解 説

The Ronchi Test for Aspherical Optical Surfaces

A. CORNEJO-RODRIGUEZ

Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE),
Apdo. Postal 216, Puebla, Pue., MEXICO, 72000

(Received August 25, 1982)

1. Introduction

In the area of testing optical surfaces (TOS), there are diverse kinds of devices which regularly are used in such task. The two oldest and most classical tests are the knife-edge or Foucault[1] test and the Newton's rings.[2] Both tests are mentioned here because they represent the two main paths in the TOS, i.e. the first one considering mainly geometrical optics basis, and the second, taking into account physical optics concepts. But, of course, many of the testing methods can be analyzed from the two points of view.

Along the head lines of the so-called geometrical and physical tests, there are many techniques which have been developed along the time, and most of them have been deviced for the testing of plane and spherical surfaces, as well as angles between surfaces. However, more recently, an increasing interest in the construction and testing of aspherical surfaces has emerged strongly.

As a general information and in order to recognize several aspects of the methods applied in the TOS, there are various review papers which can help the reader to get acquainted with this area of the TOS. Let us mention the following: Murty,[3] Tew,[4] Briers,[5] Malacara, Cornejo and Murty,[6] Caulfield and Friday,[7] and Cornejo, Caulfield and Friday.[8] For the specific case of aspheric surfaces, there is a review by Dukhopel, Konstantionovskaya, and Fedina,[9] and a section of Ref. 7).

Among all those classical and modern techniques in the TOS, in this paper we will concentrate in the study of the Ronchi[10] test (Lenouvel,[11] Jentzch,[12] Schulz,[13] Anderson and Porter,[14] and Adachi[15]). Even though this Ronchi test has been studied since a long time ago, and has been applied to different situations (Cornejo[16]), the main topic of this review is on its applications to the testing of aspherical surfaces.

2. Ronchi Test

The Ronchi test generally is used for the testing of concave surfaces of different shapes. In **Fig. 1** the typical set up is shown. The light passing through the Ronchi ruling, once it has been reflected on the optical surface, will give us information about some zonal errors in the polishing of the surface and the smoothness and/or type of surface being polished; i.e. spherical or aspherical. Although originally the light source was a white point source, **Fig. 1** shows an extended white light source illuminating one side of the Ronchi ruling. Of course, instead of a white light source, a low power He-Ne laser can also be used. **Figure 1 (a)** shows a magnification of the so-called Ronchi ruling, whose structure is a series of dark and light bands. The number of such bands per unit of length can be changed and, as it will be seen later on, this is an important parameter for the testing of aspherical surfaces. In some experiments, it is useful to use phase gratings[17,18] instead of the amplitude ones.

In **Figs. 2 (a)** and **2 (b)** are shown some typical Ronchigrams (name coined by Schulz[13]) showing a perfect spherical surface with and without defocusing, and another being affected by spherical aberration but that can also represent the pattern for an aspherical surface like a parabola. The patterns shown in **Figs. 2 (a)** and **2 (b)** were calculated by a computer and graphically done by a plotter. The results were derived using the mathematical theory that will be explained in

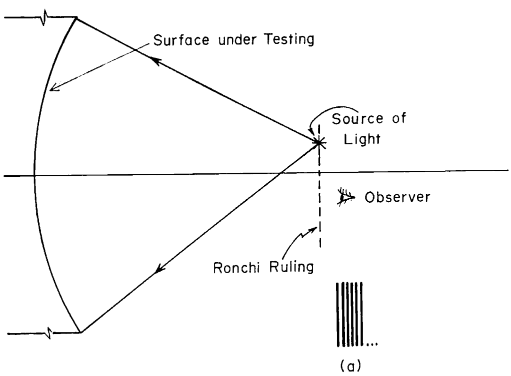


Fig. 1 Experimental set up for the Ronchi test.

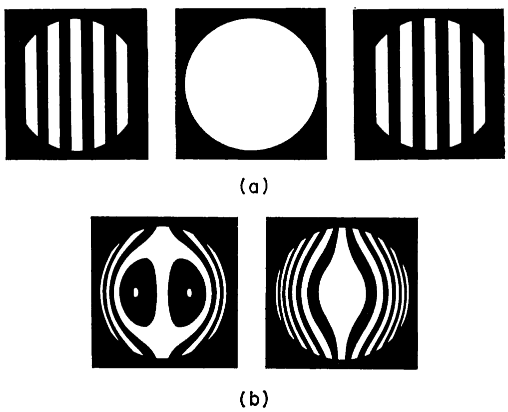


Fig. 2 (a) Ronchigram for a spherical surface showing no aberrations and only defocussing. (b) Ronchigram for a spherical surface showing spherical aberration plus defocussing.

the next section. From the experimental point of view, the Ronchigrams are not so-well defined and some aspects about this particular characteristic of the Ronchi test will be briefly commented in the text. **Figure 3 (a)** shows an experimental Ronchigram, and **Fig. 3 (b)** shows how the pupils are sheared by using the Ronchi rulings with a big number of bands per cm (×80 l/cm). Given this last phenomenon, the Ronchi test usually is also classified as a lateral shear interferometer (Toraldo di Francia[19] and Malacara and Cornejo[20]).

3. Theory of the Ronchi Test

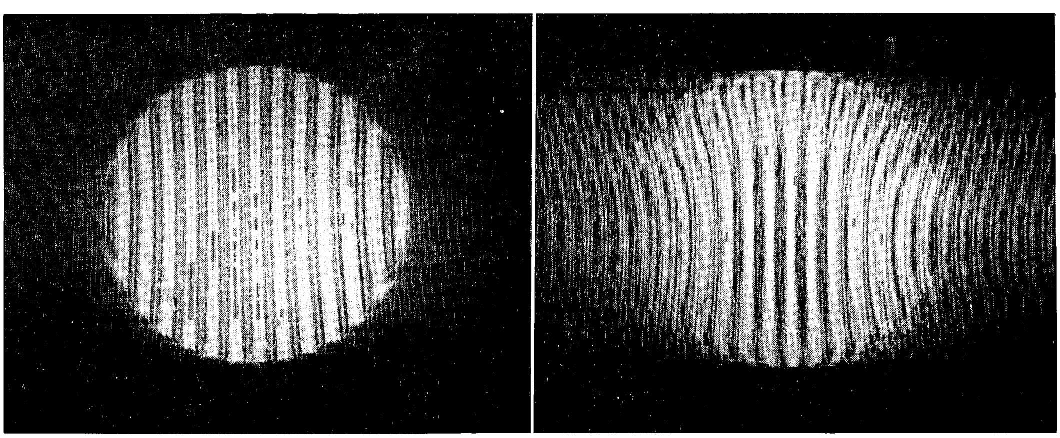
In this section some theoretical and general aspects of the Ronchi test will be presented.

