PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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1. Historical background

The decision to initiate radio and radar satellite tracking work at the Royal Radar Establishment was taken at the end of 1960, and followed directly from our experience in working with Echo 1 satellite.

During the week following its launch, positional information on Echo 1 was transmitted to N.A.S.A. Goddard Space Flight Center by teletype. The equipment used was a 10 cm radar feeding a 45 ft. paraboloid dish aerial, which was steered by slaving to an optical sight; it was a system adapted in a hurry from its main work programme of Moon-echo investigations, and very limited in its capability for extended satellite tracking work.

In order to participate in communications tests via Echo 1, another aerial was recovered from disuse and pressed into service at short notice. This was a 20 ft. wood-and-wire-netting device. A primitive system of semi-automatic steering control was designed and built, a receiver on 960 Mc/s headed by a parametric amplifier was supplied by the Post Office Engineering Department, and, after 10 days' intensive work, signals were received at Malvern via Echo 1 from Bell Telephone Laboratories, Holmdel, New Jersey. Although the signal level was below the frequency-modulation threshold, so that intelligible speech could not be received, the signal strength was measured to be within half a decibel of its theoretically predicted value for the air-and-space transmission path.

This successful initial experiment, performed jointly by the Post Office and R.R.E., was a landmark in the progress of U.K. work in the space/ground environment, and led by separate paths to Goonhilly Downs and the present R.R.E. Satellite Tracker. The influence of the 1960 experiment, and in particular the prediction-aided pointing control method used, can be discerned at both installations today.

2. Description of the Malvern facility

The basic element of the present system at Malvern is a 45 ft. paraboloid dish specially constructed with the rigidity requirements of servo-controlled autotracking in mind. Control at the full accuracy of better than $\pm 0\cdot 01^\circ$ in angle is maintained at angular rates up to $2\frac{1}{2}^\circ$/s, giving a dead zone for overhead satellite passes of approximately 100 km radius centred on Malvern. The mounting is of the conventional Altitude/Azimuth type, and the main servo drives have very closely controlled velodyne characteristics and high-speed anti-windage loops. For a photograph of the dish see plate 1.

The optics of the aerial can be chosen to be single-feed or static-split at will, and of principal-focus or Cassegrain form. Auxiliary structures provide ready access to both focus positions for installation and maintenance. Such flexibility was a conscious design target—it was recognized from the outset that the facility would be unique in the U.K.—and on several occasions the operating mode has been changed completely (e.g. from radar tracking for orbit improvement, to communications tests on a different wavelength) between two passes of a given satellite. In addition, facilities exist for reading telemetry on 136 Mc/s while tracking by radar at 10 cm, and a newly fitted semi-transparent Cassegrain subreflector is expected to extend simultaneous multifrequency operation to 3 cm wavelength.

A variety of pointing-control methods is available. Pure autotracking, with the servo loop closed on the aerial's angle sensors, is available but rarely used, because of its inherent inaccuracies and also because of the radar reflexion characteristics of the majority of space objects. A large second-stage rocket body, when tumbling in free space, can show specular reflexions from its cylindrical sides up to 40 dB in excess of its general signal level. In principle, this could increase the tracking capability of the system by a factor up to ten in range, compared with its capability against a non-fluctuating target as expressed by its radar parameters. To exploit this, a prediction-aided system is used: the aerial is steered across the sky by means of a paper control tape, previously prepared off-line by an Elliott 803A computer which forms part of the system, and corrections to the predicted track are applied manually in accordance with error indications derived from the angular sensors on the aerial. The nonlinear perception and integration capabilities of the trained human operator have proved invaluable in this work.

The same computer is also used for processing digitally recorded satellite position data both during and after a pass. A three-dimensional track point, with time, can be made available at a remote site by line teleprinter within 20 s of recording, and this facility has been used regularly to slave remote aerials, at R.A.E. (Farnborough) and S.R.D.E. (Christchurch), onto satellite targets.

