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Effect of ESEX 26-kW Arcjet Operation on Spacecraft Communications

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Tests designed to observe the electromagnetic compatibility of the Electric Propulsion Space Experiment 26-kW ammonia arcjet on normal spacecraft communications and operations showed no conclusive adverse effect. Two onboard antennas sensitive to the 2-, 4-, 8-, and 12-GHz frequencies detected no increase in signal amplitude clearly identifiable with arcjet operation. Analysis of the bit-error-rate test data revealed no obvious correlation between arcjet operation and the observed increases in bit-error rate. Finally, a series of qualitative observations consistently indicated the benign nature of arcjet operation on normal spacecraft events. For example, commands uplinked without abnormal rejection rate and telemetry downlinked successfully during arcjet operation.

Introduction

ON 23 February 1999, a Delta II rocket launched the U.S. Air Force's Advanced Research and Global Observation Satellite (ARGOS) into an 850-km, 98.7-deg inclination orbit. The U.S. Air Force Research Laboratory sponsored Electric Propulsion Space Experiment (ESEX), one of nine manifested experiments, demonstrated operation of a 26-kW ammonia arcjet, becoming the highest powered system successfully operated on-orbit before the International Space Station. The experimental objectives were to demonstrate the feasibility and compatibility of a high-power arcjet system, as well as to obtain on-orbit data for comparison with ground results. The overview by Bromaghim et al.[1] contains an overview of the ESEX program.

Briefly, the ESEX flight system, shown schematically in Ref. 1, consists of a propellant feed system, power subsystem including the power conditioning unit (PCU) and the silver–zinc batteries, commanding and telemetry modules, onboard diagnostics, and the arcjet assembly. The flight diagnostic suite includes thermoelectrically-cooled quartz crystal microbalance (TQCM) sensors, radiometers, antennas to detect electromagnetic interference (EMI), sample solar array cells, a video camera, and an accelerometer. ESEX was designed and built as a self-contained experiment, thermally isolated from ARGOS to minimize any effects from the arcjet firings. This design allowed ESEX to function autonomously, requiring support only for attitude control, communications, radiation-hardened data storage, and housekeeping power for functions such as battery charging and thermal control. The arcjet is grounded from the anode to the chassis.

Spacecraft engineers, with the responsibility to ensure the compatibility of spacecraft systems and payloads, have questioned the electromagnetic compatibility (EMC) of electric propulsion thruster systems with spacecraft. A 1989 survey of electromagnetic emission experiences using electric propulsion systems was compiled by Sovey et al.[2] They indicated that the bulk of flight experience for electric propulsion thrusters, such as magnetoplasmadynamic thrusters pulsed-plasma thrusters, ion thrusters, and resistojets, suggested that adherence to MIL STD 461B and MIL STD 462 is adequate to achieve EMC.

Electromagnetic signatures of low-power arcjets have been studied,[3–6] and the general conclusion is that sound design practices can ensure compatibility between arcjet thrusters and spacecraft. For example, Carney was able to show that the most probable disruption or distortion of communication signals by operation of a 1.5-kW class arcjet would be for refraction, rather than absorption or reflection of the electromagnetic signal by the arcjet plume.[3] Numerous low-power arcjets are successfully flying on operational communication satellites.

Although facility affects can be problematic for ground-based EMI measurements, proper experiments can reasonably validate design practices that ensure good electromagnetic compatibility between the spacecraft and thruster. It is increasingly difficult to achieve high-fidelity ground-based EMI measurements for higher power arcjets.

One purpose of the ESEX program was to observe the EMC of a 30-kW class arcjet while operating on-orbit and to compare the results with ground-test data. Johnson et al. conducted laboratory EMC testing of the same thruster design that flew on ESEX.[7] The study examined the EMI levels in the frequency range from dc to 10 GHz and noted that, to measure electromagnetic radiation, the antenna must be protected from exposure to charged particles,

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otherwise it acts as a langmuir probe sensing the plasma environment. The maximum signal occurred near 200 kHz and generally decreased with higher frequency.

The impact to normal spacecraft functions and communications of operating the ESEX arcjet on-orbit were observed both quantitatively and qualitatively, and preliminary results were reported by Dulligan et al.[8] Onboard antennas measured electromagnetic radiation in the gigahertz range communications bands during all eight arcjet firings. Bit-error rates (BER) were measured during both arcjet firing and nonfiring periods, permitting a detailed and quantitative analysis of the impact arcjet operation has on communications. Qualitative observations generally compared the limited event history noted from times of arcjet operation to the extensive event history recorded from all other periods of normal spacecraft operation. Observations included examining the command uplink integrity during arcjet operation and studying the telemetry downlink integrity during arcjet operation.

Onboard EMI Measurements

The onboard EMI measurement system was designed to measure electromagnetic radiation emitted by the arcjet that might cause interference to the normal spacecraft functions. Although data were gathered for each of the eight firings, during quiescent spacecraft periods, and during routine spacecraft operations, only slight, if any, variations were observed in the measured signals.

Equipment Configuration

The EMI unit measures the radio frequency noise levels received by onboard spiral cavity antennas (Datron–Transco, Inc., P/N 9C36800-5), which is processed by a custom electronics processing unit [(EPU) TRW P/N 810571-1], schematically shown in Fig. 1. The EPU internally switches between the two inputs. The selected input is then split into four frequency channels of 2-, 4-, 8-, and 12-GHz ±2.5% bandwidth. The output of these filter channels are then amplified and passed through zero bias Schottky detectors. The output of these detectors is then scaled from 0 to 10 V for a 15-dB dynamic range at the rf inputs. This scaled voltage is then applied to four A/D converters, whose outputs are 4-bit words. These words are then multiplexed out of the unit with two telemetry bits (indicating which antenna is being sensed) in an 18-bit serial data stream. The unit internally switches between the two antenna inputs such that the data are recorded one time each second overall, but in an alternating fashion at half hertz repetition rate for each antenna. The data resolution is 1 dBm/Hz with a 15 dBm/Hz dynamic range from −165 to −150 dBm/Hz, referenced to the antenna input.[9]

The antennas are sensitive over the frequency range 2–12 GHz with gains of −7 dBI at 2 GHz, 0 dBI at 4 GHz, and +1 dBI for both 8 and 12 GHz, and the antenna factors are 168, 181, 188, and 192 dB for 2, 4, 8, and 12 GHz, respectively. The measured losses in the entire EMI package were measured to be 7 dB ±0.5%, which includes cable losses and losses in the processor. An incoherent bandwidth correction was applied. Signals are reported in power spectral density due to the uncertainty caused by the plasma environment created by the arcjet operation near unshielded antennas.

