Tracking systems for satellite communications

G.J. Hawkins
D.J. Edwards
Prof. J.P. McGeehan

Indexing terms: Satellite links and space communication, Radar and radio navigation, Radiocommunication, Antennas

Abstract: Satellites in nominally geostationary orbits possess diurnal motion which causes the apparent position of the spacecraft to wander in the sky as seen by an earth station. If uncompensated this causes a variation in the performance of the communications link. The motion of the satellite therefore has to be tracked by the earth station antenna. During the past twenty years or so a considerable amount of work has gone into the development of tracking schemes for satellite communication systems. Here a review of the various techniques is presented. For each method used the principle of operation is described and the various salient features extracted. Comparisons are made where appropriate and practical implementations of the systems discussed. The application of intelligent control algorithms to tracking is also considered. The areas covered include, orbit determination, optimal estimation techniques, performance, and practical implementations. Recently introduced techniques are considered and likely future developments projected.

1 Introduction

Research in many areas has been promoted as the economics of satellite communications has evolved and emphasis is now placed on cost reduction. As satellite lifetimes have been extended the operators of the system have looked at various schemes to reduce their costs. One option open to spacecraft controllers is the slackening of the orbital specification requirements placed upon the satellite. This policy allows the orbit to develop beyond the bounds that have been the norm until recently, particularly in the north–south, or inclination plane. For the satellite operator this offers an economic advantage in terms of an extended satellite lifetime as on board fuel usage is reduced. For the earth station operator the loosening of the orbital specification results in the spacecraft wandering in the sky more than has previously been the case. Consequently earth stations now have to employ some pointing control where previously none was needed.

Tracking has generally been required in situations where the communications link specification dictates that the received and transmitted signal levels over the satellite link be maintained within defined limits. This usually becomes necessary when the antenna beamwidth is of the same order of magnitude as the angular motion of the satellite. The required pointing accuracy is primarily determined by the beamwidth of the antenna (which is a function of antenna diameter and operating frequency) and the allowable losses on the communications path. Other factors also play a part such as propagation conditions, the mechanical performance of the antenna and the local weather, all of which serve to perturb most systems.

Broadly speaking there have been three areas in which tracking techniques have been developed. The first involves ground station tracking of a subsynchronous orbiting satellite. Here the satellite is in view from any point on the earth's surface for a limited period of time and sweeps a path across the observer's sky in a period of time determined by the orbital parameters of the spacecraft. Without some form of tracking, even for a fairly wide beamwidth antenna, the ground station would soon lose contact and the communications link would suffer. The second situation involves ground station tracking of a geostationary satellite. Now the satellite movement is limited to a narrow window usually not exceeding ±3°. For an antenna with a beamwidth of the same order as this motion it is possible that no tracking will be required and the antenna can be fixed, perhaps requiring occasional manual correction to account for satellite drift. If, however, an antenna is used with a much narrower beamwidth then tracking again becomes necessary. The third area involves satellite-to-satellite links. Here the predominant features of the tracking technique are not only accuracy, but weight and reliability. This places new constraints on the method employed.

Over the past 25 years, work has progressed so that four classes of tracking system have evolved to meet the various needs of satellite communications. These can be described as:

(*a*) manual/programme tracking
(*b*) monopulse or simultaneous sensing
(*c*) sequential amplitude sensing
(*d*) electronic beam squinting

The latter three techniques can be classified under the general heading of automatic tracking or autotracking. These schemes represent closed-loop tracking systems and once satellite acquisition has been established, tracking continues with no operator intervention. All autotracking schemes rely on the reception of a continuous beacon signal transmitted by the satellite. The received beacon signal is used to derive pointing error information which supplies control signals to the antenna drive servo mechanisms. The antenna is driven so as to attempt to minimise the pointing error and hence null the tracking

---

Paper 6208F (E9), first received 5th May 1987, and in revised form 18th February 1988

The authors are with the Department of Electrical and Electronic Engineering, Bristol University, Bristol, United Kingdom

error. The sequential amplitude sensing systems and monopulse systems are widely used in satellite communications today. Electronic beam squinting is relatively new and although still in the early stages of research is beginning to be deployed at several earth station facilities.

Each of these four classes will now be examined in turn. Emphasis is to be placed upon the principle of the tracking method and the consequent effect on overall system performance. For the autotracking schemes, this entails a detailed description of the radiofrequency processing necessary to derive the tracking error signals. The effect of the servo mechanism and control systems, employed in the antenna drive, are not considered since these are relatively independent of the error detection mechanism. It must be appreciated, however, that these elements do have a significant effect on overall system performance.

2 Manual and programme steering

In the absence of an autotracking system, antenna pointing is either undertaken manually or using programmed steering. Manual tracking involves an operator controlling the movement of the antenna until the received signal strength is maximised. Programme steering uses prepared data describing the path of the satellite, seen from the earth station as a function of time. This information is fed to the antenna positioning servo system which points the antenna in the appropriate direction.

Programme tracking was used extensively at early satellite tracking installations to track the first generation of orbiting satellites, such as Telstar. The Goonhilly No. 1 antenna [1] was one such example, being initially equipped in the mid-1960s with a programme steering system which remained in service until the late 1970s when it was replaced during the installation of a new autotracking facility. At that time the equipment required to process the data tapes, perform calculations and then provide steering commands was complex. Preparation of the data tapes was time consuming since the high angular velocity of the satellite with respect to the ground station required that either, the tapes were frequently updated, or sophisticated interpolation techniques were used on subsequent transits of the satellite.

Most of these problems were recognised at the time and radar experience provided the basis for exploring the possibilities of autotracking or at least initially deriving tracking error information. Programme steering decreased in popularity as these new systems were developed but was often employed as a back-up scheme in case the primary tracking method failed.

In circumstances where the tracking accuracy required is not too stringent, this form of satellite tracking still has applications. One example of modern day usage was at the BT Research Laboratories at Martlesham Heath [2]. Here a 6.1 m Cassegrain aerial was used to track the Orbital Test Satellite (OTS-2) launched by the European Space Agency in the spring of 1978. Tracking was achieved using data provided by the satellite control centre. With occasional manual control following satellite manoeuvres, a pointing accuracy of 0.01° in both azimuth and elevation was reported to be maintained.

Programme tracking was also used for the reception of signals from the NOAA satellites at the University of Dundee [3]. The wide beamwidth of the 1.8 m antenna did not require the use of an accurate autotrack technique. A similar argument applied to the Nimrod aerosatcom terminal described by Cummings and Wildey [4]. In this system antenna pointing was achieved using programme tracking based on satellite ephemeris and the aircraft inertial navigation system (INS). The most prominent causes of pointing error are described as aircraft flexing, friction and velocity lags. Although confirmed flexing data was not available for the tail-fin location of the aerial, the authors estimated angular errors were well below the required overall pointing accuracy of $\pm 2°$.

3 Monopulse systems

In the examination of sequential amplitude sensing systems which follows later, it will be shown that a finite time period is required in order to extract the pointing error signal. In the time interval in which measurements are made the beacon signal should ideally contain no amplitude modulation (AM) components other than the modulation produced by the tracking mechanism. If this is not the case and additional modulation components, caused, for example, by changes in the atmospheric propagation path, are present the tracking accuracy might be degraded. In practice the presence of AM interference can be sufficiently serious to form the main limit to the achievable tracking accuracy of a sequential amplitude sensing system.

Amplitude fluctuations of the beacon signal will have no effect on tracking accuracy if the pointing error information can be obtained from the received beacon signal at a single time instant. Monopulse tracking schemes offer just such a capability and consequently promise improved operational performance compared to systems which take a finite time to derive the pointing error signals. Monopulse schemes employ either spatial amplitude comparison, phase comparison or amplitude-phase comparison techniques. Such systems have been used widely for satellite tracking and are described in a number of papers [5–21].

The simplest form of monopulse technique is the simultaneous lobing system which utilises amplitude-comparison. Anders *et al.* [5] describe such a scheme, the ‘Precision Tracker’, as employed on the tracking stations at Andover (Maine, USA) and Pleumeur-Bodou in France in 1963. These were used for tracking the early Telstar satellites.

The antenna for the ‘Precision Tracker’ has a four-horn feed system which creates overlapping antenna patterns. The beacon energy received by the four horns is processed by a comparitor to develop three different antenna pattern response characteristics: the sum pattern corresponding to a conventional antenna pattern; the elevation difference pattern, having two main lobes in the elevation plane with a deep null on the boresight axis; and the azimuth difference pattern, having two main lobes in a plane perpendicular to the elevation plane with a deep null on the boresight axis. These patterns are shown in Fig. 1 along with the modes in the horn apertures and the angle error signal. Mathematically these patterns can be expressed as:

$$\text{sum} = A + B + C + D \tag{1}$$

$$\text{azimuth difference} = (A + B) - (C + D) \tag{2}$$

$$\text{elevation difference} = (A + C) - (B + D) \tag{3}$$

Since the difference signals arise from the antiphase addition of signals from the appropriate pair of horns, phase sensitive detectors must be used in the receiver. With two channels being required, for the sum channels and each of the difference channels, the tracking receiver must therefore be a four channel coherent device. In practice a single sum channel is frequently used.

