THERMAL VACUUM INCLINOMETRY: A TEST FACILITY FOR ANTENNA POINTING MECHANISMS

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ABSTRACT

The development of a measurement and test facility at ESTL suitable for the assessment of pointing mechanisms is described. The system allows measurements of high accuracy and resolution to be made on mechanisms operating under ambient or thermal vacuum conditions (-40C to +80C). The basis of the facility is a high precision tilt sensor which can be used in high vacuum. Data acquisition from such sensors is by means of an LSI/11-23 based computer which, in addition, allows data processing and programmed control over mechanism movements. In static measurements the system displays high accuracy (±0.001 degrees), high resolution (0.0004 degrees) and good repeatability (0.0005 degrees). Examples of tests made possible by this measuring system are presented.

Keywords: Pointing mechanisms, thermal vacuum, inclinometry.

1. INTRODUCTION

In thermal-vacuum testing of satellite mechanisms the measurement of angles of tilt is conventionally undertaken by optical means. Thus, for example, when measuring the pointing angle of antenna pointing mechanisms a standard technique is to employ an autocollimating theodolite located outside the test chamber to detect changes in tilt of a plane mirror attached to the mechanism under test. Such a method - whilst having the undoubted merit of inherent high accuracy - is, by nature of its manual operation, slow and labour-intensive. Furthermore it is, by necessity, applicable only where the optical path between theodolite and mechanism can be maintained, a factor often precluded by test chamber geometries. The method is also prone to errors introduced by window distortion and thermally-induced distortion of the vacuum chamber.

For these reasons a project was undertaken at ESTL to develop a measurement facility capable of providing accurate angular data in a fast, efficient manner. The task, in the first instance was to develop a facility specifically for the testing of pointing mechanisms and having the following requirements:

(a) to measure pointing angles accurately over an angular range ±9 degrees and in the temperature range -40 C to +80 C in high vacuum (10^{-7} torr)

(b) to enable pointing angles to be measured relative to the base plate of the mechanism so that small angular shifts resulting from thermally-induced displacements of the base plate do not undermine the accuracy of angle measurement

(c) to provide outputs suitable for intake by a computerised data acquisition system so as to enable fast, on-line data processing.

