AEROSPACE REPORT NO.
TOR-98(1550)-3

Tracking the Tempests: The Creation of the SSMIS

January 1999

Prepared by

A. A. FOTE
Electronic Systems Division
Engineering and Technology Group

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE MATERIEL COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

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TRACKING THE TEMPESTS: THE CREATION OF THE SSMIS

Approved by

P. J. Peters, Director
Electro-Optical Systems Department
Electronic Systems Division

R. J. DeLorenzo, Principal Director
DMSP
Polar Orbiting Environmental Satellite Systems
Space Systems Group

The information in a Technical Operating Report is developed for a particular program and is not necessarily of broader technical applicability.

Abstract

This document describes the development of a sophisticated set of new space-based sensors designed to measure microwaves emitted by Earth's atmosphere and surface. Meteorologists combine such data with that from other sources in order to evaluate and predict weather conditions.

The construction of these sensors did not proceed easily. Originally projected for completion in October 1992, the Air Force received the first of the five units 5 years after that date.

We present the following history, not to criticize, but to inform. Those attempting to design and build hardware of any sort do well to study the experiences of their predecessors. A motto of research and development states that one learns far more by studying difficulties and failures than successes. This holds true because such difficulties usually arise because one has entered previously uncharted territories of engineering knowledge.

We also emphasize that, despite all of the setbacks along the way, the completed sensors represent a great technological achievement. The major fault lies with an initial underestimation of the magnitude of effort required.

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1. INTRODUCTION

At 7:00 am on October 10, 1997, just as an ascending red sun cleared the peaks of the San Gabriel Mountains, a tractor-trailer circled Building 160 at the Aerojet facilities in Azusa, California and then gently backed against the loading dock. A short time later technicians opened the loading dock doors and wheeled out a large gray shipping container which the truck would transport to Princeton, New Jersey. There, other technicians would open the container and mount the contents onto one of the Air Force's newest weather satellites, at that moment under assembly and testing.

The shipping container encased a sophisticated sensor, the first of five, with the long-winded name of Special Sensor, Microwave Imager/Sounder (SSMIS). To dissect this title, we explain that the sensor measures the intensity of microwaves emitted by components of the Earth's atmosphere. Complex computer algorithms use those data to determine how the temperature and humidity of the atmosphere varies with altitude. Thus, they generate profiles, or to borrow an old Navy term, make "soundings" of the atmospheric sea. The sensor also generates microwave images which provide a variety of additional information about the surface of the Earth. These include, among others, the moisture of the soil, the wind speed at the ocean surface, and the concentration and age of ice sheets.

The imagery and soundings will ultimately become distributed world-wide. Meteorologists operating computers in Omaha will use them for long range weather forecasts. Military personnel will use small mobile computers to determine local weather conditions. Finally, researchers will experiment with the data to find ways to improve their algorithms for weather and climate analysis.

SSMIS represents the second generation of fully operational space-based microwave sensors (Fig. 1). Detecting microwaves at 24 channels, covering various frequencies and polarization, it will combine, and extend, the capabilities of three separate sensors in current use, specifically SSM/T1 and SSM/T2, which perform temperature and humidity soundings respectively, and SSM/I, an imager which gathers data about the surface of the Earth.

On the exterior, SSMIS most resembles a work of modern art (Fig. 2). The main section has the overall shape of a cylinder with an octagonal cross section, the whole covered with arrays of heat-reflecting mirrors and of gold-colored thermal blankets. In operation, this "canister" spins on its axis so that the mirrors reflect a kaleidoscope of colors. A parabolic dish, attached to the sensor and rotating with it, receives the microwaves emitted by the atmosphere and focuses them onto a line of six microwave feedhorns which project from the top of the glittering canister.

If one removes the mirror-covered panels and peers inside the canister, one discovers an astonishingly intricate and densely packed structure of electronic components (Fig. 3). In fact, this sensor has approximately 60% higher internal density than its predecessors. Meanwhile, the sensor

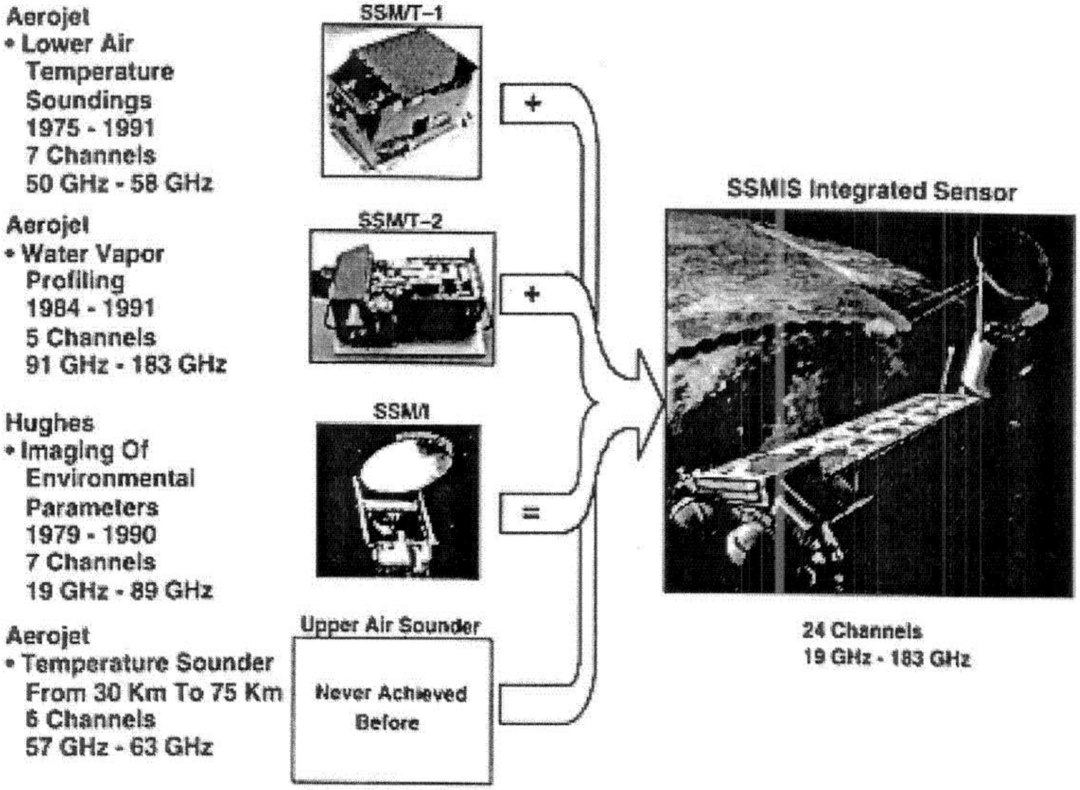


Figure 1. Evolution of DMSP microwave sensors.

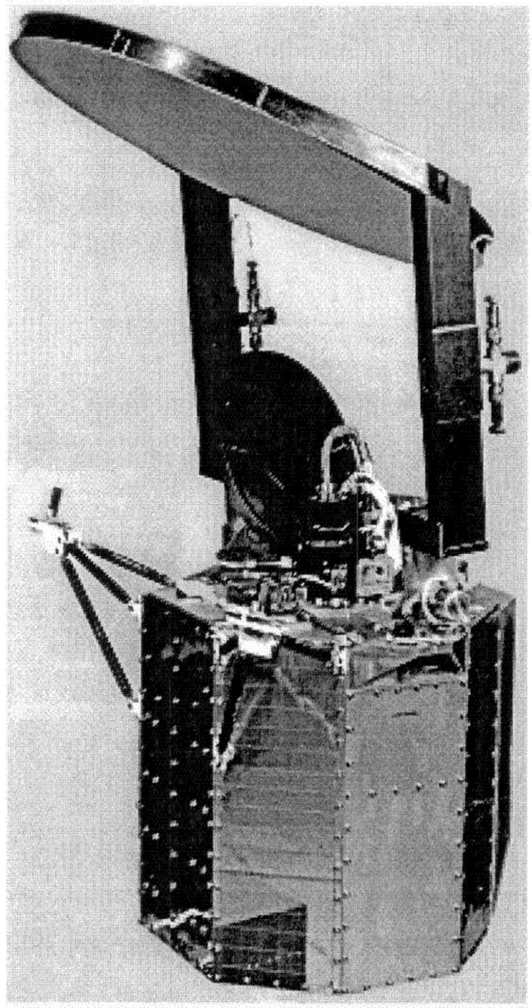


Figure 2. SSMIS with main reflector deployed.

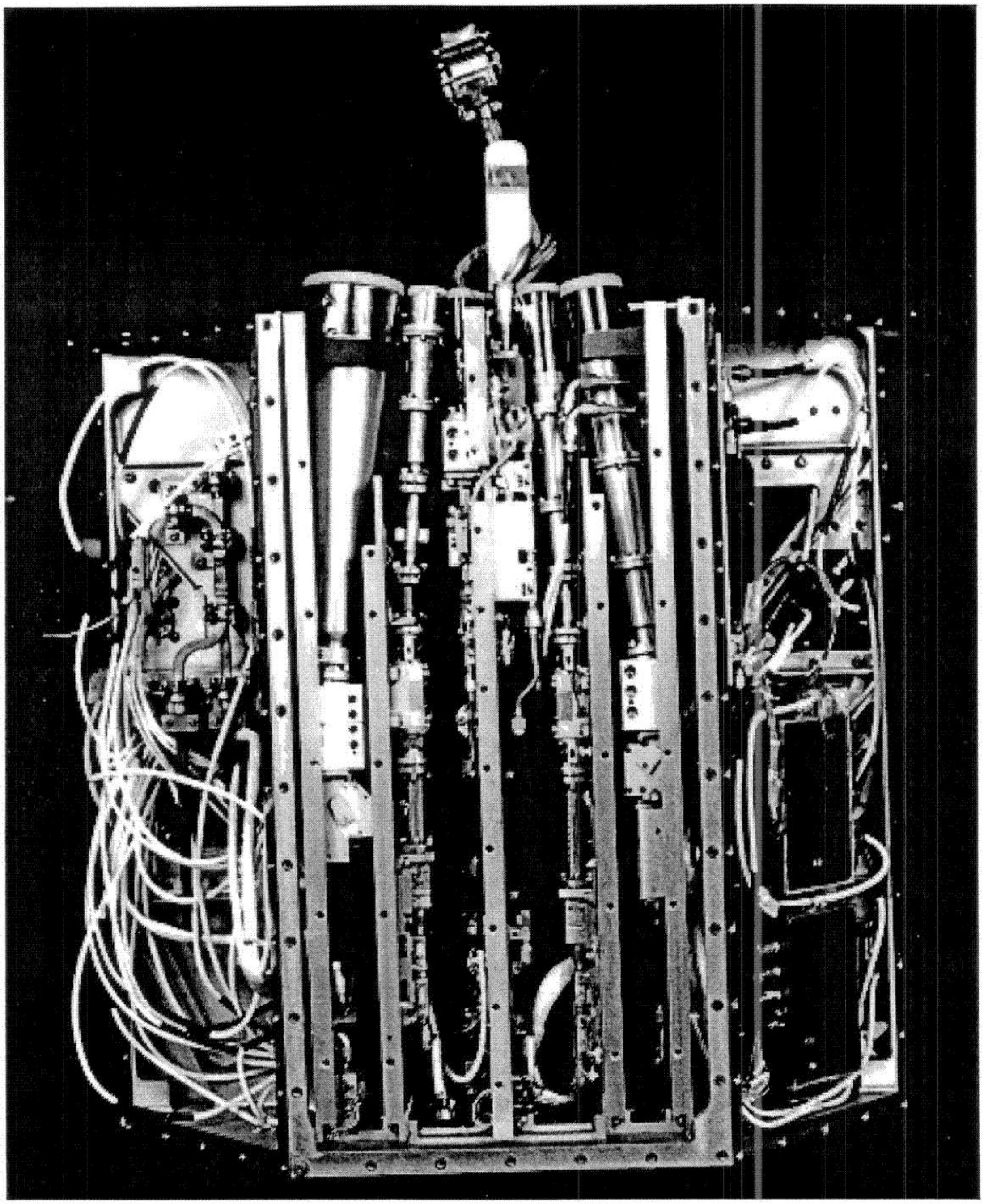


Figure 3. Canister with panels removed to reveal receiver shelves and their upward viewing feedhorns.

has 88% and 50% higher sensitivity than its predecessors in measuring temperature and water vapor, respectively.

Unfortunately, the construction of this first SSMIS did not progress easily. Originally projected for completion in October, 1992, its appearance on the loading dock occurred 5 years beyond that date. As costs escalated and schedule delays followed each other with dismaying regularity, the program eased close to cancellation on a number of occasions. Vexing problems multiplied and emergency "Red Teams" of experts gathered to discuss possible solutions. At the program's nadir, the contractor instituted a lawsuit against the U. S. Air Force to recover part of the funds that overran contract values.

