PTA-InSAR rock slope monitoring at the Gascons site, Gaspé Peninsula, Quebec

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ABSTRACT
An unstable rock slope situated between Port-Daniel and Chandler in the Gaspé Peninsula (Quebec) has been impacting a railway line for several decades. As part of a detailed monitoring program, a set of artificial targets were installed in the vicinity of open fissures, on unstable rock blocks, and on infrastructure in fall 2009. These targets are remotely monitored by SAR (radar) satellite signals orbiting at an average altitude of 798 km to measure slope movement. This paper briefly presents the site conditions at the Gascons rock slope and reviews the PTA-InSAR technique. It describes the installation of the corner reflectors, including the anchoring systems.

RÉSUMÉ
Entre Port-Daniel et Chandler dans la Péninsule gaspésienne, un versant rocheux instable affecte depuis plusieurs décennies un segment d'une voie ferrée. Dans le cadre d'un programme de surveillance étoffé, un ensemble de cibles artificielles ont été installées à l'automne 2009 au voisinage de fissures ouvertes, de blocs rocheux instables, et sur des infrastructures en place. Ainsi, les movements de pente sont télésurveillés par des signaux provenant de satellites radar orbitant à une alitude moyenne de 798 km. Cet article présente brièvement les conditions de terrain au site de Gascons et revoie la technique PTA-InSAR. Il décrit le déploiement des réflecteurs en coin ainsi que leurs systèmes d'ancrage.

1 INTRODUCTION

Remote sensing including InSAR (Interferometric Synthetic Aperture Radar) techniques are increasingly being used in both rock and soil slope stability assessment and applied to landslide hazard environments (Nichol & Wong 2005; Tralli et al. 2005). The application of interferometric techniques to monitor landslides has been developing rapidly, including its application to landslides (Colesanti and Wasowski 2006; Singhroy 2008; 2005) and mass movements in remote areas (Alasset et al. 2007, Singhroy et al. 2008) and in vicinity of infrastructure (Singhroy and Molch 2004).

This paper presents the application of InSAR techniques to an unstable rock slope in the Gaspé Peninsula that has been impacting a railway line for several decades.

The use of InSAR techniques to monitor rock slope movement is part of a near real-time monitoring program that has been recently developed at this site to strengthen the railway network and to ensure a safer railway service in the Gaspé Peninsula (Locat et al. 2010; Danisch et al. 2010; Lord et al. 2010; Cloutier et al. 2010). The InSAR monitoring will contribute to the two main objectives of this multidisciplinary project: 1) development of long-term monitoring techniques for measuring physical parameters responsible of slope movement; and 2) a better understanding of causes and consequences of slope movement to provide decision-makers with better tools in hazard and risk management.

The following sections of this paper briefly describe the monitored site and geological conditions, and discuss the installation of the corner reflectors, as well as preliminary results obtained from SAR imagery.

2 STUDY AREA

2.1 Location and background

The study area is situated between the village of Port-Daniel-Gascons and the town of Chandler on the south coast of the Gaspé Peninsula, Quebec (Figure 1). The study area that comprises the unstable rock slope is called the Gascons site. This site is located at the mileage 30.5 of the Chandler Division along the railway line linking the city of Gaspé and the interprovincial railway network. This section of the railway line has been disrupted by slope movements over the last several decades and has required continuous maintenance and multiple repairs.

Previous field studies carried out in the 1990's by researchers from Université Laval (Locat & Couture 1995a; b) revealed a complex network of large open fissures beneath and in the vicinity of the railroad. Monitoring data obtained in the mid-1990's showed that some rock blocks and fissures are characterized by significant displacement. On July 23, 1998, a rock failure occurred closing the railway for several days.

2.2 Geomorphological and geological setting

The unstable rock slope is composed of three main sectors (Figure 2). The paper by Cloutier et al. (2010) in these conference proceedings describes the site in more detail. The first sector is a southeast facing 60 m-high cliff overhanging the Pierre-Loiselle Cove of the Baie des Chaleurs. This sector is characterized by partly vegetated colluvium and bedrock. It also comprises a large unstable rock block adjacent to the railway line called the Petit-

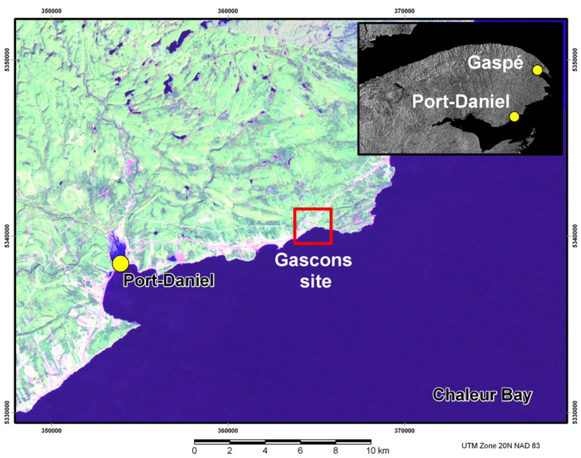

Figure 1. Location map of the Gascons rock slope. Sources: Landsat7 scenes (000906-010909), RADARSAT mosaic 250m (pixel size), © Department of Natural Resources Canada. All rights reserved.

massif which was subjected to a previous failure in 1998 and is still subjected to significant movement.

