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Standard-M Mobile Satellite Terminal Employing Electronic Beam Squint Tracking

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Abstract

In recent years, extensive experience has been built up at the University of Bristol in the use of the Electronic Beam Squint (EBS) tracking technique, applied to large earth station facilities. The current interest in land mobile satellite terminals, using small tracking antennas, has prompted the investigation of the applicability of the EBS technique to this environment. In this paper the development of an L-band mechanically steered vehicle antenna is presented. A description of the antenna is followed by a detailed investigation of the tracking environment and its implications on the error detection capability of the system. Finally, the overall hardware configuration is described along with plans for future work.

Introduction

Currently at the University of Bristol work is progressing on the development of a mechanically steered array for use in L-band MSAT applications. This antenna configuration offers a number of advantages when compared to either an omni-directional antenna or electronically steerable phased array systems. Compared to an omni-directional antenna it offers improved gain characteristics reducing the requirement on satellite transponder power. A high degree of directivity provides better discrimination against multipath effects, and further reduces off-axis radiation with a consequent easing of frequency co-ordination problems. On the receive side, similar considerations offer an improvement of antenna G/T and hence a possible widening of link budget margins. When compared against the electronically steerable phased array, although not offering as elegant a solution to the vehicle mounted antenna, it is more realisable in terms of current technology and hence offers lower production costs.

The antenna gain requirement was a minimum of 10dBic in the direction of the satellite throughout the coverage region, which extends 0° - 360° in azimuth and 20° - 60° in elevation.

Error Detection Systems

Recently the EBS tracking scheme [1,2] has been developed for application to reflector antennas. With this system, a number of mode generators coupled to the primary-feed of the antenna are controlled electronically to sequentially produce, from higher order modes generated in the feed at the beacon frequency, a secondary beam deviation (squint) in a series of predetermined directions. Step scanning of the secondary beam axis is thus achieved without movement of the antenna or the primary beam. Hence, a tracking error signal can be derived by measurement of the beacon signal strength in much the same way as with a step-track system. The essential difference, however, is that the electronic deflection can be achieved at high speed and therefore EBS represents a form of pseudo-simultaneous amplitude sensing scheme. This yields the potential of operational tracking accuracies approaching that of a monopulse based system, at an implementation cost similar to step-track. Further, EBS does not suffer from the problems of dynamic response associated with a step-track facility [3].

If it is assumed that the main beam shape of the antenna approximates to a parabola, then the signal fall off in dB is given by:

$$G = 12\left(\frac{\theta}{\theta_{3dB}}\right)^2 \qquad (1)$$

where θ is the angle away from the antenna boresight and θ_{3dB} is the half power beamwidth of the antenna. By squinting the beam to two positions equally placed about the antenna boresight, a gain loss of G_1 and G_2 will be observed given by:

$$G_1 = 12\left(\frac{\theta-\alpha}{\theta_{3dB}}\right)^2 \tag{2}$$

$$G_2 = 12\left(\frac{\theta+\alpha}{\theta_{3dB}}\right)^2 \tag{3}$$

where α is the squint angle. Re-ordering and subtracting yields the gain difference equation:

$$\Delta G = \frac{48\theta\alpha}{\theta_{3dB}^2} \tag{4}$$

Simple rearrangement of this relationship therefore gives the present satellite position, θ, in terms of the observed signal variation between squint positions, ΔG, as:

$$\theta = \frac{\Delta G\theta_{3dB}^2}{48\alpha} \tag{5}$$

Employing this relationship in a signal processing controller it can be seen that a simple, yet effective, closed loop control system is formed.

Microstrip Patch Array

A single-layer microstrip array antenna has been developed to provide the beam squint operation described above, in the land mobile environment. The antenna feed network, shown in Figure 1, consists of four circularly polarised array elements (centre-to-centre separation of 0.8λ) connected to a four-way power splitter/combiner with two phase shifters inserted in the outer feed lines. Under normal operation, the phase shifters are not activated; therefore, with no additional phase shifting in the feed network, the array has a broadside main beam. By applying a 50° phase delay in either one or other of the outer feed lines, the position of the azimuth beam can be moved off broadside by a few degrees. This achieves the beam squint action necessary to derive the required azimuth tracking error signals.

