Research on Atmospheric Disturbance Correction method of ground-based radar interferometry

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Abstract. The high-frequency signal is often used as the communication signal of Ground-based radar, which is susceptible to atmospheric effects. An atmospheric disturbance correction of radar signal is required to obtain the monitoring accuracy of better than millimeter in precision deformation monitoring using ground-based radar interferometry. In this paper, we analyzed the experimental-data change of ground-based radar in the atmospheric disturbance statistically and proposed a correction method based on the discrete stable point in the global environment. The following experiment proved that this method can optimize the measurement results for the scene of small-scale.

1. Introduction

Recently, radar interferometric techniques have been successfully extended from space- to ground-based observations. Ground-based interferometry proved itself to be a valuable tool for the monitoring of small scale areas, as it can operate at short revisiting time and with millimetric accuracy on a fine resolution map of the scene. The stepped-frequency continuous wave (SF-CW) is usually used as a communication signal for GB-SAR \cite{1}, however it is most sensitive to atmospheric disturbance (especially water vapor) effect. It was reported that at a distance of 1000 m, the atmospheric effect induced by a humidity change of 1 % along the propagation path at a temperature of 20 °C and a pressure of 1013 hPa atmospheric phase amounts to almost 42° for Ku-band radar. Therefore the atmospheric effect becomes the main constraint to improving the measurement accuracy for GB-SAR\cite{2}. Ameliorating its effect is one of the key factors to improve the GB-SAR measurement accuracy.

There are many papers regarding the atmospheric disturbance effects on spaceborne SAR interferometry, but the effect on GB-SAR interferometry has not been researched properly. In the last few years, some methods for mitigating atmospheric effect in GB-SAR differential interferometry have been proposed. G.Luzi \cite{3} analyzed the atmospheric disturbance effects in GB-SAR interferometric measurement and then corrected the effect by PS technique during a real campaign for monitoring a landslide. L.Iannini\cite{4} investigated the capabilities and the flaws of a compensation approach based on modeling the delay through the available on-site atmospheric parameters (pressure, temperature, and humidity). It demonstrated that, under low-turbulence atmospheric conditions, the correct method based on the model refinement through a humidity calibration step, leads to significant improvements in the compensation performance. A drawback of these models is that the phase delay only depends on range. Atmospheric variations in cross-rang are not modeled.
In this paper, an atmospheric disturbance correction method presented and based on corner reflector was proved by an experiment of ground-based radar interferometry. In section 2 a mathematical overview of the target model with reference to the atmospheric delay is provided. In section 3 the atmospheric effect on ground-based radar measurement is discussed by an outfield experimental data set and an improved method to compensate the environment effect is proposed. In the end, the compensation results are illustrated and commented in section 4.

2. Atmospheric delay model

The atmospheric disturbance is one of the primary disturbances affecting the microwave propagation. In the GB-Radar case, the medium is the troposphere. The approximated formulation of the equivalent atmospheric delay expressed in meters for almost straight paths is[5]:

\[
    d_{\text{atm}, p(i)} = 10^{-6} \int_{L_p} N(r(\vec{I}), i) dl
\]  

Where \( N \) is the refractive index of the atmosphere, it is defined as \( N = (n - 1) \times 10^6 \), where \( n \) is the refractive index of the medium. \( r \) means the space between the radar and the target. Equation (1) states that the delay results from the integration of the refractivity function along the ray path \( L_p \) from the radar to the target. The distribution of \( N \) is inhomogeneous, as it depends on typical atmospheric parameters (pressure \( P \), temperature \( T \) and relative humidity \( H \)). The refractivity model is proposed in [6]. Its expression is

\[
    N = N(P, T, H) = 0.2589 \frac{P_d}{T} + (71.7 + \frac{3.744 \times 10^5}{T}) \frac{e}{T}
\]  

Where \( P \) is the total atmospheric pressures, \( P_d \) is the partial pressure of dry gases, \( e \) is the partial pressure of water vapour. The pressures \( P \), \( P_d \) and \( e \), linked by the relationship \( P_d = P - e \), are expressed in \( hPa \). \( T \) is the temperature in Kelvin. \( e \) can be computed using the Magnus-Teten formula in[7].