This rather slow computer is used for operations planning, control data preparation, recorded data processing, and when necessary for local orbit determination; hence it is in a state of continuous overload, and in fact it forms the bottleneck in the main information loop of the system. During 1967 it is hoped to introduce a small, fast computer to supply the background of pointing-control data on-line, with the object of relieving the 803 of the data preparation load and thereby doubling the number of tracks that can be handled in any given time. The present limit is between twenty and thirty fully-instrumented tracks per week, depending on the number of satellites involved and the configurations of their orbits.

3. Accuracy and alinement

The position reference for the Malvern Tracker is the crossed-axis point of an associated optical tracking sight, which is equipped with two 4 in. aperture telescopes and sited on a tower in the vicinity of the main aerial. The reference point was established by first-grade survey, and quoted with reference to both Airy's and the International Spheroid in three dimensions to perhaps unnecessary accuracy. This sight also provides the basic reference for North and Upright for the system, which is then checked through step-by-step.

The survey provided azimuths and elevations of various local landmarks, which are used initially after careful levelling of the sight. Orientation is then improved by sighting on stars, to obtain an optimized system of axes relative to the ground, a process requiring about a fortnight's work and performed about once a year. Shaft positions so determined are transferred with extreme care to all other shafts in the system by coarse/fine synchro techniques. Levelling of the aerial mount is accomplished independently, after which the mechanical axis of the aerial is checked against that of the master optical sight, via the synchro system, by means of a boresight television camera, attached to the aerial, which is capable of detecting a dozen or so of the brighter stars and planets.

The electrical or radar/optical boresight of the angular detection system is then alined to the mechanical axis of the aerial by the use of a collimation site on the local hill, 1 mile distant at 7° elevation. This alinement check is performed on a weekly basis. Finally a test is made for selective misalinement by tracking one or other of the Echo balloons, simultaneously by radar, by optical master sight, and by boresight television. Radar ranging is checked against an internal substandard before every tracking pass, and once a week against prominent television masts in the Midlands area.

Many individual sources of error are thus compounded when one attempts to describe the observed position of a fast-moving satellite in ground coordinates. At Malvern, the contribution of each error source has been held down to better than $\pm 0{\cdot}01°$ in angle and ± 100 m in range, with the exception of one gear train which slightly exceeds this figure. As a result, we believe that no satellite track point ever leaves the Malvern Tracker, unless accompanied by a query mark (?), which is not accurate to $\pm 0{\cdot}1°$ in angle and ± 1 km in range. Actual calibrations against satellites in 'known' orbits show results better than this, with residuals often dependent, one feels, on the qualities of the reference orbits used. Typical peak residuals have been of the order 0·03° (2′), with distributions inside this figure more systematic than random.

4. Radar performance

Overall radar sensitivity is calibrated about once every three months, or when system improvements are made, either against a balloon-borne 12 in. sphere (for the high-signal end of the dynamic range) or against a copper-plated ping-pong ball (for signals within 10 dB of threshold noise). In the latter case the target is ejected from the signalling pistol of an aircraft at high altitude over the Irish Sea, at ranges up to 200 mi, and tracked for up to 5 min in free fall. Confidence in these results is ± 1 dB or better.

With this sensitivity, a useful radar range performance is available against typical satellite targets. Horizon-to-horizon tracks are obtained on all low-level rockets and most payloads, but medium-level stabilized payloads are often very difficult targets. Detection range for both the Echo balloons is horizon limited. The maximum radar range yet recorded (excepting the Moon) was a track to 9200 km on Pageos-A, in late summer 1966. Work towards further improvement in transmitter power and receiver noise performance forms part of the continuous programme of system development.

5. Operating problems and methods

The radar beamwidth of the Tracker is of the order $\frac{1}{3}°$ between half-power points; it can be visualized as having half the angular cross-section of a cigarette-end held at arm's length. Even when a search pattern can be used, the effective field of view is limited to perhaps $3^\circ \times 3^\circ$ overall. Target acquisition is therefore a major problem, and considerable effort is expended at the facility to achieve this.

