NEAR-FOCUS ACTIVE OPTICS: AN INEXPENSIVE METHOD TO IMPROVE MM-WAVELENGTH RADIO TELESCOPES

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IRAM N°398

To be published in Radio Science

1996
Near-focus active optics: an inexpensive method to improve mm-wavelength radio telescopes

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Abstract. The application of active and adaptive optics allows the construction of large diameter light-weight optical telescopes for observations below the seeing limit of the atmosphere. Active wavefront correction in a Cassegrain/Gregory type radio telescope can be made with a deformable main reflector or deformable subreflector. Here we suggest the possibility of correcting spatially large-scale wavefront deformations with a small size corrector located near the focus of the telescope. Using representative examples of the IRAM 30-m millimeter wavelength telescope, we calculate the improvement expected from the correction of (1) the systematic component in homology deformations, (2) the large-scale residual errors of a reflector adjustment, and (3) the beam degradation experienced in observations with a wobbling subreflector. The improvement in surface/wavefront precision obtained from piston correction with a corrector of some 50 elements is of the order of 30 - 40 %.

We investigate in particular the systematic component of homology deformations, their representation by low order Zernike polynomials, and their elimination by near-focus correction. We study in detail the homology deformations of the IRAM 30-m reflector.

1. Introduction

The spectacular progress in the construction of large diameter optical telescopes, and the success in the correction of atmospheric seeing degradation at near-infrared and visible wavelengths, are primarily due to the development and application of active and adaptive optics [cf. Tyson 1991, Ryabova & Zakharenko 1992, Beckers 1993]. In optical terminology, active optics is the correction of gravity, temperature, and wind induced large-scale and slowly varying deformations of the telescope main mirror and telescope structure; adaptive optics is the correction of fast deformations of the incident wavefront produced by instabilities of the Earth's atmosphere. The application of active optics allows the use of thin light-weight monolithic mirrors and of segmented mirrors (e.g. the VLT, ESO, and Keck, USA, telescopes); the application of adaptive optics allows the use of single telescopes and optical interferometers near the diffraction limit of the principal aperture. In radio astronomy, active wavefront correction is obtained by application of homology [von Hoerner 1967] and deformation of the subreflector surface in Cassegrain/Gregory systems. The lack of detailed and fast two-dimensional imaging prevents the application of adaptive optic techniques, although anomalous refraction may severely disturb the radio beam [Altenhoff et al. 1987, Downes & Altenhoff 1990].

We discuss for millimeter wavelength radio telescopes the possibility of active wavefront correction near the focus where the beam and the corrector are relatively small in diameter. The small size of the beam at this location allows the correction only of spatially large-scale wavefront errors which, nonetheless, may contribute a substantial part of the total wavefront deformation. An active near-focus corrector of some 50 elements is sufficient for this purpose and its construction and operation should be relatively easy. To date, two experiments have demonstrated the feasibility of near-focus wavefront correction at
millimeter wavelengths.

We summarize the methods of active radio wavefront correction either proposed or applied so far, and present three numerical examples concerning the IRAM 30-m telescope to illustrate the improvement that can be obtained from near-focus wavefront correction. The examples are: (1) the correction of elevation-dependent residual systematic surface deformations of homologous reflectors; (2) the correction of large-scale main reflector adjustment errors; and (3) the correction of beam degradation produced by wobbling of the subreflector. The discussion concentrates, in particular, on the correction of the systematic component in homology deformations, as analyzed in detail for the IRAM 30-m telescope. None of the examples is based on real time sampling of the wavefront deformation since sufficiently large two-dimensional receiver arrays do not exist. The information of the wavefront deformations discussed here is obtained from structural calculations, reflector surface holography, and aberration theory. Future developments, in particular of sensitive multi-element bolometer arrays, may change this situation so that real time wavefront sampling may eventually be possible.

2. Methods of active wavefront correction

Active wavefront correction can be made with the main reflector (I), the subreflector (II), or a deformable mirror near the focus (III). Corrections made with deformable mirrors are achromatic and do not affect the amplitude of the wave.

