

Research on Error Analysis and Correction Technique of Atmospheric Refraction for InSAR Measurement with Distributed Satellites

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Abstract

SAR interferometry with distributed satellites is a technique based on the exploitation of the interference pattern of two SAR images acquired synchronously. The interferogram contains geometric, atmospheric, topographic and land deformation. This paper focuses on atmospheric effects on SAR interferometry, which shows theoretically that the relationship among ionosphere TEC and troposphere parameters such as temperature, relative humidity and pressure with respect to slant range changes. An atmospheric correction method is given in the end.

Keywords

InSAR, Atmospheric Refraction, Troposphere Delay, Ionosphere Delay, Error Correction

1. Introduction

With the development and the maturity of SAR Interferometry technology, its accuracy is increasing largely and it is significant to study the factors which can lower the accuracy of SAR Interferometry technology [1] [2]. SAR interferometry system with distributed satellites is based on the exploitation of the interference pattern of two SAR images acquired synchronously, from which useful information is extracted. Atmospheric refraction is one of the main errors because that the temporal and spatial uncertainty of atmospheric change causes different delay of radar signal [3] [4] [5] [6]. The paper discusses the fundamental theory of electromagnetic wave signal's atmospheric propagation delay and the main model of Troposphere delay correction and Ionosphere delay

correction, establishing the relationship between tropospheric parameters and the distance change. Then the magnitude that Ionosphere and Tropospheric parameters exert influence on the ranging accuracy is analysed. The method to inhibit or eliminate the influence is discussed in the end.

2. Fundamental Theory and Model

2.1. Troposphere Delay

According to the Fermat principle and Snell's law in the basic theory of light propagation, the optical range ρ from satellite to ground point is formed as

$$\rho = \int_{r_0}^{r_1} \frac{n}{\cos \theta} dr \tag{1}$$

where r_0 is the center distance for a ground point (Figure 1), r_1 is the center distance for the top of neutral atmosphere, z is the view zenith distance of Any point at signal propagation path, θ is the view height Angle of Any point at signal propagation path, and n is atmospheric refractivity [7] [8] [9].

Define N for the difference of atmospheric refractive index:

$$N = (n - 1) \times 10^{-6} \tag{2}$$

In a spherically symmetric layered medium, according to Snell law, a formula is given by

$$nr \sin z = n_0 r_0 \sin z_0 = const \tag{3}$$

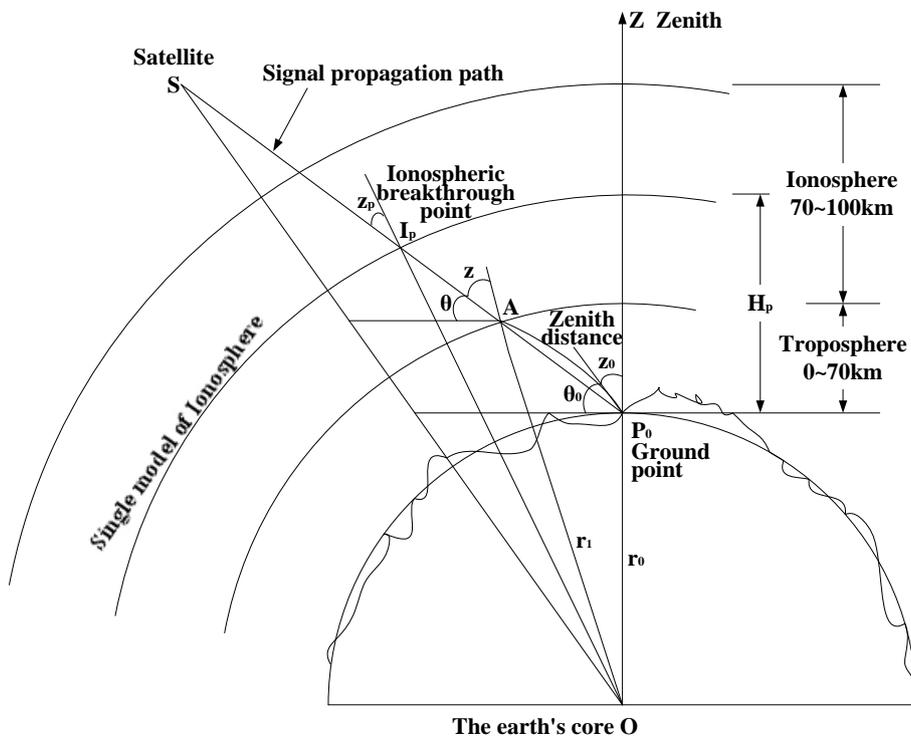


Figure 1. Signal propagation path.