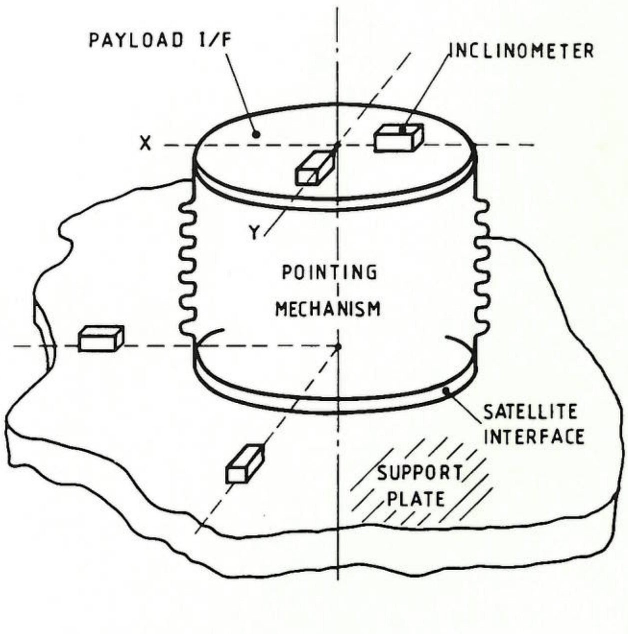

FIG. 1 ARRANGEMENT OF INCLINOMETERS ON POINTING MECHANISM

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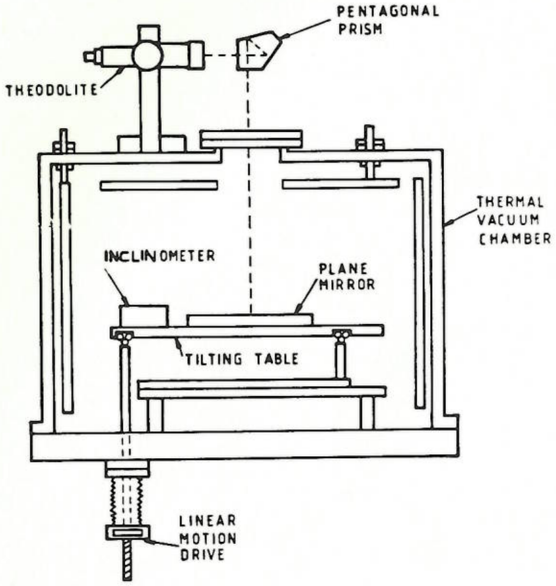


FIG.2 SCHEMATIC DRAWING OF TILTING TABLE RIG IN 60 cm DIAMETER THERMAL VACUUM CHAMBER

2. IN-VACUO INCLINOMETRY

These requirements call for a tilt sensor capable of high accuracy and operable under thermal vacuum conditions. Early studies aimed at finding a suitable transducer had centered on the use of force-balance, pendulum accelerometers but these were shown to lack sufficient accuracy. This was ascribed to poor repeatability (imprecision) resulting from stiction occurring at the dry (unlubricated) jewel pivots which support the pendulous component of the accelerometer. Oil-filled inclinometers, manufactured by Schaevitz, USA, were then considered as these, whilst operating on a similar principle, employ flexure pivots and, in consequence, offer higher precision. A main objection to their use in vacuum, however, was their use of a silicone damping fluid as this oil posed an unacceptable threat to chamber cleanliness in the event of its escape (instances of this problem are known). An attempt to overcome this problem was made by replacing the silicone oil with an oil of extremely low vapour pressure (a perfluorinated ether, vapour pressure 10^{-13} torr at 20C) such that even in the event of escape vacuum integrity would be maintained. The oil has the further merit of having a high viscosity index and low pour point that permits operation down to below -40 degrees C. Following extensive testing under high vacuum and over the temperature range -40C to +80C a mass spectrometric analysis of the vacuum showed no detectable contamination. On opening the test chamber following tests the inclinometers showed no sign of oil leakage. Thus use of this substitute oil proved entirely satisfactory.

2.1 Application

Fig 1 depicts how four inclinometers would be positioned on a pointing mechanism in order to assess its pointing accuracy. Two inclinometers are mounted along orthogonal axes x and y on the tilting surface (the payload interface). Two additional, similar inclinometers are located on the support plate on which the pointing mechanism is mounted and are aligned along axes which parallel x and y. The purpose of these additional basal inclinometers is to detect any changes in the attitude of the support plate that might occur as a result of mechanical disturbance or changes in thermal conditions. Thus the electrical outputs from the four inclinometers can be combined to give information from which may be derived the angle of pointing relative to the support plate.

2.2 Calibration of inclinometers

Calibration of the inclinometers was undertaken using the test rig shown schematically in Fig 2. The rig consisted of a tilting table on which the inclinometers were mounted, the whole being located within a thermal vacuum chamber. Tilt angle was measured by means of an autocollimating theodolite which allowed measurement of the angular displacement of a plane mirror mounted on the tilting table. The theodolite was mounted on the chamber lid, outside the test chamber, the optical path being by way of a pentagonal prism and an optically flat chamber window. The relatively long optical path necessitated the use of a large diameter (200 mm) plane mirror to allow angular measurement over the intended range (±9 degrees). However the effective aperture of the pentagonal prism was such as to limit measurements to ±7 degrees and, as such, calibration was limted to this angular range.