In this document, we present a technical history of the SSMIS program, up to the delivery of the first sensor. We emphasize that term "technical." We have the goal of explaining the many unexpected difficulties managers and engineers usually confront in designing and building such a complex assemblage of hardware.

On the other hand, we have not, for the most part, discussed high-level government decisions during the life of the program. Obviously, the Air Force confronted many difficult choices, first in defining the contract, and then in re-evaluating it as difficulties mounted over the years.

Section 2 of this report describes the SSMIS operation and hardware. Section 3 chronicles the events up until the October, 1997 delivery date. The fourth section summarizes the major problems that plagued the program and seeks the underlying causes. Section 5 offers a yet wider view and presents conclusions and "lessons learned."

Many readers may find it advantageous to initially skip over the Hardware section and proceed directly with Chronology. They can then treat the Hardware section as a reference, returning to it as desired for further information. Furthermore, readers less interested in a detailed Chronology can skip that section as well; they will find a summary of events and a list of lessons learned in the fourth and fifth sections.

Although this document reveals apparent errors of judgment, it does not seek to cast blame. Instead, it recognizes that SSMIS represents a new and highly complex sensor. Development efforts such as this send designers into a technological wilderness only partially explored. Human limitations and technological complexity will always combine to result in mistakes, underestimates, and oversights. Although one cannot eliminate such events, one can learn from them and plan accordingly.

2. HARDWARE DESCRIPTION

2.1 Canister

The main portion of the SSMIS, the canister, has the overall shape of a cylinder but with an octagonal cross section. It has approximate dimensions of 17 in. height and 18 in. width (Fig. 2). To provide passive temperature control, an array of sunlight-reflecting mirrors and gold-colored mylar blankets encase its outer surfaces. Mounted atop the canister, a large parabolic reflector receives the ascending microwaves emitted by Earth's atmosphere (Fig. 4) and focuses them downward into six feedhorns which project out of the upper surface of the canister (Fig. 3). Via the reflector, therefore, the feedhorns' field of view extends 45 deg from the vertical in the downward direction. The canister and reflector rotate together once every 1.9 sec and, as they do so, that field of view sweeps out an arc that lies athwart the direction of travel of the spacecraft. In consequence, because of the orbital motion of the spacecraft, the arcs combine to provide coverage over a wide swath of the atmosphere below.

In its stowed position, prior to deployment, the reflector lies folded down against the top of the canister. The firing of pyroelectric explosives releases the reflector allowing it to swing into its final position on its hinges (Fig. 5).

2.2 Calibration Subsystem

The feedhorns view the main reflector, and Earth, during only half of the canister's rotation. During the other half of the sweep, they pass below two other components which, attached to the central axis of the canister, remain stationary. These two components allow the SSMIS to calibrate itself every rotation by providing two microwave signals of fixed and known intensity. One of these calibrators, the "warm load," consists of a microwave-emitting temperature-controlled "target" (Fig. 6). The other calibrator consists of a small parabolic reflector which directs the feedhorns to view cold empty space (Fig. 2). Together, then, the warm load and the cold calibration reflector generate known microwave signals at the upper and lower ends of the range of measurement. This allows the sensor to measure microwave energy, in units of radiometric brightness temperature, to an accuracy of better than 1 K.

Upon deployment, after release of the main reflector, the cold calibration reflector must also rotate and lock into its operational position.

2.3 Deployment Subsystem

After launch and orbital insertion, the SSMIS sensor must deploy from its stowed configuration by simultaneously rotating 90 deg to the upright position and translating outward. The deployment subassembly (Fig. 7), mounted between the sensor and the spacecraft, accomplishes this

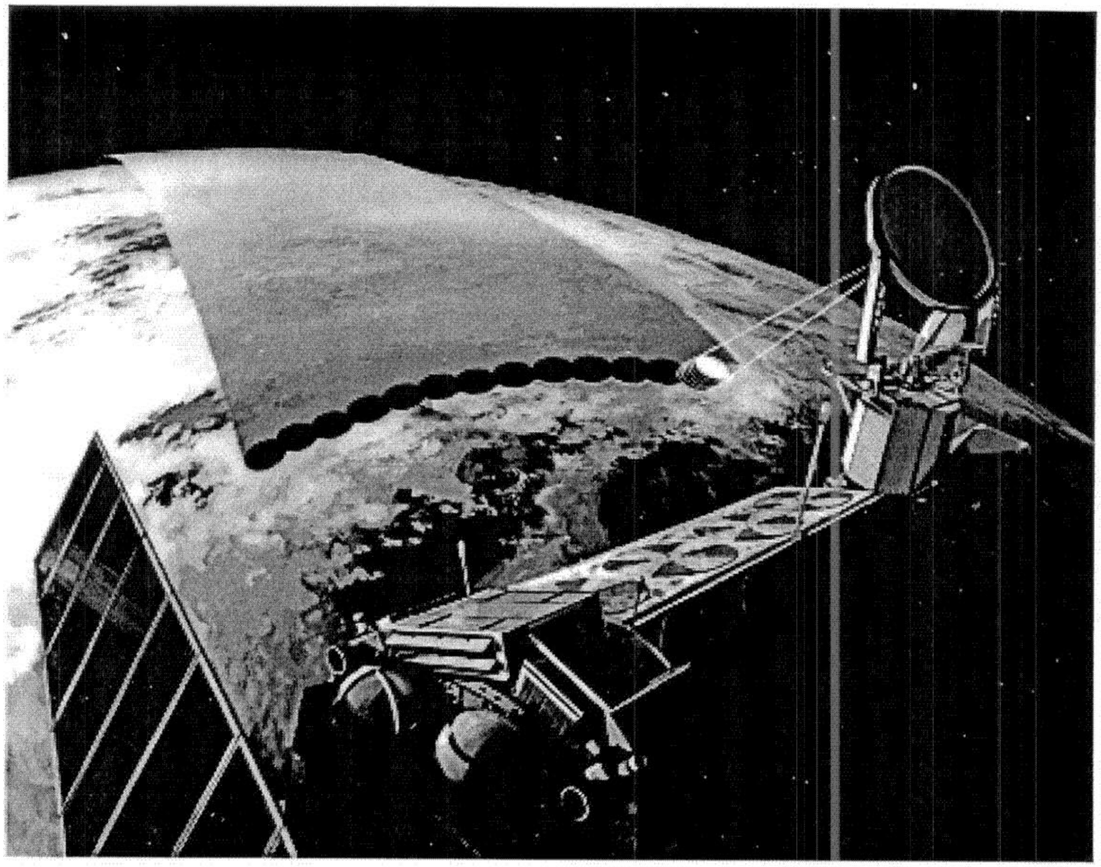
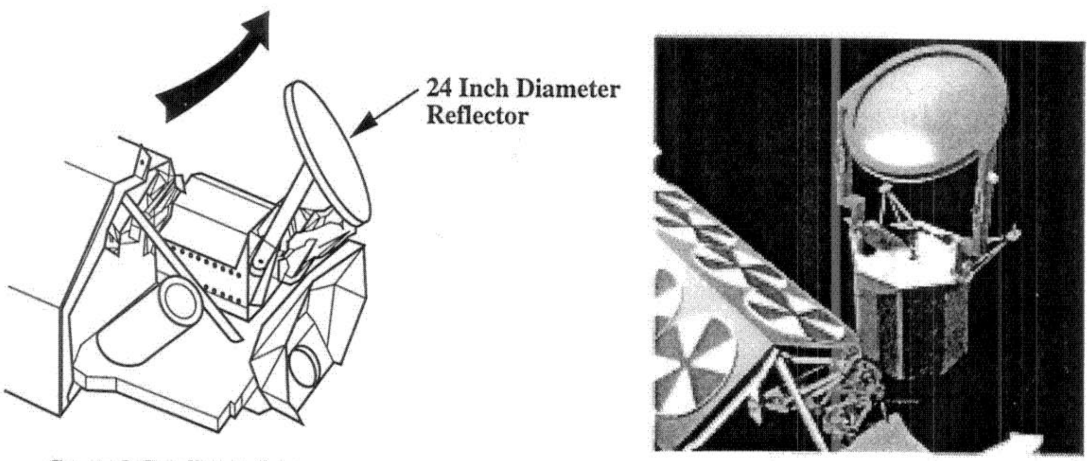


Figure 4. SSMIS, mounted on the spacecraft, rotating, and collecting microwave data.



Stowed Configuration

Deployed Position

Figure 5. Deployment of the SSMIS.

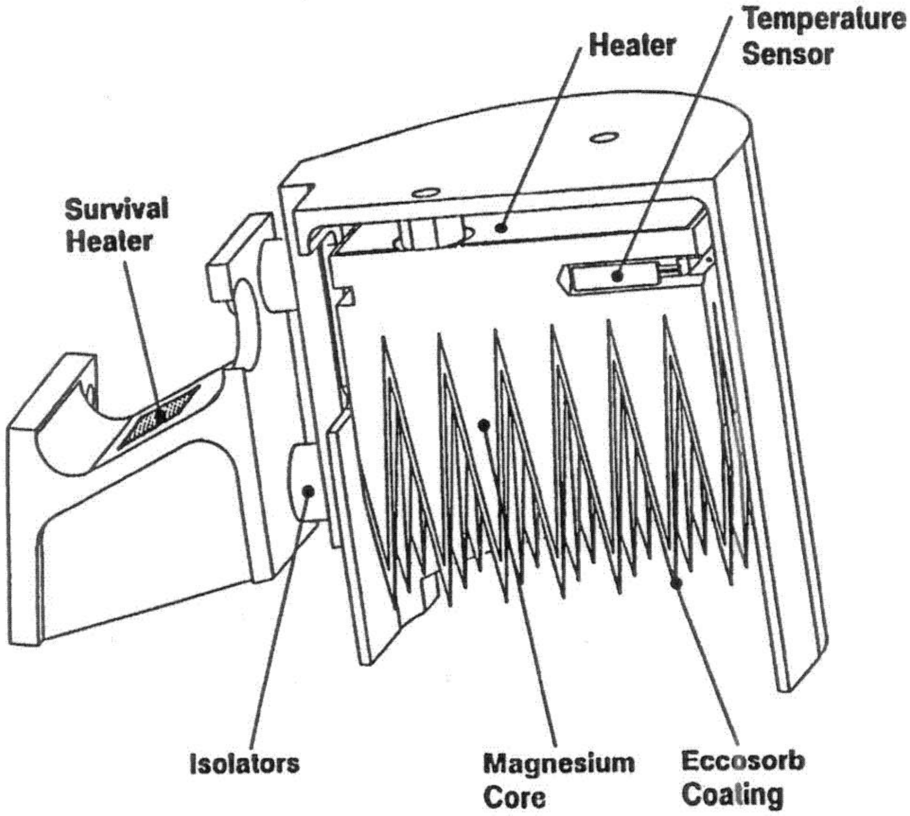


Figure 6. Sketch of the warm load calibration target, normally mounted atop thecanister.

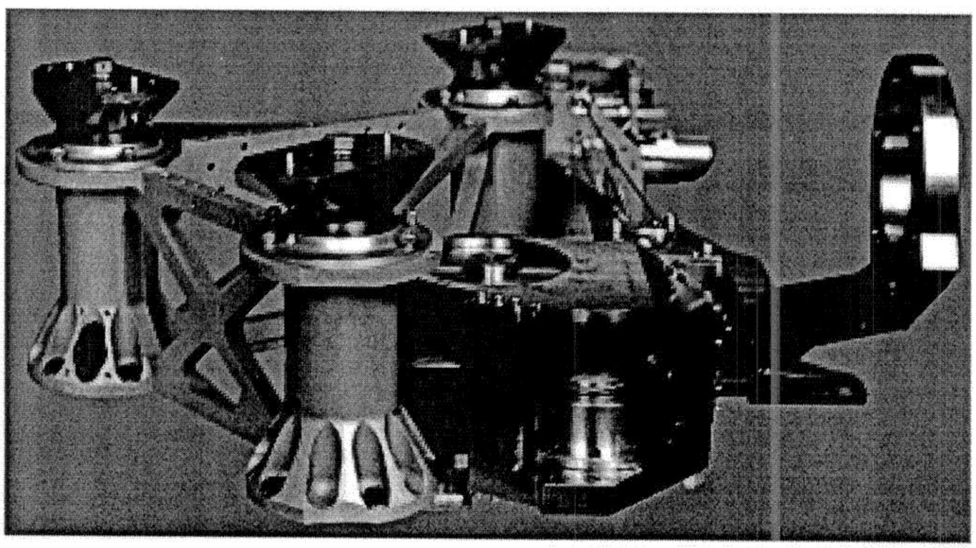


Figure 7. Deployment subassembly in the deployed configuration. The canister mounts onto the annular structure at the far right..

task, as well as continuing to support the sensor afterward. It consists of a support arm, to which the sensor attaches, and a base, which bolts onto the spacecraft. During deployment, two spring motors in the base pull the support arm along a track, thereby providing the necessary translation. Along its length, the track carries a spiral guide which rotates the arm during the translation.