The two antennas have 7-cm input diameters, oriented such that the antenna axis of symmetry is parallel to the thruster axis of symmetry. The deck-mounted antenna is placed on the diagnostic platform, such that the linear distance from the center of the arcjet nozzle to the center of the antenna input is 55.3 cm; however, the stainless steel shield on the arcjet blocks a direct line of sight between the two points. The deck-mounted antenna is positioned 32.8 cm behind the arcjet exit plane. The boom-mounted antenna is located at the end of a deployed boom, such that the linear distance from the center of the arcjet nozzle to the center of the antenna input is 114.4 cm and is within a direct line of sight of the arcjet plume. The boom-mounted antenna is also 32.8 cm behind the arcjet exit plane. The positions are schematically shown in Fig. 2. The antennas are not insulated from plasma contact.

Data Acquisition

Proper function of the EMI system was demonstrated during ARGOS assembly,[10] and correct operation of the EPU was verified on-orbit by invoking the check routine; however, no means of verifying proper antenna operation was available once the spacecraft was established in orbit. The check routine is a function commanded from the ground and is intended to verify only that the electronics is functioning properly by applying a check signal at the antenna output that should result in a digital word of 0001.

The EMI unit was activated during three classes of satellite operational conditions. For the purpose of characterizing the EMI unit behavior, data were recorded during satellite dormant periods. The EMI unit was activated during the majority of contacts between

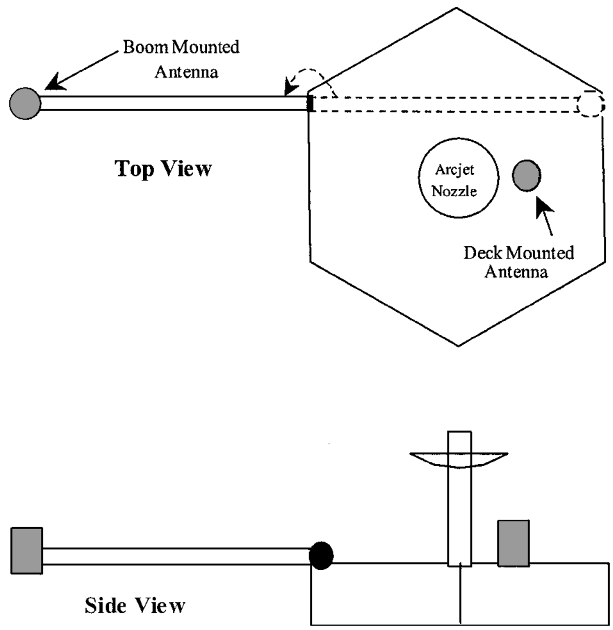

Fig. 2 Antenna positions.

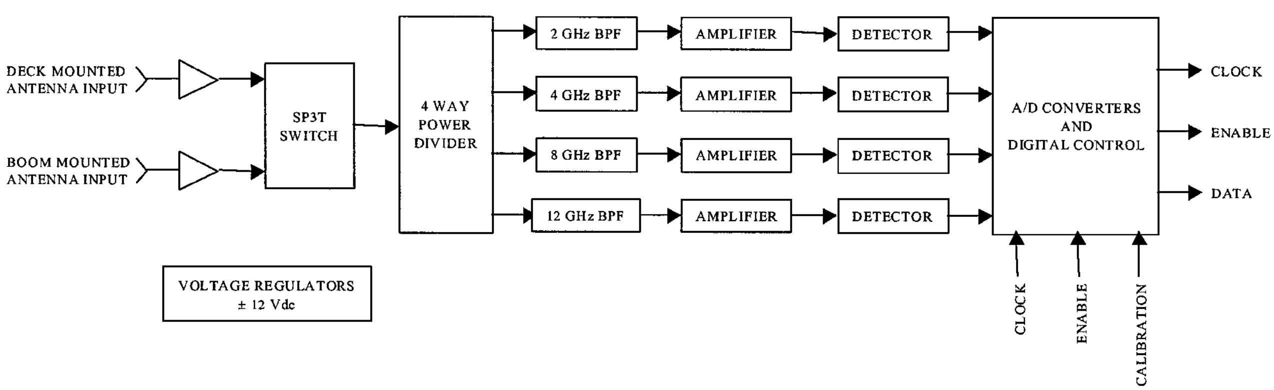

Fig. 1 EMI experiment block diagram.

ARGOS and the controlling ground stations for the purpose of noting any responses of the EMI unit to normal spacecraft operations. Most important, the EMI unit was activated for all eight arcjet operations for the purpose of observing possible rf interference in the 2-, 4-, 8-, and 12-GHz bands.

The EMI unit was not actively temperature controlled, and the unit temperature was not monitored during the flight; however, during acceptance testing, stability of the electronics unit was established over the temperature range from −9 to +47°C. To avoid overheating and maintain operational consistency, the standard procedure was to operate the EMI unit for 20 min each time data were recorded and to invoke the check routine 1 min after EMI unit activation to confirm normal operation of the control circuitry. The same procedure for acquiring data from the onboard antennas was employed for all arcjet firing opportunities and generally was applied when data were acquired during normal spacecraft operations and during dormant spacecraft conditions. For arcjet firing opportunities, the EMI unit was powered on approximately 10 min before arcjet ignition and remained active for 20 min. The time ARGOS was in contact with the controlling ground station was typically 10–15 min.

Discussion

Previous experiments of a 30-kW class arcjet[7] revealed no measurable emissions at the 2-, 4-, 8-, and 12-GHz frequency bands in the range of −120 to −130 dBm/Hz. The ESEX noise detection range from −165 to −150 dBm/Hz was expected to determine an upper limit of the EMI radiated at these frequencies. Although these power levels are not significant for low-Earth-orbiting satellites, emissions of this magnitude may have a measurable impact on deep space missions. Data from the EMI unit acquired during quiescent periods serve as an appropriate baseline for comparison with data acquired during the other two classes of spacecraft activity. All of the data values from the quiescent periods are equal for both the boom- and deck-mounted antennas and are uniform at the values of −163, −164, −162, and −164 dBm/Hz for the 2-, 4-, 8-, and 12-GHz frequency bands, respectively. Data from the periods of normal spacecraft operations are also uniform with the baseline data. The actual data from such times are not shown, but appears identical to that shown in Fig. 3.

