A REVIEW OVER THE EFFECTS OF ATMOSPHERE ON INSAR PRODUCTS

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ABSTRACT:

For two decades *Interferometric Synthetic Aperture Radar* (InSAR) has demonstrated its ability for topographic mapping and surface displacement measurements. There are several sources which affect the accuracy of InSAR results; the most considerable one being atmosphere. The atmospheric effects can be categorized in two main groups: general and special. The general effects are almost present in the InSAR results while the special ones occur under specific conditions. Based on a comprehensive literature review, this paper presents the atmospheric effects being most influential on InSAR results. In this regard, water vapor and hydrostatic effects were identified as general error types, and rain rate identified as a special effect. The constant availability of the water vapor makes it the most important atmospheric effect on InSAR images. Therefore, several experiments made by the others to remove the effect of water vapor from the InSAR measurements are also reviewed and presented in this paper. In addition to the mentioned literature review, the author experiments showed that the gravity waves are also special effects which need to be considered. Therefore, methods to remove this effect are also suggested.

1. Introduction

Interferometric Synthetic Aperture Radar (InSAR) has demonstrated its ability in measuring surface displacements (Massonnet et al., 1993; Zebker et al., 1994b) and topographic mapping (Zebker et al., 1994a). However, there are some limiting factors which affect the Radar signals. These factors may affect both amplitude and phase parts of a Radar signal or either of them (Hanssen, 2001). As considered by many researchers, atmosphere is one a significant error source on interferometric measurements (Massonnet et al., 1993).

Atmospheric phenomena always exist in a single ray of Radars (Zebker et al., 1997). However, the errors in the interferometry which utilizes two Radar images would appear when the atmospheric conditions vary between two acquisition times (Hanssen, 2001; Zebker et al., 1997). Otherwise, the atmospheric error will be reduced while processing the interferograms and just a small difference may remain due to the small changes of incident angle along the baseline (Zebker et al., 1997).

In this paper, as phase errors are needed to be considered for InSAR techniques, these types of error will be highlighted. For this purpose, the atmospheric influences on phase part of Radar signals are categorized in two main groups. The first group is the general effects which almost present on the phase measurements and the second group includes the effects which occur under specific conditions. These types of influences usually cause inhomogeneous and elevation independent errors on InSAR products (Hanssen, 2001).

Based on a comprehensive literature review, this paper presents the atmospheric effects being most influential on InSAR results. Therefore, water vapor and hydrostatic effects as general error types and the turbulences caused by gravity waves, and rain rate effects as special effects will be considered.

The major amount of atmospheric general errors on InSAR images are caused by phase fluctuations due to Troposphere (Hanssen, 2001). Tropospheric parameters are usually categorized in two main groups, wet term parameters and dry term or hydrostatic term parameters (Goldhirsch and Rowland, 1982) Wet term parameters consist of different phases of water in the atmosphere. Whereas, dry term parameters include the general properties of atmosphere such as pressure or temperature.

Water vapor is one of the considerable parameters which cause significant error on InSAR products (Zebker et al., 1997). The hydrostatic term of the atmosphere causes significant contaminations on the InSAR images. However, the amount of this error is not as problematic as the water vapor effect (Zebker et al., 1997).

Special effects can be generated by several specific atmospheric conditions which contaminate the phase part of Radar rays. Moreover, some of the special effects such as the Gravity Waves occur in the special climates (Byers, 1974). Usually, these effects make inhomogeneous regional errors. Therefore, they need the accurate meteorological studies to be modeled or reduced.

Rain rate, in comparison with the other types of special effects is simple. This influence causes rather homogeneous errors on the InSAR products and its nature makes it less problematic in comparison with the other sources of error (Hanssen, 2001). On the other hand, this error should be calculated accurately due to its error magnitude (Danklemayer, 2004).

Gravity waves have been considered as complicated phenomena which result in spatial and temporal irregularity in atmospheric dry and wet parameters (Andrews et al., 1987). These sudden changes make quasi-sinusoidal errors on InSAR products or even in a single image both in amplitude image or phase diagram. Gravity waves are formed due to buoyancy restoring forces in mid-latitude regions (Byers, 1974).