n_0, r_0, z_0 are the corresponding values of ground measuring site. The path delay is given by the product of the tropospheric zenith path delay and the function of satellite-zenith distance z (the so-called mapping function). Only considering the first order effect, mapping function $f(z)$ is approximate to $1/\cos z$.

$$f(z) \approx f_d(z) \approx f_w(z) \approx \frac{1}{\cos z} \tag{4}$$

According to Saastamoinen model (1972) of the atmospheric refraction, the zenith delay of atmospheric refraction can be given by

$$\left. \begin{aligned} f(\Phi, H) &= 1 - 0.0026 \cos 2\Phi - 0.00028H \\ \Delta\rho_d^z &= 0.002277P/f(\Phi, H) \\ \Delta\rho_w^z &= 0.002277e[0.05 + 1255/(273.15 + T)]/f(\Phi, H) \end{aligned} \right\} \tag{5}$$

where $\Delta\rho_d^z$ is the dry air delay of the zenith (dry item), $\Delta\rho_w^z$ is the water vapor delay of the zenith (wet item), P is the surface atmospheric pressure (Pa), H is the atmospheric high (km) of ground point, T is the surface temperature ($^{\circ}\text{C}$), Φ is the geographic latitude of measuring station, E is the vapor pressure (hPa) [10] [11].

According to Magnus' empirical formula, the relationship between vapor pressure and relative humidity at the condition of air temperature T ($^{\circ}\text{C}$) can be expressed as

$$e = \frac{R_h}{100} \times 6.11 \times 10^{\frac{7.5T}{237.3+T}} \tag{6}$$

2.2. Ionosphere Delay

Due to variable insolation of the Sun the spatial distribution of the layers varies during the day. The impact of the state of the ionosphere on the propagation of waves is characterized by the Total Electron Content (E), where

$$E = \int_{P_0}^S n_e d\rho \tag{7}$$

The integral contains the total number of electrons that are included in a column with a cross-sectional area of 1 m^2 , counted along the signal path ρ between the ground point P_0 and the satellite S . The unit of measurement is the TECU (Total Electron Content Unit): $1\text{TECU} = 1 \times 10^{16} \text{ el/m}^2$.

The ionosphere is a dispersive medium for radio waves. For the formula of dispersion (e.g. Davies, 1990) of the index of refraction, rearranging and neglecting higher order terms gives [12] [13] [14]:

$$n_1 = 1 - \frac{an_e}{f^2} \tag{8}$$

where the parameter a is a constant.

According to Equations (7) and (8), the ionosphere delay along the signal propagation path $\Delta\rho^I$ is given by

$$\begin{aligned} \Delta\rho^I &= \int_L (n_1 - 1) d\rho = -\frac{aE}{f^2} \\ a &= 40.3 \times 10^{16} \text{ m} \cdot \text{s}^{-2} \cdot \text{TECU}^{-1} \end{aligned} \tag{9}$$

That is to say, if we can get the E(TEC) along the signal propagation path, we can calculate the propagation delay directly.

3. Analysis of Influence on Ranging Accuracy Exerted by Atmospheric Refraction

3.1. Troposphere Atmospheric Refraction Error

The atmospheric refractive effect of Troposphere is independent of the frequency but is decided by the atmospheric temperature, pressure and humidity. Atmospheric refractive error of Troposphere includes the dry item and the wet item. Refraction error of Tropospheric atmosphere in zenith direction is about 2.0 - 2.7 m, which is computed approximately (**Figure 2**). Among them, the dry item of distance error caused by the refraction is about 2.4 m and the wet item is about 0.05 - 0.05 m.

The inland distribution of distance error caused by Tropospheric atmosphere refraction, which is obtained by using the historical meteorological sounding data of 10 years, is shown in **Figure 3**.

From the above research on the inland distribution of distance error, we can get some conclusions as follow:

- 1) When the elevation of the satellite is above 30° (viewed from the ground), the distance error caused by Tropospheric atmosphere refraction is mostly less than 5.5 m.
- 2) The dry item of refractive error can be estimated accurately from the ground meteorological parameters due to its regular and steady changes. The wet item of refractive error is the main part of the residual error for refractive error correction due to its irregular changing with time and space.
- 3) The proportion changes of distance error caused by the wet item of the refraction vary with month and quadrillage obviously but do not vary with elevation.

