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Thermal effects on the pointing of the 32-m MERLIN radio telescope at Cambridge

A.M. Bayley[1], R.J. Davis[1], J.S. Haggis[1], and H. Kärcher[2]

[1] University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, UK
[2] MAN GHH, Gustavsburg, Germany

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Abstract. The pointing performance of large quasi-paraboloidal radio telescopes may be dominated by temperature differences in the structure. Previous work has concentrated on actively controlling these differences. This paper describes investigations into the pointing of the 32-m MERLIN telescope sited at Cambridge, in particular techniques employed to overcome the influence of thermal effects. It has been found that by measuring temperatures at strategic places on the structure and, using an algorithm derived from the finite element analysis, pointing can be controlled by 6″ rms through the sunrise period and in direct sunlight, thus improving the pointing performance by a factor of four.

Key words: telescopes – atmospheric effects

1. Background

With developments made in the design of large quasi-paraboloidal radio telescopes, particularly the four point support concept (Hachenberg 1969) and homology (von Hoerner 1967), the problems of gravitational deformations are minimized (Baars 1983) and the limiting factors then become the influence of wind and temperature. In this paper we address the effects of temperature on pointing. Previous workers have attempted to compensate for temperature changes by active control of the entire telescope environment as in the James Clark Maxwell Telescope (JCMT) (Bregman & Casse 1985) or by controlling the temperature in the immediate vicinity of the backing structure as in Millimetre Radio Telescope (MRT, IRAM 30 m radio telescope Baars et al. 1988). We describe a method where monitoring of temperatures is combined with modelling of the structure to give improved pointing.

Send offprint requests to: R.J. Davis

2. Determination of pointing corrections and initial results

The bowl is supported by an altazimuth alidade consisting of elevation bearings mounted at the top of the two A-frames (see Fig. 4). The structure rotates in azimuth on a wheel and track system. The A-frames are mainly constructed from 0.5 m welded box section.

The specification of the telescope control system requires that the telescope be pointed to within 5″ rms of the target astronomical source during "precision conditions". (Precision conditions are defined as wind speed below 25.2 km h^{-1}, temperature gradient below 3 K h^{-1}, and no direct sunshine.) Given accurate timing information and knowledge of the telescope's position, it is straightforward to compute the azimuth and elevation of the radio source. However many factors conspire to give a scatter in the telescope beam pointing, such as structural misalignments, instrumental errors, and gravitational, thermal and atmospheric effects. Most of these are systematic in nature, and, provided they are sufficiently well understood, can be removed by the inclusion of suitable terms in the pointing model. The starting point for much of the work was data from the structural survey carried out by the Contractor during construction of the telescope. The subsequent refinement of the coefficients of the pointing terms was one of the first tasks undertaken on the new telescope after its handover in late 1990.

2.1. Initial results

Raw azimuth pointing was found to be within 7″ rms and required only minor adjustments, mainly to compensate for the tilt of the azimuth track of a few arcseconds towards the east.

However two problems became apparent with the elevation pointing:

1. On some mornings the elevation pointing error would increase to over 1′ within a few hours, subsiding to its original value some hours later (see Fig. 1). This was most noticeable during clear still weather conditions.

2. Comparison of data taken on successive nights (i.e. during precision conditions) sometimes showed differences of over 20″ in the elevation pointing, (the so-called "encoder jumps") (see Fig. 2).

The first effect (termed the "sunrise effect") appeared to be closely related to the influence of sunshine on the structure, causing an effective droop in the beam of the telescope. This effect was further investigated by monitoring