The design proved challenging in requiring redundant motors of sufficient strength to deploy the sensor within the specified time period while not exceeding the restrictive weight and volume budget.

2.4 Scan Drive Subsystem

This consists of the scan drive assembly and the scan drive electronics (SDE).

The scan drive assembly has the shape of a long narrow cylinder that fits inside the canister and astride its long, vertical, axis of rotation (Figs. 8, 9). It has two main functions. The bottom portion contains the motor that spins the sensor once every 1.9 sec. The upper portion contains 24 slip-ring/brush assemblies. These serve to transfer power and data between the rotating outer canister and the stationary central core, attached, via the Deployment Subassembly, to the spacecraft.

The scan drive electronics box, mounted on the spacecraft as a separate package, and connected to the scan drive assembly via cables, contains the circuitry which primarily controls the spin of the sensor.

2.5 Receiver Subsystem

Inside the canister, five closely-spaced vertical metal plates support both the six feedhorns and a dense assemblage of associated microwave and radio frequency (RF) circuitry (Figs. 10, 3). The centrally positioned receiver shelf, A3 (Fig. 11), has the highest complexity and has proven the most difficult. It carries the two smallest feedhorns, which detect radiation at the highest frequencies of 150 GHz (channel 8), 183 GHz (channels 9-11), and 91.655 GHz (channels 17-18). It also carries two Gunn diode oscillators, which require their own temperature control heaters mounted on the shelf. The microwaves from the feedhorns combine, via mixers, with microwaves generated in the Gunn diode oscillators, to generate lower frequency RF signals. For this purpose, channels 8 through 11 use two G-band mixers manufactured by Aerojet. Channels 17 and 18 use mixer/amplifier combinations provided by a vendor.

The A2 and A4 receiver shelves detect microwaves over the range 50 to 56 GHz (channels 1-5) and 57 to 63 GHz (channels 6-7 and 19-24). They also use mixers to downshift their frequencies into the RF band. For the requisite reference frequencies, they use signals generated in phase locked oscillators (PLO) (Fig. 12), mounted separately in the canister.

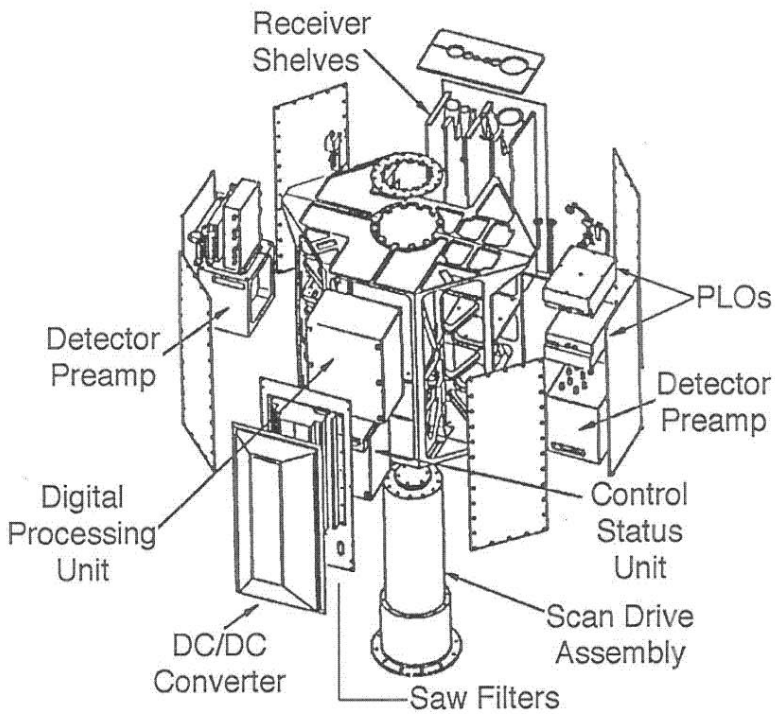


Figure 8. Exploded view of the SSMIS canister.

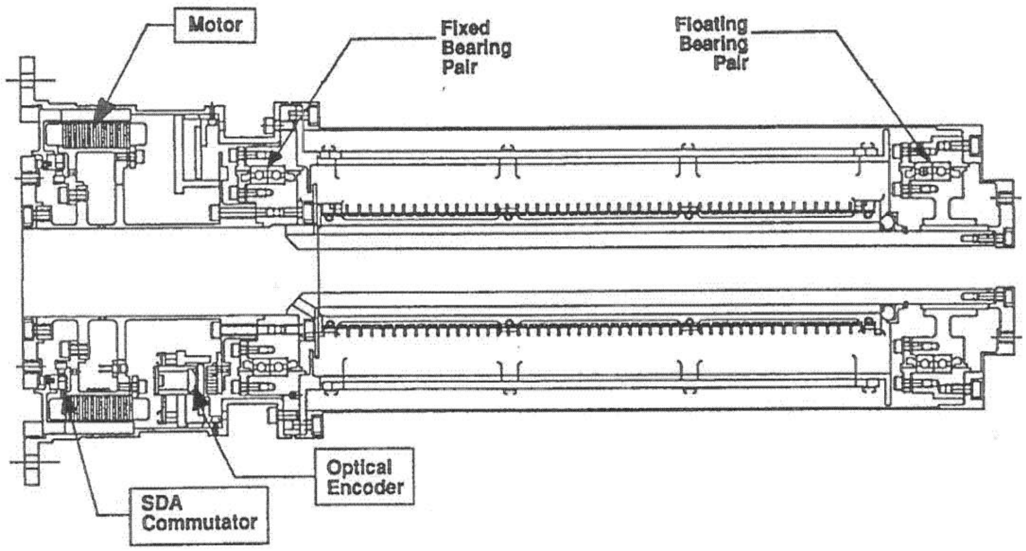


Figure 9. Sketch of the scan drive assembly.

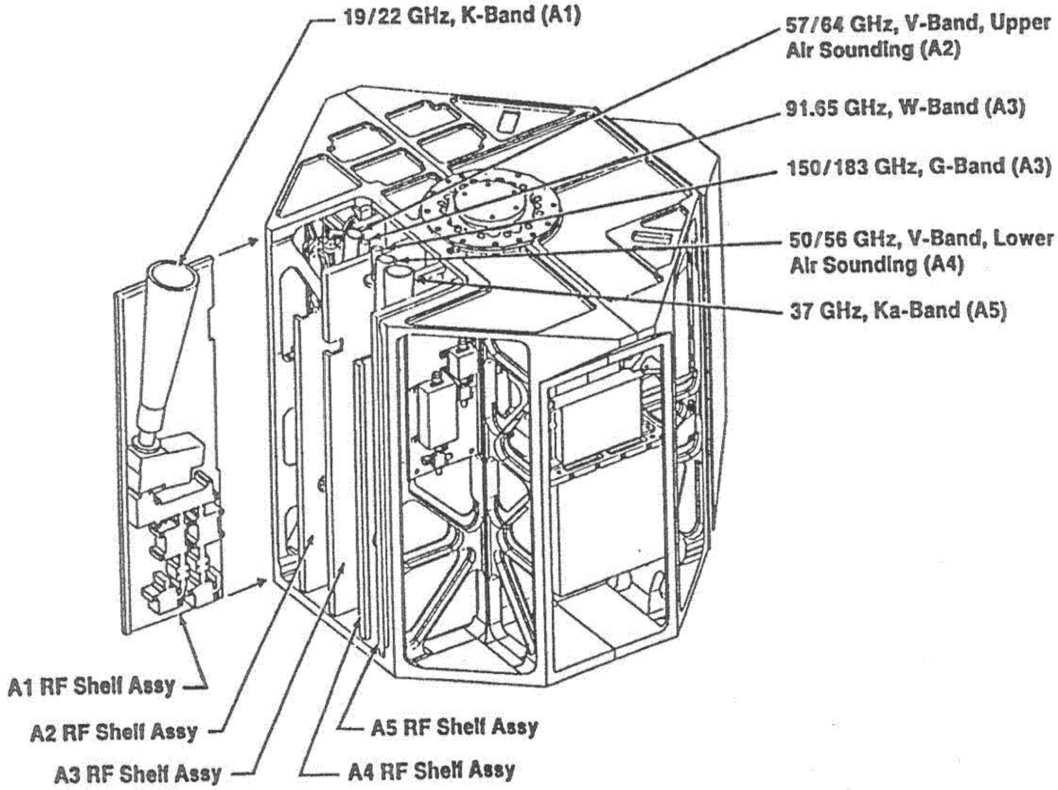


Figure 10. Sketch showing placement of receiver shelves in the canister.

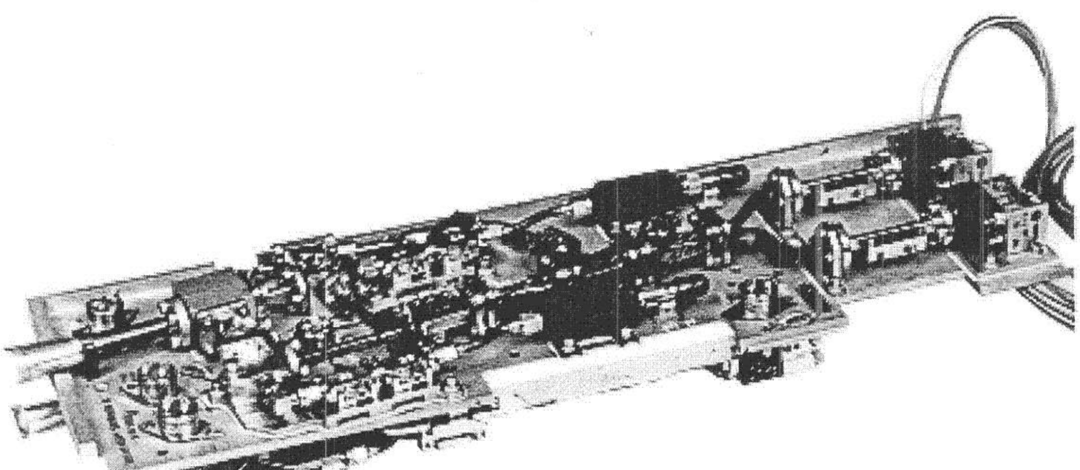


Figure 11. A3 receiver shelf.

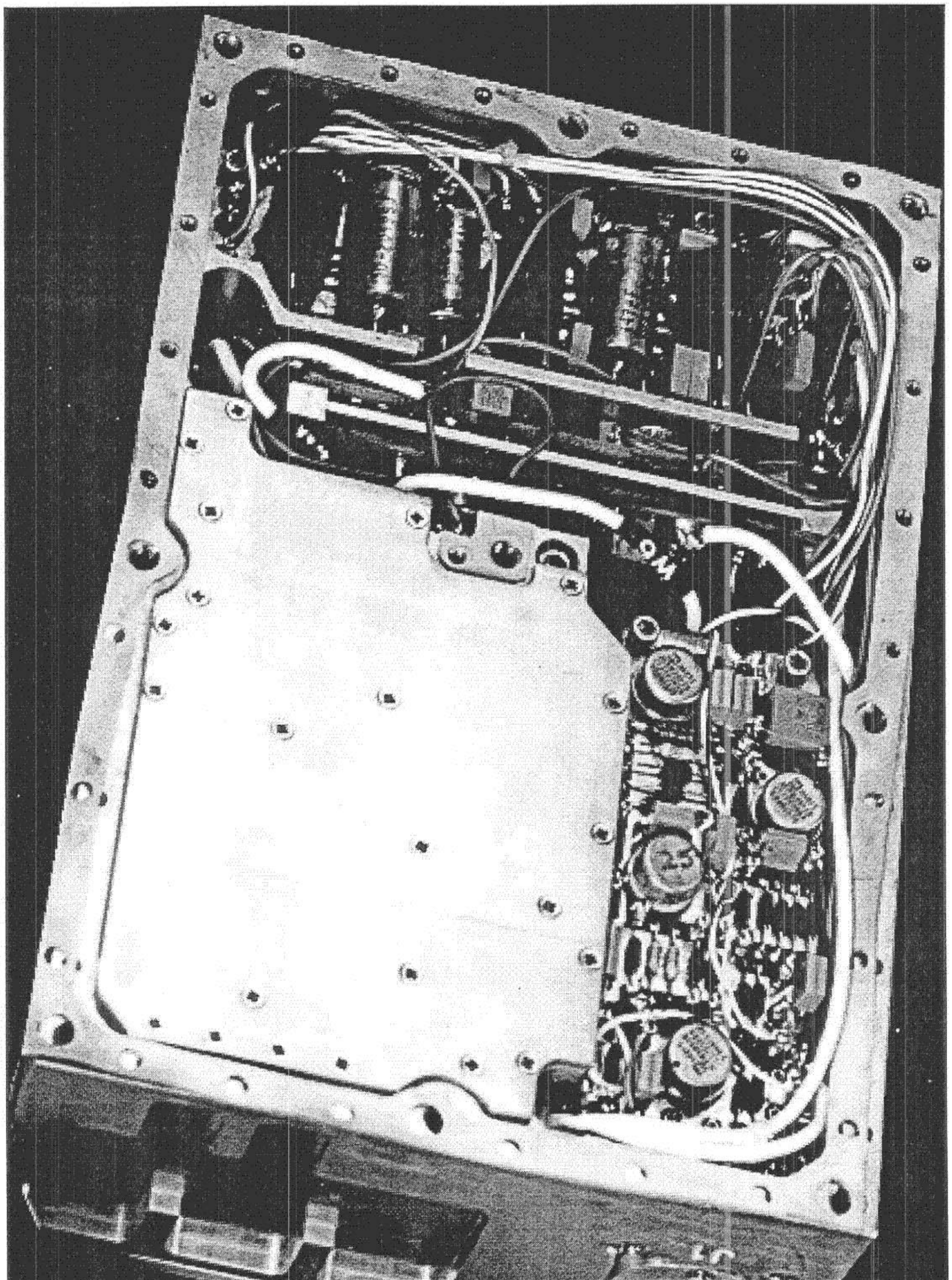


Figure 12. Phase-locked oscillator with cover removed.

