NATIONAL RADIO ASTRONOMY OBSERVATORY

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COMMENTS ON THE DESIGN OF THE 22-METER AUSTRALIA TELESCOPE

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This Report is about the "Australia Telescope" (AT), one of the six transportable 22-meter diameter antennas, of the seven-element array to be built at Culgoora, Australia. I was given the "Review of the Antenna Element Design and Performance" of August 1983, and was asked for comments and suggestions.

I. DESIGN FEATURES

1. General

The present "AT" design is a good improvement as compared to its predecessors. I do not see anything wrong or doubtful with its basic features, and I agree with most of its details. Regarding the mounting, I also would prefer the wheels on a circular track on the ground for a stationary antenna, but the wide azimuth bearing ("slew ring") on top of a non-rotating pedestal ("base frame") for the transportable antennas.

There is only one basic change which I recommend: to make the whole telescope accurate enough for 115 GHz, not just the inner 10 meter. This seems well feasible, to be discussed in Section III.

The present Review contains the structural analysis of three gravity loads (0°, 50°, 90° elevation), but not of the thermal and wind loads during observation, and it does not discuss structural stability in survival loads. But all of this is needed for the judgement of a design. It is recommended to do always all of these analyses simultaneously; once the inverse of the stiffness matrix has been obtained, which takes most of the computer time, it may then as well be multiplied with a larger number of load vectors. And this should be done even if the environmental data from the site are not yet available; just use data from comparable sites, and apply scaling factors later.

As a general philosophy, I suggest to 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 as far as possible. The design cost must be seen relative to the manufacturing cost, and the design time relative to the future useful life of the telescope.

Make first cost estimates not too low. If finalizing the design yields a considerable cost increase, it will lead to severe problems and personal friction. A low first cost estimate may even completely prevent the proper optimization of the performance. Finally, do all basic developments inhouse, give all conventional items to engineering firms of good experience.

2. Some Details

First, a note of caution regarding the azimuth bearing. Our VLA antennas at Socorro sit on a three-point supported open-frame pedestal, topped off by a very solid-looking ring of plates, which carries the bearing. On this moves the plated yoke structure, holding on its two tops the elevation bearings. In my investigation of the pointing errors, 1981 and 1982, we mounted tilt sensors in x- and y-direction at the yoke bottom and at one of the yoke arm tops next to the elevation encoder. When the yoke rotates in azimuth, these tiltmeters should show only a simple sine wave (allowing for a tilt of the axis). But a Fourier analysis showed in addition very significant terms of second and third order, though none higher. They are stronger at the yoke bottom (up to 21 arcsec amplitude) which indicates internal warp of the bottom plate, and smaller but still not negligible at the yoke top (up to 4.9 arcsec amplitude) where it matters for the pointing errors.

This was explained by a difference in symmetries: The pedestal has a 120° symmetry, the yoke a 90° one. If both have hard and soft parts, a rotation should show second and third order terms, but no higher ones. Since it seems most natural to support the elevation axis at two points but the pedestal at three, it means that one must make the parts below and above the azimuth bearing extremely stiff, a good deal more so than a simplified structural analysis might demand. Furthermore, we found a hysteresis at both investigated antennas (13 and 15 arcsec peak-to-peak), at some narrow azimuth range only; no cause could be found, and our guess is some damage during transport. For details, I enclose VLA Test Memo 135 [Ref. 1].

This Memo contains also the test data about the results of the thermal shielding of the yoke sides and of several pedestal members. Thermal shielding is important for accurate pointing, and it should be provided already in the design, not only be added later on as done at the VLA and the 140-ft at Green Bank. Also, it is good to see that the AT avoids closed plated box structures, for example, with the open-framed alidade. And enclosing the whole base frame with a thermal insulation is also to be recommended.

