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SOME REMARKS REGARDING THE 10-METER SUBMILLIMETER TELESCOPE

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I. INTRODUCTION

This Note is in answer to a call from Peter Mezger. He described the project, done in cooperation between the Max-Planck-Institut at Bonn and the University of Arizona; he asked several questions and wanted some comments.

1. Data

The diameter is D = 10 m, the shortest wavelength of observation is λ = 350 μm, and the total surface rms wanted is σ = 10 - 20 μm. It will probably be exposed during observations, otherwise shielded by a roll-away hut. Probably a 3-mirror optics.

Materials: the alt-azimuth mount will be of steel. The backup structure will use members of CFRP (carbon fiber reinforced plastic), where the elasticity E is equal to that of steel, the density ρ is 1/5 that of steel, and the thermal expansion C_{th} is 1/20 that of steel.

The surface consists of about 28 panels in 3 concentric rings. The panels are honeycomb with two CFRP skins and aluminum core, the upper surface is aluminized by a simple spray-on process. One test panel has already been made, on a Pyrex mold, achieving an accuracy of 3.5 μm rms.

The backup structure approached homology by trial-and-error, with a structural analysis yielding gravitational surface rms deviations of

$$\sigma = \begin{cases} 2.3\ \mu\text{m in zenith pointing,} \\ 3.5\ \mu\text{m in horizontal pointing.} \end{cases} \qquad (1)$$

2. Numbers Used

For the following estimates, I use a wanted accuracy of $\sigma(\text{total}) \leq 15\ \mu m$. I assume a balanced error budget with 6 major contributions: backup gravity, backup thermal or wind, panel manufacture, panel measuring and setting, panel gravity, panel thermal or wind. Then, for each single contribution:

$$\sigma(\text{single}) \leq 15/\sqrt{6} = 6\ \mu m. \tag{2}$$

I assume that the CFRP members must have metal joints, degrading some material constants a bit. I use: E = steel, ρ = steel/4, C_{th} = steel/15. For the panel length, I use L = D/6 = 167 cm. Regarding gravity, I assume that the values (1) mean: Let the surface be perfect without gravity; then switch on gravity, determine the present best-fit paraboloid with 4 degrees of freedom, and call Δz the rms deviation between this paraboloid and the deformed surface.

3. Enclosures (quoted as R1 ... R8 in the text)

R1. Alternative Design ... (Hounddog Note 12, 1982)

R2. Comments and Suggestions. (Hounddog Note 10, 1982)

R3. Internal Twist ... 4-Cornered Surface Plates ... (IEEE AP, 1981)

R4. Gravitational Deformation and Astigmatism ... (IEEE AP, 1975)

R5. Minimum-Noise Maximum-Gain Telescopes ... (IEEE AP, 1978)

R6. Derivative Tensor of the Stiffness Matrix ... (EUROMECH, 1982)

R7. Comments to the 30-Meter Telescope. (IRAM, 1974)

R8. A 65-m Telescope for Millimeter Wavelengths (Findlay + von Hoerner, NRAO, 1972)

II. GENERAL COMMENTS

1. Mounting

Fig. 1 of R1 shows the type of mounting which I would prefer, for telescopes between 2 and 20 meter diameter, say. It was developed for the design of a 3-m optical telescope, University of Washington in Seattle. For details and reasons, see the text of R1.

Regarding the 10-m telescope, the elevation structure must be different because an approach to homology is wanted. But azimuth structure and pedestal might still be worth a discussion. The pedestal could be of lesser height, partly or mostly buried into the ground. (The optical people wanted a certain height above ground for better seeing.)

2. CFRP

Very good properties indeed, especially C_{th} is very important here. But is it expensive? How will the joints be made? Is there any experience, regarding joints and honeycomb, about creep and fatigue of the bonding? If CFRP is used for the members, please use it throughout, not with the central steel hub of the Grenoble design.

Several papers at the EUROMECH meeting (Universitaet Siegen, Oct. 1982) dealt with the optimization of CFRP materials, regarding the angle of fibers in different layers, the layer thicknesses and numbers, and others. The proceedings of this meeting will appear as a book.