Serving as representative data, the EMI antenna signals recorded from the boom and deck-mounted antennas during the sixth arcjet firing are shown in Fig. 3. The ordinate has units of decibel referred to 1 mW per hertz, referenced to the antenna input, and the abscissa denotes coordinated universal time (UTC). In general, the deck- and boom-mounted antennas register identical data values for each frequency range, with the occasional exception of the 4-GHz channel, for which the deck-mounted antenna value is often 1 dBm/Hz lower than that from the boom-mounted antenna. The step function at the bottom of Fig. 3 indicates when the arcjet is firing and the 1-min gap in the data occurs during operation of the electronics check routine. The EMI antenna data from the seventh arcjet firing are shown in Ref. 8.

The data from the deck-mounted antenna obtained during the arcjet operation passes are identical to the baseline data. More important, the data values do not change when the arcjet fires. The data from the boom-mounted antenna obtained during the arcjet operation passes are nearly identical to the baseline data. The exception is found on examination of the 4- and 12-GHz bands, which exhibit oscillations between adjacent bits. For example, consider the data shown from the sixth arcjet firing pass (Fig. 3), in which the indicated signal strength for the 4- and 12-GHz bands fluctuate between −164 and −163 dBm/Hz. In five of the eight cases, the bit oscillations occur in the 4 GHz band during the period of arcjet operation. In three of the eight cases, the bit oscillations occur in the 12-GHz band during the period of arcjet operation. In one of the eight cases, the bit oscillations occur in both the 4- and 12-GHz bands during the period of arcjet operation. Conversely, in five of the eight cases, the bit oscillations frequently occur, and in another two of the eight cases, the bit oscillations infrequently occur in the 4-GHz band when the arcjet is not in operation. In the same three cases in which oscillations are observed for the 12-GHz band during arcjet operation, oscillations are also observed at times the arcjet is not operating. The digital nature of the signal processing and the 1-dBm/Hz resolution may give rise to the observed fluctuations in recorded rf field strength. Even if the increase in observed signal strength is due to arcjet operation, the magnitude of change is not large enough to pose problems to spacecraft communication or function. The raw energy may oscillate in value at the decision threshold between two discrete digital bits, resulting in a fluctuation in output field strength. Alternatively, variations in the EMI unit temperature might affect the internal unit noise level, which sets its noise floor and may cause the observed bit fluctuation.

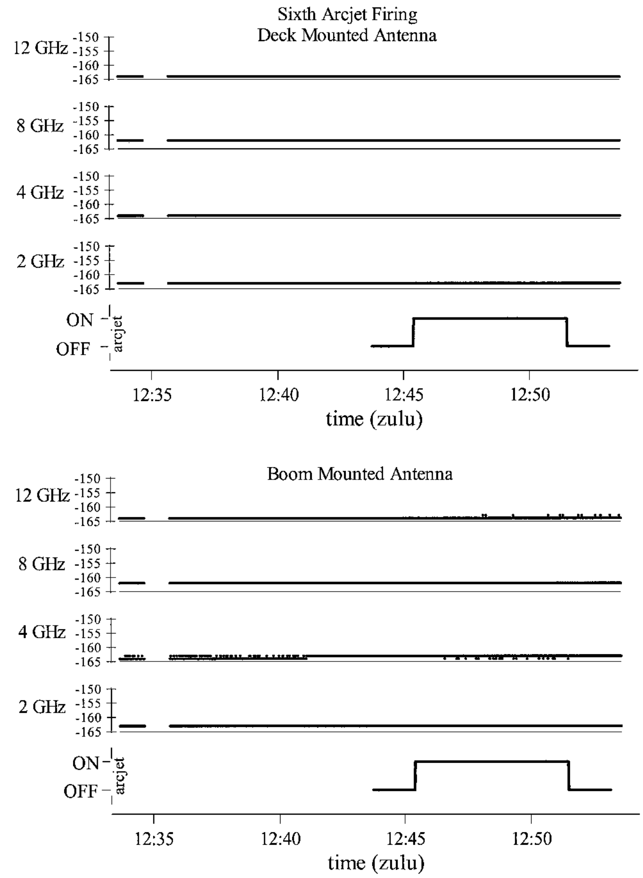

Fig. 3 Onboard EMI antenna data from the sixth arcjet firing.

Caution is warranted in drawing conclusions when the instrument detects no changes. The trivial explanation of malfunctioning equipment and, therefore, no recorded signal changes must be addressed before discussing the meaning of the data. The ideal test would have been to irradiate the onboard antennas from the ground with a known signal intensity at the antennas while on-orbit to not only verify proper operation but to also calibrate the measurement; however, circumstances prevented this test from being conducted. In all cases the internal check-routine results were consistent with proper signal processing behavior.

If the EMI detection equipment functioned as designed, the data suggest that operation of the 26-kW ESEX arcjet does not adversely interfere with the 2-, 4-, 8-, and 12-GHz communication bands. This is consistent with the ground-test observations, in which measured rf signals caused by arcjet operation exceeded ambient levels only over the frequency range from 10 kHz to 5 MHz (Ref. 7).

BER Test

The BER test enabled a quantitative study of the effect operating the ESEX arcjet had upon S-band communications for the particular configuration of the ARGOS spacecraft. Control of ARGOS is accomplished via the satellite ground-link system (SGLS) architecture, which operates over a number of S-band channels near 2 GHz. ARGOS SGLS communications include encrypted command and telemetry channels, as well as an unencrypted dedicated ranging channel used for orbit determination. Typically, to determine the range to the satellite, a pseudorandom noise (PRN) signal pattern is transmitted from a ground site of the Air Force Satellite Control Network to the spacecraft, which in turn frequency shifts the signal and retransmits the code back to the ground site. Synchronization of the PRN code is used to determine the time delay, which is used for range determinations. The return carrier is either offset from the uplink carrier by a specific delta frequency (coherent mode) or is established independently from the uplink by a spacecraft reference (incoherent mode). The coherent mode is used to obtain range rate (velocity) measurements from Doppler frequency shifts. The BER test utilizes the SGLS range channel, but replaces the PRN ranging code with a 2048-bit error-counting code. The transmitted bit pattern, is compared with the received bit pattern, and the bit-error rate is quantitatively measured. Data are accumulated at a rate of 1 Hz.

