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# REMARKS FOR THE 10-METER SUBMILLIMETER TELESCOPE, II: SUGGESTIONS AFTER THE MEETINGS AT BONN AND FRIEDRICHSHAFEN

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On July 4, 5, and 6, Dornier had invited for a meeting with members of the MPI-Radioastronomy, Steward Observatory, and Krupp. The following is a summary of a few selected topics which I would like to suggest for further discussions.

## I. SPECIFICATIONS

For the planned future design work, some of the old specifications could be relaxed, and some new ones should be added.

### 1. Wind Specifications

The old specifications are: $v_{obs}$ = 12 m/s = 27 mph for telescope deformations during observations; $v_{open}$ = 25 m/s = 56 mph for stability of telescope and hut with open doors; $v_{surv}$ = 52 m/s = 116 mph for survival stability of closed hut. In comparison with specifications of other telescopes, it seems to me that these demands are too stringent and could be relaxed. And since wind deformations are the largest item in the error budget[1)], a rediscussion is suggested. In addition, we must also investigate (and specify) the influence of the surrounding hut on wind speed and vorticity inside: a wind reduction factor, and expected telescope torques in azimuth and elevation.

We would need the following basic data (I have written to B. Ulich and W.-Y. Wong, and will also collect some NRAO data):

a. Velocity distribution F(v) on Mt. Lemmon, for selecting $v_{obs}$ and $v_{open}$.

b. Highest speed $v_{max}$ ever recorded, and duration of these observations. From this, together with F(v), we may extrapolate $v_{surv}$.

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1) Feasibility study of Dornier, page 41 (June 1983).

c. Any strong regularities? For example, at the VLA site almost all strong winds come from WSW, and only during early afternoon. If specifying a large $v_{obs}$ would demand an expensive stiff structure, one could relax the specification and schedule the observations according to the regularities.

d. We need either (expensive) wind tunnel tests, or some simple homemade experiments plus good estimates, and/or torque measurements (B. Ulich) at existing similar telescopes, in order to know the wind properties inside the hut.

We then need three definitions, and I would like to suggest the following:

$$v_{obs} = \text{third quartile of } F(v); \quad (1)$$

$$v_{open} = 95\% \text{ level of } F(v); \quad (2)$$

$$v_{surv} = \text{once in 100 years.} \quad (3)$$

Furthermore, I think that the old specification of 2 meter snow is too much, on a slant roof of limited size, high above ground. We should relax it if that decreases the cost of the hut.

## 2. Thermal Specification

Regarding thermal deformations during observation, there are three old specifications:

(a) Slow ambient air change: from +10°C to −10°C, and to +30°C, uniform for all members.

(b) Temperature gradient in backup structure, of $dT/dx = 6°C/D$, across the dish in x-direction (vertical, when pointing to horizon), where $D = 10m$ is the diameter.

(c) Temperature gradient of $dT/dz = 0.5°C/cm$ through panels, normal to surface. Used was $\Delta T = 4.5°C$ for panels of 9 cm thickness.

I suggest to add two more specifications:

(d) Temperature gradient in backup structure of, say, $dT/dz = 4°C/H$ in z-direction (parallel to optical axis) where H = z-distance between surface rim and pedestal interface.

(e) Fast ambient air change, $dT/dt$, after sunrise and sunset, yielding a thermal lag of thick-walled members; $dT/dt$ should be measured on Mt. Lemmon.

For example, after measurements on several sites, we used for NRAO designs $dT/dt = 5.4°C/hour$ after sunset, on the 95% level. The thermal lag between member and air then is $\Delta T = \tau\ dT/dt$, with $\tau = 1.74$ hours per inch of wall thickness for steel tubes with white paint, and half that value for open shapes ($\tau = 1.14$ hours/inch for aluminum tubes). The time constant $\tau$ should be found experimentally for carbon fiber members, using the same paint or wrap as planned for the telescope. Steel joints will lag, too.