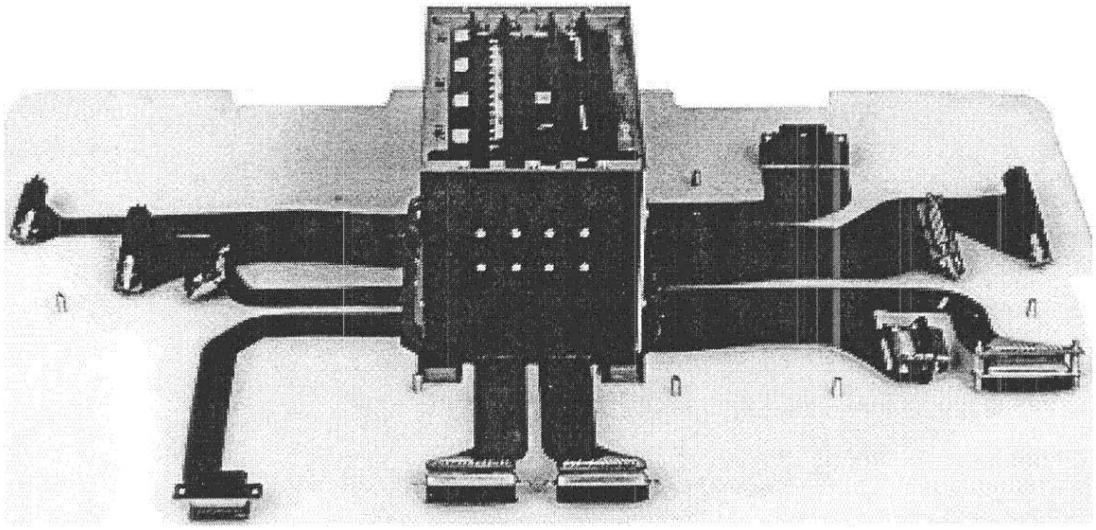


Figure 13. Digital processor unit.

The A1 and A5 receiver shelves carry the largest, lowest frequency feedhorns. They detect microwaves at 22 GHz (channel 14) and horizontally and vert3ically polarized microwaves at 19 GHz (channels 12-13) and 37 GHz (channels 15-16). The A1 and A5 channels do not use mixers, and detectors on the shelves directly demodulate and amplify the signals.

2.6 Signal Processor Subsystem

This consists of a number of electronics-encased boxes which perform a variety of functions relating to data processing, telemetry, power distribution, and sensor control (Fig. 8).

The detector preamp box receives the microwave signals from either the surface acoustic wave (SAW) filters (for channels 19-24), multiplexers (for channels 1-7), or directly from the receiver shelves (all the other channels). This box demodulates the signals from all channels except 19 through 24, already demodulated, and amplifies them further.

The control status unit primarily receives and conditions various telemetry signals, controls the heaters, and distributes power.

The digital processor unit, also called the signal processor, responds to commands sent via the spacecraft, synchronizes the data acquisition with the rotation of the sensor, and works with the sensor data. In the latter capacity, it receives the data, performs the calibration, formats the data, and transmits it to the spacecraft.

Each of these three boxes contains a motherboard into which plug a number of smaller circuit boards. Because of the severe weight and volume constraints, the boxes do not use typical cables for wiring. Instead, the motherboards have, hard-wired to them, flat, flexible multilayer ribbon cables. The board for the digital processor unit has the greatest complexity (Fig. 13). The rigid board has conducting leads in a total of 12 sandwiched layers. It has, attached to its perimeter, 11 flexible cables, which carry between 20 and 40 conductors in six layers. These cables must often accommodate sharp bends in order to maneuver through the narrow spaces available. Hence, technicians must exercise extreme care to avoid fracturing the delicate wires inside. We know of no other space programs that use flex cables let alone ones of this complexity.

Finally, the DC/DC converter receives the 28 volt power supplied by the spacecraft, converts it to various lower voltages, and distributes them via 14 output lines to their required destinations. Here again, the size requirements necessitated that Aerojet hybridize the circuitry, packing a large amount of electronics into a relatively small package. Both the resulting complexity and heat dissipation contributed to the design challenge.

2.7 Surface Acoustic Wave Filters

Channels 19 through 24 detect microwaves emitted by the upper atmosphere, the so called "upper air sounding channels." Upon leaving the A2 receiver shelf, the signals pass through the SAW filter assembly, which selects the microwave bands of interest. For channels 19 and 20, the SAW filter transmits signals that fall within two bandwidths. For each of these channels, the circuitry contains two filters in parallel. For channels 21 through 24, the SAW assembly passes signals within four bandwidths, requiring four parallel filters each. In consequence, the SAW filter assembly contains 2x2 plus 4x4 filters for a total of 20.

As an example, consider channel 21. The incoming signal divides into four equal-intensity signals for the four parallel filters. The vendor tunes these filters for the proper bandwidths by adjusting inductors in the circuitry. This tuning involves a tedious iterative process because adjusting one filter alters the tuning of neighboring filters. This occurs due to the proximity of the filters and the impedance mismatch of the circuits. Meanwhile, the mechanical stress of bolting the filter in place could cause enough mechanical motion to alter the bandwidths.

A better design could have involved power splitters and impedance matching to better isolate the individual filters. However, that would have necessitated additional amplifiers and the resultant higher power consumption, something the power budget could ill afford. In fact, only one out of the three vendors initially approached chose to attempt construction of the SAWs given their difficult power budget.

2.8 Phase Locked Oscillators and Reference Oscillator/Calibrator

The PLO (Fig. 12) and reference oscillator calibrator (RO/C) must work together to perform demanding and critical tasks. The PLOs generate three separate high frequency microwave signals of 56.4, 6.768, and 4.512 GHz. Channels 1 through 7 and 19 through 24 use the 56-GHz output to downshift, via mixers, the incoming microwave signals into the intermediate frequency range for subsequent processing. Channels 19 through 24 use the two other outputs to perform a second frequency downshifting prior to sending the signals onto the SAW filters.

Channels 19-24, because of their narrow bandwidths, also require compensation for the frequency shift introduced, because of the Doppler effect, by the motion of the spacecraft. In consequence, the 6.7 and 4.5 GHz outputs must have an approximately 1 MHz sinusoidal variation in their frequencies. This originally introduced a 4 to 5 K calibration error due to variations in gain over that tuning range. Hardware and software modifications succeeded in reducing this below the 1 K specification. At the same time, the circuitry must insure the long term stability of these outputs to better than 60 kHz, 100 times tighter than on the previous microwave sensors. The RO/C provides for this stability. It compares its own generated frequency with that from the PLOs and sends the latter an appropriate correction signal.

Altogether, in a box 5.7 x 3.9 x 1.9 inches, the PLOs contain a 56-GHz Gunn diode oscillator, a 56-GHz harmonic mixer, a 6.7-GHz and a 4.5-GHz dielectric reference oscillator, a 141-MHz oven controlled, voltage controlled, crystal oscillator, and associated amplifiers and power supplies. The vendor must carefully tune the circuits to eliminate spurious harmonic output frequencies and cross coupling of signals. And, usually, repair of one circuit disrupts the operation of the other circuits due to their close proximity in the small volume.

A better approach would have involved a modular design, with the separate functions isolated from one another and capable of individual replacement. However, such a partitioned arrangement would not have met the size and weight restrictions.

2.9 G-band Mixers

Channel 8 requires a 150-GHz mixer to downshift the microwave signal into the intermediate frequency band. Channels 9 through 11 require a 183-GHz mixer for the same purpose. Unable to procure such flight-qualified devices of sufficient sensitivity from a vendor, Aerojet undertook the task of acquiring the components and establishing their own assembly and test facility.

The housing (Fig. 14), of dimensions 1.125 x 0.9 x 0.5 inches, consists of solid brass with a copper waveguide insert all precisely manufactured to extremely tight tolerances. Although Aerojet initially required gold plating of the housings, they later dropped this specification in light of the poor manufacturing yields of such housings.

Nestled in a small cavity in the housing lies a quartz substrate (Fig. 15), 341 mils long by 30 mils wide by 3 mils thick. This substrate carries a thin metal film antenna for receiving the incoming signal microwaves from the feedhorn and the reference microwaves from the Gunn diode oscillator. The substrate also carries, at one end, a tiny microchip, 10 by 5 by 3 mils, carrying two parallel GaAs diodes. The diodes (Fig. 16) combine the two microwave inputs and generate, as a beat signal, an output in the form of a lower frequency intermediate frequency (IF) signal.

Two 2-mil wide gold ribbons establish electrical contact between the diode end of the substrate and the brass housing. Only after many failures and much experimentation was Aerojet able to position the substrate and attach the wires to obtain stable and reliable mixers. Early mixers exhibited poor stability from having the wires too long. Shortening the wires in later mixers led to fractured wires due to the lack of stress relief. Aerojet subsequently restored stress relief by incorporating an indium pad at the housing end of the wires. Meanwhile, they improved the design and assembly of the mixers in numerous other ways over the years.

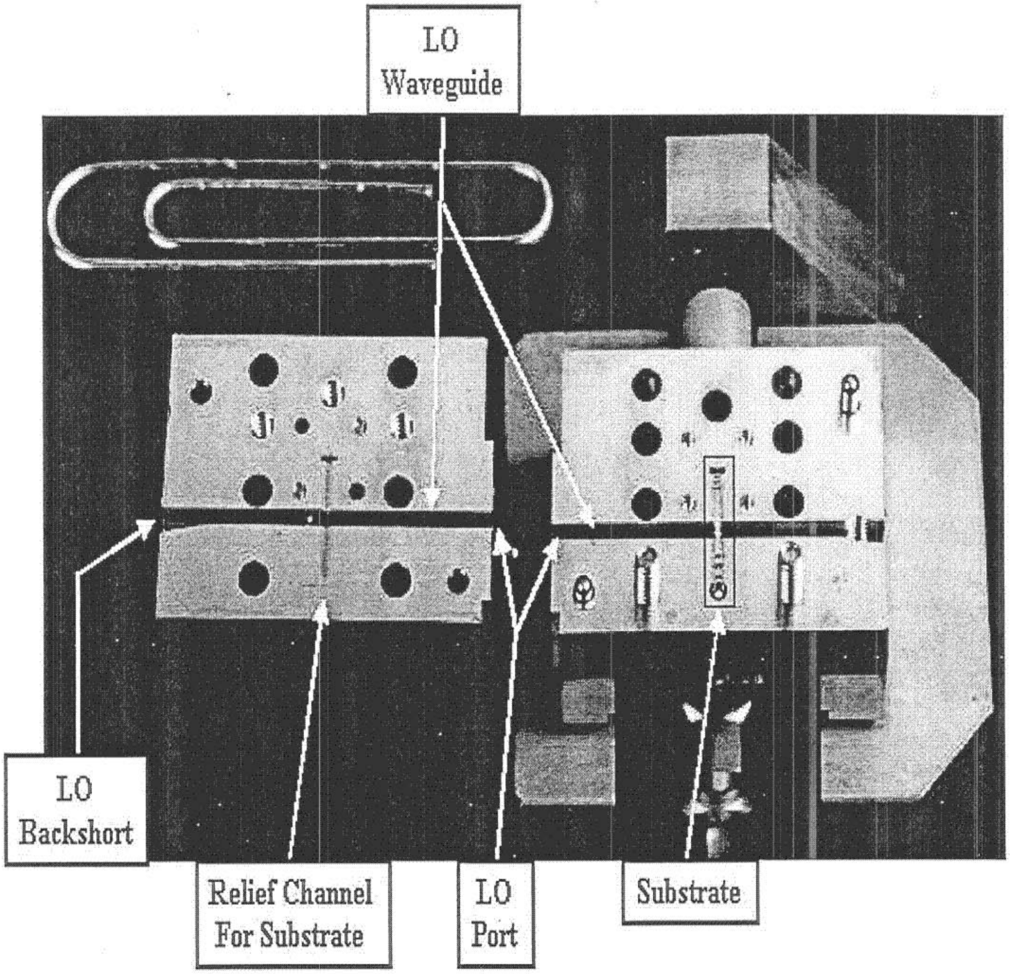


Figure 14. G-Band Mixer Internal Configuration.