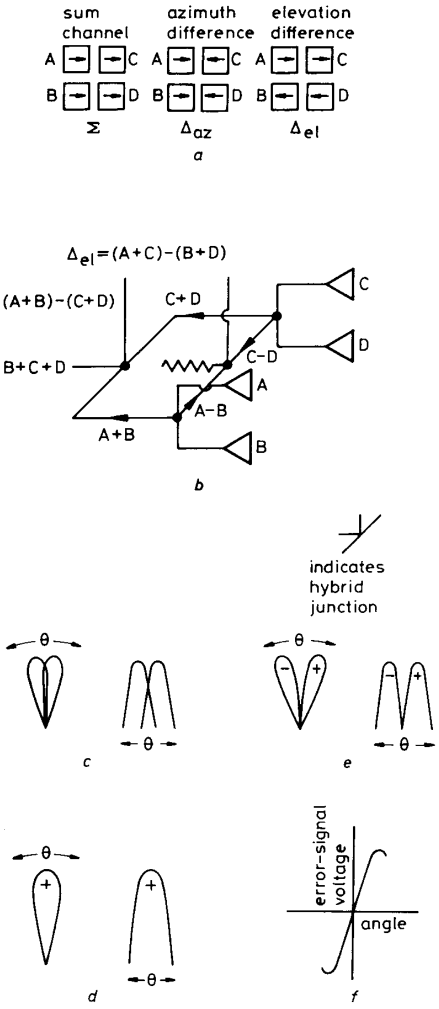

Fig. 1 *Simultaneous lobing system*
a Modes in horn apertures
b Comparator bridge network
c Overlapping antenna patterns
d Sum pattern
e Difference pattern
f Error signal voltage

Examination of the angular error signal, for either the elevation or azimuth planes, shows its magnitude and sign depend upon the angle off boresight for that plane. Further, the scheme offers two important features; firstly it is clear from Fig. 1*f* the error function is approximately linear with respect to off-axis angle, and secondly, it can be shown that the output scale factor for the error signal is rendered insensitive to changes in absolute received signal level within the frequency response of the AGC system and the dynamic range of the receiver.

Results of tracking experiments carried out with 'Precision Tracker' which employed a 2.5 m Cassegrain reflector, having a 2° beamwidth, showed that a tracking accuracy of approximately 0.01° was obtainable with an input signal-to-noise (SNR)† of about 15 dB. The system worked with both linearly and circularly polarised signals, the former incurring a 3 dB effective loss since such a feed only accepts a single vector component of the signal.

The essential characteristics of the amplitude sensing system are the generation of a sum pattern with maximum boresight gain and difference patterns with a large value of slope at the crossover of the offset beams and hence a steep error voltage characteristic around the boresight axis. The use of the four-horn feed does not allow the optimisation of both of these parameters since independent control of the sum and difference patterns is unavailable. Less compromise and better performance may be obtained with five-horn feed in which the central horn, used for the sum channel, is surrounded by four other horns whose functions are to provide the azimuth and elevation difference patterns. Feeds of this type are described by Pratt [6] and a number of other researchers [7–9].

The other major form of monopulse system relies upon detection of higher order modes excited in a microwave feed system, to determine the discrepancy between the pointing direction of the antenna and the satellite. Such systems are generally referred to as multimode monopulse systems.

One of the first systems of this type is described by Cook and Lowell [10]. This scheme was also employed on one of the tracking antennas at Andover (Maine, USA) and the early experiments used much of the same equipment employed in the amplitude-comparison tracking arrangement described by Anders *et al.* [ibid].

With this system a circular feed was employed. The waveguide had a large enough diameter to support, at the beacon frequency, the propagation of the two lowest order modes, namely the TE$_{11}$, or dominant mode, and the TM$_{01}$ mode. With such an arrangement the magnitude and phase of the TM$_{01}$ mode component can be used to determine the pointing error information. Analysis of the TM$_{01}$ mode component reveals its magnitude is dependent upon the radial pointing error, θ (see Fig. 2). When θ is small the amplitude proves to be

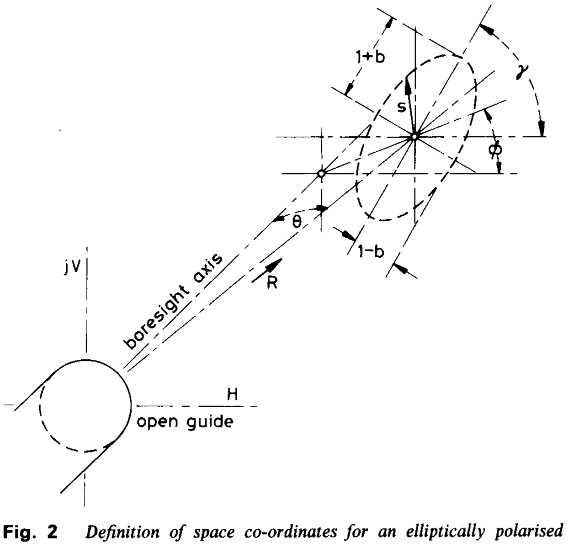

Fig. 2 *Definition of space co-ordinates for an elliptically polarised signal*

---

† All quoted SNR ratios measured at input of tracking receiver

directly proportional to the pointing error. In addition, the circumferential direction, ϕ, of the pointing error can be shown to be proportional to the phase difference between the TE_{11} and TM_{01} signals. Recovery of the azimuth and elevation tracking errors is then possible using the relationships:

$$\text{azimuth pointing error} = k_1 \theta \cos \phi \quad (4)$$

$$\text{elevation pointing error} = k_2 \theta \sin \phi \quad (5)$$

where k_1 and k_2 are constants.

The signal processing arrangement chosen for the system, described by Cook and Lowell, relied upon processing three signals to determine θ and φ. A horizontal sum signal corresponding only to the horizontally polarised component of the incident wave, the vertical sum component corresponding only to the vertically polarised component and the difference signal representing the φ-plane component. The sum and difference patterns, resemble in form and function, those of a simultaneous lobing system and correspond to the TE_{11} and TM_{01} mode patterns respectively. The extraction of θ and ϕ consisted of a straightforward comparison of amplitude and phase between the sum and difference signals. The original system achieved this using a four-channel coherent receiver in which the individual sum signals were multiplied with the difference signal to yield the two required output error voltages.

Analysis of the far-field distributions produced by the two modes, on a plane normal to the feed boresight, show that the field for the TE_{11} mode is parallel to that in the feed while for the TM_{01} mode a radial distribution is observed. In consequence, it is an essential requirement of this tracking scheme that the satellite beacon signal is circularly polarised so that the TM_{01} mode is excited with an efficiency that is independent of φ.

Simplification of the processing can be achieved by receiving only one of the orthogonal components of the TE_{11} mode, for example, the horizontal component, and then generating the other with a $\pi/2$ phase shift. Now a two-channel coherent receiver can be used but the sense of the circular polarisation must be known. Experimental work at the Andover aerial showed the use of either the two- or four-channel system led to similar operational results.

The closed-loop tracking performance of the Andover system was measured by Lozier *et al.* [11]. The 20.4 m horn-reflector antenna had a 3 dB beamwidth of 0.225° at the beacon frequency. The acquisition angle was found to be 0.2° in all directions. Measurements of the tracking errors showed that the autotrack system maintained the null axis of the antenna within 0.005° of the actual satellite direction. The practical threshold limit for successful operation was determined to be about -130 dBm at the input to the sampling coupler for the horizontal and vertical dominant mode signals.

Simplification of the multimode monopulse system has resulted in some interesting work. In 1975 Chivers and Brain [12] described a tracking system utilising the excitation of the TE_{11} and TM_{01} modes but this time using only one receiver amplifier for both the beacon and communication signals. This was accomplished by injecting the microwave pointing error signal, derived from comparison of the TE_{11} and TM_{01} mode signals, into a common receive waveguide channel. This eliminates the need for separate amplifiers in the tracking receiver system and, according to the authors, produces a more stable and reliable system. Due to the mechanical construction of the feed arrangement used, however, the scheme will only cope with the particular beacon frequency for which it was designed. This feed arrangement is currently used on the Goonhilly No. 4 antenna.

Similar schemes have been used throughout the world and are still popular some twenty-five years after the first operational systems were constructed. Hayashi *et al.* [13] describes such a system employed at the Kashima Branch of the Radio Research Laboratories in Japan. Here a 10 m antenna system is used for reception of signals from the ETS-II satellite. The antenna is notable for its multiple frequency operation. Beacon signals of 1.7 GHz, 11.5 GHz and 34.5 GHz can be received and tracked.

Another Japanese tracking station, employing a TM_{01} mode feed, was reported in 1981 by Inoue and Kaitsuka [14]. This was a *K*-band facility for use with the Japanese domestic communication satellite. The system consists of an 11.5 m earth station antenna where the half-power beamwidth of the antenna is 0.08° at 20 GHz and 0.05° at 30 GHz,. Operation with these high beacon frequencies presents special problems, one of these being induced crosspolarisation caused by rainfall along the propagation path. This leads to cross coupling between the antenna drive axes error signals and hence a worsening in tracking performance. The results of experiments using the stations at Yokosuka and Sendai show that the acquisition range of the system was 0.08° in all directions. For a large SNR, the tracking error depends mainly on wind gusts and backlash. For a SNR of 60 dB, the tracking error is less than 0.005° for an average wind velocity of 10 m/s. In strong winds the tracking accuracy deteriorated to 0.01° with average wind velocity of 25 m/s. Operation of the system in light wind conditions results in a tracking error of less than 0.003° even with 20 dB rain attenuation.

Antennas in the United Kingdom employing the TM_{01} monopulse technique include Goonhilly No. 3 (notable for its rectangular feed horn), Goonhilly No. 5 (used for INMARSAT communications), Goonhilly No. 6 (a dual frequency antenna working at 4/6 GHz or 11/14 GHz), and Madley Nos. 1–3 situated in Herefordshire, all of which are operated by British Telecom International.

