25-m Telescope
Memo No. 79
March 8, 1977

# DESIGN GOAL: $\lambda = 0.8$ mm

Sebastian von Hoerner

In order to get the telescope ever funded, we need convincing scientific justifications and a favorable comparison with other existing or planned telescopes. Both items depend crucially on the shortest wavelength, $\lambda = 16\ \mathrm{rms}(\Delta z)$. Some of our recent memos give the impression that our present design goal of $\lambda = 1.2$ mm (250 GHz) is just a bit marginal, whereas the next atmospheric window, $\lambda = 0.81$ mm (370 GHz), might give us a really good chance, especially after having decided for Mauna Kea. A discussion of the error budget will show that the only crucial contribution is the manufacturing accuracy of the surface plates. Therefore, we should make it our most urgent task to obtain more accurate plates within reasonable costs. Otherwise, our efforts to achieve homologous deformations, and the money to be spent on the astrodome, would largely be wasted.

## I. Remarks about Recent Memos

Memo 75 (R. Brown). Comparison with other telescopes shows that we have advantages for very short wavelengths only, and the shorter the better. This comparison should be done with more numerical detail, summarized in a Table. A good point is mapping sources at various frequencies above 200 GHz, yielding the transition from hot to cold; but Fig. 1 (Orion) shows clearly that one must go beyond 230 GHz, where just the minimum occurs, and the same follows from Fig. 3.

Memo 78 (B. Turner). There is too much emphasis on resolution; we then should build an interferometer and not a single dish. Furthermore, the beamwidth does not decrease with wavelength beyond the design limit (beam broadening, high sidelobes); if the telescope is designed for $\lambda = 1.2$ mm, the beam at 0.8 mm will not be 8 arcsec as mentioned, but 15 arcsec, see Section IV. A Table should be added with the molecular line frequencies for 200 - 400 GHz, indicating their individual relative importance.

Memos 69 (C. Wade) and 76 (L. Rickard). The site selection was heavily influenced by frequencies $\geq$ 230 GHz, both memos giving comparison tables up to 345 GHz. After having followed this line of thought, we should really make it stick by pushing our design goal to at least 345 GHz.

## II. The Surface Errors

Appendix A is a copy of the error budget from our 25-m Proposal of Sept. 1975; the numbers have not been changed meanwhile. There are two items sticking our far beyond all other contributions: the manufacturing accuracy of the surface plates (40 μm), and measuring the telescope surface (40 μm); the next large item is the subreflector (25 μm), while all the other ten items are smaller ($\leq$ 16 μm).

The measuring technique will surely improve during the next years, and even after the telescope has been in operation any new technique can still be applied, whereas resurfacing a telescope is very expensive. At present we need some estimate as to what a good measuring technique might yield in the future (after five or more years). This is done in Appendix B, with the result

$$\text{measuring rms error } (\geq 1982) = 15\ \mu\text{m}. \tag{1}$$

The remaining urgent question is: how good a surface can we get for reasonable means? At present, I will turn the question around and ask: how good a surface do we need for the next atmospheric window? The next window (von Hoerner, Astronomy and Astrophysics, 41, 301, 1975) covers the range $\lambda$ = 0.7 to 0.9 mm. Adopting $\lambda$ = 0.8 mm as the center, and demanding a total rms of $\lambda/16$ = 50 μm, we find from the error budget including change (1) that the plate error should be 23.3 μm. Using a round number, we then have the goal

$$\text{plate manufacturing rms error} = 25\ \mu\text{m}. \tag{2}$$

Assuming this to be possible, results and remarks are summarized in Table 1. With the old values for surface measuring and plate manufacturing, a good deal of our previous engineering effort, and of the money to be spent for the astrodome, would plainly be wasted.

Table 1. Old and new error budget (rms surface error, in μm)