Test Equipment, Configuration, and Procedure

The BER test was conducted at the Camp Parks Communication Annex (CPCA) and testing was coordinated with the Research and Development, Test and Evaluation Support Complex (RSC) controlling ARGOS at the U.S. Air Force Space and Missile Test and Evaluation Directorate, Kirtland Air Force Base, New Mexico. A schematic of the BER test activities is presented in Fig. 4. The ARGOS SGLS transponder is activated before satellite rise, broadcasting an S-band signal locked to the onboard frequency standard. The remote tracking station (RTS) receives and locks onto the signal, establishing two-way communication. When normal commanding and data downloading are complete, the RSC directs the RTS to drop the active link (cease transmitting), and then the CPCA is directed to initiate the BER test, functioning in incoherent mode. The linear distance between the ARGOS SGLS antenna and the arcjet nozzle is 236 cm, and direct view is blocked by the arcjet radiation shield.

The Fireberd 6000-bit pattern generator and comparer generates a 2048-bit pattern (in place of the PRN bit pattern), output to the signal modulator. The signal, with a modulation index of 0.6 rad, is combined with the carrier frequency (2.2655 GHz) and passed through the high-power amplifier, transmitter, and 10-m antenna. The satellite transponder demodulates the signal and immediately modulates the downlink carrier frequency (1.811768 GHz) with the 2048-bit pattern. Because the process bypasses encryption, the measured BER accurately represents the number of errors incurred in the communication cycle. The signal is received by the 10-m antenna and passes through the receiver and amplifier on the way to the Fireberd 6000. The received 2048-bit pattern is compared with the original pattern, and the number of errors is counted and output to a computer (Fig. 5).

The transmission rate was 1.024 Mbps, and the combination of CPCA transmitter power and modulation index were set such that about 10 errors/s (1 error in 10^5) were generated when the satellite slant range was at a minimum. This effectively maximized the BER

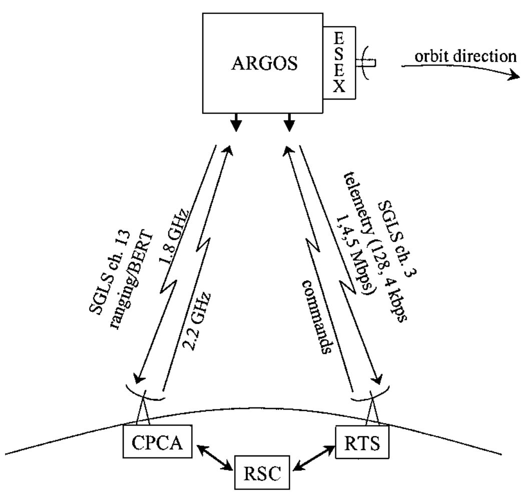

Fig. 4 Overview of BER test (BERT) assets: ARGOS, ESEX, SGLS, CPCA, RTS, and RSC.

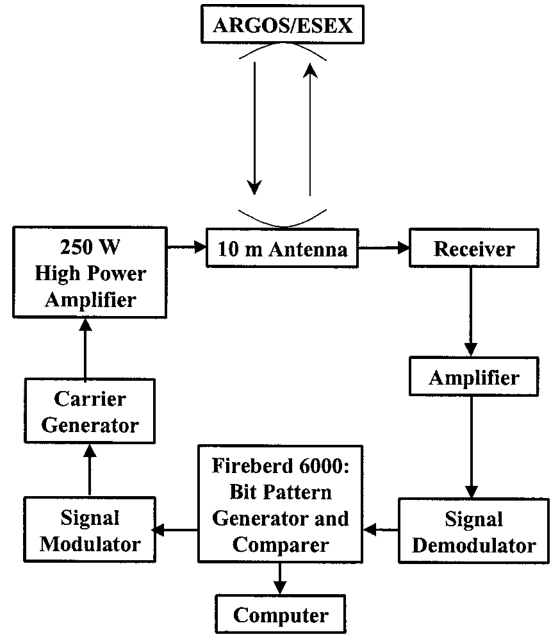

Fig. 5 BERT communication circuit.

test sensitivity by adjusting the error threshold. Typically, 1 error in 10^6 is considered acceptable in normal communication circuits. Note that a near zero error rate could be obtained for any given BER test by increasing the transmitter power or by setting an appropriate modulation index.

The BER test in this configuration was successfully proven in a trial with Miniature Satellite Technology Integration-3 and the Midcourse Space Experiment spacecraft.[11] The 2048-bit pattern was designed to emulate normal data bit patterns and thereby avoids signal resonances that can be established in the electronic equipment for cases in which the bit pattern period is too short, for example, 010101. The Fireberd 6000 generates the code and compares the transmitted and received patterns, recording the number of bit errors per second.

The CPCA in Dublin, California, served as the ground station for all BER tests. The 10-m parabolic, prime focus antenna has an uplink gain of 39.6 dB, a downlink gain of 23.6 dB, a beam width of 1.1 deg, and a slew rate of 6 deg/s (Ref. 12).

The BER for a fixed modulation is observed to be extremely sensitive to transmitter output power. A 1-dB reduction in uplink power corresponds to about a factor of two increase in measured BER at the minimum slant range point in the satellite pass. The high-power amplifier used for the ESEX BER tests is of class C type. (Maximum amplitude stability at full output power is about 200 W.) The amplitude drift after 1 h of continuous operation at full transmit power was stable to within a few 10ths of a decibel. Operation at a reduced transmit power caused amplitude drifts of several decibels for the first 20 min of operation. For a reduction in power by 3 dB, after 1 h of continuous operation, the drift was slightly more than 1 dB over 10 min. The majority of BER test data were obtained with an output power of 200 W; however, the first two arcjet firing BER tests were conducted with an output power of 100 W.