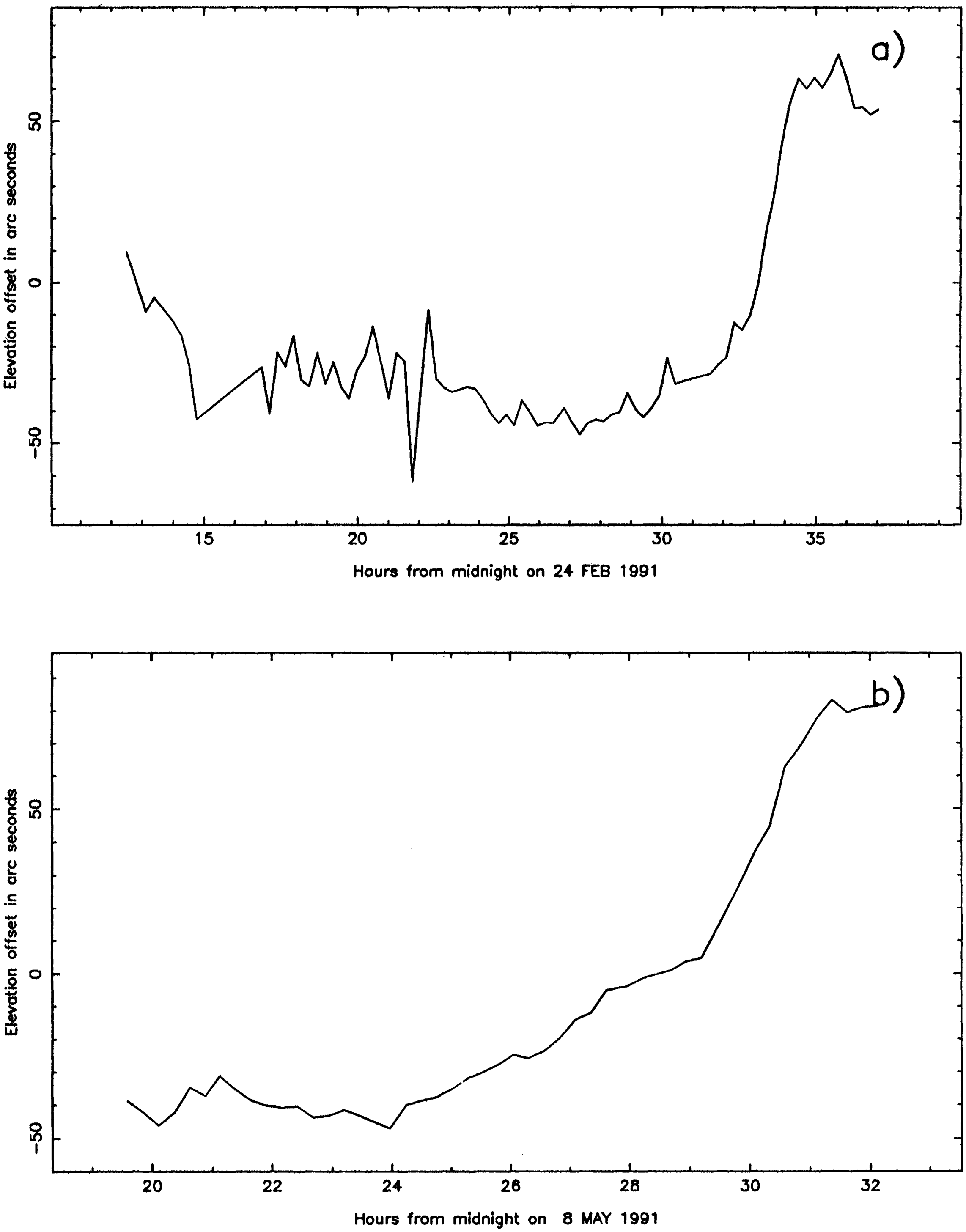
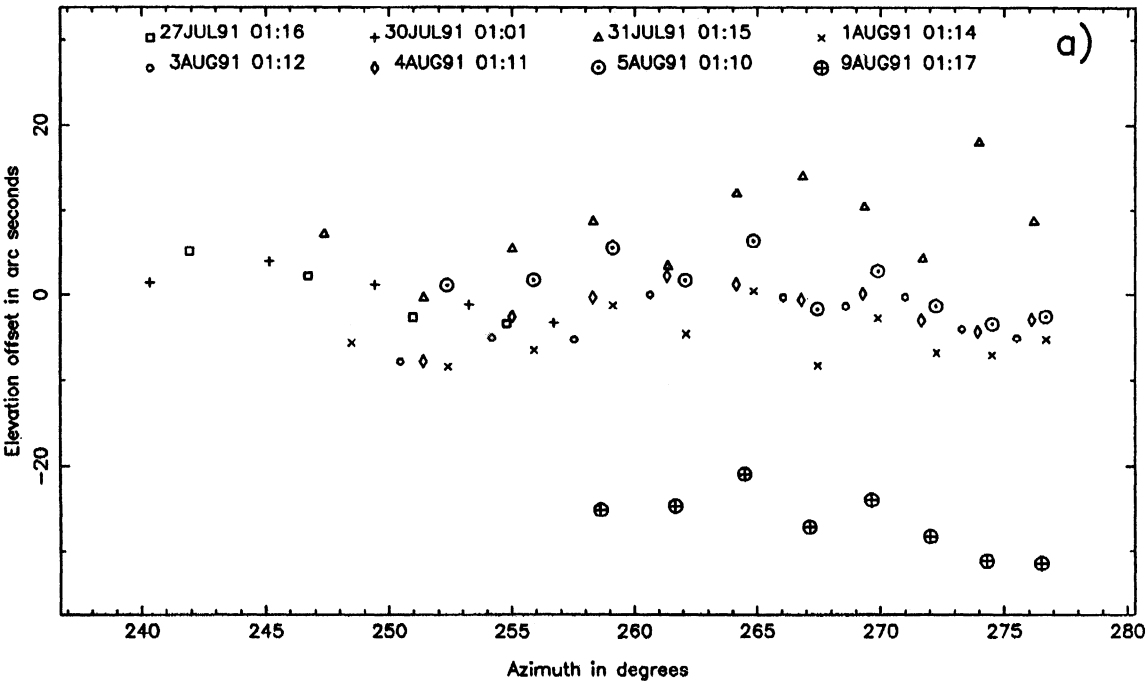