| Item | rms(Δz) | | Remarks |
|---|---|---|---|
| 1. Gravity | | | |
| surface plates | 12 | 21.2 | We have spent many years of engineering effort, to approach homologous deformations better than anyone else. |
| panel structures | 7 | | |
| backup structure | 16 | | |
| 2. Thermal | | | |
| surface plates | 16 | 20.7 | We are willing to spend about 4 M$ for the astrodome, to keep day performance equal to night performance. |
| panel structures | 2 | | |
| backup structure | 13 | | |
| 3. Wind (Ventilation) | | | |
| surface plates | 1 | 1.7 | (We might ventilate stronger, to reduce thermal deformations even more.) |
| panel structures | 1 | | |
| backup structure | 1 | | |
| 4. Others | | | |
| plate setting | 15 | 29.2 | |
| subreflector | 25 | | (Could we get a better subreflector?) |
| subtotal = | | 41.6 μm | |
| 5. To be reduced | (old) | (new) | |
| surface measuring | 40 | 15 | See Appendix B. |
| plate manufacturing | 40 | 25 | Most urgent present task. |
| total rms = | 70.2 | 50.9 μm | |
| $\lambda = 16$ rms $(\Delta z)$ = | 1.12 | 0.81 mm | Center of next atmospheric window. |
| $\lambda = 0.81$ mm<br>$\nu = 370$ MHz<br>$e^{-(4\pi \text{ rms}/\lambda)^2}$ = | 30.5% | 53.6% | Efficiency almost doubled, factor 3.0 in obs. time. |

Demand (2) could actually be somewhat relaxed, if we could get a more accurate subreflector ($\leq$ 20 μm, say) which makes sense because a small accurate surface is cheaper than a large one, and if thermal deformations could be reduced by stronger ventilation. Furthermore, in the past we demanded that the specified plate error is the rms of the deviations $\Delta z$ from a paraboloid going through the four plate corners. But if (2) cannot be met this way, we may only demand that $\mathrm{rms}(\Delta z - \overline{\Delta z}) \leq 25$ μm, although this is rather inconvenient for the plate setting, and gives away one of our "safety factors".

## III. Cost Comparison

Appendix C gives the present detailed cost estimate, including some changes suggested by D. Heeschen on Feb. 24, 1977. The total cost for Mauna Kea is 17.100 M$; of which the telescope itself is 3.427 M$, of which the surface plates are 1.371 M$. If it is crucial to go to the next atmospheric window, one might be willing to pay somewhat more for a better surface.

Memo 33 (W. Y. Wong, Oct. 1975) gives an interesting report of a trip to various firms. For example, Mechanical Specialities quote cost increase factors for various accuracies beyond their "standard" accuracy of 64 μm. From a log/log plot I derive:

| from | to | cost factor |
|---|---|---|
| 64 | 40 μm | 3.32 |
| 40 | 25 μm | 2.40 |

(3)

But since the whole step, from 64 to 25 μm, would be a factor of 8.00, it just means that some different manufacturing method should be chosen.

Tinsley mentioned that they could make a subreflector for 12 k$ with 50 μm peak-to-peak, which would be about 12 μm rms. This should be further investigated. If Leighton's total rms is 50 μm, then his plates must be at least as good as 30 μm. His low cost is difficult to understand; should we investigate some more? Aeronutronic have three panels made and measured, with 41, 28, 20 μm rms, amounting to an average of 30 μm, almost good enough for our demand (2). Table 2 summarizes some of the numbers

Table 2. Comparisons for surface plates.

| | rms($\Delta z$) μm | cost \$/ft$^2$ |
|---|---|---|
| Aeronutronic | 30 | 100 |
| Leighton | 30 | 12 |
| Tinsley | 12 | 725 |
| 25-m design | 40 | 260 |
| British 15-m | 20 | 299 |

from Memo 33 (which of ocurse are only rough unconfirmed estimates), together with our 25-m design for $\lambda = 1.2$ mm, and the British 15-m design for $\lambda = 0.80$ mm. Some more of the British cost estimates (of Nov. 1976) are given below, with 1 £ = 1.714\$.

$$\begin{aligned} \text{British project total} &= 6.619 \text{ M\$}, \\ \text{telescope} &= 2.005 \text{ M\$}, \\ \text{surface plates} &= .569 \text{ M\$}. \end{aligned} \tag{4}$$

## IV. The Beamwidth

Surface errors ($\Delta z$) will degrade the gain (factor $g < 1$, say) as well as the beamwidth (factor $b > 1$). If no energy is lost into sidelobes or far-off scatter, then

$$b^2 g = 1. \tag{5}$$

Since

$$g = e^{-(4\pi \Delta z/\lambda)^2} \tag{6}$$

the beam is broadened by the factor

$$b = e^{8(\pi \Delta z/\lambda)^2}. \tag{7}$$

At the design limit, $\lambda = 16 \Delta z$, this factor is

$$b = e^{\pi^2/32} = 1.36. \tag{8}$$

In general, the half-power beamwidth, $\beta$, is given by

$$\beta = 1.2\,\frac{\lambda}{D}\,e^{8(\pi\Delta z/\lambda)^2}. \tag{9}$$

These relations have been confirmed recently, by measuring the gravitationally deformed beamshape and degraded gain of the 140-ft (Engin. Report 103, Feb. 1977), except for a sidelobe containing 10% of the energy, which we shall neglect at present. From (9) we then derive, for the old and new surface errors:

