

Active Reflectors and Passive Corner Reflectors for Deformation Monitoring Using DInSAR Interferometry: Some Remarks from Sentinel-1 Imagery Tests

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Abstract. Passive corner reflectors are often used in spaceborne Synthetic Aperture Radar interferometry as standard ground points to achieve the monitoring of areas where Permanent Scatters are not available, as in uncoherent areas when the radar backscattering of natural targets is unstable. The main goal of the use of passive reflectors in radar interferometry is to provide a reference to check the stability of the area, for validation purposes, and often to reduce the effect of phase artefacts in data processing. The use of passive reflectors, whose size depends on the operating wavelength of the sensor, can be not suitable, especially in areas like glaciers, snow covered regions, and mountain slopes, where accessibility and installation can be very time and cost consuming, and severe weather conditions can jeopardize their performance. An alternative to passive reflectors can be the installation of active reflectors, compact and lighter, but it is mandatory to have in hands an electric power source. The stability of its amplitude and phase response is basically affected by the presence of active radio frequency components susceptible to temperature changes. When active reflectors are installed for months-to-year-long epochs, the natural variation of the scenario air temperature demands a careful understanding of the device's thermal behavior. Some products have been made available from the market for field campaigns but till now their use has not yet spread. In this paper the authors introduce the basics of passive and active reflectors and compare the recent performance obtained using an active device used for three years to estimate deformation. Finally results available from recent literature are compared to obtain the reliability and performance of the use of an active reflectors in deformation monitoring, estimating the achieved accuracy and providing suggestions for their use.

Keywords: SAR · Interferometry · Sentinel-1 · Corner Reflectors · Deformation

1 Introduction

In Radar spaceborne remote sensing Passive Corner Reflectors (PCR) are often used in Synthetic Aperture Radar (SAR) imaging, and in Differential Interferometric SAR (DInSAR) as standard ground points to increase the extension of the study areas where

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16766, pp. 374–383, 2027.
https://doi.org/10.1007/978-3-032-30539-8_29

Permanent Scatters (PS) are scarce or not available [1–3]. These limitations are usually due to a weak or instable temporal coherence over the survey interval or more generally to an instable radar scenario. Furthermore, the use of such reference targets can support the achievement of higher reliability in final products. The main goal of the use of PCRs in radar interferometry for deformation monitoring is to provide reference data to check the stability of the area, for validation purposes, also reducing the effect of phase artefacts due to atmospheric humidity and temperature variations. These targets appear in amplitude image as pixels with high amplitude and stable response over long temporal periods thanks to their high reflectivity, and they can also provide stable differential phase response too. Sometimes the use of PCRs, whose size depends on the operating wavelength of the sensor, is not suitable for low frequency (i.e. large wavelengths) cases as, S and P bands, and sometimes also for C band, especially in areas like glaciers, snow covered regions, and mountain slopes, where accessibility and PCRs' installation can be very time and cost consuming. Furthermore, severe weather conditions such as strong winds or snow and rain can jeopardize their performance. An alternative to PCRs can be represented by the installation of Active Reflectors (AR), compact and lighter but for which it is mandatory to have in hands a power source.

While a passive reflector simply reflects toward the satellite the satellite signal impinging on its surface using multiple reflections (see Fig. 1a), an AR, when the satellite passes overhead, receives the signal through a first antenna and retransmit it with a higher strength, using the energy of a power source to amplify its signal and making its response stronger than that received one (see Fig. 2a). The stability of its amplitude and phase response, which is fundamental for a successful employ, is basically affected by the presence of active Radio Frequency (RF) components susceptible to temperature changes and the RF circuit usually adds a delay due to electrical connections which must carefully deal with to avoid error in target localization. When ARs are installed for months to yearlong epochs, the electronic and radiofrequency circuits of these devices can be affected by the seasonal variations of the air temperature, and this issue demands a careful thermal understanding of the device's behavior. Some products have been made available from the market for field campaigns but till now their use has not yet spread for two main reasons: the challenge issue of achieving a phase stability as that of PCR and, nevertheless the lower cost of installation, their price is not drastically competitive with respect to that of passive device as discussed in [4]. In this paper we introduce the basics of PCR and AR and compare the recent results obtained using a prototype in the framework of a activity carried out to use DInSAR to estimate deformation of natural surfaces, to those from some studies available from literature. This paper is organized into four sections. After this introduction, the manuscript includes a synthetic section recalling the basic functioning principle of a passive target and of the AR rationale. Some examples from experimental campaigns carried out by the authors follow in the specific section. Main conclusions and remarks are finally discussed in the last section of the paper.

