Postprint: The Effect of Atmospheric Refraction on High-Precision Pointing of Radio Telescopes

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Abstract

Model analysis and calculations were conducted on the physical properties of the neutral atmosphere and the effects of atmospheric refraction on radio telescope pointing, based on an improved "three-segment" standard pointing correction model, with emphasis on investigating correction schemes for high-order pointing errors caused by atmospheric refraction, aiming to continuously improve the pointing accuracy of radio telescopes, particularly for large-aperture, high-resolution radio telescopes. Based on this model, the climate characteristics of the Nanshan Observatory site were simulated to provide reasonable calculation results. By analyzing and evaluating these results against radio telescope pointing accuracy requirements, this study provides a reference for future pointing corrections of large-aperture radio telescopes.

Full Text

Effects of Atmospheric Refraction on High-Precision Pointing of Radio Telescopes

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Abstract

This paper analyzes and calculates the physical properties of the neutral atmosphere and the effects of atmospheric refraction on radio telescope pointing. Based on an improved "three-segment" standard pointing correction model, we focus on correction schemes for high-order pointing errors caused by atmospheric refraction, aiming to continuously improve the pointing accuracy of radio telescopes, particularly for large-aperture, high-resolution instruments. Using this model, we simulate the climatic characteristics of the Nanshan observing site and present reasonable calculation results. By analyzing and evaluating these results against the pointing accuracy requirements of radio telescopes, we provide a reference for future pointing corrections of large-aperture radio telescopes.

Keywords: Atmospheric refraction; Radio telescope; Pointing error; Pointing correction

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1. Physical Properties of the Neutral Atmosphere and Mechanism of Atmospheric Refraction

The Earth is surrounded by a layer of neutral atmosphere. In mid-latitude regions, this extends from sea level to an altitude of approximately 15-20 km, and is traditionally divided into several layers based on different physical properties: the troposphere (0-15 km), the stratosphere (15-80 km), the mesosphere (80-320 km), and the thermosphere/ionosphere (320-600 km). In the radio band, the primary source of pointing errors due to atmospheric refraction is the first layer—the troposphere. Due to vibrational effects between atoms in the neutral molecular structure, two macroscopic effects occur: atmospheric absorption and atmospheric refraction. Assuming a plane electromagnetic wave propagating along the positive y-axis has the mathematical expression $E = E_0 e^{i(kny-\omega t)}$, the refractive index n has a complex form $n = n' + in''$, where the imaginary part corresponds to atmospheric absorption and the real part corresponds to atmospheric refraction. The main factors determining atmospheric refractive index in the radio band are water vapor and oxygen components. The oxygen component has a refractive frequency of approximately 60 GHz, contributing to refraction below this frequency range but not above it. The water vapor component has a refractive frequency in the near-infrared range, contributing to refraction below infrared frequencies. Since both water vapor and oxygen primarily exist in the Earth’ s troposphere, atmospheric refraction effects are concentrated in this region.

2. Atmospheric Refraction Correction Models

The refraction effect is related to the effective atmospheric thickness along the telescope’ s line of sight at different elevation angles. The improved “three-segment” standard pointing correction model is generally adopted, which calculates the pointing deviation caused by atmospheric refraction for radio telescopes operating at different elevation angles, then fits these values into the telescope’ s servo control system through software programming.

The precise calculation formula for the field strength distribution of a radio telescope’ s radiation pattern is given by:

$$E(\theta,\phi)=\frac{1+\cos\theta}{2}\cdot\frac{e^{-jkR}}{R}\int_0^{2\pi}\int_0^{D/2}E_a(\rho',\phi')e^{jk\rho'\sin\theta\cos(\phi-\phi')}\rho'd\rho'd\phi'$$

where D represents the telescope aperture, θ represents the offset angle of any point in the radiation pattern relative to the polar axis direction, k represents the electromagnetic wave number, and J_1 is the first-order Bessel function. Since the variable ϕ has an axisymmetric relationship with the polar axis direction of the pattern, and considering only the distribution properties of the radiation pattern, the equation can be written as:

$$E(\theta)=\frac{1+\cos\theta}{2}\cdot\frac{e^{-jkR}}{R}\int_0^{D/2}E_a(\rho')J_0(k\rho'\sin\theta)\rho'd\rho'$$

The pointing accuracy of a radio telescope is generally defined as the offset angle size when the received power drops to half of the maximum received power. The approximate formula for calculating pointing accuracy within this range is:

$$\theta_{HPBW}\approx 1.02\frac{\lambda}{D}$$

Assuming a radio telescope operating frequency of 30 GHz and aperture $D=110$ m, the pointing accuracy requirement would be 2.0 arcseconds. If the pointing accuracy requirement is improved to 1.0 arcseconds, then the calculation of atmospheric refraction angles becomes critically important.

