The High Temperature Superconductivity Space Experiment (HTSSE-II) Design

Thomas G. Kawecki, Gerald A. Golba, George E. Price, Vincent S. Rose, and William J. Meyers, *Member, IEEE*

(Invited Paper)

***Abstract*— The high temperature superconductivity space experiment (HTSSE) program, initiated by the Naval Research Laboratory (NRL) in 1988, is described. The HTSSE program focuses high temperature superconductor (HTS) technology applications on space systems. The program phases, goals, and objectives are discussed. The devices developed for the HTSSE-II phase of the program and their suppliers are enumerated. Eight space-qualified components were integrated as a cryogenic experimental payload on DOD's ARGOS spacecraft. The payload was designed and built using a unique NRL/industry partnership and was integrated and space-qualified at NRL.**

I. Introduction

THE high temperature superconductivity space experiment (HTSSE) program, initiated by the Naval Research Laboratory (NRL) in 1988, focused applications for HTS materials on satellite electronic components. The program was conducted in successive phases. Descriptions of the initial phase (HTSSE-I) are contained in [1]–[11]. This article describes in detail the second phase (HTSSE-II).

II. HTSSE-II Phase and Devices Developed

The HTSSE-II mission objective is to demonstrate the functionality of advanced HTS devices and subsystems as well as advanced cryocoolers in space. In early 1991, NRL solicited proposals via public announcements and a broad agency announcement (BAA). Thirteen HTS device proposals were selected and resulted in the eventual delivery of ten space qualified experiments, eight of which are on HTSSE-II (see Table I). These experimental devices had to pass space qualification tests. Determination of long term effects on these devices and the cryogenic subsystem that supports them is a specific objective for HTSSE-II. Their performance will be measured in detail during the one- to three-year mission life of the host spacecraft. Details concerning specific devices are in other articles in this special issue.

Selection of each device for development was based primarily on DOD system requirements and the potential for the device to provide improved performance or power or weight savings. The channelizers, multiplexers, filters, receivers, downconverter, and antenna array all relate to communications functions. The cueing receiver, analog-to-digital (A/D) converter, digital instantaneous frequency measurement system (DIFM), digital multiplexer, and delay lines have signal processing applications. Whether or not a specific device became part of the HTSSE-II payload involved several additional factors. The size, geometry, and cooling capacity of the cryogenic bus for the devices dictated that only seven could be accommodated. The Loral multiplexer and NASA Lewis/JPL downconverter, although both were fully functional and space qualified, were not manifested due to these constraints. The location of the HTSSE-II payload on the host spacecraft precluded the Wuppertal HTS antenna from having a usable field of view, thus eliminating it from consideration. Development of the TRW 60 GHz communications receiver was terminated because millimeter wave HTS phased array components, especially the phase shifter, proved to be beyond the state-of-the-art at that time. Furthermore, HTS digital technology, on which the Conductus A/D and the TRW digital MUX were based, had not matured sufficiently to build the circuits originally proposed. The Conductus A/D program was redirected to terrestrial applications while the TRW digital MUX was drastically simplified, consistent with the maturity of HTS digital technology at the time of the delivery to NRL for HTSSE-II integration.

Each of the devices to be flown on HTSSE-II had to undergo very stringent space qualification testing (see [12]). Several issues had to be addressed concerning the packaging of each device. Techniques for bonding lead wires to HTS thin films, precisely mounting patterned HTS thin films inside machined cavities, and integrating conventional electronics with HTS on the same substrate were developed. These techniques had to survive the rigors of space qualification testing which include three axis vibration, acoustic vibration, and thermal cycling. When something failed during testing, the device would be returned to the vendor for redesign or rework. This was initially done using what is called the "qualification" unit to validate the design. Once this unit had passed all space qualification testing, the "flight" unit was built using the same

Manuscript received February 15, 1996; revised March 11, 1996. This work was supported in part by the Advanced Development Office, Space Technology Program, Space and Naval Warfare Systems Command (SPAWAR), NASA, ARPA, BMDO, the Canadian and German governments, and the Air Force Space Technology Program Office.

T. G. Kawecki, G. A. Golba, and G. E. Price are with the Naval Research Laboratory, Washington, DC 20375-5320 USA

V. S. Rose is with V. S. Rose Consultants, Bowie, MD 20720 USA.

W. J. Meyers is with Allied Signal Technical Services Corp., Columbia, MD 21045 USA.

Publisher Item Identifier S 0018-9480(96)04810-7.

TABLE I
HTSSE-II DEVICES SELECTED FOR DEVELOPMENT

Device Category	Major Design Features	Supplier
Channelizers/Filters	4 Channel input multiplexer @ 4 GHz	ComDev
	4 Channel filter @ 4 GHz	Westinghouse Science & Technology Center
	5 Channel input multiplexer @ 8 GHz	Space Systems/Loral
Receivers	60 GHz Comm. Receiver	TRW
	Wideband Cueing Receiver, > 2 GHz Chirp BW	Lincoln Laboratory
	Hybrid 9 GHz Channelized Receiver with MMIC mixer	Naval Research Laboratory
	Low-Noise HTS/GaAs Downconverter: 7 --> 1 GHz	NASA/JetPropulsionLaboratory and Lewis Research Center
A/D Converter	Digital logic using Josephson Junctions	Conductus
Digital IFM	5 bit, 16 MHz resolution $f_c = 4$ GHz BW = 500 MHz	Conductus
Digital Multiplexer	Logic using HTS SQUID	TRW
Delay Line	40 nS delay line	Westinghouse Science & Technology Center
Antenna Array	Adaptive nulling design 4 elements $f_c = 5$ GHz	University of Wuppertal & Siemens (Interatom)
HTS-Material Environmental Effects Monitor	Measure space radiation effects on T_c, J_c, R_s and λ	Naval Research Laboratory

design as the qualification unit. The flight unit was subjected to "acceptance" level testing, a lower level than qualification tests, (for example, the "acceptance" level for vibration was 3 dB lower than for "qualification") which verified workmanship of the device before the device was installed on the flight cryogenic cold bus.

III. HTSSE-II PAYLOAD AND HOST SPACECRAFT

The HTSSE-II payload was manifested on the Air Force Space Test Program Advanced Research and Global Observation Satellite (ARGOS) in March 1993. ARGOS is a three-axis stabilized, nadir-pointing satellite weighing 2500 kg with total power of 1 K. It is the host to eight experiments with launch scheduled on a Delta 2 rocket in Spring 1997. ARGOS will operate in a 450-nautical-mile circular orbit at a sun synchronous inclination. ARGOS will remain in orbit for a long time; however, data on HTSSE-II may only be taken for one to three years.

HTSSE-II is located on the zenith deck of ARGOS with volume available on both the interior and exterior sides. The principal structural component of HTSSE-II is a 1.02 m by 1.27 m honeycomb deck which bolts onto the ARGOS frame and becomes an integral structural component of the host. There are standard power, command, and control and data bus interfaces with ARGOS. Electronic boxes are mounted on both sides of this deck. HTS experiments and supporting cryogenic subsystems are located on the exterior side to take advantage of passive cooling available in a sun synchronous orbit. The only component not mechanically mounted on this deck is the antenna which is mounted on the nadir side of ARGOS in order to receive ground transmitted signals used to test the HTS devices. Fig. 1 is a drawing of the ARGOS spacecraft with HTSSE-II installed. The larger exploded view shows the exterior HTSSE-II deck with thermal blankets and some structure removed for clarity. As with all space applications, strict limits were placed by the host ARGOS spacecraft on mass, volume and power allocations. The HTSSE-II payload design stayed well within these allocations with the power constraint being the most demanding.

IV. HTSSE-II PAYLOAD SYSTEMS DESIGN

HTSSE-II has three principal goals which drove the systems design: 1) fly the maximum number of HTS experiments; 2) develop and demonstrate a cryogenic subsystem which would

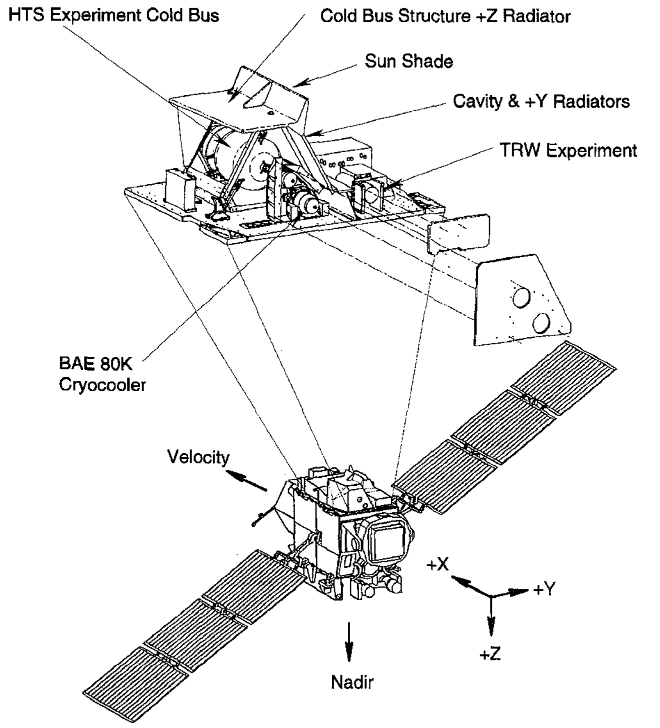


Fig. 1. Drawing of ARGOS host spacecraft with detail of HTSSE-II payload.

provide a continuous 77°K ± 1° Kelvin (K) environment to support a long life space application; and 3) demonstrate one year operation on orbit (three years desired). To achieve these goals required extensive and complex systems design trade-offs in numerous areas. Lessons learned in building the cryogenic cold bus for HTSSE-I contributed significantly to this decision process (see [4] and [6]). To help understand these issues, a brief discussion concerning the design of cryogenic subsystems for spacecraft follows.