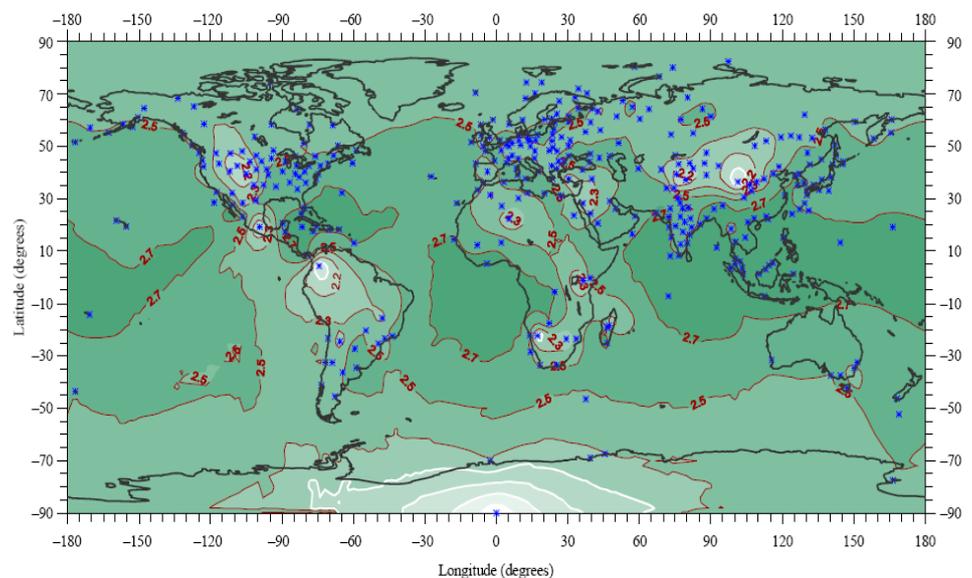


Figure 2. The global distribution of refraction error from ITU-R P.834.

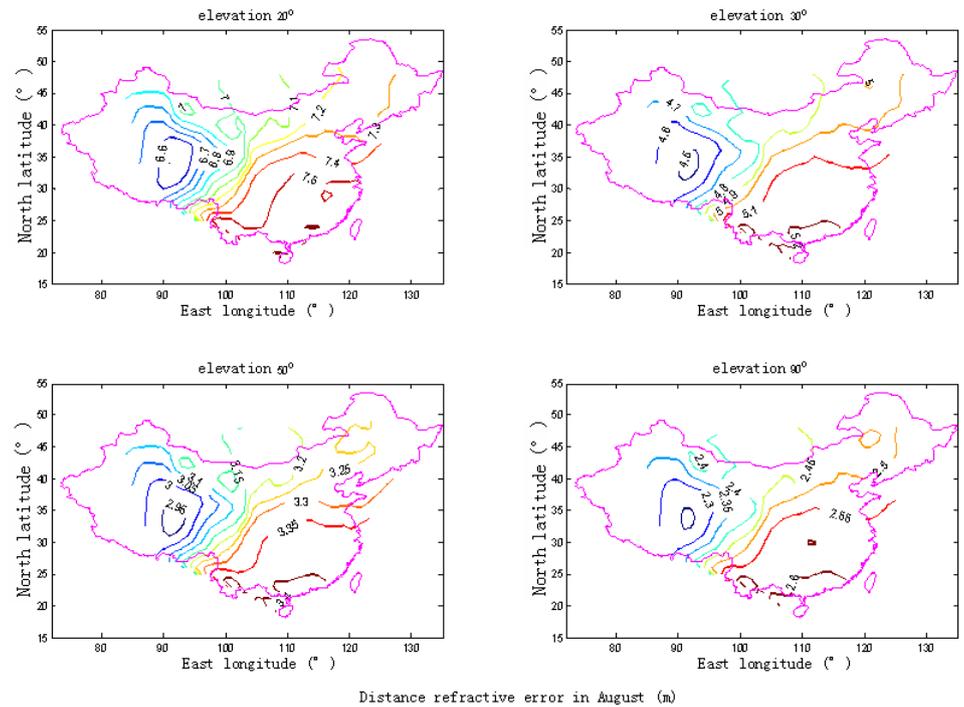


Figure 3. The inland distribution of distance error caused by Tropospheric atmosphere refraction.

3.2. Ionosphere Atmospheric Refraction Error

The refractive error of Ionospheric atmosphere has a close relationship to systemic working frequency, degree of solar activity, etc. To take Haiko as an illustration, the changing of distance error caused by Ionosphere atmospheric refraction with solar activity and working frequency is shown in **Figure 4**, which is achieved by using the reference Ionosphere model.

By the analysis, we can get the following conclusion: when the frequency is in the X band and the elevation of the satellite is above 30° (viewed from the ground), the maximal distance error caused by Ionosphere atmospheric refraction is about 0.5 m, even in high solar activity years.