3. Panel Shape

I prefer trapezoidal panels, because triangular panels need twice the number of molds (two per surface ring), and 1.5 times the number of corners to be adjusted; all for equal radial length.

Four-cornered panels will give the same accuracy, if all four degrees of freedom are used in a least-squares adjustment (as opposed to the conventional true-corner adjustment). This includes an internal twist of the panel. A simple method of how to do it, plus several confirming test measurements, are described in R3.

If panels are manufactured over a mold, they may flatten out a bit when removed, in which case the mold should have a bit more curvature than wanted for the panel (ESCO does it this way). Does this apply here, too?

4. Optics

It might be interesting to ask Bruce Balick about the 3-mirror optics of the Seattle design (Paul + Baker type, improved by Epps + Dittmer). It has several nice advantages.

An asymmetric (off-axis) Cassegrain system had been discussed for the 10-m design. I enclose R5 which gives a method to calculate asymmetric shaped surfaces, for minimum noise and maximum gain. However, avoiding scatter for minimum noise is important only for extremely low-noise receivers; and shaping for maximum gain helps only for directional feeds, not for bolometers.

The question was raised whether an asymmetric backup structure can be made homologous. I am sure it can be done with the computerized iterations (R6), but it may be difficult with trial-and-error because the simplifying radial symmetry is lost.

5. Which rms?

In general, we mean σ = rms (of the deformed surface minus some reference). Regarding gravity, its effects are repeatable and known, and the focal equipment can be moved to the proper location (as a function of the elevation angle). Thus, the reference for the backup structure is its best-fit paraboloid with <u>four</u> degrees of freedom (which we may call: Δx and Δy of the vertex and of the focus). And for the panels, the reference is the average deformation of each panel, which gives for slender panels, as can be shown: $\mathrm{rms}(\Delta z - \overline{\Delta z}) = (2/3\sqrt{5})\Delta z_c = 0.30\ \Delta z_c$ where Δz_c is the deformation at the panel center. But to be on the safe side considering the neglected width of the panel, I use

$$\sigma \;=\; 0.5\ \Delta z_c \quad \text{for panel, gravity.} \tag{3}$$

Thermal and wind effects are not known. Regarding the backup structure, we do not know the proper focus location, we must leave the focal equipment unmoved. Thus, the reference for the backup structure is its best-fit paraboloid with only <u>two</u> degrees of freedom (Δx and Δy of the vertex). We will get pointing errors in addition, and a further gain loss for being off-source. And regarding the panels, we would have no reference to be subtracted if the deformations of the panels were uncorrelated, which would give $\sigma = \mathrm{rms}(\Delta z) = (\sqrt{8/15})\ \Delta z_c = 0.730\ \Delta z_c$. Actually, there is always some correlation, and an estimate gave

$$\sigma \;=\; (2/3)\ \Delta z_c \quad \text{for panel, thermal or wind.} \tag{4}$$

By the way, we always say "thermal <u>or</u> wind" because both cannot have their maximum effect at the same time, since strong winds smooth out large temperature differences.

III. PERFORMANCE ESTIMATES

The following estimates are done in order to see which of the various deformations may be critically large, asking for special design features.

Estimates of this kind are normally good within ± 30%, as long as the assumptions used are valid, which may sometimes not be the case. Anyway, all this should soon be replaced by proper computer analysis, and by actual measurements of temperature differences and panel deformations.

1. Backup, Gravity, and Adjustment Angle

We use equations (3) to (20) of R4, and the graph Fig. 1 of R7. Omitting all the details, we derive from our values (1) under the last assumption of Section I,2:

$$\text{best adjustment angle} \;=\; 53° \text{ elevation.} \tag{5}$$

With this surface adjustment we find $\sigma = 2.2$ μm at the zenith, $\sigma = 1.6$ μm at elevations 20° and 80°, $\sigma = 0$ at elevation 53°, and $\sigma = 2.3$ μm at the horizon. We have $\sigma = 1.5$ μm rms over the full range, a very good result.