Cryogenic temperatures are difficult to achieve and maintain over a long time on a spacecraft. Spacecraft electronics and propellants need to be kept warm which typically requires a 0–40°C spacecraft bus temperature. Controlling temperatures to this range is handled very adequately in conventional satellite designs, but creates a stressing environment for cryogenic subsystems. There are many approaches to achieve cryogenic temperatures, e.g., stored cryogen, passive radiative cooling, and mechanical cryocooler. One must also consider how to connect the components to be cooled to the cooling source. One approach is to colocate all components on a single cooler (cold bus cooling). A second approach has each component with its own individual cooler (local cooling). Yet another approach is to have a common cooler and distribute a cryogenic fluid to each component requiring cooling. Each has its pros and cons which impact on system design and mission life. There are other limitations placed on any cryogenic subsystem design because of the inherently limited power, weight, and volume available on a spacecraft as well as cost factors. Reference [13] addresses several of these issues.

The cryogenic subsystem was the principal driver for the design of the HTSSE-II payload. There are three sources of heat affecting any space-based cryogenic package: conduction, radiation, and internal electrical (ohmic) losses. There is no convection in the vacuum of space. Conduction loss comes from heat flow along the physical structure which supports the cryogenic cold bus and from input-output (I/O) cables that connect the electronics and instrumentation on the cold bus to warm ambient temperature electronics. Conduction loss is proportional to the temperature difference between the cryogenic bus and the warm environment and a thermal conductance which is material and form factor dependent. Radiation loss comes from thermal radiation absorbed by the cryogenic cold bus from the structure which surrounds it. Radiative heat transfer is proportional to the difference between the fourth powers of the temperatures of the radiator and absorber, and the area and optical properties of the surfaces involved. Because of the strong temperature dependence of radiative heat loads, a small decrease in the warmer environment surrounding the cryogenic payload leads to a large decrease in thermal load. The large number of I/O cables going into the cold bus was another major design consideration. Internal ohmic heat generation was not a large thermal load for HTSSE-II. The superconducting components on the cold bus dissipated no heat. Any heat load due to conventional electronic devices in the cold package was small due to low duty cycle during the experiment.

The thermal design of most spacecraft maintains 0–40°C internal temperatures to ensure the proper operation of the electronics and propulsion components. External spacecraft components such as solar arrays and radiators can vary from −100 to +100°C depending on the optical coating, view to space, and external environmental heat fluxes (sun and earth). Large ambient to cryogenic temperature differences of 100 to 200°C inherent with cryogenic space applications can result in high heat fluxes. Thus low radiative and conductive losses are required to provide efficient thermal designs. The HTSSE-II design strategy used two approaches to minimize the cryogenic cooling load on the cold bus. First, the ambient temperature of the spacecraft area surrounding the cryogenic payload was reduced as much as possible; second, materials were used which limited conductive and radiative thermal parasitics into the cryogenic bus. The heat load on the HTSSE-II cryogenic component had to be at the absolute minimum because of the limitations on the cooling method selected.

If HTSSE-II is indicative of future HTS device payloads, future cryogenic HTS commercial payloads are likely to have significant volumes and numerous input/output (I/O) thermal parasitics. Additionally, commercial space payloads typically require lifetimes of at least five years, preferably ten years. Based on HTSSE-I and HTSSE-II experience, cryogenic cooling capacities on the order of 300–1000 mW (or greater) in the 60–80 K temperature range are likely to be the norm for electronic payloads. Cryogenic thermal loads of this magnitude over long time periods preclude the use of solid cryogens for primary cooling due to the high mass and volume that would be required. Cryogenic radiators are undesirable for large thermal load payloads in this temperature range because they greatly constrain orbit options and have a large impact on the overall spacecraft design. Long life, high reliability mechanical refrigerators ("cryocoolers") appear to

TABLE II
INDUSTRIAL PARTICIPATION

System or Component	Major Design Features	Supplier
RF Input/Output Cables	Low thermal loss stainless steel coaxial cables (0.021" diam.)	Gore
Multi-Layer Insulation (MLI) blanket for cryogenic cold bus	Aluminized mylar layers separated by silk net	Lockheed
Mechanical Cryocoolers using Stirling cycle	Maintain cryogenic cold bus at 77 K with 500 mW heat load	British Aerospace (now part of Matra/Marconi)
	Stand alone cryogenic system at 65 K with 250 mW heat load	TRW
	Cryocooler drive electronics (CDE) with closed loop control	Lockheed
Digital Instrumentation	Digitization of data from RF processing system	Aeronics
RF and Video Instrumentation	Detection/processing of RF test signals	ITT Government Systems
HTSSE Remote Terminal (HRT)	Satisfy all command and control and data telemetry needs	Gulton
Receive Antenna	Receive C- and X-Band signals transmitted from ground	Antenna Corp of America (ACA)

be the best cooling method for large thermal load/long duration cryogenic payloads. Reference [14] provides an excellent overview of the current status of mechanical cryocoolers for spacecraft.

Based on the HTSSE program goals, a British Aerospace (BAe) 80 K Stirling-cycle cryocooler was selected for the HTSSE-II cryogenic bus cooling source. During the payload design effort in 1993 a number of promising pulse tube and Stirling cycle cryocoolers were just finishing their development cycles. However, only the BAe cryocooler had demonstrated on-orbit operation of greater than one year. Demonstrated reliability was paramount because the cryocooler on HTSSE-II was a single string failure point. The complexity, cost, weight and technical risk of incorporating a redundant cryocooler on HTSSE-II were considered too high. For a five to ten year commercial or DOD application, redundant cryocoolers would probably be desirable. One should also note that for some space applications vibrations from a mechanical cooler can be a serious problem. This is not the case for HTSSE and microwave applications of HTS.

The BAe 80 K cryocooler has a nominal cryogenic cooling capacity of 780 mW @ 75°K when rejecting heat to a 20°C environment. This cooling capacity drove the size of the HTSSE-II cryogenic bus and the number of HTS experiments that could be flown. Borrowing from the experience of previous space cryogenic payloads, the HTSSE-II cryogenic bus was designed for a thermal load of 50% of the cryocooler cooling capacity at nominal rejection temperature. Due to the uncertainties of building cryogenic packages, a launch criterion was that the flight payload had to have at least 30% reserve cooling capacity. These considerations highlight the need for a thermally efficient cryogenic system design to minimize the cryocooler's impact on spacecraft design issues of weight, power, vibration, heat rejection and electromagnetic interference/compatibility (EMI/EMC). Larger thermal loads would require larger coolers which would certainly magnify these potential problems.

The final HTSSE-II payload design configuration involved partnerships between NRL and several industrial suppliers of systems, subsystems and components (see Table II). This involved fabrication of unique components to meet cryogenic as well as spacecraft requirements. The Lockheed Research Laboratory fabricated a highly efficient multilayer insulation radiation blanket for the cryogenic bus which consisted of alternating layers of aluminized mylar and silk net. Great care had to be exercised to insure that the seams of the various layers of MLI did not overlap and that the MLI was carefully wrapped around the support straps and input/output leads which penetrated through the radiation blanket into the cryogenic bus.

Another design issue solved with Lockheed's help was a flexible, thermally conductive, detachable link to connect the cryocooler to the cryogenic bus. Gore Industries developed very small diameter (0.53 mm/0.021″), low thermal conductivity RF coaxial cable for I/O to the cold bus to reduce conductive heat loads. Structural Composites Industries provided high strength, low thermal conduction tension structural straps to support the cryogenic cold bus which reduced structural conductive parasitics. Several suppliers provided some of the ambient electronics subsystems.

The NRL Naval Center for Space Technology (NCST) developed the overall design for the HTSSE-II payload. After the performance of the flight HTS devices was verified using laboratory instrumentation, they were mounted on the cold bus, thermally insulated, and integrated with the ambient flight electronics, all of which were mounted on the deck. It was NCST's responsibility to integrate all the subsystems and ensure end-to-end functionality. NCST provided the completed, space qualified HTSSE-II deck to the ARGOS prime contractor, Rockwell International Corp., and assistance with payload integration and testing at the ARGOS spacecraft level.

V. Cryogenic Cold Bus Thermal Design Overview

HTSSE-II payload is divided into five temperature controlled zones: the electronics deck, the BAe cryocooler, the cryogenic cold bus, the cold bus support structure (CBSS), and the TRW experiment package. Operating temperatures for the electronics deck and the BAe and TRW cryocoolers are separately controlled to temperatures in the nominal spacecraft range (approximately 0–40°C) using standard spacecraft design techniques (see [15]). The HTSSE-II cryogenic subsystem design is unique to space-deployable cryogenically cooled electronics, in general, and microwave applications, in particular. The design of this cold bus will be the focus of the rest of this section.

The heart of the cryogenic subsystem is a central cold bus with seven HTS experiments cooled by the BAe cryocooler. This cryocooler has a nominal 780 mW of cooling capacity at the operating cold bus temperature of 77°K, thus requiring a highly efficient cryogenic package. To achieve this, the design provided high thermal resistance links between the cold bus and its surrounding environment and attempted to lower the temperatures of the surrounding environment to reduce radiative thermal loads as much as possible. Conduction occurs through the mechanical support structure and the I/O leads (RF, dc, temperature sensors, etc.). The warmer ARGOS spacecraft structure (300 K nominal) is the source of radiation heat load. Any ohmic heating effects in the HTS experimental devices are not a significant thermal load due to the negligible ohmic losses of superconducting devices and the short testing time of each device.