3.1 Information from the Ronchi Test

It is convenient to recall the fact that the Ronchi test gives us information about the transverse aberration[21] of a wavefront, and not a direct information of the wavefront itself, as in the case of the Twyman-Green[22] or Fizeau[23] interferometers. From geometrical considerations, it is well established the mathematical relation between the wavefront and its transverse aberration,[24] that can be written as

$$\partial W/\partial x = -TA_x/r, \qquad (1)$$

where W is the wavefront, TA_x is the transverse aberration along the x direction, and r is the paraxial radius of curvature of the wavefront. On the other hand, Nyssonen and Jerke[25] have shown that in order to have a complete information about W, it is necessary to have information of the transverse aberrations along two directions. Con-



(a) (b)

Fig. 3 (a) Experimental Ronchigram showing spherical aberration. (b) Laterally sheared pupils using a high frequency Ronchi ruling.

sequently, a similar expression to Eq. (1) should be written and used but now along the y direction; i. e.

$$\partial W/\partial y = -TA_y/r. \qquad (2)$$

Therefore, after measuring TA_x and TA_y, and by means of Eqs. (1) and (2), a knowledge of W will be obtained once that some numerical calculations are done. It is convenient to mention that even Eqs. (1) and (2) were derived by geometrical considerations, and taking some approximations, Rayces[26] showed that such equations can be considered as truly exact ones.

3.2 Geometrical and Physical Interpretations of the Ronchi Test

Before explaining how Eqs. (1) and (2) can be used for deriving information from experimental Ronchigrams, in this section, the use of geometrical and physical interpretations of the Ronchi test will be explained, as well as how they can be compared to each other.

From a geometrical point of view, the Ronchigrams can be interpreted as the projections of the rulings, of the Ronchi grating, upon the optical surface under test. With respect to the physical optics concepts, the Ronchi test is a result of the interference of the beams being diffracted by the Ronchi ruling. When this Ronchi ruling is a low frequency one, both interpretations agree very well, as it will be seen later on.

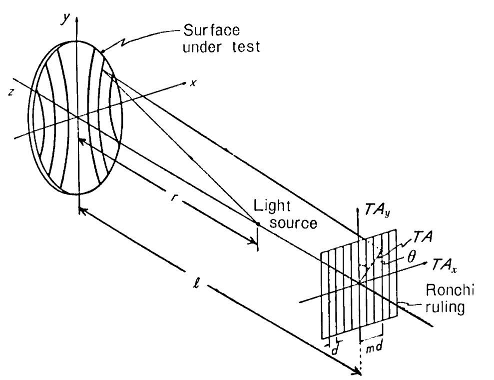


Fig. 4 Geometrical concepts for the Ronchi test.

Figure 4 shows the Ronchi test under geometrical considerations. Using Eq. (1) and considering the rulings parallel to the y axis, the transverse aberration $TA_x = md$, where d is the line separation in the ruling, and m is the order number which can also be identified as the interference order. Substituting this value of TA_x into Eq. (1),

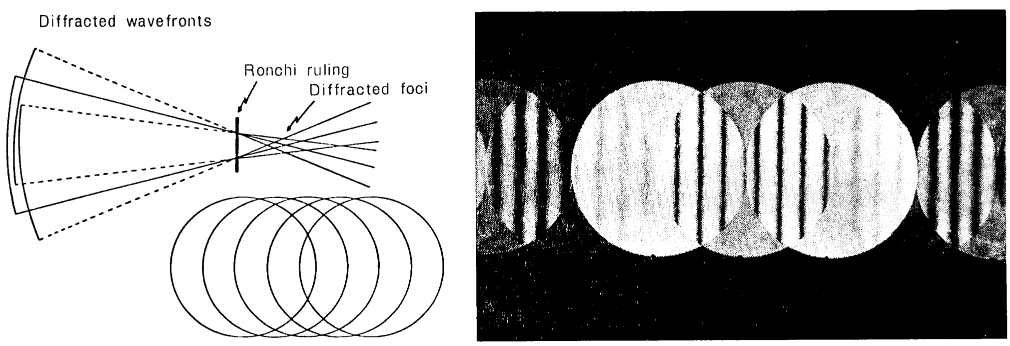
$$\frac{\partial W}{\partial x} = -\frac{TA_x}{r} = -\frac{md}{r}. \qquad (3)$$

If the ruling is oriented with its lines parallel to the x direction, a similar expression can be written by using Eq. (2). However, for a general orientation of the Ronchi grating, it can be written that

$$\frac{\partial W}{\partial x}\cos\phi - \frac{\partial W}{\partial y}\sin\phi = -\frac{md}{r}. \qquad (4)$$

The patters shown in Fig. 2 were obtained using this last Eq. (4), and according to Cornejo.[16]

As it has already been mentioned, from a physical point of view, the Ronchi test should take into account the interference and diffraction phenomena. Some of the pioneering works in this direction were done by Ronchi[10] himself, Di Jorio,[27] and Toraldo di Francia.[19,28] More recent works using Fourier and spatial filtering theories were developed by Adachi[29] and Barakat,[30] respectively. Following these last developments, Cornejo[16] derived the following summarized results; **Fig. 5 (a)** shows the effect of the Ronchi ruling.



(a) (b)

Fig. 5 (a) Physical concepts for the Ronchi test. (b) Laterally sheared beams and interference fringes in the overlapped areas.