Data Analysis and Discussion

Satellites in polar orbits track across the sky, rising to a maximum elevation and then setting below the horizon either east or west of the ground station. In the case of ARGOS, all BER tests were conducted such that the satellite rose in the south and set toward the north of the CPCA. BER testing could begin as early as a rising elevation of 3 deg, corresponding to a slant range of nearly 3700 km. Correspondingly, BER testing could be sustained as late as a setting elevation of 3 deg. Maximum elevations greater than 85 deg generally present difficulties in SGLS tracking because the antenna dish must rapidly rotate to maintain appropriate polarization alignment, and for elevations near 90 deg, the antenna rate of motion is unable

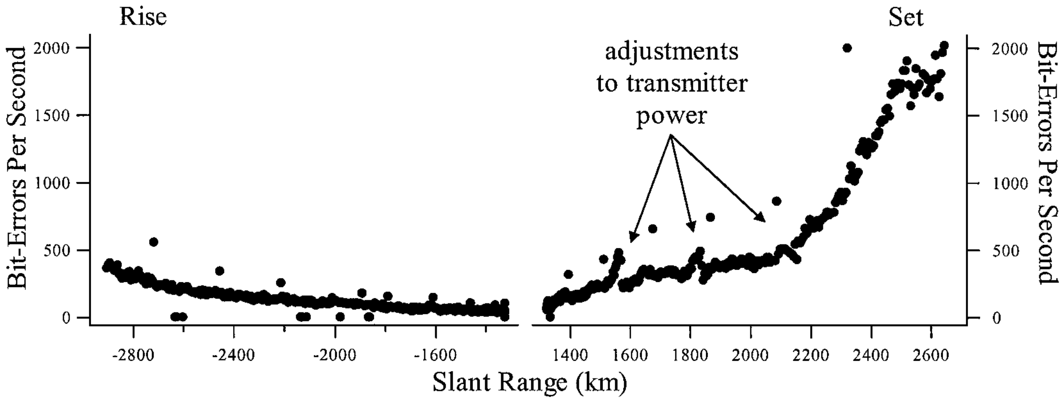

Fig. 6 Representative BERT data: negative slant range is defined as the rising portion of the satellite orbit; positive slant range is defined as the setting portion of the satellite orbit.

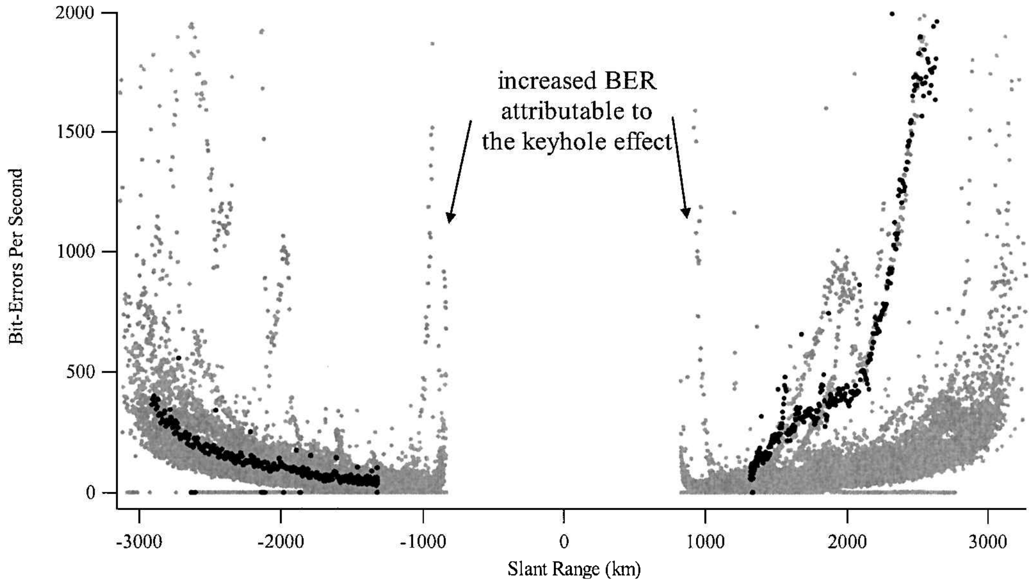

Fig. 7 Composite of 38 BERT results with data from Fig. 7 shown as black dots.

to keep up with the satellite track. This situation is commonly referred to as keyhole effect. For the ARGOS orbit, an elevation of 90 deg corresponds to a slant range of 850 km and continuous tracking of the satellite for overhead passes was troublesome because the CPCA 10-m antenna drive mechanism was not fast enough to rotate the dish to maintain proper electromagnetic wave polarization and sustain SGLS communication signal lock. Fortunately, it was a rare occasion that the maximum elevation was greater than 85 deg during the ESEX BER test opportunities.

An example of BER test data is shown in Fig. 6, in which several issues related to this type of test are illustrated. The BER is proportional to slant range, primarily due to atmospheric absorption of the 2-GHz carrier signal strength. The ordinate shows the number of bit errors counted per second, and the abscissa shows the slant range, defined as the line-of-sight distance from the CPCA antenna to the ARGOS SGLS antenna. For convenience, negative slant ranges are defined as the rising portion of the satellite orbit (elevations increasing with time) and positive slant ranges are defined as the setting portion of the orbit (elevations decreasing with time.)

The rising BER data in Fig. 6 were recorded with a modulation index of 0.6 rad and a transmitter power of 200 W. The measured BER decreases from nearly 500 bit errors/s to less than 50 near the minimum slant range of 1300 km. The curve is smooth because the output transmitter power was stable to within 5%. In contrast, the BER curve for the setting half of the pass is discontinuous with an increase in measured errors because the transmitter power was reduced by 12 dB, drifted, and was periodically reset. The variation in transmitted power was verified by examining the on-board antenna receiver signal strength data. The transmitted power fluctuated because the class C amplifier had not stabilized and the BER is sensitive to transmitter power. For example, the transmitter power was set to 20 W at the minimum slant range and had drifted toward lower powers. At the setting slant range of 1575 km, the transmitter power was abruptly reset to 20 W, reducing the BER from 479 to 242 bit errors/s. A 0.8-dB increase in transmitter power corresponded to a factor of two decrease in measured BER, denoting the sensitivity of the BER test to transmitter power. The transmitter power was adjusted again at a setting slant range of 1850 km with a corresponding reduction in BER. The transmitter power was allowed to continue drifting toward lower power at a slant range of 2150 km, giving rise to the bend in the BER curve. Note that using a class A amplifier would stabilize the transmitted power and provide improved BER test results.