2 Reference Targets for DInSAR Processing

In SAR imaging a processed SLC (Single Look Complex) image associates an amplitude and phase value to each pixel. Differential phase information can be retrieved using two or more images, while amplitude values represent the reflectivity associated to the pixel, or more precisely the amplitude of the backscattering coefficient; its value can be associated to surfaces and to outstanding targets included in the pixel area. The amount of energy reflected by the target can be estimated through its Radar Cross Section (RCS), a parameter defined on the bases of the radar equation [5] and which quantitatively represents the area intercepting that amount of power which, if radiated isotropically, produces the same received power in the radar. Targets with an RCS are significantly higher than the signals coming from the surrounding pixels, namely the radar clutter, appear brighter in the image, easy detectable, and can provide a high phase stability. As DInSAR processing needs phase stable pixels to retrieve the surface deformation, these targets are often installed in the observed areas to monitor ground motion by techniques such as the Persistent Scattering (PS) to retrieve temporal series [6], achieving deformation estimates from a set of SAR images acquired at different dates. Deploying artificial coherent scatters in areas with low interferometric coherence as vegetation layers, which can mask the surface radar response, or snow-covered slope, or glaciers, improve the density of coherent points making the in DInSAR technique application more affordable.

2.1 The PCR

A passive corner reflector (PCR) is a device capable of providing high reflectivity when illuminated by a radar signal. These objects are typically metal structures, with a specific geometry that allows for the efficiency of a large surface area with an optimized shape for its footprint; its capacity to backscatter the impinging radar signal is due to the specular reflectivity of the metal surface at microwaves and on its internal multiple reflections as depicted in Fig. 1a. The PCR 's response is typically not very directional, as this would otherwise make it difficult to orient when installed for satellite imagery acquisition. It allows to estimate the differential phase response which is the fundamental parameter from which using DInSAR measurements can retrieve estimates of the deformation over the monitored areas. To evaluate the quantitative achievement of a target response, RCS must be sufficiently high, and the Signal to Clutter Ratio (SCR) which estimate the ratio between the RCS of the target and the signal, as noise, coming from the pixel surrounding that corresponding to the target [7]. A detailed knowledge of the response of PCR must consider factors as the geometry of the installation and the surrounding surface, as deeply analyzed in [8], but most of their applications use a basic approach to obtain its signature. In particular, the phase accuracy expected in DInSAR data processing is usually estimated through the magnitude of the SCR and for a stochastic backscattering environment, a simple formula can be used [9]:

$$\Delta\varphi = \frac{1}{\sqrt{2\,SCR}}$$

Triangle Trihedral Corner Reflectors (TTCR) are the most diffused PCR used to calibrate the amplitude response available from a SAR image and give a reference phase point in DInSAR data processing. Their main performance is a fairly large RCS for its size, over a broad range of aspect angles, whose maximum can be easy calculated through the following formula:

$$RCS = \frac{4\,\pi\,l^4}{3\,\lambda^2}$$

where λ is the radar wavelength, and l is the inner-leg dimension, RCS is in m^2.

When designed to be used for C band, the operating frequency of Sentinel-1 (S1), and even more with spaceborne radar operating at lower frequencies, the PCRs are bulky because the maximum achievable RCS is related to its size. For example, to obtain an expected accuracy of 1 mm at C band (e.g Sentinel-1 signal with centre wavelength = 5.5467 cm) is necessary to install a TCR whose size is greater than 1.7 m (see Table 1 pag.6 [9]). This fact often results in further issues when hard weather conditions, such as heavy rainfall, strong winds and snowfall are frequently occurring in the installation site. In addition, their placement can be difficult in sites of hard accessibility as mountain slopes, glaciers etc. Different kind of PCR have been proposed in literature and recently the test a novel low-cost prototype has been published [4]. In Fig. 1b a picture of a Square Trihedral Corner Reflector (STTR), a metal structure 0.60 m size, installed in a mountain area to support the monitoring of a landslide in the framework of the deformation monitoring campaign carried out using Sentinel-1 imagery and DInSAR processing [10]. This type of PCR with respect to the most used TTCR performs a higher RCS without increasing excessively the encumbrance and the installation at the cost of slightly smaller angle of aperture.

