FROM PASSIVE SUPPORT SYSTEMS TO THE NTT ACTIVE SUPPORT

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1. Introduction

ESO has two telescope projects: the NTT (New Technology Telescope) with 3.5 m aperture and the VLT (Very Large Telescope) with 16 m equivalent aperture. The former is already in the engineering phase and should be completed in 1987; the latter is still in the study phase and will be described at this conference by our colleague, D. Enard.

This paper is concerned with the primary support system of the NTT. The basic principles and layout of this support have already been described in the literature (1,2,3).

In order to understand the design approach of the NTT primary support, it is instructive to consider briefly the evolution of the "soft" support and its fundamental role in the development of the reflecting telescope. Some major milestones were:

- W. Herschel:	Stiff radial ring plus "semi-hard" axial support	- 48 inch 1789
- Th. Grubb }	Whiffle tree triangle	- 36 inch 1835
Wm. Parsons}:	3-tier whiffle tree support	
(Lord Rosse)	with 81 supports with levers	- 72 inch 1842
- W. Lassell:	General purpose lever	- 9 inch 1842
	Lateral lever support	- 24 inch 1845
- Th. Grubb:	Whiffle trees on axles	
	Melbourne reflector	- 48 inch 1865

At this stage, the "soft" support was already accepted as standard technology but the transition from the "semi-hard" support of Herschel (with its inevitable cell flexure problems) to a general optimised "soft" support of levers and 3

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fixed points was made by:

- G. Ritchey: "Optimised" lever support - 60 inch 1908

Ritchey's support represented the triumph of the astatic principle of soft supports based on the application of correct forces and the elastic behaviour of monolithic blanks. The cell flexure problem and the problem of an absolute reference for the support position were thus largely solved, apart from the effect on the three fixed points. This residual problem has remained with us to this day and is one of the main reasons why decentering is by far the most common optical defect in Cassegrain telescopes.

Experience has shown, therefore, that the soft support in some form is ideal for gravity flexure, but it cannot cope with the modern problem of wind buffetting. For conventional "thick" mirrors of modest size in wind protecting domes, wind buffetting has not been important; but with the modern trend towards thinner, more flexible mirrors of very large size combined with more open buildings we shall require either

- careful windscreening or windbreaking

or

- harder supports.

In many cases, investment in windbreaking may be the more cost-effective solution.

ESO is considering a VLT configuration with 8 m unit telescopes. For these, we are thinking about the possibilities of a support combining "soft" and "hard" characteristics depending on the time frequency of the response and controlled by band-pass filtering; but no details have yet been worked out.

2. The basis of the NTT prime mirror support

With a free diameter of 3,5 m and an aspect ratio (AR) of 1:15, the NTT meniscus primary is only relatively thin, comparable with UKIRT. Nevertheless, the weight saving compared with conventional mirrors with AR = 1:6 is already a factor of about 2.5. It is important to note that the building concept allows for adequate wind protection through variable wind-breaking screens. We have therefore concluded that wind buffetting effects on the NTT primary are not a problem and that a purely soft axial support is quite adequate. We believe that wind buffetting effects at the top end of the tube, causing telescope vibration, are

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far more dangerous.

The NTT axial support is essentially a soft, passive support with active modulation possibilities.

The passive support has 78 individual supports on 4 rings and has been designed to give the same passive quality as the ESO 3.6 m telescope, allowing also a reasonable margin for manufacturing tolerances of the optics. The support design was done by Schwesinger - details are given in ref. (2).

The radial support is a push-pull support round the edge, adapted to the uni-directional altitude movement of the telescope tube and with central hole location. Schwesinger's calculations have shown that the limits of such a support for an f/2.2 meniscus with AR = 1:15 are given by the "sag" coma. This is the S-shaped bulk sag of the material (Fig. 1). Most of this coma is third

Fig. 1: S-shaped "sag" coma with a push-pull radial support

order and is easily corrected in the NTT by translation of the secondary. The fifth order residual, however, can only be corrected in the axial support.

This brings us to the active optics correction which is intended to produce "fine tuning" of the telescope errors to maintain constant performance near the diffraction limit[1-3]. (The active optics system is not intended to correct atmospheric seeing: it is hoped to do this in the NTT using a supplementary plane mirror with a size adapted to the isoplanatic angle). The active optics system makes use of an image analysis virtually identical with that we use routinely in ESO for off-line telescope testing. The terms corrected are[1]