These types of errors could be reduced by two methods.The first method is to consider a stochastic model while the second method can remove the mentioned effect based on image processing techniques.

Since the Gravity waves effect is mostly dependent on the rate of changes of inhomogeneous amount of water vapor along the baseline, and the water vapor is the most precluding parameter on InSAR products, therefore, a comprehensive knowledge of water vapor removal will be required to mitigate the Gravity waves effect.

The water vapor removal strategies can be separated in two main groups; stacking methods and calibration methods (Li et al., 2005). The first method consists of special techniques for choosing the images to generate the interferograms or preprocessing more than a pair of images to make an interferogram (Li et al., 2005). However, the calibration methods attempt to remove the water vapor with respect to its behavior on the images.

In the following section, the general atmospheric effects which noted above will be discussed. In the next section, Gravity waves and rain rate influences will be considered as the special effects and some discussions over the existed or suggested methods of water vapor removal will be noted. In the last section, some concluding remarks and suggestions will be mentioned.

2. General Atmospheric effects

General atmospheric effects on the phase of SAR images are considered as two different stratums; Troposphere and Ionosphere (Hanssen, 2001). Tropospheric phase delays, contrary to the Ionospheric phase fluctuations, are independent of the measurement frequency (Zebker et al., 1997). Hence, these contaminations cannot be reduced by multi wavelength measurements.

The phase part of a ray, propagated through the atmosphere in the zenith direction could be expressed by (Zebker et al, 1997):

$$\phi = \frac{2\pi}{\lambda} x + \frac{2\pi}{\lambda} \Delta x \quad (1)$$

where Δx is the extra distance, recorded by the sensor. General phase shift due to atmosphere depends on the measuring wavelength, the path length and the refractive index (Zebker et al., 1997). The phase shift can be stated by:

$$\Delta\phi = \frac{2\pi 10^{-6} N(x)}{\lambda} x \quad (2)$$

Where λ is the measuring wavelength, $N(x)$ is the refractivity and x is the path length.

In Eq. (3), the refractivity in the troposphere could be described as (Davis et al., 1985):

$$N = k_1 \frac{P}{T} + \left(k_2' \frac{e}{T} + k_3 \frac{e}{T^2} \right) + 1.45w \quad (3)$$

where P is the total pressure of the atmosphere in mbar and is equal to $P = P_d + e$. T is the absolute temperature in Kelvin. k_1 , k_2 and k_3 are the equation coefficients. Smith and Weintraub (1953) evaluated these factors as:

$$k_1 = 77.6 KhPa^{-1}$$
$$k_2 = 71.6 KhPa^{-1}$$
$$k_3 = 3.75 \times 10^5 K^2 hPa^{-1}$$

These values are considered to be accurate to 0.5% of N (Resch, 1984).

In the Eq. (3), k_2' is used instead of k_2 and it is equal to (4):

$$k_2' = k_2 - \frac{R_d}{R_v} k_1 = 23.3 KhPa^{-1} \quad (4)$$

Where

$$R_v = 461.524 JK^{-1}$$
$$R_d = 287.053 JK^{-1} Kg^{-1}$$

In the Eq. (3), the first term is considered as hydrostatic or dry term, the next two terms (in brackets) are labeled as main wet terms, and the following term is the liquid term.

The extra propagated path (Δx) is typically separated in two parts (Goldhirsch and Rowland, 1982):

$$\Delta x = (\Delta x)_{dry} + (\Delta x)_{wet} \quad (5)$$

Where the two components are represented as hydrostatic and wet delay terms respectively.

In the next subsections, these delays will be discussed in detail.

2.1 Wet delay

Most researchers agree that the main cause of atmospheric phase fluctuations is the instability of water vapor content of atmosphere between the two acquisition times (Zebker et al., 1997; Dankelmayer et al., 2004; Li et al., 2005). Furthermore, the role of atmospheric liquid water should be considered in accurate calculations (Hanssen, 2001). Though, water vapor has the mostsigni ficant effect on InSAR products.

