitude control or an on-board computer failure, their chief concern is regaining control of the spacecraft. Collection of scientific data is suspended until normal communications, possibly through TDRSS, can resume. However, according to project officials, it is possible that a spacecraft could experience a failure in its on-board communications system that permanently prevents it from using TDRSS for scientific data transmission but does not prevent it from continuing to conduct its scientific missions. Such a mission would need continuing communications coverage from ground stations in order to carry out its scientific work.

Of the five satellite missions that have used TDRSS since 1983, one has already experienced this problem. The Solar Maximum Mission satellite, which is used to examine solar flares and their effect on the earth, experienced such a problem in February 1986 when the antenna it was using for TDRSS communications froze in a fixed position and could no longer be pointed directly at TDRSS. As a result, data and commands since that time have been relayed through ground stations using the spacecraft's omnidirectional antenna. According to a project official, all available ground stations, including both Ground Network and Deep Space Network sites, have been used, with the Guam (Ground Network) station being used most frequently. The spacecraft's orbit has degraded naturally over time, due to atmospheric drag, and the spacecraft is expected to reenter the earth's atmosphere in December 1989. However, the project's director said that if the Solar Maximum Mission were to continue operations, the planned Ground Network station closings would reduce the amount of scientific data recoverable from the mission by 60 percent.

A spacecraft's TDRSS communications system also potentially can fail if the signal amplifiers associated with the TDRSS antenna degrade with use. For example, the operations director for the Landsat missions, which provide detailed images of the earth's surface to commercial users, said that these signal amplifiers have only lasted from nine months to two years. According to this official, the Landsat-4 spacecraft has both a prime and a backup amplifier for TDRSS communications. One of these has failed, and the remaining amplifier has approximately two to three years of service left. Once it is gone, transmission through TDRSS will no longer be possible. The Landsat-5 spacecraft's prime amplifier has also failed, with a backup amplifier now performing erratically. The Landsat operations director said that the potential for failures in on-board TDRSS communications equipment was another reason why a ground-based backup communications system offering wide global coverage is needed. In his opinion, stations at Hawaii and Ascension could significantly add to the probability that ground stations will be available in the proper locations to provide emergency backup communications support.

Project officials of some future missions, such as the Hubble Space Telescope and Upper Atmosphere Research Satellite, are also concerned about this problem because NASA's position is not to provide for ongoing ground-based communications, including the transmission of scientific data, in the event that TDRSS communications become impossible. NASA documents defining communications support services for spacecraft missions specifically exclude capture of scientific data from the services to be provided during an emergency. The Deep Space Network ground stations will provide only "health and safety" backup communications support for spacecraft experiencing emergencies, according to these documents. Such support is envisioned to last one or two days; there is no pre-arranged provision for long term support, including transmission of scientific data.

A June 1988 study by the Jet Propulsion Laboratory shows that the 26-meter antenna system at the Deep Space Network sites that would provide emergency support to earth orbiting spacecraft is already heavily loaded with normal support requirements for other earth orbiting missions. These normal support requirements plus a 10 percent reserve to support spacecraft emergencies account for more than 90 percent of the system's capacity. Goddard officials stressed that, in an emergency, a spacecraft experiencing problems will be given the first priority for use of communications systems. Officials at both Goddard and the Office of Space Operations confirmed that, even if these antenna systems were designated to provide longer term scientific data support, there would be little or no capacity to receive transmissions through this antenna system without pre-empting support that has already been allocated to other missions.

The Associate Administrator for Space Operations said that since 1975 NASA's decision has been to provide emergency backup support for the safety and proper functioning of the spacecraft only and not for the transmission of scientific data to the ground, since operating both a space-based network and a ground network would be too expensive. Instead, some future missions — the Hubble Space Telescope and Gamma Ray Observatory — will be serviced by space shuttle missions. For example, the Hubble Space Telescope is scheduled to be periodically serviced on orbit, and an on-board TDRSS communications problem could be fixed at that time, or the spacecraft could be returned to earth for repair and launched again at a later date. According to the Associate Administrator, other missions that are not designed for on orbit servicing may not be able to continue science operations if their TDRSS communications system fails. We asked the Office of Space Operations for formal documentation of this decision, however the Office was unable to provide any.