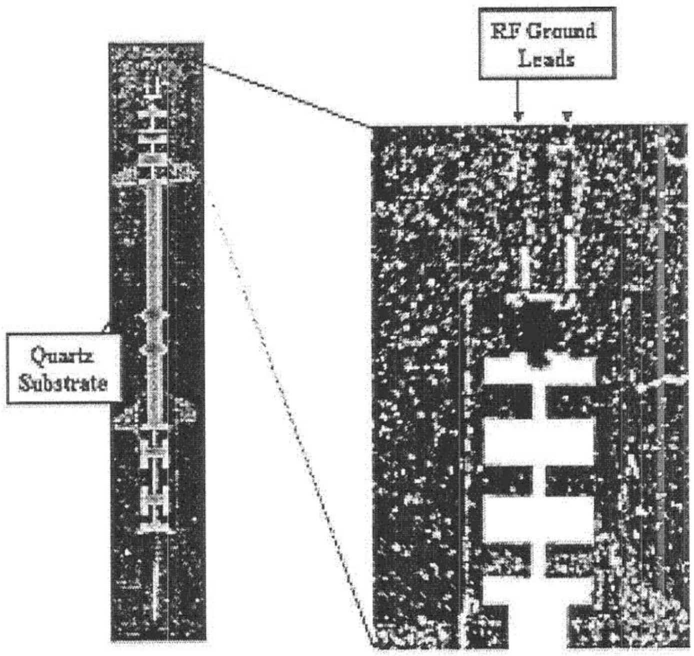


Figure 15. G-Band Mixer Substrate.

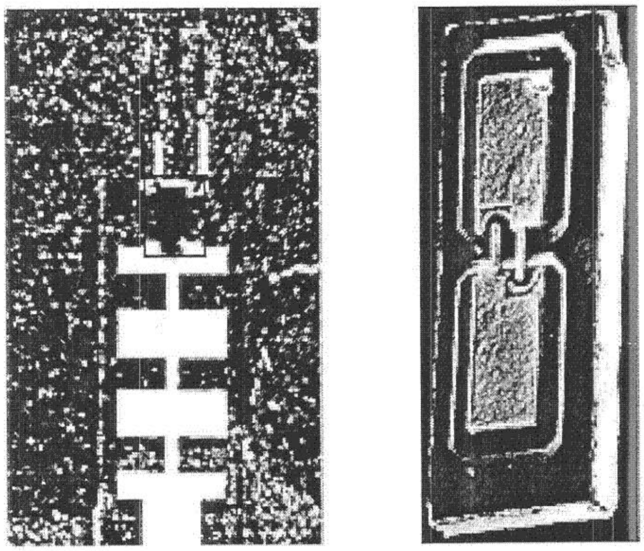


Figure 16. G-Band Mixer Diode.

Aerojet acquired the GaAs diode chips from the University of Virginia, the only source for devices of the requisite quality. The University of Virginia makes these diodes primarily for radio astronomers. They have a junction width of only 0.7 μm and a fragile three-dimensional construction structure consisting of two thin beams spanning an air gap; the structure resembles microscopic bridges over a chasm. Aerojet technicians must carefully solder these chips by hand onto the substrate, aligning its axis with that of the substrate as close as possible for optimum performance. The slightest amount of electrical overstress will destroy these devices.

3. CHRONOLOGY

A just chronology would list not only the mistakes but also the triumphs. Such triumphs would include ingenious designs, circumvented problems, painstaking workmanship, and exacting analyses. However, because the list of successes far outnumber the failures, inclusion of such detail would expand this document into one of book length. Also, we seek to provide a "lessons learned" document and, unfortunately, one mostly learns from one's mistakes. Therefore, we caution the reader to keep this document in perspective. Recall that the occasional error, although often highly disruptive to schedules, occurs but infrequently among the mass of details, decisions, and designs encountered by the technicians, engineers, and managers.

As a second caveat, the reader should recognize that this chronology does not even list all of the difficulties that required solution. Such a complete list would exhaust both reader and author alike and provide few additional insights. Furthermore, a huge number of small difficulties, while troublesome, often became resolved within the schedule's "Red Time" included for just such contingencies. In contrast, we wish to focus on the major, and unanticipated, events and to understand their causes.

3.1 January 1987: Pre-Contract Phase

Our history begins in January of 1987, when The Aerospace Corporation (Aerospace) began developing the specifications for the SSMIS. In response, during November, 1987, three contractors, Aerojet, Hughes, and Westinghouse, provided the results of their studies on the feasibility of the envisioned sensor.

Over the following year, Aerospace worked to complete the Technical Requirements Document and the Statement of Work. In November, 1988, the government issued its Request for Proposal and in March, 1989, awarded the contract for the five SSMIS to Aerojet. This original contract specified the completion of all of the sensors prior to July, 1993. However, in June, 1989, Aerojet and the Air Force agreed to modify the contract to specify the delivery of the first SSMIS in October, 1992, with the others following in 1 year increments.

The contract contained a provision for the inclusion of additional channels for the "sounding" of the upper air. For this purpose, the authors anticipated a separate sensor, distinct from the main SSMIS canister mounted on panel #2. In August, 1989, the Air Force exercised the option to include such an upper air sounder.

The contract had a significant division. Through the milestone represented by the Preliminary Design Review (PDR), held in May 1990, and ending with the Manufacturing Readiness Review, shortly after the Critical Design Review (CDR), held in June, 1991, it operated on a cost plus basis, with the Air

Force providing extra funds as needed to complete the design. After this the contract became fixed price, with no further increases in costs to the Air Force. This contractual arrangement gave heightened importance to the CDR milestone.

3.2 March 1989: Early Design Problems

In the time period between the award of the contract and the CDR in June 1991, Aerojet found itself with a far more difficult design effort than they had expected. The Technical Requirements Document had provided Aerojet with only a rough guide as to the volume which the spacecraft would make available for the SSMIS. However, in April, 1989, General Electric, the spacecraft contractor, now completed a more detailed space interface definition, and this revealed inadequate volume for Aerojet's existing design. Ultimately Aerojet would change the outer configuration of the canister from a simple cylinder to one with an octagonal cross section. Nevertheless, over the next few years, the resolution of continuing stay-in-zone issues would involve the Air Force and the contractors in numerous analyses and compromises as Aerojet attempted to reduce the volume of the SSMIS and General Electric sought to discover a few more inches of space here or there.

Also in the pre-CDR phase, Aerojet's thermal model did not predict the need for operational heaters to prevent excess cooling of the electrical components in the space environment. More careful analysis, along with refinement and maturity of the design, now indicated the necessity for such heaters. Adding them did not prove an easy task because their design already pressed against the weight and power budgets. Neither Aerojet nor the customer (the Air Force) had allowed much margin in their budgets to accommodate such increases. After much struggle, Aerojet met the design goals by introducing pulse-width regulators for the heater power supplies. These have the advantage of operating at nearly 100% efficiency in energy consumption, but the disadvantage of generating high-frequency noise that could corrupt the highly sensitive RF circuitry.

In a further change to conserve heater power, Aerojet increased the temperature range over which the microwave components must operate. Their final design allowed most of the circuitry to fluctuate over a 40° C range, twice the 20-deg range common to the SSM/T-1 and SM/T-2. Only in the case of the Gunn diode oscillators, which were used to generate the critical high-frequency reference signals and could not meet frequency stability requirements over the broader temperature range, did they maintain the narrower temperature range by the use of local heaters.

The volume and power budget did not represent the only interface problems. Recall that the Air Force had agreed to fund the additional upper air sounding channels. With the exercise of this option, they allowed an additional 15 lb for the inclusion of the necessary hardware. However, the original concept envisioned a separate upper air sounder mounted on another panel from that supporting the main

SSMIS canister. But with further consideration, everyone now saw the advantage of having these channels better integrated, and co-registered with the other SSMIS channels. The designers best achieved this goal by incorporating those additional upper air receivers into the main SSMIS canister. This created a new problem, because the initial studies indicated that the spacecraft's panel #2 could not support the extra weight.

The vibration specification further complicated this task of remaining within the weight budget. The original Technical Requirements Document had left this specification as "TBD", or To Be Determined. With the loss of the Space Shuttle Challenger a recent memory, and the composition of the launch vehicle fleet somewhat uncertain, the customer became cautious. After the start of the contract, they chose a vibration specification of 0.27 g^2/Hz, insuring that the sensor could survive any launch environment. Aerojet had not expected so demanding a specification. However they did commit themselves to it.

Like the volume and power issues, the weight specification would lead to numerous analyses, compromises, and redesigns. Since the predicted weight on spacecraft panel #2 had grown considerably from the 135.7 lb estimate given at the time of the PDR, General Electric conducted an analysis in February, 1990 and indicated the acceptable weight for panel #2 as 156 lb. However, this did not end the weight problems. By March of 1991, just before the CDR, the SSMIS weight had further grown to at least 161.1 lb with potential additional weight growth of 17.2 lb.

The design of the deployment subassembly represented another issue that first emerged prior to CDR. In February, 1990, Aerospace declared that the deployment mechanism design would not provide effective control of the sensor mass during the deployment. Because of this, and of vibration mode issues, Aerojet, in June, 1990, introduced a new design for the deployment system involving a three-post truss with separation nuts. In December 1990, they authorized the fabrication of this deployment mechanism. Unfortunately, this would not end the difficulties with the deployment subassembly.

In the pre-CDR phase of the SSMIS program, the digital electronics designer suddenly passed away. He left his concept only partially completed and documented. In consequence, the new designer had to almost begin anew. This threw Aerojet's electrical design and verification effort considerably behind schedule.

To compound this difficulty, shortly before the CDR, Massachusetts Institute of Technology discovered a design flaw affecting the narrowband 60-GHz channels, used for temperature sounding the upper atmosphere. The velocity of the spacecraft introduces a Doppler shift into the received microwave signals and the magnitude of this Doppler shift varies during the sensor's rotation. Furthermore, the Doppler shift has a magnitude comparable to the bandwidth of the channels. Thus, at the extreme scan positions, signal loss would result because the microwave energy of interest would partially fall outside of the channel's bandwidth.

Aerojet initially responded to this issue by considering a two-fixed-frequency approach (for the spacecraft approaching or receding from the targets.) However, by February, 1991, they concluded that a variable frequency approach to the Doppler problem appeared a far superior solution. This would require the redesign of the motherboard inside the digital processor unit and the inclusion of additional complex circuitry on a totally new design signal processor circuit board.

In consequence of these two events, Aerojet entered the post-CDR phase with their electrical design largely untested. That testing, which continued through early 1993, would ultimately reveal numerous factors needing alteration, problems that they would normally have discovered earlier, but whose correction at the later stage would contribute in delaying the delivery of the first SSMIS.

In April, 1991, with numerous thermal, mechanical, and electrical issues unresolved, the Air Force, having previously agreed to reschedule the first sensor delivery for February 1993, now again changed it to August 31, 1993. Shortly thereafter, in June, 1991, Aerojet held its Critical Design Review and the program entered its fixed price phase.

3.3 October 1991: Vendor Delays

With component procurement and testing underway, numerous hardware problems conspired with the design issues to interfere with the schedule and to incrementally push back the delivery date of the first SSMIS to January 1994.

In October, 1991, Alpha, the vendor for the PLOs, and Phonon, supplier of SAW filters, had difficulties meeting their delivery schedule. Aerospace discovered that FEI, manufacturer of various complex and critical high frequency components, had used some commercial parts. These had failed to pass destructive physical analysis. In consequence of these vendor problems, Aerospace assembled a tiger team to review Aerojet production schedules and subcontract delivery dates. This assisted Aerojet in the process of monitoring vendors and finding alternate suppliers.

Nevertheless, the vendor delays continued. In April, 1992, Honeywell, the vendor for the scan drive assembly, the unit that both rotates the sensor and provides, via slip rings, the electrical interface between the rotating and stationary parts of the SSMIS, discovered that the plated silver coatings on the slip rings would gradually peel away and form slivers that could create short circuits. The solution involved replating the slip rings with a harder silver and insulating various exposed conductive surfaces.