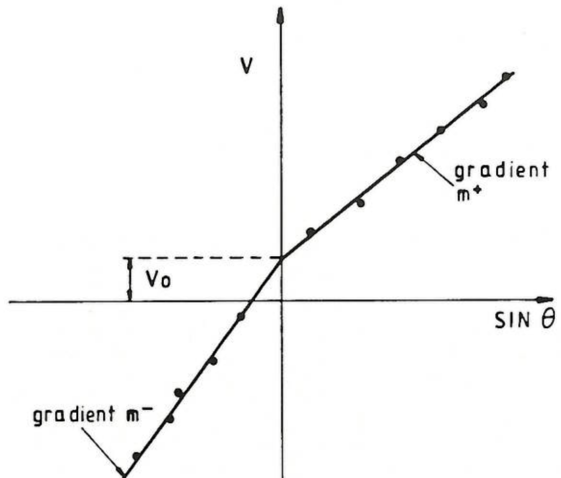


FIG.3 ILLUSTRATING TWO-SLOPE CALIBRATION OF INCLINOMETER OUTPUT PLOTTED AGAINST SINE θ (INCLINATION) TO REDUCE LINEARITY ERROR

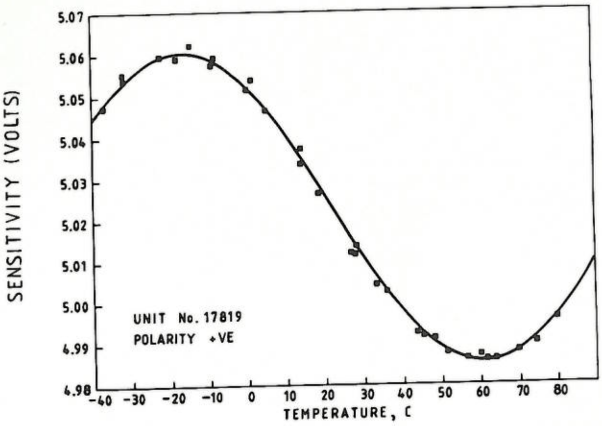


FIG. 4 EXAMPLE OF VARIATION OF INCLINOMETER SENSITIVITY WITH TEMPERATURE

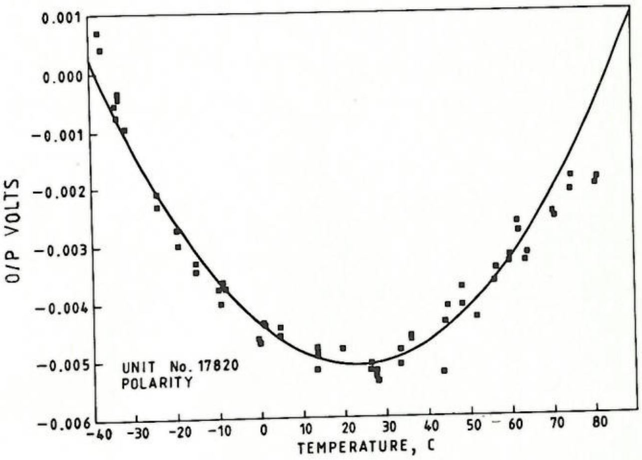


FIG. 5 VARIATION OF INCLINOMETER O/P AT HORIZONTAL WITH TEMPERATURE

Calibrations were undertaken under high vacuum (10^{-7} torr) and over the temperature range -40 deg.C to +80 deg.C. To reduce calibration error, measurements were made for both positive and negative angles of tilt as exemplified in Fig 3. Note that these calibration plots are characterised by two parameters, namely the sensitivity of the device (m^+ and m^- in Fig 3: these being the gradients of the calibration plots) and the voltage output at zero tilt, (V_o in Fig 3). Measurements of m and V_o with changing temperature indicated that the sensitivity of the devices varied sinusoidally with temperature (Fig 4) whereas V_o varied parabolically with temperature (Fig 5). These relationships provided a mathematically precise method of thermal calibration and one easily programmed into the computerised data acquisition system.

2.3 Accuracy of inclinometers

Four components of error were identified and measured. These errors, designated a, b, c and d, are listed below together with their measured values (standard deviation).