Most important for a new design, regarding panel size, number of supports, and type of backup structure, will be a change of specification (c). As B. Ulich reported, a test panel of true size and 6.3 cm thickness was vacuum-aluminized on both sides. Temperatures were then measured at its front and back skin, $T_f$ and $T_b$. Calling $\Delta T_a$ the difference between average panel and ambient air temperature (causing mainly only a larger size), and $\Delta T_i = T_f - T_b$ the internal temperature difference (causing a larger radius of curvature), the measurements gave:

| | $\Delta T_a$ | $\Delta T_i$ | | |
|---|---|---|---|---|
| full sunshine | 5.0 | 0.4 | °C | (4) |
| clear night | 0.1 | 0.1 | °C | |

With the old specification (c) and 6.3 cm thickness, we would have had $\Delta T_i(\text{sun}) = 3.2°C$, whereas the new measurements of 0.4°C would allow for a considerable relaxation, by a factor of eight. However, the question of aging and lifetime was raised, and a cost of $70,000 was mentioned for a single protective coating of all panels.

If $\Delta T_i$ indeed were small and long-lived, the new design could be favorably changed, see Section III, 4. It would thus be very important to get more measurements:

1. Repeat measurements, with panels of different thickness. For example, with 4 cm, 6 cm, and 9 cm.
2. Do the same for some panels with protective coatings, expensive and cheap ones.
3. Do experiments with "accelerated aging".
4. Measure the thermal time lag between front and back skin, for different thickness.

### 3. Pointing Errors

Specifications for pointing errors should be the same as for surface deformations, regarding thermal effects and wind. Except that temperature differences of the mount will be reduced by its protective thermal shielding (how much reduced?); but the thermal lag will be large for its thick-walled shielded members, which makes exact symmetry very important.

Not just the total pointing error should be given, but also its single contributions: from primary deformation, leg deformation, secondary rotation, and mount deformation. Any compensation, among items with different sign, should be regarded with caution. Sunshine and wind may partly be shielded, and wind is gusty not only in time but also in space.

4. Combined Effect of Wind and Temperature

When summing up all items of an error budget, please keep in mind that strong winds will smooth out large temperature differences; we may have either one, but not both. We call $\delta_a$ to $\delta_e$ the single maximum errors according to the thermal specifications (a) to (e), and $\delta_v$ the error induced by the wind $v_{obs}$. This may apply to surface errors as well as pointing errors. We call

$$\delta_s^2 = \begin{cases} \delta_b^2 + \delta_c^2 + \delta_d^2 + \delta_e^2 & \text{for surface errors} \\ \delta_b^2 + \delta_e^2 & \text{for pointing errors} \end{cases} \quad (5)$$

and

$$\delta_m = \max(\delta_s, \delta_v). \quad (6)$$

The combined error then is

$$\delta_t = \sqrt{\delta_a^2 + \delta_m^2}. \quad (7)$$

## II. VARIOUS DEFINITIONS OF "SURFACE RMS"

1. General

For each single type of surface deformation, we must have a clear definition, telling which quantity the root-mean-square shall be taken of. This quantity is mostly the difference between the actual deformed surface, and some best-fit shape, with n degrees of freedom for the best-fit procedure. The lack of such definition once caused unpleasant friction between NRAO and a manufacturer.

A simple two-dimensional illustration is given in Fig. 1. It shows a straight line, its deformation, and the possible choice of best-fit straight lines: n = 0 means that nothing is subtracted from the deformed line; n = 1 subtracts the average deformation; and n = 2 allows a least-squares slope, too.

There must be an agreement already in the design phase, between the manufacturer and the future user, about the method of surface adjustment planned for the erection, and about the focal movements to be provided by the structural design.

## 2. Backup Structure

What matters is the rms difference between the deformed surface and its own best-fit paraboloid. This needs two agreements: First, which kind of weighting the "mean" of the rms should use. Backup structure deformations are usually calculated only for the structural joints of the surface, which are unequally spaced, thus the area represented by each joint must be used as weight. (One may also use the pathlength error instead of the z-deformation, if wanted.) And it must be specified whether or not the illumination taper should be used as weight; I would suggest not to use it, because we may consider shaped surfaces yielding small or no taper.