Considering $F_0(x_0, y_0)$ the phase deviations of the wavefront under test, measured with respect to a sphere with its center at the Ronchi grating, the field $U(x_r, y_r)$ at the ruling plane will be

$$U(x_r, y_r)=\iint_{-\infty}^{\infty} F_0(x_0, y_0) \times \exp\left[-i\frac{2\pi}{\lambda r}(x_r x_0+y_r y_0)\right]dx_0 dy_0. \quad (5)$$

According to the concepts of spatial filtering theory (Barakat[30]), the Ronchi grating can be considered as a filter in the Fourier transform plane x_r-y_r. Therefore, in the observation plane x_1-y_1, that is the image plane of the pupil plane x_0-y_0, the amplitude in that plane can be written equal to

$$G(x_1, y_1)=\iint_{-\infty}^{\infty} U(x_r, y_r)\cdot M(x_r, y_r) \times \exp\left[\frac{2\pi}{\lambda r}(x_r x_1+y_r y_1)\right]dx_r dy_r. \quad (6)$$

The Ronchi rulings with equidistant, straight and parallel bands can be written mathematically as

$$M(x_r)=\sum_{n=-\infty}^{\infty} B_n \exp\left(i\frac{2\pi n}{d}x_r\right), \quad (7)$$

Thus, substituting Eqs. (5) and (7) into Eq. (6), and after some manipulations, the next result can be derived

$$G(x_1, y_1)=\sum_{-\infty}^{\infty} B_n F_0\left(x_1+\frac{\lambda r n}{d}, y_1\right); \quad (8)$$

from this Eq. (8), it can be concluded that the different image pupils are shifted by $\lambda r/d$, and therefore it is explained how a multiple interference fringe will be produced at the common areas of the diffracted and overlapped beams. **Figure 5(b)** shows a typical interference pattern for the Ronchi test in the situation that the beams are sheared.

In order to show the connection between the geometrical and physical concepts, first we will assume that the irradiance at the exit pupil is

$$F(x_0, y_0)=\exp\left[i\frac{2\pi}{\lambda}W(x_0, y_0)\right], \quad (9)$$

where $W(x_0, y_0)$ represents the polynomial wavefront. Considering a very coarse ruling (geometrical approach), it is possible to assume that no more than two sheared beams will interfere with each other; therefore, substituting Eq. (9) into Eq. (8), and taking only two consecutive orders interfering, it is possible to write

$$|G(x_1, y_1)|^2=B_{n1}^2+B_{n2}^2+2B_{n1}B_{n2} \times\cos\left\{\frac{2\pi}{\lambda}W\left(x_1+\frac{\lambda r n_1}{d}, y_1\right) -W\left(x_1+\frac{\lambda r n_2}{d}, y_1\right)\right\}, \quad (10)$$

where the third term is giving the interference effect.

For the particular condition of bright fringes, shifting the origin of the interference pattern to the center of the overlapped images, expanding the results in a Taylor's series, and eliminating the high order terms, we can obtain

$$\frac{\partial W(x_1, y_1)}{\partial x_1}=-\frac{md}{r} \quad (11)$$

which is similar to Eq. (1). Following more simple concepts and reasonings, Cornejo and Malacara[62] reached the same results about the relation between the geometrical and physical concepts.

4. The Testing of the Aspherical Surfaces

Given the importance of the aspherical surfaces in the performance of some optical instruments, as well as some economic aspects related to their use, each time the interest on this type of surfaces increases, not only from the design point of view, but also mainly about the construction and testing techniques more suitable for a most effective and extensive use of these aspheric surfaces (Dukhopel *et al.*,[9] Williams[31]). Until now, the efforts for these surfaces have been concentrated mainly on the so-called conic surfaces (parabolic, elliptic, hyperbolic), but also there is a general interest in other types, as is the case of the Schmidt corrector plates.

Since the aspherical surfaces have been used since a long time ago, several efforts have been made to test such kind of surfaces. There are some methods using mechanical techniques, Karlin[32]; others use null correcting lenses, Burch,[33] Ross,[34] Dall,[35] Offner,[36,37] for being used in some interferometric or geometrical testing methods. With the development of the holographic methods (Van Deelen and Nisenson,[38] Wyant,[39] Lurionov, Lukin and Mustafin[40]), the technique of using synthetic holograms as compensating devices for the aspheric surfaces was started by MacGovern and Wyant,[41] Wyant and Bennett,[42] and later on followed by authors as Fercher and Kriese,[43] Ichioka and Lohmann,[44] Takahashi, Konno and Kawai,[45] and many others. Some hybrid techniques are those developed by Faulde *et al.*,[46] Dil, Greve and Mesman.[47] The books by Twyman,[48] Devê,[49] Malacara,[50] and Horne[51] have complete chapters describing several techniques according to the time of their publications, and their reading is highly recommended.

Among all those types of techniques and devices, the Ronchi test is a very suitable testing method for aspheric surfaces, given its characteristics of a simple set up, and the fact that this test can be analyzed from geometrical and physical-interferometric-concepts. Unfortunately, there are some problems about the thickness of the interference fringes, that limit the accuracy of the Ronchi method. In the next section several topics in the use of the Ronchi test applied to the testing of aspherical surfaces will be presented and discussed.

4.1 The Aspherical Surfaces

The most used mathematical representation of an aspherical surface in Optics is

$$Z=\frac{cs^2}{1+[1-(K+1)c^2s^2]^{1/2}}+A_1s^4+A_2s^6+\cdots, \tag{12}$$

where $c=1/r$ is the paraxial radius of curvature, $s^2=x^2+y^2$, A_j are the aspheric deformation coefficients, and K is the conic constant representing the surfaces according to the following table

$K<-1$	Hyperboloid,
$K=-1$	Paraboloid,
$-1<K<0$	Ellipsoid rotated about the major axis,
$K=0$	Sphere,
$K>0$	Ellipsoid rotated about the minor axis.

The first term of Eq. (12) represents all the conic and spherical surfaces and in this case all the A_j coefficients are zero. The actual shape of a non-spherical surface is considered very frequently as the departure from a certain spherical surface, whose radius of curvature can be defined in several ways. The most used reference sphere is the so-called osculating sphere whose radius of curvature is equal to the paraxial one; then, at the paraxial region, the surfaces can be considered spherical; thus, as we are going off axis, the departure of the aspheric increases with respect to the sphere, and more interference fringes will appear in the field of view during the testing stage of the aspheric surface, setting a limitation in some of the most used techniques in the TOS.

It is also interesting to point out that the radii of curvature for the different zones of an aspherical surface, besides having different values, the respective centers of curvature for each zone are localized outside the optical axis of symmetry. This fact was shown experimentally by Wadsworth[52] for a parabolic surface, applied later on by Platzeck and Gaviola[53] for an optical test; and Cornejo and Malacara[54] developed a simple set of formulas for finding the positions of those centers of curvature in the case of conic surfaces. But, in general, the centers of curvature for any aspheric surface are localized along the so-called caustic surface, introducing an extra troublesome factor for the testing and alignment of the aspheric surfaces.

