REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
03-11-1997

2. REPORT TYPE
Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

The Electric Propulsion Space Experiment (ESEX) – A Demonstration of High Power Arcjets for Orbit Transfer Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER
6340

5e. TASK NUMBER
RH65

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
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8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-TP-1998-005

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20020115 090

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					D.R. Bromaghim
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	A		(661) 275-5473

THE ELECTRIC PROPULSION SPACE EXPERIMENT (ESEX) - A DEMONSTRATION OF HIGH POWER ARCJETS FOR ORBIT TRANSFER APPLICATIONS

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Abstract

The Electric Propulsion Space Experiment (ESEX) is a high power (30 kW) ammonia arcjet space demonstration sponsored by the Propulsion Directorate of the Phillips Laboratory with TRW as the prime contractor. ESEX is one of nine experiments being launched in early 1998 on board the Advanced Research and Global Observation Satellite (ARGOS). ESEX will demonstrate the feasibility of using a high power arcjet for orbit transfer. ESEX is instrumented with various sensors to address all of the expected interactions with ARGOS including electromagnetic interference, contamination, and radiated thermal loading. The performance of the arcjet will also be measured using ground tracking, an on-board GPS receiver, and on-board accelerometer. In addition to the performance and spacecraft interaction studies, ground-based spectroscopic and radiometric measurements will be performed to observe plume species as well as determine the effect of the arcjet firing on the space environment. ESEX is currently undergoing integrated testing with the spacecraft bus and the eight other experiments to verify the full operability of ARGOS while on-orbit. These tests include basic functionality of the system in addition to the normal suite of environmental tests including electromagnetic interference and compatibility, acoustic and pyro-shock testing, and thermal vacuum tests.

