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An Aeronautical Mobile Satellite Experiment

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ABSTRACT

This report details the various activities and findings of a NASA/FAA/COMSAT/INMARSAT collaborative aeronautical mobile satellite experiment. The primary objective of the experiment was to demonstrate and evaluate an advanced digital mobile satellite terminal developed at the Jet Propulsion Laboratory under the NASA Mobile Satellite Program.

The experiment was a significant milestone for NASA/JPL, since it was the first test of the mobile terminal in a true mobile satellite environment. The results were also of interest to the general mobile satellite community because of the advanced nature of the technologies employed in the terminal.

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1.0 EXECUTIVE SUMMARY

This report details the various activities and findings of a NASA/FAA/COMSAT/INMARSAT collaborative aeronautical mobile satellite experiment. The primary objective of the experiment was to demonstrate and evaluate an advanced digital mobile satellite terminal developed at the Jet Propulsion Laboratory under the NASA Mobile Satellite Program.

The experiment was a significant milestone for NASA/JPL, since it was the first test of the mobile terminal in a true mobile satellite environment. The results were also of interest to the general mobile satellite community because of the advanced nature of the technologies employed in the terminal.

The experiment was performed in two parts during the first several months of 1989. The first segment of the experiment consisted of establishing a full-duplex 4800 bps digital data-and-voice communication link (in a 5 kHz channel) through the INMARSAT MARECS B2 satellite between the FAA Technical Center in Atlantic City, New Jersey, and the COMSAT Coast Earth Station in Southbury, Connecticut. The second segment consisted of establishing the same communication link between Southbury and a Boeing 727 B100 aircraft flying along the East Coast of the United States. During both segments, a series of tests was performed to characterize the performance of the terminal over the links. The experimental setup and the results of the speech and data experiments are presented in this report. Differences in performance between theory/simulation, laboratory, and field operation are emphasized and analyzed.

Overall, for both the ground and flight segments of the experiment, the system-operating point (a bit error rate, BER, performance of 10^{-3}) was achieved at an E_b/N_0 of no worse than 9.7 dB; this equates to a C/N_0 of 46.5 dB·Hz. This worst-case performance, observed during flight tests in the presence of heavy turbulence, is approximately 1.0 dB worse than that measured in the laboratory for additive white Gaussian noise (AWGN). For more typical, clear-weather flight segments, an E_b/N_0 of 8.9 dB was required to achieve the 10^{-3} BER. The fading-induced degradation for clear weather conditions has been estimated to be 0.3 dB. This is far less than the loss generally associated with the aeronautical channel, i.e., a Rician channel with a K factor of 15–20, or a 1.3 dB equivalent loss.

Voice transmissions were digitally encoded at 4.8 kbps and were found to be acceptable, in both quality and intelligibility, to both FAA and JPL personnel. The voice link was demonstrated to be robust under all the flight conditions experienced during the experiment.

2.0 INTRODUCTION

Since the early 1980's, NASA, through the Jet Propulsion Laboratory, has been involved in developing both system concepts and high-risk technologies to enable the early introduction of a U.S. commercial Mobile Satellite Service (MSS). The Mobile Satellite Experiment (MSAT-X) program was created at JPL, in 1983, to achieve this goal. By early 1988, proof-of-concept mobile terminal hardware, a system architecture, and accompanying networking protocols were developed within MSAT-X. These elements of a MSS were developed to efficiently utilize the critically scarce resources of bandwidth, power, and orbital slots.

The efficient utilization of the resources needed to realize a commercially viable MSS is achieved in MSAT-X through the development of 4800-bps digital near-toll quality speech codecs, trellis-coded 8DPSK modulation, special pulse shaping, interleaving optimized for the real-time fading voice channel, and medium-gain directive (approximately 10 dBi) antennas. These developments, together with a networking protocol that integrates data and voice, comprise the MSAT-X system, which is based on a Frequency Division Multiple Access (FDMA) architecture, wherein each 4800 bps channel is efficiently squeezed into a 5 kHz slot.

The mobile, multipath links over which the MSAT-X technologies will operate form channels with memory that are typically difficult to analyze. Therefore, the design approach has emphasized software simulations, analysis when possible, hardware tests in the laboratory, and ultimately field tests under conditions that resemble typical operational conditions. The transition from one phase of the approach to the next has witnessed system design and technology refinements to overcome the hardware and operational problems. As is well known in engineering practice, the transition from the laboratory to the field invariably results in the discovery of unforseen operational conditions and the need to deal with them. This report presents a synopsis of the conditions encountered in the fixed ground- and the aeronautical satellite-link environments, and a summary and analysis of the performance of the MSAT-X equipment therein. Differences between field, and laboratory and simulation performance of the MSAT-X system are emphasized.[1]

3.0 EXPERIMENT BACKGROUND

In the 1988/89 time frame, mobile-satellite experiments for concept validation and technology demonstration were necessary to support

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[1] The conclusions and analysis presented in this report do not necessarily reflect those of COMSAT, the FAA, or INMARSAT.

NASA's ultimate goal of technology transfer to U.S. industry. Unfortunately, the MSS regulatory process extended throughout most of the 1980s, and only recently was the American Mobile Satellite Corporation (AMSC) licensed to construct and operate a U.S. MSS [1]. In the absence of a true MSS satellite, and while the regulatory process proceeded, JPL turned to interested U.S. government agencies, and operators of other satellite systems, for validation and demonstration of the technologies developed in the MSAT-X program.

Two groups expressed interest in performing a joint experiment: the Federal Aviation Administration (FAA) and INMARSAT. The FAA expressed considerable interest in the MSAT-X technologies to potentially support the oceanic air-traffic control functions over the Atlantic Ocean. At present, real-time voice services between air-traffic control centers and aircraft flying over the Atlantic can be difficult to establish. The MSS would be a good candidate to support such a critically important application. INMARSAT operates satellites that provide data and voice services for maritime operations. The INMARSAT Convention has recently been amended to permit the organization to provide the space segment for improving aeronautical communications [1]. The joint experiment described in this report provided an excellent means of satisfying the technology demonstration goals of NASA, the voice quality and robustness investigations of the FAA, and the space segment capabilities of INMARSAT.

The experiment was conducted by utilizing the INMARSAT MARECS B2 satellite that provides coverage of the Atlantic region. The objectives were to characterize the MSAT-X mobile terminal performance, in terms of quality and robustness, for both the fixed ground-link and aeronautical mobile satellite-link environments. The FAA was most interested in the evaluation of the performance of the 4800 bps digital speech codecs over the aeronautical satellite link. Link and equipment characterizations were performed by collecting specific information both on the ground and in the air. This information included bit error rate (BER) results at various signal-to-noise ratios, as well as qualitative and quantitative evaluations of the speech-link performance.

The experiment was conducted in two segments. A ground-based segment occurred during the first three weeks of January 1989. As a result of damage sustained by the aircraft during a windstorm immediately prior to the ground segment, the aeronautical portion of the experiment was postponed and performed during the last week of March 1989.

4.0 EXPERIMENT CONFIGURATION

The ground experiment consisted of a ground-to-ground full-duplex communications link between the FAA Technical Center in Atlantic City, New Jersey, and the COMSAT ground station (Coast Earth Station) in Southbury, Connecticut, through the Marecs B2 satellite. This is illustrated in Fig. 1. Shown also in the figure is the Coast Earth Station Terminal (CEST) communicating through the satellite to the ground-based FAA Terminal (FAAT) located on the roof of the FAA hangar.

The aeronautical portion of the experiment resembled the ground segment, with the communications terminal installed on the aircraft (the ACT, or aircraft terminal), and the experiments performed both while the aircraft was stationary (for calibration) and while the aircraft followed prescribed flight paths. This portion of the experiment is also shown in Fig. 1.

During the experiments, the CEST transmitted a pilot tone and data signal at C-band to the satellite, which then translated these signals to L-band and then retransmitted them for reception by the FAAT/ACT. The FAAT/ACT transmitted data to the satellite at L-band, which translated this signal to C-band and retransmitted it to the CEST.

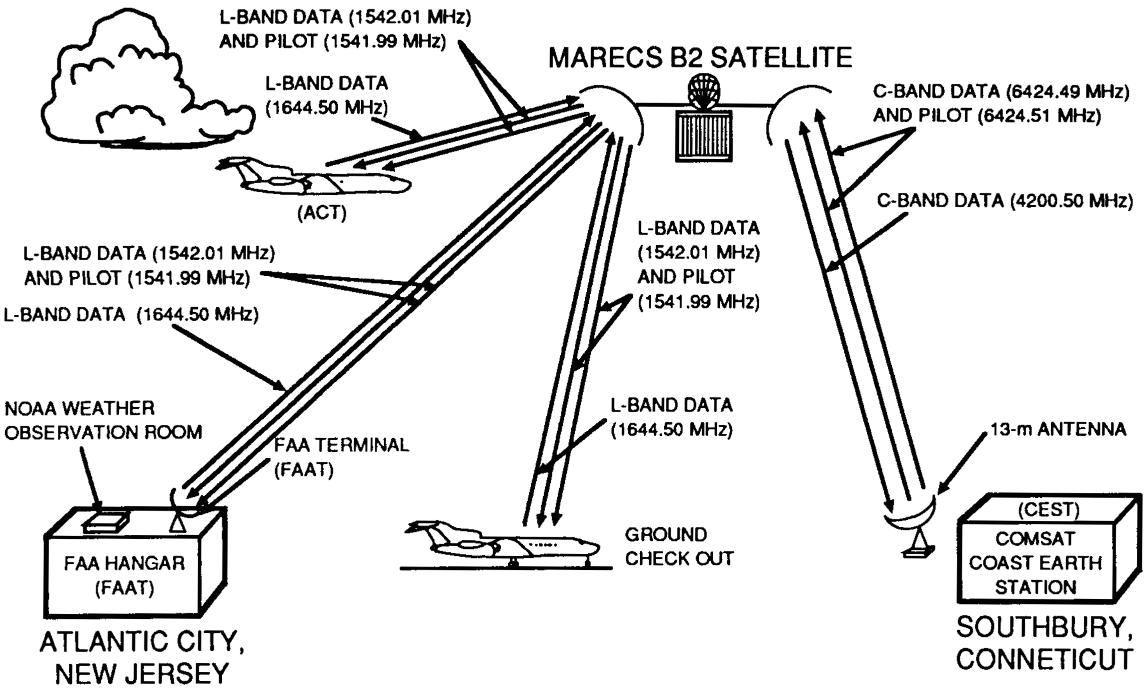


Figure 1. JPL/FAA/COMSAT/INMARSAT Experiment

Both the ground and aeronautical experiment segments were governed by the procedures and parameters set forth by INMARSAT [2], particularly those pertaining to maximum EIRPs, center frequencies, and frequency uncertainties. These parameters are summarized in Table 1. It should be noted that the Coast Earth Station (CES) also has an L-band receive capability that allows it to receive its own transmissions for monitoring purposes.