For an approximate plane-parallel atmosphere, the calculation of refraction angle becomes relatively simple:

$$R=(n-1)\tan z$$

where z represents the telescope's zenith distance and R represents the refraction angle (in radians). This is an approximate formula.

For zenith distances in the range $[90°, 25°]$, the Earth' s atmospheric curvature effects must be considered to obtain results consistent with actual conditions. The complete spherical atmospheric refraction angle formula is:

$$R=\int_{r_0}^{\infty}\frac{rn(r)\sin z}{\sqrt{r^2n^2(r)-r_0^2\sin^2 z}}\cdot\frac{dn}{dr}dr$$

where r_0 represents the distance from Earth' s center to the surface, r represents the distance from Earth' s center to a certain height in the atmosphere, and $n(r)$ represents the atmospheric refractive index at distance r. Direct solution of this nonlinear integral formula is inconvenient, so the integration formula must be simplified through segmentation.

For zenith distances in the range $[25°, 10°]$, the formula can be simplified to:

$$R \approx (n_0 - 1) \tan z + \Delta R$$

where ΔR represents the residual correction value for the refraction angle due to different geographic locations and altitudes of the observing station, and n_0 represents the atmospheric refractive index at the Earth' s surface.

The effective thickness of the atmosphere in the vertical direction can be divided into dry and wet conditions. The effective thickness under standard atmospheric conditions is approximately $h_0|_{\mathrm{dry}} \approx 8000$ m for dry conditions and $h_0|_{\mathrm{wet}} \approx 2000$ m for wet conditions. provides reference values for residual corrections of atmospheric refraction angles at different altitudes under standard atmospheric conditions.

When telescopes operate near the limit range $[10°, 5°]$, atmospheric refraction effects become more complex. Referencing the correction algorithm used by the Green Bank Telescope (GBT), the refraction angle calculated by the plane-parallel formula is multiplied by a factor $[1+0.0012(35.8-\theta)]$, where θ represents the elevation angle. The difference between this fast algorithm and precise iterative algorithms can be controlled within 1.5 arcseconds.

To obtain atmospheric refraction angles using the above models, a local atmospheric refraction model must be established. The refractive index is related to ambient environmental properties and can be calculated using the atmospheric refractive index formula:

$$N = 77.6890 \frac{p_d}{T} + 71.2952 \frac{e}{T} + 3.75463 \times 10^5 \frac{e}{T^2}$$

where T represents the local temperature (in K), p_d represents the pressure value for dry atmospheric conditions (in hPa), and e represents the partial pressure of water vapor in the atmosphere (in hPa).

Meteorological parameters measured by weather instruments are temperature, pressure, and relative humidity. Absolute humidity refers to the mass of water vapor per unit volume of moist air (water vapor density), which is not easily measured directly. Therefore, relative humidity is more commonly used in practice. Relative humidity is the percentage ratio of actual water vapor pressure to saturation water vapor pressure at the same temperature, indicating how close the air is to saturation. The saturation vapor pressure can be obtained using the Magnus empirical formula:

$$E = E_0 \times 10^{\frac{at}{b+t}}$$

where E represents the saturation vapor pressure at a certain temperature, t represents the temperature in Celsius, and under standard horizontal conditions, $a = 7.5$, $b = 237.3$, and $E_0 = 6.11$ hPa. compares different correction models for zenith distances from 0° to 85° under standard pressure conditions ($p_d = 1013$ hPa, $T = 273$ K) and relative humidity of 20% ($e = 1.22$ hPa).

3. Summary of Calculation Results

The calculation of atmospheric refraction angles is divided into three ranges based on elevation angle: $[90°, 25°]$, $[25°, 10°]$, and $[10°, 5°]$, constituting the so-called improved "three-segment" radio telescope pointing correction model. For the range $[90°, 25°]$, the calculation results from the plane-parallel formula differ from the exact values by less than 1.2 arcseconds. For the range $[25°, 10°]$, the calculation results from the simplified spherical formula differ from the exact values by less than 3.0 arcseconds. For the range $[10°, 5°]$, the refraction angle is obtained by multiplying the simplified formula by the factor $[1+0.0012(35.8-\theta)]$. As the observed zenith distance increases, the deviation values show an increasing trend. [Figure 1: see original paper] shows the residual errors between the three-segment correction model and the values listed in the *Nautical Almanac* under standard pressure conditions ($p_d = 1013.25$ hPa, $T = 273$ K).