I. Correction using the main reflector

As a particular concept of mechanical construction, a homologous reflector [von Hoerner 1967] provides active wavefront correction by constraining the gravity induced deformations of the backstructure such that for all elevations the deformed reflector remains a paraboloid within the tolerance specification.

Several operating millimeter wavelength telescopes (for instance JCMT, IRAM, SEST) have actuator supported panels, but these devices have not yet been used to actively shape the main reflector surface. The GBT 100-m telescope (USA) [Vanden Bout 1991], presently under construction, will have actuator controlled panels to compensate gravity, temperature, and wind induced surface deformations. The ‘instantaneous’ data for correction will be supplied from a laser ranging surface surveying system [Payne et al. 1992]. The proposed radome enclosed 50-m millimeter wavelength telescope (LMT, USA-Mexico) will have an active main reflector to compensate gravity and temperature induced surface deformations. Computer simulations of the surface precision and diffraction calculations of the beam pattern obtained from active control on this telescope have been published by Cortes-Medellin & Goldsmith [1994].

II. Correction using the subreflector

There are two reported applications of a deformable subreflector: one for correction of elevation-dependent astigmatism of the Greenbank 43-m reflector [von Hoerner & Wong 1979], the other for correction of gravity induced deformations of the Haystack 37-m reflector [Antebi et al. 1994, Barvainis et al. 1993]. A contoured, though not deformable subreflector has been used on the Kitt Peak 12-m telescope [Mayer et al. 1994] and on the Yebes 14-m telescope [Garrido-Arenas et al. 1995]. The theory of a shaped subreflector for correction of main reflector deformations was published by von Hoerner [1976], Langley & Parker [1979], Milner & Bates [1980], and Lawson & Yen [1988].
Dependent of the diameter to wavelength ratio \((d/\lambda)\) of the subreflector, geometric optics ray tracing or the Kirchhoff–Huygens–Silver formalism of diffraction [cf. Silver 1984, Rush & Potter 1970] can be used to derive the subreflector contour which compensates the main reflector surface deformations. In the ray tracing approach the contour of the subreflector is derived from Snell's law and the condition that rays have equal path length and do not cross. Ray tracing is appropriate for subreflectors of large ratio \(d/\lambda\) and smooth surface gradients. Von Hoerner [1976] presents calculations for a correcting subreflector of size \(d/\lambda = 3.2\ \text{m}/1.3\ \text{cm} = 240\), as used on the Greenbank 43-m telescope. In the Kirchhoff–Huygens–Silver formalism of diffraction the compensating contour is derived from the far-field phase distribution of a spherical wave emanating from the focus and being scattered on the surface of the deformed subreflector. This theory was used by Langley & Parker [1979] to derive the contour of a subreflector of size \(d/\lambda = 15\ \text{cm}/7.5\ \text{mm} = 20\). Similar cases are discussed by Rush [1963], Potter [1967], and Rush & Potter [1970].

III. Correction using an intermediate near-focus mirror

Active wavefront correction is also possible near the focus, though only of large-scale deformations because of the small beam diameter at this position and of the relatively large size corrector elements necessary in order to avoid additional diffraction when using a discontinuous surface. Contoured, though not deformable mirrors located near the focus were used on the Texas 5-m telescope [Mayer et al. 1991] and on the IRAM 30-m telescope [Greve et al. 1994] for correction of wavefront deformations from the main reflector.

Wavefront correction near the focus is possible if the phase distribution in the corrector plane is similar to the deformed phase distribution of the aperture plane, namely the main reflector or subreflector surface. The corrector plane should be located in the far-field of the feed which on the IRAM 30-m telescope is \(z_{ff} = 2d^2/\lambda \approx 500\ \lambda\) for feeds of aperture diameter \(d \approx 10 - 15\ \lambda\). The co-rotating Nasmyth mirror at 3.5 m distance from the focus is in the far-field and thus a convenient place for a corrector, as verified in our experiment. Wavefront correction of the principal large-scale aberrations (for instance defocus, astigmatism, and coma) seems possible at near-field distances, as evident from wavefront shaping made with special horn–lens combinations. However, detailed diffraction calculations are required to investigate the possibility of correction at near-field distances of wavefronts with significant distortions.