Fig. 2 shows the cryogenic subsystem mechanical design. The cold bus with experiments (located in the center of this figure) is supported by glass epoxy thermal isolation tension straps which fasten to an ambient temperature cold bus support structure (CBSS). The cold bus has a cylindrical shape (242 mm in length by 228 mm in diameter) with a "Tee" frame between two circular end plates. The HTS devices are mounted in the three "cavities" formed by this structure. A multilayer insulation (MLI) radiation blanket is constructed around the cold bus to limit thermal radiation parasitics and is not shown in Fig. 2 for clarity. This blanket consists of approximately 40 layers of 6 μm thick double-sided aluminized Mylar with silk net separators between each layer. Computer modeling shows 240 mW of radiative heat loss for the MLI blanket. If the MLI were not used and the facing surfaces coated with low emissivity gold ($\varepsilon = 0.02$), the model showed 830 mW loss.

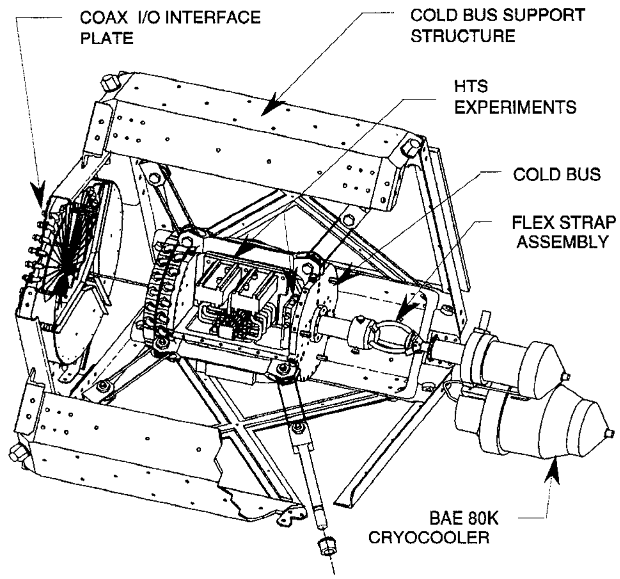


Fig. 2. Cutaway drawing of HTSSE-II cold bus and support structure.

The I/O cable interface is on the left side of the cold bus in Fig. 2 and the BAe cooler with flex strap assembly is on the right. All I/O cables to the cold bus are brought through the radiation blanket in one 6 mm diameter (0.25″) bundle. To reduce the potential for cryocooler induced electrical noise in the low-frequency, unshielded dc I/O lines, the cold bus I/O interface is located at the opposite end of the cold bus from the cryocooler. The HTSSE-II experiments require RF coaxial cables for most of the input and output signals. To reduce the associated thermal load, low thermal conductivity RF cables with only 0.5 mm (0.021″) outer diameter are used. These cables have stainless steel outer conductor, expanded Teflon dielectric insulator, and stainless steel center conductor which had a thin multi layer coating of silver and copper to reduce RF losses. The overall thermal conductance ratio of conventional 0.141″ stainless steel coaxial cable to this 0.021″ stainless steel coaxial cable is 191 to 1. This results in an estimated thermal load of 3 mW per cable to the HTSSE-II cryogenic cold bus. The RF attenuation for these cables is 6 dB per 305 mm (12″) at 10 GHz which is acceptable for HTSSE-II experiment testing and characterization but may be excessive for use with operational systems.

The BAe cryocooler connects to the cold bus via a flexible thermal link. A cylindrical beryllium cold stem extends from the cold bus through the MLI radiation blanket. Three flexible copper braid straps are soldered to a fixture which bolts to the cold finger of the cryocooler. The other ends of these straps are soldered to a copper collar with a precision bore which snugly fits over the beryllium stem at room temperature. The collar shrinks to provide high contact pressure and low thermal interface resistance at cryogenic temperatures due to the difference in the coefficients of thermal expansion between copper and beryllium. This interface is repeatable, thermally efficient, and provides an easily separable joint. The copper braid minimizes residual assembly and thermal contraction loads on the cold finger. This is important because the long life potential of the BAe cryocooler is primarily due to the

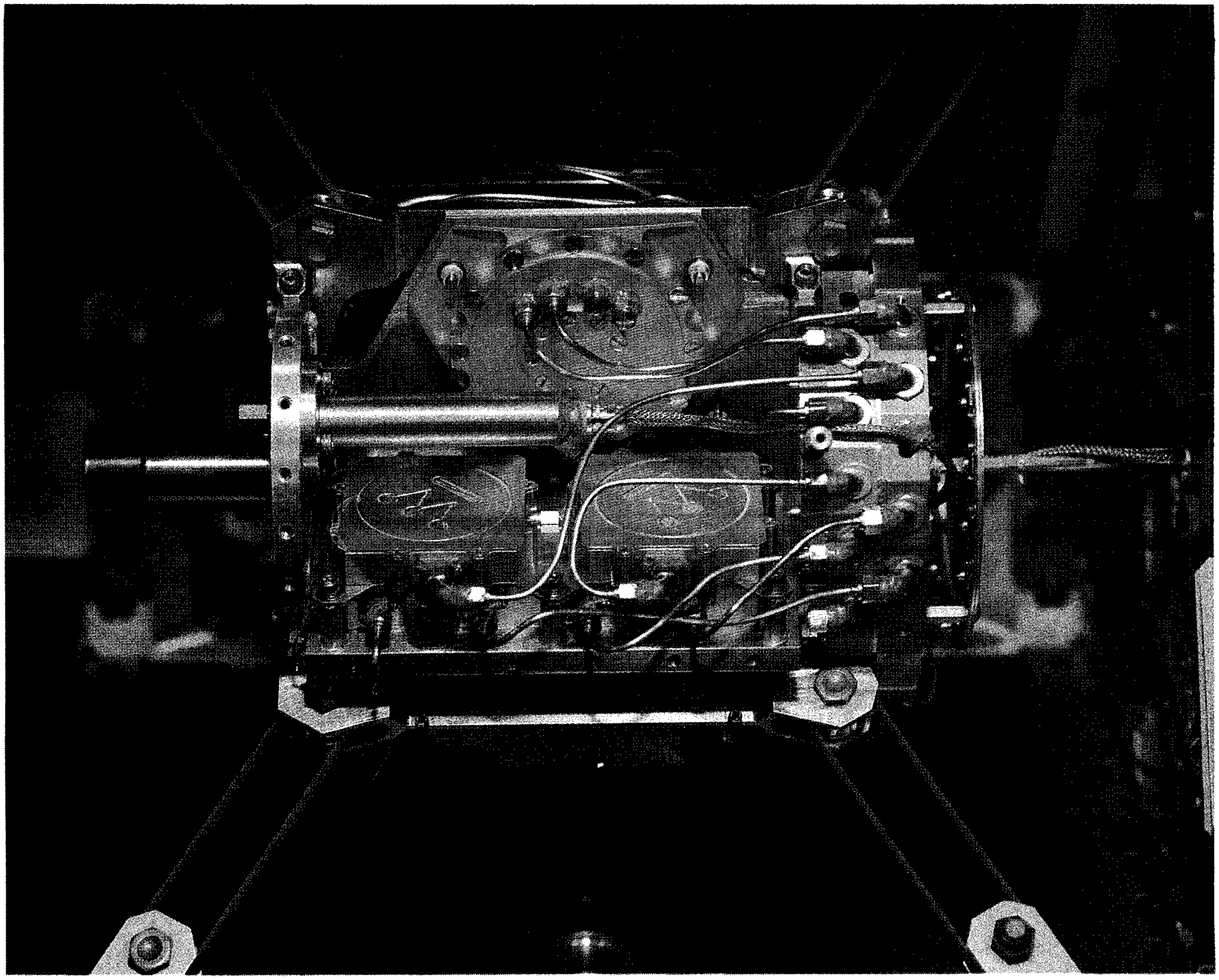


Fig. 3. Photograph of HTSSE-II flight cold bus prior to radiation blanketing.

use of clearance seals to eliminate contacting mechanisms that cause wear. Transverse forces greater than 50 grams on the cryocooler cold finger can cause clearance seal contacting and subsequent cooler failure. Significant design priority focused on maintaining clearance seal integrity to ensure long life.

Fig. 3 is a photograph of the assembled flight cold bus before the installation of the MLI radiation blanket and cryocooler flex strap. Four of the six glass epoxy tension structural straps and four of the seven experiments are visible in this view. Semirigid 0.141″ and 0.085″ diameter copper coaxial cables are visible in the center and connect the HTS experiments to a coaxial cable interface ring on the right side of the cold bus. The cable bundle that contains all the cold bus I/O lines extends to the right of the interface ring. The beryllium cold stem which connects to the cryocooler is visible at the left end of the cold bus.

Taking into consideration all of these factors, the thermal design model of the HTSSE-II cold bus had a total predicted heat load of 400 mW. The radiation losses are 239 mW while the structural support straps contributed 56 mW and the I/O cables about 105 mW. The radiation losses in this model are approximately 60% of the total which again emphasizes why efficient thermal blanketing of the cold bus is essential.

The location of the CBSS and electronic boxes on the HTSSE-II take advantage of the ARGOS orbit. Because the HTSSE-II deck is on the zenith side and the orbit is sun synchronous, an excellent passive cooling situation exists because the deck faces toward deep space. This allows mounting passive radiators which lower the CBSS assembly temperature into the 200 K range (−73°C), thereby reducing thermal parasitics to the cold bus. Temperatures lower than 200 K were not possible due to the relatively hot (60°C) +Y solar panel that comes into view of the passive radiators periodically.

The CBSS assembly is attached to the HTSSE-II deck with thermally insulating kinematic mounts. Three passive radiators are mounted to the CBSS, two are connected to the structure and the third to a thermal lining on the interior of the CBSS. The radiators are positioned to maximize the view toward deep space. One of the radiators has an extension to act as a sun shade and increase its efficiency (see Figs. 4 and 5).