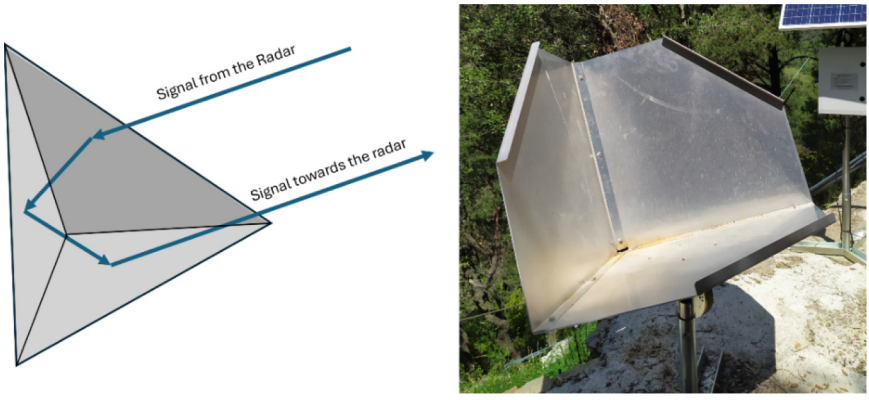

Fig. 1. Left: Working principle of a TTCR; right: Photo of a STCR.

2.2 The AR

Differently from a passive reflector, an AR, receives, amplifies and retransmit the received signal finally making its response stronger than that received one. The stability

of its amplitude and phase response, which is fundamental for a successful employ, is basically affected by the presence of active Radio Frequency (RF) components susceptible to temperature changes. In this paper we analyse the performance of an AR designed and implemented according to a design rationale focused on the achievement of the performance required for its use in deformation monitoring where aspects as a low cost, easy installation, and a low power consumption. These characteristics make simpler the setup of a dense network often demanded in large low co-herence areas deformation monitoring. In Fig. 2 the working principle and a photo of an AR prototype are shown.

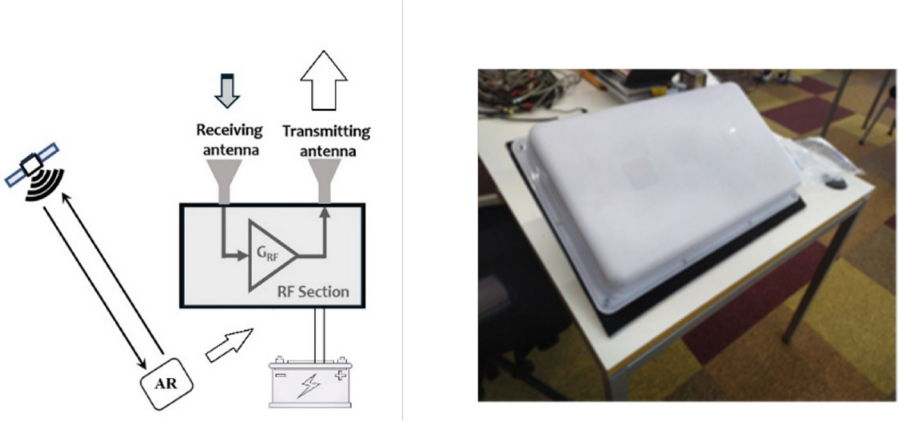

Fig. 2. Left: Working principle of the AR; right: Photo of a recent prototype available at CTTC.

An AR is available on the market since several years: the Electronic Corner Reflector (ECR-C) from Metasensing [11]; more recently a device designed to be used with the same satellite imagery, has been proposed in [12]; data discussed in this paper have been acquired using this device. The C-band AR proposed as an alternative to passive reflectors in a context where the required accuracy is of the order of a few millimeters as in application cases of interferometry used for deformation and land-slides monitoring with Sentinal-1 imagery. In the last decade some papers discussed the potential and issues of compact active transponders on an experimental basis [13–15]. The AR used in [12] was designed to provide a sufficiently stable phase response with reduced encumbrance and low power consumption and cost. In this paper we compare the accuracy achieved using this prototype to the observation's outcoming from some literature. We summarize the main outcomes achieved in [16] in the following section before discussing the comparison between AR and PCR.