To track satellites transmitting beacon signals with either circular or linear polarisation using the multimode monopulse technique, it is necessary to use a feed which excites either orthogonal TE_{21} modes or both the TM_{01} and TE_{21} mode. Some of the possible approaches are described below.

Choung *et al.* [15] discusses a tracking feed for use in the Ku-band that utilises the generation of orthogonal higher-order TE_{21} modes. With this arrangement when the main beam axis is not aligned with the boresight axis, TE_{21} modes are excited in the feed, the amplitude of the higher TE_{21} mode being proportional to the angle of misalignment. Orthogonal TE_{21} modes are sensed in a coupler and used to derive the required azimuth and elevational error signals. The overall layout of the coupler is shown in Fig. 3. Four coupling arms are summed through a hybrid network to obtain a single TE_{21} mode coupler. The two mode couplers are then summed together through a final 90° hybrid to separate the azimuth and elevation error signals. Mode rejection between the TE_{11} and TE_{21} modes is claimed to be approximately 40 dB. The authors do not state if this feed was incorporated in a tracking facility. A similar system is reported by Savini [16]. The scheme uses four instead of eight coupling positions and relies upon rotation of the coupler, by the servo system, to obtain orthogonal pointing error measurements from the TE_{21} mode signal.

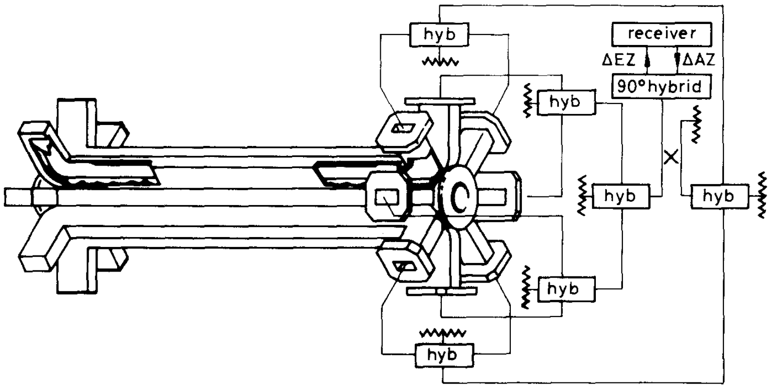

Fig. 3 *Layout of TE_{21} mode coupler using two orthogonal modes*

The use of feed systems utilising the excitation of both TM_{01} and TE_{21} modes to derive tracking information are widespread. Such systems difference the individual higher order mode components to recover the required orthogonal tracking error signals. One such scheme is described by Watson *et al.* [17]. The feed, based on work previously carried out by Molker and Watson [18] separates out sum and difference (x and y in orthogonal planes) signals which are multiplexed into a four-channel tracking receiver to produce normalised error signals to control satellite pointing. Utilising these inputs, it was shown [19] that the tracking system is rendered insensitive to the deleterious effects of atmospheric depolarisation.

The key component in the feed chain is a planar mode-extractor (Fig. 4), which has four symmetrically positioned transverse coupling apertures between the main central circular waveguide and individual rectangular waveguides. This mode coupler is interposed between the corrugated horn and a high performance circular waveguide polariser. The size of the central circular waveguide is such that both the TE_{21} and TM_{01} mode can propagate. Results of laboratory tests presented in the paper show cross coupling to be less than 32 dB between the difference channels with null depths for the difference patterns exceeding 50 dB. The system was intended for use on-board the ESA's large satellite (OLYMPUS) to provide a direct TV broadcast beam covering the Italian region. The angular accuracy of the complete tracking system was specified as 0.1°. A similar arrangement is described by Reinders and Oei [20] for earth station antennas employed to track the Orbital Test Satellite.

Other examples of stations employing monopulse techniques include the maritime terminals used with the SKYNET system [21] and many large Intelsat earth stations, especially those working at 11/14 GHz [22, 23].

4 Sequential amplitude sensing systems

The monopulse techniques, although highly successful in operation, require relatively complex wavefront processing to derive the tracking error information. This processing inevitably requires at least a two-channel coherent receiver and often a four-channel system is necessary. This presents two major disadvantages; first, the tracking system is expensive and secondly, owing to its complexity, it is mechanically large. For an earth station, mechanical size is relatively unimportant but in space this presents a serious problem since ultimately the usable satellite communication payload will be reduced if the mass of the control system is large.

Until recently sequential amplitude sensing offered the only alternative to the monopulse technique. Two

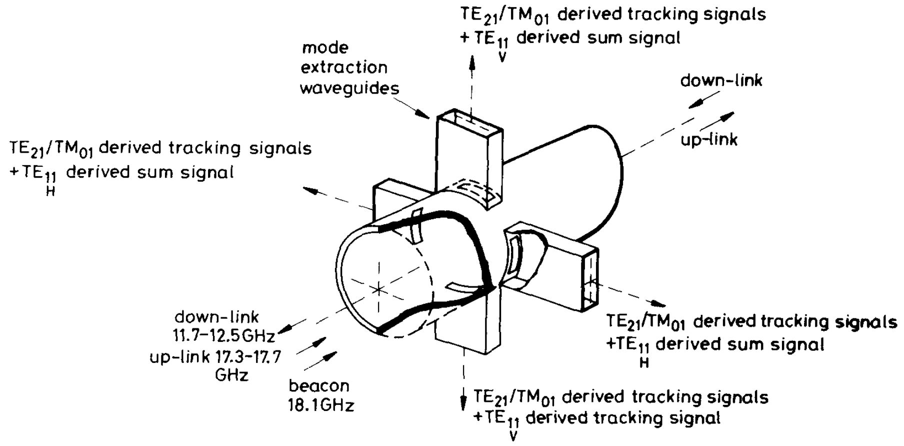

Fig. 4 *Tracking mode coupler for TE_{11}, TM_{01} and TE_{21} mode extraction*

methods are available; conical scanning and the step-track or hill-climbing technique. Conical scanning evolved from the conical scanning radar developed after the Second World War for the detection of airborne targets. The step-track technique was introduced in an attempt to significantly reduce the overall cost of satellite tracking facilities. Both use a single channel receiver and employ time-division multiplexed, spatially distributed measurement of the beacon signal to derive the tracking information.

4.1 Conical scanning

The principle of conical scanning is shown diagrammatically in Fig. 5 and described by Skolnik [24]. The concept relies on continuously rotating an offset beam about the boresight axis of the antenna. When the satellite is off this axis the received signal in the beacon channel is modulated at a frequency equal to the rotation rate of the beam. The amplitude of the modulation will depend upon the shape of the antenna pattern, the squint angle and the angle between the satellite line of sight and the rotation axis. The phase of the modulation depends on the circumferential angle between the satellite and the rotation axis. The conical scan modulation is detected in the tracking receiver and applied to the servo-control system which continually positions the antenna on the satellite. When the antenna points directly at the satellite, the line of sight to the satellite and the rotation axis coincide and the conical scan modulation is zero. It is clear this method constitutes a very similar situation to that which exists for a monopulse system utilising TM_{01} mode excitation. Again the amplitude and phase of a derived tracking error signal is being used to determine the azimuth and elevational tracking errors. It therefore follows that these errors can be derived using relationships similar to those in eqns. 4 and 5.

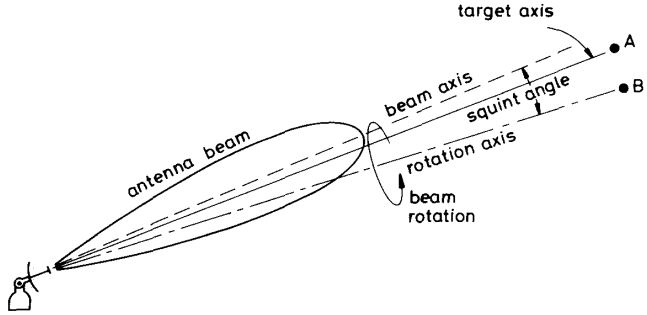

Fig. 5 *Conical scan tracking*

The simplest form of conical scanning can be achieved by rotating the complete antenna about the boresight axis. It is obvious such a method is only suitable for small aerials but such systems have been used. The later SCOTT military shipborne satellite terminals are one such example [25]. Here the autotrack system rotated the whole antenna using servo motors at a frequency of 1 Hz. Earlier terminals had no autotrack capability and relied on a stabilised platform and manual positioning [26].

For a large Cassegrain antenna conical scanning can be achieved either by rotating an offset feed, or by using a fixed feed and rotating an offset sub-reflector. The offset feed was used on the Goonhilly No. 1 antenna and was described by Knox and Doble in 1970 [27]. Use of the offset sub-reflector was unpopular because of its mechanical complexity and was only used on a limited number of tracking stations. The most notable of these being the Apollo Ascension station commissioned in September 1966 [1].

Both of the previously described techniques result in modulation of the up-link transmission as both the transmission and reception paths through the antenna are the same. For the Goonhilly No. 2, Bahrain and Hong Kong 1 antennas, mode conversion techniques were applied to the conical scanning principle in order to overcome this problem. The scheme was patented in 1968 by the Marconi Company Ltd. [28]. Lockett and Shinn [29] described the operation of such a feed mechanism, shown in cross-section in Fig. 6, as though it were transmitting. This simplifies the explanation of the scanning mechanism and is valid since the principle of reciprocity will apply when the antenna is operating in the receive sense.

The feed used on these antennas has a circular cross-section throughout. At its smallest diameter only the TE_{11} mode can exist in the guide. Next there is a conical transition followed by the cylindrical tracking section in which TM_{01} mode can also exist. An unsymmetric mismatch is introduced into this section and has the effect of converting some of the TE_{11} mode to TM_{01} mode.