Following the argumentation of Garrido–Arenas et al. [1995], we may set a limit on the size \((d)\) and number \((n,\ \text{in one dimension})\) of the corrector elements by requiring that the beam of each individual element \((\theta \propto \lambda/d)\) illuminates an area of the main reflector with size \((L)\) typical of the deformation distribution. This leads to the relation

\[
\theta F_{mc} \approx (\lambda_{max}/d) F_{mc} \leq L
\]

(1)

with \(F_{mc}\) the distance between the corrector and the main reflector. \(\lambda_{max}\) is the longest wavelength of observation. Since there are as many elements on the corrector (of diameter \(D_c\)) as areas to be corrected on the main reflector (of diameter \(D_m\)) we have \(d \approx D_c/n\) and \(L \approx D_m/n\), so that relation (1) becomes

\[
n \leq \sqrt{D_c D_m/\lambda_{max} F_{mc}}
\]

(2)

For the IRAM 30-m telescope we have \(D_m = 30\ \text{m}, D_c = 0.35\ \text{m}, F_{mc} = 16\ \text{m}\), so that
n ≤ 15 for λ_{max} = 3 mm. This condition is fulfilled for the experimental corrector used on the 30-m telescope [Greve et al. 1994] and for the corrector discussed here. While this argumentation is useful for the design of a corrector, a comprehensive analysis which considers the diffraction of each individual element of the near-focus corrector requires a detailed physical optics calculation of a spherical wave which emanates from the feed and propagates via the corrector and the subreflector towards the main reflector aperture plane. This calculation is outside the scope of the paper (see the discussion by Kildal et al. [1994] of the Arecibo telescope with similar relative aperture dimensions d/λ).

3. The systematic component of homology deformations

A homologous reflector design minimizes gravitational deformations and allows the construction of large diameter, high precision, steerable radio telescopes. Inspection of the surface error topography of the IRAM 30-m reflector [Baars et al. 1994] and other homologous reflectors [cf. Hachenberg 1968, Mar & Liebowitz 1969] shows that the elevation-dependent residual gravity deformations consist in one part of large-scale systematic deviations and in another of small-scale errors, often of random distribution. While it is difficult to reduce the small-scale errors, here we demonstrate that it is worth trying to remove the component of systematic deformations by active wavefront correction.

In the concept of homology, the best-fit contour of the tiltable reflector remains at all elevation angles (ε) a paraboloid with tolerable surface deviations of rms (root mean square) value $\sigma(\epsilon)$. The panels of the reflector are adjusted to the specified surface contour at the elevation $\epsilon_0$ (≈ 45°) around which most of the observations are made. This adjustment eliminates at $\epsilon_0$ the gravity deformations whereby for all reflector elements i (= 1, 2, ..., K) the effective homology deformations (measured in the direction normal to the best-fit surface) are $\delta_{H,i}(\epsilon_0) = 0$, while otherwise in general $\delta_{H,i}(\epsilon) \neq 0$ for $\epsilon \neq \epsilon_0$. The rms–value $\sigma_H(\epsilon)$ of the homology deformations is

$$\sigma_H(\epsilon) = \sqrt{\sum_{i=1,K} \delta_{H,i}(\epsilon)^2/K} , \quad \sigma_H(\epsilon_0) = 0$$  \hspace{1cm} (3)

and

$$[\sigma_H(\epsilon)]^2 = [\sigma_H(0)]^2[\cos \epsilon - \cos \epsilon_0]^2 + [\sigma_H(90)]^2[\sin \epsilon - \sin \epsilon_0]^2$$  \hspace{1cm} (4)

with $\sigma_H(0)$ and $\sigma_H(90)$ the surface rms–values at horizon (ε = 0°) and zenith position (ε = 90°) [von Hoerner 1975]. The specified reflector contour at elevation $\epsilon_0$ is realized only with the precision of the adjustment $\sigma_a(\epsilon_0)$ (rms–value) so that, when tilted at elevation $\epsilon$, the homology deformations are superimposed and the effective precision of the reflector is $\Delta(\epsilon) = \sqrt{\sigma_a(\epsilon_0)^2 + \sigma_H(\epsilon)^2}$. [We assume that the homology deformations and adjustment errors are uncorrelated.]