Fig. 1a and b. Plots of elevation offsets versus hours on **a** 24 Feb. 1991 and **b** 8 May 1991



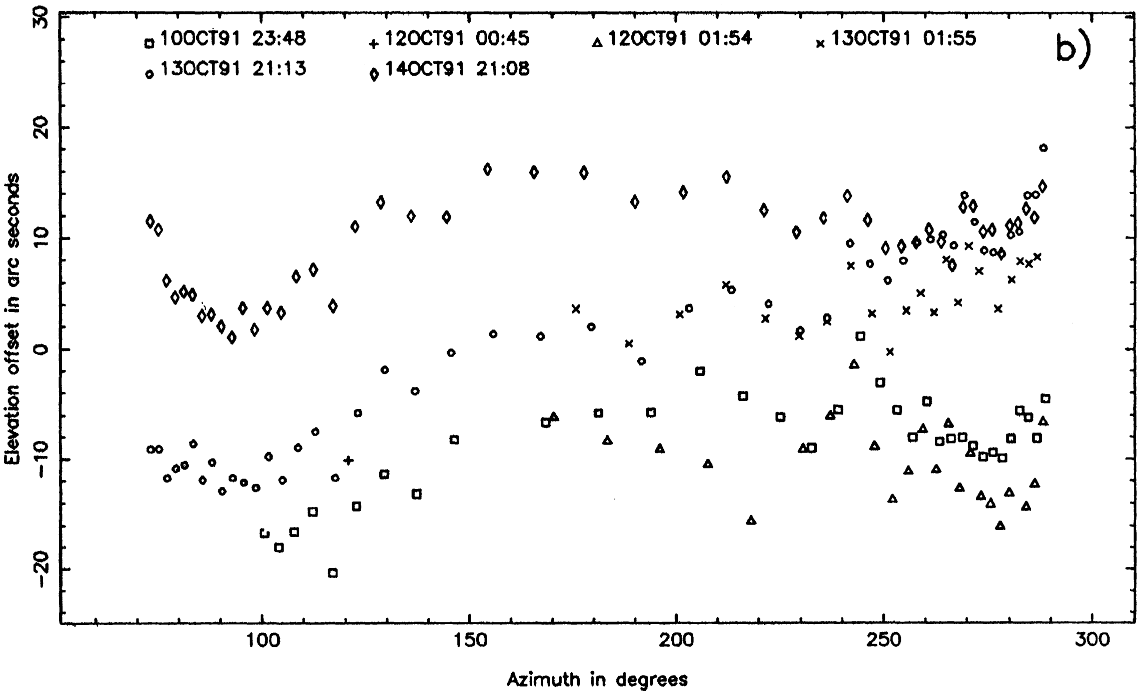


Fig. 2a and b. Plots of elevation offset in nighttime calm conditions **a** July–August 1991 and **b** Oct. 1991

the elevation encoder readout over sunrise with the telescope stationary and the brakes on. Changes in the elevation encoder of over 1′ were recorded. It was concluded that thermal distortions were occurring in the alidade A-frame, leading to movements in the elevation encoder.