Generally it is assumed that the refraction index \( n \) depends only on the time that the measure is performed. This means that it does not vary with the range distance \( r_n \) and also stays constant during the time interval that the wave needs to go from the radar to the target and back. Thus the absolute phase of a monochromatic wave at frequency \( f \) can be expressed as [8]

\[
    \varphi(i) = \frac{4\pi f c r_n n(i)}{c}
\]  

Where \( c \) is the velocity of light in vacuum, if two echoes from the same motionless target are acquired under different atmospheric conditions at time \( i_1 \) and \( i_2 \), a phase difference can be expressed as

\[
    \Delta \varphi = \frac{4\pi f c r_n (n(i_2) - n(i_1))}{c}
\]  

Where \( \Delta \varphi \) is the interferometric phase due to atmospheric disturbance, it can be noticed that interferometric phase is proportional to the carrier frequency.

3. Atmospheric disturbance statistics

Generally the high frequency signal is the transmission signal of ground-based radar[9], and in order to observe the influence on the high frequency signal by atmospheric change in the scene of small-
scale, the IBIS system is applied to measure the stable target in a small scene for a long time observation. Since the signal noise ratio (SNR) of the target is high, the mean deviation of the interferometric phase is small relative to atmospheric disturbance, therefore the displacement from the stable points is considered to be influenced by atmospheric disturbance consistently.

The experiment was carried out on April 19, 2012, and it was sunny without wind all day. It takes 8 observation periods to detect the atmospheric disturbance, and the radial displacement of the stable points is shown in figure 1.

![Figure 1. The displacement diagram of stable points in different observation periods.](image)

In figure 1, from (a) (b) we can see that the water vapor changes greatly in the morning, and under this circumstance the other points appear to have obvious time correlation except from No.63 point in diagram (a). The total deformation influenced by environment is up to 0.6-0.7mm. Through the (c) - (f) we know that the temperature changes have a smaller effect on deformation, and the deformation of stable points swings mostly within the limits of 0.15 mm. The deformation has a 0.15 mm linear decline in the period of 800-1000s in diagram (e), and similarly diagram (h) displays a 0.2 mm linear rise near the PM 18:00 in the evening, after which No.55, 63 have a 0.3 mm deformation. At the same time, the analysis of No.37 point indicates a relatively bigger observation noise, and the example such as diagram (g) which appears to have a 4 mm dithering has a low signal noise ratio (SNR), which results in a larger deviation. The other points in Diagram (e) and (g) also appear to have abnormal dithering, which turns out to be measurement noise of the IBIS system. The performance of the noise is displacement-value mutation with relatively large amplitude, which can be eliminated through the filter, therefore having no impact on the measurement results and data analysis in the late period. It is known from figure 2 that in the long time observation, IBIS system observation accuracy is seriously influenced by the water-vapor factor, having a maximum 0.7 mm linear deformation in this experiment. The measurement error influenced by water-vapor changes has a time correlation. At the same time, in the short-distance measurement scene, the different cross-range target deformation has no obvious linear relationship with distance. In order to improve the reliability of atmospheric disturbance correction, its stable point should be located where it has a high SNR in the scene.

4. Atmospheric disturbance correction experiment

4.1. Test description

A stepper platform was used to control a target simulating the deformation on the LOS of radar in the measurements campaign. The accuracy of the platform is 0.001mm. The analysis has been carried out on the experimental data collected on April 22, 2012. The test was performed as follows: fix a target on a stepper platform, and move it towards radar by 0.05mm for every step with five steps in total (a
time interval of 30s is essential for every step), then away from radar for five steps by the same distance and interval, at last repeat the process once. A GB-Radar IBIS system manufactured by Ingegneria Dei Sistemi, IDS, constantly monitors the target in the scene during the test. The device works in the Ku-band with a central wavelength of about 1.8 cm and is able to achieve a range resolution of 0.5m. Figure 2 shows the map of the exhibition. The concrete pier in the scene was considered as a stable point, thus a corner reflector fixed on a concrete pier can be used as a stable point to correct the atmospheric disturbance using the traditional single point correction method.