The large-scale systematic component of the homology deformations $\delta_{H}(\epsilon,\rho,\theta)$ (of a circular reflector with normalized polar coordinates in the aperture plane $\rho$ [0 ≤ $\rho$ ≤ 1] and $\theta$ [0 ≤ $\theta$ ≤ 2π]) is conveniently expressed as a superposition of Zernike polynomials $Z_{nm}(\rho,\theta) = R_n(\rho)\cos(m\theta)$ and small-scale random residuals $\delta_{RAN}(\epsilon,\rho,\theta)$ such that

$$\delta_{H}(\epsilon,\rho,\theta) = \sum_{n,m} \alpha_{nm}(\epsilon) Z_{nm}(\rho,\theta) + \delta_{RAN}(\epsilon,\rho,\theta)$$  \hspace{1cm} (5)
The radial functions $R_n$ are given by Born & Wolf [1980]; the orders $n, m$ used in this investigation are listed in Table 1. The coefficients $\alpha_{nm}$ of Eq.(5) can be uniquely determined from a least squares calculation [Wang & Silva 1980].

We are only interested in large-scale wavefront deformations of low order $n$ and $m$ which represent areas of the reflector surface larger than panel dimensions and which can be smoothed with a small size near-focus corrector. Hence we restrict the decomposition of $\delta_H(\epsilon, \rho, \theta)$ to polynomials of the order $n \leq N_0 = 7$ and $m \leq M_0 = 7$. Figure 1 shows for the IRAM 30-m reflector the coefficients $\alpha_{nm}(\epsilon)$ for $L \leq 20$. It is evident from this figure that not all polynomials of the range $(N_0, M_0)$ are important and that a subset $n^* \leq N^* (\leq N_0)$ and $m^* \leq M^* (\leq M_0)$ of polynomials exists which gives a good representation of the actual systematic deformations. For the IRAM reflector we select 7 terms: $L^* = 3, 7, 9, 12, 13, 15, 17$. The systematic surface deformation $\delta_Z$ represented by these leading Zernike polynomials is

$$\delta_Z(\epsilon, \rho, \theta) = \sum_{n^*, m^*} \alpha_{nm}(\epsilon) Z_{nm}(\rho, \theta)$$

Figure 2 illustrates the decomposition for the IRAM 30-m reflector. The figures indicated $H$ show the homology deformations $\delta_H(\epsilon)$ predicted from the structural calculations. The figures indicated $Z$ show the systematic deformations $\delta_Z(\epsilon)$ of the leading Zernike polynomials $(N^*, M^*)$. The figures indicated $H-Z$ show the homology deformations with the leading Zernike polynomial deformations being removed, leaving the random errors $\delta_{RAN}(\epsilon)$.

4. Improvement from elimination of Zernike polynomial deformations

It is evident from Fig. 2 that the elimination of the low order Zernike polynomial deformations gives a surface with smaller and more randomly distributed errors (figures $H-Z$). We quantify this improvement by calculating the increase in reflector surface precision and the corresponding smoothing of the gain–elevation dependence. For this we introduce the rms-value $\sigma_{H-Z}$ of the residual surface errors of which the Zernike deformations $\delta_Z$ are removed

$$\sigma_{H-Z}(\epsilon) = \sqrt{\sum_{i=1,K} [\delta_H,i(\epsilon) - \delta_Z,i(\epsilon)]^2 / K}$$