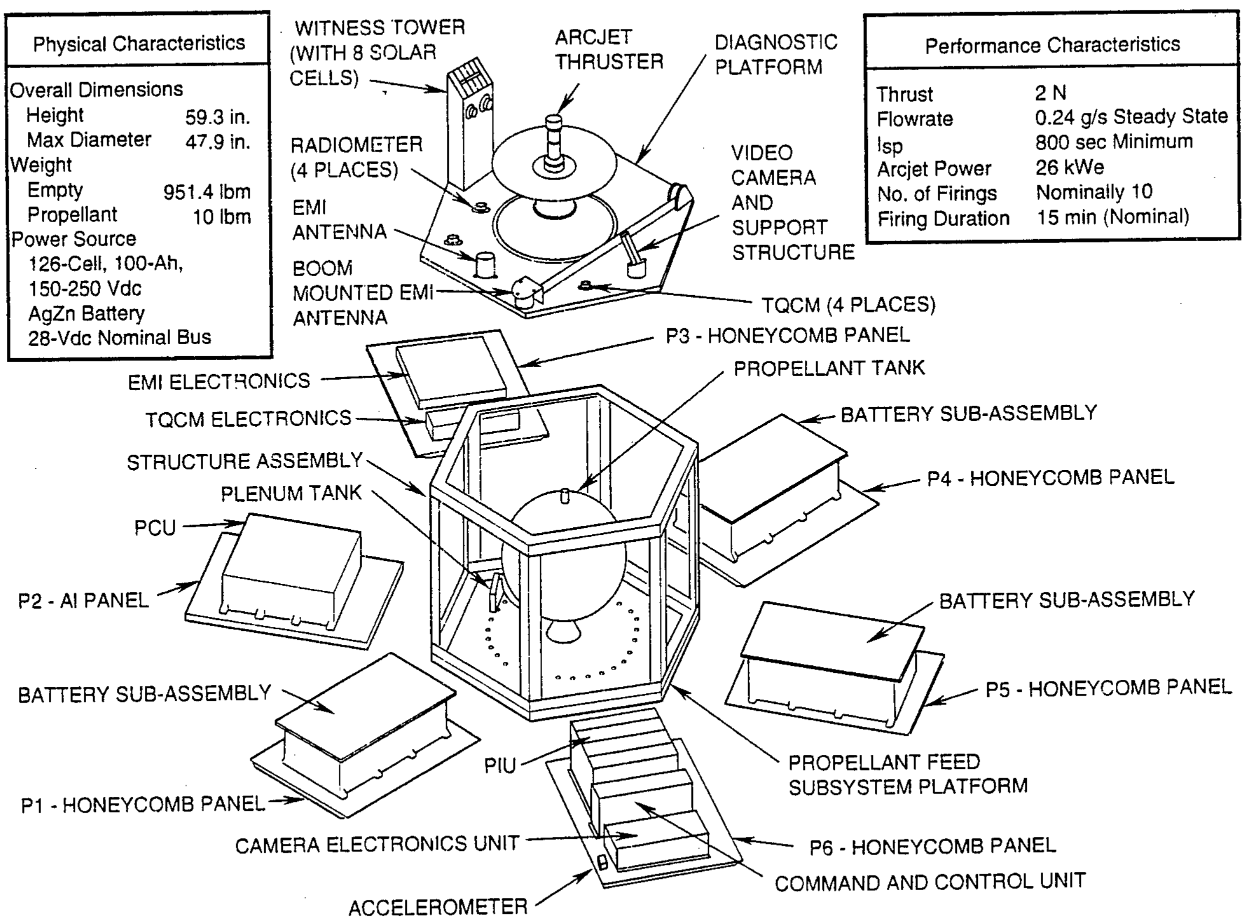


FIGURE 1. Exploded View of the ESEX Flight Unit

INTRODUCTION

The Electric Propulsion Space Experiment (ESEX) is a space demonstration of a 30 kW ammonia arcjet sponsored by the Phillips Laboratory with TRW as the prime contractor. The experiment will demonstrate the feasibility of a high power arcjet system, as well as measure and record flight data for subsequent comparison to ground results (Kriebel 1992, Sutton 1995, and LeDuc 1996). The flight diagnostic suite includes four thermo-electrically-cooled quartz crystal microbalance (TQCM) sensors, four radiometers, near- and far-field electromagnetic interference (EMI) antennas, a section of eight gallium-arsenide (Ga-As) solar array cells, a video camera, and an accelerometer. ESEX is one of nine experiments being launched in early 1998 on the Advanced Research and Global Observation Satellite (ARGOS). ARGOS is managed by the Space Test Program Office of the Space and Missile Test and Evaluation Directorate at Kirtland AFB, NM. The ARGOS satellite will be launched on a Delta II into a 460 nautical mile, 98.7° inclination orbit.

The ESEX flight system, Figure 1, includes a propellant feed system (Vaughan 1993), power subsystem (Biess 1994), commanding and telemetry modules, on-board diagnostics (Kriebel 1993), and the arcjet assembly (Vaughan 1993). ESEX is a self-contained, hexagonal structure which is thermally isolated from ARGOS. This design allows ESEX to function autonomously, requiring support only for attitude control, communications, radiation-hardened data storage, and 28 Vdc power for housekeeping functions such as battery charging and thermal control.

ESEX completed the flight qualification phase (Sutton 1995) of the development program in July, 1995, and was delivered to the ARGOS prime contractor, Boeing North American (BNA), in early March, 1996. ESEX and the remaining eight experiments have since been, and continue to be, a part of the qualification testing of the ARGOS satellite. Testing to date has included a series of functional verifications, an electromagnetic compatibility (EMC) test, and the acoustic and pyro-shock environment verification. The thermal vacuum/balance test is scheduled to begin in mid-August. Since the ESEX flight unit has already been flight qualified, the integrated space vehicle (ISV) testing primarily serves to verify the interface between ESEX and ARGOS. However, the ISV testing also serves to verify one of the major objectives for the ESEX program - to demonstrate the feasibility of integrating high power electric propulsion systems with operational satellites.

This paper summarizes the ARGOS system-level testing accomplished to date. It also presents the status of the flight planning effort. The paper will also summarize the progress of the experiment development efforts in each of the four science objective areas - optical observations, contamination, electromagnetic compatibility, and arcjet system performance.