The data indicated by 0 bit errors/s on the rising half of the BER curve, shown in Fig. 7, represent moments when the Fireberd 6000 experienced momentary loss of synchronization with the bit stream, termed sync loss. Sync losses are spurious artifacts of the test configuration and occur when the synchronization bit happens to be the bit in error. Thus, for maximum test sensitivity, the goal is to adjust the modulation index and transmitter power such that at maximum elevation the number of errors is small but quantifiable, and sync losses are uncommon. The individual data points above the average BER values occur without regular frequency and are not obviously correlated to any of the test parameters.

To characterize fully the novel BER test, more than 45 sets of data were acquired for a wide variety of experimental conditions. Figure 7 is a composite of 38 BER curves, with the example data from Fig. 6 shown in black and the rest of the data shown in gray. The increase in BER at the minimum slant ranges is due to the keyhole effect. The BER data with errors greater than 300 for slant ranges less than about 2500 km correspond to passes in which the transmitter power was set less than 100 W. The majority of baseline BER data were obtained with a transmitter power of 200 W, and the data typically reflect less than 200 bit errors/s at a transmitted rate of 1024 kbps (200 errors per 10^6 bits).

Arcjet Firing 2 BER Test

The BER curves shown in Fig. 8 are related to arcjet firing 2. The two curves were obtained on sequential passes, with a fixed modulation index of 0.6 rad and a constant transmitter power of 100 W, stabilized by operating the transmitter into a dummy load for an hour before BER testing. Data were obtained only on the setting portion of the satellite track because the rising portion was utilized for spacecraft commanding and data downlinking during those passes. The unadjusted transmitter output power drifted to lower power by about 1 dB during both passes. The first pass followed an easterly track, represented by open circles in Fig. 8, with a maximum elevation of 29 deg and a minimum slant range of 1490 km, and it serves as a baseline condition because the arcjet was not firing during this pass. Data for slant ranges shorter than 1750 km were unavailable for the baseline pass because the CPCA was given control of the spacecraft very late in the orbit. The next orbital revolution followed a westerly track, represented by closed circles, with a maximum elevation of 33 deg and a minimum slant range of 1370 km, and the arcjet was continuously firing for the entire duration of the BER test.

The BER curve from the baseline segment closely overlaps that portion of the BER curve from the arcjet firing for slant ranges between 1750 and 1950 km, beginning to diverge slightly as slant range increases. That portion of the BER curve from the arcjet firing for slant ranges between 1530 and 1645 km show numerous sync losses and relatively high BERs. Though it is not possible to draw a conclusion regarding the influence of arcjet operation on measuring the BER based solely on the data shown in Fig. 8, some discussion may be useful. The same behavior of a sudden, temporary increase in measured BER with a simultaneous increase in sync loss frequency has been observed in several BER tests conducted during periods when the arcjet was not operating, as can be seen in Fig. 7. Though the transmitter power was not recorded as a function of time during each BER test to verify the following behavior, it has been observed that the power could drift in such a way that sync losses are promoted with a corresponding increase in BER.

If the operation of the ESEX arcjet adversely influenced SGLS communications, the BER test would be sensitive to the increased number of errors. It is unlikely that the arcjet would introduce errors sporadically, rather it is expected that the interference from arcjet operation would be continuous. The observed increase in BER followed by recovery to overlap the baseline BER curve suggest an error source related to the test equipment. Note that even if operation of the ESEX arcjet did cause the increase in observed BER that increasing the transmitter power from 100 to 200 W would probably reduce the BER to within acceptable tolerances.

Arcjet Firing 4 BER Test

The BER curve obtained during arcjet firing 4, a representative baseline BER curve, and the arcjet power are shown in Fig. 9, represented by closed circles, open circles, and a line, respectively. For the BER curve obtained during arcjet firing 4, the transmitter power was 100 W, and the easterly orbit had a maximum elevation of 67 deg with a minimum slant range of 920 km. For the baseline BER curve, the transmitter power was 200 W, and the westerly orbit had a maximum elevation of 47 deg with a minimum slant range of 1080 km. For both BER curves, the modulation index was 0.6 rad.

Two features of the BER curve obtained during arcjet firing 4 are apparent. The number of bit errors per second decreases sharply at a slant range of 2115 km, and the sync losses occur for slant ranges less than 2071 km. The arcjet was ignited before beginning the BER test, and the arcjet turned off at a time corresponding to a slant range of 2185 km, as indicated by the arcjet power trace shown in Fig. 9. The difference between the time the arcjet turned off and the time the BER sharply decreased is 9 s with an uncertainty of 1 s. The BER test data were time stamped by the Fireberd 6000 and were adjusted forward by 1 s to synchronize with UTC. The ESEX telemetry used to calculate the arcjet power trace was time stamped by the ESEX clock and was adjusted such that the maximum error between UTC and the ESEX clock was 1 s. Given that the arcjet shut off 9 s after the qualitative change in the BER curve appearance and that the arcjet power trace is approximately constant, it is unlikely that operation of the ESEX arcjet caused the increase in sync losses and measured BER.