Second, how many degrees of freedom should be allowed in the best-fit procedure? We call z the optical axis, y the elevation axis, and x perpendicular on both. A paraboloid of revolution has a total of six degrees of freedom: three translations, two rotations (none about z-axis), and one focal length. But not all degrees may show up in a deformation, and of those which do, not all may be used. For those showing up but not to be used, the best-fit program must have been given a constraint.

### a. Gravity

For an x,y-symmetric backup on an alt-azimuth mount, two degrees do not show up (zero in Table 1): y-translation, and rotation about x-axis. This leaves four degrees: two translations, one rotation, one focal length. Or, with other words:

$$\begin{array}{l} \text{x and z translation of best-fit parabola vertex,} \\ \text{x and z translation of best-fit parabola focus.} \end{array} \qquad (8)$$

Feed and receiver will always automatically use both freedoms of the vertex shift, where we assume that any resulting changes of axial direction are taken care of by the pointing program, since gravity is repeating and predictable. But the use of the other two freedoms depends on the structural design. Most telescopes provide a remote control of the focal length (z-translation), and three degrees may be allowed if this is computer controlled as a function of elevation E, with two constants $F_o$ and A to be calibrated:

$$F = F_o + A \sin E. \qquad (9)$$

The fourth degree may also be used if the focal equipment has a computer-controlled lateral movement (x-translation); if adjusted at zenith pointing, the movement is:

$$X = X_o + B \sin(90° - E). \qquad (10)$$

For example, the 140-ft telescope at Green Bank has A = 18 mm and B = 30 mm. But as a polar mount it shows also a y-deformation according to hour angle pointing, with a term similar to (10) and a constant $B_2$ = 71 mm. The effect causing large values of B and $B_2$ from small surface deformation is described in a previous paper [2] and is explained as a "gliding rotation" of the best-fit paraboloid along the deformed surface above a point somewhat

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2) "Strong Coma Lobes from Small Gravitational Deformations", IEEE Trans. AP-28, 652, 1980.

above 2F on the axis. The rim deformation causing B is only 1.1 mm on the 140-ft, the one causing $B_2$ is only 3.2 mm.

b. Uniform Temperature Changes

Slow temperature changes according to specification (a) of Section I.2 will give no x or y deformation for a symmetric structure. They may give a change of focal length (steel joints), and if the focal location along the z-axis is "peaked up" a few times per day, we may allow two degrees of freedom, see Table 1.

c. Temperature Differences, and Wind

The worst items are the fast, unpredictable and mostly asymmetric temperature differences, specifications (b), (d) and (e), and gusty wind forces. Both sun and wind may come at oblique angles and with part-shielding which changes with telescope pointing. In this case, all six deformations show up, but only one degree of freedom can be allowed for the best-fit: the z-translation of the vertex. The focal equipment cannot be moved to its best position, and a change of the axial direction cannot be taken care of by a pointing correction.

The best-fit procedure then must yield a paraboloid of revolution whose focus is located at the apex of the deformed legs (where the receiver or Cassegrain actually is), and whose axial direction is still parallel to the undeformed direction (as defined by the radio source which is observed).

3. Surface Panels

The panel deformations from gravity will change focal length and axial direction of the telescope, both to be taken up by focal movements (9) and (10) and by the pointing program. We thus may subtract the average deformation, $\mathrm{rms}(\Delta z - \overline{\Delta z})$, for the dead load deformation.

The slow uniform temperature change will only change the focal length of the telescope, and assuming a "peaking up", we may again subtract the average.

Deformations from sunshine and wind, however, are fast and non-uniform, thus nothing may be subtracted: rms($\Delta z$).

The definition of the manufacturing rms accuracy depends on the future method of panel adjustment of the telescope. In the past, panels were mostly adjusted with their corners on the telescope paraboloid. This "true-corner adjustment" does not allow any degrees of freedom: in the measuring machine, all panel adjustment points must be set on the prescribed height, and the rms of the surface errors is to be taken directly, nothing subtracted. Much better is of course a "least-squares adjustment", for example with three degrees of freedom for triangular panels, allowing a rigid-body movement with an average lift plus two slopes. Still better is it with four degrees, for four-cornered panels adjusted at their corners, allowing an additional warp (saddle-shaped) which has been worked out in a previous paper [3].