Table 1. Transmit/Receive Parameters

Signal	Maximum EIRP (dBW)	Uplink Frequency (MHz)	Downlink Frequency (MHz)	CES Frequency (MHz)
FAAT/ACT Data	23 (Terminal)	1644.50 ± 1000 Hz	4200.50 ± 1000 Hz	93.00 ± 1000 Hz
CEST Pilot	22 (Satellite)	6424.49 ± 230 Hz	1541.99 ± 230 Hz	91.99 ± 230 Hz
CEST Data	25 (Satellite)	6424.51 ± 230 Hz	1542.01 ± 230 Hz	92.01 ± 230 Hz

4.1 FAA Terminal

The FAAT consisted of the basic terminal components and additional equipment for the experiments. The basic components of the communications terminal are the speech codec [3], the terminal processor [4], the modem [5,6], the transceiver, and the antenna [7].

The speech codec provides good quality speech at 4800 bps. The terminal processor acts as the heart of the terminal and implements the networking and control functions. The modem converts data from the terminal processor at 4800 bps into a baseband waveform, as well as demodulates a low intermediate frequency (IF) from the receiver to provide 4800 bps digital data to the terminal processor. The transceiver up-converts the baseband waveforms to a suitable L-band transmit frequency, receives signals at L-band, and down-converts the received signals to a 28.8 kHz IF required by the modem, or baseband, as required for the tracking antennas and propagation measurements. The antennas developed for MSAT-X are generally steerable, tracking antennas [7]; however, for this experiment, two fixed dual-helibowl antennas (for the aircraft) were used. The setup also included an L-band high-power amplifier (HPA), an external synthesizer, and the antenna, as illustrated in the block diagram of Fig. 2. The enhancements to the terminal for the experiment included a data acquisition system (DAS), a power meter and E_b/N_0 filter, and an audio record/playback unit. The DAS [8] recorded various information such as the baseband received pilot signal (for fading measurements), the terminal processor-output BER data, and the power-meter analog and digital output for E_b/N_0 measurements. The audio record/playback unit was used to record the received speech and inject prerecorded audio into the codec.

The majority of the FAAT equipment was installed in two racks as illustrated in Fig. 3. The equipment in the racks is shown in the FAAT block diagram (Fig. 2), except for the HPA, external L-band synthesizer, and antenna. The HPA and L-band synthesizer were installed in a third rack. In addition to the equipment shown in the FAAT block diagram, the racks contained a spectrum analyzer and an oscilloscope for test purposes.

The FAAT antenna was a dual-helibowl antenna mounted on a stand to allow adjustment of the elevation and azimuth angle. This antenna provided 11.8 dBi of receive gain at 1542 MHz and 12.4 dBi of transmit gain at 1644 MHz. The G/T for the free-standing antenna was measured and found to be -11.3 dB·K. It had a 3 dB beamwidth of approximately 27 deg in elevation and 58 deg in azimuth, and was right-hand circularly polarized. The antenna patterns are displayed in Fig. 4.

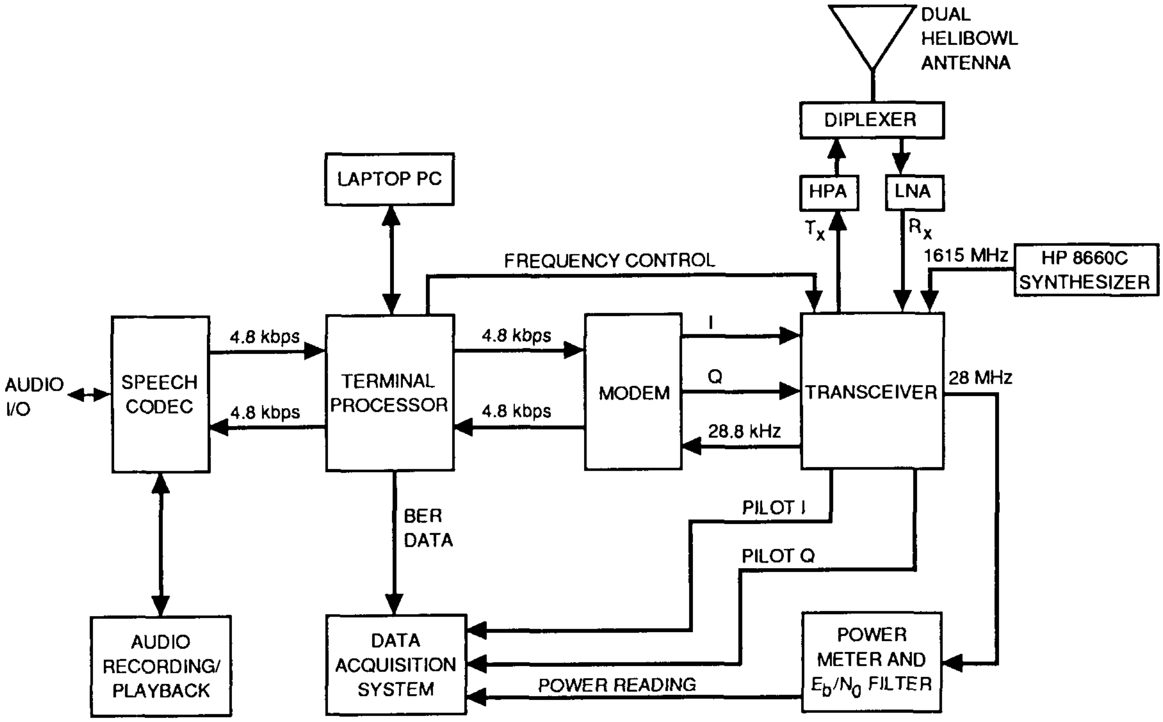


Figure 2. FAAT Equipment Block Diagram

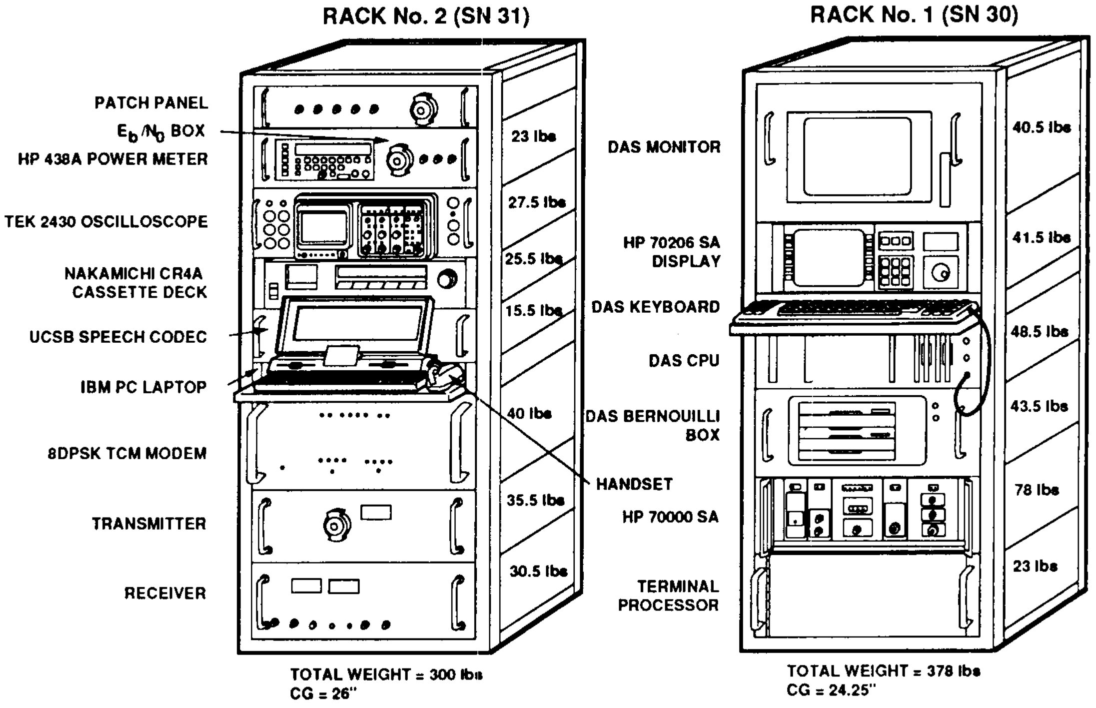


Figure 3. FAAT Equipment Racks

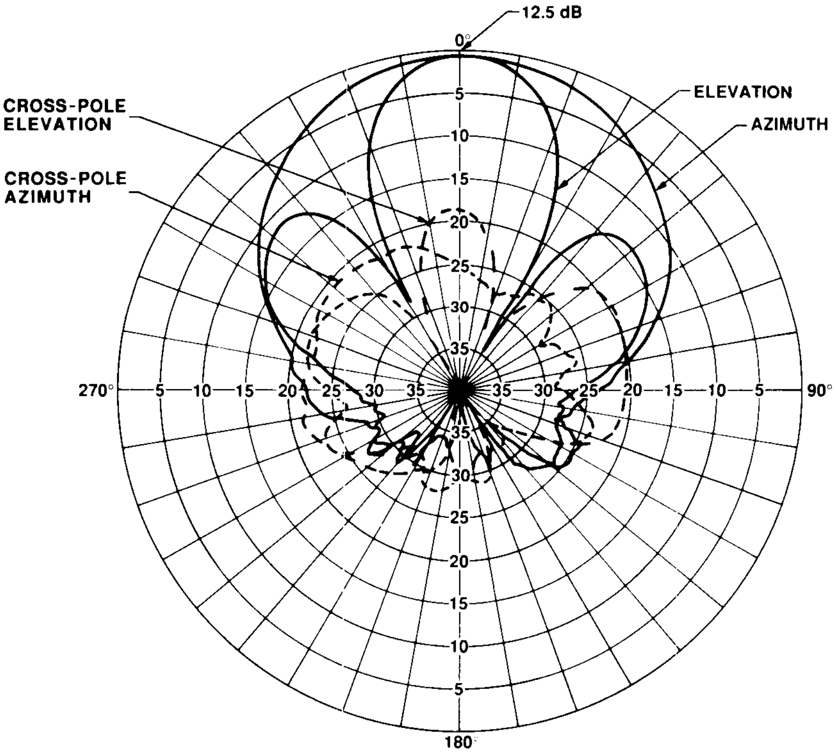


Figure 4. FAAT Antenna Patterns

4.2 Aircraft Terminal

With the exception of the antennas, the ACT equipment was identical to the FAAT equipment. The ACT antennas were electrically equivalent to the FAAT antenna, the difference arising from the mounting scheme in the aircraft. Two dual-helibowl antennas were mounted, one on each side of the fuselage in the tenth window back from the front of the aircraft. The antenna patterns for these antennas (when mounted in the aircraft) were virtually identical in shape to those shown in Fig. 4. However, due to window-aperture effects, the antennas were estimated to have approximately 0.4 dB less transmit and receive gain than the freestanding FAAT antenna (this loss is estimated from an experiment performed at JPL [9]). For these antennas the G/T was estimated to be -13.44 dB·K due to a lower gain and a higher estimated equivalent noise temperature.