(a) repeatability .... ±0.0004 degrees, this denoting the ability of the transducers to produce the same output from repeated trials of the same input

(b) linearity error .... ±0.0005 degrees, this denoting the scatter of data points about the best fit calibration plot of voltage o/p versus sine of angle of inclination. Note that this error is principally ascribed to repeatability and thus encompasses error 'a' above

(c) error arising from temperature calibration of sensitivity .... ±0.0004 deg/tilt deg, this arising from the scatter of points about the best fit calibration curve (Fig 4) of sensitivity versus temperature

(d) error arising from variation of V_o with temperature .... ±0.005 degrees, this arising from the scatter of data points about the best fit calibration curve of V_o versus temperature (Fig 5).

The total error associated with inclinometer measurement will comprise some combination of the above error components, the combination depending on the type of measurement and the conditions under which it is made. Typical measurement types and their associated errors are tabulated below.

Measurement Type	Error Type
Precision	a
Relative repointing* (constant temperature)	b
Relative repointing (changing temperature)	b+c
Repointing (relative to base plate)	b+c+d

* relative repointing is the measurement of change in pointing angle relative to datum or previous pointing angle.

3. DATA ACQUISITION AND CONTROL

In order that tests be undertaken efficiently and results be quickly produced the measuring system is computerised. The computing facilities, based on an LSI/11-23 microprocessor, allow: mechanism control by means of pre-programmed digital control; the acquisition of data from inclinometers and other transducers attached to the mechanism; data processing to interpret inclinometer output in terms of tilt angle; and data presentation in report-ready format.

4. TESTS AVAILABLE

A suite of programs has been written to allow several pertinent tests to be carried out that permit the full characterisation of mechanism performance. These tests include the following:

(a) measurement of re-pointing accuracy

(b) measurement of mechanism repeatability (precision)

(c) polar plot of pointing

(d) pointing locus integrity

(e) measurement of mechanism backlash.

5. TEST RESULTS

To illustrate some of the tests available (Ref 1) measurements have been made on an ESA breadboard pointing mechanism which, because of its prototype nature, was not built to the accuracies demanded of flight standard equipment. The choice of this mechanism (known as the POD - payload orientation device) was convenient because, being a breadboard model of a pointing mechanism, it was amply endowed with pointing errors for the test facility to measure. The POD is a swash plate device with a range of pointing of ±5 degrees. It has two swash-plates or wedges each with its own drive system comprising a train of gears and stepper motor. By rotating the wedges in opposite directions the pointing vector (the line perpendicular to the pointing surface) describes a nodding motion. Rotation of the wedges in unison in the same direction allows the pointing vector to undergo a sweep motion about the POD axis at a predetermined nod angle. The concept of sweep and nod motion is illustrated in Fig 6. A fuller description of the POD is given in Ref 2.

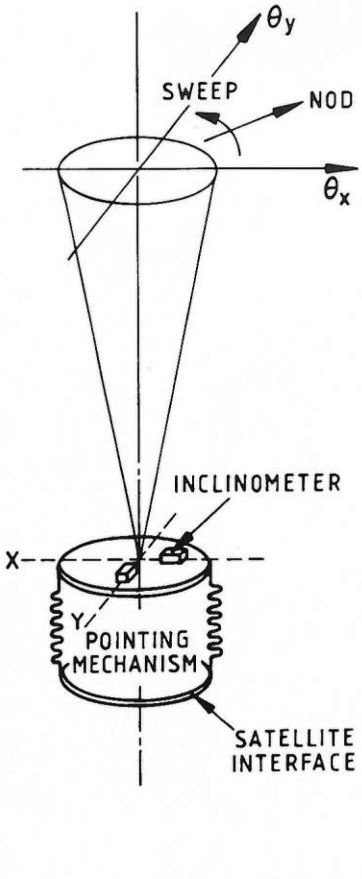


FIG.6 ILLUSTRATING TILT AXIS CONFIGURATION

5.1 Polar plot of pointing

A polar plot of pointing manoeuvres is useful as it conveys to the observer, in an immediately-assimilable form, the sense of mechanism pointing. Polar plots are obtained by connecting the inclinometer outputs to the x and y axes of an x/y plotter. An example of such a plot is shown in Fig 7(a). The sequence of manoeuvres undertaken by the POD is shown alongside the polar plot. Using this technique pointing angles can be resolved to about 0.02 degrees.