A least-squares adjustment for five or more adjustment points has not yet been worked out. This is one of the reasons why I would prefer panels with four support points, if possible, as assumed in Table 1.

## III. STRUCTURAL DESIGN

### 1. Protective Hut

It was mentioned that a roll-away hut would be less expensive, by about 400 k$, whereas a corotating hut is a good deal more convenient. I strongly recommend the corotating hut, plus a good effort to minimize its cost. It may

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3) "Internal Twist and Least-Squares Adjustment of Four-Cornered Surface Plates for Reflector Antennas", IEEE Trans. AP-29, 953, 1981.

<u>Table 1</u>. The number n of degrees of freedom, for best-fit shapes, when calculating the rms surface deformations.

0 = no deformation of this type occurring;

c = constraint needed in best-fit procedure;

f = freedom to be used in best-fit procedure.

| backup structure | vertex shift x | vertex shift y | vertex shift z | focus shift x | focus shift y | focus shift z | n | (notes) |
|---|---|---|---|---|---|---|---|---|
| gravity | f | 0 | f | f | 0 | f | 4 | (a) |
| uniform temper. | 0 | 0 | f | 0 | 0 | f | 2 | (b) |
| temp. difference | c | c | f | c | c | c | 1 | |
| wind force | c | c | f | c | c | c | 1 | |

| surface panels | average height | slopes x | slopes y | warp (saddle) | n | (notes) |
|---|---|---|---|---|---|---|
| manufacturing | f | f | f | f | 4 | (c) |
| gravity | f | 0 | 0 | 0 | 1 | (d) |
| uniform temp. | f | 0 | 0 | 0 | 1 | (b) |
| temp. difference | c | 0 | 0 | 0 | 0 | |
| wind force | c | 0 | 0 | 0 | 0 | |

Notes: (a) with computer-controlled movements, x and z, at focus:

(b) if focus is "peaked up" a few times per day;

(c) with four-point support and least-squares adjustment;

(d) with computer-controlled z-movement at focus.

help, for example, if we could relax the wind and snow specifications, as indicated in section I.1.

In addition to the considerably greater convenience, the rotating hut gives the following advantages:

a. Shielding during observation, at least to some extent and most of the time, against sunshine and wind. We do not yet have measurements about indoors wind; but I feel rather sure that the hut will give some degree of shielding even in the worst case. And since wind deformations are the largest item in the error budget, the rotating hut should save some money on the telescope.

b. In case of a rollaway hut, we would need two large shielded corotating Nasmith cabins, anyway. They will be more expensive and troublesome when put on the telescope mount.

c. In case of sudden storms, moving the corotating hut needs less force (cheaper motors, gears and wheels): the hut is first rotated <u>with</u> the storm until the doors become downwind, and then the doors are closed in a shielded position and the roof in a neutral position. Whereas the rollaway hut must be moved <u>against</u> the storm, in the worst case.

d. In case of sudden storms, the telescope is shielded faster: already after one quarter of a full rotation, in the worst case. While in the worst case with the rollaway hut, the telescope has the storm still full force, all the way, until the doors are closed.

## 2. <u>Present Backup Structure</u>

To do an all-carbon fiber design, without any other material, was certainly a very interesting try. The main difficulty is: how to make 3-dimensional many-membered joints. The present solution was a reduction to a 2-dimensional frame structure (thin-web I-beams, up to 70 cm high, replacing the third dimension), in a polar grid without diagonals (joints enforced with gusset plates). This raised two objections.

First, the backup structure is too thin, only 70 cm thick at center, which makes the outer part too slender a cantilever. This shows up mainly in the face-on wind deformations and in the uniform temperature change. It may also give large deformations for the thermal z-gradient suggested in the specification (d) of section I.2.