To highlight the influence of different climate conditions on atmospheric refraction angles, we compare two scenarios at the same altitude of 2100 m but with different humidity levels. In a dry environment, the refraction angle is approximately $60.7 \tan z$ arcseconds, while in a humid environment, it is approximately $65.0 \tan z$ arcseconds. Climate conditions at the same site exhibit periodic changes over time. lists atmospheric refraction angle values under different ambient temperature and humidity conditions, emphasizing significant differences between high and low temperature conditions. Lower elevation angles correspond to larger atmospheric refraction angles, with values differing by an order of magnitude. The comparison shows that humid atmospheric environments cause more pronounced pointing deviations for radio telescopes.

4. High-Order Correction Methods for Time-Varying Atmospheric Factors

Time-varying atmospheric factors affecting telescope pointing accuracy can be divided into two categories: large-scale spatial variations and small-scale spatial variations. Large-scale time-varying environmental factors include temperature gradient distributions, particularly horizontal asymmetries in temperature distribution. Such asymmetries result from several combined factors: oceanic climate changes, evaporative cooling from large lakes, plant transpiration, and asymmetric solar heating between morning and evening. For example, the Nanshan observing station is located 60 km south of Urumqi City on the Tianshan Mountains at 2100 m altitude, with urban residential areas to the north and snow-covered Tianshan mountains to the south. This geographic environment creates a north-south asymmetry in temperature gradient distribution.

The pointing deviation caused by such temperature gradient asymmetry can be expressed as:

$$\Delta\theta \approx 0.21 \cdot h \cdot \frac{dT}{dx} \cdot \left(\frac{1}{h_0|_{\text{dry}}} - \frac{1}{h_0|_{\text{wet}}} \right)$$

where h represents the altitude of the radio telescope (in km) and dT/dx represents the horizontal temperature gradient (in °C/km). Assuming a north-south temperature gradient of -0.16 °C/km and a telescope operating elevation of 10°, the pointing deviation is approximately 0.06 arcseconds in dry conditions and 6.0 arcseconds in wet conditions. Thus, this effect can be neglected in dry environments but must be considered in humid environments.

Small-scale atmospheric inhomogeneity represents another significant effect. Non-uniform atmospheric clouds are a common phenomenon. Cloud regions with high water vapor density produce noticeable refraction effects on radio wave propagation. When such clouds pass through the main lobe region of a radio telescope' s antenna power pattern, they cause pointing deviations. Since cloud density and scale vary with wind and other factors, real-time corrections are necessary for this type of pointing deviation. Assuming a cloud region with apparent thickness of 100 m and refractive index gradient span of 0.005, for a radio telescope with aperture D, the optical path difference in the telescope' s field direction is approximately 0.5 mm. The resulting pointing deviation at the aperture edge relative to the center is about 12.0 arcseconds for a 25 m telescope and 2.7 arcseconds for a 110 m telescope. This magnitude is comparable to telescope pointing accuracy requirements and has been detected by high-resolution submillimeter radio telescope arrays worldwide.

5. Effects of Atmospheric Refraction on Telescope Aperture Efficiency

In addition to causing pointing deviations, Earth's atmosphere—particularly the troposphere—affects telescope aperture efficiency. The so-called aperture scale effect refers to the difference between the refraction angle of the atmosphere relative to the aperture center and that relative to the aperture edge. This effect cannot be neglected for large-aperture radio telescopes at low elevation angles, as it causes defocusing that reduces aperture efficiency. For a 110 m radio telescope at 10° elevation, the aperture scale effect is approximately 7.8 arcseconds. compares the defocusing deviation at the aperture edge caused by different aperture scale effects for various radio telescope sizes. This defocusing deviation can be corrected by adjusting active surface nodes.

6. Conclusion

The three-segment pointing correction model is a high-precision algorithm. Generally, short-term time-varying characteristics of Earth' s atmosphere need not be considered. However, for large-aperture radio telescopes with more stringent pointing accuracy requirements, certain short-period time-varying atmospheric effects become prominent in actual observations, particularly at high-frequency submillimeter bands, causing non-negligible impacts on astronomical observations and pointing corrections. Addressing these time-varying atmospheric characteristics requires real-time monitoring of climate conditions and pointing corrections near observatories, placing higher demands on supporting climate monitoring equipment and systems.

This paper quantifies pointing deviations under different conditions, which is practically significant for continuously improving radio telescope pointing accuracy. Implementation involves optimizing relevant pointing parameters in telescope control software based on theoretical calculations. Pointing deviations caused by atmospheric refraction are sensitive to ambient humidity. Most ground-based radio telescope sites are not permanently arid, and humid conditions significantly increase pointing deviations. Different pointing correction model parameters must be designed according to local climate variations and fitted into radio telescope control systems.

The various effects causing radio telescope pointing deviations are interrelated, and their treatment methods differ. If a factor causes significant pointing deviation, telescope pointing model parameters must be corrected. If it significantly affects aperture efficiency, active surface nodes must be adjusted to correct the telescope aperture shape.

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Note: Figure translations are in progress. See original paper for figures.

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