4.3 The Coast Earth Station Terminal

A block diagram of the CEST is presented in Fig. 5. This terminal was configured somewhat differently from the FAAT/ACT terminal illustrated in Fig. 2. In particular, the terminal had three external synthesizers and a 90 MHz interface to the CES, instead of an L-band interface to an antenna. The purpose of the first synthesizer was to provide the pilot tone that is transmitted to the FAAT. This pilot tone would be used in a land–mobile satellite system to provide a reference for a tracking antenna and to act as a frequency reference for the mobile terminal. The pilot tone was used in this experiment as a frequency reference at the FAAT/ACT receiver and for propagation measurements. This signal was summed in with the data signal at the CEST transmitter, and the sum signal was produced at the transmitter output. The remaining two synthesizers were required by the CES interface unit to mix the CES output signal (at 90 MHz) down to the required frequency for the receiver, and to mix the transmitter output up to the 90 MHz input frequency required by the CES. This equipment was installed in a double rack, as illustrated in Fig. 6. The CEST utilized the COMSAT CES facilities [10] in Southbury, Connecticut, to provide the required transmit-and-receive capabilities to communicate with the FAAT and ACT via the MARECS B2 satellite. The COMSAT facilities consisted of the required RF equipment and a 13 m parabolic antenna.

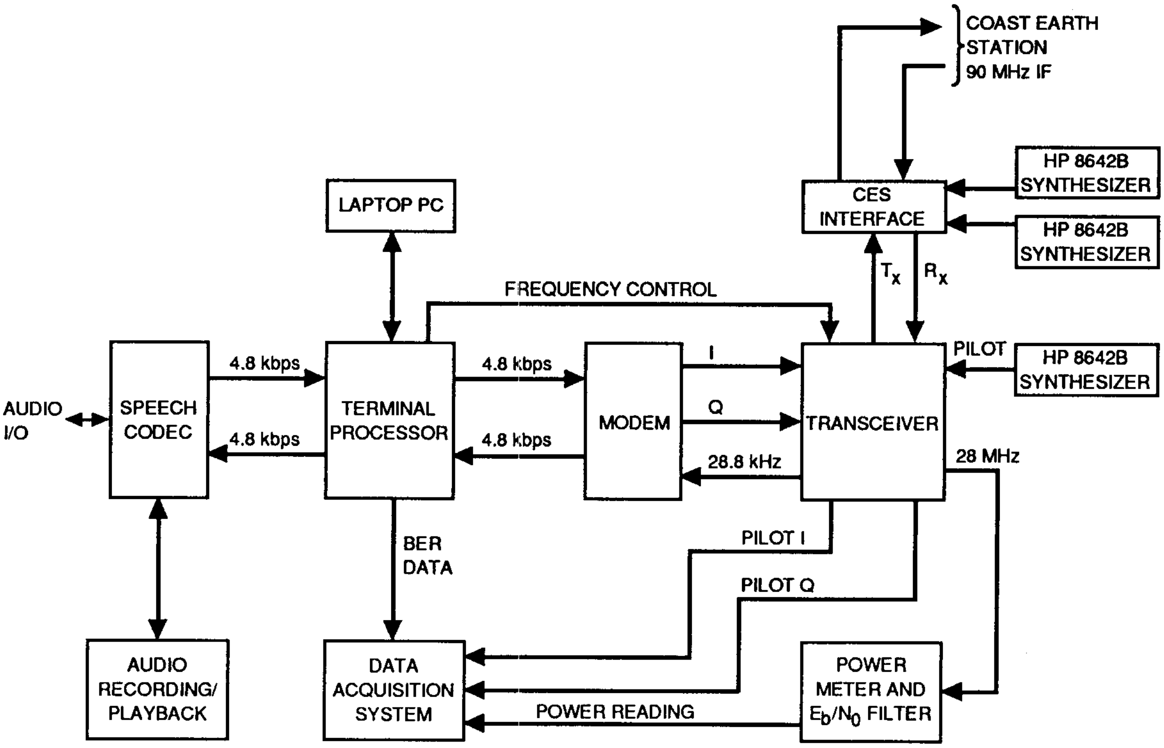


Figure 5. CEST Equipment Block Diagram

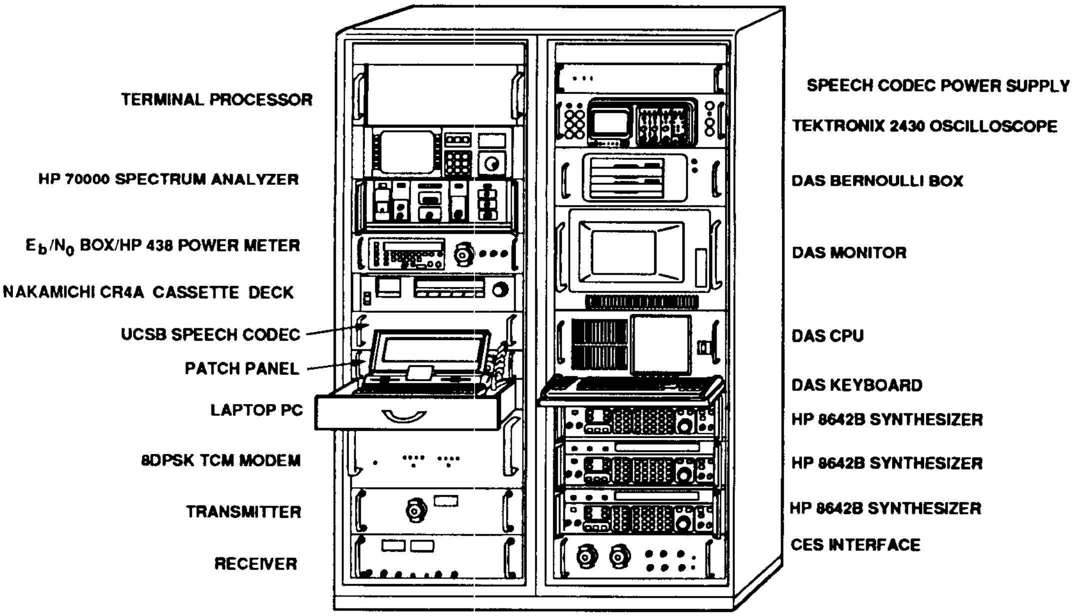


Figure 6. CEST Equipment Rack

4.4 The MARECS B2 Satellite

The MARECS satellite is located in a geostationary orbit over the Atlantic Ocean at 26 deg west longitude. This satellite is used primarily for maritime communications. At the CEST and FAAT locations, the elevation angle to the satellite is approximately 23 deg. During the flight experiments, the elevation angle to the satellite varied slightly, with an average angle of approximately 22 deg, depending on the flight path.

The satellite payload includes a C- to-L-band transponder for the shore-to-ship, i.e., forward (or CEST-to-FAAT/ACT) direction, and an L- to C-band transponder for the return (ship-to-shore or FAAT/ACT-to-CEST) direction. In the forward direction, the maximum satellite EIRP is 33.6 dBW (at the edge of coverage) derived from a transistor power amplifier. Although maximum utilization of satellite power on the satellite-to-ship downlink could result in operation near saturation [10], the JPL data and pilot signals were sufficiently lower than the maximum EIRP so that, even at the maximum allowed level of 25 dBW, no amplitude compression was expected to be observed at the FAAT. In this direction, the transponder is equipped with an automatic level control (ALC) circuit to maintain the operating point and keep the output power of the transponder at a constant level. As will be noted below, the ALC induced variations in the received signal level at the FAAT, thereby introducing some degradation in system performance. In the return direction, the amplifiers are conventional TWTs operating in the linear region. A high-gain transponder, with 15 dB more gain than the normal transponder, occupies 200 kHz close to the upper end of the band. This high-gain transponder was used in the experiment for the FAAT/ACT transmissions. As with the forward link, no amplitude compression was expected to be observed. This transponder is not equipped with an ALC.

4.5 Link Budgets

Two sets of link budgets were developed for the experiment. The first set of link budgets covers the ground-to-ground transmissions for the first segment of the experiment. This set of link budgets is presented in Table 2. A second set of link budgets developed for the aeronautical portion of the experiment is presented in Table 3. These link budgets were developed prior to the experiment, and any differences between the performance predicted in the link budgets and the actual performance are discussed in Section 4.