Quite in general, a slender cantilever will need more material, for the same stiffness, than a thicker one. Increasing the central thickness from 70 cm to, say, 110 cm may be sufficient: thermal deformations decrease inversely proportional with the thickness, gravity and wind deformations with its square. Could the present thin-webbed I-beams be made thicker, but with less material? Probably not.

Second, in the absence of diagonals we rely on the (small) bending stiffness of the members. This weakness shows up in the low dynamical mode of the z-rotation; and also in the large deformations from side wind, and from gravity in horizon pointing, which are the two main items in the error budget. Again, quite in general: a structure relying on bending (or torsional) stiffness will always need more material, for the same stiffness, than a structure acting in compression and tension. For our NRAO designs, I suggested a test: apply both truss analysis (pin joints) and frame analysis (bending and torsion included); if there is much difference regarding deformations or stability, then change the structure.

Maybe the present design could be improved by just adding diagonals in tension, from carbon fiber ropes, simplifying the many-membered joints considerably. This solution is only to be recommended if the present amount of material is mainly needed for deformational stiffness; but probably not if needed for stability, since prestressed cables introduce additional forces.

I would like to emphasize that the main objection against the present design is not the fact that its deformations are too large (specifications being almost met already), but that too much material is needed for the demanded stiffness.

## 3. Present Panels

We were favorably impressed by the work done on the panels: a variety of ten different designs were made and tested, all with two carbon fiber skins enclosing an aluminum core, four panels with honeycomb core and six with flexcomb (equal flexibility in x and y direction). From the data it seemed that we should select the flexcomb panels in spite of their somewhat higher cost, because of their better manufacturing accuracy, and better thermal stability during transport when heated to 50°C.

The present design has:

3 concentric rings of panels,
with 56 panels total, (11)
and 1.67 m x 0.94 m average panel size;
5-point panel support, 4 corners plus center.

The 5-point support was chosen mainly to decrease the thermal deformation from specification (c), the temperature difference of $\Delta T = 4.5°C$ between front and back skin in sunshine, but also to decrease the gravitational deformation in zenith position. The details of this 5-point support were well designed, not needing more backup members than a 4-point support.

In zenith position, the weight of the panel is supported, at all five points, not as usual on the joints of the backup members, but at the middle of each member, being carried in beam action. This is alright for the present backup structure, where the members are thick I-beams, with 20 to 70 cm thickness. It would not be advisable for a normal space-frame structure with slender members.

It was not clear, at present, how the panels should be adjusted later at the telescope. In section II.3 we have pointed out that this must be decided already now, because it enters the definition of the manufacturing surface rms accuracy. Either, someone must work out a method of least-squares adjustment for a 5-point support, with five degrees of freedom, or we must fall back on the less favorable "true-corner" support, including a "true center", which means that all five points are adjusted at the design parabola, and that the manufacturer is not allowed to subtract anything (no average, slope or warp).

4. Alternate Design

At our meeting it was decided that Dornier work out an alternate design of the backup structure:

3-dimensional space frame,
with diagonals and struts, (12)
and increased thickness.

The discussion then lead to steel joints, similar to the IRAM design. However, this design could be simplified, since we need only 56 panels but IRAM has 160. Regarding the thickness, I would suggest (section III.2) to try first whether 110 cm is already good enough. We must avoid a large increase of height and cost of the hut.

As mentioned in the previous section, we then have a problem with the panel supports which now should be located at the member joints (instead of their centers). And a 5-point support would then demand twice the number of radial or tangential backup ribs, or some other support for the panel center points. I would like to suggest the following:

$$\begin{array}{l} \text{4 instead of 3 rings of panels,} \\ \text{4-point panel support.} \end{array} \qquad (13)$$

The disadvantage of 4 rings is that we need now 5 instead of 4 molds (rings plus Cassegrain) and we need 80 instead of 56 panels. The advantage is that the length L of the panels is decreased by the factor 3/4 = 0.75. The gravitational and wind deformations go with $L^4$, and $0.75^4 = 0.32$; and the thermal deformations from both specifications (a) and (c) go with $L^2$, and $0.75^2 = 0.56$. We thus hope that a 4-point support then will be sufficient, supporting the four corners but omitting the panel center point.