In addition, we must consider all manufacturing and erection tolerances of the backup structure, see R8, where we found $\sigma = 91$ μm for $D = 65$ m. Scaled with D^2 to 10 m, we find $\sigma = 2.2$ μm. Quadratically added to the 1.5 μm of the last paragraph, this still yields the low value of

$$\sigma \;=\; 2.6\ \mu\text{m} \quad \text{for backup, gravity.} \tag{6}$$

2. Backup, Thermal or Wind

In R8, the 65-m design gave $\sigma = 65\ \mu\text{m}(\Delta T/°\text{C})$ thermal deformation for steel backup. Scaled with D to 10 m, and using 1/15 for CFRP, this gives $\sigma = 0.67\ \mu\text{m}(\Delta T/°\text{C})$. In R8, we measured structural temperature differences (with white protective paint) of $\Delta T = 0.8$ °C at clear nights, and $\Delta T = 5.0$ °C in full sunshine. Thus we expect now

$$\sigma = \left.\begin{array}{l} 0.6\ \mu\text{m at night} \\ 3.4\ \mu\text{m in sunshine} \end{array}\right\} \text{ for backup, thermal, exposed.} \tag{7}$$

The 65-m design gave $\sigma = 76\ \mu m$ for v = 18 mph wind ($\approx$ 30 km/h). We picked 18 mph as the upper quartile of the wind distribution. Wind deformations go with $\Delta z \sim FL/A$, where the force scales as $F \sim D^2$, the length of members as $L \sim D$. The bar areas of different members scale with exponents between 1 and 2, and we assume $A \sim D^{1.5}$. Under these assumptions we expect

$$\sigma = 5.0\ \mu m\ (v/18\ \text{mph})^2 \quad \text{for backup, wind, exposed.} \tag{8}$$

If true, this is still within demand (2), but this estimate is rather uncertain because of unknown bar areas, upper quartile at future site, gust factor, and shape factor.

3. Panel, Gravity

From R7, Fig. 5 we have for the deformation at panel center, under dead load,

$$\Delta z_c = \frac{1}{8} \frac{\rho}{E} \frac{L^4}{h^2} \tag{9}$$

for slender panels of length L and thickness h. We use (3) and derive for CFRP panels, neglecting the core weight which may be wrong:

$$\sigma = 0.8\ \mu m \left(\frac{L}{100\ cm}\right)^4 \left(\frac{10\ cm}{h}\right)^2 \quad \text{for panel, gravity.} \tag{10}$$

Using L = D/6 = 167 cm, and demanding $\sigma \le 6\ \mu m$ from (2), we derive the minimum panel thickness as

$$h \ge 10\ cm. \tag{11}$$

We see that the dead load deformation of the panels is a critical item, asking for thick panels (but not excessively thick). If length L is chosen differently, then $h \sim L^2$. This item calls for actual measurements.

4. Panel, Thermal or Wind

From R7, Fig. 5 we get for the central thermal deformation of a slender panel

$$\Delta z_c = \frac{1}{4} C_{th}\ \Delta T\ \frac{L^2}{h}. \tag{12}$$

For CFRP, using L = 167 cm, h = 10 cm, and (4), we derive

$$\sigma = 3.7\ \mu\text{m}\ (\Delta T/^\circ\text{C}) \text{ for panel, thermal.} \tag{13}$$

Demand (2) then means that the temperature difference between the two skins of the honeycomb must be

$$\Delta T \lesssim 1.6\ ^\circ\text{C}. \tag{14}$$

This should be checked by actual measurements at a panel under observing conditions. It will most probably be fulfilled at night, and certainly not in sunshine.