Table 2. Preexperiment Ground-Link Budget, AWGN, BER=10^{-3}

	Forward		Return
Uplink	Data	(Pilot)	Data
XMTR Power, dBW	---		13.0
CKT Loss, dB	---		-1.8
Antenna Gain, dBi	---		12.4
XMTR EIRP, dBW	68.5	(65.5)	23.6
Path Loss, dB	-200.5		-188.8
(Range, km)	(39500		39500)
(Frequency, GHz)	(6.4		1.6)
Atmospheric Loss, dB	-0.4		-0.2
XMT ANT Pointing Loss, dB	0.0		0.0
Polarization Loss, dB	0.0		0.0
Multipath Fading, dB	0.0		0.0*
Satellite G/T, dB·K	-15.0		-11.2
Uplink C/N_0, dB·Hz	81.2	(78.2)	52.1

*Budgeted in downlink

	Forward		Return
Downlink	Data	(Pilot)	Data
Satellite EIRP, dBW	25.0	(22.0)**	-3.2
Path Loss, dB	-188.2		-196.9
(Range, km)	(39500		39500)
(Frequency, GHz)	(1.5		4.2)
Atmospheric Loss, dB	-0.2		-0.4
RCV ANT Pointing Loss, dB	0.0		0.0
Polarization Loss, dB	0.0		0.0
RCV Antenna Gain, dBi	11.8		54.2
RCV System G/T, dB·K	-11.4		32.0
Downlink C/N_0, dB·Hz	53.9	(50.9)	60.2
Total C/I_0, dB·Hz	67.8		63.9
Overall C/N_0, dB·Hz	53.7	(50.8)	51.2
E_b/N_0, dB	16.9		14.4
Required E_b/N_0 in AWGN, dB	8.4		8.4
Loss in Multipath (K=15 dB), dB	0.0		0.0
Extra Degradation at Low RCV Pilot Levels	0.2		0.0
Required E_b/N_0, dB	8.6		8.4
Margin, dB	8.3		6.0

**Total EIRP for pilot and voice = 26.8 dB (total transponder EIRP = 34.5 dBW)

Table 3. Preexperiment Aeronautical Link Budget, Rician (K=15 dB), BER=10^{-3}

Uplink	Forward Data	(Pilot)	Return Data
XMTR Power, dBW	---		13.0
CKT Loss, dB	---		-1.2
Antenna Gain, dBi	---		12.0
XMTR EIRP, dBW	68.5	(65.5)	23.8
Path Loss dB	-200.5		-188.8
(Range, km)	(39500		39500)
(Frequency, GHz)	(6.4		1.6)
Atmospheric Loss, dB	-0.4		-0.2
XMT ANT Pointing Loss, dB	0.0		0.0
Polarization Loss, dB	0.0		0.0
Multipath Fading, dB	0.0		0.0*
Satellite G/T, dB·K	-15.0		-11.2
Uplink C/N_0, dB·Hz	81.2	(78.2)	51.3

*Budgeted in downlink

Downlink	Forward Data	(Pilot)	Return Data
Satellite EIRP, dBW	25.0	(22.0)**	-4.2
Path Loss, dB	-188.2		-196.9
(Range, km)	(39500		39500)
(Frequency, GHz)	(1.5		4.2)
Atmospheric Loss, dB	-0.2		-0.4
RCV ANT Pointing Loss, dB	-1.0		0.0
Polarization Loss, dB	0.0		0.0
RCV Antenna Gain, dBi	11.4		54.2
RCV System G/T, dB·K	-13.4		32.0
Downlink C/N_0, dB·Hz	50.8	(47.8)	59.2
Total C/I_0, dB·Hz	67.8		63.9
Overall C/N_0, dB·Hz	50.7	(47.7)	50.4
E_b/N_0, dB	13.9		13.6
Required E_b/N_0 in AWGN, dB	8.4		8.4
Loss in Multipath (K=15 dB), dB	1.8		1.3
Extra Degradation at Low RCV Pilot Levels	0.4		0.0
Required E_b/N_0, dB	10.7		9.7
Margin, dB	3.3		3.9

**Total EIRP for pilot and voice = 26.8 dB (total transponder EIRP = 34.5 dBW)

For the ground-based testing (using the FAAT), the channel was assumed to be the AWGN channel. Based on laboratory results, the 10^{-3} BER performance is obtained at an E_b/N_0 of 8.4 dB. For the forward link in the ground tests, an additional 0.2 dB degradation was allocated, due to the pilot tracking at the FAAT receiver. Taking this increased degradation into account, as illustrated in Table 2, leads to a forward-link margin of 8.3 dB. For the return link, the degradation due to pilot tracking is not present (no pilot tracking was performed at the CEST), and the link margin is 6.0 dB.

For the aeronautical portion of the experiment, two separate tests were performed (as described in Section 4). The first segment consisted of testing the links, while the ACT (i.e., the aircraft) was stationary. The second segment consisted of the flight tests. For the stationary ACT tests, the link budgets are very close to those presented in Table 2. The primary difference is in the antennas. As mentioned previously, the ACT antennas were installed in the aircraft windows, and due to aperature effects, the antennas had approximately 0.4 dB less gain than the free-standing FAAT antenna. In addition, when compared with the FAAT, the ACT had slightly lower cable losses between the transceiver and the antenna and had a higher effective noise temperature. The combination of these factors reduces the estimated G/T for the antenna by 2 dB, from -11.4 dB·K to -13.4 dB·K. Again, due to the reduced antenna gain, an additional 0.2 dB was allocated for tracking the reduced pilot level.

For the flight tests, there are several additional sources of degradation to consider. The first factor is the antenna direction. In the case of all the ground tests (FAAT and ACT), the antenna position was manually optimized to provide the highest received pilot level. When the ACT was airborne, antenna pointing was only approximate, and a 1.0 dB degradation was allocated for pointing errors. Coupled with this is the reduced pilot level. The pilot level was expected to be reduced even further than in the ground-based ACT tests, primarily because of the pointing errors. An additional 0.2 dB was allocated to overcome this degradation. Finally, channel effects must be considered. In the stationary tests, the channel was assumed to be the AWGN channel. For the aeronautical tests, the channel was assumed to be the Rician fading channel with K=10. Laboratory tests of the MSAT-X modem had indicated that a margin of 1.8 dB was sufficient to overcome the channel effects in the forward channel. For the return channel, the environment was not assumed to be as severe (K=15–20), and 1.3 dB margin was allocated to overcome the channel impairments. These additional degradations led to a margin of 3.3 dB in the forward link and 3.9 dB in the return link, as shown in Table 3.

As has been noted above, these link budgets were developed prior to the experiments, and the actual performance differed slightly from these budgets. The differences are discussed in Section 5.

5.0 EXPERIMENTAL RESULTS

5.1 Ground-to-Ground Link

The ground-to-ground tests were the first tests by JPL of a bandwidth- and power-efficient digital modulation technique for mobile applications through a satellite link. As such, emphasis was placed on determining any deviation from theory/simulation induced by satellite anomalies. Also of concern were any degradations caused by the mobile terminal (MT) hardware when operated at the low received signal levels experienced in a satellite link but not readily observable in a laboratory setup. Finally, the ground-to-ground tests served as a bench mark to be used in gauging aeronautical satellite performance.

5.1.1 Satellite Observations

A plot of the received spectrum at the CES receive port (i.e., the return link) taken from a spectrum analyzer is shown in Fig. 7. The shape of the CEST IF filtering may be observed in this plot. The satellite traffic is clearly visible as the large number of carriers in the center of the plot. The wide bandwidth signal at the higher frequency end of the transponder spectrum is the high-gain portion of the transponder, which is allocated to search-and-rescue operations. This is the portion of the spectrum to which the FAAT transmissions were assigned.

The satellite traffic was also observed at the FAAT. In general, the same types of carriers and signals were observed at the FAAT site. One noticeable difference was the absence of the high-gain channel in the forward direction. A plot of the observed activity is presented in Fig. 8. The effects of the mobile terminal's receiver filtering are evident in this plot, which also shows the location of the forward link pilot and data, as indicated by the marker. Figure 9 shows a plot of the L-band receive spectrum at the FAAT that displays the CEST transmissions. Both the pilot and data transmissions are visible.

