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(Statement A)

Refined Orbital Performance Measurements of the Air Force Electric Propulsion Space Experiment (ESEX) Ammonia Arcjet

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Abstract

During the Electric Propulsion Space Experiment (ESEX) mission, eight firings of the 26 kW ammonia arcjet were performed. Data taken from on-board systems, (GPS) and ground tracking during these firings are used to determine thruster performance. The on-board Servo Accelerometer Assembly (SAA) measured spacecraft acceleration. The mean values of thrust, specific impulse and thrust efficiency are 1.93 ± 0.06 Newtons, 786.2 ± 43.0 seconds and 0.267 ± 0.021 , respectively. This measured performance is lower than expected based on ground test. The most likely cause of this discrepancy is onboard measurement error in discharge power due to a 6% drift in the power

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† Project Manager, Member, AIAA

‡ ESEX Chief Scientist

processing unit current shunt. At the corrected power, performance falls within the expected envelope.

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some say "26" others "30"
I prefer 26 since that
is the more accurate
one.*

Introduction

The Electric Propulsion Space Experiment (ESEX) is a 30 kW ammonia arcjet experiment sponsored by the USAF Research Laboratory with TRW as the prime contractor. The experiment objectives are to demonstrate the feasibility and compatibility of a high power arcjet system, as well as to measure and record flight data for subsequent comparison to ground results.¹⁻³ The flight diagnostic suite includes four thermoelectrically-cooled quartz crystal micro-balance (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 launched on 23 Feb 99 on the USAF's Advanced Research and Global Observation Satellite (ARGOS). ARGOS was launched on a Delta II into a 460 nautical mile, 98.7° inclination orbit^{4,5} and operated from the RDT&E Support Complex (RSC) at the USAF Space and Missile Test and Evaluation Directorate at Kirtland AFB, NM.

need to be define

The ESEX flight system includes a propellant feed system (PFS)⁶ and power subsystem⁷ including the power conditioning unit (PCU)⁸ and silver-zinc battery, commanding and telemetry modules, the on-board diagnostics discussed above,¹ and the arcjet assembly.⁸ ESEX was designed and built as a self-contained experiment^X thermally isolated from ARGOS to minimize any effects from the arcjet firings.

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This paper concentrates on analysis of the refined performance data and summarizes overall performance findings. Greater detail about flight instrumentation and specific data reduction processes can be found in previous publications.⁹

Description of the Experiment

One of the primary objectives of the ESEX flight experiment is to determine the on-orbit performance of the arcjet in terms of specific impulse, thrust, and efficiency. A variety of instruments and techniques were used to collect and analyze data to obtain these results. Instrumentation built into the ESEX flight unit includes a Servo Accelerometer Assembly (SAA), pressure and temperature sensors in the PFS to determine flow rate, and electronics in the PCU to determine the arcjet power. Onboard Global Positioning System (GPS) data and ground tracking data from the Air Force Satellite Control Network (AFSCN) were also used to make an independent measurement of Δv due to arcjet firings.

Table 1 gives a summary of the arcjet firing events. In firings 1-6, the peak PCU-regulated discharge power is estimated at 27.8 kW \pm 18%. Toward the end of the firing series, battery problems forced early shut-off of the arcjet PCU.¹⁰ firings 7 and 8 never reached full power, and are, therefore, not considered in the mean thruster performance analysis. Propellant flow rate during all firings was approximately 250 mg/s, except for firing 1, which was 240 mg/s.

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Flight Measurements

Accelerometer

The onboard Servo Accelerometer Assembly (SAA) measures spacecraft acceleration. The SAA housing is 2.2 x 2.8 x 5.5 inches in size and contains the accelerometer and associated amplifier, bias, and filter electronics. The signal from the SAA is digitized and recorded by the ESEX Command and Control Unit (CCU) at 10 Hz. Ten readings of digital data are then collected and transferred from ESEX to ARGOS once each second and recorded for later downlink to a ground station. Fig. 1 shows the signal/data path.

Which number is correct?

The accelerometer is an Allied Signal QA-3000-010, the performance properties of which are given in Table 2. (Note: in this paper, "g" refers to gravitational acceleration, 9.80708 m/s².) The QA-3000-001 uses a pendulum proof mass made of fused quartz to sense acceleration. Displacement is measured with a capacitive sensor. A closed-loop feedback circuit balances the acceleration force on the proof mass using electromagnetic coils. The current driven through the electromagnet coils thus provides a proportional measure of acceleration. This current is passed through a 20k Ω input resistor in the SAA electronics. The voltage across the resistor is then filtered, amplified, and biased by other electronics in the SAA. The resulting signal output from the SAA (0 to 10V) is digitized in the CCU and made available for downlink.