HTSSE-II is instrumented to monitor and diagnose cryocooler and cryogenic payload status while on orbit. The

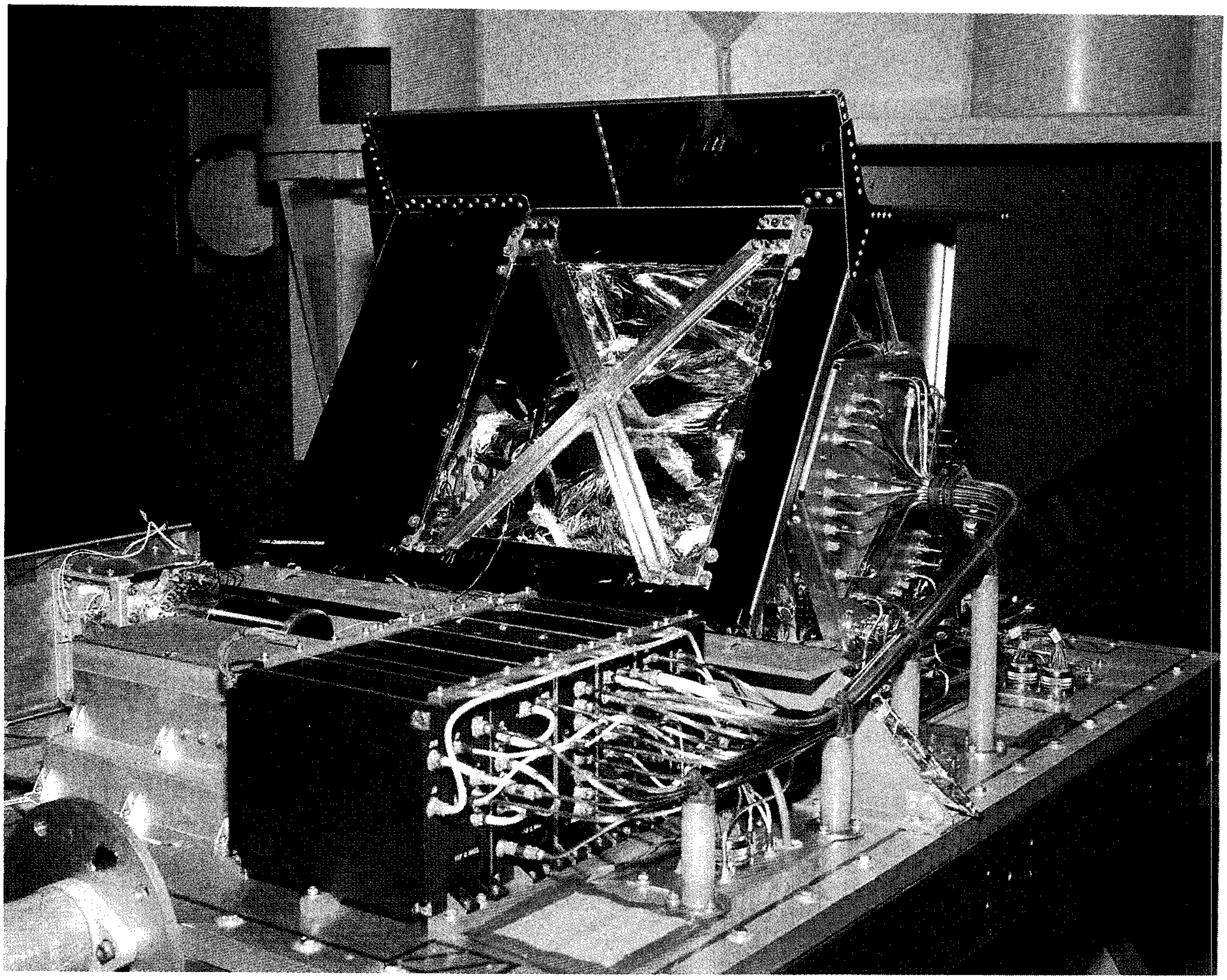


Fig. 4. Photograph of HTSSE-II flight unit prior to cavity radiator and external MLI blankets installation.

BAe cryocooler, mounted in a bracket, attaches to the main HTSSE-II deck mechanically, but it is thermally isolated to an independent radiator which biases the bracket to a temperature which is colder than the deck. The cryocooler mounting bracket has four accelerometers to provide axial and lateral vibration data for the compressor and displacer. The cold bus and cold finger ends of the flex strap have platinum resistance temperature sensors to monitor temperature. The flex strap thermal resistance has been calibrated to provide a heat flow meter to monitor cryocooler cooling performance. Lockheed's cryocooler drive electronics (CDE) provide compressor and displacer motor current data. Control circuits monitor the cold bus temperature and adjust the cryocooler's compressor stroke to maintain the desired temperature. During thermal vacuum testing, these electronics held the cold bus temperature to ± 0.2 K, well within the ± 1 K requirement, even when the ambient deck temperature was cycled from 0–+40°C.

Vibration and thermal environmental tests were conducted to verify the HTSSE-II design. Qualification and flight units were fabricated and tested. Three thermal vacuum tests verified system performance. Each lasted about two weeks with 24 hours per day operations. The cryogenic bus thermal performance requirements were met during testing by maintaining the cold bus at 77 ± 1 K with at least a 30% reserve capacity for ambient temperatures between 0–$\pm$40°C. The heat load on the cryocooler, determined during these tests from the cooler performance curves, agreed to within 10% of the HTSSE-II thermal model predictions discussed earlier. Performance and characterization tests on all the HTSSE-II devices were conducted during these thermal vacuum tests using the flight electronics, resulting in complete payload testing. Table III presents the thermal performance demonstrated in the three tests conducted.

Vibration testing confirmed that the HTSSE-II design was capable of surviving the launch environment. One objective of the program was to confirm the robustness of the HTS experimental devices. Little experience was available on the structural integrity of HTS substrates, mounting procedures, and wire bonding. In several cases, experimental devices failed component vibration tests and had to be redesigned or reinforced. The HTSSE-II vibration spectrum is presented in Table IV.

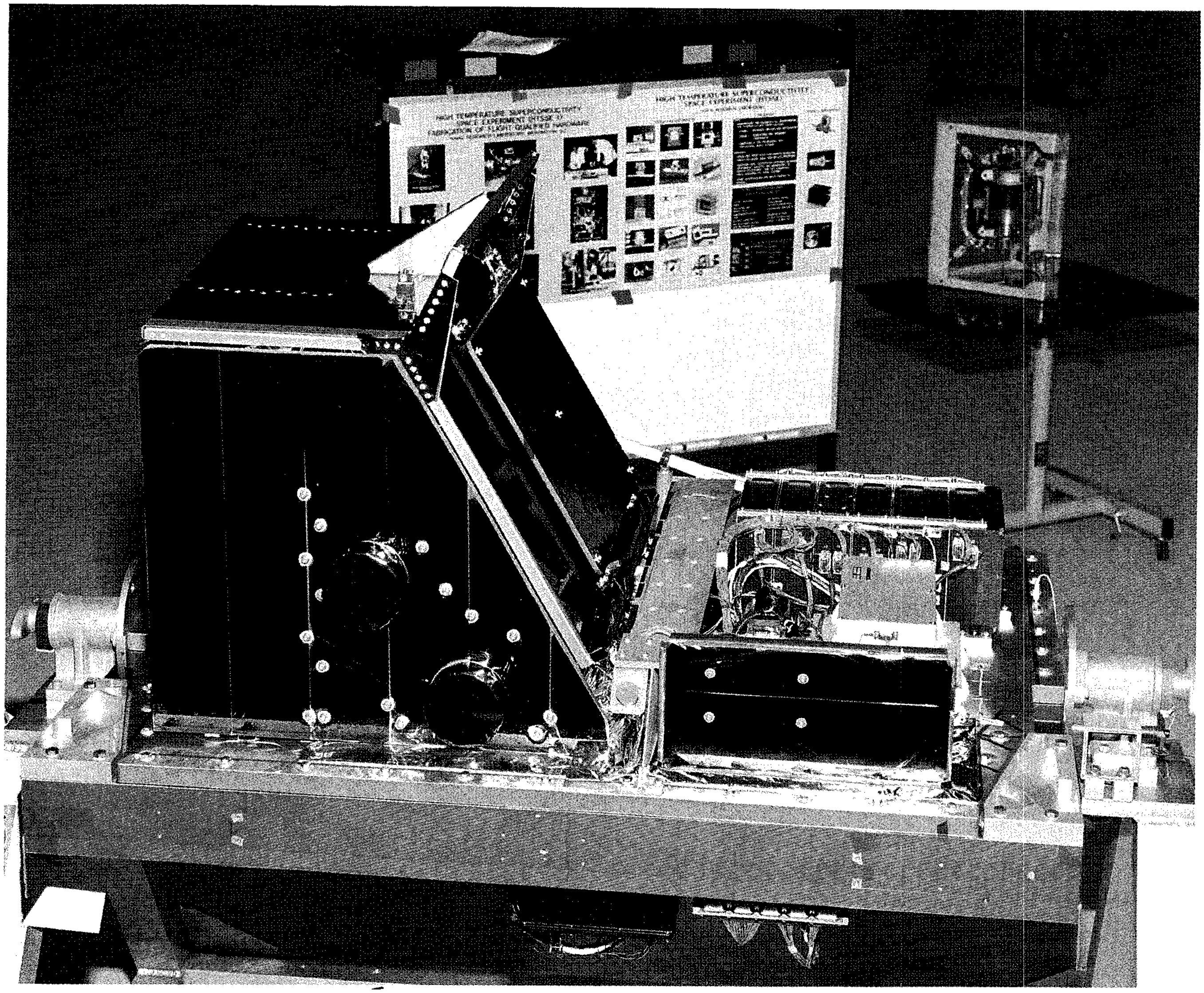


Fig. 5. Photograph of HTSSE-II flight unit prior to payload thermal blanketing.