4.2 The Ronchi Test Applied to the Aspherical Surfaces

As can be seen from **Fig. 2 (a)**, for an ideal spherical surface the fringes at the Ronchigram keep the same structure as the Ronchi rulings, for different focussing positions. However, for the spherical surface with aberrations, the fringes at the Ronchi pattern present a different structure (**Fig. 2 (b)**). From these results, it is possible to think that for any kind of aspherical surface, the interferogram from the Ronchi test will show different structures. Hence from this empirical idea, it is possible, in principle, to use the Ronchi test for studying the construction and polishing of an aspherical surface.

Some of the known early attempts for using the Ronchi test applied to the testing of aspherical surfaces are the ones carried out by Waland[55] and Schulz.[56] However, the first study in order to obtain quantitative results from the Ronchi test applied to an aspherical surface was done by Sherwood.[57] This author derived an equation for the transverse aberration, TA, at the Ronchi ruling, by means of geometrical concepts. Later on, and independently of Sherwood's paper, Malacara[58] derived similar results using the vectors theory. From the parameters shown in **Fig. 4**, the equation derived by Sherwood[57] and Malacara,[58] for the transverse aberration is given by (following Malacara's paper)

$$TA(s)=\frac{(l+L-2z)\left[1-\left(\frac{dz}{ds}\right)^2\right]+2\frac{dz}{ds}\left[s-\frac{(l-z)(L-z)}{s}\right]}{\frac{l-z}{s}\left[1-\left(\frac{dz}{ds}\right)^2\right]+2\frac{dz}{ds}}, \tag{13}$$

where s is the distance from the optical axis to the point considered on the surface. Following this result, Sherwood[59] himself and Lumley[60] calculated the ideal Ronchigrams for some parabolic surfaces. Using the results of Lumley and Sherwood, De Vany[61] applied the technique and extended it for different conic surfaces. In particular, the work by Sherwood shows a series of curves that can be applied to parabolic surfaces having different f numbers.

Considering the fact that the observed Ronchigrams in a flat surface, just located in front of the surface, and the surface itself present a slight difference in the contours of the fringes, Malacara[58] studied this effect and derived a new formula based in the one shown in Eq. (13).

A step forward in applying the Ronchi test for studying aspherical surfaces was done by Cornejo and Malacara.[62] In this paper the authors established, as it was already pointed out before, a relation between the geometrical and physical concepts for the Ronchi test. Also, taking into account some experimental results, these authors derived a mathematical formula between the asphericity of the surface and the period d of the Ronchi ruling, which will produce an acceptable visibility of the fringes at the Ronchigram.

The equations derived for the period d of the ruling, as a function of the minimum and the maximum fringe separations, at the largest, r_{max}, and the minimum, r_{min}, values of the radii of curvature of the surface under test, are given by

$$d \leqslant \frac{D}{s}(1-l/r_{min}), \text{ and} \qquad (14)$$

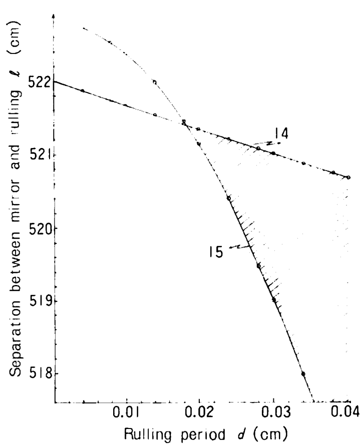


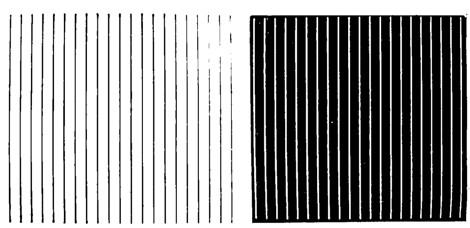
Fig. 6 Graphical results of the plotting of Eqs. (14) and (15), where the shadowed area shows the limits for l and d that can allow an observable experimental Ronchigram.

$$d \geqslant 2\sqrt{\lambda l - \lambda l^2/r_{max}}, \qquad (15)$$

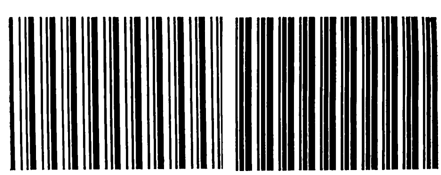
where D is the diameter of the surface, λ the wavelength of the used light; l is the distance between the ruling position and the vertex of the surface. **Figure 6** shows the results of using Eqs. (14) and (15) for a particular parabolic surface, where the shadowed region represents the values of d and the ruling position l that guarantees observable Ronchi patterns.

In this same paper by Cornejo and Malacara,[62] besides deriving qualitative information by comparison of theoretical and experimental Ronchigrams, an attempt was done to obtain quantitative results by calculating the theoretical TA (according to Eq. (13)) and comparing it against the experimental TA measured from the actual Ronchigram. This was done measuring the fringe positions along an axis perpendicular to the fringes.

On the other hand, since one of the problems in the Ronchi test is the sharpness of the fringes at the Ronchigram, Murty and Cornejo[63] started to do some attempts to improve such situation. For doing so, they constructed a kind of Ronchi rulings where the width between dark and light zones keep different ratios; one of these rulings is shown in **Fig. 7 (a)**. Later on, Cornejo, Altamirano and Murty[64] extended this method to some other kind of rulings whose structure is more complicated (Katyl[65]); this ruling is shown in **Fig. 7 (b)**. Taking into account that with the above mentioned rulings an improvement was reached in the sharpness of the fringes, then, it



(a)



(b)

Fig. 7 (a) Ronchi ruling showing a ratio of 1 : 10 between dark and light zones. (b) Ronchi ruling showing pseudo-random structure (Katyl's rulings).

is possible to say that this type of rulings will also be more helpful in the testing of aspheric surfaces, because a better fringe definition will be obtained, which sometimes is a problem in the testing of aspheric surfaces.

4.3 The Null Ronchi Rulings

From the experience of comparing curved fringes between the experimental and the theoretical Ronchigrams, and in order to obtain quantitative and qualitative results from that comparison done during the testing of an aspherical surface, it became important to find a mechanism which could provide a method to carry out an easier and more reliable comparison. As a result, at different times and each for himself, different authors gave a response to this problem; in what follows they will be mentioned according to the time of presentation of their ideas and results. Pastor,[66] in a review paper, gave a general idea of how to do some kind of rulings that can compensate the asphericity of the surfaces. Later on, Popov[67] developed a similar idea for testing astronomical surfaces, and some formulations were developed, simultaneously, by Malacara and Cornejo[68,69] for any conic surface, and Mobsby[70] for parabolic surfaces. However, after a comment from Felgett and Gee,[71] Malacara and Cornejo[72] discovered some errors in Mobsby's results. In the following paragraphs, the meaning and how these null Ronchi rulings can be constructed, will be described.

