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Description and Performance of a Digital Mobile Satellite Terminal

N. Lay, T. Jedrey, J. Parkyn, D. Divsalar
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109 USA
FAX: (818) 354-6825

ABSTRACT

A major goal of the Mobile Satellite Experiment (MSAT-X) program at JPL is the development of an advanced digital terminal for use in land-mobile satellite communications. The terminal has been developed to minimize the risk of applying advanced technologies to future commercial mobile satellite systems (MSS). Testing with existing L-band satellites was performed in fixed, land-mobile and aeronautical-mobile environments. JPL's development and tests of its mobile terminal have demonstrated the viability of narrowband digital voice communications in a land-mobile environment through geostationary satellites. This paper provides a consolidated description of the terminal architecture and the performance of its individual elements.

INTRODUCTION

A key objective of the MSAT-X program has been the development and demonstration of critical technologies required to enable a commercial land-mobile satellite service (LMSS). These technologies include medium gain tracking antennas, power and bandwidth efficient modulation techniques, and high quality low bit rate voice codecs. The demonstration of these technologies required the development of an integrated terminal to evaluate their individual and combined performance. Several different platforms were employed to field the terminal ranging from a demonstration automobile utilizing a conformal phased array antenna to fully instrumented terminals located within an experimental van and within an experimental aircraft. Figure 1 indicates one configuration of the terminal elements within the trunk of the demonstration automobile.

TERMINAL ARCHITECTURE

The mobile terminal is composed of five different subsystems: the speech codec, the terminal processor, the modem, the transceiver, and the antenna subsystem. A functional block diagram of the terminal is shown in Figure 2. The speech codec provides good quality speech at 4800 bits per second [1,2]. The terminal processor provides a terminal user interface and implements all networking and control functions [3]. The modem implements a power and bandwidth efficient modulation scheme designed for the demanding LMSS channel [4,5]. The transceiver converts the modem output to the L-band transmit frequency, and converts the received L-band signal to the modem input IF, as well as performs pilot tracking [6]. The antenna subsystem tracks the satellite and transmits and receives the transceiver output [7].

Speech Codec

The codecs developed for MSAT-X by UC Santa Barbara (UCSB) and the Georgia Institute of Technology (GIT) were required to be robust in a burst error channel at an average bit error rate (BER) of 10^{-3}. Integral to any speech coding scheme that is to operate in this environment is the ability to detect error events and take actions to mitigate the effects of these errors as well as the ability to reacquire fairly rapidly after a long error event such as shadowing. Critical in the implementation of this scheme is that it does not require a large overhead in terms of the 4800 bps data rate.

The actual voice algorithms employed in the UCSB/GIT codecs have been well described [1,2] and this general class of vector quantizing codecs has seen a great deal of recent algorithmic development. In short, the compression algorithms operate by initially removing redundancy in the input speech corresponding to vocal tract and pitch information through the use of short and long term predictors. The residual error sequences are vector quantized through the use of codebooks in the case of Vector Adaptive Predictive Coding and Pulse Vector Excitation Coding (UCSB) or are regenerated as delayed versions of the excitation sequences used at the receiver for Self Excited Vocoders (GIT). Typically error sequences are chosen by minimizing a perceptually weighted mean squared error for the entire sequence.

Terminal Processor

All elements of the terminal are tied together under the control of a central device, the terminal processor (TP). The TP implements a variety of functions in response to user input via a keyboard. Transmissions in the form of continuous or packetized data tests, voice conversations or text messages are initiated by the TP through a channel connect protocol consisting of an initial connect packet query and an acknowledgement from the far end terminal. Transmissions are similarly terminated through the use of this protocol. In addition to protocol implementation, the TP selects data transmit and pilot and data receive frequencies by directly controlling the transceiver synthesizers. Pilot acquisition by the antenna subsystem is initially performed manually under TP control. After initial acquisition, pilot reacquisition during loss of signal (from long deep fades) may be performed either manually or automatically with the TP reading pilot signal strength from the transceiver.