As with the azimuth radiation pattern, the elevation pattern has a maximum at the array broadside with the arrangement shown in Figure 1. Thus, it is necessary to mount the array at 40° to the horizontal to achieve the desired elevation coverage (20° - 60°). In order to mount the antenna flat on the vehicle, the use of parasitic elements is being explored as a means of pulling the beam away from elevation broadside.

The unsquinted azimuth radiation pattern for the prototype microstrip array antenna is shown in Figure 2. The gain of the antenna was found to be 11dBic, with a −3dB beamwidth of 16° and sidelobe levels at −10dB relative to peak. The associated elevation pattern is given in Figure 3. A −1dB beamwidth in excess of 40° is observed, and this indicates that a gain of 10dBic could be maintained in the direction of the satellite throughout a coverage region of 360° in azimuth and 40° in elevation. Activation of the individual phase shifters produced a squint magnitude of approximately 1/5th θ_{3dB}, with a gain loss due to the squinting action of less than 0.1dB. Under these circumstances maximum sidelobe levels increased by no more than 2dB.

Computer Simulation

In order to evaluate the likely tracking performance of the described EBS microstrip array antenna system, a computer simulation has been developed; one aspect of which allows the realistic modelling of the land mobile environment. A full description of the simulation is outside the scope of this paper, however, modelling of the beam squint mechanism, channel signal-to-noise ratio (SNR), atmospheric scintillation and the dynamics of a land mobile have all been incorporated.

The tracking performance has been investigated for various link specifications appropriate to the land mobile satellite service. Primarily, this has addressed the problem of acquisition for given terminal dynamics and signal conditions, as well as long term tracking performance, for various SNR's.

The selection of the appropriate sampling frequency is critical for the satisfactory operation of an EBS based antenna tracking system. Derivation of this parameter begins by establishing the relationship between the effective dynamic angular movement of the target and the induced signal level fluctuation. This is possible by considering the differential of the antenna gain loss equation (Equation 1) which yields:

$$dG = 24\left(\frac{\theta}{\theta_{3dB}^2}\right)d\theta \tag{6}$$

This equation can be re-expressed, using the relationship $dy/dx = (dy/dz)(dz/dx)$, as:

$$\frac{dG}{dt} = 24\left(\frac{\theta}{\theta_{3dB}^2}\right)\frac{d\theta}{dt} \tag{7}$$

where dG/dt is the observed amplitude fluctuation per second (dB/sec), θ is the angle of the satellite away from the boresight axis of the antenna and $d\theta/dt$ is the rate of change of the dynamic angular motion between the target and antenna positions.

An initial indication of the required sampling frequency can be obtained by considering the terminal working to a satellite at a relatively high elevation angle, say 50°, over a line-of-sight path (non-urban environment). In these circumstances, even though the antenna has a wide elevation beamwidth, multipath effects can be shown to be negligible and unwanted signal fluctuations will derive either from atmospheric scintillation effects or vehicle motion, if roadside vegetation shadowing is also ignored. By considering the case of an angular target velocity of 20°/sec (representative of the car turning on a radius of 40m at a speed of 48km/hr), use of Equation 7 shows a maximum amplitude fluctuation of 21.8dB/sec will be observed, with the satellite θ_{3dB} degrees away from the antenna boresight. This amplitude fluctuation is considerably greater than that which will result from worst case atmospheric effects. Substitution of this value into the single axis form of the sampling frequency equation for EBS systems, derived by Hawkins and Edwards [4]:

$$f_s(max) = \frac{\frac{dG}{dt}10^{(0.05SNR+1)}}{8.69} \tag{8}$$

yields a maximum required sampling frequency $f_s(max)$ of 250Hz with a SNR = 20dB. This SNR is achievable within the necessary bandwidth of the tracking receiver (1.5 x sampling frequency) if a carrier-to-noise density of 45dBHz is assumed. Such a carrier-to-noise density is typical of that which might be seen on a Standard-M LMS link, as laid down in the INMARSAT 'Strawman' specification [5].