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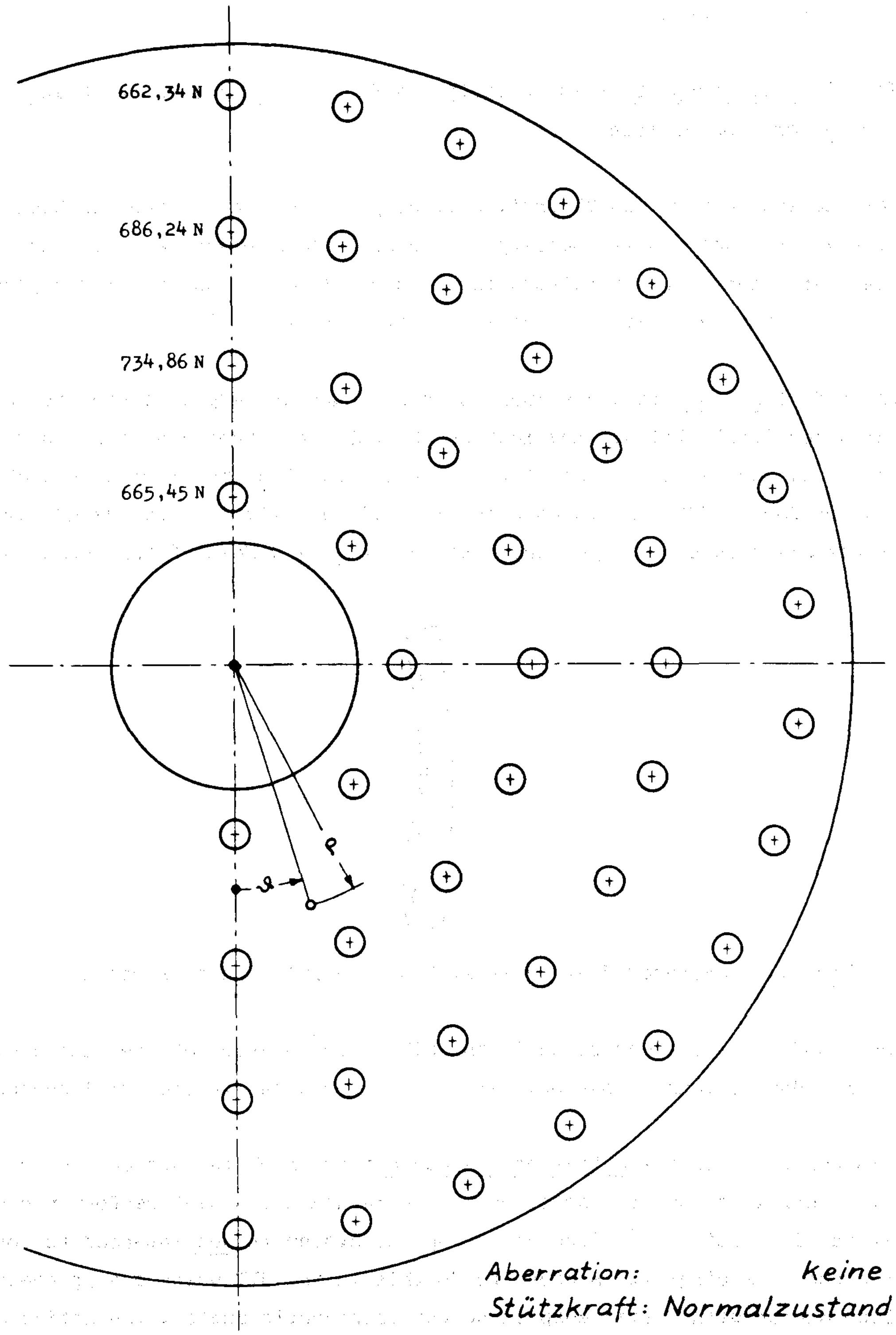

Figure 2: Force distribution in Newtons for the passive support of the NTT primary (calculated by Schwesinger).

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$Coma_3$ - by translation of the secondary

$\left.\begin{array}{c} Ast_3 \\ Sph_3 \\ \Delta \\ \square \\ Coma_5 \end{array}\right\}$ - by active control of the primary axial support

It is this active control of the primary axial support which is the concern of the present paper. An essential feature of this active control are the pre-calculations (calibrations) of the force changes required to produce a 1 λ coefficient of each aberration. Such calibrations have been done on the basis of analytical theory by Schwesinger(2). Fig. 2 shows the Schwesinger calculation of the passive support, the force for each ring being given in Newtons.

Fig. 3 shows the "calibration" force changes in Newtons calculated by Schwesinger to generate a 1 λ coefficient of the terms Ast_3, Sph_3, Δ and $\square$ with a high degree of purity. It is hoped to refine these "calibrations" further by finite element calculations - work in this connexion is described by Ballio at this conference(4).

3. The nature and function of the NTT axial support

The axial support uses mechanical astatic levers, working in "push" only. We have chosen this conventional solution because of our experience, its inherent reliability and the fact that the analysis to be presented here indicates that such a mechanical system can handle the requirements well. In principle, hydraulic or pneumatic solutions would be equally applicable. Mechanical levers have two very great inherent advantages: they give automatic compensation of the cosine function for the passive system, and their basic (passive) function generates no energy (heat).

Fig. 4 shows the cosine function for the weight of the mirror as a function of zenith distance. This function is followed automatically by the passive lever system both in the section containing the lever arm and in that at right angles to it.