Because the surface of the reflector is adjusted to the precision $\sigma_a(\epsilon_0)$, the realistic quantities to compare are the surface accuracies without correction

$$\Delta_H(\epsilon) = \sqrt{\sigma_H^2 + \sigma_a^2(\epsilon_0)}$$

and with correction

$$\Delta_{H-Z}(\epsilon) = \sqrt{\sigma_{H-Z}^2 + \sigma_a^2(\epsilon_0)}$$

For the IRAM 30-m reflector we show in Fig. 3a the quantities $\sigma_H$, $\sigma_{H-Z}$, and $\Delta_H$, $\Delta_{H-Z}$ for three values $\sigma_a(\epsilon_0)$. The figure indicates a significant increase of the reflector
surface precision, worthwhile of correction, in particular when the adjustment precision
does not dominate the reflector surface accuracy.

Following Ruze [1966], the normalized gain of the reflector is

\[ g(\epsilon) = \exp(-[4\pi\sigma_{TP}(\epsilon)/\lambda]^2) \]  

(10)

with \( \sigma_{TP}(\epsilon) \) the tapered–phase rms–value of the wavefront [Greve & Hooghoudt 1981] and 
\( \lambda \) the wavelength of observation. For a steep reflector of focal ratio \( \sim 0.35 \) and illumination
between \(-10\) dB and \(-15\) dB, we have \( \sigma_{TP}(\epsilon) \approx 0.8 \Delta(\epsilon) \). Thus the normalized gain–
elevation dependence of the wavefront without correction is

\[ g_H(\epsilon) \approx \exp(-[0.8\ 4\pi\Delta_H(\epsilon)/\lambda]^2) \]  

(11)

and with correction

\[ g_{H-Z}(\epsilon) \approx \exp(-[0.8\ 4\pi\Delta_{H-Z}(\epsilon)/\lambda]^2) \]  

(12)

Figure 3b shows the prediction of the gain–elevation dependence \( g_H(\epsilon) \) and \( g_{H-Z}(\epsilon) \) when
using the values of Fig. 3a. Evidently, the correction of the large–scale deformations produces a significant smoothing of the gain–elevation dependence.

The large–scale deformations are not strictly statistical errors. However, we have shown
earlier [Baars 1973, Greve 1980] that Ruze’s formula applied to systematic wavefront
deformations gives a good prediction of the main beam degredation, except for very
special cases of wavefront deformation. For the present cases we have verified our analysis
by diffraction calculations which give results in agreement with those presented here.

5. Near–focus active wavefront correction

We discuss three numerical examples, for application to the IRAM 30–m telescope, to
demonstrate the improvement that can be obtained from near–focus correction. The selected corrector, shown in Fig. 4, is located on the co–rotating Nasmyth mirror and has
52 square–shaped elements which allow, for simplicity, only piston correction. We ignore
diffraction at the corrector elements since the actual corrector may have as surface
a metallic, continuous, deformable membrane. On the other hand, the wavefront deformations discussed here are small so that for a segmented corrector the piston difference
between adjacent elements is of the order \( \lambda/10 - \lambda/20 \). Following Ruze’s [1966] tolerance
theory, under this condition we may neglect edge diffraction.

5.1 Active homology

From the homology calculations we derive for each corrector element the average defor-
mation of the projected main reflector surface area (Fig. 4) and we assume that the

\[ \sigma_{H-C} \] obtained from piston correction is given
in Table 2 together with the rms-value $\sigma_{H-Z}$ for correction of the leading Zernike polynomial deformations. We find $\sigma_{H-C} \approx \sigma_{H-Z}$ for $n \geq 50$ and conclude that a corrector of some 50 elements eliminates the major contribution of the large-scale deformation. For the 52-element corrector the corresponding increase of reflector precision and smoothing of the gain–elevation dependence are similar to those shown in Fig. 3a,b. When located on the co–rotating Nasmyth mirror, the diameter of the corrector is $\sim 35$ cm. For $\lambda = 1.3$ mm (230 GHz) the corresponding ratio $d/\lambda$ of the corrector elements is given in Table 2. A similar corrector for main reflector astigmatism, with elements of size $d/\lambda = 25$, performed well in an experiment on the 30–m telescope [Greve et al. 1994]. We are therefore confident that a 52–element corrector placed on the Nasmyth mirror will correct well the large-scale component of the homology deformations.