TABLE III
HTSSE-II CRYOGENIC PERFORMANCE SUMMARY

Parameter	Model Predicts (Watts)	Qual Test1 (Watts)	Qual Test2 (Watts)	Flight Test (Watts)
L = Heat Load	.404	.360	.382	.380
C = Capacity of Cooler †	.780	.780	.780	.640
R = Reserve (C-L)	.376	.420	.398	.260
Reserve Capacity (1-L/C)	48%	54%	51%	41%

† At 75 K cold finger temperature and 0°C rejection temperature

VI. DEVICE PERFORMANCE MEASUREMENTS

A. On-Orbit Test Philosophy

On-orbit measurements of the HTSSE-II experiments will be performed with a ground-based, calibrated signal source. There are several advantages of this approach over the use of an on-board signal source and associated measurement equipment. In this approach, the signal source can have greater stability, the parameters of the transmitted signal are known more accurately, the spacecraft instrumentation can be less complex, and there is more flexibility in selection of test parameters. Also, this mode of testing replicates an actual operational situation in which the devices under test could be used. This configuration resembles what is known in the communications satellite community as a "bent pipe" mode of operation.

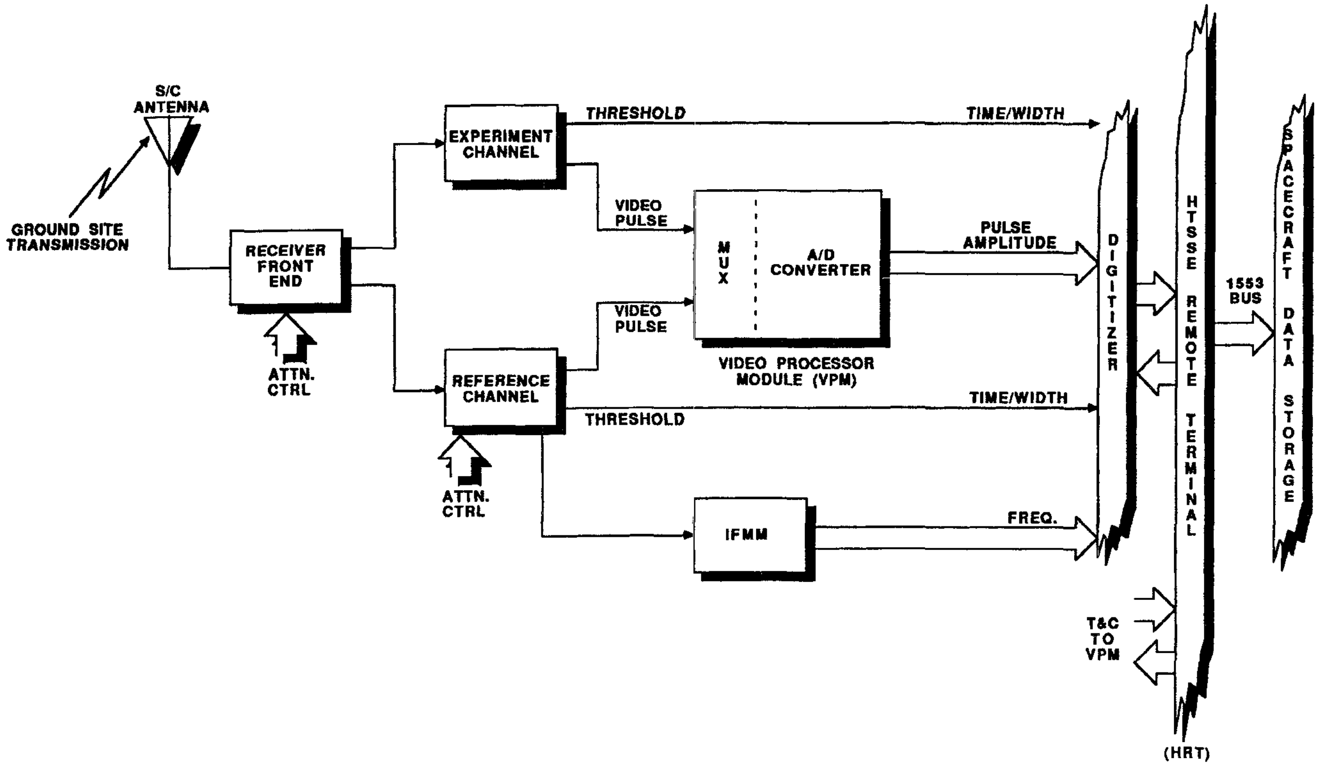


Fig. 6. Conceptual diagram for measuring an RF device.

TABLE IV
HTSSE-II COMPONENT ACCEPTANCE LEVEL VIBRATION SPECTRUM

FREQUENCY (HZ)	LEVEL (G^2/HZ)
20	0.01
20 TO 160	+3 dB/OCT
160 TO 250	0.08
250 TO 2000	-3 dB/OCT
2000	0.01

Using this bent pipe approach, test signals transmitted from an NRL ground facility are received, passed through the device under test (DUT), detected, digitized, and stored for later down-linking to the receiving site. Experiments are characterized using on-board parameter measurement equipment. Reference channels are used to establish relative incident received power in the spacecraft. On-board processors provide data on the time, pulse width, frequency, and amplitude of the received RF signals. The data is collected for subsequent ground-based data reduction and analysis.

The technique incorporates a space borne instrumentation system shown in Fig. 6. In characterizing an experiment (e.g., multiplexer, channelizer, etc.), a received pulse-modulated signal is amplified, filtered and applied to the HTS experiment. Simultaneously, the same signal is applied to the reference channel (either C-Band or X-Band, as appropriate). Both the experiment output and the reference signal are detected and digitized providing comparative amplitude outputs. Since the two signals are from the same antenna and RF front-end hardware, the pulse amplitude difference in the two paths is a measure of the response of the experiment. Effectively, since the reference channel RF front-end is common, this approach resembles an "RF leveling" method. Time of arrival techniques are used to measure relative time difference for characterizing the HTS delay line.

B. System Requirements

1) Device Measurement Parameters: Experiment test requirements and test parameters vary depending on the type of device under test. Table V is a summary of the HTS devices and their associated RF test requirements. Experiment L, the TRW digital multiplexer experiment, and Experiment M, the NRL HTS materials environmental effects experiment, require no RF testing.

2) NRL Ground Site: The ground-based signal for HTSSE-II testing is generated at a site operated by NRL whose location is known to a high degree of accuracy, permitting transmissions to be precisely timed, based on the predicted spacecraft location. The site incorporates a precision 60 ft. diameter parabolic dish on an elevation-over-azimuth pedestal. The angular coverage is 360° in azimuth and is capable of elevation coverage from 5–70° relative to the horizon. The associated transmitter is capable of various modulation modes although the primary mode for the HTSSE program is pulsed. Table VI is a summary of the signal parameters available for transmitting to HTSSE-II devices while on orbit.

C. Signal Receiving and Processing System

The spacecraft signal receiving and processing system consists of a dual-band antenna, associated payload receiver modules, a video processor module (VPM), and an instantaneous

TABLE V
RF TEST REQUIREMENTS FOR HTS EXPERIMENTS

EXPERIMENT	FREQUENCY RANGE (GHz)	CHARACTERIZATION TESTS
C - DIFM	3.75-4.25	Frequency Measurement Accuracy
D - Delay Line	3.3-5.2	Delay vs. Frequency Insertion Loss
F - Channelized Receiver	9.1-9.7	Sensitivity Frequency Response Bandpass Flatness
H - Cueing Receiver	7.2-10.0	Frequency Measurement Accuracy
I - Multiplexer	3.7-4.3	Frequency Response Selectivity Insertion Loss
J - Channelizer	3.8-4.4	Frequency Response Selectivity Insertion Loss

TABLE VI
NRL GROUND SITE SIGNAL PARAMETERS

Polarization:	Vertical
Frequency Range:	3.3 - 5.2 GHz 7.2 - 10.0 GHz
Frequency Step Size:	1 MHz
ERP:	116 - 119 dBm
Output Power Step Size:	1 dB
Pulse Modulation:	
Pulse Width	.5 - 5.0 uSec.
Pulse Rate	.5 - 5.0 KHz
Duty Factor	5%
Rise Time	15 - 300 nSec
Antenna Beamwidth:	.1° (nom.)

frequency measurement module (IFMM). The receiver module and the VPM have RF and video interfaces with the cold bus containing the HTSSE experiments. Additional interfaces are VPM to digitizer and to the HTSSE remote terminal (HRT). Receiver control functions, such as redundancy switching, attenuator controls, and channel selection, are received through the VPM from the HRT. The HRT receives this information from the ARGOS spacecraft command and control and data bus, which uses MIL-STD-1553 bus architecture. See Fig. 6.

1) Payload Antenna: The payload receiving antenna is a dual-band design, providing omni-directional coverage in the azimuthal plane (relative to the spacecraft), and directional coverage in elevation. It incorporates two elements—one for C-Band and one for X-Band. A photograph of the flight antenna is shown in Fig. 7. The pointing angle, beamwidth, and gain are optimized for receiving transmissions within the field-of-view of the ground site, from horizon to horizon, at the

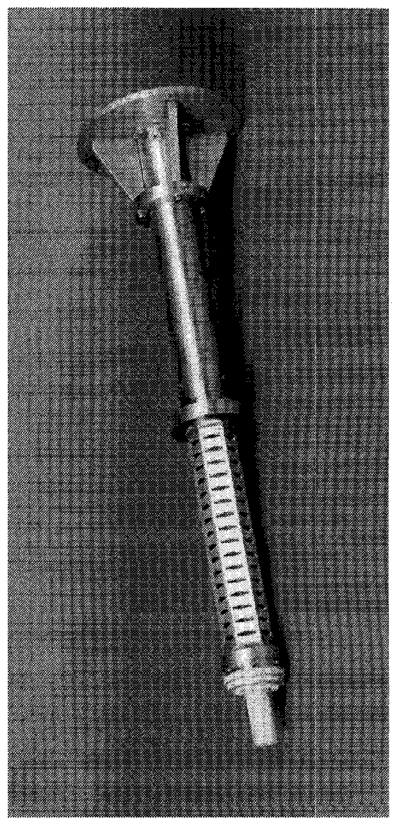


Fig. 7. Photograph of dual band HTSSE receiving antenna.