From the tracking section, both TE_{11} and TM_{01} modes reach the aperture of the feed and are radiated towards the subreflector. The secondary pattern (due to the TE_{11} mode) has a maximum on the axis of the antenna while that due to the TM_{01} mode has a zero on the axis. If these two patterns are in phase then their sum has a maximum which is off the axis and hence the main antenna beam has been offset relative to the beam axis. With the TE_{11} mode circularly polarised, it can be considered to consist of two components of mutually perpendicular polarisations, one of which is in phase with the TM_{01} component, the other being in quadrature with the TM_{01} component. Thus the beam is offset in the direction of the polarisation of the first of these components. The direction of the offset, therefore, bears a definite relationship to the orientation of the tracking section and if this is rotated, the antenna beam is seen to carry out a conical scan.

When receiving, the application of reciprocity shows that amplitude modulation of the beacon signal will occur when the satellite lies off the boresight axis and the tracking section is rotated. Since with this arrangement the feed is no longer offset, up-link modulation is removed. The technique is only effective when the beacon signal from the satellite is circularly polarised. If a linearly polarised signal is sent through the tracking arrangement the radiation pattern, instead of carrying out a conical scan, would move with simple harmonic motion in the direction of the polarisation. This results from the radiation pattern of the TM_{01} mode having a polarisation which is radial in every direction.

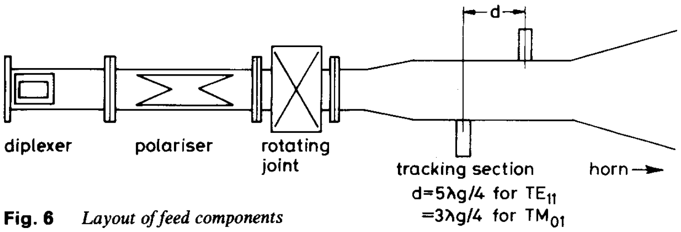

Fig. 6 *Layout of feed components*

This difficulty can be overcome by using TE_{21} mode generation and is also discussed by Lockett and Shinn [29]. It is possible with the appropriate choice of the tracking section diameter, to transform part of the TE_{11} mode into a TE_{21} mode while at the same time transforming very little energy into the TM_{01} mode. Rotation of the tracking section provides modulation of the received signal which can be used for direction finding in the same way as has been described for circular polarisation and the TM_{01} mode. Unfortunately, this cannot be described in terms of the simple conical scan relationships. Analysis shows the degree of modulation now obeys the relationship:

$$\text{depth of modulation} = \theta \cos(\phi - 2\alpha) \cos\alpha \qquad (6)$$

where θ is the off axis angle of the satellite, ϕ is the satellite circumferential angle, α is the coupling slot circumferential angle in the tracking section.

Isolation of the satellite off axis and circumferential angles is then only possible by processing the second and third harmonic components of the conical scan modulation. This requires the addition of specialised matched filters to the tracking receiver and the use of a more complex feed in order to generate these harmonics. In consequence such an arrangement is generally tuned to operate at one particular spot frequency and so although linearly polarised signals can now be received the feed constraints mean only one beacon frequency can be worked.

Application of either of these mode conversion techniques to the conical scan principle results in an improvement in tracking accuracy of approximately five-fold when compared to a system in which the up-link transmission suffers modulation.

From the description of the conical scan mechanism it is clear that unwanted amplitude modulation of the beacon signal will cause erroneous tracking error information, leading to a degradation in the achievable tracking accuracy. All the forms of conical scanning described so far are susceptible to such AM interference especially if the frequency components of the fluctuations are at or near the conical scan frequency. In general, filtering of the beacon signal is required to remove the majority of this unwanted modulation. Such a technique was employed at the Goonhilly No. 2 tracking station. Information relating to false modulation caused by polarisation of the beacon signal and effects of satellite spin were utilised to derive matched filters to eliminate all frequencies except the fundamental at the rate of rotation of the tracking section.

By the early 1970s conical scanning was well established as a method of satellite tracking. Not only was it used on the antennas at Goonhilly, Bahrain and Hong Kong but also many American systems utilised this technique, including the 64 m dish at Goldstone [30]. After this time, however, as monopulse and step-track systems were fully developed it became less popular. The conical scan system was not as accurate as the monopulse technique because of its sensitivity to AM interference. Monopulse systems were also mechanically less complex and hence more reliable. The step-track techniques, as we will see shortly, offer a low cost solution to the tracking problem. With an achievable accuracy approaching that of a conical scan scheme, these became the most viable solution for the smaller earth station installation.

4.2 *Step-track systems*

In 1970 the step-track (or hill-climbing) tracking technique was proposed by Tom [31]. The scheme aimed to provide a cheaper alternative to the satellite tracking problem by considerably simplifying the microwave and electronic elements of the tracking equipment.

The step-track technique resulted from the development of the Comptrack experiments carried out in 1967 [32]. The operation of Comptrack was similar to the operation of the manual tracking scheme except that a small computer was used to perform the functions of the operator. The experimental results of Comptrack demonstrated the conceptual credibility of a peak-seeking technique.

The step-track scheme represents a further simplification of the Comptrack system. The name 'step-track' originates because the antenna is made to step towards the energy peak of the received signal. After signal acquisition the antenna is commanded to make an initial angular move. By comparison of the received signal level before and after the move, the direction of the next move is determined. That is, if the signal has increased, the antenna continues to move in the same direction. If the signal level has decreased, the direction of movement is reversed. This process is made continuous and alternates between two orthogonal axes to give the capability of tracking.

The simplicity of a step-track system can be seen by the general block diagram shown in Fig. 7. The system only requires a signal strength detector with associated timing generator, and stepping motors. Operation would involve the following sequence of events:

(*a*) sample and measure signal strength
(*b*) move *x*-axis
(*c*) sample and measure signal strength
(*d*) move *y*-axis
(*e*) wait
(*f*) go back to (*a*)

It is clear that the antenna's boresight axis is continuously being stepped, therefore, an average pointing error exists even when the system is operating under perfect conditions. With noise perturbations erroneous decisions will occur which will serve to increase the average pointing error. Tom analysed the step-track performance by calculating the effective antenna gain loss caused by the stepping motion. This analysis showed optimum parameters exist for the post-detection filter bandwidth, the time between samples and the step size for a given satellite drift rate. Tom claimed even for the lowest practical input signal/noise ratio (SNR = 3 dB), the gain loss from tracking would be moderately small if the satellite drift rate is not excessively large.

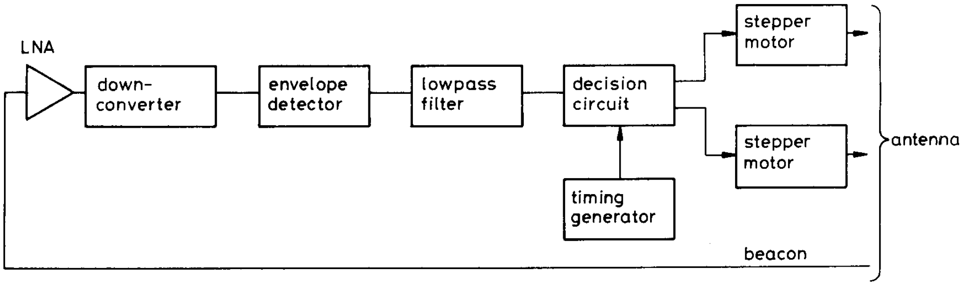

Fig. 7 *Possible step-tracking subsystem configuration*

The step-track scheme has a number of limitations. Firstly it is almost axiomatic that locating a beam maximum can never be as accurate as finding a sharp null. Secondly, its susceptibility to AM interference means an input SNR some 15 dB higher, than that required by a monopulse system, is required if two similar systems are to maintain a given pointing accuracy. A penalty is therefore suffered in terms of either requiring a proportionally higher satellite EIRP or larger antenna. Thirdly, the tracking mechanism does not work in real time. A dynamic lag always exists between the satellite position and the antenna position and this degrades the achievable accuracy to around 0.05° if no optimisation techniques are undertaken. Fourthly, the transmitted and received communications signals are amplitude modulated (at the stepping rate) due to the stepping motion. Although it is technically possible to cancel this by 'antimodulating', the solution is complicated and its reliability questionable [33]. Since modulation of the uplink is often undesirable, the tracking technique is more applicable to receive-only stations. Finally, the system has a slow dynamic response since the tracking operation involves either stepping the main antenna or mechanically nodding the antenna subreflector. Stepping the main antenna causes substantial wear and tear on the steering motors during the execution of the search patterns. Consequently on larger antennas a nodding subreflector may be preferred.

Despite these disadvantages the step-track technique has found wide application because of its simplicity and hence low cost at many of the tracking stations throughout the world. It is particularly suitable for use with geostationary satellites where the link budget does not place undue demands on the antenna pointing system. Ohashi *et al.* [34] discuss such a scheme employed on the 2 m antenna Earth station of the Radio Research Laboratories, Japan. The operational frequency of the unit is 20/30 GHz and programme tracking back-up is essential for successful operation in rainy conditions when the beacon SNR falls below the required operational threshold.