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Calibrated mean acceleration is calculated by taking the 12-bit SAA output voltage, V_a , and subtracting an instrumentation bias, $V_{a,0}$. The result is divided by a scaling factor that represents the combined effect of the accelerometer response, input resistance, and

instrumentation gain. This result is then corrected for temperature dependency and long-term drift ($BIAS'(T)$). To summarize,

$$a = \frac{V_a - V_{a,0}}{SF'(T)} - BIAS'(T) \quad (1)$$

Eq. (1) gives the instantaneous acceleration. To calculate the mean acceleration (\bar{a}) for a given firing, V_a and $SF'(T)$ are taken to be the 30-second average immediately before arcjet shut-off. $BIAS'(T)$ is always taken to be the 30-second average before arcjet start-up.

The uncertainty in the mean acceleration, $u(\bar{a})$, is derived using appropriate methods for independent measurands.¹¹ The uncertainty in V_a and $V_{a,0}$ is dominated by A/D converter discretization error. It is assumed to be one bit of resolution, which corresponds to 3.05% of nominal. Combining all measurement uncertainties,⁹ we have $u(\bar{a}) = 3.44 \mu g$, or 4.44% of nominal.

GPS

It was the intent of the ESEX team to use the GPS receiver on board ARGOS to make an assessment of the ESEX acceleration profile independent of the SAA.

Due to problems with the GPS unit and its interface with the ARGOS navigation system, however, data are only available for firing 1. The analysis of this data is complicated because the receiver frequently switched between GPS satellites and intermittently went in and out of lock. For this reason, an accurate, instantaneous, GPS-derived acceleration profile cannot be determined. However, after considerable post-processing, an estimate of ΔV was determined for firing 1 of 0.110 ± 0.003 m/s.

ΔV of 0.110 ± 0.003 m/s
 was estimated for firing 1.

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Ground Tracking

Ground tracking from the Air Force Satellite Control Network (AFSCN) is also used as an independent measurement of total velocity change during the firing. Tracking is not accurate enough to determine the instantaneous acceleration profile during a firing. However, the total change in semi-major axis from a firing can be determined. From this, ΔV is calculated.

Orbit determination is performed just prior to the propulsive event, and again, once sufficient track data has been collected after the event. Track data includes range, range rate, and antenna pointing angles. An orbit solution, typically based on 8 tracking passes over 12 to 18 hours, is computed for the "before" and "after" firing conditions. The computational orbit determination scheme differentially corrects the orbit parameters to minimize the residual of position in a least squares sense.¹²

plural or singular form

Once the orbit has been determined before and after the propulsive event, each solution is computationally propagated for 5-day periods. Brouwer mean (BM) elements are computed for each period. Then, the difference in semi-major axis (ΔSMA) is computed by taking the time average of the difference of the BM SMAs. This process serves to minimize the effects of local perturbations to the orbit. The thrust direction was retrograde, so, using the circular orbit approximation,

$$\Delta V = \frac{\pi \Delta SMA}{\bar{P}} \quad (2)$$

where \bar{P} is the mean orbital period.

The errors in SMA are computed from the in-track position differences between adjacent orbit solutions. For the investigated period, the statistical bound on the error in SMA is approximately ± 2.5 m. The uncertainty in ΔV is then determined as,

$$u(\Delta V) = \frac{\pi u(SMA)}{\bar{P}} \quad (3)$$

Mass History

The spacecraft mass was measured before launch to be 2491 kg within 0.2% of the actual value, but this decreased throughout the ESEX mission as a result of the following: 1) Material outgassing, 2) Carbon dioxide gas release from the cold gas attitude control thrusters, 3) Xenon and carbon dioxide gas released as part of the Critical Ionization experiment (CIV) and 4) arcjet firings. The total mass released by these events through firing 8 is estimated to be 9 ± 2 kg. The spacecraft mass during each firing ranges between 2488 kg (firing 1) and 2482 kg (firing 8) with uncertainty of 6 kg.

Propellant Flow Rate

The propellant flow system (PFS) on ESEX uses a sonic venturi to determine the ammonia flow rate.¹³ Once per second, the rate is calculated by the ESEX CCU from pressure and temperature data upstream of the venturi. From fluid mechanics,

$$\dot{m} = \frac{P}{\sqrt{T}} A' \quad (4)$$

where P is the absolute pressure, T is the temperature, and A' is a calibration parameter, which includes orifice area, flow expansion, etc.