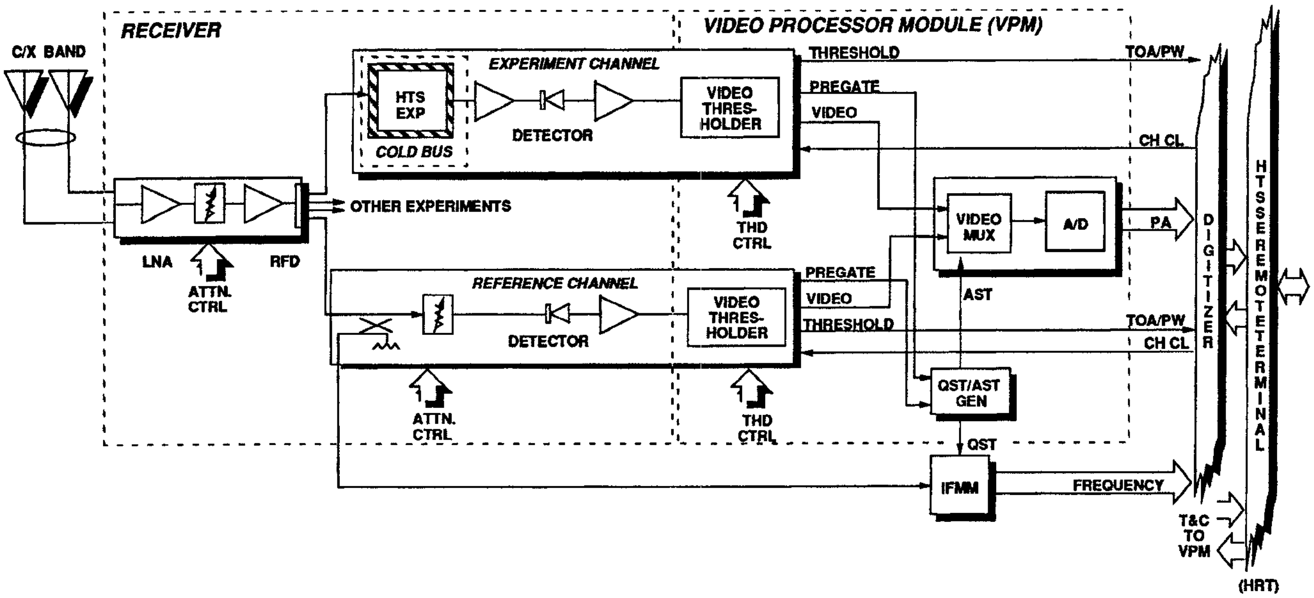


Fig. 8. Block diagram of measurement system for single device.

prescribed spacecraft altitude. The antenna is located on the nadir surface of the spacecraft, extended from the structure by approximately 20″ to avoid interaction with other spacecraft antennas and obstructions. A 0.290″ diameter, 72″ long, low loss (1.5 dB) coaxial cable (Gore Type 6) connects the antenna on the ARGOS nadir deck to the HTSSE-II payload on the zenith deck.

2) Payload Receiver: The HTSSE payload receiver consists of six RF detection modules, individually designed, and interconnected to accommodate specific experiments. Along with the front-end which is common to several experiments in both bands, each module is customized to provide the required electrical and physical interfaces with the HTS device under test. Input signal levels, switching, and detection requirements are specific to each experiment.

Typically, the goal is to use the maximum sensitivity and dynamic range to characterize device parameters, such as band-edge response. Attenuators, which can be adjusted by commands from the ground, are installed in the front-end to optimize input levels for each experiment.

Fig. 8 is a block diagram of the satellite RF measurement system. The HTS device is an integral electrical part of the experiment receiver path. Functionally, the front-end has a broadband low noise amplifier preceded by a low-loss antenna cable, resulting in a system noise figure of 4.5 dB. An RF distribution network provides required signal levels to each of the experiments. Device outputs are typically detected, video-amplified, and, then, applied to the VPM for processing. The reference and experiment channels have similar architectures. The Fig. 9 block diagram depicts the integration of each of the HTS devices with the ambient temperature instrumentation hardware.

3) Video Processor Module (VPM): Referring to Figs. 6 and 8, the VPM performs parameter measurements on the detected RF signals from the receiver. These include time-of-arrival (TOA), pulse width (PW), and pulse amplitude (PA). Ultimately, digital packets are formed for each detected pulse.

The A/D converter is an 8-bit flash converter that receives pulse inputs through a video multiplexer which alternately selects the desired experiment and reference signals. The 8-bit data output plus a 3-bit address (to identify the experiment and reference) are converted to an 11-bit serial word which is sent from the VPM to the digitizer.

In addition, the VPM controls the receiver functions through commands received from the HTSSE Remote Terminal (HRT). These commands are decoded and used to set certain receiver functions (switches, attenuators, relays, and sensitivity controls) to configure the receiver for predetermined operational tasks.

4) Instantaneous Frequency Measurement Module (IFMM): The IFMM provides good microwave frequency measurement resolution over a wide frequency spectrum. The delay line discriminator approach is used to measure phase difference which is translated to frequency and converted to an 11-bit digital output.

5) Digitizer: The digitizer handles both the analog and digital data from the detection and processing system. Its function is to provide TOA information on the logic pulses from the VPM, measure pulse width, strobe for amplitude and frequency measurements, and integrate all of these measurements into pulse descriptor packets (PDP's). Each incoming pulse will generate two PDPs—one for the reference and one for the experiment channel being monitored. The digitizer transmits these PDP's to the HRT upon request.

6) HTSSE Remote Terminal (HRT): The HRT implements all command and control and data telemetry requirements for HTSSE-II payload operations. It links the HTSSE-II payload with ARGOS via the ARGOS MIL-STD-1553 bus. The HRT employs the United Technologies Microelectronics Center (UTMC) 1750AR processor and UTMC BCRT 1553 interface chip set. The processor operates in the RISC mode, implementing a Harvard Architecture.

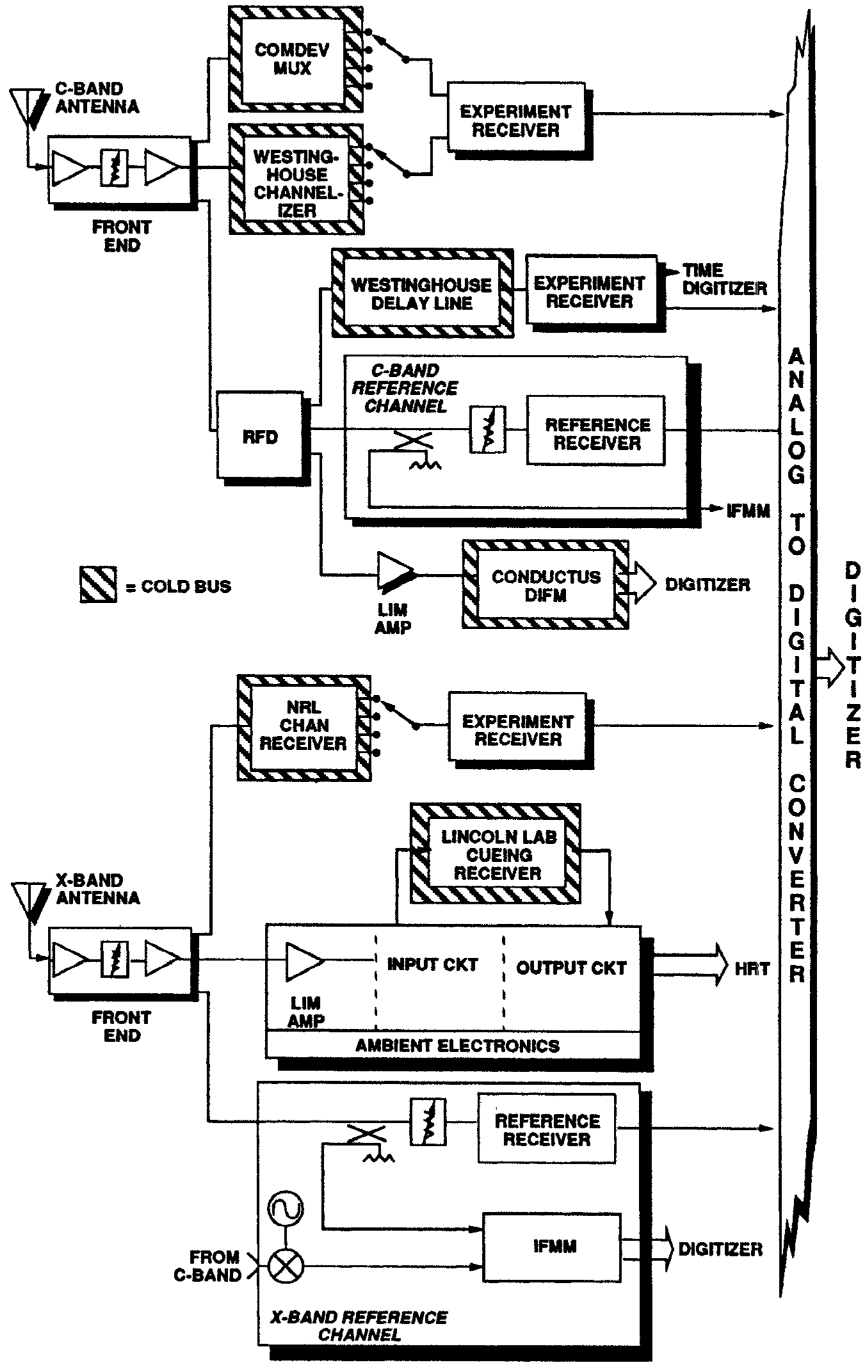


Fig. 9. Block diagram of RF measurement system.