Richharia and Verma [35] discuss the application of step-track to a larger 10.7 m parabolic antenna developed at the Indian Space Applications Centre to track the Symphonie satellite. The stepping motion was initiated by incrementing the antenna axes with a step size of 0.025°. Experimental results presented in the paper claim the achieved rms tracking accuracy in each axis was better than 0.025° with a beacon SNR >12 dB. It is further stated that tracking could be maintained at a reduced accuracy with an input SNR ratio as low as 3 dB. As the Symphonie satellite is a low-drift geostationary satellite the authors propose that once the step-track system has maximized both axes, and hunting has begun, the tracking should then be disengaged. At regular intervals tracking would then be reinitiated to realign the antenna. This eliminates unwanted AM modulation on the communication signals and reduces wear on the antenna drives. It does mean however the antenna cannot respond to wind gusting and in such circumstances tracking accuracy would be degraded, depending on the stiffness of the antenna structure.

An even larger earth station employing the step-track technique is Goonhilly No. 1. This was converted from conical scan to step-track in 1983. Step-tracking is achieved using a hydraulically driven nodding subreflector since movement of the antenna structure would have been difficult due to its physical size. This scheme utilises optimisation techniques, in the form of a control algorithm known as the smoothed step track technique, in order to achieve an accuracy better than ±0.01°.

Step-track schemes have also found extensive use for maritime satellite communication tracking systems. The MARISAT civil communications terminals discussed by Johnson [36] are one example. The sampling time at each of the sampling angles is made long enough to average the system noise. Noise in the marine environment results from two main sources; the residual dynamic angular pointing error due to the ship's motion after stabilisation, and the apparent low-frequency modulation of the received carrier due to multipath fading. For an antenna beamwidth of 10°, a step amplitude of approximately 0.5° is required with an integration time of 30 seconds. The tracking accuracy under these conditions is estimated at ±1.5°. Another maritime terminal employing the step-track system is the Standard-B ship earth stations used with the INMARSAT satellite. One such system, described by Shiokawa *et al.* [37] employs a 4-axis mount allowing El/Az/Y/X movement. Pointing errors are kept below 3° under 'normal' sea state conditions.

5 Electronic beam squinting

The appearance of the electronic beam squinting, EBS, technique has only occurred in recent years. EBS represents a pseudosimultaneous amplitude sensing system and is a logical continuation in the development of the sequential lobing technique. It employs electronic switching techniques to effectively achieve simultaneous spatial measurement of the beacon signal, and hence single time frame tracking error determination. It requires a relatively simple single channel tracking receiver (similar to that employed in the step-track scheme) and offers the potential of tracking accuracies approaching that of monopulse because of the near simultaneous nature of tracking error derivation.

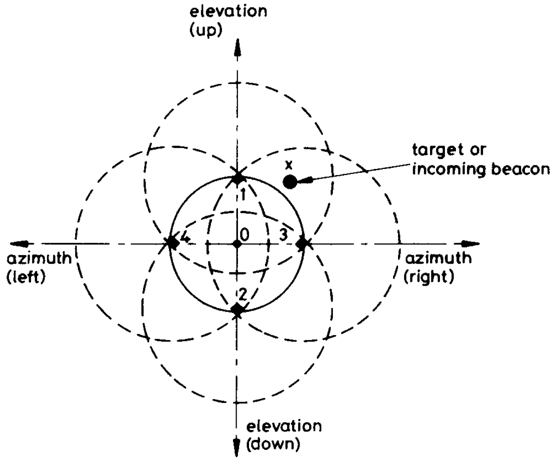

Fig. 8 *Polar diagram showing directional location of secondary beam peak levels (1, 2, 3, 4) relative to boresight (0) and incoming beacon (x)*

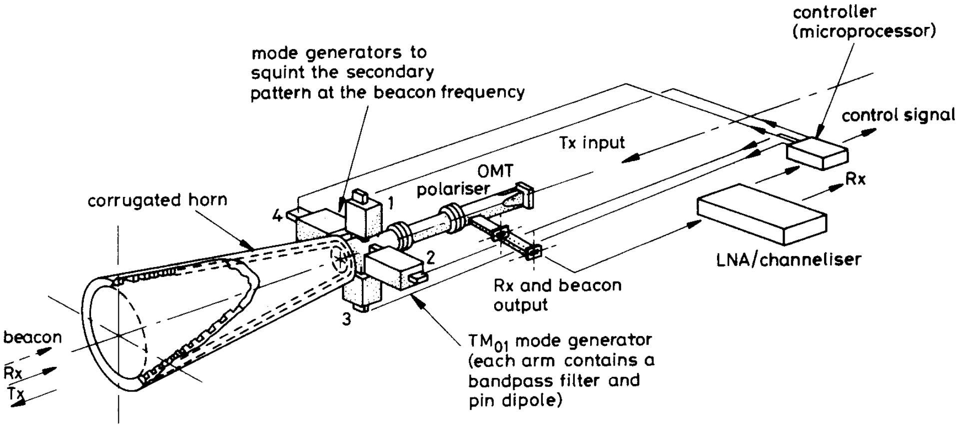

Fig. 9 *RF feed chain employing electronic beam squint tracking for circularly polarised beacon signals*

One of the earliest schemes employing the beam squint technique was the Rude Skov. II satellite receiver in the Netherlands [38, 39]. The tracking system antenna comprises a central dipole around which are located four equally positioned parasitic dipoles. These are mounted on a common ground plate, installed in the focal plane of a 3 m parabolic reflector. Individual parasitic dipoles can be made to idle (not working) or can be short-circuited (working). This has the effect of squinting the copolar beam of the antenna to four cardinal axes.

Fig. 8 shows the squinting action in contour plot form, the centre axis (ϕ) of the circle represents the direction of the boresight, while the positions 1, 2, 3, 4 represent the squint position achieved by activating each of the four parasitic dipoles. To locate a satellite off the boresight axis (x in Fig. 8) each one of the four dipoles is short-circuited in turn to steer the beam to the positions 1, 2, 3, 4 on the contour plot. The received beacon signal strength at these positions is measured in the receiver stage and stored in conjunction with its co-ordinate direction.

For the satellite position given, the measured signal will be stronger with the beam in position 1 or 3 compared to positions 2 or 4. Furthermore, beam position 1 will produce a stronger signal than beam position 3. Using the data accumulated about the off-axis performance of each direction during a single time frame, the co-ordinate position x is computed and this provides an error signal for the feedback loop operating the steering. To establish the position estimates, if a parabolic main beam shape is assumed it can be shown that the tracking error is given by:

$$\alpha = \delta G/(K\theta) \quad \text{(volts/deg.)} \qquad (7)$$

where δG is the difference in gain measured at the two squinted positions in a common plane, θ is the beam deflection, and K is a constant.

The Rude Skov. II system operating at 1.7 GHz, is used to track low orbiting weather satellites, such as the American TIROS-N, and geostationary weather satellites including GEOS, METEOSAT and the Japanese GMS. A programme track facility is available if the EBS system fails. Orbit prediction, for the programme tracking scheme, is based on the ephemeris data; time and longitude where the satellite's footprint will cross the equation and known orbital data.

A scheme utilising the same principle, but employing a different feed technology, was patented by Edwards and Watson [40] in 1984. This new technique, also described by Dang *et al.* [41] and Watson and Hart [42], takes the form of generating proportions of higher-order waveguide modes within the antenna feed horn to electronically squint the secondary antenna pattern in azimuth and elevation. The technique uses a high performance primary feed configuration intended for either on-board satellite or earth station applications. As with other methods of tracking, gross changes of antenna pointing are undertaken by incremental drive of the main axis drive motors.

A feed network was designed which produces the desired beam shift necessary to define the magnitude and direction of an antenna pointing error based on deriving error signals in azimuth and elevation using the excitation of multimode signals. The feed (Fig. 9) comprises the serial connecton of a conical corrugated horn, mode converter, corrugated polariser and conventional orthomode transducer.

With a beacon signal off the boresight of the antenna axis the feed is dimensioned so that TM_{01} and TE_{21} modes are excited in the horn in the same way as described for the multimode monopulse systems. Two discrete mode converter sections are used. A TE_{21} mode unit, consisting of two diametrically opposed auxiliary rectangular waveguides, is coupled longitudinally to the periphery of the central circular waveguide and provides azimuth plane deviation. The TM_{01} mode unit, also consisting of two diametrically opposed auxiliary waveguides, is transversely coupled and provides elevation plane deviation. Each of the auxiliary waveguides is terminated with a *pin* diode. Activation of the *pin* diode, effected by reverse biasing it, causes the appropriate incoming higher-order mode to be converted to the fundamental mode by introducing asymmetry into the circular waveguide. This, as for the previous scheme, has the effect of squinting the copolar beam to four cardinal axes.

The tracking error signals are similarly obtained by sequential activation of the mode converters to squint the beam to the four positions (Fig. 8) defined for the previous system. The complete tracking system is shown in Fig. 10. The received beacon signal is detected by a communication receiver, transformed by an A/D converter into a digital measurement, which is then passed to a microprocessor. Based on the amplitude of the tracking error voltage and the control technique employed, this then instructs the steering control mechanism. The rapid switch-and-measure sequence enables the whole search pattern to be completed in a fraction of a second and can be regarded as simultaneous.

Results presented by Dang *et al.* [41] indicate the beam-squint tracking system appears to be fulfilling the accuracy claims made of it by its designers. A feed chain has been installed in a 5.5 m diameter offset Gregorian antenna system (3 dB beamwidth 0.32°). The effective beam offset was measured at 0.063°. The beacon receiver was a commercial coherent receiver with a phase locked loop bandwidth of 3 Hz and an output time constant of 1 ms. The nominal scan frequency was set at 512 Hz. The figures provided indicate an acquisition range greater than 0.3° and steady state tracking error less than 0.003°. This corresponds to a beacon variation of less than 0.1 dB and compares very favourably to the results that could be obtained for a monopulse scheme installed on a similar sized antenna.