The most common error in prediction is in a satellite's position along-track, since this is a cumulative function of any error in the determination of orbital period. To counter this, the technique of the 'spot check' is used, in which every satellite of current interest is observed at least once per day, by timing its transit through the radar beam while the latter is held fixed in the direction of the satellite's point of closest approach. If it is suspected that the predicted position is in error by more than about 60 s of time, allowance is made for the rotation of the Earth during the observing period. The success rate in spot-check observations during the past 9 months has averaged 58%, so that satellites are observed by this method every five to ten minutes throughout a normal working day. Properly organized, the procedure is simple and economical in manpower.

This very considerable flow of observed information gives rise in its turn to a book-keeping exercise. Timing data, early or late, are entered on a file card for each satellite in the current target list, at the time of the observation. From these cards it is possible to extrapolate to determine the time correction applicable to a satellite pass at any reasonable time in the future, and by this means the success rate for full-duration tracks has been raised from 23% (1964) to 85% (1966). Of the 15% residual failures, about half are attributable to insufficient or faulty orbital data—the 'high risk' tracks undertaken, despite known lack of information, because of the operational urgency of establishing, for instance, an immediately post-launch orbit—and the remainder are found to be due to equipment faults, weather, and ever-present human errors.

Orbital elements published by the Spadats system of Norad form the normal basis for this work. When timing errors are observed to be less than about 60 s, pure time-corrections are used. Outside this limit, it is usual to adjust the satellite's mean anomaly in orbit, and to apply corrections also to the period and its derivative when sufficient spot-check or track data are held on file to permit this. When other parameters are found to be in error, as they frequently are (particularly for the balloon satellites), local track observations at Malvern can be used to generate home-made orbits for use up to a week after epoch. We have found that when a satellite is misbehaving badly these locally generated orbits are the most reliable we can obtain for our own acquisition purposes; but it does not follow that single-station observations at Malvern can be used to provide accurate predictions over the Pacific Ocean.

6. Empirical handling of drag and decay

Particular difficulties arise during the last few days of a satellite's life, when atmospheric drag becomes progressively and in the end catastrophically significant and all elements of the orbit are changing rapidly. At Malvern the main interest in this phase is not so much in the properties of the upper atmosphere, and its inconsistencies, as such, as in devising techniques by which smooth target acquisition can be ensured while the brakes are on. The higher-order derivatives of the orbital period grow progressively more important, and at the same time more difficult to measure; it was felt that any attempt to improve accuracy of prediction by conventional means was bound to fail.

In the final decay condition the eccentricity of the orbit has generally become so small that slowing occurs not only in the vicinity of perigee, but is distributed virtually all round the orbit. King-Hele (1959, 1966) has analysed this regime, and provided equations by which the decay plunge can be forecast, to an accuracy of about 10% of the time remaining, from a knowledge of present eccentricity, period, and deceleration ($\dot{p}$). His theory predicts an approximately hyperbolic change in $\dot{p}$, from its present value, towards infinity at the moment of decay. In practical terms, if $1/\dot{p}$ is plotted graphically from its present value to zero at forecast decay, the result will be very nearly a straight line. The eccentricity (e) simultaneously follows a similar law, with e^2 tending linearly to zero.

On this basis, the progressive variations of all dependent orbital parameters can be determined, and predictions of the contraction of the orbit can be made with fair accuracy. A major virtue of the method is that no detailed knowledge of the state of the upper atmosphere is needed, nor is it necessary to make assumptions concerning the drag cross-section and mass of the particular satellite. The satellite carries with it, in its present behaviour, an indication of how it will perform in the later stages of its decay.

The 803 computer has been programmed after King-Hele's theory to provide the orbital predictions needed for acquisition at Malvern, with reasonable success. Several satellites have been followed through, track by track, to their last passes visible from Malvern, an achievement which would have been impossible before the new process was introduced. The method is not exact, however, and deviations from the linear law of $1/\dot{p}$ have been observed sufficiently often to make us believe that they are real; in particular, it appears that one variation with periodicity 10 to 14 days may be present.

Studies on these lines continue.

References (Murray)

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