In August 1992, Aerojet discovered that the direct memory access chip required by the digital processor unit, and manufactured by Marconi, did not perform as advertised. Rather than redesign the chip and suffer a substantial schedule delay, Aerojet decided to redesign the SSMIS circuitry and flight software. This effort ultimately required until the middle of 1993 for completion.

3.4 April 1992: Reflector Deployment Failures

At the time of the CDR, Aerospace discovered a problem with the mechanism that deployed a smaller reflector, used by the SSMIS for calibration purposes. Specifically, the design utilized several shafts and levers, failure of any of which would prevent proper deployment. Aerospace and Aerojet spent a half year in redesigning this mechanism to use half the number of parts. Then, in April, 1992, the SSMIS main reflector assembly failed during deployment, requiring a redesign. Specifically, the shock generated by the firing of the pyroelectric devices had caused one of the support arms to fracture at the release assembly. The reflector failed a second pyroshock test in June, 1992 due to de-bonding. Aerojet undertook a further redesign, which involved strengthening the reflector supports and decreasing the energy generated during deployment.

Aerojet would later encounter a few additional difficulties with the reflectors. In September, 1993, the calibration reflector would fail to deploy due to contamination from the shaft which had entered the bottom ball bearing. In consequence, Aerojet would change both bearing and lubricant type. Two years later, in September, 1995, the calibration reflector would fail to deploy after a vibration test and require a small modification to correct an interference problem.

3.5 May 1992: Warm Load Electronics Noise

The SSMIS calibrates itself by alternately scanning, first cold space, by means of the cold reflector, and second, a temperature-controlled microwave emitter, called the warm load. At this time, Aerojet determined that the electronics that controlled the heaters in the warm load generated sufficient noise to corrupt the multiplexed data containing the warm load temperature. Recall that, in order to remain within the power budget of the SSMIS while having to add operational heaters, they had pursued the path of using pulsewidth modulated controllers. Meanwhile, the weight budget limited their use of shielding at the same time that they pressed the state of the art on sensitivity. In this case, they corrected this situation in less than 2 months by designing two new circuit boards and a new warm load electronics housing. Unfortunately, this would represent just the first of many noise and electromagnetic interface (EMI) problems that would arise from the use of the pulsewidth modulators.

3.6 December 1992: Surface Acoustic Wave Filters

Back in October, 1991, shortly after the CDR, testing of the SAW filters at the vendor had revealed an inability to manufacture the devices according to specifications. Aerospace worked with Aerojet personnel to review the vendor's existing procedures and to develop new ones. The new procedures focused primarily on removing stresses in the quartz substrates and reducing the generation of particulate contaminants.

Nevertheless, delays in manufacturing the SAW filters continued. In December, 1992, particle contamination led to the failure of SAW devices during testing. Because of additional problems including the delivery of PLOs and multi-layer circuit boards, Aerojet at this time projected a new delivery date for the first flight SSMIS of April, 1994.

After a number of incremental delays in acquiring the filters, which correspondingly held up the assembly of the first flight SSMIS, Aerojet finally received its first unit in April, 1993. However, they discovered that the filter suffered oscillations on all channels and required return to the vendor. The vendor corrected this condition by the addition of filter circuitry and, after correction of another factor that caused a failure during the vibration test, returned the filter to Aerojet in August, 1993.

This did not end the SAW filter problems delaying the integration of the first SSMIS. The vendor's omission of washers subsequently caused damage and particle generation in two SAWs, which necessitated their brief return to Phonon.

3.7 March 1993: Electronic Box Issues

Upon vibration testing, the control status unit, digital processor unit, warm load electronics, and both detector preamp boxes all experienced mechanical failures. Aerojet dealt with this group of failures by testing the robustness of the boxes under gradually increasing vibration levels and by adding damping materials as required.

Two other issues involving the electronic boxes emerged at this time. Aerojet discovered a design defect in diode detectors used in the detector preamp boxes that resulted in poor electrical grounding. They returned all of the components to the manufacturer for redesign. Aerojet also discovered that, during startup of the scan drive electronics, the rate of change of the input current exceeded the requirement. This required some redesign of the circuitry to correct.

3.8 April 1993: Deployment Subassembly Redesign

In April, 1993 the deployment subassembly, which supports and deploys the entire SSMIS canister, failed to deploy completely using a single motor. By August, Aerojet determined that the assembly required considerable redesign to meet the specification which stated the amount of time required for deployment. At this point in the SSMIS program, the deployment assembly fell into the category of critical components which threatened the delivery schedule.

Ultimately, the redesign effort would consume a year and a half. The problem had arisen because the mechanism had higher frictional resistance than predicted. Attempts to reduce the deployment resistance failed, leaving no option but to increase the spring force. However, the vendor could not manufacture a spring of sufficient force and aging characteristics for the available volume. The only solution, increasing the volume, proved challenging since the overall spacecraft/sensor geometry could accommodate only a few tenths on an inch of additional space. The redesign also pushed the SSMIS weight against its limit and, in September, 1994 led to an increase in the specification. The redesigned assembly would finally pass all of its qualification tests in November, 1994.

3.9 August 1993: Circuit Board Design Problem

During this month, Aerojet learned that flat flexible cables that comprised part of the motherboards in the control status unit and digital processor unit had, in a design error, inadequate conductor gauge. The designers had specified 26 gauge leads, sufficient to carry the requisite electrical current. However, they failed to account for the length of the wires and the requirements of the components. Although the canister has a width of less than 18 in., the leads must follow convoluted paths due to the tight space constraints. In consequence, some cables reached approximately 65 in. in length. This resulted in unacceptable voltage drops between power supplies and certain electrical components, preventing proper operation of the latter.

The discovery of the voltage drop problem came at a time when Aerojet had not yet resolved the mechanical issues involving the deployment subassembly (see above) and another problem involving intermittent noise on all channels (see below). In consequence, in September, 1993, they set back the delivery of the first flight unit from April, 1994 to November, 1994.

The weight budget for the sensor, already pressed upon by the deployment subassembly redesign, limited the options for eliminating the voltage drops. Ultimately the solution required numerous wiring changes, including the addition of 25 wires, 11 terminal boards, and two remote control relays throughout the canister assembly.

However, this did not entirely settle the circuit board issue. By mid 1994, and over a period of several months, Aerojet would experience four failures of motherboards and associated flexible cables in the digital processor unit due to handling damage. Mostly, this involved broken wires in the flexible cables. Aerojet and Aerospace would form a review team which would trace the problem to manufacturing processes at the vendor.

Aerojet, after completing the redesign of the boards in December, 1994, selected a new supplier, Teledyne, in April 1995. However, as we will see later on, another defect with one of the original circuit boards would suddenly threaten a delay shortly before the delivery of Flight Unit #1.

3.10 January 1994: Intermittent Noise

Aerojet first detected this in May, 1993 upon initial testing of Sensor #1. However, the subsequent discovery and diagnosis of the voltage drop problem in August interrupted their full investigation of this issue until January, 1994. Only then did the magnitude of the problem slowly emerge.

The problem took the form of intermittent, high and low frequency noise on many channels, but primarily affecting channels 8 to 11 and 17 to 18. The noise had a magnitude of only 0.003 dB, but, given the extreme sensitivity of the SSMIS, this caused many channels to fail specifications. The noise occurred rarely, making the diagnosis extremely difficult.

At about this time, Aerojet discovered that the sinusoidal frequency variation needed to compensate for the Doppler shift caused the gains of the upper air sounding channels to change significantly.

With these issues unresolved in March, Aerojet implemented their Pathfinder Risk Reduction Program. According to this, they re-designated the first SSMIS, #1, as Pathfinder, a quasi-prototype which they would use to solve current and future problems. Since they later would refurbish Pathfinder as Flight Unit #5, they could not treat it entirely as a prototype but would have to maintain the flight worthiness of its key components. Nevertheless, they estimated that the reduction of the associated documentation resulted in a three to four times increase in the efficiency of their troubleshooting efforts.

Sensor #2 took the place of #1 as Flight Unit #1. In April, with the new Flight Unit #1 assembled and exhibiting the same intermittent noise as found on Pathfinder, Aerojet set back the delivery date for that first sensor to May 1, 1995.

Investigation of the intermittent noise continued throughout most of 1994 and ultimately resulted in numerous design changes. In May, Aerojet discovered a main component of the noise in the power leads to the Gunn diode oscillators. They determined that they needed to electrically isolate the Gunn diode oscillators from the waveguides and add filters to the power lines. They also modified offset circuitry in the detector preamp box to eliminate cross-talk between channels and discovered the need to install isolators in the Doppler correction circuitry. On the receiver shelf they incorporated capacitive isolators (DC blocks), and moved attenuators to provide proper electrical return paths.

The latter changes, involving the DC blocks and attenuators, reduced the noise by eliminating troublesome ground loops. The term "ground loop" refers to noise-carrying currents, often small, which circulate via multiple ground connections. Ideally, one prefers a single ground connection so that such currents cannot flow. Unfortunately, most RF components do not isolate signal returns from power grounds. This tends to create ground loops and complicates the effort to eliminate them.

In June, Aerojet replaced some failure-prone coaxial cables with those of a different design but their efforts backslid when they found large output fluctuations in channel 9. In July, they traced the latter to spurious harmonic signals generated in the 75-GHz and 91-GHz Gunn diode oscillators. They corrected this by a slight change in the channel frequencies. In August, they verified that the installation of the Gunn diode oscillator filtering had eliminated the noise on channels 17 and 18, but they still struggled with noise on channel 16. In September, they finally traced this noise to a software timing error. In October they discovered and replaced a faulty attenuator and low noise amplifier. Finally, in November, among other activities, they discovered that thermal cycling resulted in mechanical stress among the components on the A3 receiver shelf. This shelf consists of a metal plate which carries two microwave feedhorns along with a dense assembly of associated microwave and RF circuitry. Aerojet modified the circuitry to relieve the stresses, primarily induced in the waveguide and coaxial connections.

By February 1995, Aerojet had completed all of the design changes necessary to eliminate the various sources of noise that they had discovered and which they have grouped under the all-encompassing term "intermittent noise." The effort had used up practically all of the Red Time in their schedule to meet the May, 1995 delivery of Flight Unit #1. Unfortunately, Aerojet had still not seen the last of the noise issues.

3.11 November 1994: Electromagnetic Interference (EMI)

In November, 1994, Aerojet began its EMI Test using the Pathfinder sensor. This test determines if the sensor generates electromagnetic emissions that could disrupt the operation of other spacecraft components. It also looks for susceptibility of the sensor to spacecraft emissions. The tests discovered serious problems in this regard. At specific frequencies, the EMI emissions exceeded specifications by as much as 60 dB. In addition, the RF circuitry exhibited susceptibility to spacecraft sources of EMI.

Aerojet undertook extensive diagnosis to determine the causes of these problems and to correct them. The investigation revealed the problem as multi-faceted, and many originated with the pulsewidth modulated heater controllers. Usually, larger EMI problems masked smaller ones. Thus, they had to proceed in a laborious and time-consuming manner, sequentially working their way down through the list of causes, analogous to the peeling of the layers of an onion.

In consequence, as the diagnosis proceeded over many months, Aerojet incrementally pushed back the delivery date of Flight Unit #1, first to July 21, 1995, then to early September, and then, when they had defined the solutions to the major EMI emissions in March, to November 29, 1995. However, even then, they still struggled with the susceptibility issues. When they established primary solutions to the latter in June, 1995, they set a new delivery date for Flight Unit #1 of late February, 1996.

Altogether, the design changes included additional filters on the power lines for the Gunn diode oscillators and the IF amplifiers as well as filters for the warm load electronics, DC/CD converter, scan drive electronics, and filter bracket. Aerojet added shielding to the Warm Load electronics and input cable. They used a spare slip ring to provide a parallel path to chassis ground. They also isolated the feedhorns from the microwave components that followed them, and they grounded the feedhorns to the chassis to prevent them from acting as antennas for the EMI. Finally, but highly important, they added a whole new assembly, the filter bracket assembly, in the interface between the canister and spacecraft.

A few additional problems emerged in July, requiring additional filters and improved grounding. In November, 1995, Aerojet still found a minor out-of-specification condition when they conducted an EMI test of Flight Unit #1. A modification to the filter bracket assembly, and a slight relaxation of the EMI specification dealt with these final problems.

3.12 June 1995: G-band Mixers

Back in 1994, during the extensive intermittent noise effort, the G-band mixers failed with dismaying regularity. These components reside on the A3 shelf and act as the detectors for the four highest frequency channels. Aerojet constructs them in their own facility using diodes provided by the University of Virginia and precision machined metal housings and glass substrates purchased from vendors. In April of that year, the failure of two G-band mixers in screen tests at Aerojet led to a review of the University of Virginia fabrication techniques. In May, Aerojet traced one of their numerous intermittent noise problems to the channel-8 mixer, which they replaced. In June, 1994, Aerojet invited Aerospace to participate in a design review of their mixers. Altogether it had required 4 months of analysis and experimentation to establish that the low-frequency variation exhibited by the mixer resulted from the placement of the substrate in the housing. To prevent this type of noise, Aerojet had to locate the end of the substrate as close as possible to the wall of the housing cavity, thereby keeping the length of the electrical ground wires to a bare minimum. Unfortunately, the G-band mixers had just begun to wreak havoc with Aerojet's schedule.