3. The measurement of thermal effects in the A-frames

3.1. Thermocouple installation

Temperature sensors were fitted to the structure as shown in Figs. 3 and 4, and their data collected by the control computer.

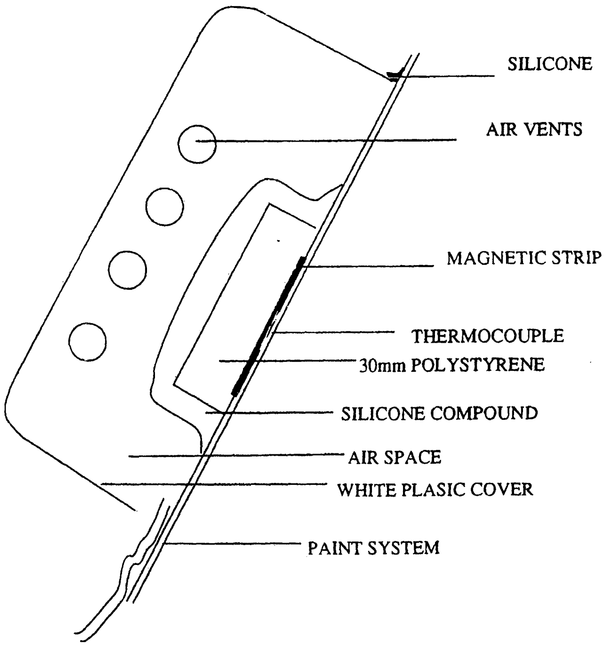


Fig. 3. The fixing details of the thermocouple to the telescope

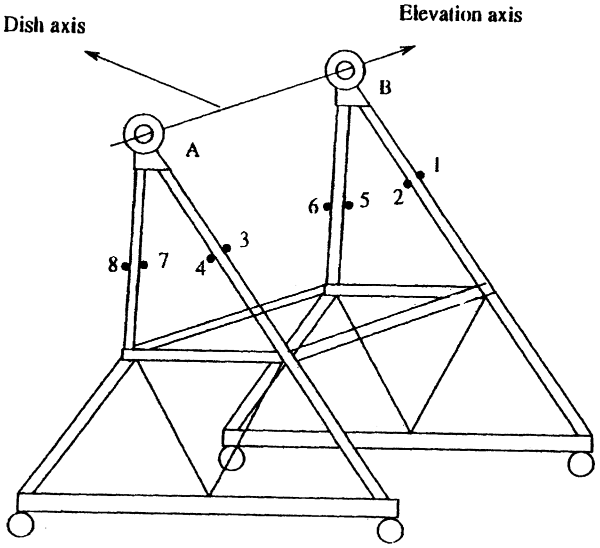


Fig. 4. The alidade showing the fixing points for the thermocouples

All trials, and the subsequent working system, were conducted with the thermocouples being placed on the painted steel surface. No evidence has yet been found to suggest that the thermocouples should be placed directly on bright steel. Having cleaned the paint surface, the magnetic strip was placed on its location covered with polystyrene approximately 25 mm thick. This was covered with waterproof sealant (silicone rubber compound) and the whole covered with a white plastic (solar proof) box to reduce the effect of direct solar radiation. The box had holes in its sides and bottom to allow an air flow as shown in Fig. 3.

3.2. Results

Measurements of encoder movement were made with the telescope stationary. A temperature differential of about 5 K between thermocouples 1 and 2 was recorded around sunrise, with the upper side of the member being at the higher temperature. A reverse differential of about 1.5 K was recorded after sunset, with the lower side of the member being at the higher temperature. While these differentials appeared to have little effect on the azimuth encoder, the elevation encoder changed by approximately 70″. There was evidently a strong correlation between temperature differential and movement of the elevation encoder.

3.3. A simple thermal correction

These measurements suggested a crude thermal coefficient of about 10″ per degree Centigrade differential between sensors T_1 and T_2, and this was retrospectively applied to the data already collected. The results were very encouraging and suggested an improvement in the overall elevation pointing performance to about 5″ rms, together with a narrowing of the apparant encoder jumps that had been noticed in the elevation pointing error on successive nights.

