The Goonhilly 85-ft Steerable Dish Aerial*

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The choice of the basic type of aerial for a satellite communication ground station is of major importance in view of its influence on the overall performance, cost and time to complete the installation. In the case of the Post Office satellite communication earth station at Goonhilly Downs, Cornwall, a decision was made early in 1961 to use an 85-ft diameter steerable paraboloidal dish aerial, without a radome for tests with the Telstar and Relay, and other communication satellites.

Tests with smaller paraboloidal dish aerials with the feed in the aperture plane had shown that a satisfactory electrical performance could be obtained, and experience with the 250-ft diameter radio-telescope at Jodrell Bank had shown that the mechanical problems could be overcome.

An important factor in the present case was the limited time—less than one year—available for the design, manufacture, construction and testing of the aerial.

DESIGN REQUIREMENTS

To specify for design purposes the requirements for such an aerial it is necessary to know the frequency range and aerial gain required, the feed arrangements and radiation patterns needed, the orbits of the satellites and the proposed method of tracking, the nature of the ground on which th aerial is to be built and the weather under which it must operate.

Radio waves in the spectrum 1000 to 10000 Mc/s are suitable for satellite communication and the Post Office decided for the Goonhilly aerial to limit its interest to the range up to 8000 Mc/s. In the case of

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Projects Telstar and Relay it had been decided that the critical satellite-to-ground link would operate at about 4000 Mc/s, with the ground-to-satellite link operating at about 6000 Mc/s (Telstar) and 1700 Mc/s (Relay). System study showed that an aerial gain of the order of 55 to 60 db was desirable at 4000 Mc/s and an 85-ft diameter 90° dish was chosen, giving a theoretical gain of 58 db.

By careful design of the feed unit mounted at the focus in the plane of the aperture the noise picked up on minor lobes could be minimised. As this would mean some fall-off in illumination toward the edge of the reflector the profile tolerance could be eased in the outer zone. The tolerance $\pm\lambda/16$, i.e. $\pm\frac{3}{16}$ inch in this case, was applied to the central area out to 50-ft diameter, and twice this tolerance between 50-ft and 85-ft diameter. These tolerances were to be maintained under all weather conditions and angles of elevation. Combined feed units for transmitting and receiving were expected to weigh several hundred pounds, and to hold them at the focus quadrupod legs were favoured straddling the centre of the reflector, leaving it free, if desired, for later conversion to Cassegrain feed. Model tests showed that the shadow cast by four legs 90° apart and springing from the bowl on a 35-ft diameter circle would be acceptable. Two of these legs at 90° and 270° could provide direct waveguide access to apparatus cabins at the back of the bowl near its horizontal axis whilst the other two legs at 0° and 180° could carry other services.

To cater for all likely orbits (circular and elliptical) in equatorial, polar or inclined planes and to follow satellites with periods as short as two hours and heights of only a few hundred miles at perigee the aerial must provide hemispherical coverage and be able to move rapidly. For the experimental aerial the velocity and acceleration were limited to 2° per sec and $1.33°/\text{sec}^2$ respectively, sufficient to track satellites not passing through or near the zenith. The beam-width at 4000 Mc/s, using only 0.2° at the half power points, a tracking accuracy of one-third the beam-width was called for. Steering was required to be from punched tape derived from orbital data transmitted to the Goonhilly Radio Station from the Goddard Space Flight Center. Time information would be provided by a high-precision quartz clock with the facility for checking against radio time signals.

The aerial site on Goonhilly Downs, Cornwall, is on the highest part of the Lizard peninsula with all-round freedom from obstruction above ½° elevation. According to Geological Survey Department records the whole area for at least half a mile beyond the site boundaries rests on solid rock over 1000 ft deep which forms the largest single mass of

Serpentine in Cornwall. The rock is tough, has indistinct cleavage, and is a very suitable base for reinforced concrete foundations on which to mount a precision instrument.

