ADVANTAGES AND LIMITATIONS OF FORWARD SQUINT SAR IN SINGLE PASS INTERFEROMETRIC MAPPING OF TOPOGRAPHY

Alexander Zakharov [a], *Pavel Denisov* [b]

[a] Kotelnikov Institute of Radioengineering and Electronics RAS, Russia, [b] Ministry of Agriculture of Russian Federation, Russia

ABSTRACT

In our paper we discuss advantages and limitations of original alternative interferometric scheme of topography mapping with one-pass single-antenna forward squint synthetic aperture radar (SAR). Key specificity of the new interferometric scheme is in forward/backward squint geometry of SAR observations, where interferometric baseline is formed thanks to observation of the surface from two points displaced along the orbit in azimuth direction. A comparison with classic scheme of interferometric observations is made and it is shown that in the new scheme the sensitivity of interferometric phase to topography variations is dependent on squint angle and interferometric baseline. The interferometric baseline length is limited by acceptable level of coherence, which is dependent on Doppler centroids decorrelation and decorrelation because of scene rotation.

Index Terms— SAR, SAR interferometry, TanDEM-X, temporal decorrelation, digital elevation model

1. INTRODUCTION

Spaceborne synthetic aperture radar (SAR) interferometry is an effective technique for detailed digital mapping of Earth surface topography. Two approaches used to be delineated by now – single-pass cross-track interferometry with two antennas interferometer (or single antenna SAR systems onboard two satellites placed on close orbits) and repeat-pass interferometry from close orbits of satellite equipped with single-antenna SAR system [1-2]. Accuracy of the topographic measurements in interferometric scheme is dependent on a number of observation parameters including the interferometric baseline length as a distance between the SAR observation points. An absence of corrupting effects in a form of the scattered signals temporal decorrelation as well as atmosphere irregularities in the first approach makes it to be preferable for the topography mapping [3-4].

In this paper we discuss preferences and limitations of original alternative interferometric scheme of topography mapping with one-pass single-antenna forward squint SAR. Key specificity of the new interferometric scheme is in forward/backward squint geometry of SAR observations, where interferometric baseline is formed thanks to observation of the surface from two points displaced along the orbit in azimuth direction.

2. OBSERVATION GEOMETRY

For a sake of comparison, we will compare classic side-looking observation geometry and forward squint geometry interferometric observations. The former one in the case of "flat" Earth is presented in Fig. 1, where point A_1 – first point of observation, and point A_2 - second observation point. Let H be satellite altitude in the first point. The distance between observation points *B is* interferometric baseline, which is declined in general case at the angle θ_i with respect to horizon. SAR signal, travelling from point A_1, arrives to surface point *P,* at the distance r_1 at the incidence angle θ.

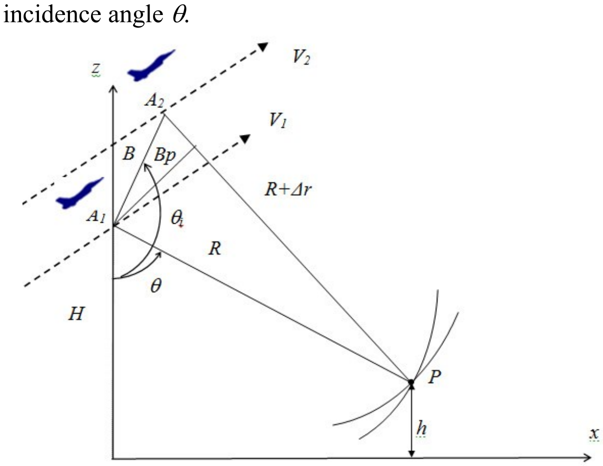

Figure 1. Side-looking geometry of interferometric observations

An interferogram is a map of signals phase difference $\Delta\varphi = \varphi_1 - \varphi_2$, which may be get from pixel-by-pixel complex multiplication of signals U_1 and U_2, acquired in points A_1 and A_2:

$$U_1 U_2^* = u_1 u_2 \exp\left(j(\varphi_1 - \varphi_2)\right) = u_1 u_2 \exp\left(\frac{j2\pi\kappa\Delta r}{\lambda}\right), \quad (1)$$

where u_1 and u_2 – signal amplitudes, and Δr – slant ranges difference from observation points till surface element P, λ - wavelength. Factor κ before Δr is equal to 2 because of double propagation path of signals in repeat-pass observation scheme. In bistatic scheme κ =1. The link of phase difference variations $\Delta\varphi_t(\Delta h)$ or topographic phase with topographic heights variations Δh is as follows [5].

$$dh = \frac{\lambda R \sin\theta}{2\kappa\pi B_p} d\varphi\,, \qquad (2)$$

where B_p -perpendicular component of interferometric baseline:

$$B_p = B\sin(\theta i - \theta)\,. \qquad (3)$$

The sensitivity of interferometric phase difference to height variations is characterized by height ambiguity

$$h_a = \frac{\lambda R \sin\theta}{\kappa B_p}\,. \qquad (4)$$

The interferometric observation geometry of single-pass forward squint SAR is presented in Fig. 2.