4. Theoretical modelling

4.1. Temperature distribution in the telescope structure: theoretical and empirical background

Disturbances in the nearly uniform distribution of temperatures in the telescope structure are mainly introduced by radiation effects, particularly by solar radiation on the telescope during the day and infrared radiation of the telescope to the cold sky during the night. The convective heat exchange between the telescope structure and the surrounding air has a compensating influence on the temperature disturbances and depends on the wind velocities. The internal heat transfer by conduction in the structure itself plays a minor role. The heat transfer with the environment by radiation depends mainly on the radiation characteristics of the structure surfaces, e.g. the painting system and the exposure of the surfaces to Sun and sky, whereas the heat transfer by convection is governed by the geometric size and shape of the structural components and the related flow velocity of the surrounding air.

To minimize the temperature increase due to the Sun the complete telescope structure is coated with a white titanium dioxide paint. Measurements on the erected telescope showed, that under calm weather conditions, when the air circulation is in the range of 5 km h^{-1} or less, and when the radiation is in the range of 2/3 of the solar constant or less, the maximal increase of temperature, compared to air temperature, of the exposed surfaces to the Sun is around 3.5 K, which is in good agreement with theoretical calculations.

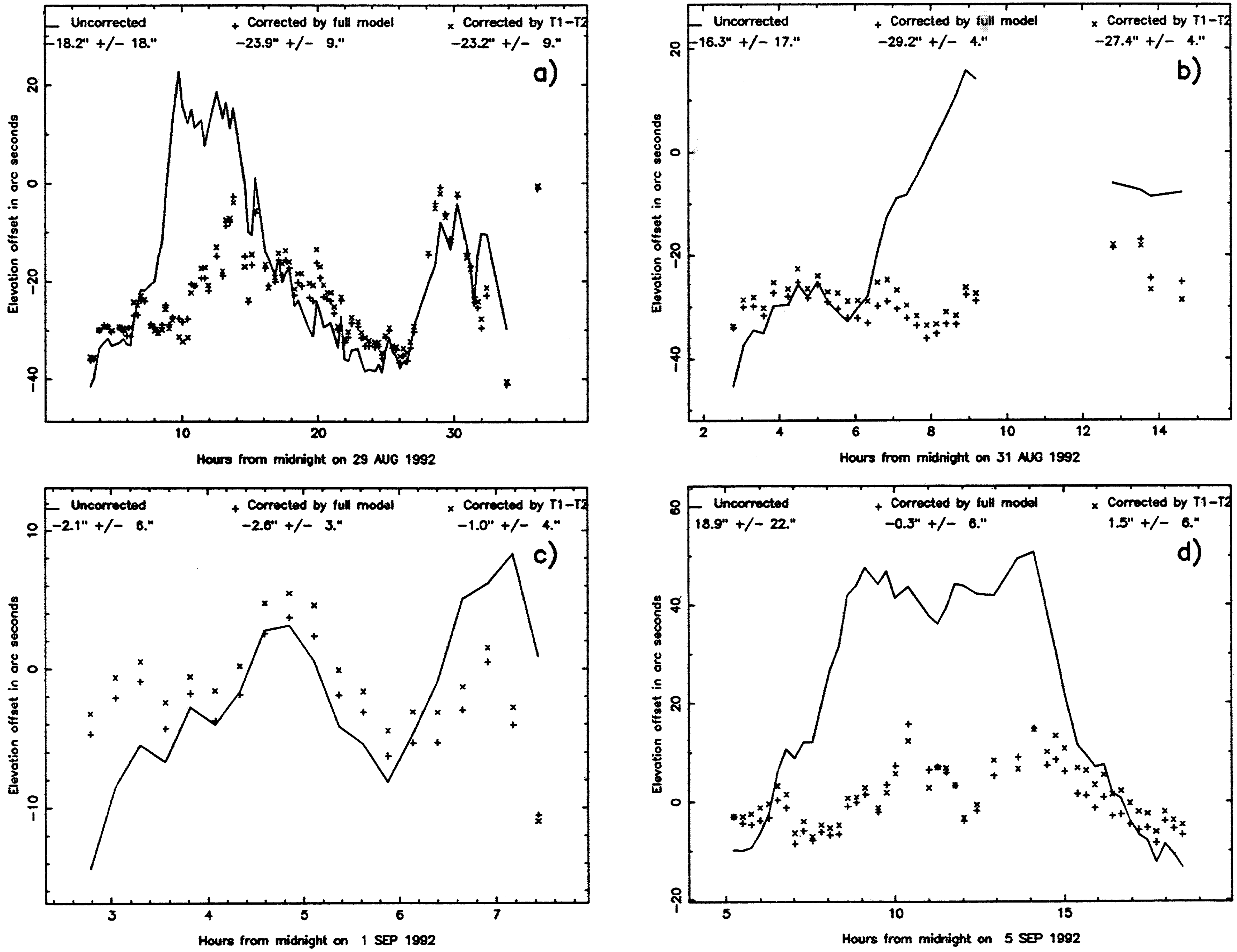


Fig. 5a–d. Elevation offsets uncorrected (full line), fully corrected (×), and $T_1 - T_2$ corrected (+) on **a** 29 Aug. **b** 31 Aug. **c** 1 Sep. **d** 5 Sep. 1992, the mean offsets and standard deviations are indicated for each model considered

