Radio Tracking at Winkfield

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1. Introduction

Winkfield is one of the stations in the Space Tracking and Data Acquisition Network (Stadan) of the U.S. National Aeronautics and Space Administration (N.A.S.A.) and is operated by the Radio and Space Research Station as a joint venture with N.A.S.A. The stations in the network, using standardized equipment supplied by N.A.S.A., receive by radio telemetry measurements from the various experiments in the satellites; they command the functioning of satellites and they track them. Tracking, with which this paper is concerned, means the measurement of quantities which contribute to the determination of the positions of satellites as a function of time. About ten stations in the network use tracking equipment and methods identical with those used at Winkfield. The network operates 24 h a day, its functioning being coordinated by the Goddard Space Flight Center of N.A.S.A. by means of teleprinter circuits which also serve to convey the raw tracking information from the stations to the N.A.S.A. computer facilities.

2. Tracking equipment at Winkfield

Radio signals, usually carrying telemetry information, are received from satellites in the 136–137 Mc/s band and, for tracking purposes, are picked up on either of two concentric interferometers. The main aerials of each are arranged at the corners of a horizontal square, the diagonals of which are some 50 wavelengths long and lie in the north–south and east–west directions. Consider a plane wave arriving at an angle θ to the north–south base-line and ϕ to the east–west base-line. The path difference expressed in wavelengths between the waves reaching the north and south aerials will be $s \cos \theta$ and, in the case of the waves arriving at the east and west aerials, $s \cos \phi$, where s is the aerial spacing in wavelengths. Measurement of the phase differences between the respective pairs of signals determines θ and ϕ and therefore the direction of incidence of the wave. The large value of s used enables small changes in the direction of incidence of the wave to be detected but introduces ambiguities in the measurement of that direction. Consider, for example, a wave incident from the south at an angle of elevation of 60°; the phase of the signal delivered by the south aerial will be $25 \times 2\pi$ radians in advance of that from the north aerial and a phase meter will indicate this as zero phase difference. But zero phase indication will also be given for all values of θ in which the path difference between the waves arriving at the north and south aerials is an integral number of wavelengths. This difficulty is overcome by the use of auxiliary aerials also arranged along the north–south and east–west directions but at much smaller spacings; measurements of the phase differences between these pairs (known as 'medium' and 'coarse') together with those from the widely spaced 'fine' aerials enable the ambiguities in direction to be resolved.

Each of the fine aerials has a fan-shaped beam directed vertically upwards: for those of the 'equatorial' interferometer, the narrow direction (11° between 3 dB points) lies in the east–west plane and the wide direction (80° between 3 dB points) in the north–south plane. Since the reception pattern of the aerials defines that of the interferometer, it will be seen that this interferometer will give the best signal/noise ratio for signals incident within the fan which, for a satellite at 500 km height, extends over overall plan distances of roughly 800 km north to south and 100 km east to west of the station. The 'polar' interferometer, arranged concentrically with the first, has similar characteristics but with the elongated part of its reception pattern lying in the east–west direction. Either the polar or equatorial system may be switched into use as required, depending on the direction of the satellite motion past the station. The ambiguity resolving aerials have wide, vertically directed reception patterns and are suitable for use with either of the interferometers.

The interferometers are calibrated two or three times a year by means of a transmitter carried on a high-flying aircraft. A flashing light, synchronized via a radio link to the clock on the ground against which the radio interferometer measurements are timed, is located at the centre of the transmitting aerial system below the aircraft. A camera at the centre of the interferometer systems is used to photograph the track of the aircraft against the star background and, at the same time, interferometer measurements are made using signals from the airborne transmitter.