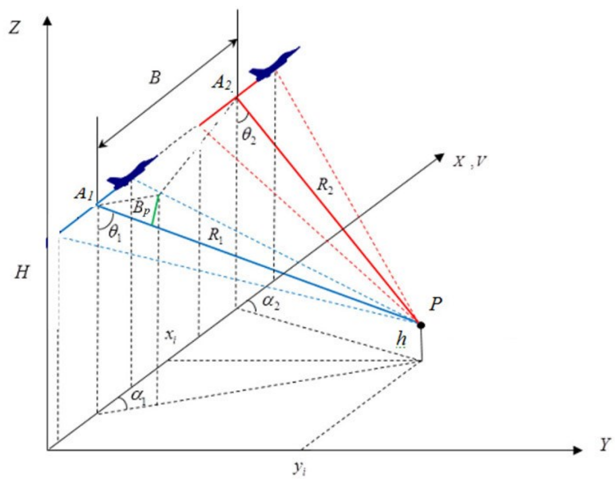

Figure 2. Forward squint geometry of interferometric observations

Here first point of interferometric observation is located in point A_1. Squint angle α_1 is counted from axis x, it is not equal to 90^0, as in side-looking geometry. Certain period of time later satellite arrives to second interferometric observation point A_2 with squint angle α_2. The distance B between the observation points here is interferometric baseline.

It may be easily shown that height variations dh maybe described with similar expression:

$$dh = \frac{\lambda R \sin\theta}{4\pi B_p} d\varphi\,, \qquad (5)$$

but perpendicular component is slightly different:

$$B_p = B\cos\theta\cos\alpha\,\cdot \qquad (6)$$

The sensitivity of interferometric phase difference to height variations is also characterized by similar expression for height ambiguity:

$$h_a = \frac{\lambda R \sin\theta}{2B_p}\,. \qquad (7)$$

The idea of forward squint interferometric SAR was expressed in [6] and studied in more detail in [7,8]. including airborne experiments, where its principal performance was confirmed.

3. COMPARISON OF TECHNIQUES

For the sake of comparison, we will conduct analysis of the techniques in the same geometry of observations. Let the satellite be on the TerraSAR-X orbit with altitude H=500 km, equipped with X-band SAR (λ=3 cm) looking at the Earth surface at 30^0 observation angle. The illuminated spot width on the surface L=3 km, slant range R till the spot center is 600 km, Doppler bandwidth of the scattered signal is 3000 Hz. Resolution in slant range is δr =1.5 m and in azimuth δa =3 m. To provide similar geometry we will set the angle θi =90^0 for side-looking SAR.

An indicator of quality of heights measurements is interferometric coherence γ , which is dependent on radar instrument thermal noise γ_N , spatial γ_{sp} and temporal γ_{temp} decorrelation, volume decorrelation γ_{vol} , Doppler centroids decorrelation γ_{dop}, decorrelation because of scene rotation γ_{rot} and noise because of processing errors γ_{proc}. Supposing statistical independence of the factors mentioned, we may write

$$\gamma = \gamma_N \gamma_{sp} \gamma_{temp} \gamma_{vol} \gamma_{dop} \gamma_{rot} \gamma_{proc}\,. \qquad (8)$$

We may suppose γ_N , γ_{vol} and γ_{proc} to be the same in both cases as well as γ_{temp} to be equal to 0. Doppler centroids decorrelation is principal and one of most serious limiting factors in forward squint SAR. Because of the distinction of α_1 *and* α_2 Doppler centroids in points A_1 and A_1will be different. Approximate expression for γ_{dop} may be written as follows:

$$\gamma_{dop} = 1 - \left|\frac{L_{dop}}{L}\right|, \qquad (9)$$

where L_{dop} -displacement of observation points in along-track direction, L. – illuminated spot width in azimuth on the surface. Total decorrelation happens in the case of observation point shift at the distance L. From what follows, that there is upper boundary for the length of interferometric baseline B<L of forward squint SAR.