The temperature measurements also showed that the struts of the alidade needed about a quarter of a day after sunrise to adapt to the changes in the thermal environment, which is also in good agreement with theoretical values, which give thermal time constants of two to four hours for structural members in the alidade struts. The theoretical results show also that, for more filigree members like the reflector trusswork itself, the thermal time constants are much shorter, typically 20 min, so that in principle the trusswork members follow all changes in the thermal environment.

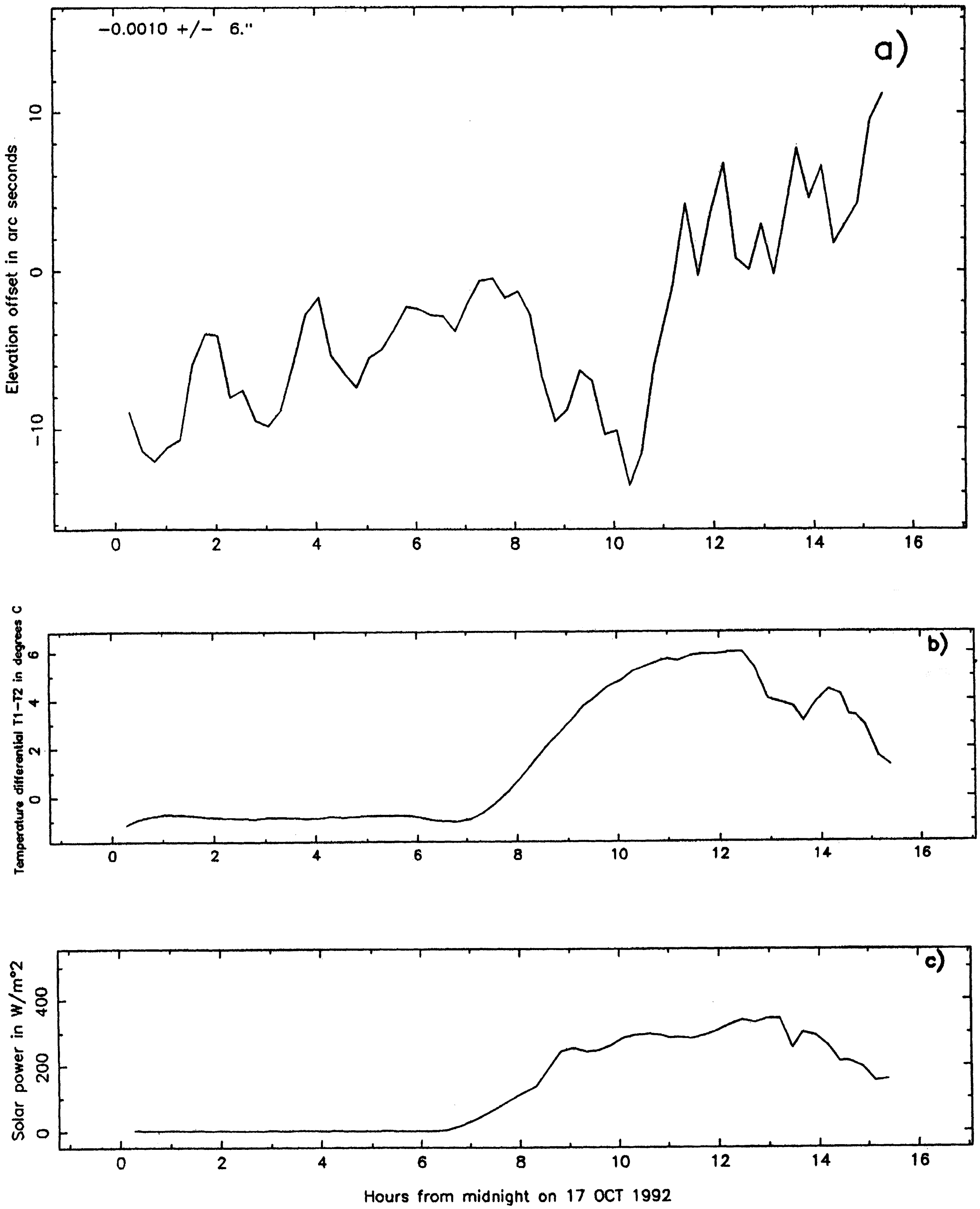


Fig. 6. **a** Elevation offsets with dynamic pointing model, the mean offset and standard deviation are indicated in the top right of the diagram, **b** temperature differential $T_1 - T_2$, **c** solar power W-m^{-2} versus time in hours on 17 Oct. 1992

4.2. Placement of the temperature sensors

On-site measurements demonstrated that the thermal differential on the upper side of the rear struts of the alidade is ~ 3.5 K. The effect on the upper part of the front struts is reduced due to shadowing and a sharper angle of incidence with the Sun. The effect on the lower part of the struts is small.

Finite element calculations for the deformations of the alidade structure under these loads are in good agreement with the measured pointing errors. The results may be interpreted as follows:

(a) the lateral displacement of the bearing blocks under radiation is small compared to the tilt given in (b);

(b) the tilt of the elevation bearing blocks caused by radiation on the upper halves of the rear and front struts of the A-frames is the most significant effect (18″ per K);

(c) radiation on the lower half of the struts has a small effect (less than 10% of the upper struts).

The calculations suggest that in order to compensate for thermal effects the temperature differential of the upper struts, front and rear, should be measured and introduced in compensating software.

4.3. The algorithm for the pointing error

To determine the resultant pointing error, two steps must be performed:

(1) calculate the structural deformations at the elevation bearing blocks;

(2) establish the geometric relationship between the deformations of the bearing blocks and the deviation of the telescope reflector axis.

To calculate the deformations of the A-frames with finite element analysis, a transformation of the temperature data in (a) uniform (t_i) and (b) differential temperature distribution (Δt_i) in the A-frame struts is used.

Finite element calculations with the t_i and the Δt_i as unit loads on the A-frames give figures for the displacements described in matrix form. Simple geometry is then used to convert to the deviation of the telescope reflector axes.