Pathfinder suffered the failure of its 183- and 150-GHz mixers in October and December respectively. Now, in June 1995, with the EMI/EMC modifications in place, Flight Unit #1 experienced a mixer failure at the start of its Comprehensive Performance Test. Then, in July, Flight Unit #1's channel 11 exhibited low frequency noise power variation traced to the new mixer, necessitating another replacement. This brought Aerojet's inventory of spare 183-GHz mixers to zero while the mixer laboratory struggled with poor yield. Their latest lot produced only one out of five acceptable units. Aerojet formed a mixer team to determine causes and solutions. Meanwhile, Aerojet changed its projected delivery date for Flight Unit #1 to March 14, 1996.

In October, 1995, they began the thermal vacuum test for the sensor but had to abort it because of another mixer failure that occurred upon cooling to -30° C. At this point, Aerojet lacked a replacement mixer and therefore could not proceed with the thermal vacuum test. While they awaited the manufacture of new mixers, they incrementally pushed back the delivery date of Flight Unit #1 to May 1, 1996, and then to June 12, 1996.

Subsequent investigation revealed that the last mixer failed because of excess solder on the diode beam. Aerojet also concluded that they needed to change the mixer screening tests. Whereas they formerly tested over the temperature range of -30 to +80° C, they would now test from -45 to +70° C to increase the likelihood of discovering such workmanship problems at the component stage.

3.13 February 1996: Thermal Vacuum Test

In February, 1996, Aerojet completed a workmanship vibration test of Flight Unit #1 and next began the thermal vacuum qualification test. However, they soon had to abort it due to the failures of an RO/C and of a PLO. The PLO failed due to a broken 30-gauge wire in the an oven-controlled, voltage-controlled crystal oscillator, a subassembly manufactured by FEI. FEI also manufactured the failed RO/C. Recall that, early in the SSMIS program, there was a concern about FEI workmanship.

Aerojet restarted the thermal vacuum test in March but again aborted it, this time due to a loose connector on an IF amplifier. They restarted it a third time and aborted it a third time when they observed an increase in the noise levels of channels 17 and 18. This last problem proved particularly vexing. It resulted from pickup from a heater, but it only occurred under the rare circumstances when the heater circuit operated at very low power. Aerojet corrected this problem by interchanging the position of two components, a DC block and a filter, for channels 17, 18, and 11, thereby improving the grounding scheme for these channels.

With these modifications in place, Aerojet again started the thermal vacuum test of the sensor in April and completed the test in May. However, these along with the earlier mixer problems had the effect of slipping the projected delivery date for Flight Unit #1 to September 17, 1996

3.14 May 1996: More G-band Mixer Problems

In May, 1996, Flight Unit #1 completed its thermal vacuum acceptance test. However, during that test, channel 8 occasionally exhibited abrupt jumps in the level of its output signal. Subsequent diagnosis traced this anomalous behavior to the channel's 150-GHz mixer. Going through their inventory of newer-design spare mixers, Aerojet found that none of them performed adequately as replacements for the defective unit. The mixers either failed to meet specifications or they exhibited the signal-level shifts. Eventually, Aerojet re-tuned an older-design 183-GHz mixer for 150-GHz operation.

With the replacement mixer installed, Flight Unit #1 subsequently passed its EMI test, a two-axis workmanship vibration test, and a Doppler correction verification test.

Meanwhile, in June, 1996, Aerojet had convened a Red Team of industry-wide experts to investigate the cause and solution of the enigmatic signal-level jumps in the G-band mixers. The team held a number of all day meetings through October, 1996. Ultimately, they concluded that the signal level jumps most likely resulted from the intermittent contact of one of the two microscopic ground wires that ran from the substrate to the housing. It had fractured because of the accumulated stress of multiple thermal cycles due, in turn, to the thermal expansion mismatch between the quartz substrate and the mixer housing. To solve this problem, the Red Team agreed with the mixer laboratory's proposal to include two major design changes. Specifically, they would henceforth machine a small recess and bevel to better control the degree of deformation of the gold wires upon assembly of the mixer. In addition, they would add an indium pad in the recess to take up the greater part of the deformation. Analysis by Aerospace concluded that this redesign would increase the cycle life to 500 test-level thermal cycles. In addition, the mixer laboratory would include more stringent thermal-cycle screen tests of its mixers before qualifying them as flight parts.

3.15 July 1996: Slip Ring Noise

In July, 1996, with the September, 1996 delivery date still holding firm, Aerojet began the calibration test of Flight Unit #1. However, upon cooling of the sensor, most of the channels began exhibiting erratic drift and jumps in signal level. By the middle of the month, Aerojet had narrowed the source of the problem to timing pulses that originate in the scan drive assembly and which communicate to the digital processor unit the instantaneous position of the rotating sensor. They found these timing pulses corrupted by additional erratic pulses of unknown origin. The corrupting pulses took the form of 20-μsec outages such as would result from intermittent open circuit conditions.

After a lengthy investigation, involving several false trails, Aerojet, by September, had narrowed the source of the corruption to the scan drive assembly, and in particular, to the slip rings through which the encoder signals pass. They next examined other scan drive assemblies for the problem and found that the engineering model, and only the engineering model, shared the phenomenon. In consequence, Aerojet again reset the delivery schedule for Flight Unit #1, to March 15, 1997.

At this point, they expected to repair the scan drive assembly, without removal from the sensor, with the addition of a few wiring modifications. They based this on an experiment which they had conducted on the engineering model at the suggestion of the manufacturer, Honeywell. Specifically, they had passed a 1-amp current through one of the noisy slip-rings for a period of 10 minutes. At the end of this time, they discovered the ring completely cured. In fact they reported it the "quietest ring" they had ever seen. However, they failed to duplicate this success with Flight Unit #1 and so, in October, they ceased further experiments and began disassembly of the sensor in order to replace the scan drive assembly.

Aerojet also investigated how they might make the logic circuit that uses the encoder signals more resistant to the outages. The resultant modifications included filtering and the addition of a timed gate circuit which discriminated against any anomalous pulses that occurred within 3.0 msec after the previous, legitimate one. Based on the time required to replace the scan drive assembly, incorporate the encoder circuit changes, and repeat many of the system-level tests (vibration, limited EMI/EMC, thermal vacuum, and limited calibration test), Aerojet projected a new delivery date for Flight Unit #1 of August 18, 1997.

By the end of February 1997, Aerojet had completed the re-assembly of the sensor and it had passed a 3-axis workmanship vibration test and its EMI Test. In addition, Aerojet more carefully analyzed the SSMIS circuitry for the effects of 20-µsec outages. They concluded that such outages could disrupt the data flow along lines to the spacecraft. Because of this, Aerojet and the customer now agreed on the need for further hardware modifications. This entailed the use of doubled, or parallel, rings in the critical areas. Given the low level of probability of outages on any given ring, Aerojet estimated that the paralleling would reduce the likelihood of data disruption by a factor of 10 or more, depending on the ring. They would obtain the extra rings by eliminating some redundant telemetry lines. This modification necessitated a 3 month slip in the projected delivery of Flight Unit #1 past the previous August date.

Meanwhile, back in November, Aerojet had formed a Red Team to study the origin of the slip ring noise and had conducted numerous investigations and experiments as well. Honeywell continued their own tests upon receipt of the assembly in December. The data indicated that the slip rings contained insulating patches which temporarily interrupted the transmission of the encoder signals. The most likely explanation envisioned the reaction of the molybdenum disulfide lubricant with water vapor to form an insulating, and sticky residue of molybdenum trioxide particles. Spinning the assembly accelerates such a reaction but it will occur even under static conditions, albeit very slowly. Although Aerojet only operated the scan drive assembly under vacuum or dry nitrogen purge, some water vapor inevitably enters the assembly. Meanwhile, the assembly suffered considerable time exposed to atmospheric conditions while stationary.

All of the experimental data collected by Aerojet and Honeywell did not completely explain the nature of the problem. The outages exhibited peculiar dependence on current, speed, and temperature. Specifically, the outages had a much shorter duration during the imposition of a 1-amp current than under normal 20-mA operation. In the latter case, the outages lasted 5 to 20 μsec, while in the former case they lasted only nanoseconds. On the other hand, the duration increased as the speed decreased. However, they abruptly disappeared altogether when the rotation speed fell below 1/2 of the nominal speed. Increased speed resulted in the return of the outages, although not necessarily immediately. Finally, the temperature dependence of the outages presented another unsolved clue. The outages usually occurred only below 4° C.

Visual and debris analysis did not reveal any difference between noisy and quiet slip rings. Honeywell measured the pressures with which the springs press the brushes against the rings. Again, they found no correlation between brush pressure and noisy rings.

All in all, this type of high-frequency slip ring noise represented a newly discovered phenomenon, quite distinct from lower frequency (kHz to Hz) noise often seen on these devices. In fact, Honeywell's routine screening tests, involving strip chart recorders, lacked the response time to even record them. At first, Honeywell claimed they had no knowledge of the problem. However, on an investigative trip to Lockheed Martin, the Air Force discovered that another satellite program, using Honeywell slip rings of almost identical operation parameters as for SSMIS, had also exhibited the high-frequency outages. Honeywell engineers had extensively investigated the problem recording tens of thousands of events. Apparently there was a simple lack of communication between different groups at Honeywell.

3.16 February 1997: Scan Drive Electronics Circuit Boards

At this time, Aerojet discovered faulty metal plating in one area of all the SDE motherboards that they inspected. The SDE, which controls the rotation of the sensor, resides in a box separate from the canister and connected to it by cables alone. As a result, Aerojet concluded that they must obtain and install replacements for all the units. Initially, it appeared that this would necessitate Aerojet's temporarily delivering a suspicious SDE box with the main canister assembly. After allowing its use for integration and testing of the sensor on the spacecraft, the Air Force would return the SDE to Aerojet for rework. However, Aerojet managed to acquire the new boards, reassemble the SDE and fully test it out for delivery with Flight Unit #1.

3.17 March 1997: Thermal Vacuum Test

In March of 1997, Aerojet began the thermal vacuum acceptance test of Flight Unit #1 but soon had to abort when two separate problems developed. The output of channel 23 erratically dropped to zero with the sensor hot and channel 19 became inoperative when its PLO cooled to 2° C.

They traced the channel-23 problem to the detector preamplifier box. However, in the process of diagnosing the cause, they inadvertently exposed the channel-23 detector diode to as much as 60 volts, thereby destroying it. The damage to the detector preamp box, while easily repaired, prevented further investigation into the cause of the original channel-23 problem.

The mishap occurred because the test engineer performed the diagnosis using two lab benches, one of which had both an ungrounded power plug and a faulty switch. Although Aerojet routinely inspects their benches, this particular bench, as an inactive one normally used only to hold manuals, had escaped a full electrical inspection. Ultimately, this was a minor incident. We merely include it in this report to indicate the types of traps that await the unwary. It helps to demonstrate why diagnostic efforts often require a great deal of time and effort when one deals with flight hardware.

Meanwhile, Aerojet corrected the channel-19 problem by replacing the PLO. Not having any spare PLOs in inventory, they had to obtain it by removing a PLO from Flight Unit #3.

At this point, we find it appropriate to discuss the status of the PLOs. Originally, Aerojet had 11 PLOs manufactured by their vendor Alpha, giving them the requisite two per sensor along with one spare. Starting in early 1993, because of failures due to components and workmanship problems with the units, Aerojet had added additional screening tests. They now subjected all the units, coupled together, to eight thermal cycles, during which, in October 1996, PLO #4 failed. At this point, Aerojet had four PLOs in need of repair.

However, the original vendor, Alpha, had divested itself of further PLO work and would not repair the units. That task went to a new company, Advanced Control Components (ACC), who acquired Alpha's blueprints. Not until February, 1997 had ACC fully established itself and succeeded in repairing and returning the first PLO, #3, to Aerojet. However, this PLO failed Aerojet's screening and was quickly returned to ACC.

We could write a long saga about ACC's attempts to repair PLOs throughout 1997 and 1998. Repeatedly, they would declare a PLO finished and would deliver it to Aerojet only to have the unit fail yet again. May, 1997 marked the low point with six PLOs requiring repair. However, these continuing problems, while affecting the production of Flight Units #3 through 5, did not further delay the delivery of Flight Unit #1. Therefore, we will not provide a detailed history of these occurrences. Suffice it to say that the units suffered from problems such as cracked indium solder joints, shorted components due to metallic debris, unstable operation requiring re-tuning, poor-workmanship components, and spurious high frequency output harmonics.