5.2 Nodding locus integrity

The nodding locus illustrated in Fig 7(b) shows how the test facility can resolve deviations from a perfect pointing path. In this example the pointing mechanism was commanded to undertake the following sequence of manoeuvres starting at its datum: nod +5 degrees, nod -10 degrees, nod +5 degrees. The pointing locus of an ideal mechanism would describe a straight line coincident with the nod axis (x axis of Fig 7(b)). The plot shows that the actual path is elliptical and modulated by a small but discernible angular oscillation in the y direction. Analysis of the mechanism design indicates that the observed elliptical shape of the pointing locus can be attributed to a difference in wedge angles of the two swash plates. A measure of this difference is given by the displacement of the locus from the origin at the point where the locus intercepts the y axis (in this case the difference amounts to 0.051 degrees). The oscillatory deviation is caused by the mechanical design of the POD gear system in which a planetary gear, as it rotates, imparts a radial force on the swash plate bearings. In this development model POD the bearings have a slight clearance, thus the radial force causes the bearings to tilt, producing the cyclic error.

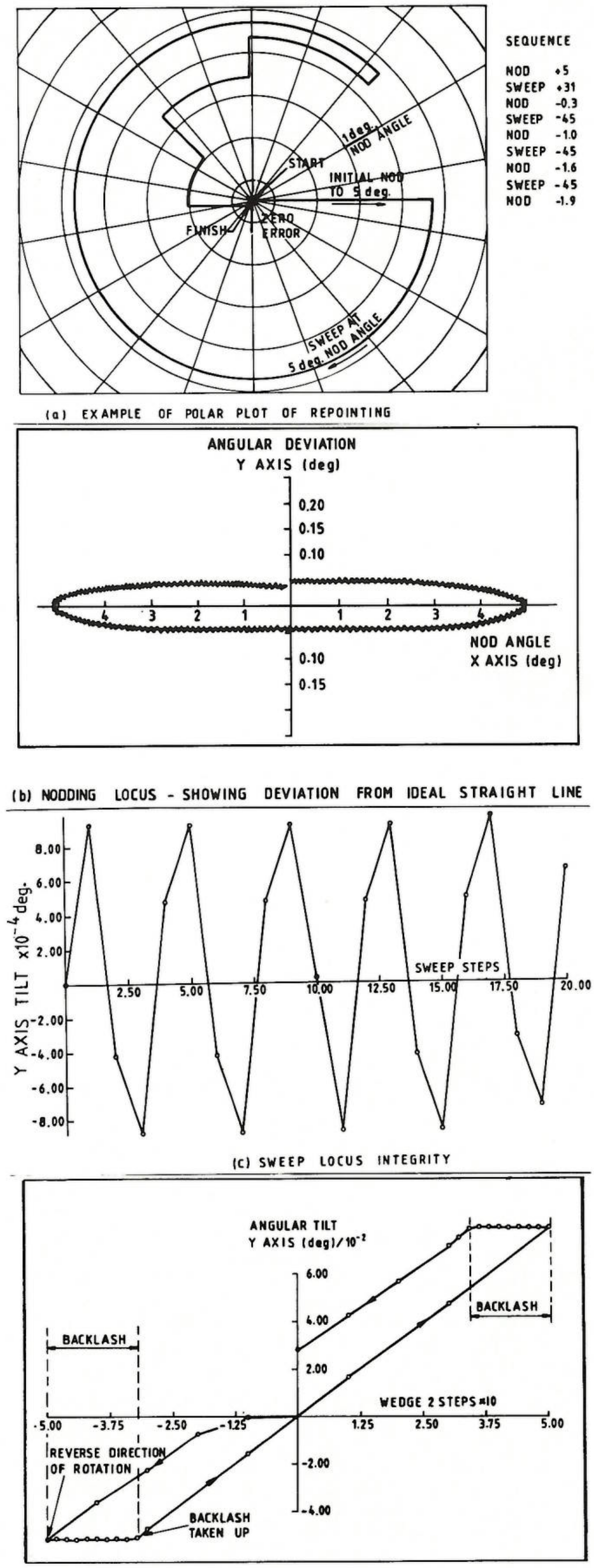
5.3 Sweeping locus integrity

This test is similar to the Nodding Locus Integrity test in that it examines the deviation of pointing from a demanded path: the difference in this case being that the pointing vector describes a circular path (as a result of a "sweep" motion). In order to carry out the test the mechanism must first be commanded to a given nod angle. In the present example a nod of 5 degrees was chosen. The angle of sweep can be between 0 and 360 degrees. In this example the mechanism was commanded to sweep over a very small angle in single motor steps (each step being equivalent to a sweep rotation of 0.037 degrees). After each step movement the deviation of pointing was measured. Fig 7(c) indicates that as the POD sweeps it undergoes a slight but regular rocking motion (caused by the gear drive as described above). The amplitude of this cyclic motion is about 0.001 degrees, one cycle being completed every four steps. Note that this observation demonstrates well the high resolution of the facility since changes of tilt angle of 0.0004 degrees are clearly resolved.

5.4 Measurement of backlash

A measure of backlash within a pointing mechanism can be obtained by making the mechanism undergo a cyclic pointing manoeuvre over a small angle.

With a swash plate mechanism of the type examined



(d) MEASUREMENT OF MECHANISM BACKLASH