As it has already been mentioned, the main idea of this kind of null Ronchi gratings is to compensate the asphericity of the surfaces in such a way that, at the Ronchigram, the interference fringes will appear straight, equidistant and parallel to each other. In this respect, these null Ronchi gratings can be thought of as equivalent to the null lenses developed previously by Burch,[33] Offner[36] and others; or as some kind of computer generated hologram developed by MacGovern and Wyant.[41] However, in comparison with the holographic techniques, the construction of the null Ronchi rulings can be achieved more easily from the point of view of mathematics; it is required only ray tracing, and usually the computer time used is smaller. Of course, even though the limitation of accuracy exists, intrinsic in the Ronchi test, the visibility of the fringes produced by this method shows slight improvements compared to the Ronchigrams derived from the classical Ronchi rulings (see **Figs. 9 (b)** and **9 (c)**).

Following the work by Malacara and Cornejo,[69] and taking into account that it was devoloped for any conic surface, **Fig. 8** shows the geometry and parameters used for the design of the null Ronchi rulings. In order to do the ray tracing, it should be noticed that the desired interference fringes at the surface are straight lines and the rulings at the grating must have some curvature. In order to know the shape of the rulings on the grating, let us consider a certain point P on the grating and the surface (see **Fig. 8**), then we can write, according to the geometry shown, that

$$\cos\theta=\frac{X_S}{r'}=\frac{X_R}{TA(r')}, \tag{16}$$

and from this last Eq.

$$X_R=X_S\frac{TA(r')}{r'}; \tag{17}$$

similarly, for the coordinate Y_R it is possible to derive an equivalent equation; then

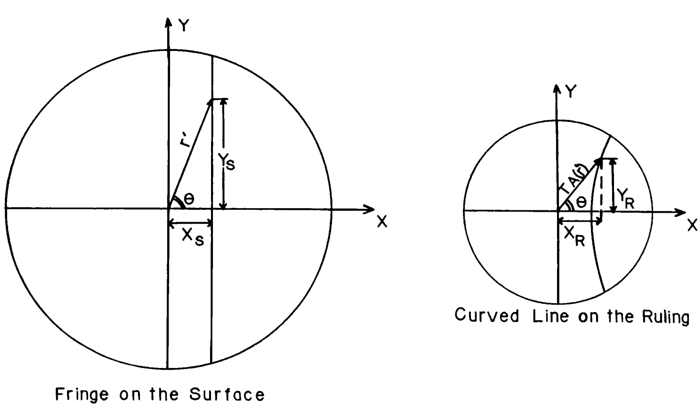
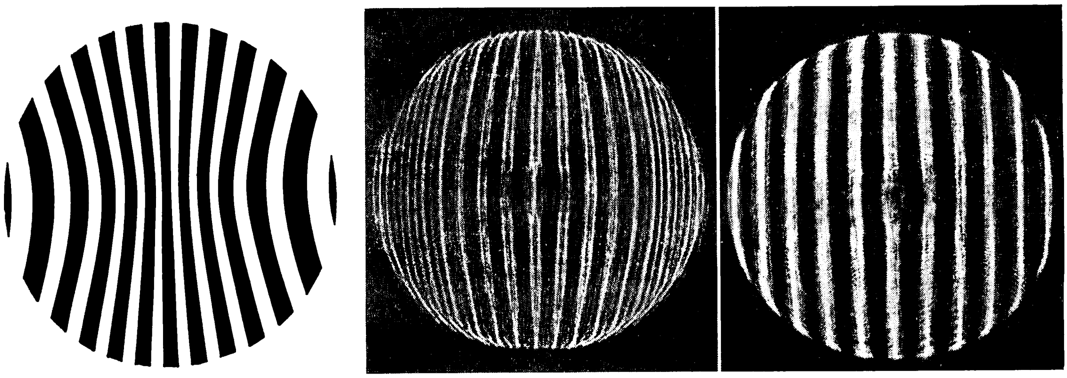


Fig. 8 Geometry and parameters at the surface and rulings to produce a Null Ronchi ruling.



(a) (b) (c)

Fig. 9 (a) Null Ronchi ruling for a paraboloid with $r=202$ cm and diameter of 30 cm. (b) Ronchigram using normal Ronchi rulings. (c) Ronchigram using the Null Ronchi ruling of **Fig. 9(a)**.

$$Y_R = Y_S \frac{TA(r')}{r'}. \qquad (18)$$

Thus, since $r'^2 = X_S^2 + Y_S^2$ and considering straight fringes at the surface, for one value of X_S several values of Y_S can be assigned, and the corresponding value of $TA(r')$ can also be evaluated. Then, by using Eqs. (17) and (18) the contours of the rulings for the grating can be calculated by means of a computer program. In order to know the values of $TA(r')$, Malacara and Cornejo[69] obtained the polynomial transverse aberration produced by the asphericity of the mirror; they used a ray tracing program at the beginning, and later on the coefficients of the polynomial were determined. By means of Eqs. (17) and (18) the edge of the rulings were plotted using a computer program and an electronic plotter.

Once the ruling was drawn in a paper, a reduced photograph of the grating was obtained, which has the proper size for the position where the TA was previously calculated. **Figure 9(a)** shows a null Ronchi grating for a parabolic mirror, produced by the method above described and using as a point source of light, a low power He-Ne laser. **Figures 9(b)** and **9(c)** show the experimental results of using a normal and the null Ronchi rulings of **Fig. 9(a)**, respectively.