The HRT flight software contains five major modules. These are:

1) CMD—Command prioritization and command card I/O module.
2) BCRT—1553 B interface module.
3) EXECUTIVE—Schedule module.
4) MEMORY—Memory management module.
5) TLM—TLM acquisition and telemetry I/O module.

VII. Device Characterization

Characterization of the HTSSE-II devices requires a test program which includes a sequence of measurements to assure space qualification and acceptance. Initially, pre and postvibration RF measurements are performed at the device level in the laboratory using an HP-8510 network analyzer. This establishes a baseline for tracking each device and subsequent performance comparisons. All the devices were characterized at 77°K. They were also characterized at other temperatures (77°K ± 3°) to ascertain any temperature dependence.

The device is next characterized in the HTSSE-II test bed. This test bed, which replicates the on orbit integrated receiver configuration, is used to perform automated receiver measurements to assure compatibility of the device and the ambient spacecraft hardware. The devices are then installed in the spacecraft cold-bus, integrated with the supporting ambient temperature RF and processing modules, and subjected to system-level thermal vacuum measurements. Experiments are characterized with the cold-bus at 77°K ± 1° and the ambient satellite equipment at predetermined temperatures between 0–40°C. System data is digitized, sent to the HRT, and collected by the HTSSE Aerospace Ground Equipment (HAGE) control and processing system

All the HTSSE-II device providers supplied NRL with both qualification and flight versions of the experiments. With a few exceptions (see below), all performed as expected (see [16]–[22] for details). Measured data did not change from the initial measurements at the provider's facility prior to shipment through postthermal vacuum payload system level testing at NRL. This leads to confidence that the data to be taken on orbit will provide consistent results. The procedures to verify and space qualify the payload used the same standard spacecraft procedures that NRL has used to build over 130 conventional satellites and payloads over the past 30 years. Therefore, if any changes or variations in performance are observed, they will most likely be associated with either launch or space environment effects on the HTS devices and subsystems.

There are two instances of device performance degradation. The TRW digital multiplexer was to have contained four similar circuits. Two of the four failed prior to shipment from TRW. Due to time constraints, TRW elected not to open their cryogenic device package and attempt to fix the problem. During characterization and space qualification at NRL at both device and system levels, there was no observable degradation in the performance of the two functioning circuits. The digital multiplexer will be launched in this status with only two functioning circuits.

The second involved the NRL channelized receiver. This device consisted of a four-channel, manifold-coupled HTS analog multiplexer with MMIC mixers and detectors integrated on the same substrate. The qualification unit successfully performed throughout the entire characterization and space qualification cycle at both the device and system levels. The flight unit also passed characterization and space qualification at the device level. However, after integration onto the flight cold bus and system level vibration testing, the device did not function properly. Subsequent trouble-shooting during thermal vacuum testing of the entire payload indicated that all four detector circuits were open-circuited. Because of time and cost constraints and risk to the other experiments, opening the MLI blanket to get to the cold bus to fix the problem was not feasible. The ambient temperature RF cables from the NRL receiver were reconfigured so that the RF outputs from each of the multiplexer channels can be measured, thus providing data on the performance of the HTS portion of this device. The NRL receiver will be launched in this configuration.

VIII. On-Orbit Measurements

The ARGOS spacecraft contains eight experiments including the HTSSE-II payload. HTSSE-II operations are planned on a timesharing basis with these other experiments. There will be two measurement opportunities each day as ARGOS passes over the NRL ground site. Typically, the characterization of one HTS experiment per pass will be possible. However, for some of the experiments, due to limitations with the ground site antenna feeds and their frequency coverage, two consecutive passes may be required to allow time for completion of the measurements.

A. RF Measurements

On-orbit measurements will consist of performance data from each of the HTS experiments and the appropriate reference channel simultaneously. The A/D provides two outputs representing the response of the device under test and the reference channel. A calibration is performed at the center frequency of the device to be characterized, providing a normalization of the A/D output as a function of RF input power. The difference of the device response and the associated reference yields the true response of the device. This data is independent of the variations in received power at the spacecraft, antenna performance, or front-end hardware response. This approach allows tracking frequency response and relative insertion loss over time. This applies to experiments such as the ComDev multiplexer, the Westinghouse channelizer and delay line, and the NRL cryogenic receiver. In addition to these parameters, the delay line requires measurements to quantify time delay. This will be accomplished using the TOA measurements.

The Lincoln Laboratory cueing receiver and the Conductus DIFM generate digital outputs representing measured frequency. On-orbit characterization requires frequency stepping across the operational band at predetermined power levels. The resulting output frequency is compared to the transmitted frequency to characterize performance. Correlation with either the ground-based synthesizer frequency or the on-board reference IFMM determines the device accuracy. The reference A/D measurement provides knowledge of the power level at the spacecraft to assure proper input to the device under test.

B. Experiment Commands

Each HTS experiment requires a unique combination of the ambient electronics modules and RF switch settings. The NRL HTSSE-II processing facility generates a configuration file for each device, describing which ambient modules must be used, their setup, and switch positions. This file contains a specific time (UTC—derived from GPS data) for execution to coordinate HTSSE payload setup with operations at the NRL ground site.

C. Digital Interfaces with ARGOS Satellite

The primary HTSSE-II command and control and telemetry interface to ARGOS is the MIL-STD-1553B data bus. ARGOS has allocated 64 Kbits of bandwidth to HRT telemetry. This consists of 125 message transfers, each containing 32 16-bit words. The first message contains housekeeping telemetry. The HRT commutates deck status (temperature, switch settings, etc.) into the housekeeping portion of telemetry. The remaining

124 messages contain science data. The content of the science data varies as a function of the HTS device currently under test. Each experiment requires a specific science data format which is contained in the configuration file and command upload.

ARGOS will store housekeeping and science data from HTSSE-II in its solid state data recorder (SSDR). The housekeeping data will also be available as part of the narrowband downlink of ARGOS. ARGOS will periodically dump the contents of the SSDR as ground station availability dictates. The SSDR memory dumps are received by Air Force satellite control network (AFSCN) ground stations and forwarded to their central facility for local processing.

D. Data Distribution to NRL and HTS Device Developers

SSDR memory dumps will arrive at the NRL HTSSE-II processing facility as 8 mm data tapes. These will be processed, correlating UTC's and configuration files to determine science data content. The science data will then be collated by experiment and placed in archival files for distribution. The HTSSE-II processing facility has access to the Internet. Consequently, electronic transfer of science data to HTS device developers will be available immediately after archival processing.

E. Measurement Accuracy

The primary mission of HTSSE-II is to characterize the HTS experiments with accuracy sufficient to detect possible long-term changes. The approach establishes a well controlled spacecraft parameter measurement system which develops a performance database for each experiment. Error contributions are minimized by incorporating reference channels to compensate for variations in RF signal levels received at the spacecraft, as well as receiver response variations. In addition, temperature stability of the supporting electronic equipment results in minimal error contribution.

Parameters that require consistent accuracy and stability for precise performance tracking include amplitude, frequency and time delay. Amplitude measurements are performed with A/D converters having resolution of 0.5 dB. During thermal vacuum testing, data collected had accuracy well within 1.0 dB. Additionally, since these measurements will be repeated numerous times over the spacecraft's operational time span, repeatability is of primary importance. This has been shown to be on the order of 0.5 dB over a 6-month period involving two thermal vacuum tests.

On-board frequency measurements are performed with a resolution of 1.25 MHz and overall accuracy of ± 1.5 MHz. Ground processing can be accomplished with either the frequency data in the data packets downlinked from ARGOS or the precision frequency data from the ground-based transmitter.

The third parameter, time delay resolution, is dictated by the digitizer which has 10 nS resolution. A higher degree of accuracy can be achieved by averaging many pulses for a given transmission. As mentioned earlier, this parameter is used only for characterizing the delay-line experiment.

IX. Conclusion

The HTSSE-II space experiment program is designed to focus the HTS community on possible space applications for advanced superconducting devices and subsystems. Another major goal is to demonstrate the feasibility of constructing a low-cost cryogenic space experiment containing both superconducting and cooled semiconductor components, when they have a technological advantage. The experiment procured, through a unique Government, industry, and university partnership, 13 devices which showed the utility of HTS for space applications. By having definite launch dates, the HTSSE program forced HTS device fabricators, at an early stage in device development, to address the formidable problems of packaging and space qualification.

The HTS devices delivered and integrated into the HTSSE-II experiment have undergone extensive testing over a period of two to three years and have demonstrated stable, reliable, and reproducible performance. Tests include temperature cycling, radiation testing, vibration, and space qualification such as thermal vacuum. HTSSE-II demonstrates that a reliable cryogenic package using mechanical refrigerators to cool HTS devices and subsystems can be built. Furthermore, these devices and subsystems can be space qualified and integrated onto a spacecraft. When the HTSSE-II experiment is launched on the ARGOS spacecraft in 1997, and performs successfully, it will have demonstrated that HTS technology can be implemented into operational space systems where the HTS technology demonstrates a convincing operational advantage over current technology.

Acknowledgment

The authors would like to thank the HTSSE-II device providers who had to meet stringent requirements and deadlines. Their cooperation in providing extensive technical detail about their devices and their willingness to work with the authors concerning the specifics of the integration of their devices into the HTSSE-II payload is greatly appreciated.