5.2 Active reflector surface adjustment

The adjustment of large main reflector surfaces is extremely labour consuming, unless the reflector panels are supported by motorized actuators. A typical case is the IRAM 30–m reflector where panel adjustments can only be made manually so that it is worthwhile to consider wavefront correction for elimination of large-scale adjustment errors.

Figure 5a shows the surface error topography determined October 1993 from holography measurements at $\epsilon = 43^\circ$ elevation using the geostationary satellite ITALSAT at 39 GHz (D. Morris, IRAM). At the outer panel rings the surface shows large–scale deviations resembling that of an incomplete annular zone. The application of the proposed 52–element piston corrector reduces the surface rms–value from $\sigma_a = 0.120$ mm to $\sigma_a = 0.078$ mm. The corresponding reduction of the phase–tapered rms–value from $\sigma_{TP} \approx 0.096$ mm to $\sigma_{TP} \approx 0.064$ mm will improve the gain by a factor 1.6 at $\lambda = 1.3$ mm. The predicted smoothing of the surface error topography is shown in Fig. 5b. [The reflector was later improved by further adjustment].

5.3 Active wobbling

At millimeter wavelengths the strong and rapidly changing emission/absorption of the Earth’s atmosphere swamps weak cosmic signals unless differential observing procedures are applied. A frequently used method of sky subtraction is based on on–source/ off–source measurements where the beam is displaced on the sky by wobbling of the telescope’s subreflector. At the 30–m telescope the wobbling is made with a frequency of $\sim 1–10$ Hz and a beam throw of $30–300''$. The subreflector of a Cassegrain system wobbles around a point located between its vertex and the main reflector focus. Wobbling around the main reflector focus introduces the smallest wavefront deformation [cf. van der Stadt 1984], however this implies the largest mechanical momentum so that often a shorter distance of the wobble axis is used. In order to observe under symmetric conditions, the on–source and off–source positions are located at equal and opposite off–axis distances.

The tilt ($\Delta\alpha$) and associated shift ($\Delta x$) of the subreflector introduces a coma–like wavefront deformation with corresponding beam degradation noticeable as reduction of the beam peak power and the appearance of a coma–lobe. Figure 6 shows the reduction in peak power at 2 mm (150 GHz) and 1.3 mm (230 GHz) wavelength introduced by wobbling of the subreflector. The observational data are extracted from calibrated scans across Mars with the subreflector tilted such that the off–axis displacement of the source was $60''$ and $120''$, respectively. An active near–focus corrector, which follows the wobble frequency (here $1–2$ Hz) and corrects the wavefront according to the applied wobble throw, could restore to large extent the beam profile and the loss in power. We illustrate
the improvement expected from the 52-element piston corrector.

Following Ruze [1969] and Zarghamee & Antebi [1985], the tilt $\Delta \alpha$ and the associated shift $\Delta x$ of the subreflector introduces a displacement of the beam in the focal plane $\Delta \beta = \Delta \beta_\alpha - \Delta \beta_x$ where

$$\Delta \beta_\alpha = (c - a)[K(n) + K(N)] \Delta \alpha / f$$  \hspace{1cm} (13)$$

$$\Delta \beta_x = [K(n) - K(N)/M] \Delta x / f$$  \hspace{1cm} (14)$$

with $\Delta x = p(c - a) \Delta \alpha$, $(c - a)$ the distance between the subreflector vertex and the primary focus, and $p(c - a)$ ($0 \leq p \leq 1$) the distance of the wobble axis from the subreflector vertex. For the 30-m telescope $(c - a) = 690$ mm and $p = 0.56$. The tilt and shift introduce a coma-like wavefront deformation $\varphi(p, \theta) = \varphi_\alpha(p, \theta) - \varphi_x(p, \theta)\) where