Afterwards, Malacara and Cornejo[73] derived more simple formulas that can be used for obtaining null Ronchi rulings without using a computer. For deriving them, they made some assumptions and considered only the third order aberration introduced by the aspheric surface. Following the idea of considering only the third order spherical aberration, Hopkins and Shagam[74] proposed that

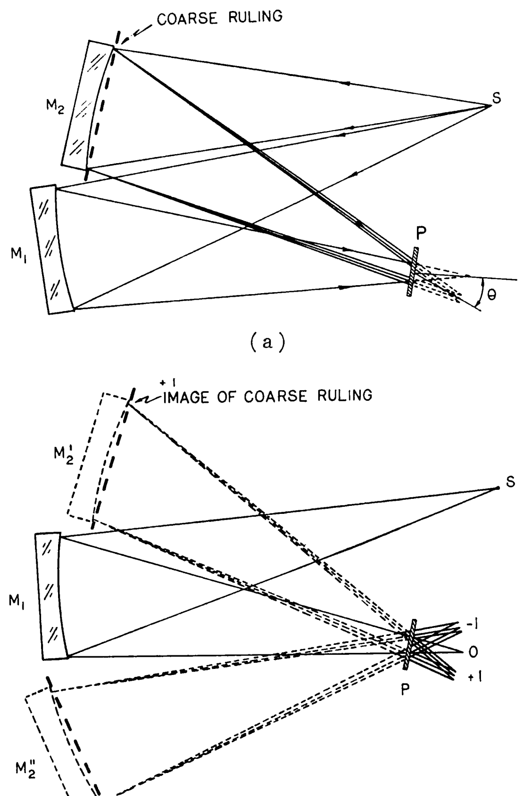


Fig. 10 (a) Experimental set up for producing the hologram in the sideband Ronchi test. (b) Arrangement for observing the hologram in the same test with the M_2 mirror removed.

by means of a computer optical design program, the null Ronchi rulings can be designed. They proposed a rectangular pupil grid, and using an optical design program, a spot diagram was obtained, which gives actually the contours of the rulings of the null Ronchi grating.

4.4 Holographic Ronchi Test

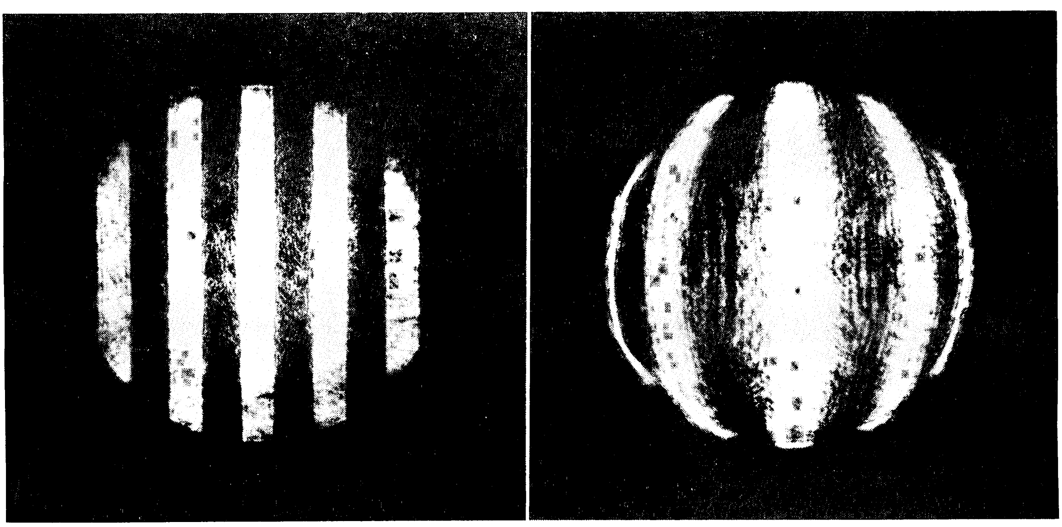
With the idea of finding a technique for testing aspherical surfaces with the Ronchi test, where the sharpness of the fringes can be improved, Malacara and Cornejo[75] devised what they called a side band Ronchi test. **Figures 10 (a)** and **10 (b)** show the set up for producing the hologram, and the use of it for testing the surfaces, respectively.

In the stage of producing the hologram (**Fig. 10 (a)**), two mirrors M_1 and M_2 were used and they were illuminated by the source of light S (low power He-Ne laser). The mirror M_2 has in front of it a coarse Ronchi ruling, and the reflected light from both mirrors was registered on a photographic plate, P, which turns out to be the hologram. When this hologram is positioned as is shown in **Fig. 10 (b)**, but the mirror M_2 has been removed, the new mirror M_1' (under test) substitutes the mirror M_1. As the observed images at the $\pm$ 1st diffraction orders must reconstruct the image of M_2, if mirror M_1' has the same shape of mirror M_1, or is the same mirror M_1, the interference patterns do not show any change; but if that is not the case, a change in the patterns should be noticed. The observed $\pm$ 1st order diffracted images using the set up of **Fig. 10 (b)** are shown in **Figs. 11 (a)** and **11 (b)**. From these pictures, the difference of the interference patterns when an aspheric surface is tested can be noticed. Besides having sharper interference fringes for the $\pm$1st order, other advantages obtained by this method are that the quality of the reference mirror M_2 is not so important, and also the hologram obtained can be used as a reference plate for the testing not only of one piece, but also of many pieces that should have the same characteristics. Using the same method, circular gratings can be used for detection of astigmatism in the surfaces.

Following the technique explained above for the sideband Ronchi test, Malacara and Josse[76] developed a similar method and applied to the testing of aspherical lenses. As in the previous experiment, the method has two steps; in the first one the hologram is produced having a reference aspherical lens, and in the second phase the observed patterns of the tested lens are observed. The experimental arrangements are very similar to the ones shown in **Figs. 10 (a)** and **10 (b)**.

4.5 Other Related Tests

As it has already been mentioned, the Ronchi test usually is classified as an interferometric test, and many references can be found under the title of grating interferometers; of course, not all the interferometers of that type belong to the Ronchi test type. However, it is interesting to call the attention to the interferometers that using Ronchi



(a) (b)

Fig. 11 (a) Null Ronchigram observed with the setup shown in **Fig. 10 (b)** for the first positive diffracted order. (b) Ronchigram observed with theset up shown in **Fig. 10 (b)** but for the first negative diffracted order.

rulings make use of the so-called Talbot effect (phenomenon also referred to as Fourier imaging and self-imaging, as it was already mentioned by Lohmann and Silva[77]), combined with the Moiré fringes produced by the superposition of another grating at the observing image plane. Some examples of this kind of interferometer are the ones developed by Yokoseki and Susuki,[78] Silva,[79] and Yokoseki and Ohnishi.[80] More general aspects about the Moiré effect as a measuring method in the terms of these interferometers can be seen in the work done by Burch.[81] Very recently and also using two gratings, but not making use of the Talbot effect, Schwider[82] applied the Ronchi test to microscope objectives; but besides that, the paper contains a very important review of the Ronchi method.

Using only the Talbot effect in the classical Ronchi test (**Fig. 1**), Malacara and Cornejo[83] studied the effects of it in the Ronchigrams. They found that sharper fringes can be observed besides some amplification due to the fact of having a convergent beam incident on the ruling.

