THE USE OF ASTROMETRIC INSTRUMENTS IN VACUUM CHAMBERS

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ABSTRACT

This paper discusses the effect of using a vacuum chamber with a horizontal entrance window to eliminate astronomical refraction, dispersion and irregular refraction in a telescope tube. Some engineering problems arising in connection with the entrance window are dealt with. The actual results obtained by vacuum photoelectric astrolabes and a vacuum photographic zenith tube are presented.

1. VACUUM CHAMBER EFFECT

1.1 Introduction

Astronomical atmospheric refraction has been applied as a correction to precisely measured zenith distances since the 17th century. As a rule, the atmospheric pressure and temperature at the position of the observer must be determined at the instant when the zenith distance is being measured in order to compute the appropriate theoretical refraction value. In the past several years, we have, however, successfully eliminated astronomical refraction in astrometric instruments with the aid of a vacuum chamber.

1.2 Refraction in the atmosphere described by the plane parallel layer model.

If the Earth's atmosphere is modelled by plane parallel layers, the atmospheric refraction ($\rho = Z_0 - z$, see Fig. 1) can be developed in the form (Mahan, 1962)

$$\rho = (\mu - 1)\tan Z + \frac{(\mu - 1)^2}{2}\tan^3 Z + \frac{(\mu - 1)^3}{2}\tan^5 Z + \quad , \qquad (1)$$

where μ is the index of refraction of the air layer at the position of the observer and Z the apparent zenith distance. Eq. (1) shows that ρ depends only on Z and μ, and not on the indices of refraction anywhere else in the atmosphere. This result

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is valid for any refractive medium (e.g., glass) with plane parallel equidensity surfaces.

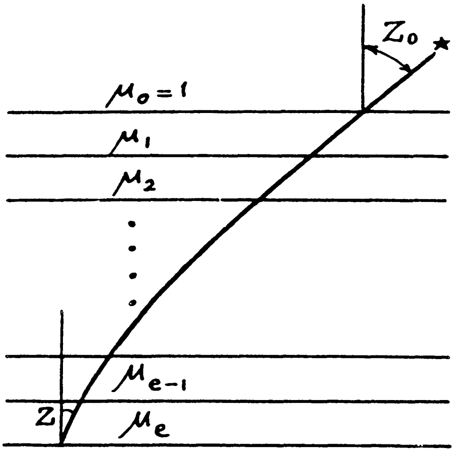

Fig. 1

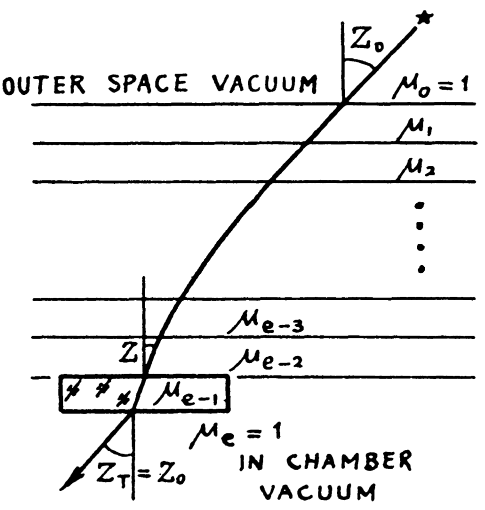

Fig. 2

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For standard atmospheric conditions (760 mm Hg, 0°C), $\mu_e = 1.0002927$, whence $\rho = 60'' \tan Z$.

The coefficients of all terms in Eq. (1) become zero, thus leading to $\rho = 0$, if the ray passing through the horizontal plane parallel glass entrance window enters a vacuum chamber (see Fig. 2), where the index of refraction equals unity. This means that a ray is refracted by an amount $-\rho$ when it enters the vacuum from the last air layer whose refractive index is μ which exactly counteracts the refraction caused by the entire atmosphere above the instrument.

Refraction will thus be largely eliminated if the observations are made in a vacuum which is sealed against the atmosphere by a horizontal layer, such as a plane parallel glass plate.

