Real Beam vs. Synthetic Aperture Radar for Slope Monitoring

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Abstract— In the last years ground-based radar interferometry has become a popular technology for displacement monitoring of landslides and slopes in open-pit mines. Several research groups and companies have worked on it, and currently two quite different technologies are emerging: real beam radar and synthetic aperture radar. The aim of this paper is to discuss the fundamental differences of the two techniques, with emphasis on the principles rather than on particular implementations and commercial products.

1. INTRODUCTION

The first embryonic idea of SAR (Synthetic Aperture Radar) is probably due the mathematician Carl A. Wiley [1] that in 1951 described a "Doppler Unbeamed Search Radar". It was not a SAR as known today, nevertheless it provided the basis of a radar with improved angular resolution using the Doppler shift of a travelling antenna. Other developments were done in 1950s, but they were covered by military secret. The civil history of SAR begins in 1960, when the idea was first acknowledged publicly [2]. Today SAR is the standard for satellite radars, as they require the best possible angular resolution for focussing on the earth surface operating from an orbit [3]. Since 1990s with the launch of ERS-1 (1991), JERS-1 (1992), RADARSAT-1 and ERS-2 (1995) [4, 5], satellite-based SAR has been able to exploit the phase information of images for detecting ground displacements. These developments had an early follow-up in analogue ground-based radar systems in the late '90s.

In 2003 Tarchi et al. [6] proposed for the first time to exploit Ground Based SAR Inteferometry for slope monitoring. Since those early days of ground based SAR, the technique has been developed and tested in the field for about a decade [7–10] until its consolidation as a commercial equipment [11–14]. At the same time, more traditional radars with physical aperture antennas have been proposed and used with the same purpose [15]. Currently the two different technologies (Real Beam and Synthetic Aperture) are both popular as instruments for displacement monitoring of natural and engineered slopes. Just for reference, IBIS [11] of IDS company and LisaLab [9] of Ellegi are radars for slope monitoring based on synthetic aperture, SSR of GroundProbe [15], MSR of Reutech and GPRI of Gamma Remote Sensing [16] are radar systems based on physical aperture antennas.

The aim of this paper is to discuss the fundamental differences of the two techniques with emphasis on the principles rather than on specific implementations and commercial products.

2. GROUND BASED RADAR INTERFEROMETRY FOR SLOPE MONITORING

Landslides and slopes of open pit mines can be remotely monitored by a ground-based inteferometric radar installed in a position where it can have a suitable view of the unstable area (Figure 1).

This equipment images its field of view with a range resolution ΔR related to the operated bandwidth B, given by

$$\Delta R = \frac{c}{2B} \tag{1}$$

with c speed of light. In each resolution cell the component Δr along the view direction of the terrain movement Δs is detected by exploiting the differential phase information $\Delta\phi$ of the radar signal:

$$\Delta r = \frac{\lambda}{4\pi}\Delta\varphi \tag{2}$$

with λ wavelength.

3. REAL BEAM AND SYNTHETIC APERTURE

Generally speaking, a radar is able detect the distance (range) and the direction of a target, transmitting and receiving electromagnetic waves. The distance is obtained by evaluating the time of flight of a returning electromagnetic pulse (alternatively using compressed or synthetic pulses,

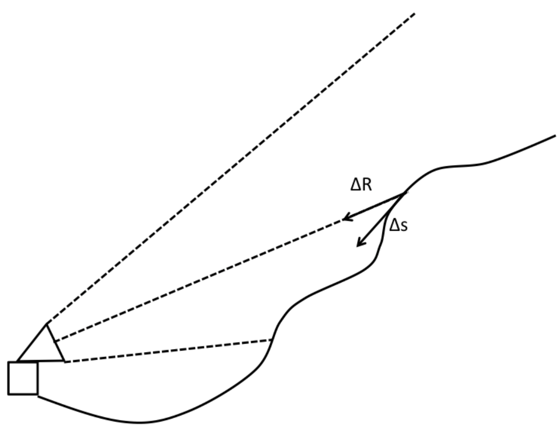

Figure 1: Ground based radar installation for slope monitoring.