3 A Test Based on Experimental Data

The data concerning this analysis was collected with the aim of monitoring an area threatened by a rockslide landslide. In a previous study [10], the AR was used as a reference point for the calculation of the interferometric phase of a set of PCRs, all

distributed in a large unstable area to provide a set of PSs for monitoring a large area. The orientation of the AR is azimuth North-100° and elevation East-51°, its position: Lat. 42° 26' 53" N, Long. 1º 29' 00" E, altitude: 980 m a.s.l. The selected area is indeed an area with very unstable temporal coherence due to the presence of vegetation. The AR is powered by a battery (12 V and capacity 70 Ah) and a solar panel (60 W). In order to evaluate the deformation data, 114 SAR images from Sentinel-1 SLC, descending geometry, orbit 110 and VV polarization were used. The interval covers the period from 4 December 2020 to 3 August 2023 for a total of 413 interferograms. The data was processed using the CTTC Persistent Scatterer Interferometry (PSI) processing chain [17]. The Digital Elevation Model (DEM) available from the Shuttle Topographic Mission (SRTM) was used with a resolution of 30 m. For interferometric processing, acquisitions in IW mode were processed. Figure 3a and Fig. 3b show two amplitude images obtained after applying a coherent average over 70 images, when the AR was not present, and 114 images with the AR working respectively. Both images include the response of a square trihedral corner reflector whose inner edge length is 0.60 m always working. The AR response clearly outstands with respect to that of PCR. Before analyzing the phase data, it is important to verify also if the amplitude values maintain sufficiently high and stable as previously commented. In Fig. 4 we show the amplitude (backscattering coefficient) obtained from the GRID images vs the acquisition date of the S1 images; except for some data missing due to battery drawbacks the average and standard deviation of the three data sets are satisfactory stable (see Table 1):

Table 1. Mean and standard deviation (STD) of the backscattering coefficient series for the AR and the surrounding clutter.

Target	Mean(dB)	STD(dB)	SCR(dB)
AR	+11.23	0.838	+24.00
Clutter	−21.17	1.803	+32.40

The corresponding trend for the phase data is shown in Fig. 5 which shows the data retrieved from the interferometric processing vs. the acquisition date. As expected, we observe the presence of periodic behavior which can be correlated to the seasonal variation of the air temperature at the satellite pass time on the AR electronics; anyway this correlation appear weak, as confirmed through the analysis of temperature internal to the case [16], but this can be ascribed to the limited range of variation of temperature values. Table 2 reports the mean, and the standard deviation of the displacement values plotted in Fig. 5.

Over the whole period of observation, the AR maintains the fluctuations within a two millimeters range of variation and 0.5 mm of bias. In previous paper focused on the use of a network of PCR during the same campaign [10] the stability associated to a stable PCR was estimated a bit worse than 1 mm per year; of note that this data is obtained over lapse of time, one year, shorter than that of the data of AR here analyzed which cover almost three years. Considering the accuracy required during a landslide or deformation monitoring in Line of Sigh (LOS) direction, this value can be considered satisfactory.

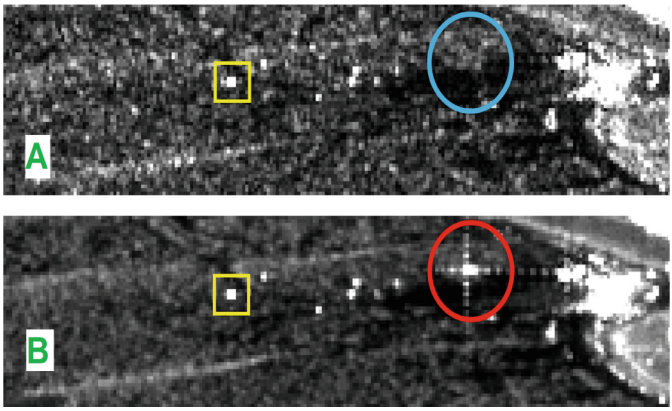

Fig. 3. Example of mean amplitude images with and without the AR. The yellow square indicates the PCR response. (After [16]); A without the AR, B with the AR switched on.

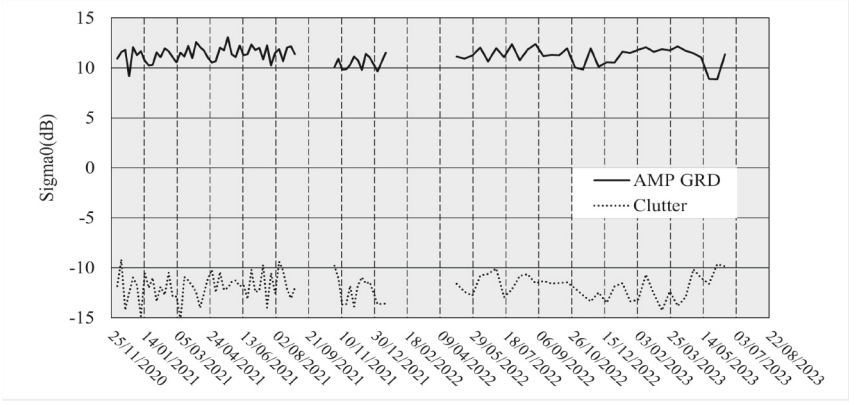

Fig. 4. Temporal series of amplitude for the AR.