$$\varphi_\alpha = k(c - a)[E(\rho, n) + ME(\rho, N)] \Delta \alpha \sin \theta$$  \hspace{1cm} (15)$$

$$\varphi_x = kp(c - a)[E(\rho, n) - E(\rho, N)] \Delta \alpha \sin \theta$$  \hspace{1cm} (16)$$

with $k = 2\pi/\lambda$, $n = f/D = 0.35$ the focal ratio of the main reflector, $M = 27.8$ the magnification of the telescope, and $N = Mn = 9.7$ the effective focal ratio of the system. $(\rho, \theta)$ are the normalized polar coordinates of the aperture. The function $E(\rho, m)$ is

$$E(\rho, m) = (8m\rho)/[(4m)^2 + \rho^2]$$  \hspace{1cm} (17)$$

The beam deviation factors $K(m)$ are taken from figure 3 of Zarghamee & Antebi's publication, i.e. $K(n=0.35) = 0.75$ and $K(N=9.7) = 1.0$ for a taper $f(\rho) = 1 - \alpha \rho^2$ with $\alpha = 0.75$.

As evident from Fig. 7, the piston correction of a 52-element near-focus corrector predicts a convincing restoration of the beam profile. The predicted recovery of the beam peak power is shown in Fig. 6.

Conclusion

To date, the feasibility and efficiency of active radio wavefront correction has been demonstrated for only a few cases in which most have employed the subreflector surface as the active element. Here we have illustrated an alternative method whereby large-scale wavefront deformations are eliminated with a near-focus corrector of relatively small size and a reasonably small number of elements ($\sim 50$). Two experiments at millimeter wavelengths [Mayer et al. 1991, Greve et al. 1994] have already demonstrated the success of near-focus wavefront correction.

We have discussed three examples of near-focus correction of large-scale wavefront deformations known from structural calculations, holography, and aberration theory. Although these examples are specific to the IRAM 30-m telescope, they demonstrate the improvement that can be obtained and hence may stimulate further experiments and the application of (piston mode) near-focus correctors on other telescopes.
The discussion, however, does not advocate the construction of cheap radio telescopes to be corrected later by active optics. On the contrary, the discussion aims to demonstrate the possibility to improve operating telescopes, or to correct telescopes with accidental wavefront deformations like transient thermal deformations. Evidently, also a non-homologous reflector with precisely known deformation topography can be improved in this way. The realization of a near-focus corrector may be similar to the experimental honeycomb plate corrector constructed by Backhaus & Forman [1990].

Acknowledgements: The homology calculations of the IRAM 30-m telescope were made by ARGE KRUPP (now VERTEX Antennentechnik GmbH)-MAN, Germany. D. Morris (IRAM) kindly provided the holography measurements of Figure 5; S. Navarro (IRAM) helped with some calculations. Ruze's (1969) notes were brought to our attention by R. Predmore (FCRAO). We thank the referees, among whom Dr. D. Emerson, for their constructive comments. Dr. C.D. McKeith helped to improve the presentation.

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Captions to the Figures

Figure 1

IRAM 30-m reflector. Decomposition of homologous reflector deformations in Zernike polynomials (for the index $L$ see Table 1). Coefficients $\alpha_{nm}$ for $\varepsilon = 90^\circ$, $75^\circ$, $60^\circ$: solid lines, for $\varepsilon = 30^\circ$, $15^\circ$, $0^\circ$: dashed lines. The reflector is assumed to be perfectly adjusted at $45^\circ$ elevation, thus $\alpha_{nm}(45^\circ) = 0$.