Generally, two different types of water vapor errors are considered through the InSAR calculations (Hanssen, 2001). The first one depends on the amount of atmospheric parameters such as partial pressure of water vapor and temperature and the elevation. This signal depends on the vertical stratification of the troposphere between the lowest and the highest elevations in the area (Lyons and Sandwell, 2003). Moreover, this effect could be detected when the water vapor content varies between two acquisition times of single images which are used for the processing of the interferogram (Zebker et al, 1997). If the atmospheric parameters were the same in both of the images, the errors would omit themselves and the resulting interferogram would not contains the water vapor errors.

The mentioned water vapor influence should be considered in the general group of atmospheric water vapor turbulences.

The second type of water vapor error is independent of the geographic or physical condition of the earth's surface. The main cause of this error is the local variability of water vapor content of atmosphere in a scene. This may result in an inhomogeneous error in a single interferogram. This effect will be discussed in the following section.

For water vapor estimation, it is somehow impossible to measure water vapor content in different layers of troposphere. It was considered that a model of phase delay with the surface temperature and surface partial pressure of the water vapor could be used to obtain a relation between the wet parameters of the atmosphere and phase delays (Goldhirsch and Rowland, 1982). In these models, the surface parameters vary with a linear model (Zebker *et al.* 1997). As suggested by Zebker *et. al.* the temperature and the pressure of water vapor decrease linearly and exponentially respectively, with the increase of the height. Figure 1 shows the phase delay against the changes of the relative humidity between two acquisition times.

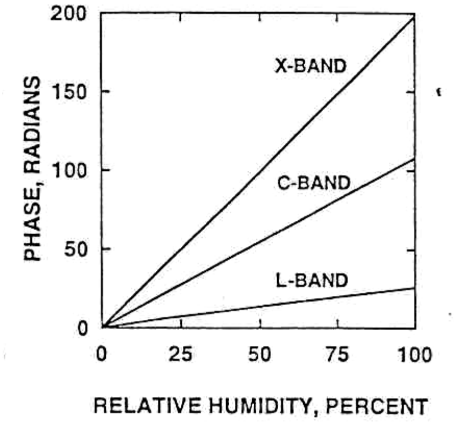

Figure 1: Atmospheric phase delay due to the humidity variation at three SIR-C/X-SAR wavelengths. (Adapted from Zebker et al., 1997)

Where the values demonstrated in the plot assume a nominal tempreture of 300 Kelvins.
Bevis *et al.*, (1996) showed that the phase delay due to the atmospheric water vapor could be represented by:

$$PD_{wv} = 6.5PWV \quad (6)$$

In this equation PD stand as the phase delay and PWV is the precipitable water vapor amount.
Furthermore, Hanssen, (2001) estimated the phase delay due to the atmospheric liquid water content as:

$$PD_{lw} = 1.4PLW \quad (7)$$

Where PLW is the precipitable liquid water amount.
The liquid water content of atmosphere usually increases when the relative humidity and respectively water vapor content are relatively high (Hanssen, 2001). It can be concluded that the liquid water could not be considerable like water vapor.
As an instance, Hanssen, (2001) noted that for a 4 Km depth cumulus, phase delay will be the phase cycle of around 0.2 which is well detectable but much less than the water vapor effect. On a single ray, the effect of liquid water is very low in comparison with the water vapor content. As a result, neglecting the liquid water effect may cause about of 10 percent overestimation in water vapor content (Hanssen, 2001).

2.2 Hydrostatic delay

The atmospheric hydrostatic delay depends on the dry parameters of atmosphere including the temperature and pressure of the atmosphere (Smith and Weintraub, 1953). The temperature changes result in a change in partial pressure of water vapor. So, it is important to consider it as an influential factor on the hydrostatic delay. Therefore, the temperature fluctuations should be given more weight in the wet term analysis.
Saastamoinen, (1972) and Jet Propulsion Laboratory, (1979) suggest that the hydrostatic extra distance could be expressed as:

$$\Delta x = \left(2.27 \times 10^{-3} - 1.11 \times 10^{-5} Cos\Lambda\right) P_s \quad (8)$$

Where the subscripted value is the total surface pressure of atmosphere and Λ is the latitude of the observation point. Note that due to the measurement difficulties, the surface parameters are taken into consideration instead of the parameters along the satellite path
Zebker et al., (1997) show that the changes of 50 millibars in the pressure could make a phase delay around 35 radians in C band assuming the nominal value of 300 K. for temperature. Figure 2 illustrates their studies in details:

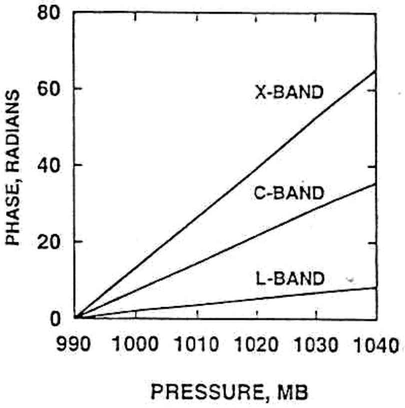

Figure 2: Atmospheric phase delay due to pressure variation at three SIR-C/X-SAR wavelengths. (Adapted from Zebker et al., 1997)

The phase delay due to the hydrostatic term is smooth as well and usually causes a few millimeters of error in the interferograms (Hanssen,2001). Moreover this amount of error could occurr by the orbital measurements. These errors could be reduced by using tie points. Hence, it can be ignored in small scale cases.

3. Special Atmospheric effects

3.1 Rain Rate

Rain rate is a special effect which causes a detectable error on InSAR images. This parameter is neglected by many researchers due to the amount of its effects on images. In the contrary of other special effects that will be discussed in the next subsections, rain rate is somehow regular. Moreover, the rain rate effect on InSAR products is similar to the water content contaminations.

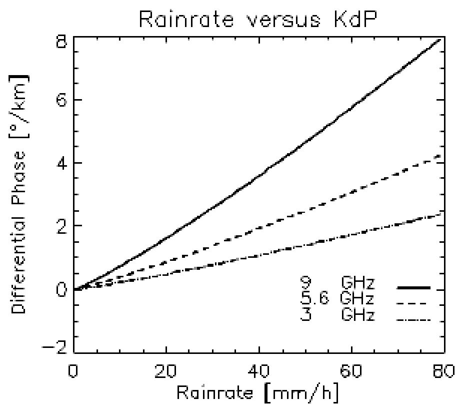

Figure 3: Rain rate versus differential phase (Adapted from Dankelmayer, 2004)

Dankelmayer, (2004) represented that the total phase delay due to the rain rate is proportional to the height of precipitation and the measuring frequency. Figure 3 shows the effect of the rain rate on the Radar measuring phase.
This figure shows that the phase delay will be increased by the amplification of the rain rate or by choosing the higher frequencies.

3.2 Gravity waves

There are many phenomena which affect the atmospheric parameters locally. Sudden changes in atmospheric parameters would result in unexpected and spatially inhomogeneous contaminations in the images. One of the major effects following the mentioned rule is Gravity Wave.
Atmospheric gravity waves have a basic role in establishing atmospheric circulation and forming the vertical structure of wind and temperature fields (Gossard and Hook, 1975; Lighthill et al., 1978; Chonchuzov et al., 2000). They cause fluctuations in wind speed (Sato, 1990; VanZandt et al., 1990), temperature (Orlanski and Bryan, 1969) and ozone concentration (Bird et al., 1997) over a wide range of spatial and temporal scales (Chonchuzov et al., 2000).
In fluid dynamics, Gravity waves are called to that part of waves which are formed in a medium with variable density or between two mediums (Koch et al, 1997). Gravity waves are produced by buoyancy restoring forces (Andrews et al., 1987). In other words, when a fluid moves inside a varying-density medium or between two different mediums, buoyancy forces try to restore that fluid to its first equilibrium condition.
Internal Gravity waves refers that group of Gravity waves that form in a single density variable medium and only under the effects of buoyancy forces (Andrews et al., 1987) (not the coriolis forces). These types of waves are detected as a group of waves with a qusi-sinusoidal form (Chonchuzov et al, 2000). They usually have the wave lengths of a few hundred meters to at most 15 Kms.
In meteorology, Lee waves are the types of gravity waves that form as standing waves (Wikipedia, L.A. Dec. 2006). These waves have an extra factor of topography to be established. They are also called *Mountain waves*. They would cause periodic changes in atmospheric pressure, temperature and orthometric height in an air current due to vertical displacement. Figure 4 shows the formation of different levels of lee waves.