A study of wind records for the Lizard peninsula for the last forty years showed that although high winds peaking up to 90 mph for short periods could be expected almost annually, higher figures were most unlikely, and winds above 100 mph virtually unknown. Using a gust factor of 1.4 appropriate to the terrain it was therefore required that the aerial should have the following properties:

Be fully operational in winds up to 55 $\text{mph}_{\text{mean}} \times 1.4 = 77\ \text{mph}_{\text{peak}}$;

Be structurally and mechanically suitable for working in winds up to 65 $\text{mph}_{\text{mean}} \times 1.4 = 91\ \text{mph}_{\text{peak}}$;

Safely withstand winds up to 75 $\text{mph}_{\text{mean}} \times 1.4 = 105\ \text{mph}_{\text{peak}}$.

DESIGN CONSIDERATIONS

If a radome is used to protect an aerial from the weather, the aerial itself may be relatively light in construction and the drive/control requirements will be correspondingly less stringent. However, energy losses in receiving through the radome, especially when the latter is wet, may lead to a significant increase of the overall noise temperature of the receiving system. The cost of a light aerial with a radome may also be greater than that of a heavier and more stable unprotected aerial.

The alternative approach, which was adopted for the Goonhilly aerial, is to use a heavy, stiff, and stable supporting structure together with a well balanced, stiff dish to minimise deflections in high winds, driven by motors normally working well below their maximum capacity. The application of these principles has resulted in an aerial of good accuracy and radio efficiency, at relatively low cost.

So far as wind speeds are concerned the first requirement is that the aerial must be designed to survive the maximum winds it can be expected to encounter. Next consideration must be given to the maximum wind speed at which the aerial must remain fully operational, i.e. maintain accuracy of shape when moving at full speed and within the specified following accuracy. The torque required to rotate the aerial in wind is proportional to the square of the wind speed, and the driving horsepower is proportional to the product of torque and angular speed, so that size of the driving motors will increase rapidly as the "full operational speed maximum wind" requirement is raised. It was not considered necessary, at least initially, to provide drives able to continue rotating the Goonhilly aerial at full speed in winds gusting above 77 mph with the dish at the angles corresponding to maximum wind torque.

The expected satellite orbits were such that operational speeds in excess of 2° per second were unlikely except when a satellite passed over or nearly over the earth station zenith.

The selection of the azimuth speed required careful consideration since this speed, combined with the selected maximum operational wind speed, determines the required horsepower of the azimuth motor. The combined horsepower of the azimuth and elevation drives must also be considered with respect to the total electrical power supply to be provided. For most of the time the aerial was expected to be operating in winds considerably below the maximum and at speeds below its maximum operational speed, i.e. the drive horsepower normally required would be very much below the maximum which may be occasionally required. If the specified maximum azimuth speed or the maximum operational wind speed were higher than was strictly essential, the electrical power requirements and the capacities of the various transformers, switches, etc., would be correspondingly increased.

The azimuth speed was fixed at 2°/sec giving a theoretical maximum drive motor size of 75 hp. The torque/speed calculations for elevation motion, after allowing for unbalanced moving parts, gearbox losses, etc., indicated that a 100 hp drive motor was required. In practice, both elevation and azimuth drives were eventually standardised at 100 hp.

The accuracy with which the aerial can be made to follow a satellite when under automatic control depends on the following factors:

1. The accuracy, rigidity and stability of the structure as a whole and of its major component parts.
2. The accuracy with which the actual angular position in azimuth and elevation can be determined at any time.
3. The reduction to a minimum of any backlash or uncontrolled motion in the drives.
4. The achievement of a stable and accurate but fast-responding servo-control system for the drive motors.
5. The provision of reliable and accurate control signals to control the servo in accordance with the demands of the satellite orbit to be followed.

With regard to these factors, and the fact that orbital information would be available already processed into demanded azimuth and elevation angles at given times, the following basic decisions were made to enable the required following accuracy to be achieved:

The dish supporting structure would be of reinforced concrete, having a relatively high moment of inertia so as to give a steadying effect in gusty winds and high structural stability against deflections from all wind pressures.

Shaft angular position determination would be by use of 16-bit optical shaft encoders, gaving a basic resolving power of 1 in 65536 (approx. 20 seconds).