The system clearly offers many advantages over the standard approaches of either monopulse or step-track techniques. The principle of these are:

(i) no need for a separate or expensive tracking receiver

(ii) relatively simple feed arrangement

(iii) fast electronic acquisition, which implies the system can cope with all the effects encountered in tracking movement, thus maintaining EIRP stability

(iv) improved noise performance due to high data sampling rate

(v) achievable pointing accuracy should compare with the traditional monopulse techniques

(vi) employment of this method leads to a reduction of the mechanical motion during acquisition, placing less demand and wear on mechanical parts and hence minimising maintenance times and cost

Research on the beam-squint tracking technique is presently being undertaken at the University of Bristol under the guidance of McGeehan and Edwards. It is the aim of the research programme to develop the method for use at frequencies up to 60 GHz and investigate the use of novel phase-locked loop and automatic gain control techniques to further enhance the operational performance.

6 Control algorithms

With the advent of inexpensive and powerful digital computing, the application of control algorithms to tracking systems has become possible. Such techniques allow optimisation methods and orbit prediction to be accomplished which can yield improvements in the dynamic performance of the system and hence lower the minimum required signal/noise ratio. This section does not aim to examine in detail all the possible approaches but should give a flavour of the work that has been, or is being undertaken in this area.

6.1 Optimal control techniques

There has been little published material addressing optimal control techniques applied to satellite tracking systems. The earliest example of work is that undertaken by Prime [43] who considered the subject in 1966. Modelling the geometrical form of the radiation lobe as a two dimensional 'hill', he examined the development of hill-climbing strategies, and identified the significant features as:

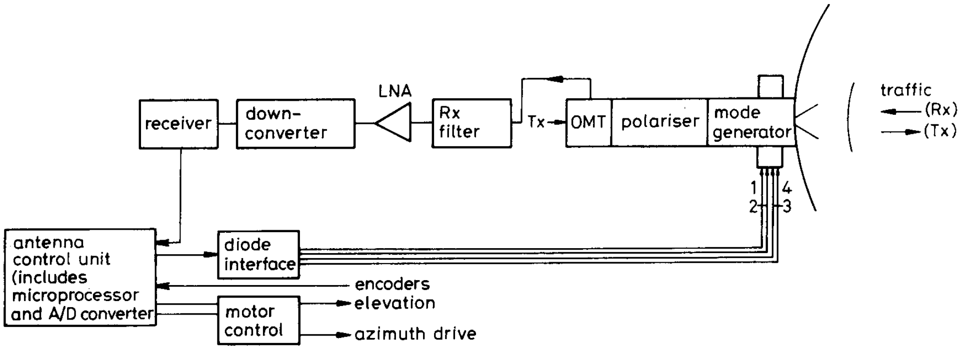

Fig. 10 *Simplified block diagram for beacon and receiver channels*

(*a*) that the optimising process has to be adapted to a system controlled in terms of axial co-ordinates, rather than one characterised by conventional Cartesian co-ordinates

(*b*) the mode of operation is subjected to a performance criterion involving minimisation of mean square error in the presence of constraints

Prime considered a control strategy whereby the beacon signal strength is made to ascend the quadratic hill (preferably along the maximum slope) as the antenna aligns itself with the target. The method relies upon *a priori* knowledge of the lobe geometry and under perfect conditions the procedure described was exact and solutions could readily be obtained. The introduction of signal noise, however, creates a nonlinear function with consequent interaction of the control signals. This problem was addressed later by Stacey and Prime [44] from which developed the gradient algorithm.

This and other early work laid the foundations for the development of optimal control techniques applied to satellite tracking. Many optimisation methods have been applied to other control systems (aircraft stabilisation, radar, fire-control units) and these offer the opportunity to enhance the operational characteristics of the satellite tracking system. Techniques which could be employed included regression, Fourier transform methods, polynomial filters and estimation techniques for signal trends.

Of the work that has been published, that described by Choi [45] and Raghavan and Satyanarayana [46] is typical. Choi examines three types of filter, the standard Kalman filter, the time-varying α-β filter, and the adaptive Kalman filter. Details of algorithms for each type of filter are given and performance characteristics examined using tracking data obtained from the Eastern Test Range at the Eastern Space and Missile Centre. The results presented show all three filters offer good performance when tracking a slowly moving satellite. For a manoeuvring target, however, the time-varying α-β offers superior tracking performance. It also has the advantages of a lower processing requirement and easier system implementation.

Raghavan and Satyanarayana [46] discuss the use of a recursive filter in a microprocessor-based digital antenna controller. Mathematically this filter can be represented as:

$$Y(nT) = \sum_{k=1}^{N} a_k X(nT - kT) - \sum_{k=1}^{N} b_k Y(nT - kT) \qquad (8)$$

where $Y(nT)$ is the predicted response, this being a function of the present response and past N values of the response. The authors do not discuss the calculation of the filter coefficients or give experimental results of its use.

6.2 Orbit determination

The problem of orbit determination, utilising least squares estimation techniques, was first addressed by Gauss in 1795. Much work has been undertaken from Gauss via Kalman to present-day numerical stable and accurate estimators for precise orbit determination.

Orbit determination is the process of describing the orbit of a satellite or other body, based on a set of observations. Consideration of the possible tracking scenarios shows these observations will either be made at a ground station or from sensors on-board a satellite. A high-precision orbit estimator takes the system noise into account and determines an orbit that provides the best fit to the collected data subject to the known dynamics of the orbital motion of the body. Such a process can greatly enhance the achievable tracking performance of a tracking facility in the case where:

(*a*) the orbital estimator is integrated in the autotracking facility and forms part of the closed loop control mechanism

(*b*) the orbital estimator, using data from a number of tracking facilities, predicts the satellite orbit. This data being used by programme track facilities to control antenna positioning

The major constituents of an orbit determination process are the system model, the method of measurement and the estimation technique. Raol and Sinha, in probably the only paper of its kind [47], examine in detail the topic of orbit determination and review the various techniques which have been employed in these three areas.

Many system models have been used to describe the motion of a body in space. These include the classical orbit elements (C6) model, the unified state model (USM), the position-space measurement model and combinations of the above. Organisations predicting satellite orbital data, for use at programme tracking stations, will choose a method dependent upon the accuracy required and the measurement data available. Where orbit prediction is being used as part of an autotracking system, such models are often too accurate and implementation in real-time impractical. In these circumstances simplified satellite motion models will be used. Richharia [48] examining an optimal strategy for tracking of geostationary satellites proposed a simplified model based on an elliptical orbit perturbated with sinusoidal and linear functions. A computer simulation for the model showed if the tracking was based on the model prediction alone, the 3σ error would only be (the half-power beamwidth of the antenna)/100. Edwards and Terrell [49] also use a simplified model in their smoothed step-track antenna controller. This model, originally conceived by Slabinski [50], consists of a polynomial part, quadratic in time, a simple trigonometric part whose period is the siderial day, and two Poisson terms. Slabinski showed the error in such a point expression to be less than 0.015° over a 28-day interval.

The type of measurements used in the orbit prediction process again depend upon the problem in hand. A ground station employing autotracking will generally just have azimuth and elevation data derived from the tracking process whether it be monopulse, step-track etc. A satellite employing satellite-to-satellite tracking techniques might also have inputs available from on-board instruments such as star-trackers, horizon trackers and gyro units. Highly accurate orbital models will require possibly range, range rate, spacecraft-based observation data, as well as azimuth and elevation data from one or more ground stations at various locations throughout the world.

The orbital estimation problem can be expressed as:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}(t), t) + \boldsymbol{n}(t) \qquad (9)$$

$$\boldsymbol{z}(t) = \boldsymbol{h}(\boldsymbol{x}(t), t) + \boldsymbol{v}(t) \qquad (10)$$

where eqns. 9 and 10 represent the system and measurement models respectively, associated with the orbiting satellite and data tracking system. Here $\boldsymbol{x}$ is the vector of n-states of the chosen co-ordinate system and other augmented parameters; $\boldsymbol{z}$ is the vector of observables; $\boldsymbol{f}$, $\boldsymbol{h}$ are known, nonlinear function relationships; and **n**, **v** are process and measurement noise vectors. Given these models and some *a priori* information on **x**(0), **n**, **v** and the 'noisy' measurements available, a filtered estimate of **x** is required. This can be achieved using an estimator.

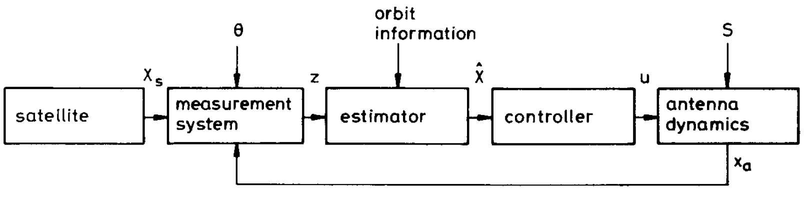

Fig. 11 *Estimator/controller tracking system*

Raol and Sinha discuss more than ten types of estimator that have been used, or considered, for orbit prediction applications. These range from the well known techniques of Gaussian least squares differential correction (GLSDC), Kalman filtering and Adaptive filtering to the less well known methods, including the SBDC technique and Pugahev filtering. The reader is directed to Reference 47 for a comprehensive list and more complete description.