Another important item to be analyzed is the thermal lag. During a fast temperature change of the ambient air, dT/dt, thin-walled members will follow soon while thick-walled ones will lag behind. The difference between member and air is $\Delta T = \tau(dT/dt)$, and experiments at Green Bank have given

$$\tau = \left. \begin{matrix} \nearrow 1.74 \text{ (steel)} \\ \searrow 1.14 \text{ (aluminum)} \end{matrix} \right\} \text{ hours, per inch of wall thickness} \qquad (1)$$

for tubular members (and half these values for open shapes) with white paint and in calm air. Ideally, all members thus should have the same wall thickness for avoiding temperature differences, especially after sunset and sunrise. In our recent designs, we have limited the wall thickness of all members of the backup structure within the narrow range of

$$0.1 \leq \text{wall thickness} \leq 0.4 \text{ inch.} \qquad (2)$$

In order to decrease their shadow, the quadrupod legs must be as thin as possible laterally (while the radial thickness does not matter). They can be made thinner than usual if guy wires, at half the leg's length, provide lateral stability against buckling. This is done at most NRAO telescopes.

I think that wind force measurements on models could be done a lot cheaper and less heavy-handed than in wind tunnels if the model is moved on a driving truck. I enclose NRAO Engineering Memo 151 [Ref. 2] which presents a suggestion and asks for comments.

A bit awkward looks the turret which provides fast receiver change. Instead of rotating a large turret with all receivers on it, one could rotate a slightly asymmetric Cassegrain, as done on our 140-ft and the VLA antennas. Or, the best solution seems to be the rotation of a plane mirror at the vertex, as done on the new version of the 12-m telescope at Kitt Peak.

At three items the Review seems to contain an inconsistency. First, on page 13 it says that the surface will be shaped for uniform illumination; and that the whole telescope of 22 meter diameter will be used up to 43 GHz, and the inner diameter of 10 meter up to 115 GHz. However, one can have a shaped inner diameter, or a shaped whole telescope, but not both. Which is another argument in favor of making the whole telescope good for 115 GHz. And, regarding shaping, has an asymmetric shaped antenna been discussed? I enclose the MINIMAX paper of 1978 [Ref. 3] which solved this problem (after it had been proved unsolvable 15 years before) and gave nice solutions.

Second, on page 14 the Review says that the quadrupod will have "a future mechanical item" which, however, at present is omitted because of its heavy weight at an undesirable position. But if the weight is essential, it must be included in the analysis. I think that two mechanical movements of the secondary are necessary for short wavelengths: a focal adjustment along the optical axis, and a lateral movement perpendicular on optical and elevation axis (or maybe a tilt of the secondary is adequate, too); both are computer-controlled as simple sine functions of the elevation. The "gliding rotation" which calls for the lateral movement or tilt is described in an enclosed paper of 1980, "Strong Coma Lobes ..." [Ref. 4]. The 140-ft has two more movements: the Cassegrain is rocking, or nutating, for beam switching on-off-source up to 4 Hz; and it is mechanically deformable for correcting the non-homologous deformations of the main reflector, which are mainly astigmatic.

Third, page 18 says that the cabin will provide additional rigidity by interacting with the backup structure, and that it will be air conditioned and thermally insulated; while page 20 says that cabin and feed cone are not structural. This question needs a decision. I think, regarding the size and location of the cabin, that its structure should be integrated into the backup, but if so, it cannot have a different temperature. Only the cabin proper may have insulating (inner) walls and air condition.

II. SPECIFICATIONS

1. Wind Speeds

Specifications mostly use three wind speeds:

v_{obs} = limit for observation with full accuracy, neglecting short gusts;

v_{red} = limit for observation with reduced accuracy, defined by structural stability in all pointing angles, including gusts;

v_{srv} = survival condition, structural stability in stow position (pointing at zenith), including gusts.