1.3 Atmospheric refraction produced by a concentric spherical shell model.

The radii of the atmospheric shells are a little larger than the Earth's radius (6357km). Since the effective height of the refracting atmosphere is less than 80km, the difference in atmospheric behavior between these two models should not be appreciable for observations at small or medium zenith distances. As a result, the refraction effects produced by these two models would differ only slightly for zenith distances less than 50°, say. It is noted that the theoretical small difference between the refraction values obtained from these two models can be regarded as the difference between the vacuum chamber refraction and the refraction produced by the concentric spherical shell model.

Woollard and Clemence (1966) give the following expression for the concentric spherical shell model refraction:

$$\rho = (\mu - 1)(1-k)\tan Z - (\mu - 1)(k - \frac{\mu-1}{2})\tan^3 Z, \qquad (2)$$

with $k = SP/r\delta$ where P is the atmospheric pressure in mm Hg at the observer's location, r the Earth's radius; S and δ are the densities of mercury and the air layer at the position of the observer, respectively.

Comparing Eqs. (1) and (2) and disregarding higher order powers of the tangent, we get

$$v = -k(\mu-1)(\tan Z + \tan^3 Z),$$

or, under the standard air conditions,

$$v = -0\overset{''}{.}076(\tan Z + \tan^3 Z). \qquad (3)$$

v, although small, should in principle be added to the zenith distance measured in a vacuum chamber to obtain the "real" i.e., apparent zenith distance. For example, v is $-0\overset{''}{.}058$, only 0.2% of 34" which is the corresponding atmospheric refraction at Z=30°.

2. THE ADVANTAGES OF A VACUUM CHAMBER

2.1 Astronomical refraction no longer needs to be corrected for.

Obviously, errors in computing the value of refraction caused by the inaccurate measurements of air pressure and temperature, and by neglecting the effect of water vapor pressure can be avoided. Note that a measuring error of 0.5°C temperature causes an error of $0\overset{''}{.}062$ in the computed value of the refraction at 30° zenith distance. Using sensitive electric thermometers we found that the air temperature fluctuates near the telescope objective often by 0.5°C or more during only a fraction of a minute. Such rapid fluctuations cannot be sensed by ordinary mercury thermometers with large thermal inertia. A difference of 20 mm Hg between water vapor pressures for summer and winter causes a refraction variation of 0".13 at 30° zenith distance, and if such an error is not corrected, systematic errors will be introduced into the reduced measurements.

2.2 **The effects of atmospheric dispersion are nearly eliminated.**

The difference between the effective wavelengths of an M5 star and a B5 star is 188 Å for a visual Danjon astrolabe. Thus the corresponding zenith distance difference caused by atmospheric dispersion, i.e., the so-called spectral type correction, amounts to 0".054 at 30° zenith distance. For the Chinese photoelectric astrolabes (type I and II; Construction Group 1973, and Astrolabe Division 1976), which use S-20 photocathodes, the difference between the effective wavelengths of an M5 star and a B5 star reaches 912 Å, causing a spectral type correction of 0".215 at Z=30° if no vacuum chamber is used. The theoretical value above agreed well with that obtained from observations.

Ideally, the vacuum chamber also reduces atmospheric dispersion to a negligible amount. Practically. however, because of the unavoidable flaws in the entrance window as well as the deformation of the window under atmospheric pressure and the the temperature gradient in the window the window itself tends to be slightly wedge-shaped (usually less than 3"). This will produce a spectral type correction of about 0".015 for a photoelectric astrolabe for comparing spectral types M5 and B5.

2.3 **Irregular refraction and seeing effects caused by nonuniform air density in the telescope tube can be eliminated.**

Air temperature gradients in the instrument tube will produce bad seeing caused by irregular refraction, which would reach a fraction of an arcsecond in a horizontal tube, because of the appreciable vertical temperature gradient.

The air turbulence caused by uneven temperatures in the tube will degrade the seeing. It has been suggested and even tried to solve this problem by circulating the air or by filling the tube with helium. In this paper, however, we advocate avoiding the problem altogether by using a vacuum chamber.