| $\Delta z$ ($\mu$m) | | $\beta$ (arcsec) $\lambda$ = 1.2 mm | $\lambda$ = 0.81 mm | $\lambda$ = 0.70 mm |
|---|---|---|---|---|
| (old) | 70.2 | 15.6 | 14.5 | 15.3 |
| (new) | 50.9 | 13.7 | 10.9 | 10.5 |

(10)

It should be mentioned that the permitted pointing error $\Delta\phi$, for the new design goal of $\Delta z$ = 50.9 $\mu$m, then is for any short wavelength

$$\Delta\phi = \begin{cases} 1.0 \text{ arcsec, demanding } \Delta\phi = \beta/10, \\ 1.7 \text{ arcsec, demanding } \Delta\phi = \beta/6. \end{cases} \tag{11}$$

Appendix A shows the estimated pointing error of our 25-m Proposal, with $\Delta\phi$ = 0.7 arcsec, which still is very low even for our new design goal.

**Appendix A.**

### Table III.1 (25-m Proposal, Sept. 1975)

### Mechanical Performance of the 25-meter Telescope

| | Open | | | Enclosed |
|---|---|---|---|---|
| | Noon | Night | | |
| | Calm, Sun | Calm | 30 km/h wind | 10 km/h wind |
| Surface Errors | (μm) | (μm) | (μm) | (μm) |
| Surface Plates | 259 | 73 | 61 | 62 |
| Manufacture | 40 | 40 | 40 | 40 |
| Gravity | 12 | 12 | 12 | 12 |
| Setting | 15 | 15 | 15 | 15 |
| Measurements | 40 | 40 | 40 | 40 |
| Thermal | 252 | 42 | 7 | 16 |
| Wind | - | - | 10 | 1 |
| Panel Structure | 29 | 9 | 9 | 7 |
| Manufacture & Gravity | 7 | 7 | 7 | 7 |
| Thermal | 28 | 5 | 1 | 2 |
| Wind | - | - | 5 | 1 |
| Backup Structure | 212 | 39 | 20 | 21 |
| Assembly & Gravity | 16 | 16 | 16 | 16 |
| Thermal | 211 | 36 | 6 | 13 |
| Wind | - | - | 11 | 1 |
| Subreflector | 25 | 25 | 25 | 25 |
| Manufacture & Gravity | 25 | 25 | 25 | 25 |
| Total Error (1) | 337 | 87 | 70 | 70 |
| Pointing Errors | (Seconds or arc) | (Seconds of arc) | (Seconds of arc) | (Seconds of arc) |
| Servo and Drive | 0.5 | 0.5 | 0.5 | 0.5 |
| Thermal | 6.3 | 1.1 | 0.0 | 0.4 |
| Wind | - | - | 3.2 | 0.3 |
| Total Error (1) | 6.3 | 1.2 | 3.2 | 0.7 |

(1) Total error is the quadratic sum of the individual, uncorrelated, rms errors.

## Appendix B: Future Surface Measuring Error

In Memo 68 (Jan. 1977) John Findlay suggested a stepping method which looks very promising. It was tested in Memo 70 with good results. What could the final accuracy be, after several years?

Single Step Error. Findlay discusses the Schaevitz inclinometer with about 1 arcsec accuracy, and an (improvable) 16-bit A/D converter with 1.6 arcsec/bit. This adds up to about $\Delta\theta = 2$ arcsec. If the earliest chance for getting funds is 1979, and if it takes three years for detailed design and building, we have at least five years to improve the method; and, in any case, it still could be improved thereafter. It seems reasonable to assume a final accuracy of, say,

$$\Delta\theta = (1.0 - 1.5) \text{ arcsec.} \tag{B1}$$

Edge Error. Findlay suggests for practical reasons $N = 25$ measuring points per radius. This is 3 points per radius per panel, with a cart length of $L = 50$ cm. The edge error, at the rim of the telescope, then is

$$\Delta z_e = L \, \Delta\theta \sqrt{N} = 12.1 \, \Delta\theta \text{ µm/arcsec,} \tag{B2}$$