Modem

The key design goals for the MSAT-X modem required the transmission of 4.8 kbps data over a Rician K=10 channel at an average E_b/N_0 of 11 dB while achieving a 10^{-3} BER. In addition, the modem was required to be robust in the presence of shadowing and time varying Doppler [4].

The modem accepts as input a serial 4.8 kbps data stream. This data is encoded with a 16 state rate 2/3 trellis code which achieves a coding gain of 1 dB at a BER of 10^{-3} relative to uncoded DQPSK in AWGN. This gain increases to 2 dB when considering a Rician LMSS channel. Three bit symbols from the trellis encoder are mapped to one of eight phases and then block interleaved (16×8) prior to differential encoding. Baseband inphase and quadrature signals are pulse shaped prior to analog output to the transmitter. The modulator employs a square root raised cosine pulse shape with 100% excess bandwidth to achieve spectral efficiency.

At the demodulator, the signal is quadrature demodulated by sampling at four times the IF and decimating by two the inphase and quadrature signals. The signals are time aligned by averaging one stream and lowpass filtered to the signal bandwidth plus the maximum expected Doppler (or frequency offset) of 200 Hz. Both signals are interpolated for greater timing resolution and then subsampled. The symbol timing recovery mechanism incorporates a random walk filter to smooth jitter in the recovery process and to provide an extremely robust estimate of symbol timing during loss of signal due to shadowing. After subsampling the two intersymbol interference free points per symbol period of the pulse shape, an instantaneous Doppler estimate is formed by differential detection. These estimates are smoothed by a lowpass filter whose bandwidth is on the order of the maximum expected Doppler rate. This smoothed estimate is utilized in the matched filter implementation and residual Doppler correction after differential detection. Sixteen bit soft decision outputs are passed to the de-interleaver and Viterbi decoder. A 4.8 kbps serial data stream is then output to the TP.

Transceiver

The MSAT-X transceiver provides a flexible RF package to interface the antenna and modem in a mobile environment. The transceiver provides pointing information for the antenna controller, frequency translation for the modem and test points for propagation data gathering. Input data lines are provided for frequency selection by the TP and output lines provide a sampled version of noncoherent received pilot power.

The front end provides transmitter to receiver isolation while sharing a common antenna, RF filtering and low noise receive amplification. The transmitter and receiver are isolated through the use of an RF diplexer. This unit accommodates the broad frequency range required for the various field experiments as well as provides low insertion loss and high isolation. The front end exhibits an overall measured noise figure of 1.8 dB. The transmitter accepts inphase and quadrature baseband output from the modem and upconverts these signals to L-band in a controlled manner to preserve spectral efficiency.

In the receiver, the RF input from the front end is mixed down to an IF of 28 MHz and bandlimited to 4 MHz. Pilot and data channels can be selected independently anywhere within this band to a resolution of 5 kHz. Pilot and data signals are downconverted through separate IF chains where final bandlimiting is performed on each signal. The data signal is output to the modem at an IF of 28.8 kHz. A narrower bandpass filter rejects noise from the pilot signal prior to its downconversion to a tracking loop. All synthesizers within the receiver can then be locked to the received pilot. This provides some measure of Doppler tracking for the data signal and allows the derivation of amplitude and phase information for use by the antenna pointing circuitry.

Antennas

Antenna development for MSAT-X has concentrated on medium gain (8-12 dB) steerable antennas for power efficiency and to combat multipath fading and intersatellite interference. The antenna development has followed a dual design approach consisting of two phased array development efforts under contract to JPL and an in house mechanically steered tilted array design [7]. Average antenna gains for these units range from 10 to 13 dB. Elevation beamwidths range from 28° to 55°, while azimuth beamwidths range from 38° to 55°. Three of these antennas are shown in Figure 3 -- the Teledyne Ryan Electronics (TRE) phased array and two versions of the JPL mechanically steered tilted array antenna, an initial prototype and a mechanically re-engineered lower profile version. Both of the JPL antennas as well as the Teledyne array were employed in land-mobile satellite field tests along the eastern Australian coast during July, 1989.

