

Application of synthetic aperture radars for the ground displacement monitoring in mineral mining areas

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Abstract. The authors discuss applicability of synthesized aperture radars to monitor the ground surface displacement in mineral mining areas in terms of a synthesized-aperture interferometric radar. The operation principle of the interferometric method is demonstrated on studies of the ground surface displacements in areas of oil and gas reservoirs. The advantages of the synthetic aperture radar are substantiated.

A number of merits of synthesized aperture radars (SAR) and advanced SAR-based techniques for making radiolocation images of Earth surface (subsurface) provide the grounds to consider the feasibility to employ them to monitor mineral deposits. As for SAR merits, first, of prime importance is indiscriminateness of these systems to brightness of a study area and immunity to weather conditions in a survey zone along with rather high spatial resolution. High penetration capacity of radio waves allows overcoming the screen effect of vegetation mantle, to detect subsurface formations and to observe geophysical processes [1, 2].

In the present research the feasibility to apply SAR to monitor mineral deposits is considered in terms of satellite SAR interferometry because of its competitive advantages over the surface techniques:

- a single image covers area up to 100 km²;
- precision of displacement evaluation is within centimeter scale;
- feasibility to obtain and to analyze archive images.

In view of the above it is explicit that SAR interferometry is applicable to survey displacements of natural and technogenic objects. Survey of displacements in mine fields, sedimentations over mines and tunnels, monitoring of bridge stability and overhead roads are important to provide life safety, and to minimize risks of negative effects on technogenic objects.

Satellite interferometry is widely used in development of oil and gas deposits in the Russian Federation. Considering climate and geographic peculiarities of survey territories it should be kept in mind that SAR data processing is a complicated procedure.

SAR interferometry itself represents construction of digital relief models (DRM) and enables to monitor Earth surface dynamics for a certain period.



Interferometry procedure provides a pair of images of the same Earth surface area [3], made from two close locally parallel orbits (Figure 1). The second image is made by the same satellite or its tandem couple (this process was realized in the period of simultaneous operation of satellites ERS-1 and ERS-2). Two images are used to compute an integrated interferogram representing also 2D matrix, where each element is product of the first image signal and a complex conjugate signal of the second image. Thus, a phase of each element of a complex interferogram is equal to phase difference of two images [3]. To introduce corrections described in details below requires a digital relief model which can be derived based on independent evidence or two radar images of the same area. The images must be made in periods of insignificant deformations. Provided that displacements of a reflecting surface element are absent, the phase difference is expressed through difference of respective inclined lengths to the survey area in two satellite positions r_{1G} and r_{2G} + (Figure 1):

$$\varphi_G = \frac{4\pi}{\lambda}(r_{2G} - r_{1G}), \quad (1)$$

where λ is wave length, corresponding to carrying frequency of radar radiation.

On-board radiolocation satellite systems (hereinafter RSS) of European satellites RS-1/2 and ENVISAT have $\lambda = 5.6$ cm. For PALSAR RSS (abbreviated version of Phased Array type L-band Synthetic Aperture Radar), mounted in Japanese satellite ALOS (Advanced Land Observing Satellite) $\lambda = 23.6$ cm. Difference of inclined lengths (Figure 1) can be expressed through distance from a survey area to vertical projection of satellite position on Earth surface (length by spheroid) and from the survey location topography, namely, altitude of the area where the reflecting element locates, over spheroid. The use of data on orbit position and DRM, respectively, makes it possible to exclude interference of these dependences in the differential interferogram [1]. Thereto, the second dependence itself is the basis of the process for derivation of the digital relief models with the help of SAR-interferometry. Local altitude z can be expressed as:

$$z = H - r_{1G} \cos \theta, \quad (2)$$

where H is orbit altitude over averaged Earth surface (Figure 1).

Let the reflecting surface displaced for a period between two successive shots (vector D). Then an inclined length becomes equal to r'_{2G} . As it was proved above, because of difference in RSS positions (equivalent to presence of distance B , termed as interferometer base) the phase of interferogram depends not only on surface displacements, but on topography as well. Using DRM before deformations the differential interferometry method allows elimination of topography interference. In formula of phase difference in the case of Earth surface displacement it is possible to single out member D_G , corresponding to difference of inclined lengths related to reflector displacement, member H_G conditioned by interference of topography, atmosphere dynamics and noises is:

$$\varphi_G \frac{\lambda}{4\pi} = (r'_{2G} - r_{2G}) + (r_{2G} - r_{1G}) = D_G + H_G. \quad (3)$$