In addition to eliminating irregular refraction within the instruments and thus the problems caused thereby altogether, the vacuum chamber offers a clean environment for the optical elements, especially for the mercury level.

2.4 **A vacuum chamber will raise the cost of the instrument by an acceptable amount.**

3. ENGINEERING PROBLEMS

3.1 **Window deformation.**

The shape of the entrance window under pressure, especially its thickness, must be controlled in order to prevent harmful deflection of the light rays passing through the slightly deformed window. The deflection W of a plane parallel window plate under uniform atmospheric pressure and the weight of the plate itself, and the slope dW/dr of the deformed surface and the maximum tensile stress σ_{max} in the window etc. can be expressed as (cf. Fig. 3).

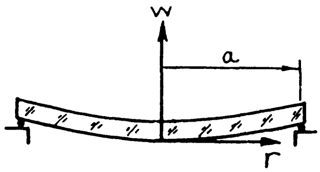

Fig. 3

$$W = \frac{3P(1-S)}{16Ed^3} \; (6+2S)a^2r^2 - (1+s)r^4 \; , \tag{4}$$

$$\frac{dW}{dr} = \frac{3P(1-S)}{4Ed^3} \; (3+S)a^2r - (1+S)r^3 \; , \tag{5}$$

$$W_{max} = \frac{3(5+S)(1-S)}{16} \frac{Pa^4}{Ed^3} \; , \tag{6}$$

$$\frac{dW}{dr}_{max} = \frac{3(1-S)}{2} \frac{Pa^3}{Ed^3} \; , \tag{7}$$

$$\sigma_{max} = \frac{3(3+S)}{8} \frac{Pa^2}{d^2} \; , \tag{8}$$

where P is the pressure load per unit area, E and S are the Young modulus and the Poisson ratio, respectively, of the plate material; d and a are the thickness and radius, respectively, of the plate, and σ_{max} is the maximum tensile stress at the lower center of the plate surface.

For example, with the parameters having the values: a = 12cm, d = 5cm, P = 1.04kg/cm^2, E = 7.4 x 10^5 kg/cm^2, S = 0.16, we obtained the following results for W, dW/dr etc. for a fused silica entrance window: W_{max} = 1.9 μm, the maximum slope of the deformed surface $(dW/dr)_{max}$ = 0".04, and σ_{max} = 7.1kg/cm^2.

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The deflection W is represented by a fourth order surface. We are interested mainly in its slope dW/dr because such slopes confront oblique incoming rays as weak wedges (see Fig. 4).

As is well known, a light ray will be deflected if it passes through a wedge with angle Θ. The deviation v_2 can be expressed as

$$v_2 = (n \frac{\cos i}{\cos Z} - 1) \quad , \tag{9}$$

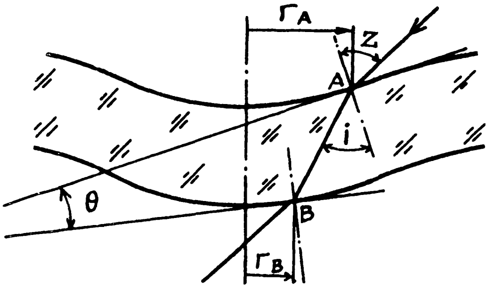

Fig. 4

where n is the refractive index of the window material. It can be seen from (9) that Θ is a function of the zenith distance Z. Fig. 5 shows a plot of dW/dr against r for a window with parameters as in the previous example.

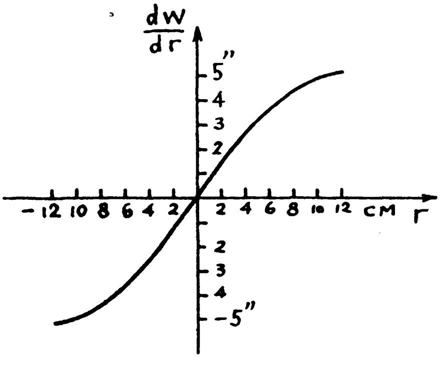

Fig. 5

Assuming that the slanted incoming ray enters the window at position A and leaves at B (Fig. 4), the wedge angle can be readily found as the difference between the two slopes at A and B. Table 1 gives for the window mentioned the deflection v_2 for the rays passing through the central region of the window.