Both antennas use inertial rate sensors to maintain point during periods of signal loss due to shadowing or fading when the closed loop tracking methods are inoperative. Closed loop pointing information is derived from a coherently demodulated pilot signal provided by the transceiver. The closed loop tracking technique utilized in the phased array is based on a sequential lobing technique, while the mechanical antenna employs a single line pseudo-monopulse technique.

In addition to these antennas, omnidirectional drooping dipoles, and more recently a planar Yagi array [8] have been developed for experimental purposes.

TERMINAL PERFORMANCE

Subsystem specifications, and subsystem and overall mobile terminal performance gathered from laboratory and field tests are presented in this section.

Speech Codec

The performance of the speech codecs developed for MSAT-X can be characterized in two ways: (1) the actual quality of the compression algorithms in accurately reproducing the input audio signal, and (2) the performance of the codec in an error environment typical of the land-mobile satellite channel. The first type of performance evaluation has been reported in a variety of sources [2,9]. These performance evaluations have been performed primarily for the UCSB VAPC algorithm. To summarize these results, the Diagnostic Rhyme Test and Diagnostic Acceptability Measure scores for this codec in the quiet background environment are 91.9 and 65.5, respectively.

The second type of performance characterization has been performed by evaluating the use of the codec (the UCSB codec) in the actual land-mobile satellite environment. In this channel, burst errors are expected as a natural part of the channel characteristics and techniques need to be adopted to partially compensate for these errors. These include frame synchronization and error detection/correction and mitigation strategies [1,2]. The net effect of the above strategies was an effective muting of the received digital speech in a high error rate environment. This threshold was achieved very quickly due predominantly to the steepness of the modem performance curve. As a result, subjectively unpleasant audio artifacts were kept to a minimum. The approximate threshold that corresponded to this muting response occurred at an approximate BER of 5×10^{-3} and above. Below this threshold, the speech quality was acceptable, and error induced audio artifacts were negligible.

Modem

Modem performance has been previously reported for both AWGN and Rician K=5,10 dB channels [4,10]. In this section, new results are presented for the BER performance in the presence of static and time varying frequency offsets. In addition, BER degradation results due to phase noise in the received signal are presented.

In Figure 4, modem performance curves are shown for a variety of frequency offsets ranging from 0 Hz up to 400 Hz. The 0 Hz curve corresponds to the laboratory measured AWGN performance. Note that in the land-mobile arena, the maximum offset due to Doppler can be upper bounded by 200 Hz, and that performance degradation above this offset can be primarily attributed to loss of signal energy outside the passband of the initial demodulator lowpass filters. The tracking performance is also shown for a linearly varying frequency offset ranging from 0 Hz to 200 Hz at a rate of 100 Hz/s -- a rate substantially higher than any expected land-mobile Doppler rates. There is less than 0.3 dB of degradation for static and tracking performance up to a 200 Hz offset. At offsets of 300 and 400 Hz the degradation increases to 0.75 and 1.5 dB respectively. This resultant loss could be decreased by increasing the front end lowpass filtering bandwidth to completely allow the received signal to pass undistorted.

Another area impacting modem performance is degradation induced by oscillator phase noise. The sources of this phase noise are distributed throughout the communication link, however, the satellite transponder and the terminal receiver (due to pilot tracking at low levels) have been identified as the two primary sources of phase noise. A software simulation of a transponder phase noise specification was developed, and the effects of the phase noise on the modem simulated [11]. The phase noise model was based on data for the one sided power spectral density of the INMARSAT II satellite, provided by Hughes Aircraft. Simulation results indicate that a model with roughly 10 dB more phase noise power than Inmarsat II was shown to introduce less than 0.3 dB of degradation in both AWGN and K=10 fading, indicating robustness in the presence of satellite transponder phase noise. Tests involving the terminal receiver are discussed in the following section.

Transceiver

The mobile terminal transceiver fulfills two important roles. It provides a phase locked pilot tracking reference for antenna pointing, and as a local frequency reference. Typical receive signal levels range from -130 to -120 dBm, while transmit levels can range up to +46 dBm. The performance specifications which enable these levels of operation are summarized in Table 1.