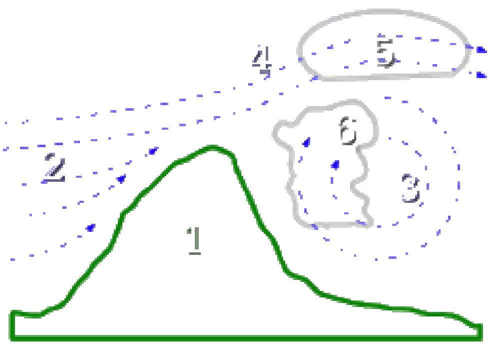

Figure 4: Lee waves establishment (Adapted from Wikipedia, Last Accessed Dec. 2006)

As it could be seen in Figure 4, wind pushes the air and water vapor to the obstacles (Wikipedia, L.A. 2006). Elevated obstacles lead the noted elements to the higher elevation. Air stability causes the elements to return to their original elevation. This will result in a local instability in a stable condition of the observed location.
Considering the changes of dew point in different heights, allows us to note that Lee waves can form typically cumulus street clouds due to the suitable wind rate and sufficient amount of humidity (Wikipedia, L.A. 2006).
As discussed above, Gravity waves would result in a group of local fluctuations in atmospheric parameters such as humidity, pressure and temperature. Spatial changes of these fluctuations are comparatively severe. If Gravity waves exist in at least a single InSAR image time of acquisition, the spatial changes in atmospheric parameters and especially water vapor will cause an extensive inhomogeneous error in products. This error will be obviously seen in an interferogram from which the topography effect has been removed. This effect would be detected as a sinusoidal wave in an interferogram. In an unusual condition when the Gravity waves exist in both SAR images which are used to produce the interferogram, the effect may be observed as an irregular contamination.

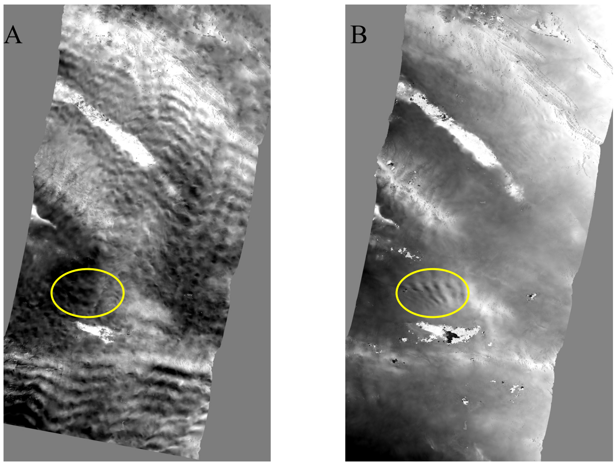

Figure 5: Two interferograms with a common SAR image

Figure 5 illustrates two interferograms with a common SAR image. Figure 5-A and 5-B exhibit two interferograms generated from SAR images, acquired in 06-14-2004/07-19-2004 and 06-14-2004/11 01-2004, respectively. The interferogram shown in figure 5-A is significantly affected by the Gravity waves effect. It can be concluded that the Gravity waves exist in 07-19-2004. The highlighted area in figure 5-B shows that the limited Gravity waves have occurred in the common image as well. In figure 5-B this error could be detect as a simple sinusoidal error. However this error could be recognized as a complex irregular error in figure 5A.

4. Removal strategies

As discussed in the previous section, water vapor is the main atmospheric source of error. In many cases even the remained water vapor error after the implementation of a reduction technique is higher than many of InSAR errors. Consequently, many of these effects due to the wet-term error are somehow inconsiderable. On the other hand, some complicated effects like Gravity waves may contaminate images due to irregularity of water vapor content of atmosphere. Hence, many studies are carried out in order to reduce the water vapor effects.
Two different methodologies can be suggested to mitigate the water vapor effect from the InSAR images. The first method

consists of special techniques for choosing the images to generate the interferograms or preprocessing more than a pair of images to make an interferogram (Li et al., 2005).
Zebker et al. (1997) suggested the following options to achieve the InSAR products in the mean accuracy:

1- Using the longest possible wavelength with respect to Faraday rotation limits and atmospheric scintillation.
2- Using the longest possible baseline for topographic mapping within the decorrelation limits.
3- Applying multi observations and averaging the derived products for surface displacement measurements.