The sonic venturi calibration parameter and the pressure transducer[✓]-rated accuracy dominate the uncertainty analysis. A root sum of squares combination of these errors gives approximately 4.5% uncertainty in the measurement of pk.

PCU

The PCU provides current-regulated power to the arcjet. Both the current and voltage are telemetered from the PCU as 0-5V signals. They are digitized by a 12-bit A/D converter and transferred from the ESEX CCU to ARGOS for downlink.

The current and voltage telemetry from the PCU was calibrated at Primex Aerospace Corporation during acceptance testing. Uncertainty in power (using the product of voltage and current from telemetry) is determined in this analysis from the statistical variation of error from several independent acceptance tests to be 60% W.

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Analysis and Discussion

The accelerometer voltage signals for each firing are converted to acceleration signals by application of Eq. (1) at each data point. The calibrated acceleration for a representative firing (firing 5) is given in Fig. 2.

Features in the acceleration history correspond to operational phases of the arcjet firing. Four minutes before initiation of the arcjet discharge, a valve opens between the plenum tank and the thruster, and propellant flow begins.¹⁰ In this phase, the arcjet is operating as a cold-gas thruster, producing a 20 μ g acceleration, which ramps down to 8 μ g. Next,

the arcjet discharge initiates with a programmed start-up sequence. This is seen as a ramp in acceleration from 8 to 76 μg . After the ramp, the PCU switches to constant power mode at approximately 26 kW. The exponential drop-off of acceleration occurs after the arcjet discharge is shut off. Nominal flow continues for 5 to 6 minutes after shut-off as the plenum tank bleeds down. This generates additional thrust ^{which} diminishes as the arcjet cools.

Total velocity change, ΔV , is obtained by integration of the instantaneous acceleration curve. The trapezoidal rule is used, and the uncertainty is computed based strictly on systematic sources, assuming the random components cancel. Those numbers are shown in Table 3 in comparison to results from ground tracking and GPS.

Fig. 3 shows a graphical comparison of ΔV from the accelerometer data with ΔV from ground tracking. The line represents a perfect match. If the accelerometer measurements differ from the ranging data by a scaling factor, that factor should be proportional to the line of fit. The slope of a linear least squares fit is 1.0083, indicating only ⁰.83% scaling factor error, with an RMS relative residual of 3.01%. Thus, the accelerometer data correlate to within 3.1% of independent ground tracking data for all ^{eight. (suggest only)} firings, and with GPS data for firing 1. Thus, there is a high probability that the accelerometer measurements are more accurate than the instrumentation analysis shows. The uncertainty in the measurement of acceleration is, therefore, reduced from 4.4% to 3.1% for the mean steady-state performance analysis below.

Average steady-state acceleration is determined from the individual averages of the accelerometer voltage, scaling factor, and bias over the last 30 seconds of each firing. Likewise, performance parameters are determined from the individual 30-second averages of the acceleration, flow rate, and discharge power. Table 4 is a summary the steady-state results.

Final performance figures can be determined as the mean of the five 30-second means from firings 2-6. This gives, for the 250 mg/s flow rate:

$$\begin{aligned}\bar{F} &= 1.93 \pm 0.06 \text{ Newtons} \\ \bar{I}_{SP} &= 786.2 \pm 43.0 \text{ seconds} \\ \bar{\eta} &= 0.267 \pm 0.021\end{aligned}$$

The uncertainties are computed as the RMS of the uncertainties of the individual firings. Therefore, final mean accelerometer-based measurements of F , I_{SP} , and η are believed accurate to 3.1%, 5.4% and 7.9%, respectively.

The original design specification for the arcjet¹⁴ requires F , I_{SP} and η to be 1.96(N), 800 seconds and 0.307, respectively. These measurements indicate that the F and I_{SP} specifications were met during on-orbit operation within the uncertainty of the instrumentation. η , however, fell below the specification.

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Fig. 4 shows the mean specific impulse in comparison with ground data. The vertical error bars represent uncertainty in I_{SP} , taking into account the uncertainty in power and flow rate. The horizontal error bars represent the combined standard uncertainty for

$\frac{P}{I_{sp}}$, with $u(P) = 2.2\%$ and $u(I_{sp}) = 4.5\%$. The diagonal lines represent a regression fit of previous Air Force NH_3 arcjet data and 3σ bounds on that fit.¹⁵ It is within this 3σ envelope that flight measurements are expected to fall. It is clear from Fig. 4 that the mean on-orbit I_{sp} is somewhat low for the corresponding $\frac{P}{I_{sp}}$.