Figure 2

IRAM 30-m reflector. H: predicted homology deformations ($\delta_H$), Z: deformation of leading Zernike polynomials ($\delta_Z$), H–Z: homology deformations minus leading Zernike polynomial deformations ($\delta_{H-Z}$), H–C: homology deformations minus piston correction of the 52–element corrector shown in Fig. 4; calculated for the elevation $\varepsilon = 0^\circ$, $30^\circ$, $60^\circ$, $90^\circ$. The reflector is assumed to be perfectly adjusted at $\varepsilon_0 = 45^\circ$. Contour levels: 0.02 mm.

Figure 3

a) Increase in reflector surface precision by elimination of the leading Zernike polynomial deformations. Not corrected ($\sigma_H, \Delta_H$): thin lines, corrected ($\sigma_{H-Z}, \Delta_{H-Z}$): thick lines. The inserted values indicate the adjustment accuracy $\sigma_a(\varepsilon_0)$ (mm).
b) Predicted gain–elevation dependence $g_H$ without (thin lines) and $g_{H-Z}$ with (thick lines) correction of leading Zernike polynomial deformations; for the IRAM 30-m reflector with $\lambda = 1.3$ mm (230 GHz): -----, and $\lambda = 0.86$ mm (350 GHz): - - -.

Figure 4

Aperture plane projection of the 52 square–shape element piston mode near–focus corrector. The dots show the positions for which homology calculations are available (IRAM 30-m telescope). Four adjacent dots outline a panel frame, each supporting 2 panels. The contour levels show the homology deformations at horizon.

Figure 5

IRAM 30-m reflector surface error topography (untapered) at elevation $\epsilon = 43^\circ$; October 1993 (later re-adjusted). Contour levels of 0.025 mm.

a) Measured topography showing the actual deviations.

b) Predicted error topography after piston correction with the 52–element corrector shown in Fig. 4.

Figure 6

IRAM 30-m telescope loss in peak power in observations with the wobbling subreflector. Dots: measurements; thin lines: loss in peak power calculated for the wavefront deformation of Eq.(13–14); thick lines: restoration of peak power by application of the 52–element piston corrector of Fig. 4. [There are no observations at 0.86 mm].

Figure 7

Calculated beam profiles at 230 GHz showing the predicted performance of the 52–element piston corrector (Fig. 4) for a beam throw of 60" and 120". Countor levels of thin lines: - 30, - 25, -23 dB, of heavy lines: - 20, - 15, - 13, - 10, - 5, - 3 dB.

a) Degraded beam pattern.

b) Corrected beam pattern.
Table 1. Zernike Polynomials used in the Decomposition of Surface Deformations (Definition of the Index L).

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<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are special designations for $L = 3$ (n=4,m=0): spherical aberration, $L = 6$ (n=3,m=1): coma, $L = 9$ (n=2,m=2): astigmatism.

Table 2. IRAM 30-m telescope. Predicted Surface/Wavefront Improvement by Piston Correction using an n-Element Corrector [Values in mm].

<table>
<thead>
<tr>
<th>Elevation</th>
<th>0°/90° a)</th>
<th>30°/60° a)</th>
<th>d/λ b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No correction</td>
<td>$\sigma_H$</td>
<td>0.055</td>
<td>0.020</td>
</tr>
<tr>
<td>Zernike Polyn.</td>
<td>$\sigma_H-z$</td>
<td>0.028</td>
<td>0.010</td>
</tr>
<tr>
<td>Piston n = 32</td>
<td>$\sigma_H-C$</td>
<td>0.040</td>
<td>0.014</td>
</tr>
<tr>
<td>Piston n = 52 c)</td>
<td>$\sigma_H-C$</td>
<td>0.034</td>
<td>0.012</td>
</tr>
<tr>
<td>Piston n = 86</td>
<td>$\sigma_H-C$</td>
<td>0.031</td>
<td>0.011</td>
</tr>
</tbody>
</table>

a) identical values for $\epsilon$ and $90° - \epsilon$. For $\epsilon = 45°$: $\sigma = 0$.
b) for $\lambda = 1.3$ mm (230 GHz) and the corrector located on the Nasmyth mirror.
c) the corrector is shown in Fig. 4.