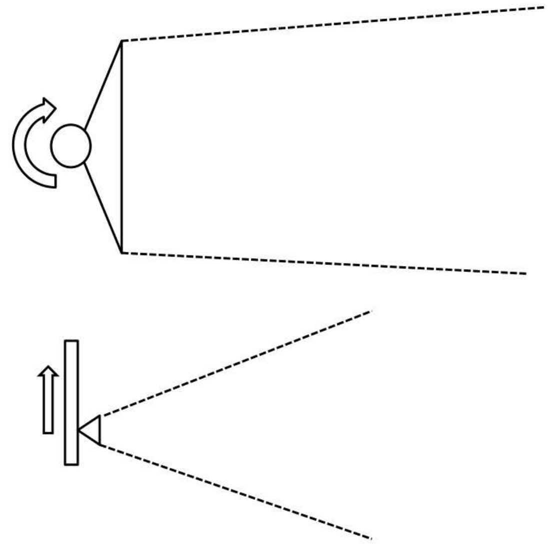

Figure 2: Real beam antenna and synthetic aperture.

but a discussion about this is beyond the aim of this paper). The direction of target is obtained using a real beam or a synthetic aperture. In the first case a large high gain (i.e., very directive) antenna is rotated to scan all directions, in the second case a small low-gain antenna is moved along a guide in order to "simulate" a larger antenna (Figure 2).

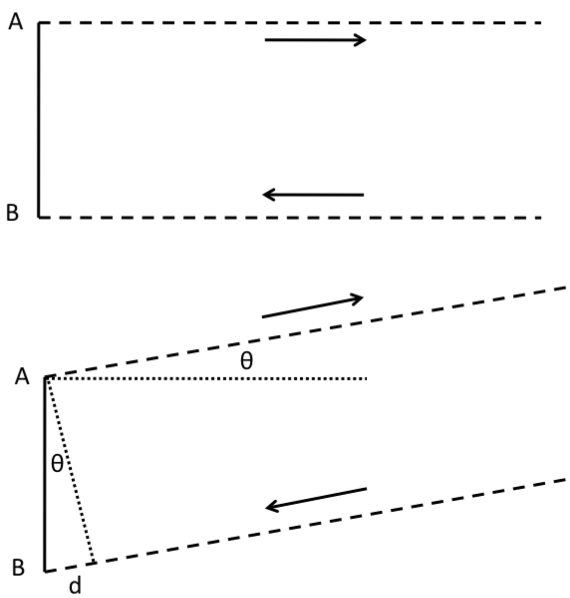

Figure 3: Angular resolution for a real beam antenna.

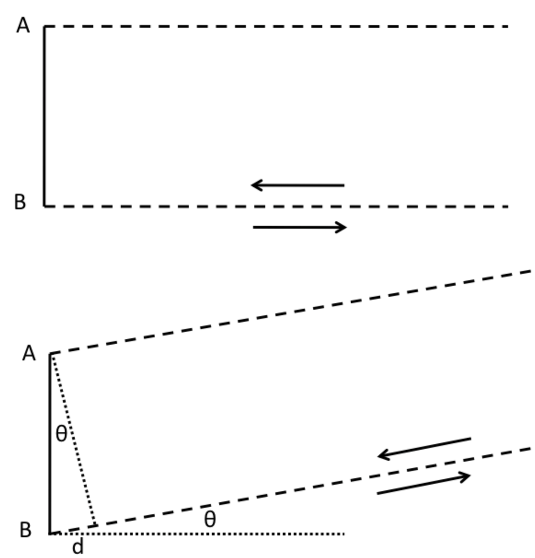

Figure 4: Angular resolution for a synthetic aperture radar.