The type of estimator employed again depends upon the application. Factors including the computational power available, the type of measurement data, noise properties and the required accuracy, all have to be considered. Possibly the best known and most widely used estimator is the Kalman filter. Dressler and Tabak [51] reported its use in a high-performance satellite tracking system in 1971. This system (Fig. 11) was the first which combined the use of optimal estimation and control techniques. The estimator, an extended Kalman filter (EKF), generates an estimate $\hat{x}$ of the present system state **x** based on all the noise-corrupted measurements *z* up to that time. This estimate is then employed in the controller to compute a control signal **u** to drive the antenna so as to optimise the tracking performance criterion. Extensive simulations of the tracking system utilising the estimator/controller algorithms were performed in conjunction with models of a 10 m and 25 m antenna. Dressler and Tabak reported that the simulations demonstrated that a real-time tracking accuracy of 0.0005° could be achieved when tracking orbiting satellites. Similar systems are described by Orlando and Neto [52] and Richharia [48]. Richharia's scheme, mentioned earlier, utilises a scalar Kalman filter and much simplified orbital model. Computational requirements are therefore much reduced but tracking errors of up to 0.01° can be expected under worst case conditions.

Tracking facilities employing both orbit prediction and optimal control techniques are now becoming more common-place. Two such systems will be briefly examined, the smoothed step-track antenna controller [49] and a shipboard satellite terminal described by James and Maney [53].

The smoothed step-track (SST) controller, described by Edwards and Terrell [49] has already been mentioned with regard to the method of orbit prediction used. The SST technique exploits the concept of step-track measurement, in combination with orbital prediction, to form an accurate estimate of the satellite track, which is used for continual prediction of the present satellite position. At any time the accuracy of the position estimate will depend on a host of data spanning the previous days of tracking. Therefore the error in estimating the position from an individual step-cycle measurement tends to get greatly reduced by the smoothing effect of the tracking algorithm. This allows the system to work at a much reduced SNR compared to the standard step-track scheme.

Edwards and Terrell used a least squares algorithm in order to fit the tracking data to the orbital model. Analysis, it is claimed, of the mathematical properties of the algorithm result in the RMS pointing error being reduced by a factor of typically 5.5. The factor of 5.5 improvement in allowable beacon level fluctuations translates to a corresponding improvement in operational SNR. That is random Gaussian beacon noise may be:

$$20 \log_{10} 5.5 = 15 \text{ dB} \tag{11}$$

times as great for SST as step-track for a given pointing performance. Therefore whereas step-track typically requires SNR 35–40 dB, SST will tolerate less than 25 dB tracking signal SNR.

Computer simulation of the tracking algorithm with a 0.035° step-cycle suggested an RMS tracking error of about 0.003° was possible. Practical trials were carried out using the 32 m Madley No. 3 Cassegrain antenna and an 8 m commercial Gregorian system. For the 32 m Madley antenna, using a 0.005° step-cycle, the tracking error did not exceed ±0.007° over a 3 day period. For the 8 m system, using a 0.05° step-cycle, the communication channel fluctuation is kept below 0.25 dB. The SST system, following this experimental work, was installed on the Goonhilly No. 1 antenna in 1983.

The use of a tracking system employing orbital estimation and optimal control techniques is presented by James and Maney [53] as a way of overcoming many of the special problems associated with shipboard satellite terminals. Of these, one of the most serious is the effect of the ship motion. This causes misalignments to couple into the antenna position as time-varying components with roll, pitch and heading frequencies and their cross harmonics. Standard autotrack techniques are adequate to track the satellite, but usually lack sufficient bandwidth to null these time varying errors.

James and Maney's approach for tracking the satellite and solving the misalignments is shown in simplified form in Fig. 12. The scheme utilises the Kalman filter operating on a nonlinear representation of the two orthogonal pointing errors and multiple pointing error measurements to solve for the multiple error sources. In these circumstances the pointing error model becomes a weighted sum of the misalignment variables, with time varying coefficients.

The results of a number of computer simulations are presented by the authors. These show the necessary convergence in the alignment corrections and their dependence on the measurement noise. Further it is clear a trade-off exists between the steady-state noise jitter and dynamic errors. In all, the results indicate that tracking

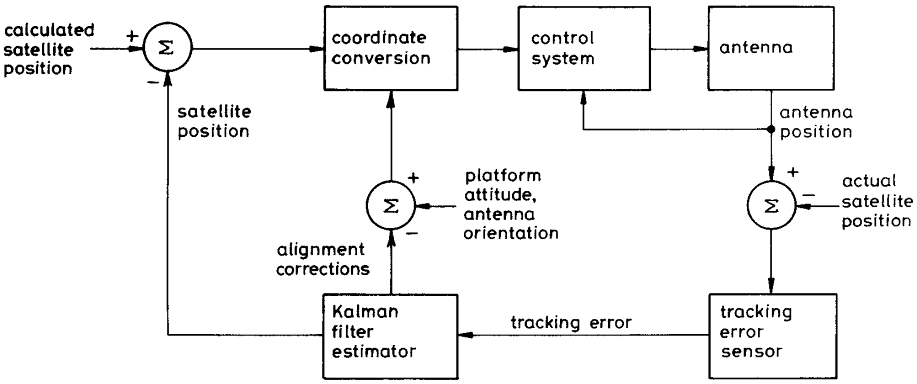

Fig. 12 *Maritime tracking system*

Table 1 : Summary of satellite tracking systems

Tracking category	Subcategory	Remarks	Performance	Usage
Manual		non-autotracking; simple; requires operator	tracking accuracy dependent on operator — generally low	many stations can revert to manual tracking if other tracking methods fail
Programme steering		non-autotracking; simplistic with modern technology; requires operator intervention; accuracy reliant on orbit prediction	tracking accuracies approaching 0.01° possible	often employed as back-up in case primary tracking system fails
Monopulse	Simultaneous lobing [1] Multimode — TM_{01} [2] — TM_{01}/TE_{21} [3] — orthogonal — TE_{21} [4]	autotracking tracking information obtained in a single time frame; 2, 4 or 8 channel coherent receiver required; expensive	tracking accuracy very good, typically 0.005°; operational SNR ∼15 dB; fast dynamic response	widespread in many of the larger earth stations; also shipborne terminals, sat-to-sat comms
Conical scan	Rotation of antenna [1]; rotation of offset feed [2]; rotation of sub-reflector [3]; TM_{01} mode [4]; TM_{01}/TE_{21} mode [5]; Conopulse [6]	autotracking; sequential amplitude sensing system; sensitive to AM interference; mechanically complex; uses single channel receiver; methods 1–3 result in modulation of uplink transmission	tracking accuracy typical 0.01°; operational SNR ∼30 dB; medium dynamic response	widespread up until mid 70s; monopulse and step-track then preferred
Step-track	step antenna [1]; nodding sub-reflector [2]	autotracking; sequential amplitude sensing system; sensitive to AM interference; simple low cost system; single channel receiver; method [1] results in high wear of mechanical drives	tracking accuracies of 0.01° have been obtained, typically <0.1°; operational SNR ∼30–45 dB; slow dynamic response	widespread where lower accuracy acceptable and cost important; many of the smaller earth stations, ship-borne terminals
Electronic beam steering	dipole feed [1]; TM_{01}/TE_{21} mode; conversion techniques [2]	autotracking; pseudoamplitude sensing system; much reduced sensitivity to AM interference; uses single channel receiver; relatively simple	tracking accuracy approaching monopulse, 0.005°; operational SNR 15–30 dB; fast dynamic response	use limited to mainly experimental tracking systems; shows good overall tracking performance; well suited to sat-to-sat comms; should be widely used in future

errors of less than 0.01° could be expected if using this system.

7 Conclusions

Over the past 25 years or so a number of error sensing techniques have been used in satellite tracking systems. These are summarised in Table 1.

Of these, two have become prevalent, they may be described as monopulse and step-track. The monopulse technique relies on sensing the received wavefront and processing the signal to derive the pointing information. By tracking the amplitude and phase of a higher-order wavefront, tracking errors less than 0.005° can be achieved. Unfortunately, the system relies upon at least a two-channel coherent receiver for its operation which incurs the penalties of mass and expense. Whilst such factors can be absorbed in a typical ground station, they represent a high penalty in terms of a spacecraft and the mass of the monopulse system leads to a reduction in the effective communications payload. In the case of step-track systems, a relatively simple noncoherent receiver can be used to sense the amplitude of the signal. Whilst this leads to a significantly cheaper implementation than the monopulse technique, the performance of the communications link is sacrificed and a minimum signal/noise ratio of some 30 dB is required for satisfactory operation. This is to be compared with a figure of 15 dB for the monopulse technique. Furthermore, as error detection of the system is not real-time it suffers from dynamic lag, the overall accuracy is degraded and the systems have significant dynamic limitations.

In the early eighties electronic beam squint techniques have emerged. These techniques, while still very much in the research stage, appear to have overcome many of the problems associated with the early systems. They offer a tracking accuracy and dynamic performance similar to that of the monopulse system while at the same time being relatively simple. Only a single-channel receiver is required, resulting in a relatively cheap and low mass system. In addition to this, the acquisition range of these techniques is considerably beyond that of monopulse systems as the error signal is derived from the primary beam of the antenna. The electronic beam squint system seems ideally suited for use in the next generation of satellite tracking applications as the trend towards digital processing continues.

Furthermore, the availability of cheap, small and powerful microprocessors offers the opportunity of applying signal processing techniques to satellite tracking. Theoretical and practical work in the areas of optimal estimation and orbital prediction show significant improvements in system performance can be achieved beyond that of simple error sensing. In many future systems it is clear that, such techniques, will form as much an integral part of the tracking facility as the type of radio-frequency sensing technique employed.