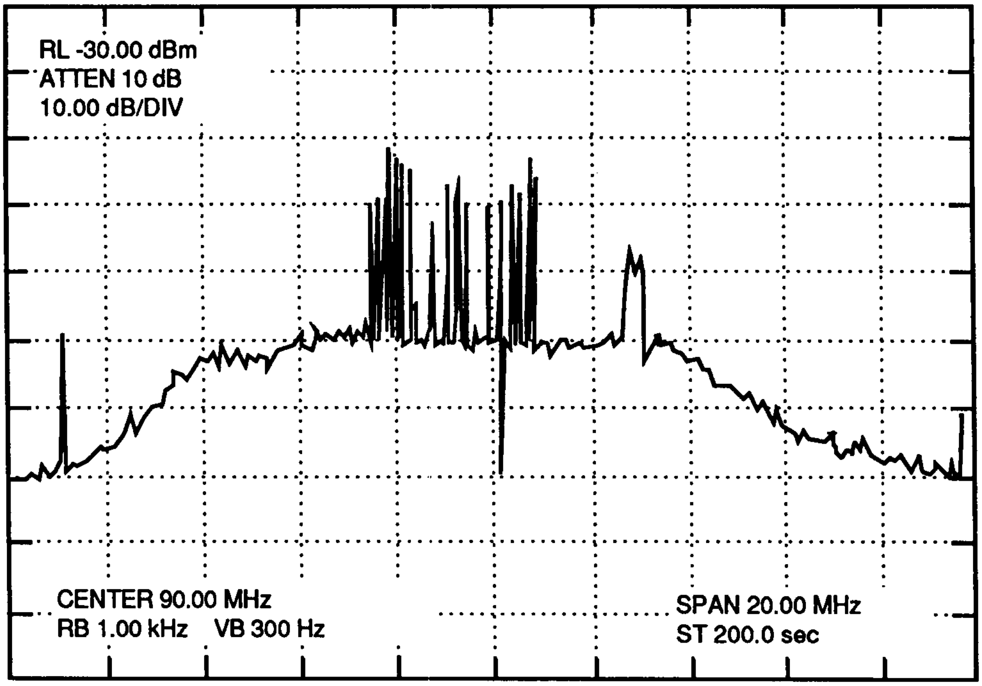


Figure 7. CEST C-Band Receive Spectrum

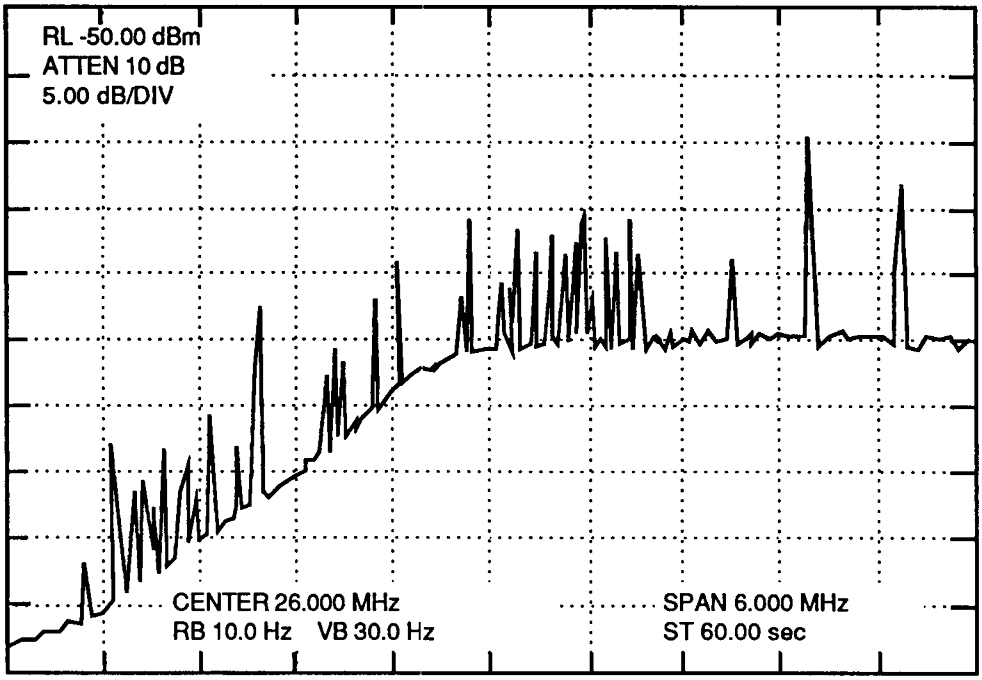


Figure 8. FAAT Receive Spectrum

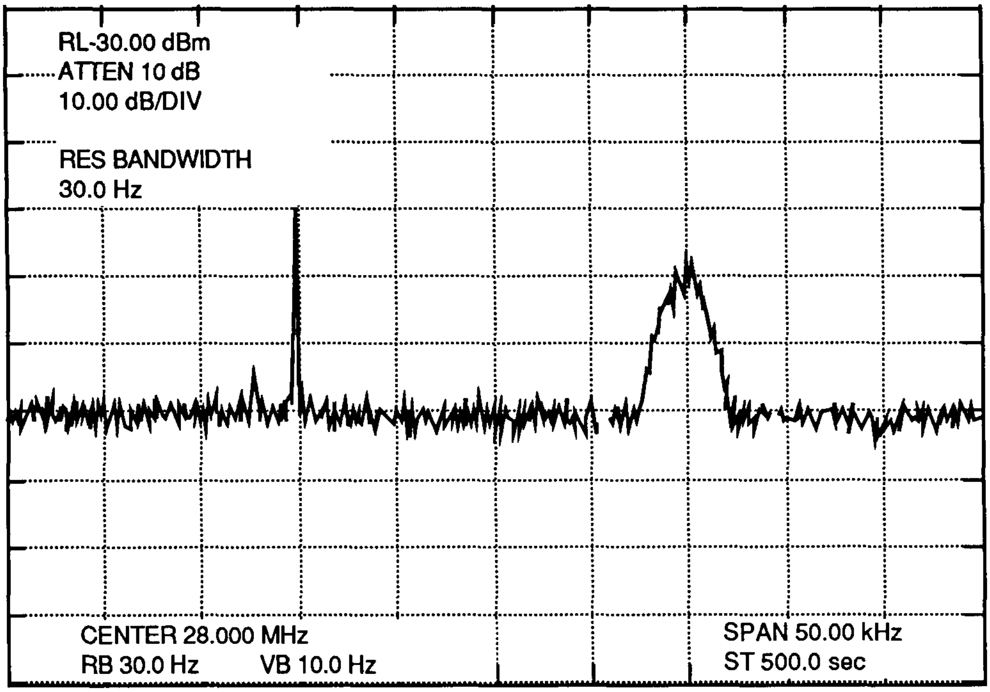


Figure 9. FAAT Receive Pilot and Data

Significant signal fluctuations were observed at both the CEST and the FAAT, however, even more were observed at the FAAT. Over the forward link (at the FAAT), the observed signal levels would vary approximately ±1.5 dB over the short term (several seconds) and could vary by several dB over longer periods (several hours), depending on the traffic loading. By contrast, on the return link, the short-term variations were approximately ±0.5 dB. The higher signal variations observed on the forward link are attributed to the ALC on the satellite, which varies the output signal level to maintain a constant overall output power as the traffic varies.

During the experiment, the effects of AM/AM and AM/PM conversion effects introduced by the satellite transponders (and the HPA's in the link) were a major concern. Typically, the signals used by INMARSAT for voice and data are constant envelope-modulation schemes, and as such are not affected by these effects. By contrast, in MSAT-X, the combination of power and bandwidth efficiency is achieved at the expense of a nonconstant envelope signal; hence the heightened interest in AM/AM and AM/PM effects. Fortunately, due to the MSAT-X modem architecture and the choice of a pulse shape [6], these effects can be mitigated. To measure the AM/AM effects, tests were performed in both directions. The tests consisted of transmitting a pilot tone in each direction, varying the input power to the transmitter by a known amount, and then measuring the received power. The measurements are presented in Fig. 10, where the received pilot power is plotted as a function of the transmit pilot power.

Over the range of transmitted powers used in the experiments, the links were linear within the measurement error of ±0.5 dB. AM/PM tests were planned; however, due to fact that the BER results obtained (presented in the next section) were very close to laboratory/simulation results over the AWGN channel, these tests were not performed.

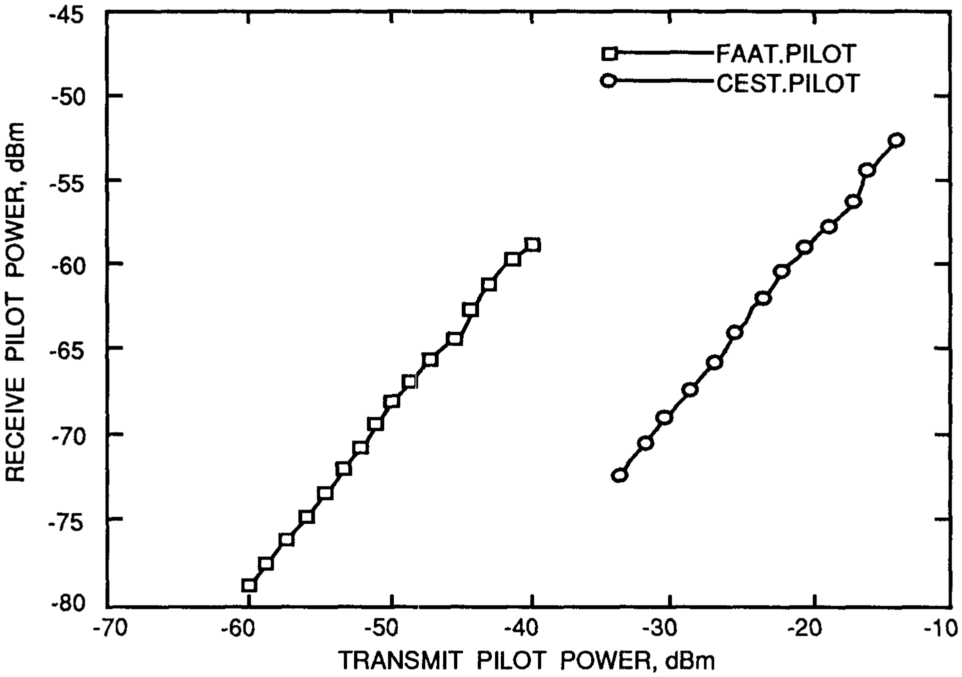


Figure 10. Forward (CEST-to-FAAT) and Return (FAAT-to-CEST) Link AM/AM Measurements

5.1.2 BER Measurements

BER values were recorded at various signal-to-noise ratios for both the forward and return links. As noted above, in addition to the data carrier, an unmodulated pilot signal was transmitted in the forward direction. The utilization of a pilot signal produces phase-locked local oscillators referenced to the received pilot signal for the data channel in the FAAT receiver. For all testing, the pilot signal was maintained at the maximum level allowed by INMARSAT (Table 1). The resulting pilot signal C/N_0 was approximately 50.5 dB·Hz (variations were observed in this level due to the effect of the ALC).

The measured BER performance for the forward link (FAAT.BER) is shown in Fig. 11. Plotted on the same graph are the curves for simulation (SIM.BER) and laboratory hardware tests (LAB.BER), both for an AWGN environment. The observed experimental curve appears to be about 0.5 dB from the measured laboratory performance results.

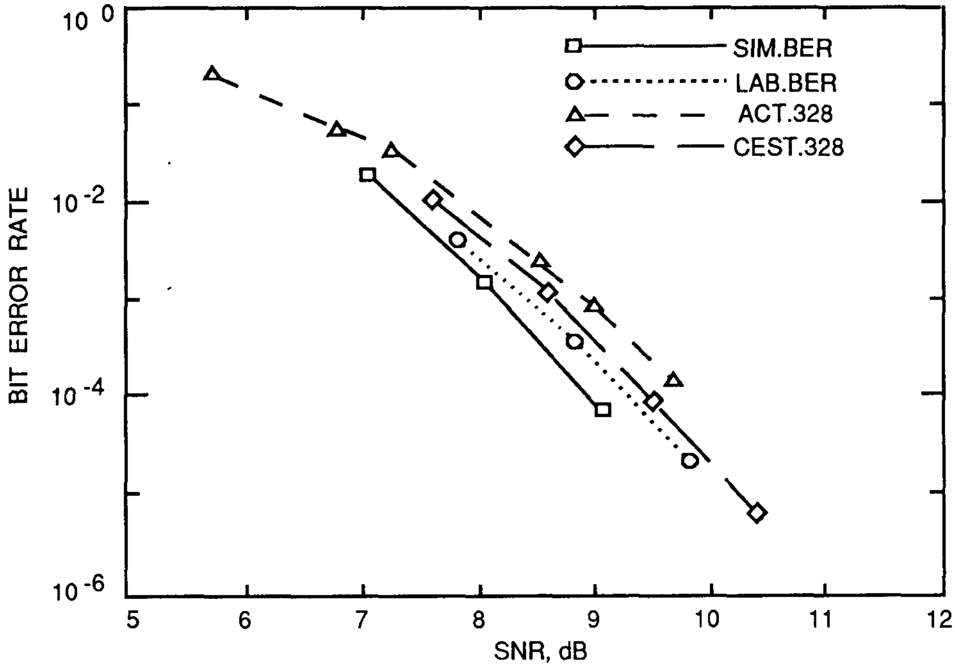


Figure 11. Forward- and Return-Link BER Measurements

The much more severe land–mobile multipath channel is described by a Rician amplitude distribution with a typical, average K (ratio of direct to diffuse signal power) of 10 dB. This is a standard model used for comparisons in land–mobile satellite communications. The MSAT-X modem specification is for a BER of 10^{-3} (the nominal operating point of the MSAT-X system — for acceptable, generally outage-free voice quality) at an E_b/N_0 of 11 dB for the standard channel. Naturally, performance is significantly better in the AWGN channel (as would be the case in a stationary link). From Fig. 11, it appears that the 10^{-3} BER performance is achieved at an E_b/N_0 of approximately 8.8 dB, or a C/N_0 of 45.6 dB·Hz, which corresponds to an EIRP of approximately 16.7 dBW from the satellite (this estimate is approximate, due to the operation of the ALC).