Another kind of grating interferometers that can be related to the Ronchi test are those developed by Wyant.[84] In this type of interferometers, two crossed diffraction gratings of high efficiency, produced holographically, are used. When such crossed gratings are illuminated by the beam under test, a set of two lateral shear interferograms is obtained in two orthogonal directions. Given the compactness of the system, and due to the fact that the information is derived at once in two orthogonal directions (see Section 3. 1), this arrangement allows a fast processing of the results. Following with the idea of this kind of interferometer, later on Hariharan, Steel, and Wyant[85] made a further development on it. Further work has been done by Thomas and Wyant[86] using a dichromated gelatine for the recording of the crossed gratings.

Even though all these types of interferometers are not specially designed for aspherical surface testing, given the intrinsic characteristics of the lateral shear interferometers (including the Ronchi test), their use for this type of surfaces is evident.

5. Conclusions

Among all the different kinds of testing procedures for the testing of optical surfaces, since a long time ago the Ronchi test has a special place as one of the most used; given its characteristics of simple set up and easy alignment, very economic components (i. e. the rulings), and that also quite simple qualitative information can be derived. In order to obtain quantitative information, the procedures are not so simple but, as with other tests, the use of computers is required. Thus, in this sense, there is not a big disadvantage of the Ronchi test compared to the others. At the present moment, there are already some works done in this area of obtaining quantitative information using computers (Nyssonen and Jerke,[87] Rimmer,[88] Malacara and Cornejo,[89] Cornejo and Malacara[90]).

In the specific area of testing aspherical surfaces, the Ronchi test still keeps its main characteristics of simplicity and economical requirements for the equipment and setup, even for the new arrangements shown in Sections 4. 2, 4. 3 and 4. 4. Unfortunately the broadness of the interference fringes at the Ronchigrams remains as the main drawback for improving the accuracy of this test. However, this test can be improved and modified; for example, there is the possibility of studying the results that can be obtained from the combination[91] of the Null Ronchi rulings (Section 4. 3) with the structure of Katyl's gratings of Section 4. 2. Of course, there are many more examples as this one, and the field is open for studying new developments of the Ronchi test, which can allow this method to keep its place and pace in the continuous developing area of testing optical components.

References

1) L. M. Foucault: Arn. Obs. Imp. Paris, **5** (1859) 197.
2) I. Newton: *Optiks* (Dover Publication, New York, 1952). Original book date from 1904.
3) M. V. R. K. Murty: Bull. Opt. Soc. India, **1** (1967) 29.
4) E. J. Tew: Appl. Opt., **5** (1966) 695.
5) J. D. Briers: Opt. Laser Technol., **4** (1972) 28.
6) D. Malacara, A. Cornejo and M. V. R. K. Murty: Appl. Opt., **14** (1975) 1065.
7) H. J. Caulfield and W. Friday: Appl. Opt., **20** (1981) 1497.
8) A. Cornejo-Rodriguez, H. J. Caulfield and W. Friday: Appl. Opt., **20** (1981) 4148.
9) I. I. Dukhopel, N. V. Konstantionovskaya and L. G. Fedina: Sov. J. Opt. Technol., **42** (1975) 416.
10) V. Ronchi: Ann. Sc. Norm. Super. Pisa, **15** (1923)
11) M. L. Lenouvel: Rev. Opt., **3** (1924) 211 and 315.
12) F. Jentzch: Phys. Z., **24** (1928) 66.
13) G. Schulz: Annal. Phys., **35** (1928) 189.
14) J. A. Anderson and R. W. Porter: Astrophys. J., **70** (1929) 175.
15) I. Adachi: Atti. Fond. Giorgio Ronchi Contrib. Ist.