They claimed the accuracy of 10 meters for topographic mapping and 1 centimeter for displacement measurements.
The second type includes calibration methods. Many scientists have suggested algorithms to improve the accuracy of InSAR products by calibration. Among these methods, Li et al., (2005) issue a method of water vapor removal by integrating MODIS and GPS datasets and InSAR images. They obtained subcentimeter accuracy for InSAR deformation products.
In their method at first, they produce a MODIS precipitable water vapor (M-PVW) image. Whereas this image was sensitive to the cloud, they utilized a method to mask the cloudy pixels. Since the MODIS water vapor information is overestimated from 5% to 20% compared to the GPS measurements (Li et al., 2003), the MODIS PVW images were then calibrated using a GPS network. Finally, the zenith tropospheric delay due to water vapor was mapped and implemented to the InSAR image.
However, in some locations, a dense GPS network is unavailable. Therefore, it is suggested to use radiosonde dataset instead. Despite the acceptable accuracy of the radiosonde datasets, their discontinuity makes the method independent of the time of gathering datasets.
In the case of Gravity waves, two reduction methods can be implemented; image processing-based methods and stochastic modeling ones. Appropriate image processing approaches which can be used widely for Gravity waves reduction are based on frequency domain.
Whereas Gravity waves have a shape of a quasi-sinusoidal turbulence (Andrews et al., 1987), a comprehensive stochastic model considering the effective parameters could be suitable for Gravity wave reduction of InSAR products.

5. Conclusion

In this paper different phenomena, affecting InSAR products were discussed. Atmospheric effects could be separated in two parts of General and special effects. General effects always affect the single Radar ray. In the other side, Special effects were those which needed special conditions to happen. Studies carried out by scientists show that the effect of water vapor on InSAR images is more important and should be considered in the accurate geometrical calculations.
In this paper, general effects were separated in two groups. The first one was the wet-term influences. These effects included water vapor and liquid water. The studies have shown that mitigating the liquid term will result in up to 10 percent overestimation in water vapor content (Hanssen, 2001). Moreover, the fact that liquid water usually increases when relative humidity is high, leads many scientists to ignore the effects of liquid water.
It was shown that the errors caused by water vapor are directly proportional to the measuring frequency (Zebker et al., 1997). On the other hand, when the amount of water vapor is different in the Radar images, its effect can be detected in InSAR products. Otherwise two- ray-path errors will be eliminated by each other (Zebker et al., 1997).
The second type of general effects discussed above was the dry term effects. These influences are highly dependent on the atmospheric total pressure. Zebker et al., (1997) claim that the hydrostatic delay on InSAR products in a same condition are much less than wet-term delay. Dry-term delay is a regular effect due to the smooth changes of pressure of the atmosphere in an area with the size of a Radar scene.
Rain rate is a special effect which should be considered in the accurate calculations. This effect depends on the measuring frequency (Dankelmayer, 2004) as well. In addition, the height of precipitation should be noted.
The most influential special sources of error in InSAR images are Gravity waves. One type of the Gravity waves is Lee waves. The Gravity waves need special atmospheric condition to happen. Sufficient amount of water content and topography are the necessary factors which excite the effects of Gravity waves and would cause serious contaminations on the InSAR products. Spatial inhomogeneity of the Gravity waves contaminations makes this type of error more serious.
Several atmospheric error reduction strategies have been suggested by now. Water vapor due to its importance and extensive effects on InSAR images have been considered in many cases.
Stacking and calibration strategies are applied for water vapor removal (Li et al., 2005). The rules identified by stacking methods are used to gather appropriate datasets to reach more accurate results while the calibration methods try to reduce errors after generating interferograms.
Moreover, the wet term parameters are the most important general effects on InSAR images. To achieve the accurate InSAR products, atmospheric effects removal methods should be studied more. Furthermore, Gravity waves which are complex errors and can be generated by a couple of general and special influences should be considered more.

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