Computing and Data Transmission for the Prediction Steering of the Goonhilly Satellite-Communication Aerial*

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The Goonhilly satellite-communication aerial uses an 85-ft. diameter paraboloidal reflector with waveguide feed at the focus. The aerial is movable in azimuth and elevation, and is provided with independent feedback control systems for these two motions. During a satellite pass, the aerial must be steered so that its axis points continuously, and with high accuracy, in the direction of the satellite. Of the various possible methods of achieving this result, that based on prediction of satellite position has been adopted for the first transatlantic communication experiments using the Telstar and Relay satellites. The process by which orbital predictions originating in the USA are converted to substantially continuous real-time azimuth and elevation pointing instructions at Goonhilly is described herein.

PLANNING CONSIDERATIONS

The following considerations influenced the planning of the system. On one hand, data on the observed position of the satellite at known times would be received at the Goddard Space Flight Center, USA from various sources, including the world-wide Minitrack network of tracking stations, and would be processed there to derive the basic parameters of the satellite orbit, from which the future position of the satellite could be predicted. On the other hand, the need at Goonhilly would be to present to the inputs of the azimuth and elevation control systms, 50 times per second throughout a satellite pass, statements of the azimuth and elevation required at each instant (the "demanded" azimuth and elevation) in digital form to the nearest 2^{-16} revolution (0.33 minute of arc).

The passage from orbital elements known in advance at GSFC to angular demands in real time at Goonhilly would involve considerable computation and, at some stage in the process, transmission of data

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across the Atlantic. The computation could be begun in advance at GSFC, continued in advance at Goonhilly, and completed in real time at Goonhilly; the division of the work between these three stages was a matter for practical compromise. Advance computation at GSFC would reduce the computing load at Goonhilly (and at any other stations that might use similar data) but would increase the volume of data to be transmitted. At Goonhilly, the experimental nature of the project would make it appropriate to carry out as much of the remaining computation as possible in advance; for this purpose it would be possible to employ a general purpose computer of well established design, which could also be used part-time for other work such as the analysis of records. The results of the advance computations could be checked before the time of the satellite pass. However, the need for subsequent data storage (e.g. on punched paper tape) would set a limit here, and it would be convenient to leave some simple computing to be carried out in real time by special purpose apparatus in the aerial control equipment.

DESCRIPTION OF THE PROCESS

The considerations mentioned above have led to the following arrangements. At GSFC, the satellite position is predicted for intervals of one minute throughout each pass, and is expressed in topocentric Cartesian coordinates, i.e. in a rectangular coordinate system with axes in the direction East, North, and Vertical and origin at the centre of motion of the Goodhilly aerial. Predictions in this form are transmitted to Goonhilly over a transatlantic telegraph circuit, and the receiving teleprinter produces simultaneously a page print and a perforated tape (the "Predictions Tape"). The data for each minute occupy one line of the page print and are accompanied by a "sum of digits" check. The data message includes a statement of the time to which the first prediction for each pass refers, and is sent in a standard format covering not only features visible on the page print but also the incidence of all functional characters (carriage return, shifts etc.) that will be punched on the Predictions Tape. The time taken in transmission is about six seconds for each minute of a satellite pass. When the orbital elements for a particular satellite are well established, predictions can be sent once a week, to cover all the time during the ensuing week that the satellite will be above the Goonhilly horizon.

At Goonhilly, advance computations are carried out by a small general purpose computer. The Predictions Tape is used directly as data input to the computer, and the first operation is to check the validity of the whole data message (normally covering many passes), applying the sum-of-digits check and examining the tape for errors in format. This operation is quite quick (0.13 second for each minute of pass) and is preferably concurrent with the reception of the data; if an error is detected, all the data for the pass affected are transmitted again.

For those parts of selected passes that are to be used for communication experiments, a further run on the computer, with the Predictions Tape as data input, calculates and prints azimuth, elevation and range for one-minute intervals. This run takes 1.2 seconds of computer time for each minute of pass. The print is useful to show the general nature of each pass. Specifically, it enables the operator to make a decision that is needed because the aerial is not designed to rotate continuously in azimuth, but has a range of movement limited to 500 degrees, so that over a range of 140 degrees any direction has two alternative numerical values; therefore two sets of azimuth values are printed and if one set shows a discontinuity the other must be selected. This decision accompanies the input data to the computer for the next operation.