One should know the distribution function f(v) of the wind velocity v at the future site, and its cumulative function F(v). The numerical definition of the three speeds then is a matter of opinion, compromising lost time against cost or antenna size, and I would like to recommend the following definitions:

$$v_{obs} = 75\% \text{ level}, \quad F(v_{obs}) = 0.75; \tag{3}$$

$$v_{red} = 90\% \text{ level}, \quad F(v_{red}) = 0.90; \tag{4}$$

$$v_{srv} = \text{once in 100 years, extrapolated.} \tag{5}$$

As long as data from the site are not yet available, one may use, for example, an average from other sites:

$$v_{obs} = 18 \text{ mph} = 8 \text{ m/s}; \tag{6}$$

$$v_{red} = 36 \text{ mph} = 16 \text{ m/s}; \tag{7}$$

$$v_{srv} = 110 \text{ mph} = 50 \text{ m/s}. \tag{8}$$

At some sites, high winds are so regular that proper scheduling can take care of it, and specifications could be relaxed. At the VLA, almost all winds above 22 mph occurred at early afternoon and came from WSW. [See Ref. 5].

2. Thermal Values

Specifications are mostly given for:

(a) T_{min}, T_{max} = extremes of ambient air temperature for observation;

(b) ΔT_x = lateral temperature gradient, across the diameter of the backup structure (vertical when pointing at horizon);

(c) ΔT_z = axial temperature gradient, from rim to lowest backup joint;

(d) ΔT_p = temperature gradient through panels, normal to surface;

(e) dT/dt = change of ambient air temperature with time.

Item (a) is mostly of small importance for accuracy, unless there are strong bimetallic effects in the structure; (b) and (c) depend somewhat on the protective white paint to be used; (d) depends strongly on design type, thickness and paint of the panels; and (e) must be measured at the future site. For preliminary values, I quote from our 65-meter design book [Ref. 6, page 89] giving averages from several sites, for the 95% level:

	ΔT (°C)		dT/dt (°C/hour)	
	clear night	noon sun	clear night	after sunset
surface plates	1.1	6.6	0.8	4.8
backup structure	0.8	5.0	0.8	4.8

3. Wind and Thermal Combined

There are various ways of combining single errors in an error budget. I recommend the following one, which defines the total error as the root-sum-squares (rss) of the worst combination of single errors δ; where δ is the root-mean-square (rms) over the aperture, under maximum specified weather conditions, for the worst pointing angle. And which type of best-fit is to be used for the rms will be discussed in the Appendix.

Strong winds smooth out large temperature differences; we may have either extreme but not both. We call δ_a to δ_e the single errors for the specified thermal values (a) to (e), and δ_v the one for the maximum observational wind, v_{obs}. We call the sum of squares

$$\delta_s^2 = \begin{cases} \delta_b^2 + \delta_c^2 + \delta_d^2 + \delta_e^2, & \text{for surface errors,} \\ \delta_b^2 + \delta_e^2 & \text{for pointing errors,} \end{cases} \tag{10}$$

and the maximum:

$$\delta_m = \max(\delta_s, \delta_v). \tag{11}$$

The combined total error then is

$$\delta_t = \sqrt{\delta_a^2 + \delta_m^2}\,. \tag{12}$$

4. Performance

We mostly specify the shortest wavelength λ as the one where the total surface error σ has decreased the gain by about a factor two, or

$$\sigma = \lambda/16; \tag{13}$$

and the total pointing error $\Delta\phi$ we mostly specify as 1/6 of the beamwidth β

$$\Delta\phi = \beta/6 = 0.6\ \lambda/D. \tag{14}$$

For 22 meter diameter and 115 GHz ($\lambda = 2.6$ mm), this would be

$$\sigma = 0.160\ \text{mm}, \tag{15}$$

$$\Delta\phi = 4.9\ \text{arcsec}. \tag{16}$$

We call n the number of main contributions, which should have about equal size in a well-balanced error budget. For the surface error, we mostly include: panel manufacture, surface measuring and adjusting, panel deformations; backup gravity, backup thermal or wind; subreflector. This then is $n = 6$, and for each single contribution we thus demand

$$\sigma_1 = \sigma/\sqrt{6} = 0.067\ \text{mm}. \tag{17}$$

The pointing error should have only one main contribution: thermal or wind, but we will summarize everything else into a second one. Thus $n = 2$, and

$$\Delta\phi_1 = \Delta\phi/\sqrt{2} = 3.5\ \text{arcsec}. \tag{18}$$

I would like to mention some details. A good alt-azimuth mount should have eight independent pointing parameters, from misalignments, gravity, and refraction. The enclosed VLA Test Memo 136 [Ref. 7] gives their definition and it describes which parameters are the same for all antennas of an array (and thus can be obtained with higher accuracy), and which ones do not change when an antenna is transported to another location (thus old and new values can be averaged). The mean errors of the parameters, and their correlation matrix, are discussed.