We now turn to the phase-measuring equipment which, as mentioned above, may be switched to the fine aerials of the polar system or to those of the equatorial system depending on the track of the satellite past the station. Six separate phase-difference measurements have to be made as a function of time; that is between signals from the north and south fine, medium and coarse aerials, and similarly between signals from the east and west aerials. The principle of the method of measurement is the same in each of the six cases; we choose the north–south fine measurement as an example. The signal from the north aerial is heterodyned to an intermediate frequency by means of a crystal oscillator, and that from the south aerial by means of a voltage controlled oscillator. The frequency of the latter is arranged by means of a servo-loop to be 100 c/s above that of the crystal oscillator. This is achieved by mixing voltages from the two oscillators, extracting the beat note, comparing it with a standard 100 c/s voltage (derived from a highly stable source) in a phase comparator and using the output from the comparator to control the frequency of the voltage controlled oscillator. Thus, the intermediate frequency signals from the north and south aerials when added together produce a signal amplitude-modulated at 100 c/s. This composite signal is passed through a single chain of crystal-controlled frequency changers and intermediate frequency amplifiers and finally to a detector where the 100 c/s signal is extracted. It will be observed that if the movement of the satellite causes a change δ to occur in the phase difference between the radio frequency signals from the north and south aerials, this will result in a change δ in the phase of the 100 c/s output signal. Thus, apart from a constant, the required phase difference between the signals from the north and south fine aerials is equal to that between the 100 c/s output signal and the 100 c/s signal used in the frequency changing process at the beginning of the receiver chain. The calibration constant is determined by applying locally generated, cophasal radio frequency voltages to the input terminals of the north and south fine receiver before each satellite pass; a check is also made after each pass.

After passing through a narrow band-pass filter (bandwidth adjustable between 0·03 and 3 c/s, depending on the angular rate of the satellite) the phase of the 100 c/s output signal is compared with that of the reference. The phase difference, measured by a digital method, is expressed as three decimal digits, the full 360° thus being quantized into 0·36° units: this applies to the fine aerial measurements but in the case of the medium and coarse, two digits are used corresponding to steps of 3·6° of phase difference.

All the phase measurements are made cyclically and automatically and appear on a punched paper tape in a format which is identical throughout the Stadan. In the print-out of the tape, each line covers measurements made over 1 s of time. A line comprises five values of north–south fine phase differences at 0·2 s intervals, five of east–west fine similarly spaced in time, and one each of north–south and east–west medium and coarse values. Also included in each line are five values indicative of the received field-strength from the satellite, a digit to show which of the two interferometers is in use, two digits identifying the observing station, and a total of nine digits showing time as day of year, hours, minutes and seconds.

After a pass of a satellite, the central part of the paper tape, covering usually the 30 s or 1 min in time when the satellite crossed the meridian (or due east or west) of the station, is extracted, prefaced with one line of information punched during the pre-pass calibration referred to above, and sent by teleprinter to the Goddard Space Flight Center.

3. INSTRUMENTAL PERFORMANCE

The quantization of the fine phase differences into units of 0·36° corresponds at zenith to about 4″ in the respective cardinal directions. Examination of a few records obtained with a filter bandwidth of 1 c/s, suggests that, for this bandwidth and for inputs to the fine receivers in excess of −110 dBm, noise does not introduce significant scatter in the phase difference measurements, but at −120 dBm some deterioration becomes evident. These receiver inputs correspond to incident power fluxes from a satellite of about 6×10^{-16} and 6×10^{-17} W/m^2 respectively or field strengths of about 0·5 and 0·2 μV/m.

The direction of the radio zenith of each fine aerial pair of the interferometers is deduced from the aircraft calibrations, and provides a correction to the results obtained from satellites. From the practical point of view, therefore, it is the change of the correction during the period of a few months between calibrations which is of importance. Taking all four fine aerial pairs together and the results of twelve calibrations spread over a period of $5\frac{1}{2}$ yr, the average change of correction from one calibration to the next is about 11″; the maximum change which has been observed on any aerial pair is about 40″.

The internal time standards at Winkfield are of high stability and are compared at intervals during each day with time ‘as received’ from high frequency, standard-frequency transmitters such as WWV or MSF. Taking account of experimental errors in the comparison, it is considered that the maximum error of the station clock at any given time relative to ‘received’ time is less than $\frac{1}{2}$ ms. An error of 1 ms corresponds to an effective angular error of about 4″ for an overhead satellite at a height of 400 km.

4. The scale of operations at Winkfield

The station was established in November 1960 and, until the spring of 1962, was manned only at times of passes of the very few satellites involved. From that time the station has been operating 24 h a day and there has been a considerable and continuing increase of its work. Thus, for example, in the second 6 months of 1962 there were about 700 tracking, 1300 telemetry and 400 command operations on thirteen different satellites; during the corresponding period of 1964 the figures were 2500, 2900, 800 and 23 respectively; and during the first half of 1966 the respective numbers were 4200, 3200, 1500 and 34.

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