or, with (B1)

$$\Delta z_e = (12 - 18) \text{ µm.} \tag{B3}$$

Weighted Rms-Error. At distance r from the center, $(\Delta z)^2 \sim r$. As for the weights, the area goes with r, and the illumination shall be assumed parabolic, $(1 - r^2)$. The total weight thus is $(r - r^3)$, and

$$\overline{(\Delta z)^2} = (L \, \Delta\theta)^2 \, N \int_o^R (r^2 - r^4) dr \Big/ \int_o^R (r - r^3) dr = \frac{8}{15} (\Delta z_e)^2 \tag{B4}$$

or

$$\text{rms}(\Delta z) = 0.730 \, \Delta z_e . \tag{B5}$$

With (B3) we have

$$\mathrm{rms}(\Delta z) = (9 - 13)\ \mu\mathrm{m}, \tag{B6}$$

and, leaving some contingency, we finally adopt for the future error, in five years,

$$\mathrm{rms}(\Delta z) = 15\ \mu\mathrm{m}. \tag{B7}$$

Appendix C, 1

# 25 - Meter Telescope

## Cost Categories (Thousands of 1976 Dollars)

| | Kitt Peak, AZ | Mauna Kea, HI |
|---|---|---|
| **Development Cost** | | |
| Design 1-A-D | 1046 | 1046 |
| Consultant Fees 8-D | 0 | 19 |
| Surveys and Soil Tests 8-H | 25 | 35 |
| | 1071 | 1100 |
| **Telescope Installation** | | |
| Telescope Installed 2-A-Q | 3343 | 3427 |
| Astrodome Installed 3-A-I | 3874 | a) ~~4113~~ 3813 |
| Water, Grading, Power, Road and Telephones 4-A, B, C, E, 8-C | 157 | 654 |
| Construction Salaries and Travel (Includes Some Design Cost) 8-B, F, I, J, K, L | 793 | 1613 |
| | 8167 | ~~9807~~ 9507 |
| **Requirements for Operation** (Assets) | | |
| Dormitories, Labs, Offices, Auxiliary Power 4-D, F, G | 607 | 1128 |
| Telescope Controls, Interfaces, Cabling, and One Receiver 5-A, C, D, E, F, G | 465 | 465 |
| Computers 6-A-J | 331 | 331 |
| | 1403 | 1924 |
| **Requirements for Operation** (Capital and Expense Items Which Normally Are Paid Out of Operations) | | |
| Three Cooled Receivers and Test Equipment 5-A, B | 570 | b) ~~930~~ |
| Freight, Employee Relocation, Salaries for Electronics Construction 8-A, E, G | 288 | 597 |
| Machine Shop, Tools, Various Equipment, Furniture, Supplies, Etc. 7-A-U | 298 | 987 |
| | 1156 | ~~2514~~ 1584 |
| Sub Total | 11797 | ~~15345~~ 14115 |
| **Possible Cost Changes** | | |
| 20% Contingency | 2359 | ~~3069~~ 1412 |
| Foundations, Housing, Vehicles 9-A-C | 0 | 1473 |
| Cost Changes With 36' Shutdown 10-A-I | (295) | 100 |
| | 13861 | ~~19987~~ 17100 |

Meeting Feb. 24, 1977,
according to Heeschen:
a) No range calibration
b) Omit receivers
c) 10% contingency

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25 - Meter Telescope

Appendix C, 2.

## 2. Telescope Installed (Thousands of 1976 Dollars)

| | | Kitt Peak, AZ | Mauna Kea, HI |
|---|---|---|---|
| A. | Surface Plates | 1371 | Same |
| B. | Intermediate Panels | 304 | S |
| C. | Feed Support | 78 | S |
| D. | Subreflector | 46 | S |
| E. | Backup Structure | 503 | S |
| F. | Counterweights | 43 | S |
| G. | Bearings and Drive | 461 | S |
| H. | Servo | 257 | S |
| I. | Tower Structure | 242 | S |
| J. | Foundation and Track | 238 | 288 |
| K. | Ladder and Walkway | 33 | S |
| L. | Control Cabling | 55 | S |
| M. | Painting | 72 | S |
| N. | Final Setting System | 85 | S |
| O. | Freight | 1 | 35 |
| | Sub Total | 3789 | 3873 |
| P. | Telescope Design | (417) | (417) |
| Q. | Foundation Design | (29) | (29) |
| | Total | 3343 | 3427 |

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