Of the 0.5 dB degradation observed in the performance of the forward link relative to laboratory results, approximately 0.25 dB can be attributed to tracking a noise-corrupted pilot signal [11]. The remainder results from the cumulative effects of link nonlinearities, such as the variation in E_b/N_0 due to transponder traffic, as described above. When comparing these results to the link budget for the forward link in Table 2, the two agree very closely. In particular, the forward link budget from Table 2 estimates that the 10^{-3} BER will be obtained at an E_b/N_0 of 8.6 dB, when it is actually attained at 8.8 dB. The additional 0.2 dB degradation can be attributed to the link nonlinearities (such as the ALC).

The measured BER performance for the return link (CEST.BER) is also presented in Fig. 11. This improved performance, relative to the forward link, corresponds almost exactly to the laboratory performance (LAB.BER). The superior performance in the return link is attributed to the presence of more stable local oscillators in the CES down-conversion chain, which eliminate the pilot-recovery degradation, and the lack of an ALC, which results in a more stable data carrier signal to the CEST modem. Again, the nominal operating point of the MSAT-X system is at a BER of 10^{-3}. This occurred at an E_b/N_0 of approximately 8.4 dB or a C/N_0 of 45.2 dB·Hz, and corresponded to an EIRP of -9.3 dBW from the satellite. As in the case of the forward link, the results agree very closely with the link budget presented for the return link in Table 2. In fact, the link budget predicts that the 10^{-3} BER will be obtained at an E_b/N_0 of 8.4 dB, which is the signal-to-noise ratio that was obtained in the experiment.

5.1.3 Speech Experiments

The first tests of MSAT-X speech codecs over a satellite link were performed during the ground-to-ground segment of the experiment. Half- and full-duplex voice links were established to demonstrate the concept of near-toll quality 4.8-kbps digital speech transmitted over a narrow-band, spectrally efficient satellite channel. The voice compression was executed in a speech codec developed for MSAT-X by the University of California at Santa Barbara (UCSB). The particular algorithm employed by the codec is Vector Adaptive Predictive Coding (VAPC) [2]. Independent tests of this codec both in the United States and Australia have indicated that the codec has a Mean Opinion Score (MOS) of approximately 3.2 (on a 5.0 scale). For reference, toll-quality speech attains a MOS of approximately 4.2.

Since the in-the-air time of the aeronautical part of the experiment was expected to be quite limited, most of the extensive validation tests of the codecs were performed during the ground-to-ground segment. Four different types of speech were recorded at each ground site: (1) casual conversations, (2) continuous recorded text read by 3 male and 3 female speakers, (3) Diagnostic Rhyme Test (DRT) word lists read by 3 male and 3 female speakers for an intelligibility measure, and (4) Diagnostic Acceptability Measure (DAM) phrase lists also read by 3 males and 3 females for a subjective quality or listener-preference measure. The casual conversations were run in full-duplex mode, and the remaining types of speech were run in half-duplex on both the forward and return links. The half-duplex transmissions were established using both a high E_b/N_0 (BER < 10^{-6}) and a low E_b/N_0 (BER approximately 10^{-3}). A BER test was run both before and after each recording to determine the approximate BER for the speech.

Initial impressions of the voice quality can be characterized as very favorable. While noticeable, the total delay induced by speech encoding/ decoding, modem data interleaving/deinterleaving, and signal propagation did not inhibit the users in carrying out conversations with ease. At BER's of 10^{-3} or better, the quietness of the link, i.e., the abscence of background noise typically observed in analog voice-communications systems, was very noticeable. Another observation that is typical of digital communication systems is how quickly the link quality degrades once a signal-level threshold is reached. The nature of this threshold can be traced back to the steep performance curves of the modem; typically, a change of 1.0 dB will lead to an order-of-magnitude change in the received BER, thus producing the threshold effect in speech quality. As the BER approached 10^{-2}, the speech codec performance degraded dramatically. However, at the 10^{-3} operational point or better, corresponding to a C/N_0 of approximately 46.0 dB·Hz or better, the speech codec performed to expectations.

5.2 Aeronautical Links

After installing the equipment in the aircraft, both ground calibrations and flight tests were performed. These tests consisted of both speech and data transmissions in each direction, using both of the ACT antennas. The results of these tests are presented below.

5.2.1 Ground Calibrations

The ground calibrations were intended to determine the repeatability of performance obtained in the ground-to-ground tests performed 10 weeks earlier, and to provide a bench mark for comparison of the aeronautical results. The Boeing 727 was positioned on the runway at the Atlantic City airport, as depicted in Fig. 12. Data tests in each direction (ACT to CEST, CEST to ACT) were performed, and the system performance at each site was characterized in terms of the BER as a function of E_b/N_0. Transmissions from both the right- and left-side antennas were performed; the aircraft as shown in Fig. 12 was rotated 180 deg for the latter test. The same sequence of tests in the forward and return links was run as described above in the ground-to-ground segment. The average performance (over both left-side and right-side antennas) for both the forward and return links is shown in Fig. 13.

In this figure, the performance of the forward link (CEST to ACT) is shown by the curve ACT.328, and the performance of the return link is shown by the curve CEST.328. For comparison, the performance of the modem in the laboratory (LAB.BER) and simulation (SIM.BER) for the AWGN channel are also shown.