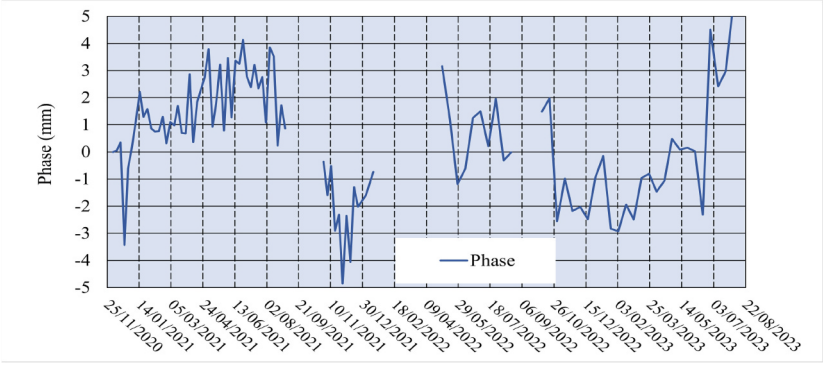

Fig. 5. Temporal series of the differential phase for the AR.

Table 2. Main statistical parameters of the phase data calculated form the temporal series expressed in mm of LOS displacement.

Target	Mean	STD	Min	Max
AR Phase (mm)	0.50	2.11	−5	6

4 Conclusions and Remarks

The values recalled in the previous section must be compared with data obtained from other experimental campaigns. One of the first comparisons of active reflectors' performance is in [13], where the applicability of active radar transponders for deformation measurements is studied and validated. Using more than one hundred of transponder-InSAR observations, from Envisat and ERS-2 imagery, and independent validation measurements such as levelling and the GPS, the authors achieve an empirical precision range of 1.8–4.6 mm, for double-difference (spatial and temporal) transponder phase measurements in the radar LOS. The study includes different scenario conditions as a quiet meadow and in an operational field case. On this basis, the authors consider a transponder "a compact and lightweight alternative to a corner reflector" [13]. This value is close to that achieved in [16] nevertheless the different device and incidentally data source (Sentinel-1). In a subsequent paper based on the use of the same device and using Sentinel-1, a longer set of time series, corresponding to almost one thousand measurements over 21 months is analyzed [14]. They found a partial correlation with surface temperature changes and the phase stability compared to a stable reference passive reflector corner is estimated to be 0.5–1.2 mm. The capacity to provide a stable reference also in geodetic survey is analyzed; the phase is confirmed to be significantly correlated with environmental temperature variations, showing variations within a range of 6 mm. This aspect demands a specific calibration for each device, as suggested in [12]. It depends on the specific case study, and this demands a careful analysis of the clutter signal characteristics. A most recent paper focuses on the usability and long-term performance of the AR referred as Compact Active Transponder (CAT) evaluated using two CATs from METASENSING in a field test [15]; in the study a vertical displacement of a CAT has been achieved using InSAR with an accuracy better than 1 cm, possibly a few millimeters and that the mean vertical velocity calculated from 14 months of InSAR displacement time series, can be determined with an accuracy of a few mm/year. It is confirmed that the LOS phase error is generally found to be moderately correlated with temperature, and the LOS error is ruled by linear relationship between and temperature ranging between approx. 0.1 and 0.2 mm/°C, a value close to that achieved in [12]. Finally, the main recommendations from the lesson learn according to the few papers available on the operative use of ARs can be resumed in the following. The device must be characterized not only through standard laboratory tests but also by providing calibration reports carried out in field conditions or disposing of some passive reflectors close to their installation site. In case of geodetic use, the delay added by the device, which appears to be significantly different in different devices, see [12] and [15], must

be carefully considered. Finally, we underline that although at C band the main advantages are not strictly from a quantitative performance point of view, i.e. better stability or higher accuracy, the AR demands an easier and lower costs of installation especially in hard environments. These advantages become more effective for lower frequency radar observations, see for example recent new space-borne SAR missions as NISAR and Biomass, where the installation of PCR with sufficient RCS should require unfeasible size.

Acknowledgement. This work has been partially funded by AGAUR, Generalitat de Catalunya, through the Consoli-dated Research Group RSE, "Geomatics" (Ref: 2021-SGR-00536) and it was conducted as part of the EU-funded project PERMAPYRENEES (INTERREG-POCTEFA 2021–2027, EFA063/01).

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