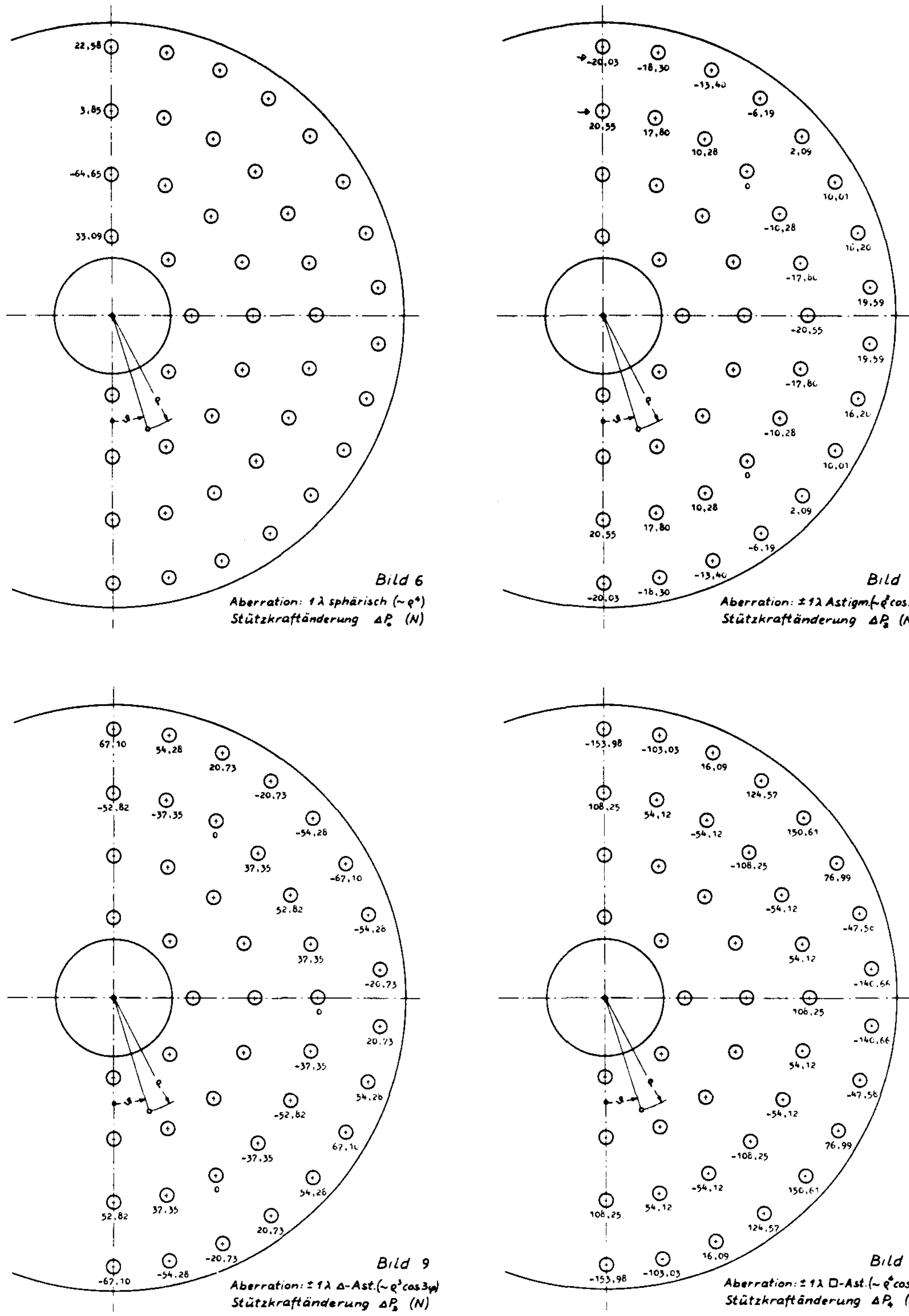

Figure 3: "Calibrations" (pre-calculations) of the force changes in Newtons required to generate a 1 λ coefficient of 4 aberrations to be actively corrected by the primary support. Bild 6 = 3. order sph. ab.; Bild 8 = 3. order astigmatism; Bild 9 = "triangular coma"; Bild 10 = quadratic astigmatism. (All calculations by Schwesinger).

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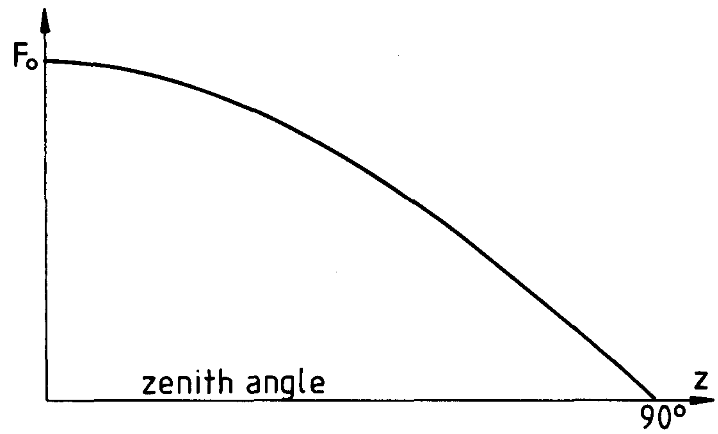

Fig. 4: Cosine function corrected automatically by the passive lever system.