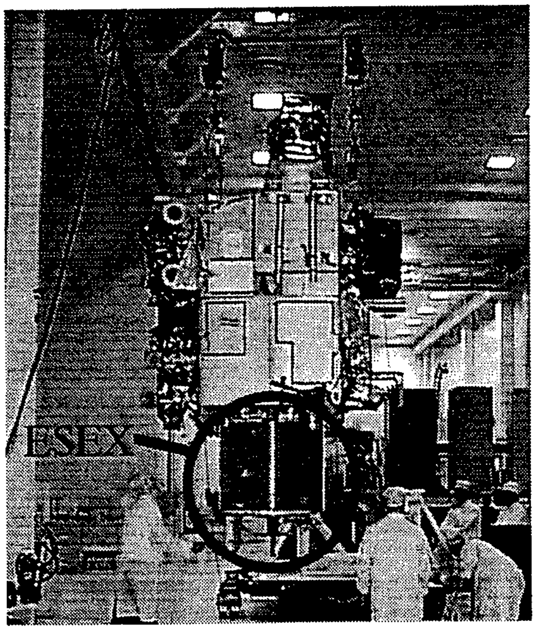
ISV TESTING

The ESEX flight unit is unique on the ARGOS spacecraft in that this experiment is mated and de-mated several times throughout the ISV test flow in order to accommodate test requirements and restrictions. This provides a convenient time for ESEX to perform several ground operations including battery installation and propellant loading (Bromaghim 1996). Recent papers have summarized all but the most recent test accomplishments (Salasovich 1997) and give a description of the remaining tests (Bromaghim 1996). The results of the ARGOS acoustic test are summarized below.

Acoustic Testing

For the acoustic testing, the ESEX flight unit was mechanically mated to ARGOS and installed in the acoustic chamber (Figure 2) as soon as the remaining functional tests were completed. As described elsewhere (Salasovich 1997), the first time ESEX was mated, there was an unanticipated gap ranging from 0.5 to 1.0 mm between the six ESEX feet and the ARGOS bulkhead. Originally it was thought that this gap was due to twisting of the ESEX structure induced from changing the mechanical configuration of the flight unit. For this second integration then, the ESEX flight unit was configured the same as it was for the original ESEX measurement (Sutton 1995) and as it will be for the final flight installation. Because of this change, it was anticipated that the gaps would be much smaller. When the integration occurred, however, the gaps were relatively unchanged. Subsequent analysis indicated that the ESEX structure was too rigid to be subject to deformations from opening and closing the access panels. No further measurements of the flatness of either side of the interface are planned, and shims will remain installed for flight.

The acoustic test was conducted in early July, 1997 at the BNA test facilities in Seal Beach, CA. The acoustic test was divided into three runs – one at 140 dB (3 dB below the protoflight level) for 20 seconds, one at the



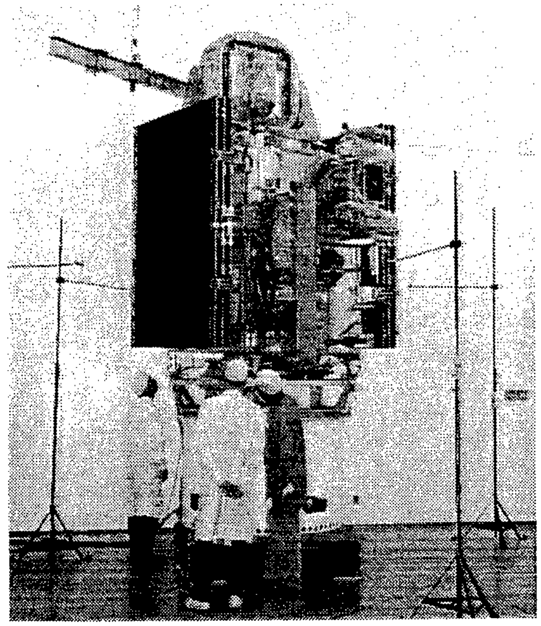


FIGURE 2. Mating the ARGOS and ESEX Flight Units and Installing the Integrated Space Vehicle in the Acoustic Chamber

protoflight level of 143 dB for 20 seconds, and the final run at the protoflight level for 40 seconds. Each time, the accelerometer output was evaluated after the run to ensure the vehicle response was as predicted. The ESEX flight unit had two sets of three orthogonal accelerometers installed – one on the interface bulkhead between ESEX and ARGOS, and one on the witness tower behind TQCM sensor #4. During the ESEX flight unit random vibration testing, this TQCM sensor failed due to a known problem with the mounting scheme for the internal crystal.