Regarding wind deformations, the textbooks give for a beam

$$\Delta z_c = \frac{5}{192} \frac{L^4\ P}{E\ t\ h^2} \tag{15}$$

where t is the thickness of the single CFRP skin, and the wind pressure is

$$P = 0.00256\ \text{lb/ft}^2 \left(\frac{v}{\text{mph}}\right)^2 . \tag{16}$$

Applying the beam equation (15) to a two-dimensional panel is valid for a slender panel, which means we assume the tangential width appreciably smaller than the radial length. With L and h as above, and with (4), this gives

$$\sigma = 3.0\ \mu\text{m} \left(\frac{\text{mm}}{t}\right) \left(\frac{\theta}{18\ \text{mph}}\right)^2 \text{ for panel, wind.} \tag{17}$$

Since the CFRP skins will be more than a millimeter thick, this item is not critical. But actual measurements of a panel deformation under equal-distributed loads is to be recommended.

5. Mounting, Thermal

This concerns pointing errors. The beam will be, for a good surface and 15 db taper,

$$\beta = 1.2\ \lambda/D = 8.6 \text{ arcsec,} \tag{18}$$

and one should demand for the pointing error at least

$$\Delta\phi \le 1 \text{ arcsec.} \tag{19}$$

For thermal deformations we use equation (13) and Fig. 7,b of R2:

$$\Delta\phi = \frac{1}{2}\left(\frac{2h}{b} + \frac{b}{2h}\right) C_{th}\ \Delta T \tag{20}$$

with height h and base b. Assuming h = 1.5 b, for example, we have for steel:

$$\Delta\phi = (5/3)\ C_{th}\ \Delta T = 4.1 \text{ arcsec } (\Delta T/°C). \tag{21}$$

Demand (19) means that the temperature differences across the mount should stay below

$$\Delta T \le 0.24\ °C. \tag{22}$$

This then is certainly a critical item, asking for extremely good thermal shielding of mount and foundation. Furthermore, I do not have data to estimate wind deformations, and the total error budget will also contain drive and reading errors. Maybe one should consider inclinometers at both elevation bearings, for on-line pointing corrections. However, the inclinometers give useful values only for the elevation error, but no values for the azimuth error. The latter could be estimated by reading the current of the azimuth drive as a measure of the wind-induced azimuth torque.

IV. DISCUSSION

The table gives a summary of our performance estimates. As already mentioned, some estimates may be off because of lack of detailed data. Several items need actual measurements (all panel items) or detailed computer analyses (backup and mount).

item	surface σ (μm)	condition	seems ok	critical	impossible
backup, gravity	2.6	53° elev. adjustm.	x		
thermal, night	0.6	ΔT = 0.8 °C	x		
thermal, sun	3.4	ΔT = 5.0 °C	x		
wind	5.0	v = 18 mph		x	
panel, gravity	6.0	h = 10 cm		x	
thermal, night	3.0	ΔT = 0.8 °C	x		
thermal, sun	18.5	ΔT = 5.0 °C			x
wind	3.0	v = 18 mph, $t \geq 1$ mm	x		
	pointing $\Delta\phi$ (arcsec)				
mounting, thermal	1.0	ΔT = 0.24 °C		x	

Regarding the panels, it seems they just need a certain thickness as defined by gravitational deformation, and then everything else is alright (but excluding good observations in sunshine at λ = 350 m). Regarding the backup structure, nothing looks critical except maybe the wind deformation, which then just would ask for somewhat thicker main members.

Regarding the pointing errors of the mount, we need extremely good thermal shielding and air circulation, and we could not estimate the wind deformation. Also, we must consider the thermal lag. We call $\dot{T} = dT/dt$

the time variation of the air temperature within the thermal enclosure of the mount, and τ the thermal time constant of the structural material, which is (equation 19 of R2):

$$\tau = 1.73 \text{ hours per inch of wall thickness, for steel tubes} \tag{23}$$

and half this value for open shapes. The resulting thermal lag then is

$$\Delta T = \tau \dot{T}. \tag{24}$$

It thus is very important to design all essential parts of the mount with about the same wall thickness.

On-line corrections of the pointing error are possible, but incomplete or bothersome. The best would be a gyroscope plus tiltmeter in the backup center, if it could be found for one arcsec at a reasonable price.