Table 1

Z	10°	20°	30°	40°
v_2	0".19	0".42	0".72	1".54

This will introduce astigmatic aberration to the light rays, because the relation between dW/dr, r and v_2 is nonlinear. Such an aberration, which can be determined by a ray-tracing calculation of necessary, is clearly detrimental to precise astrometry. This harmful effect can be minimized by adopting a rectangular entrance window instead of a circular one, supported only at its two longer edges. All four edges must be air-tight. In this case, the air pressure will deform the window into the shape of a cylinder mantle. Such a cylinder shaped window has lines on its surfaces parallel the cylinder axis, and if the incoming rays lie in planes with respect to the length of the cylindrical window (as shown in Fig. 6), their direction will not be influenced by the deformation of the window.

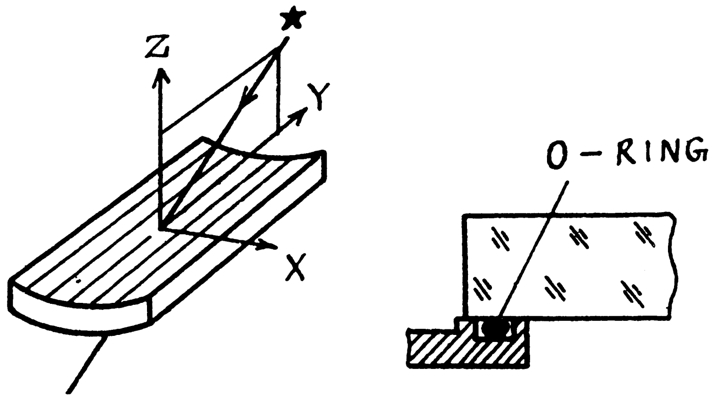

Fig. 6

If the window must be circular, then it is advisable to manufacture the window with a small wedge angle ε and let ε be $-\theta$. The effect of θ could thus be partly counteracted by that of ε.

The stress caused by deformation of the entrance window will introduce birefringence to the oblique rays passing through the window, therefore the stress should not exceed a certain amount, say about 15-30kg/cm^2 depending on the value of the incident angle of the ray.

3.2 **Temperature difference between the inner and the other surface of the window.**

The two surfaces of the entrance window will normally be at different temperatures during observation. The plane parallel window will thus tend to approximate a spherical shell with very large radius of curvature R, and if we ignore the elastic resistance, we may write $R = d/\alpha\Delta t$, where d is the thickness of the window, α the thermal expansion coefficient of the window material, and Δt the temperature difference. Note that such a shell-shaped window will also react with the oblique rays as a wedge, thus introducing V_3 where

$$v_3 = (n \frac{\cos i}{\cos z} - 1)\ \alpha\Delta t\ \tan i \quad . \tag{10}$$

For a fused silica window, for example, for which $\alpha = 5.6 \times 10^{-7}/C°$ and Δt = o.4°C, the deviation v_3 will be 0".01, nearly negligible. But for a glass window, v_3 will reach the larger value 0".13, because α is much larger for glass. Note that v_3 is not a constant but a function of the temperature difference Δt which usually changes during the course of the observations.

A rectangular entrance window probably helps reduce temperature deformation. A thermal or cooling device to reduce the temperature gradients in the window as much as possible is another way for keeping temperature deformation under control.

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3.3 Influence of an intrinsic wedge angle Θ in the window.

In this case, the correction v_4 must be applied, given by

$$v_4 = (n \frac{\cos i}{\cos Z} - 1)\ \Theta\cos\beta \quad , \text{ where} \tag{11}$$

β is the azimuth of the wedge.