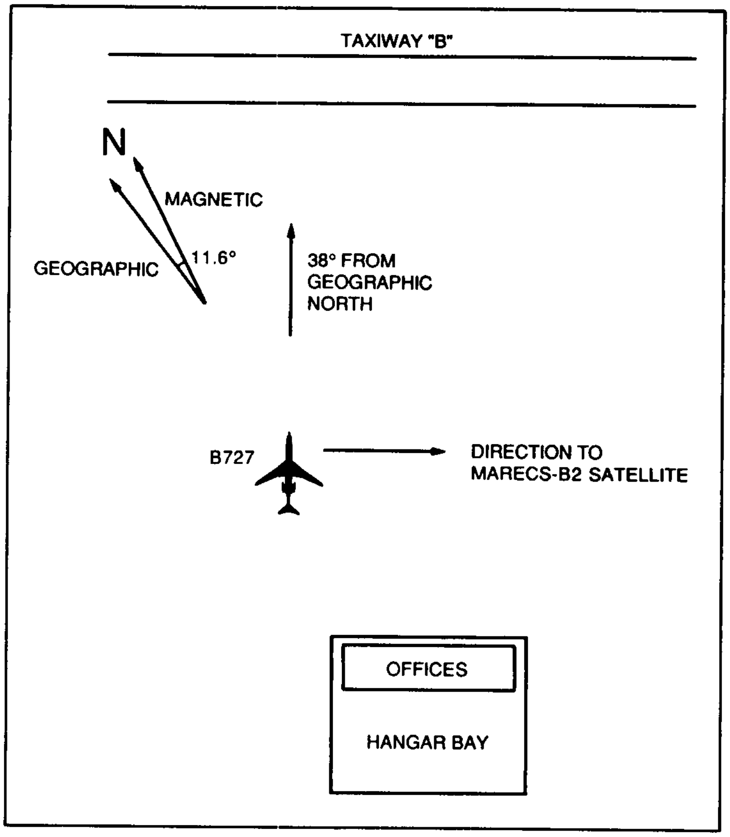


Figure 12. Experiment Setup at FAA Technical Center

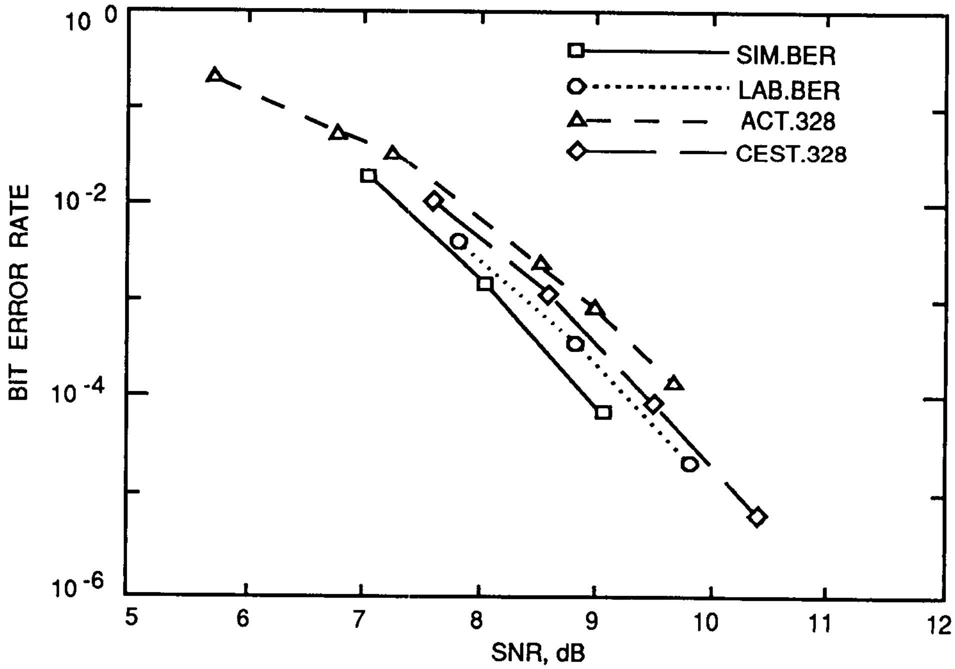


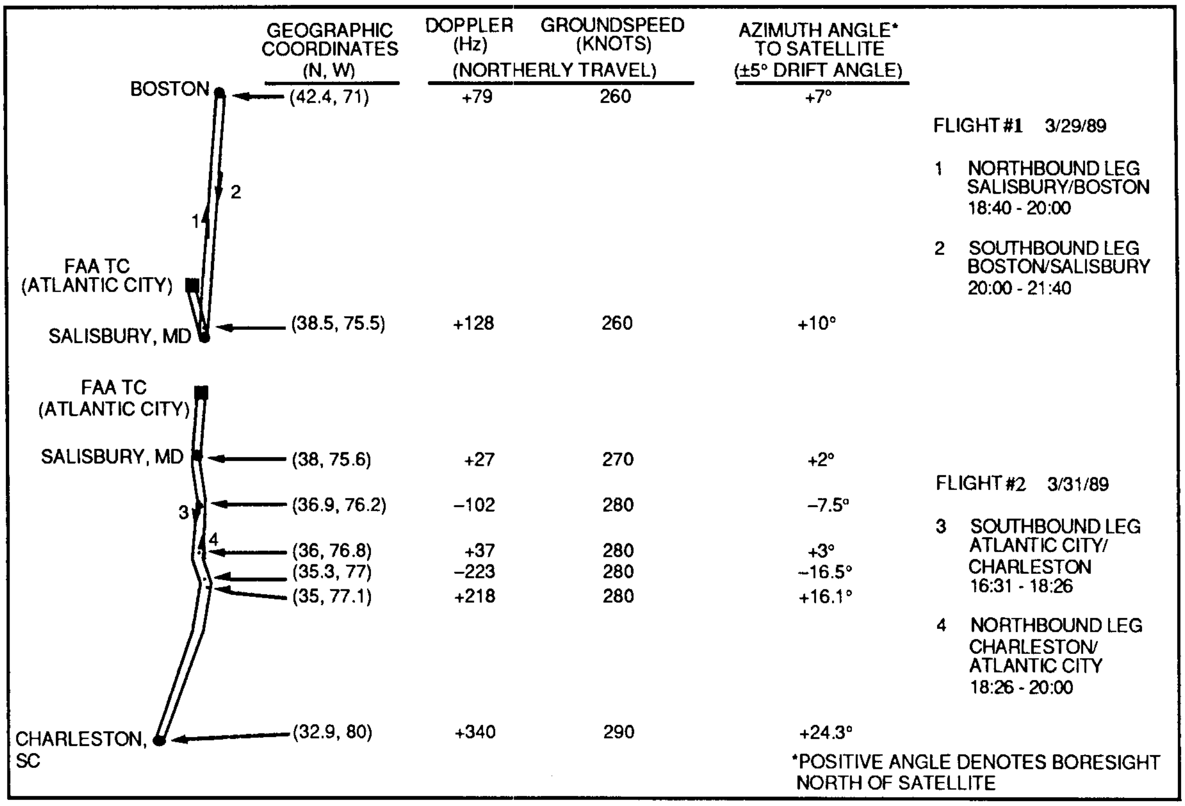
Figure 13. Average Ground Tests BER Results

As may be observed from the curves, the degradation in the forward link is no more than 0.5 dB, and no more than 0.2 dB in the return link. The results are very close to the results from the ground-to-ground tests. A point to note about these tests is that the March 28, 1989, ground calibrations were performed late at night, when the satellite was very lightly loaded (as compared with the FAAT/CEST tests, which were performed earlier in the day). The lightly loaded satellite translated into a higher absolute received pilot level (by as much as 4 dB), which resulted in smaller degradation due to the pilot tracking. This provides an indication that the primary source of degradation in the forward link for these tests was the operation of the satellite ALC. If one uses the FAAT tests as a bench mark for measuring the ALC-induced degradation, the expected degradation is approximately 0.2 dB. This leaves an additional 0.3 dB of degradation unaccounted for. The additional degradation comes from several possible sources, including the window-aperture effects, a lower ACT antenna G/T (reduced-gain and higher effective temperature), operation of the system from the aircraft power, and the measurement error (±0.2 dB).

As in the FAAT/CEST tests, except for an additional 0.1–0.2 dB of degradation, these results agree very well with the link budgets discussed in Section 3.5.

5.2.2 Flight Tests

Two aeronautical tests were performed on separate days. The first flight occurred on March 29, 1989, and followed the path detailed in Fig. 14. The second flight occurred on March 31, 1989, and followed a different path, also detailed in Fig. 14. Both flight paths differed from those originally planned and were suboptimum in terms of the azimuth angle to the satellite and the expected Doppler. The last-minute changes in flight plans were caused by inclement weather conditions in the area where the original flights were planned. During both flights, the aircraft was flown at an altitude between eight and nine thousand feet, with a ground speed that ranged between 180 and 290 knots.



GEOGRAPHIC COORDINATES (N, W)	DOPPLER (Hz) (NORTHERLY TRAVEL)	GROUNDSPEED (KNOTS) (NORTHERLY TRAVEL)	AZIMUTH ANGLE* TO SATELLITE (±5° DRIFT ANGLE)
(42.4, 71)	+79	260	+7°
(38.5, 75.5)	+128	260	+10°
(38, 75.6)	+27	270	+2°
(36.9, 76.2)	−102	280	−7.5°
(36, 76.8)	+37	280	+3°
(35.3, 77)	−223	280	−16.5°
(35, 77.1)	+218	280	+16.1°
(32.9, 80)	+340	290	+24.3°

FLIGHT #1 3/29/89

1 NORTHBOUND LEG SALISBURY/BOSTON 18:40 - 20:00

2 SOUTHBOUND LEG BOSTON/SALISBURY 20:00 - 21:40

FLIGHT #2 3/31/89

3 SOUTHBOUND LEG ATLANTIC CITY/ CHARLESTON 16:31 - 18:26

4 NORTHBOUND LEG CHARLESTON/ ATLANTIC CITY 18:26 - 20:00

*POSITIVE ANGLE DENOTES BORESIGHT NORTH OF SATELLITE

Figure 14. Flight Paths

On the first flight, data tests were performed in both directions. Along both flight paths, severe thunderstorms caused heavy turbulence. The low flight altitude required to maintain a low ground speed magnified the effects of the turbulence. The average performance in the forward link for both legs of the flight is shown in Fig. 15, by the curve labelled ACT.329. The return-link performance is also shown and given by the curve CEST.329. Also shown in this figure is the average forward (ACT.328) and return (CEST.328) link performance for the ground calibration. As may be observed from the curves, there is approximately an 0.8–1.0 dB degradation in link performance due to the aeronautical environment. This degradation comes from several factors, including the pitch and roll of the aircraft due to the heavy turbulence, the satellite being slightly off-boresight, and the change in the received Doppler (mainly at the CEST site, because the ACT receiver tracks the received pilot signal and removes a large portion of the received Doppler) as the plane traveled along the flight path. The Doppler shift on this flight was estimated to vary gradually between approximately 128 Hz at one end and 79 Hz at the other (see Fig. 14).

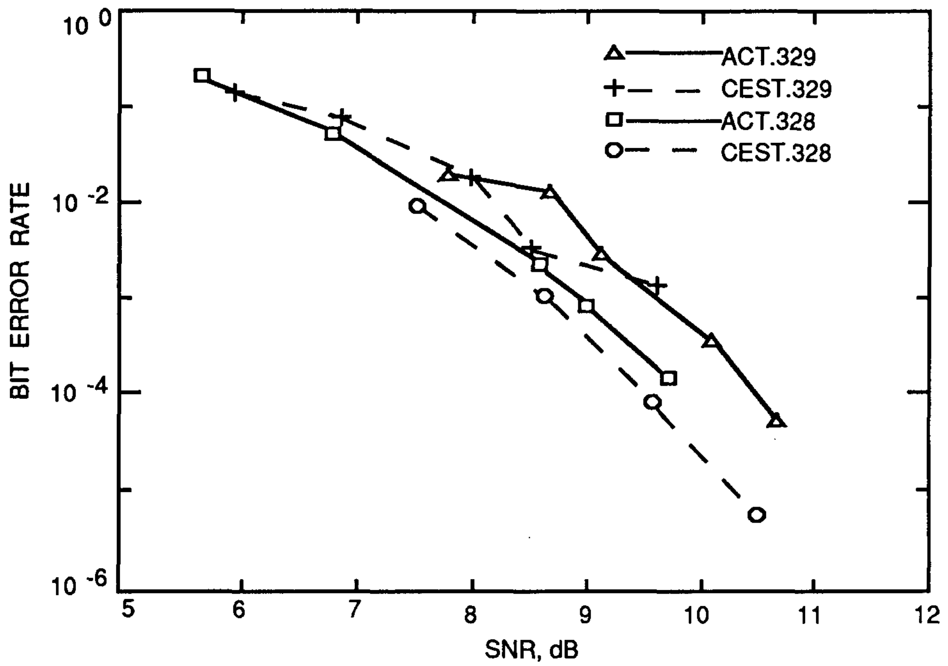


Figure 15. Flight #1 BER Performance

To illustrate the effects of the signal fluctuations due to the turbulence, a plot of the cumulative bit errors versus time, and a plot of the corresponding received signal plus noise power as a function of time, are presented in Fig. 16 for one of the points along the curve ACT.329. Note that the received signal plus noise power measurements for this data point varied by as much as 2.5 dB from point to point (taken at 4-second intervals).

Comparing the performance of these tests with the aeronautical link budgets presented in Table 3, one can observe some differences between the performance levels obtained in the links and the expected performance levels in the link budgets. In particular, on the forward link, the preexperiment link budget had predicted that the nominal 10^{-3} BER would be attained at an E_b/N_0 of 10.7 dB, while in the actual tests, this performance level was attained at an E_b/N_0 of approximately 9.6 dB, despite the heavy turbulence experienced during the entire flight. During the data tests, the received pilot C/N_0 varied between 50.0 and 52.0 dB·Hz, thus indicating that up to 0.25 dB of the observed degradation may have been attributable to the pilot tracking. The remainder of the degradation results primarily from fluctuations in satellite output power caused by the ALC (approximately 0.3 dB), the heavy turbulence encountered, and the transmission channel. On the return link, the link budgets predicted that the 10^{-3} BER would be attained at an E_b/N_0 of 9.7 dB, and in the actual tests, this performance level was attained at an E_b/N_0 of approximately 9.7 dB. However, it is estimated that the high level of turbulence encountered during the flight, and not the fading channel, played the major role in reducing the system performance over this link (see flight #2 results below), as indicated in the link budget.

The second flight was performed two days later on March 31, 1989. The flight path dictated by weather and traffic-control conditions is also shown in Fig. 14. The piecewise irregularity of the path is starkly reflected in the very irregular Doppler profile of the flight (also shown in Fig. 14).