At low elevation angles, the full severity of the LMS tracking environment becomes apparent. Work by Beach *et al.* [6] investigated both line-of-sight (LOS) and multipath propagation for a Standard-M antenna system receiving transmissions from the MARECS B2 satellite. Experimental trials were carried out in southern England which resulted in a working elevation angle of approximately 25°. Results shown in Figure 4 relate to the LOS operation. The signal seen in either channel of the receiving equipment (data for two channels is presented as the work was concerned primarily with diversity combining techniques) consists of a dominant LOS component, a small multipath contribution obtained from signal reflections off grassland surrounding the road being used by the vehicle, as well as some shadowing effects from roadside trees.

Examination of the signal characteristics seen in this figure reveal maximum amplitude fluctuations in the order of 4dB for a spatial movement of the vehicle of 0.2λ. Considering a vehicle travelling with a velocity of 48km/hr this yields the maximum rate of observed signal variation of approximately 1400dB/sec. Such a variation considerably increases the required sampling frequency of the EBS system and because of the wider receiver bandwidth needed to preserve the tracking modulation, means much lower operational SNR's have to be considered. If an SNR of 10dB is initially assumed, use of Equation 8 indicates that a sampling frequency of 5000Hz should be implemented. With a carrier-to-noise density of 45dBHz this means that the actual SNR 'seen' at the input to the tracking controller will be 8dB.

Since it has been already shown that the vehicle motion dynamics impose only a required sampling frequency of 250Hz, and hence an antenna positioning update rate of approximately 125Hz, use of a 'sample mean estimator' as part of the tracking controller algorithm can be shown to reduce the variance of the tracking error estimates. Simulation results obtained using the 5000Hz sampling frequency, SNR = 8dB and the averaging factor in the sample mean estimator = 20, indicate an achievable beam radial error (BRE) in the order of 1.4° with a maximum antenna slew rate of 200°/sec.

Although the LOS propagation characteristics have not been implemented in the simulation, since the maximum LOS amplitude fluctuation that will be seen during the measurement period corresponds to 0.28dB, which using Equation 5 gives a positioning uncertainty of 0.9°, it would not be unreasonable to expect that the overall BRE should not degrade much beyond 1.8°, ie. 1/9th θ_{3dB}. It is apparent that this tracking performance is comparable with that currently required for the land mobile environment [7].

Multipath dominated propagation results (representative of conditions that would be seen in an urban environment) are also reported by Beach *et al.* [6]. It is clear that observed signal fluctuations are much more severe than those for the LOS case and as such would make the use of the EBS tracking technique in this environment impracticable.

Work is currently progressing to further modify the simulation package to include a realistic propagation model to verify the tracking performance indicated above. This model will describe the direct LOS path, with little or no shadowing and only a small multipath contribution by a Rician distribution. For a received signal experiencing only light shadowing, the received signal envelope will be modelled as the sum of log-normal and Rayleigh random processes, while for the case of heavy shadowing the received envelope distribution will tend towards a Rayleigh function.

Overall Hardware Configuration

The overall configuration of the terminal hardware will be very similar to that already proposed by Berner [8] and Bell *et al.* [9], who discuss the JPL mechanically steered array. The rotating antenna platform will be mounted on a fixed supporting structure which will be located in the roof of the test vehicle. Drive to the rotating platform will be via a stepping motor. The received RF and control signals to the phase shifters will be supplied to the antenna via a rotary joint and slip rings respectively. The tracking controller will be based on a TMS 320C25 digital signal processor which will handle the tracking error derivation plus the closed and open loop control functions. This unit is easily capable of dealing with the data acquisition rates discussed and will receive inputs, not only from the tracking receiver, but also from a vehicle mounted angular rate sensor and/or flux gate compass.