The cause of the qualitative change in appearance of the arcjet BER data is unresolved. Some BER test data have features in common with the arcjet BER data. For example, when intentional and abrupt changes in transmitter power are made, the measured BER immediately reflects the change, and sync losses are common when

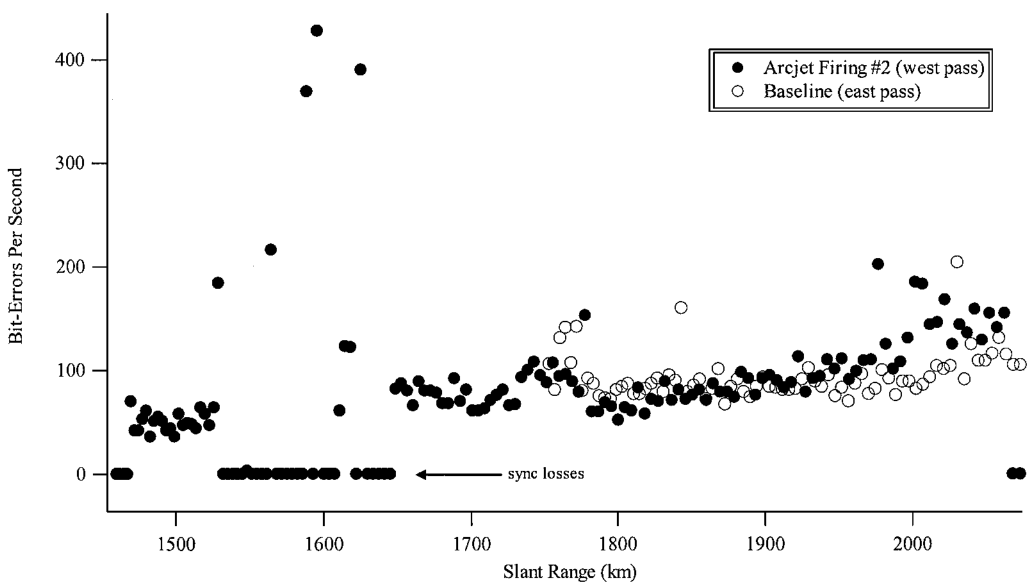

Fig. 8 Second arcjet firing BERT results.

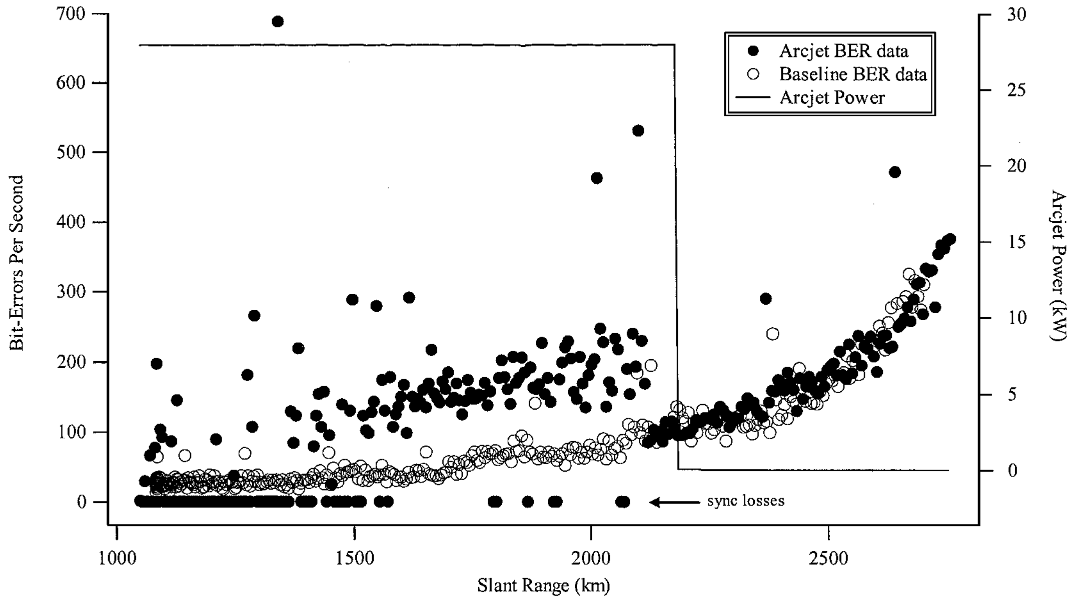

Fig. 9 Fourth arcjet firing BERT results.

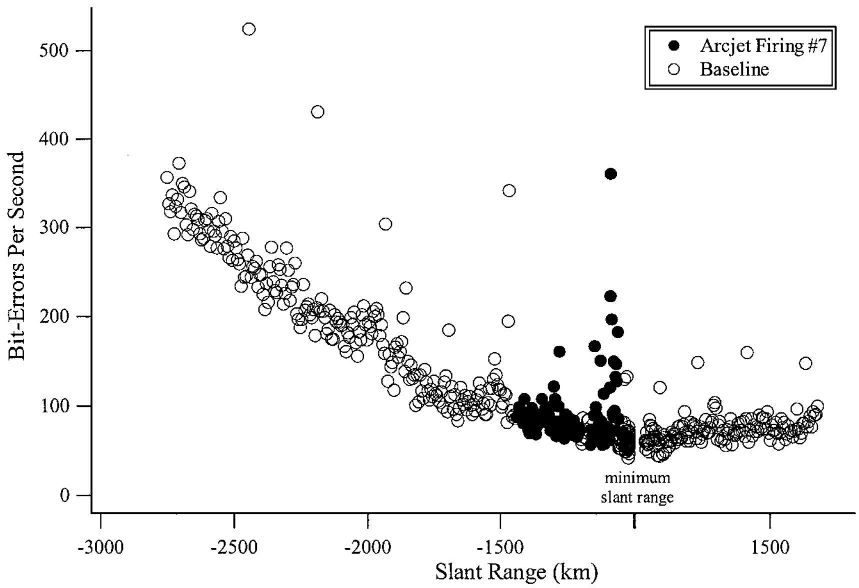

Fig. 10 Seventh arcjet firing BERT results.

the transmitter power is low. A sudden increase in transmitter power is consistent with the shift in the arcjet BER data.

The baseline BER data were obtained at a fixed power of 200 W and are compared with the arcjet BER data. The baseline and arcjet BER data precisely overlap for slant ranges greater than 2115 km, which would be consistent if the transmitter power was 200 W during the arcjet BER test. The average measured BER of the arcjet BER data is about four times larger than that of the baseline BER data for slant ranges between 1500 and 2000 km, which is consistent with expectations based on empirical observations of the effect changing the transmitter power from 200 to 100 W has on the measured BER.

Note that telemetry dropouts were experienced by the RTS during the same time period that the BER test experienced sync losses. Telemetry dropouts occur when the data transmitted from ARGOS to the ground station are corrupted, and such dropouts were experienced during many contacts in which the arcjet was not operated.