4. Error Correction Technique for Atmospheric Refraction

Distance errors caused by atmospheric refraction must be corrected to meet the accuracy demand of slant ranging in InSAR system with distributed satellites.

4.1. The Overall Technical Process

The overall technical process of distance error correction for atmospheric refraction is shown in **Figure 5**.

The key technique mainly includes the following three aspects:

- 1) Methods of radio wave refraction correction.
- 2) Researches on profile model of global tropospheric refractive index.

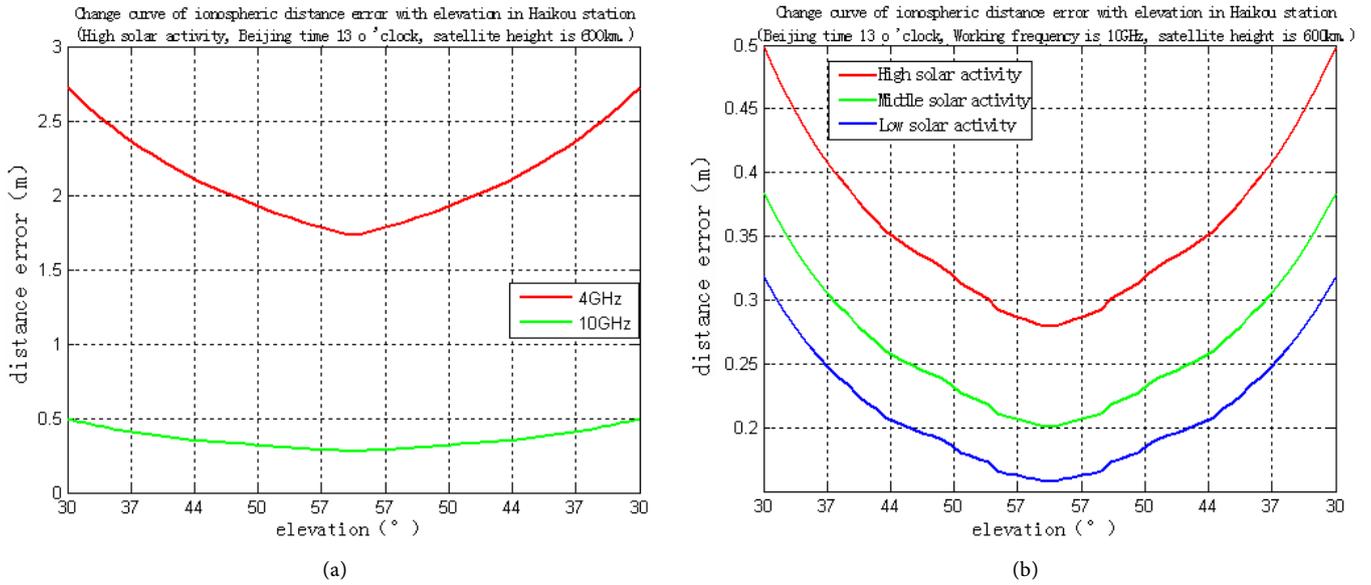


Figure 4. The change trend of the refraction error caused by Ionospheric atmosphere. (a) Change trend with frequency; (b) Change trend with solar activity.