Following the 140 dB run, the data was evaluated to ensure proper channelization of the accelerometers, and to perform a preliminary evaluation of the data to assess if any components were in danger of being damaged by the full protoqual run. When looking at the ESEX interface accelerometers, there were significant outages at frequencies near 60 Hz in one the lateral axes (z-axis). Although these levels were significantly higher than the specification, the test continued with the protoqual level run since there was no apparent recourse. Once the full protoqual runs were conducted, a review of the data showed that the response on the z-axis accelerometer was below the limit. Initially, the strong responses were thought to be structural modes of the interface bulkhead as predicted by engineers from BNA and The Aerospace Corporation. The subsequent diminishing of the signals as observed during the protoqual run was attributed to the loosening of the interface fasteners. Subsequent investigation conducted after all of the testing revealed that these signals were actually 60 Hz noise on the analog channels. This also explains the "disappearance" of the signals in the protoqual run when there was more filtering on the analog channels.

The response from the accelerometers on the witness towers was also above the limit in the 140 dB run, but these signals did not decrease at the protoqual levels. The outages occurred at approximately 80 and 110 Hz, but were not a restriction to proceeding with the next runs. The TQCM sensor, and all of the sensors, on the witness tower were tested during the combined systems functional test (CSFT) following the acoustic test and were demonstrated to be fully operational. The CSFT verified the functionality of the remainder of the ESEX flight unit as well as all of the major subsystems on ARGOS and the other eight experiments. This was the same test done on the vehicle before the acoustic test, and is used as a baseline test for all of the environmental testing.

Thermal Vacuum Testing

Following the completion of the post-acoustic CSFT, preparations for the thermal vacuum/balance were initiated. This included the remainder of the thermal blanket installation, but also included some battery operations, installing final hardware to put the vehicle in the flight configuration, and other experiment activities. Once the preparations were complete, the vehicle was installed into the test fixture and moved into the thermal vacuum chamber.

All of the experiments conducted thermal vacuum tests at the component level, so this test served as a verification of the interfaces between all of the experiments and the ARGOS bus. The test also verified the functionality of the ARGOS vehicle components at the temperature extremes including the flight computer, data recorder, command and telemetry system, and all of the other components of the ARGOS space vehicle.

In addition to the system-level verification, this thermal vacuum test allowed several of the experiments, including ESEX, to perform tests which were impossible to accomplish in ambient conditions. For ESEX these included a heater test to verify the thermal control system functioned according to design, and a test to drive the TQCM sensors to the temperature extremes. This is discussed below in the section on the contamination experiments.

Future Ground Testing and Operations

Once the thermal vacuum testing is complete, ESEX will be de-mated to perform a series of ground operations. These have been described elsewhere, and include the installation of the final flight software, loading the ammonia propellant, and installing the activated flight battery (Bromaghim 1996). These activities are divided up as follows: while ESEX is installing the flight software, the remainder of the space vehicle (SV) undergoes a verification of the weight and CG, and a solar array drive test. Once the ESEX software is installed and verified and the SV tests are complete, the ESEX flight unit will be rolled over to ARGOS and connected to the bus via extender cables. At this point, the final factory functional (FFF) test will be conducted to verify all of the ARGOS systems (including all of the experiments) are functional before the test system is dismantled and shipped to the launch site. Due to the time-limited requirement for the activated flight battery, the final closeout of the ESEX flight unit will occur approximately 60 days prior to launch. ESEX will then be re-mated to ARGOS and the ISV will be shipped to the launch site for an early 1998 launch.