The lower-than-expected I_{sp} may be due to erroneous power measurements. During acceptance tests, power was measured externally at 26.2 ± 1.5 kW.¹³ However, during on-orbit thruster firings, the voltage and current telemetry consistently indicated a power reading of 27.8 ± 0.05 kW (6% higher). An examination of the data, both on orbit and during acceptance testing at Primex Aerospace Company in 1994, indicates that the power reading is higher than actual, due, most likely, to a drift in the telemetry current.¹⁶ Arcjet temperatures and on-orbit performance data corroborate this conclusion. Also, the PCU is designed to be resistant to changes in power. Furthermore, during acceptance tests, while the independently measured power remained constant, a drift was observed in the original flight shunt (which was subsequently rejected and replaced). Although there is no way to positively identify the source of the discrepancy, these indications suggest that the current telemetry is erroneous (reading 6% too high). If the PCU is treated as a constant-power device, with actual power levels corresponding to those during acceptance tests (26.2 kW \pm 1.5%), the thrust efficiency increases 6% to 0.283 ± 0.029 , which meets specification within the uncertainty. Furthermore, $\frac{P}{I_{sp}}$ for the 250 mg/s firings becomes 105 MJ/kg, which centers the mean ISP in the expected range. The point labeled "P=26.2 kW" on Fig. 4 is the mean I_{sp} at 105 MJ/kg. However, since irrefutable

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evidence of current shunt drift is not available, the 26.2 kW power cannot be used with complete confidence.

Summary

Based on accelerometer data alone, mean arcjet thrust, specific impulse and thrust efficiency are 1.93 ± 0.06 Newtons, 787.0 ± 43.0 seconds and 0.268 ± 0.021 , respectively. These values, except for efficiency, meet design specification within the measured uncertainties. A likely explanation for the discrepancy in measured mean efficiency is drift in the PCU current telemetry. If so, efficiency increases to 0.283 ± 0.021 , meeting specification.

The dominant contributors to uncertainty in accelerometer-based performance measurement are encoding error of the A/D converter and uncertainty in flow rate. Although these factors lead to large uncertainty in measured acceleration (4.44%), measurements of ΔV from GPS and ground tracking independently support the accelerometer data to a higher accuracy (3.1%).

If possible, please try to rephrase [To use the results presented in this paper in design of spacecraft with operational ammonia arcjets, some points must be considered. First, these performance results are for steady-state operation. The additional propellant released before and after firing, and the ramp-up to full power must be taken into account ^{for} in a more complete analysis. Also, uncertainty in measured performance presented here is high. Therefore, if these numbers

are used for design, propellant/power margin should be included in accordance with the uncertainty.

Acknowledgements

The authors would like to thank the following people for their support of the ESEX mission: the TRW arcjet ATTD team, Boeing, the Delta II launch crew at Vandenberg AFB, SMC/TEL, and SMC/TEO. In addition, the authors would like to thank Alan Sutton and Jason LeDuc for assistance during flight operations and for their contributions to this performance analysis.

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Last names first

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¹⁶Hoskins, W. A., "Resolution of On-[?]Orbit Power Measurements for the ESEX 30 kW Arcjet," Primex Aerospace Corp., Memorandum to ESEX Performance Team, May 1999.

Table 1. Arcjet firing summary. Shaded rows indicate firings included in performance analysis. Flow rate is 250 mg/s unless otherwise specified. *where?*

Table 2. QA-3000-001 *is number correct?* accelerometer performance

Table 3. Total velocity change, ΔV (m/s), during firings as measured by accelerometer, ground tracking, and GPS.

Table 4. Accelerometer-based performance summary.

Fig. 1. Accelerometer signal/data path.

Fig. 2. Calibrated acceleration during firing 5.

Fig. 3. Comparison between ΔV from accelerometer measurement and ground tracking.

Fig. 4. Summary of specific impulse estimates.

Table 1.