Rejoining, then, the story of Flight Unit #1, we can quickly cover the period from April to July 1997. In April, Aerojet completed the repairs of the detector preamplifier box and the re-assembly of the sensor. They then successfully conducted the sensor's thermal vacuum acceptance test. In May, in rapid succession, the sensor passed its thermal vacuum acceptance test, its 3-axis workmanship vibration test, its calibration verification test, and its alignment test. By early July, it had also completed its spin balance test and begun its final comprehensive performance test before delivery.

3.18 July 1997: Another Mixer Failure

Unfortunately that test revealed the sudden onset of degraded performance on channels 9, 10, and 11. A lengthy investigation ensued which discovered broken ground wires on the 183-GHz mixer. This particular mixer was of "old-vintage," manufactured prior to the Red Team's recommendations. Aerojet subsequently installed a new design 183-GHz mixer on the receiver shelf. Since the 150-GHz mixer shared the same vintage and design features, they replaced that as well. Aerojet had not replaced the older mixers earlier for two reasons. First, those older mixers had successfully passed numerous thermal cycling tests. Second, until very recently, Aerojet simply didn't have replacement mixers that they considered unambiguously superior.

To understand this last statement, we should review developments subsequent to the Red Team's investigation. Since implementing the design changes that grew out of the Channel-8 Anomaly Red Team, and up to March of 1997, the mixer lab had assembled two engineering model mixers, which both failed, and ten flight mixers, seven of which failed, with the last three still in test. The two engineering model mixers failed because they required excess input power from the local oscillator, more power than the flight oscillators could provide. Of the seven failed flight mixers, one required excess power, the second had poor performance, the third a twisted ground wire, the fourth a broken ground wire, and the last three had degraded (softened) IV curves. Meanwhile, poor gold plating resulted in the loss of a batch of six out of eight housings from the vendor, thereby delaying the assembly of new mixers.

Aerojet attributed the excess power problem to the location of the diode in the waveguide and made an appropriate adjustment. They traced the degraded diodes to multiple electrical grounds in their thermal chamber. These caused ground loops and consequent electrical overstress to the mixer diodes. To deal with the shortage of housings, they agreed with their vendor to forego the gold plating on subsequent units. Finally, in yet another attack on the ground wire problem, they decided, on two engineering models, to shorten the wires and lessen the opportunity for movement during assembly by relocating the wire from above the indium pad to below. A few months later, Aerojet also switched from wire bonding to welding and from gold wires to ribbons, both of which greatly increased the reliability of the ground wires. These and other changes finally began yielding mixers in quantity in the latter half of 1997.

3.19 October 1997: Delivery of Flight Unit #1

We have now come to the final events that preceded the delivery of SSMIS Flight Unit #1. By August, Aerojet had completed the re-assembly of the sensor. In September, Flight Unit #1 completed all of its acceptance testing, including the calibration and comprehensive performance tests. Aerospace fully reviewed the test data at the functional configuration audit, and determined that the performance met specifications.

4. MAJOR PROBLEMS AND IMPACTS

In this section, we summarize the major events that paced the completion and delivery of the first flight unit. Many of the difficulties that emerged later in the program arose from decisions, problems, and delays that had occurred earlier. For this reason, we find some merit in looking at the issues in reverse order, beginning with those that occurred latest in the program.

In 1996, with the first SSMIS approaching the end of its last major test prior to delivery, Aerojet discovered the disruptive outages that occurred on the slip rings in the scan drive assembly. Replacing the scan drive assembly required substantial disassembly, re-assembly, and re-testing of the sensor and ultimately led to a delivery delay of over a year.

As we have documented, very few people had prior knowledge about the high frequency type of outage that crippled the sensor so late in the program. One can only conclude from this experience that slip ring technology remains an area in need of considerable research and development.

Among the other components, the G-band mixers manufactured by Aerojet proved the most troublesome. However, we have not mentioned the numerous other schedule disruptions caused by the failure of other various microwave and RF components. As a rough guess, the repeated failures of these parts, and the necessary repairs and re-testing that they caused probably consumed another 9 months of effort. Mostly these parts failed during thermal cycling and, to a far lesser extent, as a result of vibration testing. We have already discussed how the stringent power budget led the designers to allow wider temperature swings of the circuitry than on prior instruments.

Prior to the delays inflicted by the component failures, the program suffered perhaps a year and a half total delay as Aerojet struggled to overcome noise and EMI. The various budget restraints both contributed to the problems and complicated their resolution. The power budget led to the use of noisy pulse-width-modulated controllers for the heaters. The volume requirement, with its packing density 60% greater than previous microwave sensors, assisted the transmission and pickup of disruptive signals between components. Meanwhile, the weight budget limited the amount of shielding that the designers could employ.

These electronic difficulties had such a severe impact on the program because, not having assembled a prototype sensor, Aerojet only discovered them upon the initial assembly of the flight hardware. When design flaws appear at that late a stage, they not only erase the earlier efforts that went into finalizing the design, but they significantly increase the difficulty of finding solutions. We add that, without a prototype, one usually discovers design problems sequentially rather than simultaneously. The absence of an engineering model also postponed the discovery of the inadequate operation of the deployment subassembly. This alone would have substantially delayed the program had not the electronic issues dominated the design efforts.

As another consequence of the lack of a prototype, the start of design verification had to await the procurement of flight quality parts from the vendor. If we examine the history of the SSMIS program in its early design and procurement stages, we find that the delivery schedule slipped over a year due to various issues, exacerbated by vendor delays in providing components. These had a variety of causes already discussed.

Finally, pressing back farthest yet, to the design phase, we can attribute perhaps another 9 months or more of setbacks, during the design phase, to the death of Aerojet's digital electronics designer and to the discovery of the need to include Doppler correction circuitry.

5. CONCLUSIONS

The previous sections demonstrate that the ultimate triumph of the SSMIS did not come easily. Nevertheless, throughout it all, engineers and managers alike struggled to overcome every latest setback, rising time and again to the challenge of uncovering the causes and of inventing solutions. We hope that the chronology adequately conveys the level of their heroic efforts.

Nevertheless, the reader must wonder if the process of creating a new generation of sensor needed to cause so much pain. At the very least, if we cannot avoid the pain completely, perhaps we can lessen it by better anticipating the factors that contribute to it.

For this reason, we now provide a brief set of lessons learned. We have sought out lessons of a wide applicability, rather than ones narrowly focused on this one program. Also, the lessons learned are based on our own point of view, as well as that of the government rather than of the contractor. In consequence, the list of lessons primarily deal with decisions made at a high level and by the customer. In so doing, we do not mean to exclusively criticize the government while exonerating the various contractors, who did, after all, agree to the terms of their contracts. We merely wish to help a customer understand what factors to consider when in the process of choosing a contractor, proposing specifications, and establishing schedules. With sufficient such knowledge, one can manage an acquisition program the way one should drive an automobile, defensively.

In its early stages, the program suffered considerable delay due to the need to modify the design while remaining within the power, weight, and volume budget. In the case of the volume budget, Aerojet had only learned of the "stay-in" zone after completion of their preliminary design. Therefore, with the benefit of hindsight, we recognize the significance of the following quote from an Aerospace Corporation report of January, 1987, almost 2 years prior to the Request for Proposal. It states that "A spacecraft constraints study to define available volumes and clear field-of-view would be required to allow the sensor contractors full freedom in their designs."

As Aerojet's design matured, and revealed the need for more volume, power, and weight, numerous lengthy studies took place to increase the budgets in incremental steps. In July of 1989, in the midst of one such study, an Aerospace report states, "The stay-out zone provided by GE/ASD initially was over-restrictive and additional volume was identified which probably could be used by SSMIS without impact." Ultimately, therefore, the budget with which Aerojet struggled to comply lacked a firm foundation. As late as February, 1992, we encounter the Aerospace quote that "..Aerojet's [spacecraft] mockup is not representative of the final spacecraft configuration.., ..the needed drawings have not yet been obtained from GE."

- *Lesson One:* A demanding engineering project such as SSMIS requires a detailed interface specification study as soon as possible.

Neither Aerojet nor the customer held much in the way of reserves in their power and weight budgets. Thus, the need for greater vibration robustness, for Doppler circuitry, for operational heaters, for greater shielding, and for additional circuitry each created a crisis as engineers scrambled to remain within the allocated budget while the spacecraft analysts sought ways to increase the specifications.

- Lesson Two: Maintain a healthy reserve in power, weight, and volume budgets.

As we have discussed, the absence of an engineering model, or prototype, contributed enormously to the delays the program suffered. The first draft of the Request for Proposal specified a prototype but the final draft excluded it. Some felt that the testing of a prototype would postpone the ordering of flight components which would, in turn, significantly delay the construction of the first Flight SSMIS. However, one suffers far greater schedule disruptions if one only discovers design flaws upon assembly and testing of flight hardware at the system level.

- Lesson Three: One does not save time by eliminating prototypes.

An Aerospace report of November, 1987 declared that "The schedule requirements for S-16 [the designation of the first spacecraft to carry an SSMIS] impose severe constraints on the program." We also note that SSMIS predecessors, SSM/T-1 and SSM/T-2, with a third as many microwave channels, took as long to complete as did SSMIS, namely 8 years. Therefore, given the complexity of SSMIS, we should not find the number of design and component difficulties surprising. And given those difficulties, we should not find the development time surprising. In consequence, the original projection of 3 years for the manufacture of the first SSMIS now appears wildly optimistic. Among other things, it did not adequately reflect the lengthy procurement times required for critical components such as the PLOs and SAW filters. Attempting to meet that schedule led to unfortunate decisions, such as that of eliminating a prototype from the design phase.

- Lesson Four: One can avoid much frustration if one begins with a realistic schedule. In particular, feasibility, not desirability, should control the setting of schedules

Although difficult to document, the participants in the SSMIS development effort agree that the early years of the program suffered from an adversarial relationship between the contractor and the customer. The program began in the late 1980s when newspaper headlines repeatedly raised the specter of military contractors defrauding the government with overpriced components. This put pressure on the customer to get tough with contractors.

Meanwhile, the unusual cost plus/fixed price contract tended to pull Aerojet and the government in opposite directions. Delaying CDR would best serve Aerojet's financial interests while it would correspondingly penalize the Air Force. In its lawsuit, Aerojet would later argue that this bias led the customer to ignore design problems in their haste to pass the CDR milestone and enter the fixed price phase. After CDR, the fixed price contract would provide little incentive for the customer to assist Aerojet in solving technical problems by, for example, relaxing the power budget. Aerojet's experience in earlier cost-plus contracts did not prepare them for such rigidity.

Unfortunately, Aerojet's management initially contributed to this situation by struggling with emerging problems themselves rather than fully discussing them and seeking assistance. Consequently, the government often learned of the difficulties only after they had reached a crisis stage.

In contrast, the new program manager, who took control in late 1993, fully shared all knowledge in a timely manner. Also, Aerospace later assisted, with much gratitude from Aerojet, in the process of procurement and vendor monitoring.

- Lesson Five: A complex program like SSMIS, which seeks to create a new scientific instrument, requires cooperation from all parties to succeed.

The demanding vibration requirements undoubtedly created major design difficulties for the engineers. In fact, they proved too daunting. Therefore, in August, 1994, the customer decided to reduce the specified levels in certain frequency bands, thereby lowering the overall energy considerably.

Given the chaotic state of affairs in the launch vehicle fleet caused by the loss of the Space Shuttle Challenger, the initial vibration requirements seemed highly conservative at the time. However, the experience does illustrate the need to control one's appetite when specifying performance parameters.

- Lesson Six:Give special attention to the potential consequences of demanding specifications..

6. THE FINAL WORD

Despite all of the difficulties, we conclude this report by emphatically declaring that the SSMIS represents a great technological achievement. Ultimately, one can only criticize it for requiring considerably longer to develop than originally anticipated. However, this often happens when people launch themselves into the unexplored world of research and development. In fact, the human race has, in the majority of cases, undertaken ambitious goals only because of its ignorance of the real effort involved. In consequence, much of its technological progress rests upon a high degree of initial self-delusion.

From: "Flaming, Mark" <Gilbert.M.Flaming@noaa.gov>
To: Tom Kleespies <Thomas.J.Kleespies@noaa.gov>, Fuzhong Weng <FWeng@nesdis.noaa.gov>, Larry McMillin <LMcMILLIN@nesdis.noaa.gov>
Subject: NPOESS Coffee Cups
Date: Tue, 30 May 2000 09:05:56 -0400

HI Guys:

Lt Tim Bode recently moved from the IPO to the NRO. Before he left, he gave me three coffee cups, one with each of your names painted on it. Tim ordered them probably a year or more ago, and obviously has not made delivery. Next time you get to the IPO, please remember to pick them up; they are currently in my office. Tim said that you should give the receptionist at the front desk, Bev, $11 per cup.

Thanks,

Mark