The experiments conducted during the second flight consisted of data transmissions from the ACT to the CEST (return link) and speech demonstrations (one- and two-way). Rough compensation of Doppler was performed by an appropriate coarse shift in the pilot frequency transmitted from the CEST at various points along the flight path. Residual Doppler on the order of ±100 Hz was encountered (as observed on the spectrum analyzer at the ACT), although the received Doppler could change rapidly and widely (e.g., +218 Hz to -223 Hz, as shown in Fig. 14). Due to the irregular Doppler profile of the path and the relatively rapid changes in the Doppler along various portions of the path, the data results for only the portion from Charleston, South Carolina, to the first major course change in the flight path are presented. These results are shown in Fig. 17, where the curve CEST.RHS.331 shows the return link performance along this portion of the flight path. For comparison, the return-link performance of the ground-based ACT is presented by the curve CEST.328.

Note that, during the majority of the tests presented in this plot, the degradation from the ground-based performance is on the order of 0.1–0.2 dB. Only at the high SNR values does the degradation tend to increase. The reason for this is very simple. The lowest SNR test was performed near Charleston, followed by the next lowest SNR test as the plane moved in a northerly direction away from Charleston, and so on, up to the highest SNR test. The Doppler was precompensated for in the Charleston vicinity by zeroing it in this location versus attempting to minimize the Doppler over a leg of the flight (as had been performed on the first flight). Thus, at the lower SNR values, the received Doppler is correspondingly low, and as the plane arrives at the the first major course change (Fig. 14), the Doppler approaches -122 Hz (218 Hz–340 Hz), and as the first major change in the flight path is encountered, the received Doppler increases to -563 Hz. This observation indicates that the observed degradation from the ground performance should increase as the SNR increases, and indeed it does. As a point of reference, the expected degradation in the modem performance, as measured in the laboratory for the AWGN channel with 200 Hz of Doppler, is approximately 0.4 dB.

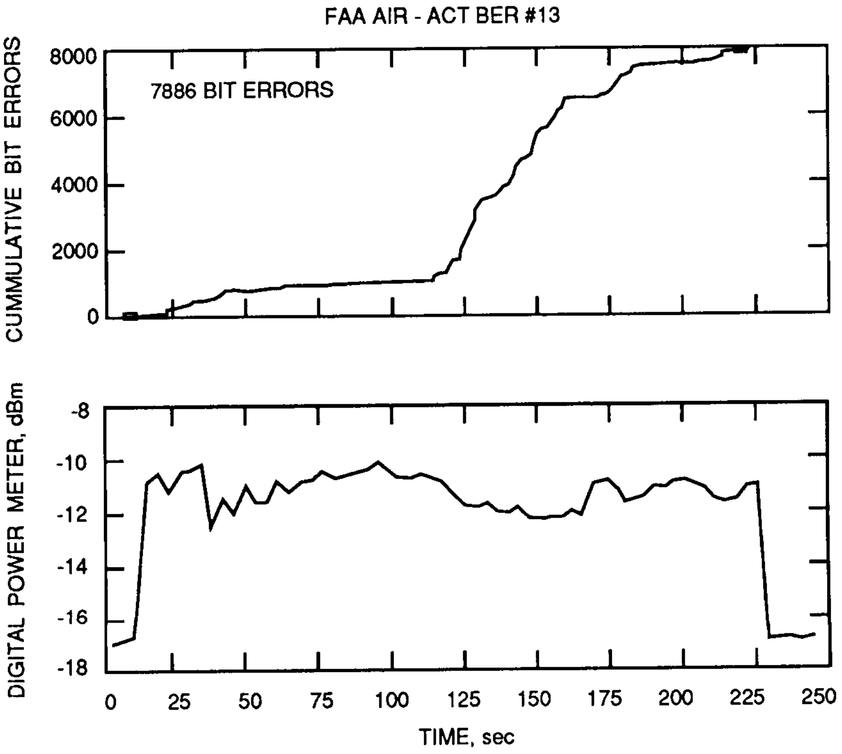


Figure 16. Example of Detailed Data Analysis

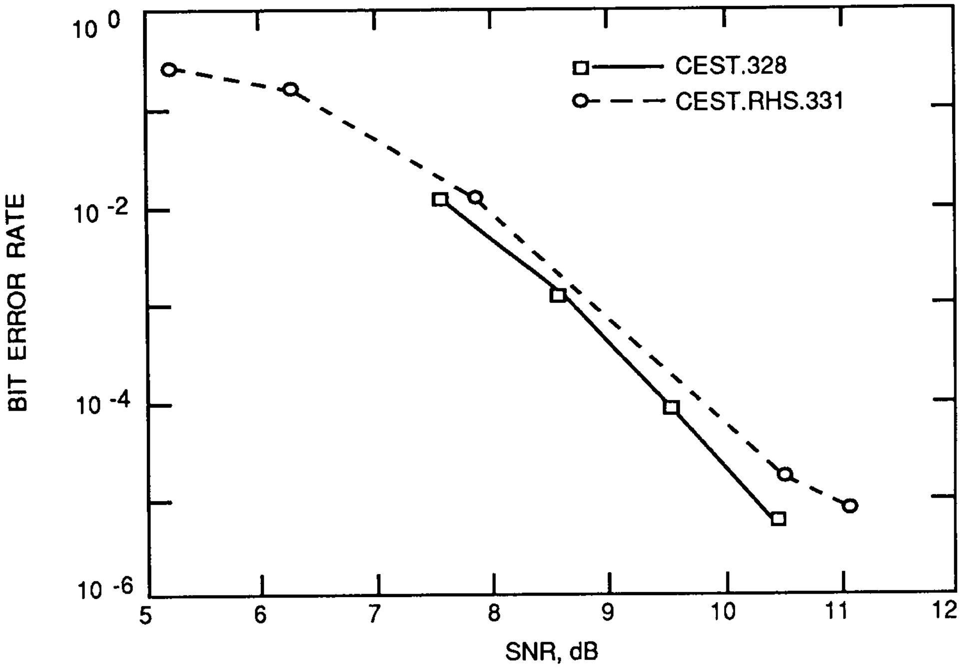


Figure 17. Return-Link BER Performance From Flight #2

To compare the performance attained in this flight with that predicted by the preexperiment link budget given in Table 3, note that the 10^{-3} BER performance is attained at an E_b/N_0 of approximately 8.9 dB, 0.3 dB worse than the ground-based ACT performance. The degradations present in the aeronautical link match those discussed above for the ground-based ACT, plus the received Doppler, the pitch and roll of the aircraft, and the transmission channel (assumed to be Rician with K=15–20). When one compares the performance attained in the test with the predicted performance given in the link budget, one finds that the link budget predicts 9.7 dB, while the actual flight data produces 8.9 dB. The primary reason for this discrepancy is that the 1.3 dB margin allocated for the Rician fading was not required; it was closer to 0.3 dB. This indicates that the aeronautical channel is much closer to the AWGN channel than initially assumed (i.e., a higher K value).

5.2.3 Voice Links and Speech Codec Demonstrations

During both flights, the full-duplex MSAT-X voice link was established often and was used as the main (in fact the only available) method for direct communication between the experimenters on the aircraft and in the CES. The links were run routinely at the same signal-to-noise ratio that resulted in a 10^{-3} BER. There was no perceptible difference in speech quality between in-flight and ground operations. Jet noise had no significant effect on the communications. Although the CEST frequencies were offset to precompensate for the average Doppler expected on different flight segments, changes in course on the second flight caused some initial offsets of up to 340 Hz. These frequency offsets were subsequently reduced to within ±100 Hz, as mentioned earlier, but the voice link was successfully used even under the higher offsets. Many of the JPL staff conversations were recorded, and they provided insight into the experiment and its difficult conditions.

A formal part of the experiment was the demonstration of the voice link for air-traffic control applications. During the second flight, an FAA engineer on board the aircraft read a variety of air-traffic control-type messages into the MSAT-X codec. The voice received at the CEST was assessed by FAA personnel and recorded. Live conversations were also recorded. The intelligibility and quality of the speech, and the robustness of the link, were deemed acceptable by the FAA staff. Remarkably, the audio output of the codec at the CEST, which was available on a headphone speaker, was acoustically (not electrically) patched to a telephone headset and through a long-distance line to an FAA listener attending a meeting in Montreal, Canada. The listener found the voice to be intelligible and its quality to be acceptable.

6.0 CONCLUSIONS

The joint NASA/FAA/COMSAT/INMARSAT experiment was a success, both in meeting its objectives and in the actual results obtained. The satellite environment had perturbations, but its overall characteristics were not far from what had been expected. While the link between the aircraft and the ground was more dynamic than had been expected, the operation of the MSAT-X mobile terminal in this environment (channel) was very close to theory and simulation/laboratory experiments. Not surprisingly, the stationary ground-to-ground communication links were found to be more benign than the ground-to-air or air-to-ground links.

For the ground segment of the tests, the performance of the forward link was approximately 0.5 dB worse than the modem performance in the laboratory. The performance of the return link improved slightly and was roughly equivalent to the performance of the modem obtained in the laboratory. For the aeronautical tests, the performance of the forward link was approximately 0.8 dB worse than the ACT ground link (approximately 1.2 dB worse then the laboratory results). For the return link, during heavy turbulence (Flight #1), the link was approximately 1.0 dB worse than the ACT ground-based link (approximately 1.3 dB from laboratory results). When the aircraft was relatively stable (during Flight #2), the performance was approximately 0.3 dB from that obtained in the ACT-based ground link (approximately 0.5 dB from laboratory results).

In the speech experiments, the performance of the speech codecs was comparable to the performance obtained in the laboratory primarily because of the link performance of the communications terminal and the inherent quietness of the digital voice link. Based on all results to date, the speech experiments proved to be successful.

The MSAT-X equipment performed very well, even in the highly adverse conditions of the flight tests. Furthermore, the experiment demonstrated that the MSAT-X communication terminal is very robust in the aeronautical environment, and that its performance in a real satellite link is very close to its performance in the laboratory.

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16. Abstract

This report details the various activities and findings of a NASA/FAA/COMSAT/INMARSAT collaborative aeronautical mobile satellite experiment. The primary objective of the experiment was to demonstrate and evaluate an advanced digital mobile satellite terminal developed at the Jet Propulsion Laboratory under the NASA Mobile Satellite Program.

The experiment was a significant milestone for NASA/JPL, since it was the first test of the mobile terminal in a true mobile satellite environment. The results were also of interest to the general mobile satellite community because of the advanced nature of the technologies employed in the terminal.

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