The servo-control system would be of the digital type, receiving incoming demanded angle information on punched tape, comparing the demanded angle for each motion with the actual angle and finally passing an analogue error signal to the servo-system.

The results of the dependent structural, mechanical and electrical decisions emanating from the aforementioned basic decisions are detailed below.

GENERAL DESCRIPTION OF THE AERIAL

The general arrangement of the aerial is shown in Figs. 1 and 2, and the components are described below.

The Dish

Both the structure and the membrane plating of the dish are of steel. The membrane is in 8-gauge Corten sheet, having good corrosion resistant properties, individual plates being screwed to the supporting structure and then continuously welded to give good electrical continuity. Steel was chosen as giving the optimum combination of good strength and rigidity, and relatively low coefficient of expansion with the minimum cost.

The balancing of the dish* is such that the natural tendency of the dish upper and lower edges to droop downwards as the dish moves from the zenith toward the horizon is automatically opposed by forces in the balance-weight supporting structure. A drainage system is provided for removal of rainwater, and snow may be removed by depressing the dish. The provision of a de-icing system for an installation in South West Cornwall was considered in view of the generally favourable weather conditions.

There are two steel cabins built into the structure behind the dish for housing radio apparatus as near to the focus as possible.

The dish is supported on a prestressed horizontal concrete beam

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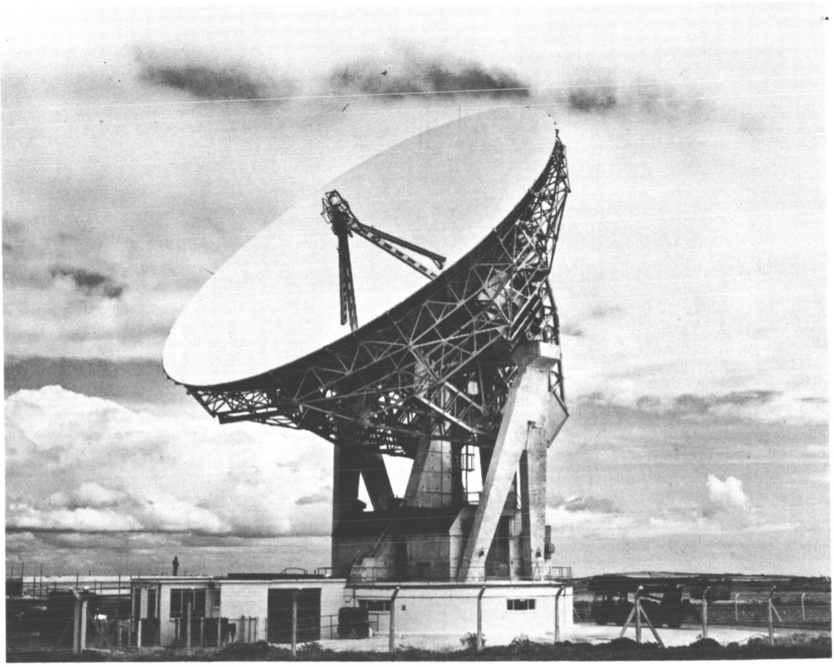

Fig. 1 — The Goonhilly aerial.

via four large split roller bearings of the self-aligning type, one of the centre pair of these being arranged to take axial thrust. The elevation optical shaft angle encoder is driven directly from the thrust bearing by an arm and pin arrangement.

The Dish Supporting Structure

The dish supporting structure comprises a horizontal concrete beam supported in turn by three reinforced concrete portal frames the outer two of which were precast and lifted into position, and the inner frame cast *in situ*. These portal frames stand on a circular reinforced concrete turntable base, which also carries a large cabin housing radio apparatus and accommodating the main cable-turning device. The latter enables connections to be made between equipment in the moving part of the structure and fixed equipment elsewhere without using slip rings. The concrete cabin is fully screened with continuous copper sheeting.

The lower fixed portion of the mount is also of reinforced concrete, taken down to the rock.