Spatial decorrelation is present in both cases; it may be described in similar way. For side-looking SAR

$$\gamma_{sp} = 1 - \left|\frac{\delta r B_p}{\lambda R tg\theta}\right|. \qquad (10)$$

For TanDEM-like constellation maximal B_p length is 6000 m. In fact, in TanDEM-X mission it was chosen to be about 300-500 m in order to support better conditions for phase unwrapping procedure on the one hand and to keep high sensitivity to topography. Taking into account the expression (6) for B_p in forward squint case, we may plot its dependence on squint angle α as on Fig. 3. Along the axis x we plot 90^0- α in order to provide more convenient perception. We can see, that for $\alpha=90^0$ $B_p=0$, what is typical for along-track interferometry. To get $B_p=300$ m and, consequently, to obtain the sensitivity to topography, which is similar to TanDEM-X case, the squint angle should be less than 60^0. Consequently, only high-squint SAR will be able to provide accurate interferometric measurements of the topography.

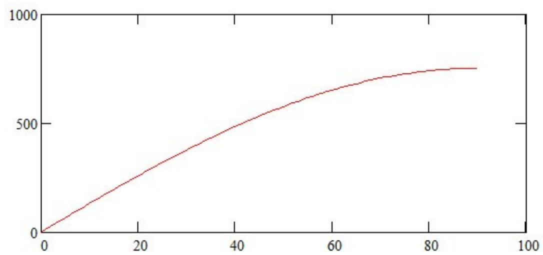

Figure 3. B_p as a function of 90^0- α for forward squint SAR

Another important factor is scene rotation as a result of squint angle variation from point A_1 to point A_2. This decorrelation factor may be expressed for relatively high squint angles approximately as [9]:

$$\gamma_{rot} = 1 - \frac{2\sin\theta\left|\alpha_1 - \alpha_2\right|\delta r}{\lambda}. \quad (11)$$

In given conditions γ_{rot}=0 also for the observation points displacement $L>B$.

4. CONCLUSION

Single-pass forward squint scheme of interferometric measurements of the topography is promising because of simpler instrument configuration then tandem missions. It is more attractive because of absence of temporal decorrelation compared with repeat pass observations. Acceptable sensitivity of the measurements, though, may be obtained in the case of highly squinted SAR. Among the negative factors are Doppler centroid and scene rotation decorrelation, and respective restriction on the interferometric baseline and, respectively, measurements accuracy.

5. ACKNOWLEDGMENTS

Authors acknowledge financial support of Russian Foundation for Basic Research under project No 18-07-00816_a.

6. REFERENCES

[1] "Shuttle Radar Topography Mission (SRTM), Jet Propulsion Laboratory", NASA, http://www2.jpl.nasa.gov/srtm/ .

[2] G. Krieger, A. Moreira, H. Fiedler et al., "TanDEM-X: A Satellite Formation for High-Resolution SAR Interferometry", *IEEE Trans. Geosci. Rem. Sens.,* Vol. 45, No. 11, pp. 3317-3341, November 2007.

[3] Rosen P.A., et al., "Synthetic aperture radar interferometry", *Proceedings of IEEE*, Vol. 3. pp. 333–381, 2000.

[4] Bamler R., Hartl P., "Synthetic aperture radar interferometry", *Inverse Problems*, 1998. Vol. 14. pp. 1–54.

[5] Zakharov A.I., Zakharova L.N., Leonov V.M., Sorochinsky M.V., "An influence of SAR instrument noise on the accuracy of topography measurements by means of radar interferometry technique", *Astronautics and Rocket Science*, 2016, No. 6, pp. 132-139, in Russian

[6] M.I.Babokin, "Airborne and spaceborne systems of Earth remote sensing with multidimensional signals processing" , *Doct. sci. thesis*, Moscow, 2010, 335 pages, in Russian

[7] Shimkin P.E., Baskakov A.I., Babokin M.I., "Analysis of the accuracy of single-pass forward-squint SAR interferometer in measurements of Earth surface relief" *Modern problems of Earth remote sensing from space,* 2017. No 5. pp. 103–112, in Russian

[8] P.E.Shimkin, "Single-pass forward squint onboard SAR for estimation of underlying surface relief ", *Ph.D. thesis,* Moscow, 2018, 140 pages, in Russian

[9] Zebker H.A., Villasenor J. "Decorrelation in interferometric radar echoes" *IEEE Trans. Geosci and Rem. Sens.,* 1992. Vol. 30. No. 5. pp. 950–959.