Naz. Ottica, **17** (1962) 252.
16) A. Cornejo-Rodriguez: *Optical Shop Testing*, ed. D. Malacara (John Wiley Inters., New York, 1978) Chap. 9, p. 283.
17) G. Vogl: Appl. Opt., **3** (1964) 1089.
18) V. Ronchi: Appl. Opt., **4** (1965) 1041.
19) G. Toraldo di Francia: Atti Fond. Giorgio Ronchi Contrib. Ist. Naz. Ottica, **1** (1946) 122; **2** (1947) 25.
20) D. Malacara and A. Cornejo: Opt. Spectra, **8** (1974) 54.
21) D. Malacara: Bol. Obs. Tonantzintla Tacubaya, **4** (1965) 73.
22) F. Twyman: Philos. Mag., Ser. 6, **35** (1918) 49.
23) H. Fizeau: Ann. Chim. Phys. (3), **66** (1862) 429.
24) W. J. Smith: *Modern Optical Engineering* (McGraw Hill Book Co., New York, 1966) p. 292.
25) D. Nyssonen and J. M. Jerke: Appl. Opt., **12** (1973) 2061.
26) J. L. Rayces: Opt. Acta, **11** (1964) 85.
27) M. Di Jorio: Ottica, **4** (1939) 31.
28) G. Toraldo di Francia: *Optical Image Evaluation*, Natl. Bur. Stand. (U. S.) Circ. No. 526 (U. S. Gov. Printing Office, Washington, D. C., 1954) Chap. 11, p. 61.
29) J. Adachi: Atti. Fond. Giorgio Ronchi Contrib. Ist. Naz. Ottica, **18** (1963) 344.
30) R. Barakat: J. Opt. Soc. Am., **59** (1969) 1432.
31) T. L. Williams: Soc. Photo-Opt. Instrum. Eng., Bellingham, Va. (1977).
32) O. G. Karlin, L. Y. Lipovetskiy and V. A. Syutkin: Sov. J. Opt. Technol., **39** (1972) 220.
33) C. R. Burch: Mon. Not. R. Astron. Soc., **96** (1936) 438.
34) F. E. Ross: Astrophys. J., **98** (1943) 341.
35) H. E. Dall: J. Br. Astron. Assoc., **57** (1947) 201.
36) A. Offner: Appl. Opt., **2** (1963) 153.
37) A. Offner: *Optical Shop Testing*, ed. D. Malacara (John Wiley Inters. Co., New York, 1978) p. 439.
38) W. Van Deelen and P. Nisenson: Appl. Opt., **8** (1969) 951.
39) J. C. Wyant: Appl. Opt., **10** (1971) 2113.
40) N. P. Lurionov, A. V. Lukin and K. S. Mustafin: Sov. J. Opt. Technol., **39** (1972) 154.
41) A. J. MacGovern and J. C. Wyant: Appl. Opt., **10** (1971) 619.
42) J. C. Wyant and V. P. Bennett: Appl. Opt., **11** (1972) 2833.
43) A. F. Fercher and M. Kriese: Optik, **35** (1972) 168.
44) Y. Ichioka and A. W. Lohmann: Appl. Opt., **11** (1972) 2597.
45) T. Takahashi, K. Konno and M. Kawai: *Proceedings of the ICO Conference on Optical Methods in Scientific and Industrial Measurements, Tokyo, 1974*, Jpn. J. Appl. Phys., **14**, Suppl. 7 (1975) 247.
46) M. Faulde, A. F. Fercher, R. Torge and R. N. Wilson: Opt. Commun., **7** (1973) 363.
47) J. G. Dil, P. F. Greve and W. Mesman: Appl. Opt., **7** (1978) 553.
48) F. Twyman: *Prisms and Lens Making* (Hilger and Watts, London, 1957).
49) C. Devê: *Optical Workshop Principles*, translated by T. L. Tippell from the French language (Hilger and Watts, London, 1945).
50) D. Malacara: *Optical Shop Testing* (John Wiley Inters., New York, 1978).
51) D. F. Horne: *Optical Production Technology* (Adam Hilger, London, 1972).
52) F. L. O. Wadsworth: Pop. Astron., **10** (1902) 337.
53) R. Platzeck and E. Gaviola: J. Opt. Soc. Am., **29** (1939) 484.
54) A. Cornejo and D. Malacara: Appl. Opt., **17** (1978) 18.
55) R. L. Waland: J. Sci. Instrum., **15** (1938) 339.
56) L. G. Schulz: J. Opt. Soc. Am., **38** (1948) 432.
57) A. A. Sherwood: J. Br. Astron. Assoc., **68** (1958) 180.
58) D. Malacara: Appl. Opt., **4** (1965) 1371.
59) A. A. Sherwood: J. Proc. R. Soc. New South Wales, **43** (1959) 19; reprinted in Atti. Fond. Giorgio Ronchi Contrib. Ist. Naz. Ottica, **15** (1960) 340.
60) E. Lumley: *Amateur Astronomers* (Sydney, 1959); reprinted in Atti. Fond. Giorgio Ronchi Contrib. Ist. Naz. Ottica, **15** (1960) 457.
61) A. S. De Vany: J. Opt. Soc. Am., **64** (1974) 558.
62) A. Cornejo and D. Malacara: Appl. Opt., **9** (1970) 1897.
63) M. V. R. K. Murty and A. Cornejo: Appl. Opt., **12** (1973) 2230.
64) A. Cornejo, H. Altamirano and M. V. R. K. Murty: Bol. Inst. Tonantzintla, **2** (1978) 313.
65) R. H. Katyl: Appl. Opt., **11** (1972) 2278.
66) J. Pastor: Appl. Opt., **8** (1969) 525.
67) G. M. Popov: Izv. Krym. Astrofiz. Obs., **45** (1972) 188.
68) D. Malacara and A. Cornejo: XVI National Meeting of the Sociedad Mexicana de Física, U. Benito Juárez de Oaxaca, Oaxaca, México, November 1973.
69) D. Malacara and A. Cornejo: Appl. Opt., **13** (1974) 1778.
70) E. Mobsby: Astron.: J. Wessex Astron. Soc., **1** (1973) 13.
71) P. B. Felgett and A. E. Gee: Appl. Opt., **14** (1975) 279.
72) D. Malacara and A. Cornejo: Appl. Opt., **14** (1975) 279.
73) D. Malacara and A. Cornejo: Bol. Inst. Tonantzintla, **2** (1976) 91.
74) G. W. Hopkins and R. N. Shagam: Appl. Opt., **16** (1977) 2602.
75) D. Malacara and A. Cornejo: Appl. Opt., **15** (1976) 2220.
76) D. Malacara and M. Josse: Appl. Opt., **17** (1978) 17.
77) A. W. Lohmann and D. E. Silva: Opt. Commun., **2** (1971) 413.
78) S. Yokoseki and T. Susuki: Appl. Opt., **10** (1971) 1575.
79) D. E. Silva: Appl. Opt., **11** (1972) 2612.
80) S. Yokoseki and K. Ohnishi: Appl. Opt., **14** (1975) 623.
81) J. Burch: *Progress in Optics*, Vol. 2, ed. E. Wolf (North Holland Pub., Amsterdam, 1963) p. 75.
82) J. Schwider: Appl. Opt., **20** (1981) 2635.
83) D. Malacara and A. Cornejo: Bol. Inst. Tonantzintla, **1** (1974) 193.
84) J. C. Wyant: Appl. Opt., **12** (1973) 2057.
85) P. Hariharan, W. H. Steel and J. C. Wyant: J. Opt. Commun., **11** (1974) 317.
86) D. A. Thomas and J. C. Wyant: Opt. Eng., **15** (1976) 477.
87) D. Nyssonen and J. M. Jerke: Opt. Eng., **12** (1973) 106.
88) M. P. Rimmer: Appl. Opt., **13** (1974) 623.
89) D. Malacara and A. Cornejo: Bol. Inst. Tonantzintla, **2** (1975) 277.
90) A. Cornejo and D. Malacara: Bol. Inst. Tonantzintla, **2** (1976) 127.
91) J. Tsujiuchi: personal communication (1982).

[コルネホ-ロドリゲス氏のプロフィル]

A. A. コルネホ-ロドリゲス氏（メキシコ）は，国立メキシコ大学物理学科卒業後，米国ロチェスター大学光学研究所で修士課程を終え，メキシコ国立天文・光学・電子工学研究所の研究者として，光学機械，とくに天体望遠鏡の主鏡・副鏡等の製作・検査に関する研究を担当している．氏は1981年9月より1982年3月まで東京工業大学工学部の客員研究員として像情報工学研究施設に在籍し，その期間に日本の主な光学関連の大学，研究所，会社等も訪問したのでご記憶の方も多いと思う．その折に執筆を依頼しておいたのが本解説論文である．

氏はロンキー格子による光学曲面検査の研究を長年手がけており，それに関する論文も多い．また単行本 *Optical Shop Testing*, ed. D. Malacara (John Wiley and Sons, 1978) の「Ronchi Test」の章も担当している．本解説論文はページ数の都合で少し記述が飛躍している箇所もあるが，それらの部分については上述の本および本論文の最後に挙げてある参考文献をご覧いただきたい．　（東京工業大学　本田捷夫）