Arcjet Firing 7 BER Test

In an effort to avoid sync losses, the transmitter power was set to 200 W for the BER test that was conducted during arcjet firing 7, shown in Fig. 10. The modulation index was set to 0.6 rad, and the westerly pass had a maximum elevation of 53 deg with a minimum slant range of 1020 km. The single BER test was initiated before arcjet ignition, continuously conducted during arcjet operation, and terminated after arcjet shutdown. The open and closed circles represent BER test data for times the arcjet was off and on, respectively.

Arcjet firing 7 experienced some difficulty in which the arcjet ignited and shut off twice. The first period of arcjet operation coincides with rising slant ranges between 1200 and 1436 km and appears to have no more bit errors per second than the trend indicated by the earlier time. The second period of arcjet operation coincides with rising slant ranges between 1055 and 1160 km and may have a slightly increased BER. This increased BER may be because the input voltage to the power conditioning unit was tens of volts below specification and the PCU might have been generating noise. Additional discussion of this anomaly is presented by Bromaghim et al.[1]

In summary, 3 arcjet firings and 38 baseline BER curves were recorded during the ESEX flight, shown together in Fig. 11, with the arcjet firings highlighted by black dots. No clear correlation

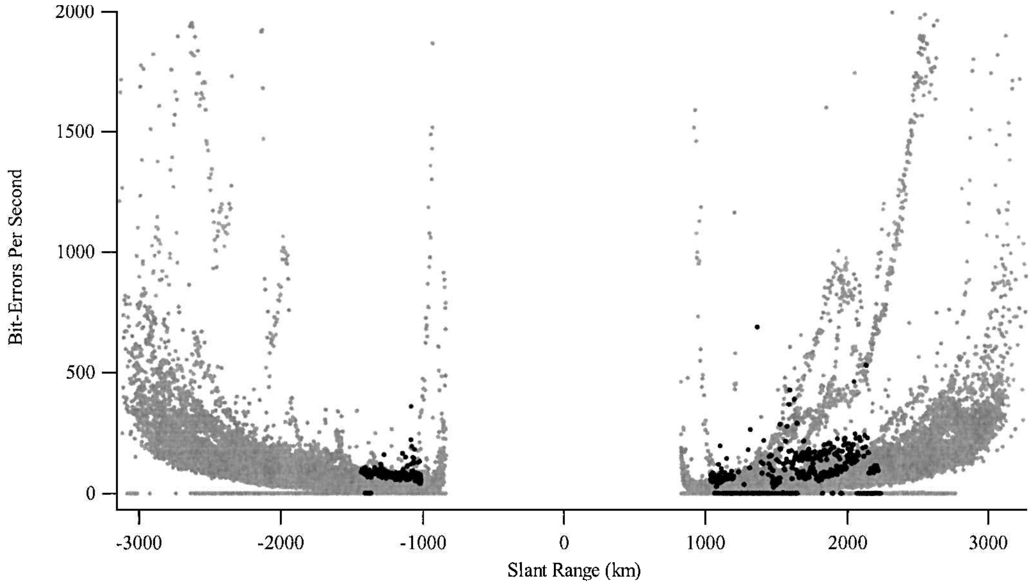

Fig. 11 Composite of 38 BERT results from arcjet-off conditions with BERT results from arcjet firings 2, 4, and 7 shown as black dots.

between features observed in the arcjet firing BER data and the operation of the arcjet has been identified.

Qualitative Observations on Command and Telemetry

The impact of arcjet operation on standard spacecraft function was studied by comparing event behavior during times of arcjet operation to normal behavior patterns.

The integrity of the uplink was studied by transmitting commands to ARGOS while the arcjet was operating. The command acceptance rate was noted and compared to the extensive database of typical command acceptance rates. In none of the eight arcjet firing operations was the command rejection rate atypical.

The integrity of the telemetry downlink was studied during arcjet operation. A known bit pattern was stored to the ARGOS recorder and then downlinked several times. The transmitted test patterns from periods when the arcjet was not operating were compared with test patterns transmitted during times of arcjet operation and differences were noted. In none of the comparisons was the number of errors larger than tolerances allow. Consider, for example, data from orbit revolution 369.4, in which arcjet firing 3 occurred. The test pattern was transmitted once before arcjet ignition as a control, with two errors counted, once such that the arcjet ignition occurred in the middle of the test pattern transmission, with three errors counted, once such that the arcjet was continuously on during the test pattern transmission, with two errors counted, and once such that the arcjet shutoff in the middle of the test pattern transmission, with four errors counted. Each test transmitted and received a total of 8,688,161 B.

The telemetry dropout rate tended to be larger than anticipated for general ARGOS operation. Some of the arcjet operations coincided with significant loss of telemetry; however, numerous ARGOS contacts in which the arcjet was not operating also experienced extreme telemetry dropouts. Examination of the dropout patterns for periods when the arcjet was on and off did not reveal any correlation between dropouts and arcjet operation. For example, during arcjet firing 1 there were no telemetry dropouts. Arcjet firing 2 had dropouts before, during, and after arcjet operation. During arcjet firing 4, dropouts occurred only when the arcjet was firing. During arcjet firing 7, the dropouts happened before and after, but not during the arcjet operation.

Conclusions

The test objective to perform an assessment of the electromagnetic impact of operating the ESEX 26-kW arcjet was achieved. No indication that the arcjet adversely affects normal spacecraft communications and operations was identified. Signals from the onboard antennas show no effect from arcjet operations on typical communications bands. Although the BER data possibly show a measurable effect from arcjet operations, the impact to future space systems is likely to be small. The 30-kW class arcjet operated satisfactorily in the space environment, and the onboard antennas did not register data values that differed from firing to nonfiring periods, suggesting low EMI arcjet output at the measured frequencies. The BER curves from arcjet firing and nonfiring periods differ slightly, but no clear correlation between the BER data and arcjet operation was identified. Commands uplinked without abnormal rejection rates and telemetry downlinked successfully during arcjet operation.

Operation of a 30-kW class arcjet does not appear to affect adversely normal spacecraft communications. This result was expected and suggests that standard spacecraft design procedures are effective in accommodating arcjet thrusters into spacecraft without encountering operational problems. Though proven and accepted for low-power arcjet operation, the ESEX program is the first to accumulate data in an on-orbit environment that indicates spacecraft design practices may be successfully extended to the incorporation of high-power arcjets.

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