Overall program management at NRL was provided by J. C. Ritter. S. A. Wolf was instrumental in HTS materials development. M. Nisenoff had overall responsibility for procurement of the HTSSE-II devices. Their leadership and support ensured a smoothly functioning team of scientists and engineers from various disciplines at NRL, other government facilities, and private industry.

The following individuals from NCST contributed significantly to the building of the HTSSE-II payload: D. Bentz, T. Richmeyer, J. Barnes, M. Yi, E. Becke, W. Lippincott, J. Freitas, D. Mahony, S. Chappie, D. Spencer, L. Turner, C. Williams, and P. Stencil. A special thank you to W. Ewen, Project Engineer, for keeping the authors well focused on the intermediate and end goals.

References

[1] J. C. Ritter, M. Nisenoff, G. Price, and S. A. Wolf, "High temperature superconductivity space experiment (HTSSE)," *IEEE Trans. Magn.*, vol. 27, no. 2, pp. 2533–2537, Mar. 1991.

[2] M. Nisenoff, D. U. Gubser, G. Price, J. C. Ritter, and S. A. Wolf, "HTS passive microwave components for space applications," in *Workshop*

on High Temperature Superconducting Devices, Kumamoto, Japan, May 1991.

[3] M. Nisenoff, D. U. Gubser, S. A. Wolf, J. C. Ritter, and G. Price, "High temperature superconductivity space experiment (HTSSE)," in *Int. Superconducting Electronics Conf.,* Glasgow, Scotland, June 1991.

[4] T. Kawecki, "High temperature superconducting space experiment cryogenic system overview," in *Proc. 8th Int. Cryocooler Conf.,* Vail, CO, June 28–30, 1994. New York: Plenum, 1995, pp. 893–900.

[5] J. C. Ritter, M. Nisenoff, S. A. Wolf, and G. Price, "High temperature superconductivity space experiment (HTSSE)," in *'92 Asia Pacific Microwave Conf. 5th Australian Symp. Millimeter and Sub-Millimeter Waves,* Adelaide, Australia, Aug. 1992.

[6] C. L. Lichtenberg, W. J. Meyers, T. G. Kawecki, A. R. Peltzer, M. S. Johnson, M. Nisenoff, and G. Price, "The high temperature superconductivity space experiment (HTSSE)," in *World Congress on Superconductivity, Proc. 3rd Int. Conf. Exhibition,* Munich, Germany, Sept. 15–18, 1992. Exeter, England: Pergammon, 1993, pp. 1313–1331.

[7] M. Nisenoff, S. A. Wolf, J. C. Ritter, and G. Price, "Space applications of high temperature superconductivity: The high temperature superconductivity space experiment (HTSSE)," in *2nd Israel Int. Conf. High Temperature Superconductivity,* Eilat, Israel, Jan. 1993.

[8] G. Price, J. Ritter, M. Nisenoff, and S. Wolf, "High temperature superconductivity space experiment (HTSSE)," in *AIAA 93-4233, AIAA Space Programs Tech. Conf. Exhibit,* Huntsville, AL, Sept. 1993.

[9] G. W. Mitschang, "Space applications and implications of high temperature superconductivity," *IEEE Trans. Appl. Superconduct.,* vol. 6, no. 2, pp. 69–73, June 1995.

[10] T. G. Kawecki, D. R. Mahoney, and S. S. Chappie, "The high temperature superconducting space experiment II (HTSSE-II) cryogenic design," in *Space Cryogenics Workshop Proc.,* Calverton, MD, July 25–26, 1995. London: Butterworth-Heinemann Ltd., 1996, to be published

[11] M. Nisenoff, "The high temperature superconductivity space experiment (HTSSE): Present status and future challenges," *Supercond. Sci. Technol.,* vol. 9, to be published in 1996.

[12] MIL-STD-1540C Military Standard Test Requirements for Launch, Upper-Stage, and Space Vehicles, Sept. 15, 1994, DoD AMSC N/A FSC 1810, Space and Missile Systems Center, SMC/SDFP, Los Angeles, CA.

[13] J. Choi, W. Meyers, M. Nisenoff, G. Price, and J. Ritter, in *Proc. Workshop Integrated Cryogenic Satellite Design: Current Practice and Future Possibilities,* Oct. 21–22, 1991, Report NRL/MR/8305-92-6946, Naval Research Lab., Washington, DC, Mar. 6, 1992.

[14] R. G. Ross, Jr., Ed., "Cryocoolers 8," in *Proc. 8th Int. Cryocooler Conf.,* Vail, CO, June 25–30, 1994. New York: Plenum, 1995.

[15] D. G. Gilmore and M. Bello, exec. eds., *Satellite Thermal Control Handbook.* El Segundo, CA: The Aerospace Corporation Press, 1994.

[16] C. Rauscher, J. M. Pond, and G. B. Tait, "Cryogenic microwave channelized receiver," *IEEE Trans. Microwave Theory Tech.,* vol. 44, no. 7, July 1996, pp. 1240–1239.

[17] S. H. Talisa, M. A. Janocko, D. L. Meier, J. Talvacchio, C. Moskowitz, D. C. Buck, R. S. Nye, S. J. Pieseski, and G. R. Wagner, "High temperature superconducting space-qualified multiplexers and delay lines," *IEEE Trans. Microwave Theory Tech.,* vol. 44, no. 7, July 1996. 1229–1239.

[18] R. R. Mansour, S. Ye, V. Dokas, B. Jolley, W. C. Tang, and C. M. Kudsia, "Design consideration of super conductive input multiplexers for satellite applications," *IEEE Trans. Microwave Theory Tech.,* vol. 44, no. 7, July 1996, pp. 1213–1228.

[19] G. C. Liang, C. F. Shih, R. S. Withers, B. F. Cole, and M. E. Johanson, "Space qualified super conductive digital instantaneous frequency measurement subsystem," *IEEE Trans. Microwave Theory Tech.* vol. 44, no. 7, July 1996, pp. 1289–1299.

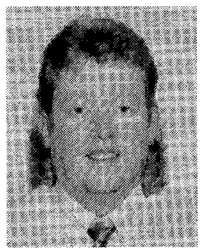
[20] W. G. Lyons, D. R. Arsenault, A. C. Anderson, T. C. L. G. Sollner, P. G. Murphy, M. M. Seaver, R. R. Boisvert, R. L. Slattery, and R. W. Ralston, "High temperature super conductive wideband compressive receivers," *IEEE Trans. Microwave Theory Tech.* vol. 44, no. 7, July 1996, pp. 1258–1278.

[21] J. H. Claassen, R. Skalitsky, and R. J. Soulen, "The NRL Josephson junction monitoring experiment on HTSSE-II," *IEEE Trans. Microwave Theory Tech.,* vol. 44, no. 7, July 1996, pp. 1308–1312.

[22] A. Silver, G. Akerling, R. Auten, D. Durand, J. Gooden, K-F. Lau, R. Orsini, J. Raab, S. Schwarzbek, E. Tward, and M. Wire, "A space-qualified experiment integrating HTS digital circuits and small cryocoolers," *IEEE Trans. Microwave Theory Tech.,* vol. 44, no. 7, July 1996, pp. 1300–1307.

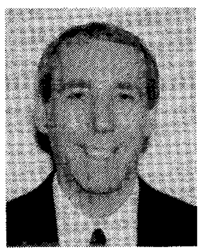
Thomas G. Kawecki was born in Detroit, MI, in 1955. He received the BSME degree in 1977 and the MSME degree in 1979 from the University of Michigan, Ann Arbor, MI.

From 1979 to 1982, he was a Consultant with EEA Inc. In 1982, he accepted a position at the Naval Research Laboratory NRL, Washington, DC, in the Undersea Vehicle Development Branch of the Marine Technology Division. In 1986, he transferred to NRL's Naval Center for Space Technology and began working in the Thermal Design branch. Since then he has been involved in cryogenic payload studies and the high temperature superconductivity space experiment (HTSSE). He was the Lead Mechanical and Thermal Design Engineer for both HTSSE-I and HTSSE-II. He is currently the Lead Mechanical Systems Engineer for the Clementine II Mission which will rendezvous with three asteroids in the 1998–1999 timeframe.



Gerald A. Golba received the bachelor of science degree from the Ohio State University in 1985.

He worked as a co-op to the Naval Research Laboratory's Spacecraft Electronics Development Section during his education and has been with NRL's Space Systems Development Department since his graduation. Since 1985, he worked on various levels of spacecraft hardware. He served as Lead Engineer on the electronics development of an attitude control system for a spin stabilized space vehicle application. He was in charge of the design, integration, and test of the interstage adapter experiment flown on NRL's Clementine I Interstage mission. For the HTSSE-II experiment, he was the Electrical Lead, and was responsible for hardware development. Presently, he is Head of the Flight Systems Section and is Flight Operations Manager for an ongoing NRL space mission.



George E. Price received the B.E.E. degree from Catholic University, the M.S.E.E. degree from George Washington University, and the M.B.A. degree also from GWU.

He has been employed at the Naval Research Laboratory since 1967. During this time, he has worked in Electronic Warfare, Information Technology, and is currently Head of the Advanced Systems Technology Branch (Code 8120) of the Naval Space Technology Center at NRL.

Vincent S. Rose was born in Westerly, RI. He graduated from Capital Radio Engineering Institute, Washington, DC.

He is a Consultant to Assurance Technology Corporation relative to space programs underway at Naval Research Laboratory in Washington, DC. He is accredited with concepts and development of spacecraft payloads since the inception of satellite applications in the late 1950s. As a result of his many contributions to Navy space programs, he received numerous awards and recognitions, including the Navy Meritorious Civilian Service Award, until his retirement from federal service in 1988.

William J. Meyers, (M'95) for a photograph and biography, see this issue, p. 1197.