A remarkable feature of this second solution is that it gives the directivity performances of a physical antenna large L, by scanning a $L/2$ length. In other words a synthetic antenna is in size a half of a real beam antenna. This can be demonstrated rigorously [17], but also by an intuitive way. Indeed, physically what allows to separate two signals incoming from different targets in front of an antenna is their difference of path: when this is greater that wavelength the signals are separable. A physical antenna transmit (or receive) concurrently by all its elements, so with reference to Figure 3 when transmit from point A receive also from point B and the largest difference path between a target in front of the antenna and a target at angle θ is $d = L\sin(\theta)$.

On the contrary, in the case of a synthetic aperture the antenna receives (or transmits) separately from each point along the aperture, so when it transmits from A receive only from A and the largest difference path is twice d as the backscattered wave travel twice the same path.

This is the reason because the size of a synthetic antenna is a half of a physical antenna, keeping constant its directivity. Radars for monitoring slopes are bulky and heavy equipment and their size is constrained by logistic reasons, therefore a synthetic aperture has performances improved of a factor 2 in terms of angular resolution, other things being equal. The higher spatial resolution of synthetic aperture radar may result in an increased capability of detecting localized slope movements (if used at the same working distance of a real beam radar) or in an extension of the operating distance of the radar. This pro has, obviously, some cons. A rotating antenna can scan 360°, while an antenna along a linear guide has a view that theoretically could be 180°, but in practice is about 90° due to the fact that a physical antenna has a beam that sure cannot cover 180°. In principle, the linear guide of synthetic aperture radar or the moving small antenna could be rotated as a physical antenna, but this is rarely done [16]. In fact, the experience shows that such a feature is not a real advantage for typical slope monitoring applications. Since radar does purely measure the components of the 3D displacement vector along its line of sight, the sensitivity to movements of radar depends on how parallel its line of sight is to the 3D displacement direction. Therefore the 360° scan capabilities of real beam radar would be a real advantage in monitoring scenarios characterized by circular shape slope geometries with the radar unit installed in the middle of that scenario, but these conditions are not very common.

In principle, both real and synthetic apertures could provide vertical or horizontal cross-range resolution, but in the practice synthetic radars are designed to have only horizontal angular resolution and to obtain vertical resolution from exploiting the fact that slope is a bi-dimensional surface and therefore 3D acquisition capability is in effect redundant. Indeed, in a real slope it is very improbable that two different targets have same range and horizontal angle (i.e., azimuth). Furthermore, if a 3D model (Digital Elevation Model) of the monitored area is available, the radar image can easily projected on this, resulting an effective 3D visualization. A DEM can be obtained by means of a laser scanner, or also using the same radar. In effect, as it is common by satellite, also a ground-based SAR can produce a DEM just performing two scans with a known baseline [18, 19].

4. NARROW BEAM VS. WIDE BEAM

Another fundamental difference between real beam e synthetic aperture is that the first scans the field of view with a narrow beam, the second irradiates always all the targets. This has the following remarkable consequences.

4.1. Steep Slope Limits

The typical arrangement for monitoring a slope by ground based radar is shown in Figure 5.

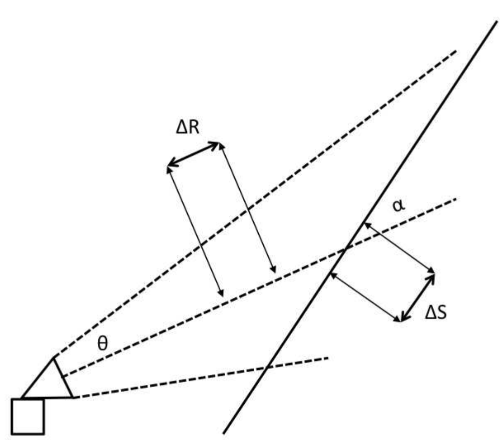

Figure 5: Sketch of a radar installation for slope monitoring.