FLIGHT OPERATIONS PLANNING

The planning function for flight operations is continuing. An outline of the ESEX firings has been defined which will accomplish all of the mission objectives including the optical observations and the communication tests as described below. This firing plan has been prioritized based on importance to the acceptance of high power arcjet technology. A plan is in work to overlay these firings with the planned releases for the Critical Ionization Velocity (CIV) experiment in order to obtain an integrated Phase II timeline that maximizes the overall scientific return.

Science Team Progress

Development of the science data effort has progressed significantly. The team is divided into four groups based on the type of data that will be returned by the ESEX diagnostics (LeDuc 1996). A brief description, as well as a status, of each of these areas is summarized below.

Optical Observations

The optical experiments include observations from the on-board video camera as well as ground observations of the luminescent thruster plume and radiating thruster body from the AF optical telescopes on Maui. Both scientific and operational objectives are thereby accomplished. DoD system operations planners require plume signature and activity observability data to develop an assessment of the robustness and survivability of arcjet systems. These observations also yield detailed information about excited state populations in the plume, which are in turn directly related to the developmental goals of assessing thruster loss mechanisms.

At this power level, dissociation and ionization are likely to be more important loss mechanisms than for the low power arcjet. The situation is not well understood for high power devices, since neither the best experimental (LIF, absorption, mass spectroscopy, plasma probes) or modeling (DSMC, PIC, etc.) techniques have been applied with the same diligence as accomplished for low power devices. A few tests have been conducted which provide the ESEX science team with spectral data of the high power arcjet in ground facilities. In addition, some plume modeling by Primex Aerospace Company (PAC) has been conducted under contract to Phillips Laboratory.

The experimental objectives will be satisfied by integrating a spectrometer and calibrated CCD detector in series with an atmospheric tracker and compensator onto the 1.6 meter diameter telescope at the Maui Space Surveillance Site (MSSS, formerly AMOS). Since the arc itself is a bright (>~ 100W) UV source, and since the arcjet plume radiates primarily in the UV-visible spectrum (arc plasma temperatures allow electronic state excitation to dominate the plume emission), much of the observational effort will be devoted to the visible and near UV. Specifically, the NH(A-X) transition, centered near 335 nm, and the hydrogen Balmer series will be targeted for Boltzman analysis to determine population distributions of the excited state populations and comparison to equilibrium temperatures.

Secondary objectives include gathering data on atomic, molecular, and ionic nitrogen emissions, blackbody radiation from the thruster body, and a survey spectrum to gather data on emitters not seen in ground tests (such as those arising from metastable states or from interactions between the plume and ambient background on orbit). Observations will also be compared to the PAC observations and plume models. The space flight observations constitute a collaboration between the AF Space Command and Phillips Laboratory telescope operators, University of Maryland observational astronomer Ken Kissell, and the ESEX science team.

Contamination

The contamination experiment includes the TQCM sensors, the radiometers, and the Ga-As solar array witness sample. The primary goal of this effort is to assess the contamination of critical spacecraft surfaces as a result of the arcjet firing

The TQCM is capable of detecting a number of different materials – especially as the crystal temperature decreases. There are four TQCMs onboard ESEX located at different positions with respect to the arcjet (Figure 1). Modeling conducted under contract with TRW indicates that the sensor closest to the arcjet will potentially see the greatest flux of anode material, however it will get too hot to measure propellant constituents during a 15-minute firing. Current plans dictate a cold gas release of GN_2 and ammonia, as well as a four-minute hot firing prior to the start of nominal operations (Bromaghim 1996). These operations (which result in a lower thermal loading) in conjunction with the flexibility to alter the duration of all of the ESEX firings may allow this sensor to detect some constituents. The other three sensors are located farther away from the arcjet so that they can be maintained at cooler temperatures. Unfortunately, this also means the sensors will be subject to less mass flow - making detection difficult.