The inclined length exceeds multifold displacements, so beams r'_{2G} and r_{2G} can be assumed parallel (so called approximation of the far zone or parallel beams [4]), it means that displacement component D_G can be assumed equal to projection of vector D in direction towards satellite – LOS:

$$D_G = |D| \sin(\theta_{inc} - \alpha_G). \quad (4)$$

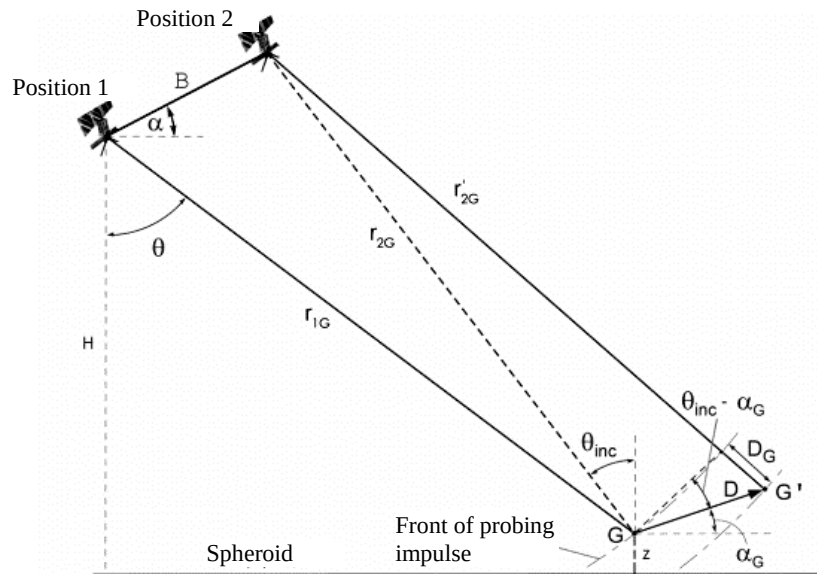


Figure 1. Geometry of interferometric imaging: r_{1G} is distance from the first satellite position to a reflector G on the Earth surface at altitude z ; r_{2G} is the second satellite position to the same point given that deformation is absent; r'_{2G} is distance from the second satellite position to point G' if displacement D is present in the period between images; θ is observation angle of RSS in position 1; θ_{inc} is falling angle of probing beam RSS in position 2; B is interferometer base; H is orbit altitude over averaged Earth surface; α is angle of base inclination; α_G is incline angle of displacement vector D ; D is Earth surface displacement in the period between two imagings; D_G is projection of displacement vector D on the observation line or LOS (line-of-sight).

Thus disregarding that DRM precision ranges within a decimeter at best, the differential interferogram enables to determine surface displacements comparable to wavelength of RSS, viz., in centimeters. Interference of atmosphere errors used to be weak to affect estimates of large-amplitude Earth surface displacements [5]. At average low velocities of displacements the interference of atmosphere errors is removed by special signal processing methods, briefed on below. It is impossible to evaluate directly altitudes or Earth surface displacements from a phase interferogram as it contains not absolute phase shift values, but values convoluted by module 2π , to be precise, lying in the range $[0, 2\pi]$. The problem of phase nonuniqueness is solved by so-called unfolding of the phase interferogram. This classic problem has been arisen long before radar interferometry development [6–8]. The problem of transition to absolute phase values is reduced to addition of a required number of full phase cycles to every phase measurement. There are different algorithms for unfolding of phase interferogram. Earth surface displacement evaluated by an interferogram is equal to projection of the full vector of displacements in the direction to the satellite, this direction is characterized by a view angle (or beam tilt angle). Analyzing data on ascending and descending orbits, it is possible to identify two projections, but it is not enough to determine three components of displacement vector. The complete vector can be determined with the use of additional data (for example, surface or satellite geodesy) or additional presumptions.

Methods of radar satellite interferometry are employed to monitor different processes accompanied with displacements of the daylight surface, such as development of mineral deposits (oil, gas, coal, and ores).

One of pioneer attempts to use SAR-interferometry to monitor subsidence over oil reservoir was made at Lost Hills and Belridge in San Joaquin, California [1]. Analysis of dual interferograms, made by only 5 images of satellites ERS-1 and ERS-2 with interval from 35 days to 26 months provided an opportunity to single out subsidence zones of funnel shape (2–5 km 52 and 2x15 km) at subsidence velocity up to 40 mm/year. Later the results of interferometric processing on Lost Hills and Belridge oil fields, California were used not only to monitor subsidence of surface over oil fields, but also to control underground processes running in oil- and gas-bearing beds with the help of geomechanical modeling [1].

The application of differential interferometry methods (DinSAR-assessment of displacements by pairs of interferograms) has a number of restrictions related to impossibility to make pairs of interferograms with good coherence under complex conditions when Earth surface is covered with vegetation or humidity is very high, etc. The methods of stable reflectors can overcome these imperfections of interferometric methods. At present there are three well-established versions of methods of stable reflectors: PSInSAR, DePSI, and StaMPS [1].

The interferometric processing technologies used in Russia so far are primitive with actually little chance to obtain robust results. More advanced technologies, for example, method of stable reflectors (DePsi, PSInSAR, StaMPS) are scantily applied in Russia to date.

Conclusion

1. Data of SAR-interferometry make it possible to obtain also in-time variations in displacement rates along with robust evaluation of amplitudes of Earth surface displacements.

2. There are a number of factors restricting the use of radar interferometry to monitor mineral deposit areas.

3. The being of a developed infrastructure in the vicinity of survey area can be considered as a positive factor as such objects are known as stable reflectors.

From the analysis of monitoring data on mining are as it is concluded that reliability and informativity of survey evidence depends on a number of factors, including integrity of satellite data, strategy of their obtaining, processing methods, efficiency of combined interpretation of surface and satellite data. The present research is based on the latest achievements of the global science in SAR-interferometry. The solution of the research problems is of actual importance for professionals working in this field.

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