The active correction that the axial support must provide can be divided up into three sorts:

(a) Initial "fixed" errors ΔF_a: These are mainly manufacturing errors of the optics or long term changes. The time constant is years.

(b) "Slow" variations ΔF_b: These are errors corrected at the start of each night's observations near the zenith, above all centering. The time constant is about 1 day.

(c) "Tilt" variations ΔF_c: Errors due to telescope tilt which are inherently functions of altitude. The time constant is about 1 to several hours.

It is clear that ΔF_a and ΔF_b require constant force changes independent of the zenith angle z. The consequences of this requirement are shown in Fig. 5 for a given lever.

If ΔF_a = const. and ΔF_b = const. are to be realised by levers it is clear that the counterweights must move continuously or at least in steps, to maintain the required constant differential force. Without a push-pull, we have the limit

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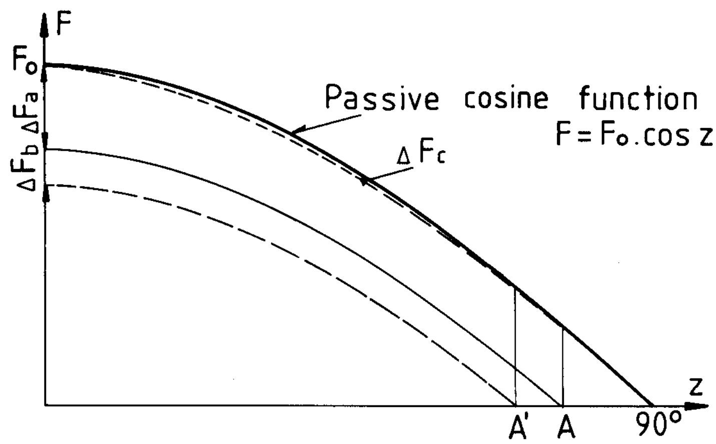

Fig. 5: Typical corrections ΔF_a, ΔF_b, ΔF_c relative to the passive cosine function.

points A or A' beyond which a negative (pull) force would be required. At A or A' the force modulation is 100% of the passive force applying at that zenith angle.

These basic considerations lead us at once to the following conclusions:

- Levers are excellent for the passive system and small modulations ΔF_c, but are not well adapted to significant fixed modulations

- Springs are not well adapted to the passive system because it is difficult to realise the cosine effect, but they are excellent for fixed modulation.

The advantage, in principle, of a combination is thus clear and such a possibility was considered in an earlier paper[2]. However, such a combination must meet the requirements for the correction limits of given aberrations, which we shall now analyse.

Suppose we have from the Schwesinger "calibrations":

SPRINGS: $\Delta F_S = x.F_o$ with $x = 1.0$ (i.e. 100% modulation at $z = 0$)
LEVERS: $\Delta F_L = y.F_o \cos z$ with $y = 1.0$ (i.e. 100% modulation at $z = 0$)

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This leads to the results shown in Table 1 which form the whole basis for the active correction possibilities of the NTT primary support. Column 1 shows the aberration type to be corrected, Column 2 the percentage of the zenith passive load required to produce a 1λ coefficient, Column 3 the equivalent force in Newtons. Column 4 shows how many wavelengths of coefficient can be produced if 100% modulation is applied to the zenith passive load without cosine effect (i.e. for springs). For example, for SPH_3 8,80% of the passive load is required to produce 1λ coefficient, so if the whole passive load were modulated to produce the maximum amount of this single aberration alone, we could generate a coefficient of 100/8,80 =11,4 λ. The AST_3 mode is by far the easiest mode to generate as Column 4 shows. The higher the order of the aberration, the harder its generation[2]. Columnns 5 and 6 show the equivalent values of Column 4 for levers, assuming cos z = 0.1 and 0.4 respectively. Column 7 shows the basic choice made for the maximum amount of correction of the different aberrations on the basis of Columns 5 and 6 (correction only by levers). Column 8 shows the percentages of F_o required to achieve these corrections individually. Assuming statistical distribution of the maximum forces required because of the different nature of the five aberrations and their phase differences in azimuth, and a limit zenith angle $z_A \sim 70°$, we may therefore conclude that the desired corrections could be achieved, with levers alone, with a maximum variation of about 0.3 F_o for any lever. However, there would be more reserve and security with regard to the correction range if a lever-spring combination could be used. The logical distribution for these two correction means is

ΔF_a - Springs (stable aberrations or long term variations)
ΔF_b - Levers (changes once per night)
ΔF_c - Levers (≤ 3 changes for $z = 0° \rightarrow 90°$)

since lever loads can be readily modified, spring loads less easily.

We must now consider the limitations to zenith angle z arising from the use of a combination of levers and springs for the active correction.