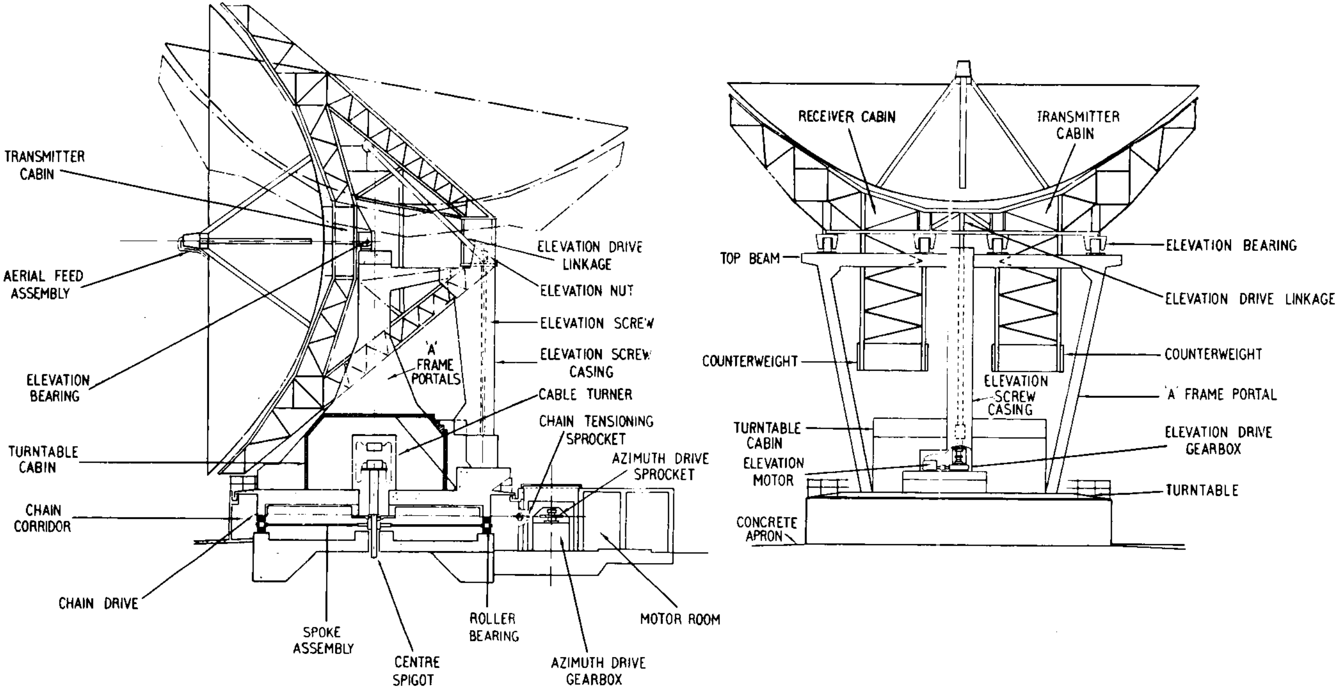

Fig. 2 — Composite sectional view of Goonhilly aerial with the bowl section at zenith.

Azimuth Mount

The moving part of the azimuth mount is carried on 54 tapered rollers, running between an upper and lower track of manganese steel, the tracks being 42 ft 6 in. in diameter, preassembled and accurately machined to the correct conical taper as complete rings. The rollers are carried in a built-up circular frame held in position by 27 tubular spokes with a central hub revolving round a fixed centre pivot. The hub is carried on the centre pivot by a heavy spherical roller bearing and a second similar but larger bearing on the pivot locates the moving part of the mount about the pivot. The arc of travel in azimuth is ±250° from true South providing a 140° overlap on the azimuth circle. Located vertically on the fixed centre pivot post is a rigid tubular tower structure on top of which the body of the azimuth shaft angle encoder is carried. The rotating disc of this encoder is driven from the rigid concrete roof of the turntable cabin previously mentioned. It is thus a feature of the design that both encoders are mounted with their axes on the relevant axis of rotation of the instrument and are driven directly from the axes of rotation.