Two control strategies are currently being considered for the proposed antenna. The first, will utilise the closed loop EBS element as the primary tracking system. In the case of the received signal dropping below a certain threshold, tracking will be transferred to open loop control based on information available from the rate sensor and/or flux gate compass. The second approach is to use a hybrid tracking system of the type employed in a number of maritime terminals [10,11]. This scheme will optimally combine (using a Kalman filter estimator) the data available from both the closed and open loop tracking elements, to produce the resultant drive signal for the antenna servo system. Results presented [10,11] indicate an improvement in tracking accuracy of 100 – 200% for the cases considered.

Conclusions

The development of an L-band mechanical steered antenna for MSAT applications has been described. Results presented for the prototype microstrip patch array fulfil the required terminal specification and demonstrate the very favourable electronic beam squint operation. Examination of the non-urban land mobile tracking environment has shown that, although this represents probably the most severe test of the tracking ability of an EBS system considered to date, suitable accurate tracking performance can be obtained. Finally, the overall terminal hardware configuration has been outlined and tracking control strategies discussed.

A complete hardware demonstrator is now being constructed in the University. Field trials are expected to take place in the near future and it is hoped these will confirm the optimism currently held in the system described.

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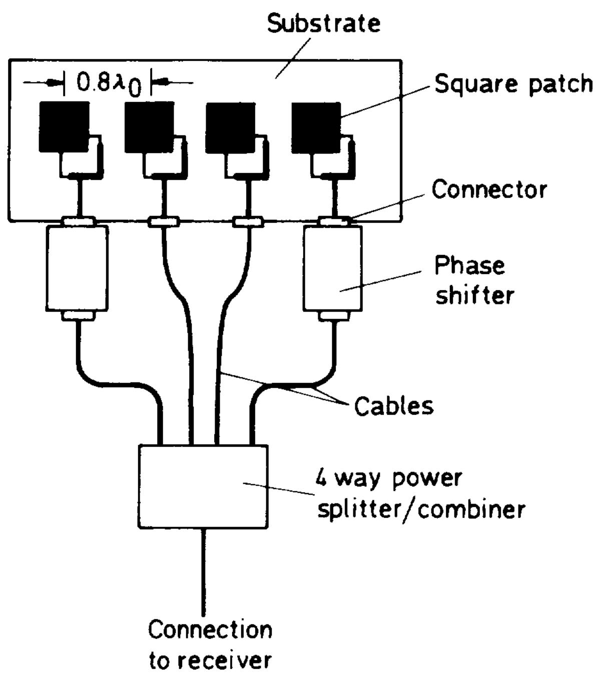

Figure 1: Four element circularly polarised microstrip patch array antenna.