The next stage represents the main computing operation undertaken at Goonhilly, and comprises the preparation by the computer of a punched paper tape — the "Control Tape" — bearing detailed azimuth and elevation data for the passes of interest. The Predictions Tape again constitutes the data input to the computer. Working in the rectangular coordinate system, fifth-order interpolation is used to derive values for one-second intervals from the one-minute data received from GSFC. Azimuth and elevation are then deduced for the one-second intervals. Finally, second-order interpolation is used to obtain the full details required on the Control Tape, (Appendix 1) and the tape is punched.

The computer programme is so arranged that corrections whose values are predictable can be applied to the calculated quantities in the course of this operation. An obvious need is for a correction in elevation to take account of the effect of atmospheric refraction; this correction is based on prior knowledge and has been included from the outset. If operational experience brings to light any systematic departure of the electrical axis of the aerial from its mechanical axis* suitable corrections can be added later.

* In this context, the term *mechanical axis* means the direction defined by the readings of the shaft-angle encoders that measure the *actual* position of the aerial.

bits, these sub-routines could be replaced by less precise, and consequently faster, versions.

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The National Aeronautics and Space Administration evolved the scheme for the telegraphic transmission of data, and have supplied the remarkable accurate predictions on which the steering of the Goonhilly aerial has been based.

APPENDIX 1

DETAILS OF CONTROL TAPE

The ultimate requirement is to present to the inputs of the azimuth and elevation control systems of the aerial, in real time 50 times per second, a complete statement of the demanded azimuth and elevation in digital form to the nearest 2^{-16} revolution. This represents 17 bits for azimuth (the range of azimuth motion being 500 degrees = 1.39 revolution) and 15 bits for elevation (100 degrees = 0.28 revolution). It is impracticable to store all these data on punched paper tape, and incremental operation must be adopted.

Suppose that, to describe the demanded azimuth (or elevation), a single incremental value is specified and that this is added to an accumulated number every 1/50 second. The result, assuming that the 1/50 second discontinuities are smoothed, will be a quantity increasing linearly with time, representing a demand for a constant angular velocity. A real demand, in which the velocity will not in general be constant, can be approximated by changing the value of the increment from time to time; the real curve of angular position as a function of time will then be approximated by a series of chords. The process is analogous to linear interpolation between given values in a mathematical table, and it can be shown that the maximum error that could be incurred (i.e. the maximum possible departure of the chord from the true curve) is given by

$$e = \tfrac{1}{8} (aT^2),$$

where T is the time-interval over which a constant increment is added repeatedly, a the maximum acceleration during this interval, and e the upper limit to error during this interval.

The solution adopted is to prescribe increments on the tape for intervals of 1/5 second, so that any one increment is added 10 times. The formula shows that the error will not exceed 0.4 minute of arc at the maximum acceleration assumed in the structural design of the aerial (1.33 degrees per second per second).

Such increments of azimuth and elevation constitute the main content of the Control Tape. However, a complete specification of demanded azimuth and elevation is essential at the beginning of an automatic run, and is very desirable at intervals afterwards, so that any casual error may not be perpetuated. The complete demanded azimuth and elevation are therefore punched on the tape for intervals of one second. This has the desirable result that the concept of a specific "starting" condition is avoided; automatic control can begin at any desired time (within about one second) during the period for which a Control Tape has been prepared. The scheme lends itself to a one-second cycle in the punching of the Control Tape and the operation of the digital part of the aerial control equipment.

A 5-track tape is employed; four of the tracks are used for numerical data, the fifth being reserved for a signal indicating the beginning of each one-second cycle. The complete punching scheme for one cycle is shown in Table 1.

TABLE I — PUNCHING OF CONTROL TAPE

Item	Number of rows
Cycle-start signal	1
Time (hr, min, sec)	6
Demanded azimuth	5
Demanded elevation	4
Slant range	3
Five increments of azimuth	10
Five increments of elevation	10
Tape code	3

APPENDIX 2

CHECKING OF CONTROL TAPE

The programme which checks a Control Tape determines that:

1. Cycle-start signals appear as prescribed

2. Time, azimuth, elevation, and tape code are within appropriate limits; e.g. the hours in a time must be less than 24, and the minutes and seconds less than 60. For azimuth and elevation this check is applied not only to the completely punched values but also to those that will subsequently be formed in the aerial control system by adding the increments.

3. Time, azimuth, and elevation are continuous: i.e. each time is one second later than the previous time; and each azimuth (or elevation) agrees with that formed by summing the azimuth (or elevation) value and increments of the previous second, due allowance being made for the effects for rounding-off in calculation.