The rotating part of the azimuth mount is fitted round its periphery with 46 teeth which engage with a 5 in. pitch, cranked-link roller driving chain of accuracy 0.015% on length and 140 tons breaking load. This form of drive was chosen as avoiding the use of large gear wheels or toothed racks whilst providing greater capacity for resisting transient shocks. The chain is provided with tensioning sprockets on both sides of its free length; tension can be adjusted readily by screwing the sprocket mounting blocks in or out in slides. The driving sprocket is mounted on the vertical output shaft of the final bevel gear box; heavy steel frames set in the concrete floor carry an outrigger bearing for the drive sprocket and support the tension spocket assemblies. The moving part of the aerial, weighing approximately 900 tons, moves silently and smoothly at all speeds, less than 2 hp being required to rotate the aerial at full operational speed in conditions of no wind.

The azimuth final bevel gear box is 8 ft 6 in. high and is preceded by a triple-reduction double-helical unit. The overall reduction ratio from drive motor to aerial is 3000:1 and all couplings are of the oil-filled gear type. The chain has an automatic lubrication system, and phosphor bronze slide supports under the whole of its free length. There is also a combined automatic greasing system for the 108 spherical roller bearings in the taper rollers, the two centre pivot bearings, and for the manganese steel track surfaces.

Elevation Mechanical Drive

The bowl is rocked over its 100° arc in elevation by a steel connecting rod attached to a large nut on a 4-start 10½ in. outside diameter vertical screw, 32 ft long over the screwed portion. The nut is split and has adjustment to enable backlash to be eliminated.

The screw is located inside a fabricated steel box and is carried in bearings at its upper and lower ends. The screw box is attached to the revolving part of the concrete mount and the centre concrete portal frame at its lower end, and its upper end it attached to a concrete cantilever built out at right angles to the horizontal prestressed concrete beam. The screw is driven at its lower end by a single reduction worm box, preceded by a single-reduction double-helical box; the overall reduction between motor and dish being again 3000:1. The reduction ratio of the screw, nut, and connecting rod system itself is 181.5:1. This form of elevation drive avoids the use of large gear wheels or heavy circular racks for the final drive, allows the dish to be supported by a number of bearings along the full length of the supporting structure, eliminates backlash and gives complete rigidity in the highest winds.

Azimuth and Elevation Electrical Drives

The two identical 100 hp dc driving motors for azimuth and elevation are of the traction type with skew slots, fan cooling, and a tachometer generator attached to the non-driving end of the shaft. Each motor has a top speed of 1000 rpm at 480 volts, full load current of 160 amps can be continuously sustained in the stalled condition, and smooth-speed range is 720:1. The couplings between the motors and the first gearboxes also carry brake drums on each of which two solenoid operated brake shoes operate. The azimuth motor shaft is equipped with a manually operated disc brake for parking. Each of the two motors has its own separate Ward Leonard motor-generator set, mounted side by side in a house built at the side of the mount; the same enclosure houses the two azimuth gearboxes and the azimuth drive motor. The Ward Leonard room also contains the ac panel for the two sets and a dc desk for manual control of both aerial motions. One part of the Ward Leonard room has been separated off and houses the helium recovery plant and storage dewars. The room is entirely shielded with cooper sheeting to all walls, roof and floor and copper gauze over the windows.

The Ward Leonard system and servo-loop are orthodox but the speed range of 720:1 is considerably greater than that normally used in this type of plant. The servo-amplifiers and control gear are located in the main control building approximately ¼ mile from the motor-generator sets.

Control System

The digital control system is fully transistorised and there is a separate system for each motion. The aerial can be driven from the control desk either manually or under automatic control from a punched tape (Fig. 3). When under automatic control, motion commences when the tape-start time and actual time coincide. Thereafter demanded angle information read from the tape is stored, passed to an arithmetic unit and then on to the comparator unit, which also receives a statement of the actual angular position from the 16-bit optical shaft angle encoder. The difference between demanded and actual angle is ultimately converted to analogue form and fed into the servo-amplifier equipment which responds accordingly. There is also a facility whereby the differential (rate of change) of error is used to eliminate hunting and overshooting by reducing the rate at which the error is reduced as the value of the error moves towards zero.