5. Implementation of thermal correction

5.1. Retrospective correction

The thermal correction for elevation described above was first applied retrospectively to data already collected, and the results are shown in Fig. 5. Two features should be noted.

1. The elevation pointing error over the sunrise period (the "sunrise effect") is reduced from about 20″ rms to about 5″ rms.

2. The differences which were previously observed in the overnight pointing error (the apparant encoder jumps) are significantly reduced.

It was therefore concluded that the pointing is affected by thermal differentials in the structure, not only on a short timescale of a few hours from the direct effect of sunshine on the structure, but also over longer periods due to reverse effect during the night, as those parts of the structure facing the ground cool less quickly than those exposed to cooler sky. Figure 5 compares the effect of the full correction employing the four sensors T_1, T_2, T_5 and T_6 which measured the two arms of the A frame, with the simple correction employing sensors T_1 and T_2 measuring only the sloping arm of the A frame. It can be seen that the results agree to within 1–2″. We therefore concluded that the simple formula could be used as a fallback if one of the sensors T_5 or T_6 failed.

5.2. Dynamic pointing model

The elevation correction was then incorporated within the online pointing model. Figure 6 shows the results of observations over sunrise on W3 at 22 GHz. The pointing error, thermal differential for sensors T_1 and T_2, and the corresponding solar radiation as measured by a solarimeter placed on the structure, are plotted against time. This demonstrates that a pointing performance of 6″ rms can be achieved even when structural thermal differentials of up 6 K exist.

6. Conclusion

This work shows how the pointing was dramatically improved, for this telescope, by the incorporation of data from temperature sensors into the pointing model. The sensors were attached to parts of the structure where temperature differentials caused distortions in the support frame of the telescope. The effects persisted over a longer timescale than the few hours over sunrise, and were responsible for the apparant encoder jumps of over 20″ seen on successive nights. The resulting pointing performance is 6″ rms even in direct sunlight. There is obviously room for further improvement in the pointing from the use of additional sensors, for instance on the quadrapod legs, but the present system has increased the availability of the telescope at full specification for the entire period of the day.

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