If we have for the maximum negative changes in any single support:

For springs: $(\Delta F)_S = -x.F_o$ with the factor $x \leqq 1$. The limit angle in combination with levers is given by
$\cos z_A = x$ (in the NTT from Table 1 $0<|x| \leqq 0.3$)

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For levers: $(\Delta F)_L = -y \cdot F_o \cos z$ with the factor $y \leq 1$.
The limit angle is given by
$\cos z_A = y$ (in the NTT from Table 1 $0 < |y| \leq 0.3$)

Suppose constant modulation $(\Delta F)_S + (\Delta F)_L$ in the range $0 < z < z_A$, z_A corresponding here to the combination. Then beyond z_A, the mirror would lift off, unless held down by clamps, because of lack of negative (pull) force! This implies that, beyond z_A, full correction of $(\Delta F)_S + (\Delta F)_L$ is no longer possible, but lift-off can be prevented by gradually compensating $(\Delta F)_S + (\Delta F)_L$ by an opposing force on the levers, giving thereby only a partial correction. This partial correction can be applied up to an angle z_B,

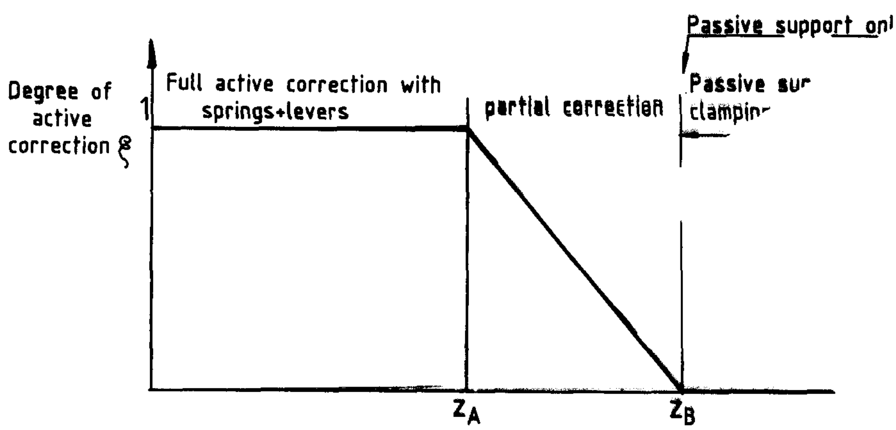

Fig. 6: Ranges of correction possibilities with a spring-lever

as shown in Fig. 6. At z_B, no correction can be applied, only the p. force distribution is maintained. Beyond z_B, even the passive force distribution cannot be maintained and clamping is necessary to prevent l. It should be emphasized immediately that the angle z_A does not depend on t. means of modulation, only on the total amount of it, since it is ultimately a consequence of the cosine effect on the levers producing the passive support.

If, at z_A, the levers are supplying the modulations

$$\Delta F_b = -y_b . F_o \cos z_A = -\bar{y}_b . F_o$$

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1	2 ****	3	4	5	6	7	8
ABERRATION TYPE	1λ COEFF. IN POLYNOMIAL MAX. CHANGE REQUIRED IN F_o FROM CALIBRATION		SPRINGS $(\Delta F)_s = (1,0)F_o$ MAX.CORRECTION IN λ POSSIBLE FOR A SINGLE ABERRATION	LEVERS $(\Delta F)_L = (1,0)F_o \cos z$ MAX. CORRECTION IN λ POSSIBLE FOR A SINGLE ABERRATION		MAX. CORRECTIONS AIMED FOR	
	$\frac{\Delta F}{F_o} \cdot 100\%$	ΔF(N)		$\cos Z_A=0,1$ $Z_A=84°,3$	$\cos z_A=0,4$ $Z_A=66°,4$	λ	% of F_o REQUIRED FOR EACH ABERRATION ALONE
SPH_3	8,80	65	11,4	1,14	4,56	4,0	35,2***
AST_3	3,02	20	± 33,1	± 3,31	± 13,24	3,0	9,1
Δ	10,13	67	± 9,9	± 0,99	± 3,96	0,8	8,1
□	23,25	154	± 4,3	± 0,43	± 1,72	0,4	9,3
$COMA_5$*	33,6	247	± 3,0	± 0,30	± 1,20	0,13**	4,4
						SUM	66,1% F_o
						÷√5	29,6% F_o

* This is fifth order coma. Third order coma does not appear in this Table as it is corrected by transl. sec.