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Firing	Date	Time (Zulu)	Duration	Flow Rate (mg/s)	Remarks
1	03/15/99	21:55:56	2:20	240	240 mg/s
2	03/19/99	22:32:24	5:02	250	
3	03/21/99	12:24:42	5:34	250	
4	03/23/99	21:27:59	8:02	250	Shut-off due to low battery voltage
5	03/26/99	12:45:29	6:05	250	Shut-off due to low battery voltage
6	03/31/99	13:05:36	4:31	250	Shut-off due to low battery voltage
7a	04/02/99	22:09:03	0:55	250	Shut-off due to low battery voltage, Low power
7b	04/02/99	22:10:08	0:37	250	Shut-off due to low battery voltage, Low power
8	04/21/99	12:22:13	0:43	250	Shut-off due to low battery voltage, Low power

Table 2.

Measurement Range	+/- 25 g
Resolution	1 μ g
Unbiased Output Noise at DC to 10 Hz	10 μ g

Table 3. *Might want to spell out completely*

Firing	Accel	Ground Tracking	GPS
1	0.1089 ± 0.0207	0.11101 ± 0.00129	$.110 \pm .003$
2	0.2590 ± 0.0244	0.26023 ± 0.00129	N/A
3	0.2850 ± 0.0244	0.27304 ± 0.00129	N/A
4	0.4010 ± 0.0326	0.40348 ± 0.00129	N/A
5	0.3203 ± 0.0303	0.32809 ± 0.00129	N/A
6	0.2275 ± 0.0216	0.22699 ± 0.00129	N/A
7	0.0626 ± 0.0177	0.06563 ± 0.00129	N/A
8	0.0248 ± 0.0137	0.02924 ± 0.00129	N/A

Table 4.

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Firing	Mean Acceleration, \bar{a} (μg)	Mean Thrust, F (N)	Mean Specific Impulse, I_{sp} (s)	Mean Efficiency, η
1	76.07 \pm 2.36	1.856 \pm 0.058	789.3 \pm 43.2	0.259 \pm 0.021
2	78.98 \pm 2.45	1.925 \pm 0.060	785.7 \pm 43.0	0.267 \pm 0.021
3	80.97 \pm 2.51	1.974 \pm 0.061	806.0 \pm 44.1	0.281 \pm 0.022
4	78.34 \pm 2.43	1.909 \pm 0.059	779.3 \pm 42.6	0.262 \pm 0.021
5	77.64 \pm 2.40	1.887 \pm 0.059	770.7 \pm 42.2	0.257 \pm 0.020
6	79.42 \pm 2.46	1.933 \pm 0.060	789.5 \pm 43.2	0.270 \pm 0.022

Fig 1.

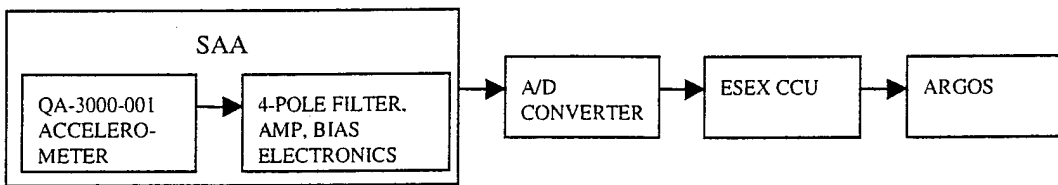


Fig 2.

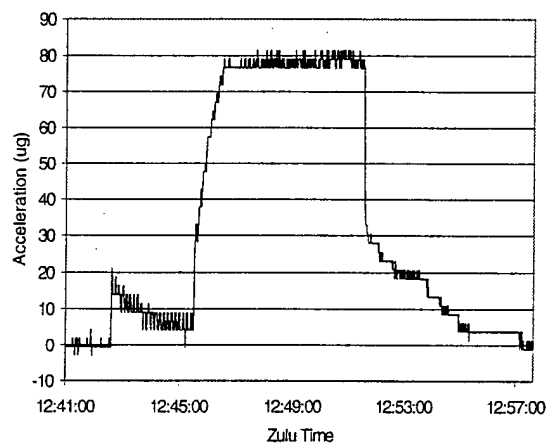


Fig 3.

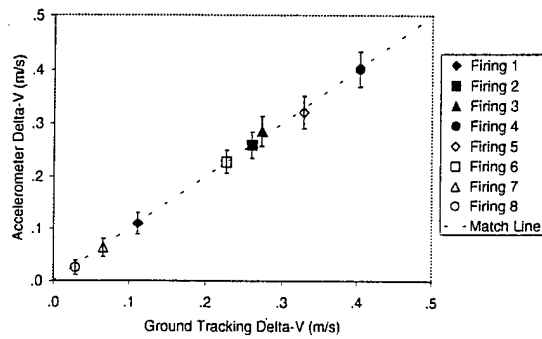


Fig 4.