A set of very rough estimates, similar to my older ones [4)] were done, but relaxing the thermal specification (c) according to (4), and relaxing the wind to 18 mph. We call h = panel thickness, and σ = rms surface deformation, using the various definitions of Table 1, and obtain:

| | σ (μm) | |
|---|---|---|
| | h = 9 cm | h = 6 cm |
| gravity, zenith | 4 | 8 |
| uniform, temp., ±20°C | 6 | 6 |
| temp. grad. Sun, 0.4°C | 6 | 9 |
| wind, 18 mph | 2 | 4 |

(14)

These values seem to indicate that a 4-point support of panels, on four rings of the backup structure, would be sufficient for a panel thickness of 9 cm, and maybe even of 6 cm. These rough estimates should of course be replaced by proper finite element analyses and by actual measurement on test panels.

4) "Some Remarks Regarding the 10-Meter Submillimeter Telescope", Nov. 19, 1982; NRAO Engineering Memo 149.

## IV. SHAPED SURFACES

The ideal optics, for future low-noise receivers, would be an asymmetric system of two shaped mirrors. An asymmetric (off-axis) configuration can be chosen such that there is no blockage at all, from feed to secondary to primary to sky; this avoids the scatter and the pickup of ground noise, from legs and secondary. Shaping means in this context to develop surfaces of primary and secondary mirrors such that some given feed pattern is transformed into some wanted aperture illumination; for example, a very narrow feed pattern, with practically no spillover beyond the secondary rim, can be transformed into a completely uniform aperture illumination for the maximum possible gain. Regarding geometrical optics only, such a system would have very near to 100% aperture efficiency.

Although a mathematical proof had been given in 1962 that the shaping problem is solvable only for the axi-symmetric case but has no solutions for the asymmetric one, I have developed in 1978 an iterative relaxation method called MINIMAX [5)] which gives after only a few iterations very good solutions, which may be called exact for all practical purposes, for all kinds of asymmetry which I tried.

For the 10-m submillimeter telescope, however, we may drop the condition of asymmetry, because we would need 80 different molds for 80 surface panels, whereas the pickup of ground noise will not be of importance for mm-wave receivers for a long time to come. But I do suggest to use shaped symmetric surfaces. And I would prefer

simple narrow feed pattern, 20 or 25 db down at secondary rim;
uniform aperture illumination, for maximum gain. (15)

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5) "Minimum-Noise Maximum-Gain Telescopes and Relaxation Method for Shaped Asymmetric Surfaces"; IEEE Trans. AP-26, 464, 1978.

If the remaining very small spillover beyond the secondary is, say, 1% of the power, and if the blocking from secondary and legs is, say, 5% geometrical which means 10% of the power, then the aperture efficiency would be 89% for geometrical optics (but somewhat reduced by diffraction, especially for longer wavelength). Uniform illumination will give a first sidelobe of 18 db down below the main beam. If that sounds too high, one could compromise and demand a somewhat tapered illumination, reducing sidelobe and gain. But this I would not recommend. First, a considerable sidelobe reduction can only be achieved with a considerable gain loss, because most of the surface is at the rim where we have to taper. Second, some sidelobes will remain, anyway, due to the 5% blocking. Third, it seems that sidelobes and confusion are much less important for millimeter wavelengths than efficiency and gain.

If wanted, I could do the shaping calculation with my MINIMAX program. I would need to be told the feed pattern and the aperture illumination wanted. Our present design study, however, could meanwhile proceed unchanged. From my previous calculations I know that the shaped surfaces still are very similar to a parabolic primary and a hyperbolic secondary. Thus, the general design, and the estimates of performance and cost, do not depend on the shaping.

## V. GENERAL PHILOSOPHY

Spend more time and money (more than is usually done) on the design and on its optimization, in order to improve performance and cost of the telescope. The design cost must be judged relative to the manufacturing cost; and the design time relative to the future useful lifetime of the telescope. Derive always various alternate designs for choice; try and check unconventional possibilities, too.