Gravitational deformations of the surface are described in a paper with Woon-Yin Wong [Ref. 8]. The error analysis should include the fact that the telescope surface has been adjusted to a good paraboloid for some given elevation angle ψ. We defined the best adjustment angle as the one which gives equal residual deviations (from the best-fit paraboloids) at 20° elevation (below which we seldom use the shortest wavelength) and at 80° elevation (above which an alt-azimuth seldom must observe); ψ depends on two structural quantities, but it is always in the range

$$42^\circ \leq \psi \leq 56^\circ . \tag{19}$$

III. WHOLE TELESCOPE FOR 115 GHz

1. Estimates

Designing only the inner 10 meter for high accuracy may save some money but not much, and not enough to justify the large sacrifice in gain, of a factor $(22/10)^2 = 4.8$; and 115 GHz with $\lambda = 2.6$ mm seems well possible for 22 m diameter.

General estimates about the shortest wavelength λ as a function of the diameter D are given in a 1975 paper [Ref. 9]. For a completely conventional telescope of $D = 22$ m, the gravitational limit would be $\lambda = 3.4$ mm. But if homologous deformations are sufficiently well approached, the thermal limit becomes active, with

$$\lambda = \begin{cases} 5.5 \text{ mm in sunshine,} \\ 1.1 \text{ mm at night.} \end{cases} \tag{20}$$

Thus, a 22-meter telescope could well observe at 115 GHz at night, and up to 55 GHz in full sunshine. Provided that a good geometry has been chosen, where backup and panels have enough thickness, and where gravitational optimization has given some approach to homology.

2. Gravity and the TA design

The TA Review (Aug. 1983) gives gravitational surface error contours and their rms values for three elevations, for 10 and 22 meter diameter, before and after optimization. The optimized rms values are, in millimeter:

	10 m	22 m
zenith	.063	.095
50° elevation	.023	.037
horizon	.065	.086

(21)

I take it that these values are the deviation between the deformed surface and its best-fit paraboloid, and that the surface adjustment has not yet been included. The values for zenith and horizon pointing then represent H_z and H_h of Ref. 8, and we have $g = H_h/H_z = 0.086/0.095 = 0.905$. From this follows the best adjustment angle as

$$\psi = 49° \text{ elevation.} \tag{22}$$

If the telescope is adjusted to a paraboloid at this elevation, the rms surface deviation from its best-fit paraboloids, at both extremes of the useful elevation range, then are

$$\sigma(20°) = \sigma(80°) = 0.047 \text{ mm.} \tag{23}$$

Which shows that the gravitational behavior is already good enough, as compared with demand (17).

REFERENCES

[1] NRAO, VLA Test Memo 135, May 1982: "Analysis of Test Results with Shielded and Unshielded Antenna."

[2] NRAO, Engineering Memo 151, October 1983: "Simple Wind Force Measurements."

[3] IEEE Trans. AP-26, p. 464, 1978: "Minimum-Noise Maximum-Gain Telescopes and Relaxation Method for Shaped Asymmetric Surfaces."

[4] IEEE Trans. AP-28, p. 652, 1980: "Strong Coma Lobes from Small Gravitational Deformations."

[5] NRAO, VLA Test Memo 130, February 1981: "16 Months of VLA Wind Data."

[6] J. Findlay and S. von Hoerner: "A 65-Meter Telescope for Millimeter Wavelengths;" NRAO, Charlottesville, Virginia, 1972.

[7] NRAO, VLA Test Memo 136, May 1982: "Pointing Parameters for an Alt-Azimuth Mount."