The aerial control desk (Fig. 4) carries digital and analogue displays of actual position, a digital display of demanded position, and manual speed controls for both motions, together with drive-motor voltage and current meters. When the aerial is under automatic (tape) control the normal speed controls change their function and can be used to apply a positive or negative correction to the motion so that the actual angular position of the aerial is the selected amount in front of or behind the position demanded by the tape. The desk also carries wind-speed and direction instruments, motor start/stop controls and coloured-lamp signalling systems indicating the state of all safety interlocks of vital parts of the drive equipment. There is also a digital display of control-clock time and another of the time on the tape corresponding to the displayed demanded angles. If synchronism between clock and tape time is lost the aerial stops at the last demanded position. The control desk also carries signal-lamp systems indicating the condition of the drive brakes, drive motor fans and lubrication systems on both motions and also red warning lights indicating that the limit of travel has been reached in either direction on either motion.

In addition to lighting the red signal lamp, operation of a limit switch at the end of the arc of travel also switches off the driving power on that motion and so stops the motion. To restart, a button in a special locked cabinet must be operated, when the aerial will automatically

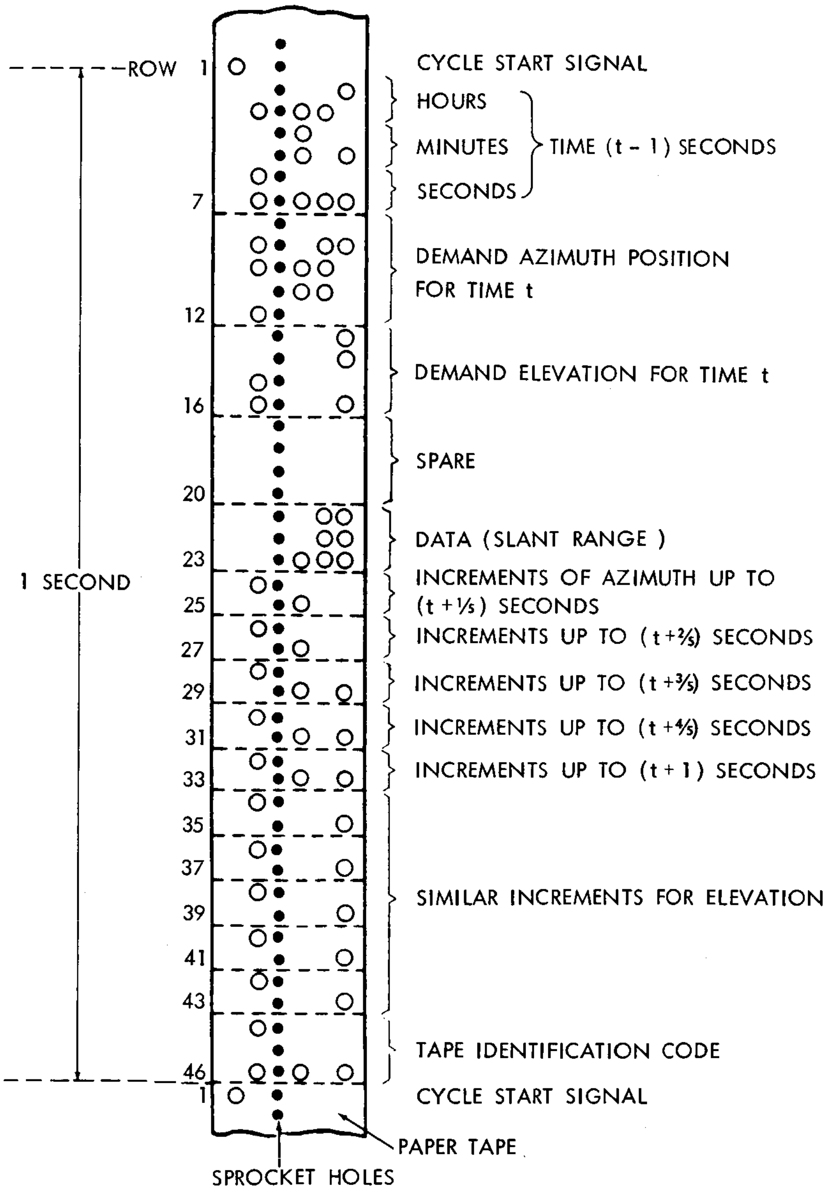

Fig. 3 — A section of control tape.