*** About 2λ of SPH_3 can be absorbed by position adjustment of final image (Δs = 71 mm for 2λ of SPH_3)

** Correction value deduced from higher order "sag" coma of push-pull radial support of primary.

**** 1λ is defined as 500 nm

Table 1: Basis for the range of active correction of the NTT derived from the Schwesinger calibrations

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and $\Delta F_c = -y_c . F_o \cos z_A = -\bar{y}_c . F_o$,

then z_A is defined by

$$F_o \cos z_A - x . F_o - \bar{y}_b . F_o - \bar{y}_c . F_o = 0$$

where $x.F_o$ is the constant force of the springs. Then

$$\boxed{\cos z_A = x + \bar{y}_b + \bar{y}_c} \quad \text{------------} \quad (1)$$

In the range of partial correction $z_A < z < z_B$, the levers progressively *remove* their own modulation $\Delta F_b + \Delta F_c$ and then also that of the springs ΔF_a, so that z_B is defined by

$$F_o \cos z_B - x.F_o + y_{max}.F_o \cos z_B = 0,$$

giving

$$\boxed{\cos z_B = \frac{x}{1 + y_{max}}} \quad \text{------------} \quad (2)$$

where y_{max} is the maximum compensating effect of the levers.

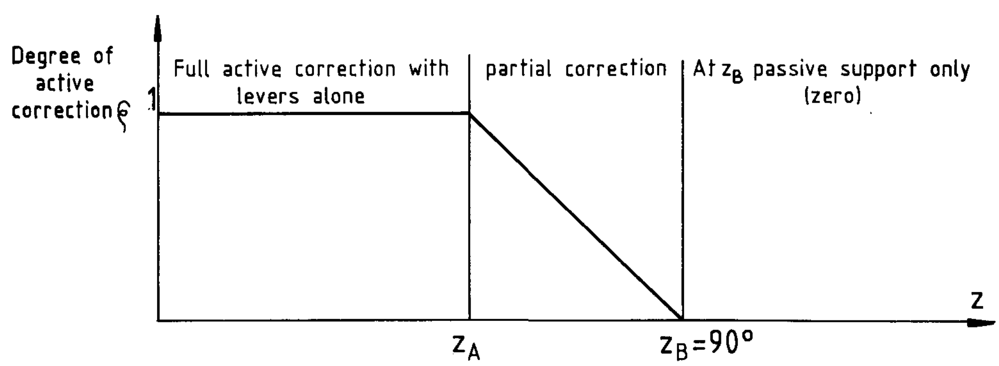

Fig. 7: Ranges of correction possibilities with levers alone

An important limit case is that with x = 0 (zero spring effect), the case of correction only with levers. From eq. 2 it is clear that z_B has no significance in this case, coinciding with the limit angle 90° of the passive support. Fig. 7 shows for this case of correction with levers alone the equivalent of Fig. 6 for the combination of springs and levers. This comparison

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shows that correction with levers alone has the advantage that we avoid the "lift-off" limit angle z_B, but this is offset by the advantages of the spring-lever combination in extending the correction range and avoiding constant driving of the counterweights to achieve the correction ΔF_a. Whether z_B is of practical significance will depend on the values for it resulting from the correction requirements. This is the final point to be analysed to validate the spring-lever correction combination for a "push-only" support system. Similarly the practical values of z_A must be acceptable whichever system is chosen.

A few limit cases, emerging from equations 1 and 2, are revealing:

(i) $\left.\begin{array}{l} \Sigma\bar{y} = \bar{y}_b + \bar{y}_c = 0 \\ y_{max} = 0 \end{array}\right\}$ No lever modulation possible - springs only, $z_A = z_B$

(ii) $x = 0$ No spring modulation, $z_B = 90°$

(iii) $\left.\begin{array}{l} x + \Sigma\bar{y} = 1 \\ \text{or } x = 1, \ \Sigma\bar{y} = 0 \\ \text{or } \Sigma\bar{y} = 1, \ x = 0 \end{array}\right\}$ 100 % zenith modulation $z_A = 0°$

(iv) $\left.\begin{array}{l} x = 1, \ \Sigma\bar{y} = 0 \\ y_{max} = 1 \end{array}\right\}$ $\begin{array}{l} z_A = 0° \\ z_B = 60° \end{array}$

Table 2 gives the range of the limit zenith angles z_A and z_B for the NTT with modulation limits $x \leq 0.3$ (springs); $\Sigma\bar{y}$ and $y_{max} \leq 0.3$ (levers). The boxed case at the bottom of the Table is that with which we expect to operate the NTT active correction. For this we have

$$x + \Sigma\bar{y} = 0.33$$

as the maximum correction force applicable. This is already significantly more than that postulated in Table 1, Column 8, which supposed

$$x + \Sigma\bar{y} = 0.296$$

The limit angles $z_A \sim 70°$ and $z_B \sim 80°$ are considered entirely satisfactory in view of the natural limits set by differential refraction and air mass near the horizon. The need to clamp beyond 80° is of no consequence to observation at all since this angle had been already set for other reasons as the observing limit of the NTT. The design of the radial push-pull support provides automatic clamping without any additional mechanism.