8 References

1 CHAPIN, J.C.: 'Antenna steering systems — past, present and future'. IEE Conference on Earth Station Technology, 1970, pp. 420–424

2 BLAKE, R.G.: 'Down-to-earth measure for space communication', *Post Office Telecom. J.*, Winter 1978/79, pp. 8–10

3 BRUSH, R.J.H., and BAYLIS, P.E.: 'An automatic high-resolution picture transmission station', *ESA Journal*, Vol. 8, 1984, pp. 425–435

4 CUMMINGS, D., and WILDEY, C.G.: 'Military aeronautical satellite communications', *IEE Proc. F*, 1986, **133**, pp. 411–419

5 ANDERS, J.V., HIGGENS, E.F., MURPHY, J.L., and SCHAEFER, F.J.: 'The precision tracker', *Bell Syst. Tech. J.*, 1963, pp. 1309–1356

6 PRATT, T.: 'High efficiency feeds with tracking capability'. IEE Conference on Earth Station Technology, 1970, pp. 250–256

7 MILNE, K., and RAAB, A.M.: 'Optimum illumination tapers for four-horn and five-horn monopulse aerial systems'. IEE Conference Publication 21, 1966, pp. 12–16

8 SCIAMBI, A.F.: 'Five-horn tracking feeds for large antennas'. IEE Conference Publication 21, 1966, pp. 158–162

9 SCIAMBI, A.F.: 'Five-horn feed improves monopulse performance', *Microwaves*, June 1972, **11**, pp. 56–58

10 COOK, J.S., and LOWELL, R.: 'The Autotrack system', *Bell Syst. Tech. J.*, 1963, pp. 1283–1307

11 LOZIER, J.C., NORTON, J.A., and IWAMA, M.: 'The servo system for antenna positioning', *Bell Syst. Tech. J.*, 1963, pp. 1253–1281

12 CHIVERS, M., and BRAIN, J.R.: 'A simple multimode tracking system for microwave aerials'. IEE Conference Publication on Satellite Communication System Technology, 1975, pp. 116–121

13 HAYASHI, R., TESHIROGI, T., KIMURA, S., KOMURO, H., YOSHIMURA, K., SUZIKI, Y., and AOYAMA, S.: 'ETS-II experiments part II: Earth station facilities', *IEEE Trans.*, 1980, **AES-16**

14 INOUE, T., and KAITSUKA, T.: 'K-band tracking system for domestic satellite communication system', *IEEE Trans.*, 1981, **AES-17**, pp. 561–570

15 CHOUNG, Y.H., GOUDEY, K.R., and BRYANS, L.G.: 'Theory and design of a Ku-band TE_{21} mode coupler', *IEEE Trans.*, 1982, **MTT-30**, pp. 1862–1866

16 SAVINI, D.: 'An improved automatic tracking system for linear and circular polarization', *CSELT Rapp. Tec.* (Italy), 1980, **8**, pp. 239–292

17 WATSON, B.K., DANG, N.D., and GHOSH, S.: 'A mode extraction network for rf sensing in satellite reflector antenna'. IEE Second International Conference on Antennas and Propagation, 1981, pp. 323–327

18 MOLKER, A., WATSON, B.K., and ERICSSON, L.M.: 'A tracking mode coupler for a circular waveguide feed system to provide off-boresight tracking capabilities'. Technical Note M1/KV8066, 5th July 1978

19 MOLKER, A., and ERICSSON, L.M.: 'Cross-polarisation effects on different rf sensing systems'. Technical Note M1/KV8099, 25th September 1978

20 REINDERS, M.A., and OEI, W.S.: 'Antenna feed system for a satellite station with linearly and circularly polarized beacon tracking capabilities'. NTG-Fachber (Germany), Vol. 57, June 1977, pp. 97–101

21 BROOKS, C.W.: 'Operational shipborne earth stations'. IEE Conference Proceeding on Satellite Systems for Mobile Communications and Surveillance, 1973, pp. 52–55

22 REED, A.G.: 'A purchaser's view of some developments in earth station technology'. IEE Conference Proceedings on Satellite Communications System Technology, 1975, pp. 102–109

23 WOOSTER, C.B., and MILLER, B.J.: 'Advances in Intelsat earth station technology'. Communication '78. IEEE Conference on Communications Equipment and Systems, Birmingham, 4–7th April 1978, pp. 220–224

24 SKOLNIK, M.I.: 'Introduction to radar systems' (McGraw-Hill)

25 HARRIES, G., and HEAVISIDE, J.W.: 'Naval satellite communication terminals'. IEE Conference Proceedings on Satellite Systems for Mobile Communications and Surveillance, 1973, pp. 48–51

26 HARRIES, G., and STANNARD, E.J.: 'Design of a small shipborne terminal ("SCOTT")'. IEE Conference Proceedings on Earth Station Technology, 1970, pp. 63–69

27 KNOX, D.M., and DOBLE, J.E.: 'The modified primary feed and tracking system for Goonhilly No. 1 aerial'. IEE Conference Proceedings on Earth Station Technology, 1970, pp. 201–207

28 MARCONI CO. LTD.: 'Satellite tracking system'. Patent UK 1171401, 24th January 1968, published 19th November 1969

29 LOCKETT, N.J.L., and SHINN, D.H.: 'Frequency selective conical scanning, using waveguide mode conversion'. IEE Conference Proceedings on Earth Station Technology, 1970, pp. 257–262

30 OHISON, J.E., and REID, M.S.: 'Conical scan tracking with the 64 m diameter antenna at Goldstone'. Contract NAS7-100, Jet Propulsion Lab. Calif. Inst. of Technology, Pasadena, October 1976

31 TOM, N.N.: 'Autotracking of communication satellites by the step-track technique'. IEE Conference Proceedings on Earth Station Technology, 1970, pp. 121–126

32 LARKIN, R.J.: Philco-Ford Invention Disclosure Memo, 16th October 1967

33 ELEY, R.G.: 'Auto-tracking receivers'. IEE Conference Proceedings on Earth Station Technology, 1970, pp. 302–308

34 OHASHI, H., IGUCHI, and HASHIMOTO, Y.: 'A geostationary satellite tracking system for small-sized earth stations', *Rev. Radio Res. Lab.* (Japan), December 1983, **29**, (153), pp. 527–538

35 RICHHARIA, M., and VERMA, N.N.: 'Design of a step-track for low cost earth stations', *IETE* (*India*), 1982, **28**, pp. 533–538

36 JOHNSON, M.B.: 'Antenna control system for a ship terminal for MARISAT'. IEE Conference Proceedings on Maritime and Aeronautical Satellite Communications and Navigation, 1978, pp. 123–126

37 SHIOKAWA, T., KARASAWA, Y., and YAMADA, M.: 'Compact antenna systems for INMARSAT Standard-B ship earth stations'. IEE Conference Proceedings on Maritime and Aeronautical Satellite Communications and Navigation, 1978, pp. 95–99

38 VOLDBY, J.E.: 'A new satellite receiver at Rude Skov. II', *Elektronik* (*Denmark*), January 1978, **1**, pp. 10–14

39 HUELE, H.T.: 'An earth station for weather satellites', *Philips Telecom. Rev.*, September 1981, **39**, pp. 118–129

40 EDWARDS, D.J., and WATSON, B.K.: 'Electronic tracking systems for microwave antennas'. British Patent Application No. 8414963, 12th June 1984

41 DANG, R., WATSON, B.K., DAVIS, I., and EDWARDS, D.J.: 'Electronic tracking systems for satellite ground stations'. 15th European Microwave Conference, Paris, France, September 1985, pp. 681–687

42 WATSON, B.K., and HART, M.: 'A primary-feed for electronic tracking with circularly-polarised beacons'. Proceedings of Military Microwaves, Brighton, June 1986, pp. 261–266

43 PRIME, H.A.: 'Application of optimal control techniques to large steerable aerials'. IEE Symposium on Design and Construction of Large Steerable Aerials, June 1966, pp. 39–44

44 STACEY, B.A., and PRIME, H.A.: 'The application of search techniques to autotracking'. IEE Conference Proceedings on Earth Station Technology, 1970, pp. 133–139

45 CHOI, J.: 'Comparison of real-time tracking algorithm for airborne target'. Conference Proceedings IEEE Southeastcon '85, USA, 31st March–3rd April, 1985, pp. 139–143

46 RAGHAVAN, S.V., and SATYANARAYANA, T.: 'Microprocessor-based digital controller for antenna pointing systems', *IETE* (*India*), 1983, **29**, pp. 57–61

47 RAOL, J.R., and SINHA, N.K.: 'On the orbit determination problem', *IEEE Trans.*, 1985, **AES-21**, pp. 274–290

48 RICHHARIA, M.: 'An optimal strategy for tracking of geostationary satellites', *JIETE* (*India*), 1984, **30**, pp. 103–108

49 EDWARDS, D.J., and TERRELL, P.M.: 'The smoothed step-track antenna controller', *Int. J. Sat. Commun.*, 1983, **1**, pp. 133–139

50 SLABINSKI, V.J.: 'Expressions for the time-varying topocentric direction of a geostationary satellite', *Comsat Tech. Rev.*, 1975, **5**, pp. 1–14

51 DRESSLER, R.M., and TABAK, D.: 'Satellite tracking by combined optimal estimation and control techniques', *IEEE Trans.*, 1971, **AC-16**, pp. 833–840

52 ORLANDO, V., and NETO, O.M.: 'Development of an algorithm for real-time control of a satellite tracking system'. 13th International Symp. on Space Technology and Science, Tokyo, 27th July 1982

53 JAMES, M.B., and MANEY, J.J.: 'Adaptive alignment of a shipboard satellite terminal'. Military Communications Conference, MILCOM '85, Boston, USA, October 1985, Vol. 1, pp. 300–305