A wide beam radar obtains spatial resolution ΔS_w along the slope, projecting its range resolution

ΔR

$$\Delta S_w = \frac{\Delta R}{\cos(\alpha)} \tag{3}$$

On the contrary narrow beam radar is able to exploit its directivity and it can provide a spatial resolution on the slope, given by

$$\Delta S_n = \frac{2\theta R}{\tan(\alpha)} \tag{4}$$

As ΔR typically is much smaller that θR, for slope not too steep spatial resolution given by (3) is better than resolution of a narrow beam radar (4). But when the slope is steep, Δs_w can became very large (it tends to infinity for $\alpha = 90°$). In order to evaluate this possible problem in a realistic case we consider: $\Delta R = 0.75\,\mathrm{m}$ (corresponding to 200 MHz, the licensed bandwidth for this kind of applications), $R = 500\,\mathrm{m}$, $\theta = 0.0075\,\mathrm{rad}$ (i.e., a real aperture of 2 m with $\lambda = 0.03\,\mathrm{m}$), then $\Delta s_w < \Delta s_n$ only if $\alpha > 72°$ that is a very steep slope.

4.2. Dynamic Range

As well known, a key requirement for the electronics of a radar is a high dynamic range for acquiring close and far targets. In other words a high radar cross section target close to the radar can blind it by saturating the receiver. In the case of narrow beam, this can be prevented switching off (or decreasing the gain) of the receiver when beam impinges the disturbing target. This is not possible with synthetic radar, that so has to rely exclusively on the dynamic performances of receiver. For early radar, this could be an insurmountable problem, but indeed current receiver have a discrete dynamic margin with respect to the range of the typical signal backscattered by natural and engineered slopes. Obviously a big excavator or haul trucks operating at a few meters from the equipment can be a problem, but at the same way it is an issue for narrow beam radar due to secondary lobes of any real antenna.

4.3. Moving Clutter

Real beam and synthetic aperture radar are affected differently by moving clutter as tracks or mining equipment in the slope. Since real beam radar has an almost instantaneous acquisition, when the beam impinges the disturbing target, the relative resolution simply gives a wrong signal. A synthetic aperture radar perform a sort of average that spread across the image the disturbance, reducing the overall signal to noise ratio, but affecting not a single pixel.

4.4. Multiple Targets in Range

Another essential difference between the two radar technique, is when multiple targets are in the same line of view, for example when a metallic cables on pylons across the scenario. In these cases a real beam radar could detect only the strongest target (the metallic cable, in the example), on the contrary a synthetic aperture radar, due to its own working principle, focuses in all the range.

4.5. Scan Time

A narrow beam radar operates scanning the area of interest line by line, while a synthetic aperture radar traveling along a horizontal guide, acquires the whole scenario in a single pass, therefore it can operate much faster. Typical scan time of modern commercial synthetic aperture radars are of the order of 2 minutes for a full resolution image at 2.5 km of operating distance, compared to 15–30 minutes for typical scan times of modern real beam radar scanning the same area of a SAR system. In principle, a physical antenna could be shaped in order to give an asymmetric beam, narrow in horizontal direction and wide in vertical direction, so also real beam radar could image the whole scenario with a single pass, fast as a synthetic radar. Indeed, this feature is not very common but has been tested [16]. A short scan time is an important figure for almost three reasons: 1) reduction of signal de-correlation due to the not-stationary atmospheric conditions inside; 2) larger phase unambiguity range, therefore higher detectable displacement velocity; 3) higher sensitivity to the detection of slope failure on-set, that could be sampled at higher speed. Of course even real beam radars can reduce the scan time if they needs, but only at the price of a reduction of the area coverage.

5. CONCLUSION

Real Beam and Synthetic Aperture radars obtain angular resolution with techniques quite different. Narrow beam radar relies on load and bulky precision mechanical systems able to move a large physical antenna, while Synthetic Aperture can make use of a positioning system smaller and lighter with mechanical requirements less severe, at the price of stricter requirements for the electronic system in terms of band and dynamic range.

Real Beam is surely a more traditional radar technology, but Synthetic Aperture allows faster and lighter systems with a greater stand-off distance (due to better angular resolution). It can make the difference for critical slope monitoring, where alarms are generated in case of impending failures and on-time detection of acceleration is crucial.

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Errata corrige

As it is evident from the context, at p. 1630, line 10: "then $\Delta s_w > \Delta s_n$ only if $\alpha > 72°$ that is a very steep slope."