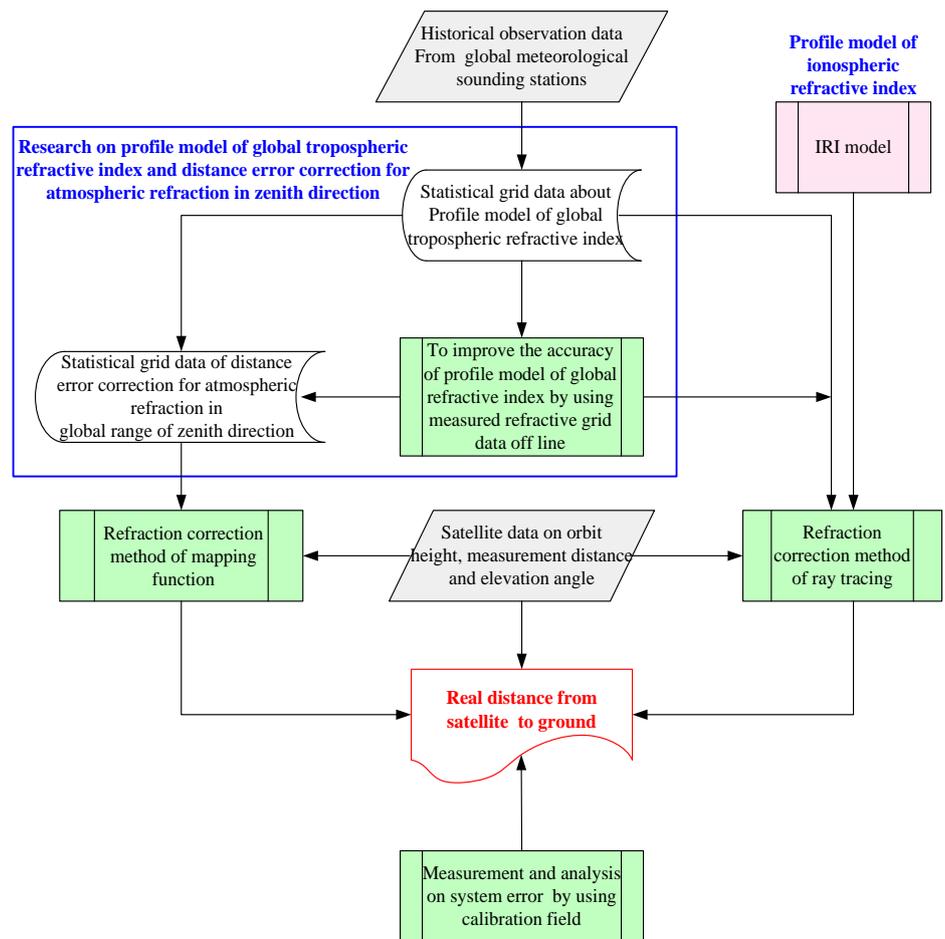


Figure 5. The overall technical process.

3) Methods of system error calibration.

4.2. Realization of Key Technique

1) Refraction correction method of mapping function

In view of the high elevation of the system, we can use the refraction correction method of mapping function under the premise of the accuracy being not affected.

The method adopts a mapping function as the following form.

$$\Delta L = \frac{\Delta L_v}{\sin \theta_0 (1 + k \cot^2 \theta_0)^{1/2}} + \delta(\theta_0, \Delta L_v) \quad (10)$$

where ΔL_v is the distance error of refraction in zenith direction, θ_0 is exterior angle,

$k = 1 - \left(\frac{n_0 r_0}{n(H)r(H)}\right)^2$, and the feature height $H = 10^6 \times \frac{\Delta L_v}{N_0}$.

2) Profile model of global tropospheric refractive index

To achieve the global distance error correction for refraction, it is necessary to establish the profile model of global tropospheric refractive index. Firstly, a global range of refractive index profile model of statistical data is established by using a great deal of historical meteorological sounding data obtained from the global observation stations. Secondly, the statistical model is corrected afterwards to improve the precision of the profile model by using the measured refractive index of global.

3) System error calibration

Microwave radiometer, which has a good real-time performance, can observe automatically and continuously on atmospheric environment in all-weather conditions. And it can directly calculate the radio wave refraction error of the propagation path by measuring the atmospheric radiation brightness temperature of the propagation path. It is shown in the study that the accuracy of refraction correction can reach 2 cm in the elevation of above 100° . Accordingly, the refractive error which calculated from the microwave radiometer measurement data can be considered as the total error caused by the radio environment.

The famous Marcor technique, which measures the additional time-delay integral of atmosphere on the path of radio wave propagation with ground-based microwave radiometer, gives distance error correction directly [15].

Due to the fact that the elevation of the satellite with distributed SAR is more than 30° , ray bending effects can be ignored. Therefore, the distance error caused by atmospheric refraction can be formulated as follow.

$$\begin{aligned} \Delta R &= 10^{-6} \int_0^R N dS \\ &= 10^{-6} \left[\int_0^R N_d dS + \int_0^R N_w dS \right] \\ &= \Delta R_d + \Delta R_w \end{aligned} \quad (11)$$

where N_d is the dry item of atmospheric refractive index, N_w is the wet item of atmospheric refractive index, ΔR_d is the distance refractive error caused by the dry item, and ΔR_w is the distance refractive error caused by the wet item.

5. Summary and Conclusions

Atmospheric refraction is the main one among the errors which influence the accuracy of the InSAR system. Distance errors caused by atmospheric refraction must be corrected to meet the accuracy demand of slant ranging in InSAR system with distributed satellites. Aiming at two satellites, error correction experiments were carried out in 2007 and 2008 by using the error correction method presented in the paper. The experiments have demonstrated that residual error is little and steady after using the distance error correction for atmospheric refraction. It shows that the method discussed in the paper is effective, which can mainly eliminate the distance precision loss caused by Troposphere atmospheric refraction and Ionosphere atmospheric refraction.

Further researches and experiments should be done in future to get a better atmospheric refraction model and a better error correction method.

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