3.4 Influence of the inclination of the entrance window.

If the entrance window is inclined by the angle γ (the sign of γ is defined such that γ>0 when the side of the window near the star is tilted lower), the direction of the ray passing through the window must be corrected by v_5 given by

$$v_5 = (\mu_e - 1)\ \gamma\sec^2 Z = \frac{60\overset{''}{.}3}{206265}\ \gamma''\sec^2 Z \quad . \tag{12}$$

Example: For Z = 30° and γ = 10", we see from (12) that v_5 = 0".0039. The influence of v_5 can thus be ignored if the inclination angle γ can be kept below about 20".

3.5 The influence of residual air in the chamber.

As discussed above, the refraction of star light depends only on the index of refraction of the last air layer through which the light ray passes, therefore the residual air pressure P in a chamber will result in a correction v_6. Using the relation between refractive index and air density, v_6 is shown to be

$$v_6 = \frac{1}{760}\ \frac{273}{273+t}\ (60\overset{''}{.}4P_a + 53\overset{''}{.}6P_w)\ \tan Z,$$

where t is temperature in °C; P_a and P_w are the pressures of air and water vapor, respectively (note: in a well sealed chamber, water vapor will be the dominant residual gas). For example, when $P_a + P_w$ = 2mm Hg, t = 0°C and Z = 30°, the corresponding v_6 = 0".09. This shows that v_6 cannot be neglected.

In the case a mercury basin is used in a vacuum chamber, some mercury vapor will be in the chamber. Since the saturation pressure of mercury vapor is lower than 0.003 mm Hg, its influence on refraction is estimated to be in the order of 0".001 and thus negligible.

4. THE PRACTICAL USE OF VACUUM CHAMBER

4.1 The use of the vacuum chamber in three Type II Photoelectric Astrolabes.

The Type II Photoelectric Astrolabe has two entrance pupils, each with a 30 mm thick rectangular entrance window having supporting dimension 200 mm x 80 mm. With the chamber evacuated, the star images seen through an eyepiece (with a total magnification of 120), still appear good. The atmospheric refraction of 34" at Z = 30° has in fact been counteracted by the vacuum chamber refraction. The wedge correction v_4 for the entrance window was found to have been about 1".

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Table 2, complied by Li-zhi Lu and Ding-jiang Luo of the Beijing Astronomical Observatory, compares, for different instruments, the closing error of the difference between groups at zenith distance $S_{\Delta z}$ and the accuracy of a single determination of the difference between consecutive groups $m_{\Delta z}$. These two values represent the systematic and random error, respectively, of the equal altitude circle observations (Lu and Luo, 1979).

Table 2

Instrument	$S_{\Delta\zeta}$	$\mu_{\Delta z}$
GDII No. 1	-0".094	±0".075
GDII No. 2	-0".130	±0".062
OPL No. 14	+1".665	±0".159
OPL No. 30	+1".195	±0".171
GDI	+0".306	±0".148

GDII: Type II Photoelectric Astrolabe (vacuum)
GDI: Type I Photoelectric Astrolabe (air draught)
OPL: Visual Danjon Astrolabe

For comparison, Hui Hu and Tiangui Ma made experimental observations on a Type II astrolabe without vacuum during a two month period in the summer of 1982 at the Yunnan Observatory in Southwest China, and compared them with series of vacuum observations. The results are: the precision for zenith distance observation of a single star with the chamber evacuated corresponds to a standard error of 0".163 as compared to 0".200 for the unevacuated chamber. The accuracies for the time observations corresponds to a standard error of 4.5 ms for evacuated chambers and 6.8 ms for the non-evacuated one. Note that the observations with nonevacuated chambers were carried out during the best observational months of the year and that corrections for astronomical refraction, spectral type and star position were all appropriately applied in the course of the reductions.