The second line of Table 2 represents the extreme case of maximum possible correction with both springs and levers (giving twice the range envisaged in Table 1) with

$$x + \Sigma\bar{y} = 0.6$$

Possibly, even these extreme values of z_A and z_B would be acceptable; but the tolerancing of the NTT is laid out in a way which makes the exceeding

x	$\Sigma\bar{y}$ (additional correction)	y_{max} (compensation)	z_A	z_B
0.3	0	0	72°.5	72°.5
0.3	0.3	0.3	53°.1	76°.7
0.3	0	0.3	72°.5	76°.7
0.2	0	0.3	78°.7	81°.2
0.23	0	0.3	77°.0	80°.0
0.23	0.1	0.3	70°.7	80°.0

Table 2: Practical range of the limit zenith angles z_A and z_B for the NTT with $x \leqq 0.3$; Σy and $y_{max} \leqq 0.3$

of the boxed case very unlikely. This case, as revealed by Column 7 of Table 1, already represents an enormous relaxation of the tolerances of an equivalent passive telescope.

Table 2 shows that, for the correction range envisaged, the practical angular limits z_A and z_B pose no problems for a spring-lever combination of the "push-only" type. This, therefore, is the basis for the axial support of the NTT primary.

4. Mechanical design of the NTT axial support lever and spring

Fig. 8 shows the conceptual design of an axial lever-spring support unit. To save space and reduce weight, a double lever system has been chosen with ratios of 2.8 for the fixed lever and a mean of 5.0 for the counterweight lever, giving

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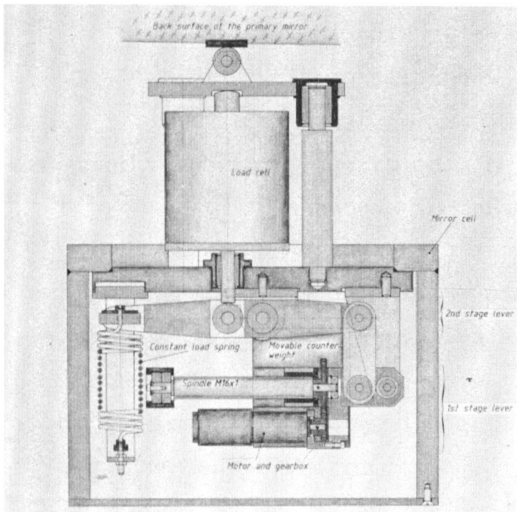

Figure 8: NTT axial support: Lever and spring design - spring and lever in parallel.

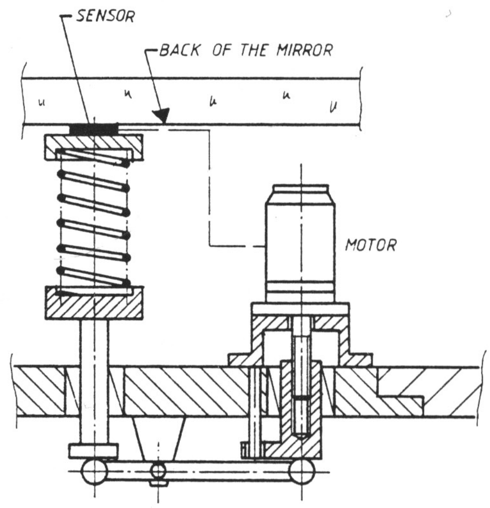

Figure 9: Spring-lever combination considered earlier (see Ref. 2, Fig. 11) - spring and lever in series.