Fig 7 Examples of measurements

here the most appropriate method is to perform the cyclic motion about the pointing angle defined by the coordinates: sweep angle 45 degrees; nod angle $\sqrt{2}$xwedge angle (=3.53 degrees in the case of the POD where the wedge angle = 2.5 degrees). At this position the pointing vector loci obtained from independent rotations of the two wedges describe circular paths which intersect at right angles, and at the point of intersection the loci run parallel to the inclinometer axes. Thus small angle rotation of one wedge will be registered as a tilting motion by the appropriate inclinometer. To obtain a measure of backlash associated with the drive of this wedge it is simply necessary to monitor this inclinometer's output as the wedge is driven in a cyclic manner. Fig 7(d) illustrates the point. One wedge was made to rotate 50 steps in the negative stepping direction in batches of 10 steps, measurements of tilt being made following the completion of each batch of steps. This completed, the wedge was made to rotate in the opposite direction in batches of two steps. On rotating in this direction there is observed no change in tilt angle until some 18 steps are completed ie. until the backlash is taken up. The wedge was further rotated in the same direction for some 85 steps at which point the direction of rotation was again reversed. A backlash of about 18 steps is again observed.

6. CONCLUDING REMARKS

By taking a flexure pivot, oil-damped type of tilt sensor and rendering it safe for vacuum usage we have obtained a transducer which forms the basis of a versatile and accurate test facility for measuring tilt angles over a wide temperature range (-40C to +80C). In addition to the measurement of repointing accuracy (fundamental to any assessment of mechanism performance) the facility can graphically illustrate where deviations from ideal, pointing behaviour occur. In so doing, information is created that allows the operator to identify the mechanical sources of pointing error.

Although designed specifically to meet the requirements of testing pointing mechanisms there is no reason why such a system should not be adapted for measurement of angles on other mechanisms. Robotic arms, deployment devices and actuator mechanisms come to mind. There may well be others to which this technique could be usefully applied.

7. REFERENCES

1. A fuller account is given in:
   Roberts E W and Golding F 1985, The ESTL pointing mechanism test facility, *ESA (ESTL) 74.*

2. Brunnen A J and Bentall R H 1982, Development of a high stability pointing mechanism for wide applications, *Proc 16th Aerospace Mechanisms Symposium, NASA JFK Centre.*