Table 1 Transceiver Specifications

Parameter	*Value*
Noise Figure	1.8 dB
Receiver Sensitivity	-130 dBm (42 dB-Hz)
Tx/Rx Isolation	>100 dB
Receive Frequency Range	1539-1556 MHz
Transmit Frequency Range	1639-1656 MHz
Step Size	5 kHz
Data Passband Delay Variation	2 μs
Data Passband Ripple	0.5 dB
Data IF Architecture	Triple Conversion
Pilot Loop Bandwidth	300 Hz
Pilot IF Architecture	Double Conversion
Long Term Stability	10^{-6}
Short Term Stability	3×10^{-8}

For transmit signal amplification a variety of units were used. In the JPL Colorado tower experiments, the transmitter's integral driver amplifier's low power output was sufficient. In the aeronautical experiments, a TWT amplifier with 200 Watt saturated capability was used in it's linear region to provide output levels ranging from 5 to 10 Watts. In the AUSSAT land-mobile experiment a solid state linear amplifier that could produce 40 Watts at the 1 dB gain compression point was loaned to JPL by AUSSAT. An equivalent solid state amplifier is currently in development at JPL for use in land-mobile experiments in North America.

As indicated in the previous section, another potential source of phase noise is the remodulation of phase noise present in the pilot tracking loop on to pilot locked local oscillators in the mobile receiver. Although the receiver local oscillators are not required to be phase locked due to the Doppler/frequency correction scheme in the modem, this investigation does yield useful insights into the required quality of free running oscillators in any future receiver design, and into the tradeoff between opening up the modem filter bandwidths versus employing a pilot tracking scheme. Performance tests have included parametrizing BER vs. pilot C/N_0, indicating degradation ranging from 0.25-1.1 dB corresponding to C/N_0 values from 51.5-42.2 dB-Hz [12]. Current investigations include parametrizing phase noise power spectral densities versus C/N_0 and generating a corresponding model for use in simulations.

Antennas

Table 2 details the tracking and acquisition performance and G/T values for each of the MSAT-X antennas [14]. The tabulated values correspond to the right hand circularly polarized version of the Ball antenna and the left hand polarized versions of the Teledyne and low profile JPL mechanical antenna. The JPL antenna includes the highest level of RF circuitry integration of all the developed mechanical antennas to reduce insertion loss and the resultant antenna temperature. Both the left hand Teledyne and JPL antennas were employed in field testing in Australia.

Table 2 Antenna Performance

Parameter	*Mechanical*	*TRE*	*Ball*
Peak Gain	11.3 dB	10.8 dB	11.5 dB
G/T	-14.0 dB	-15.4 dB	NA
Elevation Beamwidth	55^o	28^o	32^o
Azimuth Beamwidth	38^o	55^o	55^o
Acquisition Time	<15 sec.	<3 sec.	<3 sec.
Tracking Error	$\pm 2^o$	$\pm 5^o$	$\pm 7^o$

Overall Terminal Performance

A set of performance curves detailing the performance of the terminal in an aeronautical environment [14] is presented in Figure 5. The experimental results are compared to laboratory AWGN data. The curve GROUND.RHS.BER shows the terminal return link performance for the aircraft mounted terminal while stationary on the ground. Less than 0.5 dB of degradation is observed. The remaining two curves represent the flight performance on different dates. The difference in performance is attributed to light or no turbulence for the curve AIR.RHS.329, and very heavy turbulence for the curve AIR.RHS.331. In all cases, the experiment data was observed to be within 1.0 dB of laboratory performance.

A representative curve of the overall terminal BER performance data for a stationary data test taken during the JPL/AUSSAT land-mobile experiment [15], is presented in Figure 6. The mobile terminal was located near Taree, north of Sydney on the eastern Australian coast, with a clear line of sight link to the Japanese ETS-V satellite, and the fixed terminal was located in downtown Sydney. The antenna utilized for this test was the low profile JPL mechanical antenna. Also plotted is the laboratory performance of the modem for the AWGN channel. Field results are within 0.5-0.7 dB of laboratory performance. The return link (mobile-to-fixed) performance for the mobile travelling around a twenty minute test loop is presented in Figure 6. The test results are from both the JPL and TRE antennas. These tests were performed just south of Brisbane, Australia. During the tests, the van velocity ranged from 0 mph up to 40 mph. The terrain can be characterized as predominantly clear with sporadic shadowing. For all data points, the performance relative to laboratory AWGN results is within 1.2 dB.