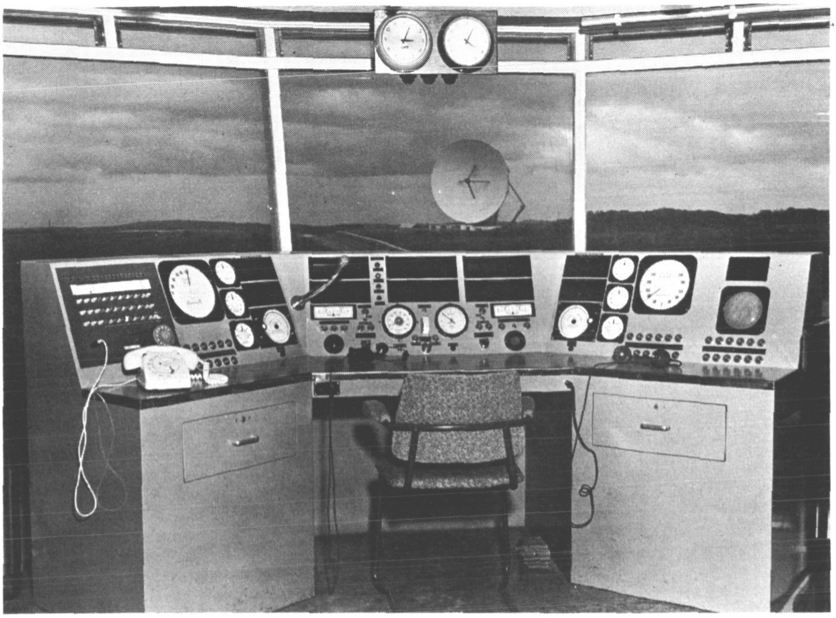

Fig. 4 — The aerial control desk.

move out a certain distance from the limit switch and then stop, after which normal driving procedure may be resumed.

CALIBRATION AND TESTING

Profile measurements on the completed dish were made with slip gauges against two accurate templets, one for the inner area and a second for the outer zone. About 1000 measurements were plotted on probability graph paper and showed 99% of the measurements within the tolerances specified with random distribution of error.

Before the dish was moved from its position as built with axis pointing to the zenith, an optical telescope was fitted in one of the cabins behind the dish with its axis truly vertical within 0.2 minutes. This then became the 90° reference condition for the elevation encoder. With the dish set to 60°, 45° and 0° in turn by the encoder, theodolite checks were made of the angle of the peripheral plane, and agreement obtained to ±15 seconds.

The azimuth zero on a true South bearing, and checks of the azimuth setting accuracy were obtained by viewing known points at a 5 to 15-mile range through the telescope fitted to the dish. The true bearings of those points were computed by the Ordnance Survey Department to an accuracy of better than one second.

First indications that the finished aerial would point accurately were obtained from successive transit observations through the optical telescope of Alpha Ursa Major. Smooth curves of the azimuth and elevation angles against time as this star moved across the sky showed that under calm conditions a following accuracy of the order of one minute could be expected.

When radio equipment became available for testing the aerial, the horizontal radiation diagram was obtained by measuring the incoming signal strength from a 4000 Mc/s transmission from a test site at Leswidden some 21 miles from Goonhilly. The measured beamwidth was found to be 13 minutes, compared with a theoretical value of 12 minutes, and the first side lobes were correctly spaced on either side of the main beam.

CONCLUSIONS

Work on site commenced on 1st June 1961, and the aerial had been tested and provisionally calibrated so that it was in full operation on the 10th July 1962. In the first eighteen months of its working life the aerial has worked satisfactorily with little attention. The British concept of a stiff dish on a sturdy mount without a radome has yielded an aerial of high performance at relatively low cost.

ACKNOWLEDGMENTS

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The aerial was designed and construction supervised by Husband & Co., Consulting Engineers.

The permission of the Engineer-in-Chief of the Post Office to use information contained in the paper is gratefully acknowledged.