In order to measure the lowest temperature these sensors can attain, a test was performed in the ARGOS thermal vacuum/balance test. This test attempted to cool the sensors to -100 °C while the heat sink (i.e. the ESEX flight unit) is at a nominal orbital temperature. If these lower temperatures can be attained, then there is a potential for measuring deposition on-orbit of the CIV releases of CO_2 and Xe, as well as the ESEX cold gas release and the short duration firing as described above.

Electromagnetic Compatibility

The electromagnetic (EM) compatibility experiments will utilize the data from the near- and far-field EMI antennas, as well as ground communications tests to determine the effect of the arcjet on standard spacecraft communications. This includes radiated EMI transmit frequency measurements at 2, 4, 8, and 12 GHz, as well as quantified testing of the bit error rate on Space-Ground Link Subsystem (SGLS) transmissions. This area also collaborates with another experimenter, as described below, to observe the effect of the arcjet firing on UHF transmissions.

In order to demonstrate the one of the three communications test concepts, a series of bit error rate tests (BERT) was conducted over the Camp Parks Test Facility in Pleasanton, CA using the MSTI-3 and MSX spacecraft. The purpose of the test was to prove the concept and gather preliminary BERT data with an on-orbit vehicle. The test made use of the spacecraft signal that accommodates a ranging channel and associated pseudo-random noise (PRN). For this test the PRN uplink was replaced with a BERT code (2047 pattern @ 1.024 Mbps) to accurately characterize generic spacecraft communications. The space vehicle transponder received the signal and remodulated the detected information onto the downlink carrier. The ground system received the mirrored BERT signal and determined a bit error rate based on a comparison with the original transmission. This test verified the feasibility of the technique and allowed for an assessment of the effect of transmit power and modulation index.

A synergistic experiment is planned with the Coherent Electromagnetic Radio Tomography Experiment (CERTO). CERTO is a UHF beacon operating at 150.012 and 400.032 MHz with full ground illumination along most of the orbit. Receivers on the ground will use differential phase techniques to derive the electron density of the ionosphere. CERTO will be operated before, during, and after arcjet operation to quantify the effect of arcjet operation on electron density in the upper atmosphere.

Performance

ESEX is using a variety of methods for measuring the performance of the arcjet including the on-board accelerometer, remote tracking, and spacecraft GPS telemetry. This area will also determine the effectiveness of the other arcjet hardware including the power conditioning unit (PCU) and the propellant feed system.

Several issues arise when using Global Positioning System (GPS) data or SGLS tracking for a performance measurement of a low thrust device like the ESEX arcjet. The resolution of the GPS measurement, for example, is highly dependent on what type of receiver is located on-board the vehicle, ARGOS in this case. For the ESEX measurements, the raw data from the GPS constellation is most important, but is not available. To compensate for this unfortunate configuration problem, ESEX will be performing some limited post-processing of the data output from the on-board receiver. For the tracking measurements, the resolution is highly dependent on the number of contacts attainable over a relatively short (i.e. 24-hour) period. Both of these issues are being evaluated and will be resolved before the flight.

In order to support the thrust vector analysis on-orbit, the alignment of the arcjet relative to the diagnostic deck was measured to form a baseline for the final alignment measurement. This measurement was made because the arcjet exit plane cannot be conveniently measured while ESEX and ARGOS are mated. The next time the alignment will be measured is after the final mating, following all of the ESEX ground operations. The final measurement will determine the alignment between the reference point on the diagnostic deck (established by this most recent measurement) and the center of gravity of the ARGOS vehicle.

SUMMARY AND CONCLUSIONS

The ESEX flight unit and the ARGOS satellite are proceeding through the flight qualification testing. Most of the pre-environmental functional testing has been completed and the environmental testing, starting with the acoustic tests, will proceed in mid-July. The planning for the flight operations and the science data reduction continues and emphasis will continue to be placed on maximizing the science return from the ESEX flight.

Acknowledgments

The authors wish to thank the ESEX science team at the Phillips Laboratory including Greg Spanjers, Keith McFall, and Jamie Malak; and the TRW program manager, Mary Kriebel, for her expertise on the flight hardware.

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