CONCLUSIONS

The MSAT-X Mobile Terminal represents the culmination of many technology development efforts necessary for a narrowband digital LMSS. The terminal integrates the approaches in each of the technology areas into a communications system suitable for demonstrating and further evaluating system operation in the digital mobile satellite arena. To date, the terminal has demonstrated robustness in the mobile environment and performance approximately within 1 dB of theory/simulation.

ACKNOWLEDGEMENT

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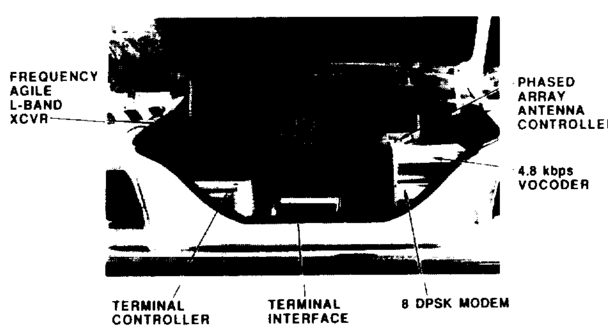

Figure 1 Terminal Configuration in Automobile

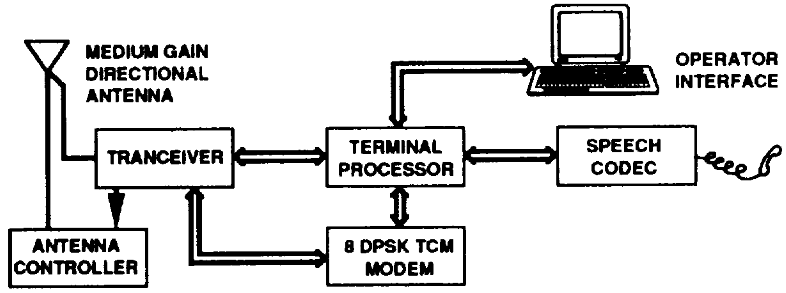

Figure 2 Terminal Block Diagram

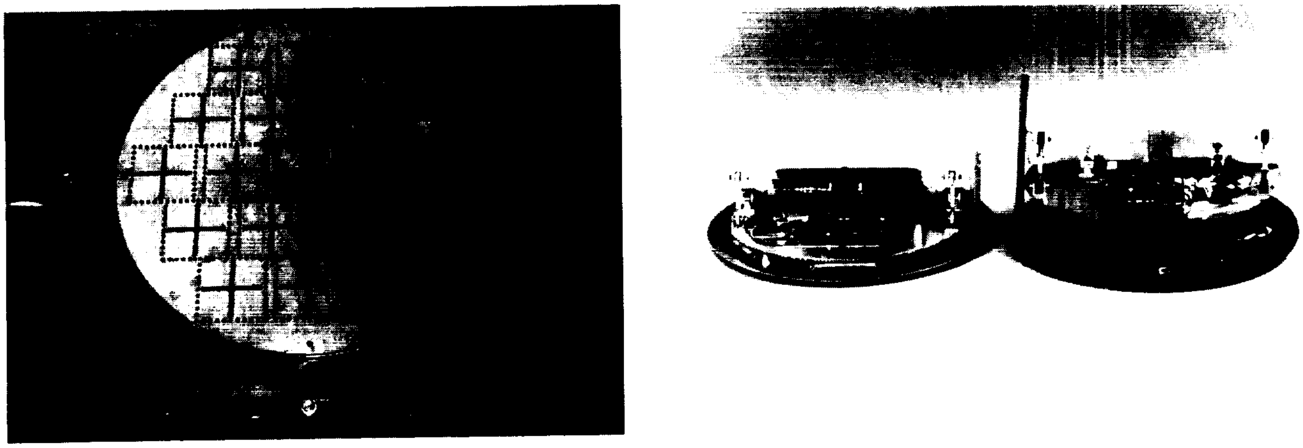

Figure 3 MSAT-X Antennas

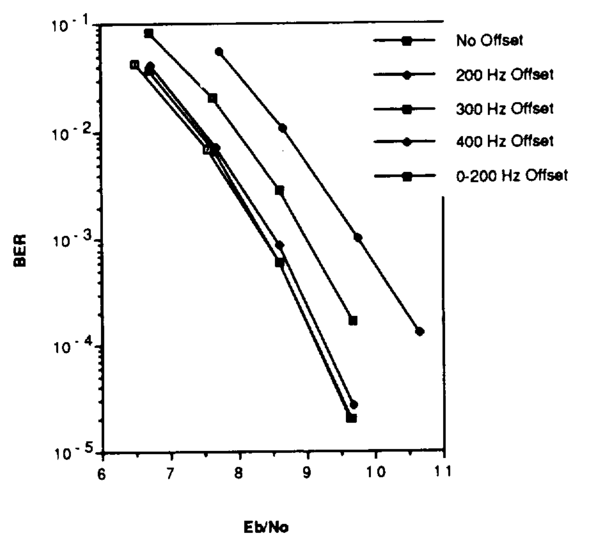

Figure 4 Performance with Frequency Offsets

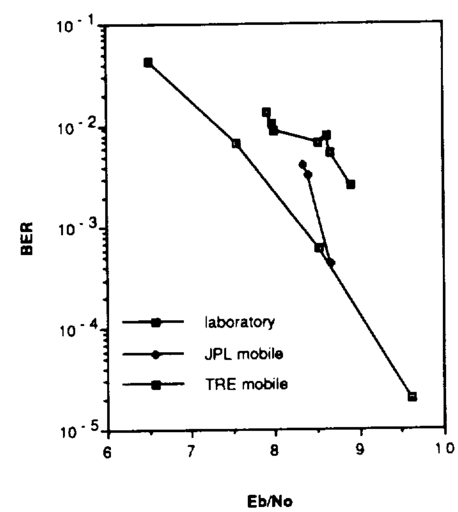

Figure 6 Terminal Mobile Performance

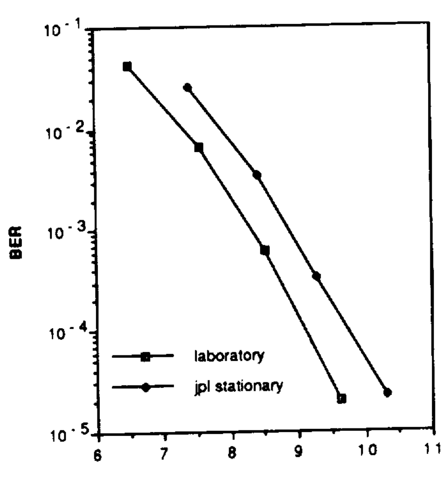

Figure 5 Terminal Stationary Performance

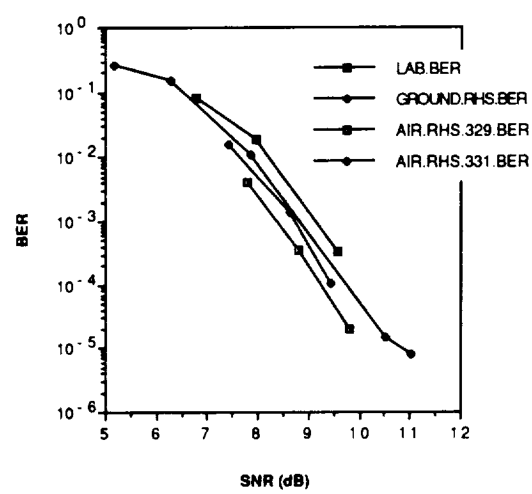

Figure 7 Aeronautical Terminal Performance