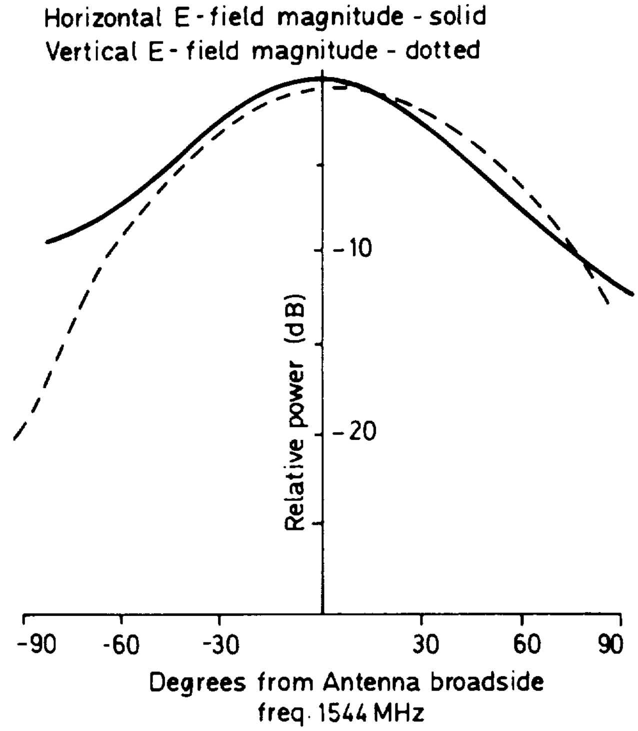

Figure 3: Measured elevation radiation pattern for circularly polarised microstrip patch antenna.

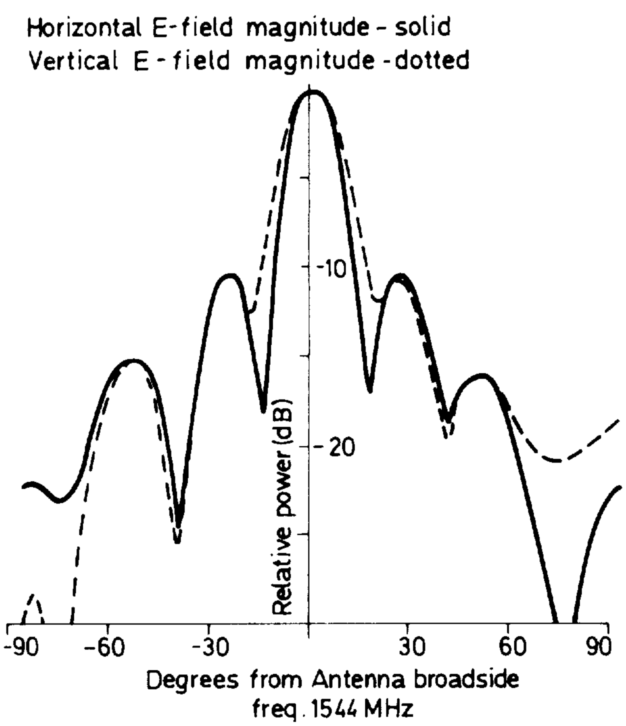

Figure 2: Measured azimuth radiation pattern for circularly polarised microstrip patch antenna.

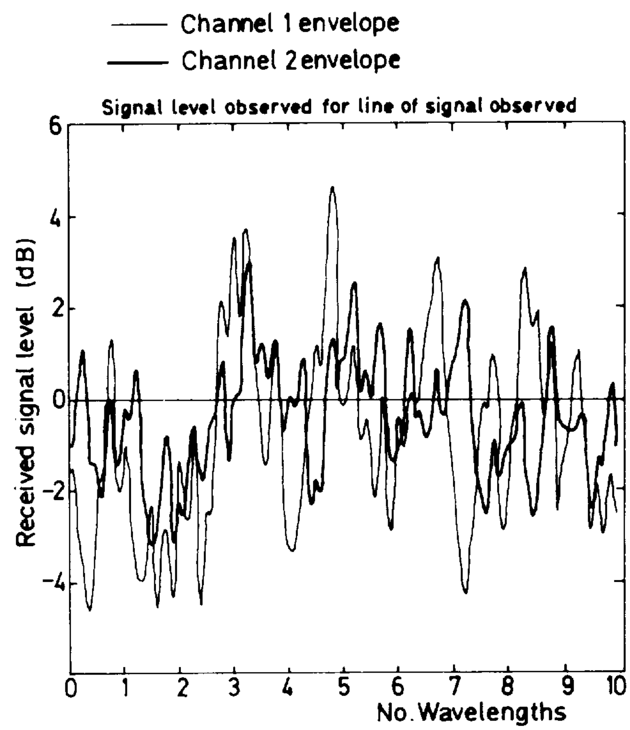

Figure 4: Fading signal envelopes observed for line-of-sight operation.