Figure 2. Map of the exhibition with targets.

Figure 3 shows the measuring results of the stable points and the target fixed on stepper platform, as shown below, these results engender linear displacement influenced by atmospheric disturbance in the three time periods marked with rectangular frame. However, the displacement of the stepper platform can’t be detected correctly in the marked time segments.

Figure 3. The measured LOS displacement of the stable points and the stepper platform.

4.2. The corrected results
In this experiment, the radar has high system stability; the stable points and the corner reflector have high backscattering; because of the high-power transmission signal and the temporal averaging performed by the CW radar, the noise effect is very small, thus the displacement eventually detected can be related to the atmospheric disturbance and the target displacement.

Figure 4. The results using traditional single point correction method.  
Figure 5. The results using the proposed method in this paper.
Figure 4 shows the corrected results of stepper platform using traditional single point correction method based on the atmospheric disturbance as well as linear relation of the distance between the point and radar. It shows 0.01-0.02mm swing when the platform is motionless. The displacement during the marked period 1 has been corrected rightly, while the results of the marked period 2, 3 can’t be properly corrected, on the contrary engendering greater error. Thus this method cannot correct the atmospheric disturbance correctly.

In this paper, a new method to correct the atmospheric disturbance is proposed using the geometrical relationship between the stable points and the target in the scene as well as the atmospheric disturbance of the stable points. First the weight of different stable points is configured using the geometrical relationship, and then the atmospheric disturbance of the target can be calculated using the weighted impact of the stable points. Its expression is

$$\Delta_{target} = \frac{\sum_{i=1}^{n} P_i \Delta_i}{\sum_{i=1}^{n} P_i}$$

Where $\Delta_{target}$ is the atmospheric disturbance of the target, $\Delta_i$ is the atmospheric disturbance of the $i^{th}$ stable point, $P_i$ is the weight of the $i^{th}$ stable point, $n$ is the number of the stable points. $P_i$ is related to the geometric distance $d_i$ between the target and the $i^{th}$ stable point through the equation

$$P_i = \frac{1}{d_i}.$$

| The results               | Difference of the displacement(mm) | Difference of the absolute position(mm) |
|--------------------------|-------------------------------------|----------------------------------------|
| Without correction       | max 0.0332  min -0.0279  std 0.0168 | max 0.0254  min -0.0251  std 0.0168     |
| the traditional method   | 0.0492  -0.0383  0.0199             | 0.0842  -0.0372  0.0309                 |
| the proposed method      | 0.0385  -0.0191  0.0133             | 0.0361  -0.0162  0.0115                 |

Figure 5 shows the corrected measuring result using the method proposed in this paper. It shows that the atmospheric disturbance of the stepper platform is eliminated effectively in the three marked period. In the three time segments, the corrected results reflect the actual displacement and show swing less than 0.015mm, while in the other period they show swing less than 0.01mm.

Table 1 shows the comparison of the differences between the three measuring results and the actual displacement of the stepper platform, including results without correction, corrected based on the corner reflector using traditional single point correction method, and corrected based on the stable points using the method proposed in this paper. According to the table 2, we can see that the method based on the single corner reflector cannot correct the atmospheric disturbance to the accuracy less than 0.05mm. However, using the method proposed in this paper, the atmospheric disturbance is eliminated effectively, and meanwhile the standard deviation of the displacement measurement and the absolute position of the stepper platform are improved by 20.76% and 31.44% respectively. It demonstrates that this correction method is more precise.

5. Conclusion

Ground-based radar differential interferometry is recognized as a powerful tool in deformation monitoring generally. The environment disturbance can strongly affect the accuracy of the results of the GB-Radar, which is the critical performance requirement for GB-Radar. In this paper, the environment disturbance is analyzed statistically in the experiment, which shows the error influenced by environment can reach millimeter level. The method based on linear relation of the distance
between corner reflector and the radar can’t effectively eliminate the environment disturbance less than 0.05mm.

A corrected procedure based on geometric relationship between the target and the stable points in the scene is presented and applied to correct the atmospheric disturbance. The experimental results have proved the method proposed in this paper to be better, using which we can obtain a measurement result superior to 0.05mm accuracy.

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