The mean spectral type corrections observed for the three evacuated Type II Photoelectric Astrolabes are negligibly small and listed as follows (Working Group of GCPA 1983):

Table 3

Spectral type	O	B	A	F	G	K	M	N
Residual correction (0".001)	1.0	1.0	-0.7	-1.4	-1.3	-0.3	1.5	1.5

Our tests show that the chamber can retain its vacuum for several months. Without effective measures to keep the chamber dry, the water vapor pressure will, however, build up during this period to about 3 mm Hg.

We found small dust-like globules of condensed mercury on the optical surface near the mercury basin. Their diameters were about 0.1 - 0.3 mm and in some cases they had accumulated rather densely. This condensation can be explained by the daily temperature fluctuation, somewhat like the condensation of dew during the night. It can be expected that larger temperature fluctuations will therefore cause more serious mercury condensation.

4.2 **Use of the vacuum chamber in a photographic zenith tube.**

The whole PZT at Tientsin Latitude Station is placed inside a vacuum chamber with a top entrance window 45 mm thick and a clear diameter of 290 mm (NAIF 1977). The total atmospheric pressure on the window is some 700 kg, under which the center sags by 5.5 μ m. Table 4 shows the diameters of star images on a PZT plate taken in vacuum.

Table 4

Star magnitude m	9	8.5	8	7.5	7	6.5	6
Image diameter μ	75	85	100	110	125	138	150

The wedge angle of the entrance window will introduce correction terms D_L and D_u to the observed latitude and time. Therefore the azimuth angle of the entrance window was changed by 180° every day or so in order to find the corrections D_L and D_u from the two groups of observing results which differ by $2D_L$ and $2D_u$. From more than a year's observation we found that D_L has a linear relationship with temperature and therefore D_L and D_u appear to have an annual variation. Hongqin Ji of Tientsin Latitude Station found

$$D_L = 0''.543 - 0''.0118\,(t-0^\circ C);$$
$$D_\mu = 0^s.000128\,(t-0^\circ C), \qquad (14)$$

where t is the temperature recorded during observation. From (14) one can see that D_L will vary by as much as 0".41 when the annual temperature variation amplitude reaches 35°C.

The dependence of D_L and D_u on temperature was not anticipated when the instrument was designed. We thought that the wedge angle of the window would not change its value even though the geometrical dimension of the entrance window will change linearly with temperature. The change of D_L and D_u

therefore still awaits explanation. A possible reason is that different parts of the window have different expansion coefficients.

The results obtained by the vacuum PZT observations prove to be quite precise. For instance, from 1979.2 to 1980.5 (PZT Section 1982), the internal precision of α single observation corresponded to a standard error of m_u=2.7 ms and m_ϕ=0".139; the standard error of the daily mean values of the time observations M_u=5.5 ms and that of the annual fluctuation of the semi-monthly mean values is E_u = 2.8 ms; the standard errors of the month by averages of the latitude observation with respect to smoothed values is M=0".026. The standard error of the smoothed values of the variable latitude is M=±0".008 (the Z terms with respect to the BIH to be deducted).

The pressure in the evacuated container during operation is about 15 mm Hg. The various electric components with voltages lower than about 300 V can function normally under this pressure, only the photomultiplier requires special treatment to prevent high voltage discharges of electricity between the socket pins of the multiplier from destroying it. The ions in the space outside the multiplier near the cathode also tend to increase the background noise multiplier output.

In addition, low volatility lubricants, suitable for the vacuum should be used.

The use of vacuum chambers in astrometry goes back to the 1970s, when vacuum meridian marks were used in a large transit instrument at the Belgrade Astronomical Observatory (Pakvor 1977). Our own experiences were derived from operating the entire astrometric instruments in vacuum chambers.

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Discussion:

DEBARBAT: You have quoted 0".0045 as the error for one group for the vacuum astrolabe. If I remember correctly, in the sixties Guinot obtained for the OPL astrolabe (Danjon type) the figure 0".0063 for one group. Does Guinot remember if I am right?

HU: Guinot says that this was the internal error and that the external one is larger.

DEBARBAT: Does the figure 0".0045 as given by the author refer to an internal or external error?

HU: 0".0045 is the external error (as it appeared in the paper).