[8] S. von Hoerner and W. Y. Wong, IEEE Trans. AP-23, p. 689, 1975: "Gravitational Deformations and Astigmatism of Tiltable Radio Telescopes."

[9] Astron. & Astrophys. 41, p. 301, 1975: "Radio Telescopes for Millimeter Wavelength."

IV. APPENDIX: VARIOUS DEFINITIONS OF "SURFACE RMS"
(Copy from a previous report)

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:

x and z translation of best-fit parabola vertex,
x and z translation of best-fit parabola focus. (24)

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:

$$F = F_o + A \sin E. \tag{25}$$

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:

$$X = X_o + B \sin(90° - E). \tag{26}$$

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 (26) 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~~ about a point somewhat 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 II.2 will give no x or y deformation for a symmetric structure. They may give a change of focal length (if bimetallic); 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), (c) 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).

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

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 (25)and (26) and by the pointing program. We thus may subtract the average deformation, 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(Δz).

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, but is in preparation.

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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.

Table 1. 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			focus shift			n	(notes)
	x	y	z	x	y	z		
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		warp (saddle)	n	(notes)
		x	y			
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.

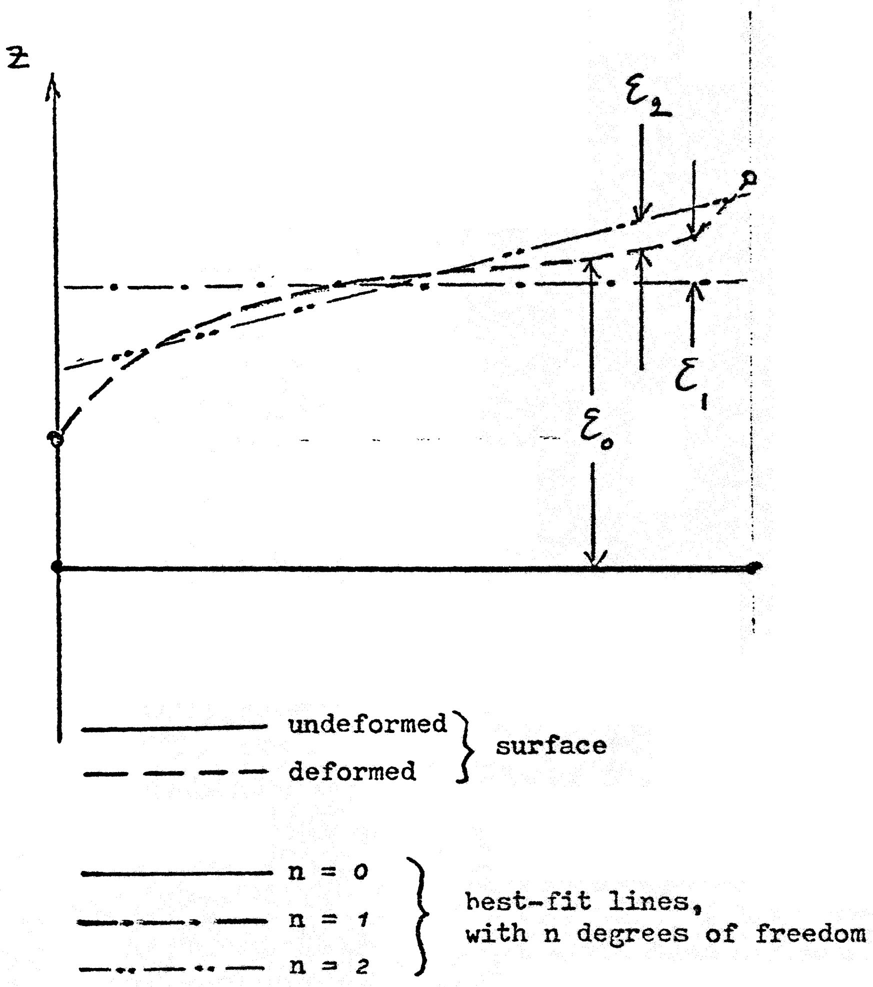

Fig. 1. Various degrees of freedom, in the definiton of surface rms.

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.