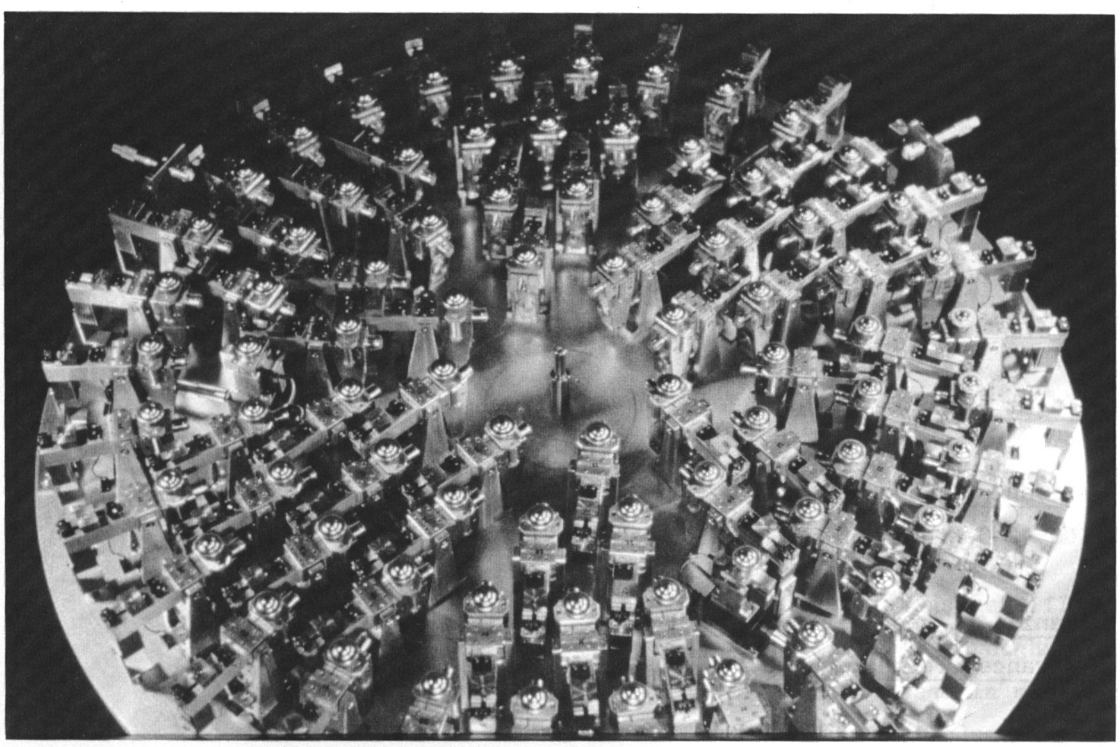

Figure 10: Support for NTT 1 m test mirror.

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a mean total ratio of 14. The springs will be either tension or compression, to be selected after the first tests following telescope assembly when the requirements of ΔF_a will be established. Note that the levers and springs work in parallel. Fig. 9 is reproduced from Ref. 2 (Fig. 11) and shows a scheme considered earlier with a lever-spring combination working in series. The parallel arrangement seems now a safer and more versatile combination.

Fig. 10 is a photo of the support for the NTT 1 m test mirror. This 1 m mirror has been scaled down from the NTT full-size dimensions according to the D^4/d^2 gravity flexure law and has the same axial support distribution in miniature, although the levers are single, not double, and there are no springs. The thin test mirror is currently being manufactured. The test mirror and support will be used to test the active optics concept and to develop the software and feedback loop. The detail design and manufacture of this support system has been carried out by Dr. Citterio and his colleagues and he will describe it in the next paper(5). It should be noted that this test system is intended to work only with vertical mirror axis, so there is no cosine effect with this support.

A final comment concerning the distinction in types of new technology aptly made by Dr. Wampler in the introductory talk of this Conference. I believe the NTT active optics technique with corrections realised by a support system of the type described here and by a simple secondary centering device, belongs firmly to his first category of a new technology application from well-known or even conventional technological procedures and equipment.

Acknowledgements

It is a pleasure to record our grateful thanks to our consultants, Dr. G. Schwesinger and Dr. O. Citterio for their major contributions to this development; also to our ESO colleagues K. Mischung and M. Tarenghi.

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DISCUSSION

J. Nelson: If the mirror cell has axial deformations, your spring system for warping will experience length (and force) changes in the springs. How do you deal with this?

R. Wilson: Of course, we have a load cell in the system directly under the back mirror surface which takes out such effects to a first order through lever compensation. However, you are right that this does not mean that we can ignore cell flexure effects on the springs completely and the springs have been designed to be as astatic as possible. Although significant force changes arising from the springs can, in principle, be totally corrected by the levers, if they are too large they might cause poor convergence to the required force or excessive use of the levers.

B. Mack: How do you compensate for cell deflections?

R. Wilson: The axial support is a "soft" sytem which is designed to be as astatic as possible. Also we have load cells in the system which measure continuously the actual force operating on any support. However, there are higher order effects which make it desirable to reduce cell flexure.

The radial support is more critical than the axial support so far as cell flexure is concerned, because the push or pull direction should go closely through the c. of g. of the mirror slice it is supporting. However, one should bear in mind the global active optics concept whereby astigmatism, for example, introduced by radial support errors will be corrected, after closed-loop detection by the image analyser, by appropriate changes in the axial support.

Our aim is to have a maximum cell flexure of no more than 100 microns.

A. Meinel: You did not mention a key problem with astatic supports: stiction or other parasitic forces. Is this because of the use of a load cell in the device?

R. Wilson: It is true that stiction is a major problem in precision lever supports. This is the reason why we are having two prototypes made, one with ball bearings and one with flexure pivots. The load cells certainly alleviate the general problem in that one can know, in spite of stiction, what the actual forces are, but too much stiction could prevent a force correction of sufficient precision. So we attach great importance to reducing stiction.

L. Barr: The "soft support" system you described does not provide any significant resistance to external forces, particularly wind loads. In future work, do you plan to make the support stiff so that it would be suitable for large, thin mirrors?

R. Wilson: You are quite right that our "soft support" does not provide any protection against wind loads. In our NTT, the primary of 3.5m diameter and AR = 1:15 is only moderately thin. We feel confident that our "wind breaking" concept in the building will protect it very adequately from wind buffets. We think that the top end of the tube is much more delicate from the point of view of wind loading and its effect on tracking, but that we can also handle with windbreaking.

For future, larger mirrors, I personally would not favour making them too flexible. I think structures such as Roger Angel's egg-crates will be best, with supports in the c. of g. surface of the structure and equivalent stiffnesses at least of the same order as our NTT meniscus. However, as I mentioned briefly in my talk, I think a support with both "soft" and "hard" characteristics may be necessary: "soft" in very low time frequencies for gravity effects, but "hard" in time frequencies corresponding to wind effects.