Make the first cost estimates not too low. If finalizing the design yields a considerable cost increase, this will lead to problems and personal friction. A low first cost estimate may even completely prevent a proper optimization of the future performance.

Have more (more direct and and more frequent) communication between astronomers and engineers, meaning between Bonn-Tucson and Dornier-Krupp. The normal procedure, giving specifications and awaiting results, is good enough for normal tasks. But new unconventional designs, pushing for a break-through, are greatly helped by a frequent and informal exchange of ideas, with a strong feedback in both directions.

Allowing only 10% of the telescope time for outside observers sounds rather narrow-minded to me. How would your astronomers like it, to be treated the same way at our VLA, or at the other sites of the national observatories? (They give over 2/3 of the time to outsiders.) Furthermore, a frequent presence of different outside observers leads also to a good deal of exchange of ideas between them and your own staff.

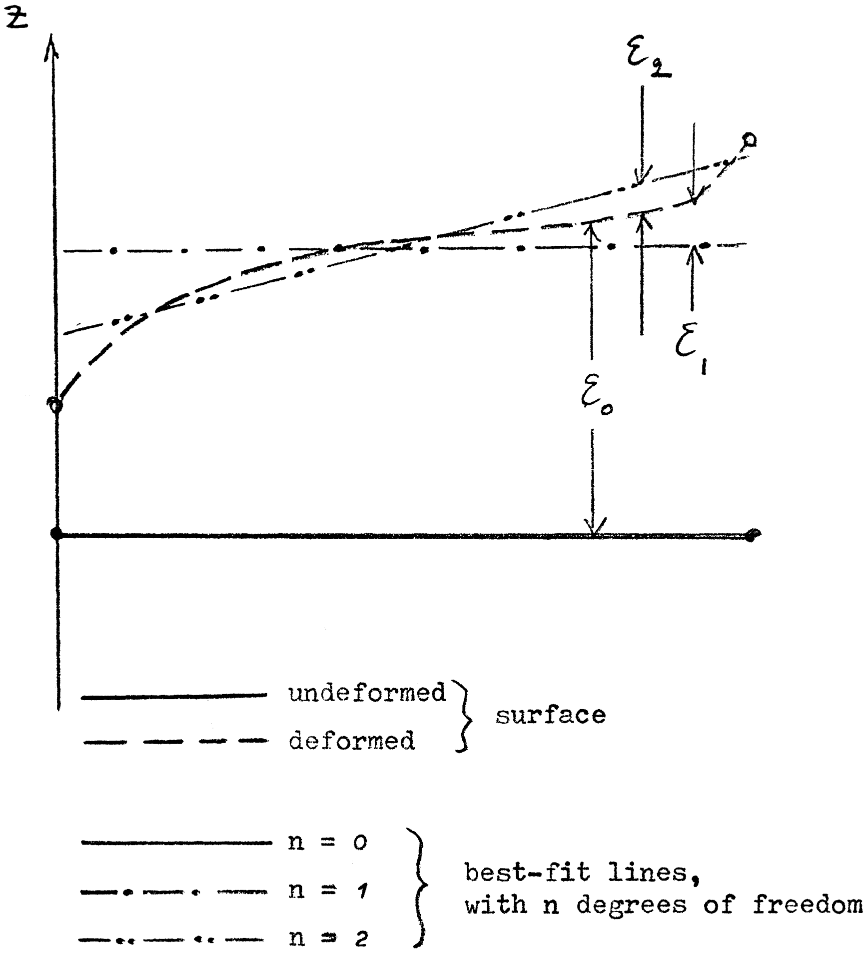


Fig. 1. Various degrees of freedom, in the definiton of surface rms.

Showing, as an exaple, an undeformed straight line, its deformation, and all possible choices of best-fit straight lines; n = 0 means that nothing can be subtracted, n = 1 subtracts the average, and n = 2 allows a least-squares slope as well.