Reliability of the TDRSS White Sands Ground Terminal

All transmissions to and from the TDRSS satellites pass through the White Sands Ground Terminal in New Mexico. The region's dry climate and sparse rainfall favors heavy electronic traffic. The terminal began operating in 1983 with the launch of the first TDRSS satellite.

NASA has encountered problems with the reliability of the automated equipment and software at the White Sands terminal. Numerous system outages, lasting from a few minutes to several hours or more, have occurred since the White Sands terminal began operating in 1983. When such a system outage occurred, earth orbiting spacecraft had to rely on ground stations for all communications.

We reviewed various types of statistical data that NASA has collected relative to the reliability of the TDRSS White Sands Ground Terminal. However, none of the available data appeared to give an accurate portrayal of the reliability of the station. Also, some of the data was not available for the first three years of the terminal's operation, 1983 - 1986.

TDRSS program officials believe the design of the terminal, which allows for numerous single points of failure, increases the risk of a system outage. A single point of failure is any subsystem or component which, if it fails, causes the entire system to fail. Single points of failure exist throughout the computer and communications systems and can be caused by hardware or software failures as well as operator errors or environmental factors.

NASA officials report that the White Sands terminal has tended to be unavailable for 3 to 4 hours a month due to failures within the computer systems at the terminal. According to TDRSS officials, failures requiring a restart of the central computer system result in outages of at least 15 minutes. Other types of failures, that require a resynchronization of the entire network at the terminal, result in 45 to 60 minute outages.

NASA is in the process of constructing a Second TDRSS Ground Terminal at White Sands in large part because of concerns about the reliability of the original terminal. The second terminal will provide a backup to the existing terminal and eliminate it as a single point of failure. When the second terminal is complete, the original terminal will be completely overhauled to be identical with the new terminal. The second terminal is scheduled to be completed in 1993, at a cost of approximately $427 million. Because it is investing heavily in the second terminal, NASA is not planning major upgrades of the existing terminal before that time. However, officials of the Office of Space Operations said they intended to spend approximately $2 million each year on minor upgrades to the existing terminal until shortly before the new terminal opens.

A Shuttle official said that the Office of Space Flight is concerned that communications be available during the critical time when the Shuttle is inserted into earth orbit. Because of concerns about the reliability of the White Sands terminal, which directly affect the availability of TDRSS, NASA has determined that the ground station at Dakar, Senegal should be kept open to provide backup support for Shuttle orbital insertion. The Dakar station is currently scheduled to remain open through fiscal year 1990. Officials at the Goddard Space Flight Center have concurred with the assessment that the ground station at Dakar, Senegal should be kept open until that time to support the shuttle.

Objectives, Scope, and Methodology

The House Committee on Science, Space, and Technology, Subcommittee on Space, Science, and Applications asked us on November 7, 1988 to report on NASA's plans for providing emergency communications support for earth-orbiting spacecraft, including information on spacecraft emergencies that have occurred that required backup communications support over the past few years and the reliability of the TDRSS White Sands Ground Terminal.

To accomplish these objectives, we obtained official documentation of NASA's emergency backup communications support plans both for spacecraft emergencies and TDRSS failures and discussed this information with representatives from Goddard Space Flight Center's Networks Division as well as individual spacecraft projects. Specifically, we discussed support requirements with representatives from the Hubble Space Telescope, Landsat, Upper Atmosphere Research Satellite, Solar Maximum Mission, Earth Radiation Budget Satellite, Cosmic Background Explorer, and Space Shuttle projects. We also obtained and analyzed historical data concerning spacecraft emergencies that occurred between 1982 and 1987. We visited the TDRSS White Sands Ground Terminal and reviewed technical data on the reliability of the TDRSS White Sands Ground Terminal in order to obtain information on TDRSS network outages. We did not independently verify NASA's cost estimates for developing future spacecraft, implementing alternative backup support options, or operating and upgrading existing ground stations. We also did not attempt to independently assess the impact of the station closings on individual projects.

In performing these tasks, we interviewed NASA officials at NASA headquarters in Washington, D.C., Goddard Space Flight Center in Greenbelt, Maryland, the Goldstone Deep Space Complex in Goldstone, California, the Jet Propulsion Laboratory in Pasadena, California, and the TDRSS White Sands Ground Terminal in Las Cruces, New Mexico. We performed our work between November 1988 and March 1989, in accordance with generally accepted government auditing standards.

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