The second sector is a large forested area located north of the railway line. This sector extends 180 m east-west and 130 m north-south. The average slope of this vegetated sector is about 15°. The sector is comprised of several blocks separated by linear fractures. These features are either fissures with openings up to tens of meters or long, narrow linear depressions. Beneath the vegetation carpet, a 0.5-2 m thick overburden mainly composed of till and blocks detached from weathered bedrock overlie the bedrock.

The third sector is defined as more or less the right-of-way of the railway line between the two other sectors. It consists of the railway foundation material, i.e. coarse granular material (ballast), colluvium and a 65 m-long two-tier retaining wall. This sector also exhibits discontinuous open cracks which are responsible for the loss of ballast beneath the railway track.

The bedrock geology in the study area mainly consists of a nodular and conglomeratic mudstone (Anse-à-Pierre-Loiselle) with bedding striking southeast and dipping 20-25° south (Figure 2). A second formation encompassing parts of the rock cliff, including the Petit-massif, is composed of nodular wackestone and mudstone (La Vieille Fm.). To the east, a third bedrock formation is composed of thick bedded sandstones (Cascon Fm.) showing the same strike and dip as the mudstone formation.

Two main orthogonal joint sets, perpendicular to the bedding planes, control the discontinuity network at the site. Two regional linear features, the Rivière Port-Daniel fault and an angular discordance, are also found at the site (thin black lines in Figure 2). The paper by Cloutier et al. (2010) in these conference proceedings describes in detail the structural geology of the site.

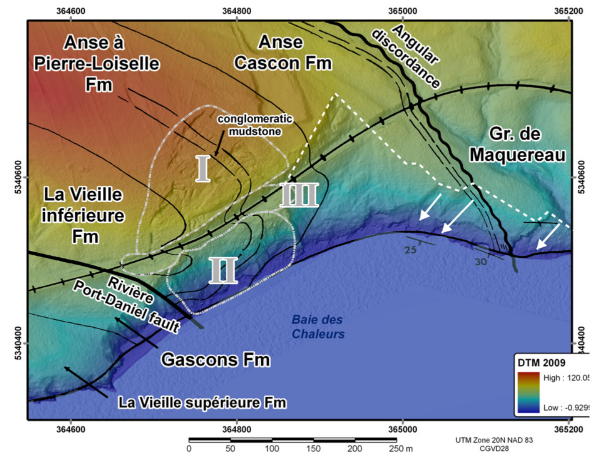

Figure 2. The three main sectors of the Gascons site and old mass movements (white dashed line) superimposed on simplified bedrock geology map. (Sources : LIDAR survey, U. Laval; Geology modified from Bourque and Lachambre 1980).

2.3 Slope movements

The site is characterized by (undated but probably historic) large slope failures. Two are located about 300 m east of the unstable rock slope inside a major scar situated immediately east of the unstable area (Figure 2). This scar has been recently discovered following the examination of images from LIDAR surveys (Figure 5; see also paper by Lord et al. in the conference proceedings).

As introduced in Section 2.2, the forested sector is characterized by the presence numerous large, open fissures mainly oriented NNE-SSW and ESE-WNW coinciding with the main discontinuity sets found in the underlying bedrock. Fissure openings vary from tens of centimetres to tens of meters (Figure 3), indicating significant slope movement and instability processes at the site. These processes generate high levels of maintenance along this stretch of the railway line as some fissures extend beneath the railway. Movement mechanisms are not fully known but they potentially involve sliding along a deep seated plan of weakness, as well as toppling in the rock cliff (Sector I). The paper by Cloutier et al. in these conference proceedings gives an insight on the possible instability mechanisms.

Figure 3. Photo illustrating a large open fissure in the forested sector (Sector II in Figure 2) above the railway corridor.

Some of these fissures were monitored in the 1990's and are now part of a new monitoring program using traditional geotechnical instrumentation. Most instrumented fissures have shown displacement of few millimeters to centimeters since fall 2009 (Lord et al. 2010 in these proceedings).

In the 1990s, the Petit-massif showed large displacements (Couture and Locat 1995b). In 1998, it was involved in a rock slope failure damaging parts of a retaining wall, closing the railway for several days.

3 ROCK SLOPE MONITORING WITH PTA-INSAR

3.1 Overview of PTA-InSAR

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that uses multiple images from radar satellites (e.g. Radarsat-2), which transmit electromagnetic waves towards the earth and record them after they are reflected back from the Earth's surface. Every pixel of the SAR images includes two types of information: i) the signal intensity, i.e. how much energy of the wave is reflected to the satellite. The intensity is a function of the electromagnetic and geometric properties of the interacting media and can be used to characterize the reflecting targets at the Earth's surface; and ii) the phase of the wave which is a function of the distance between the antenna and the target. The phase of the reflected wavefront image should be unchanged when the same radar sensor images the exact same portion of the Earth from the same location in orbit. If this is not the case, then the target has moved in the re-visit interval (e.g. slope displacement).

SAR Interferometry analyzes a pixel's phase difference between two coregistered images, for every pixel in the images. To be suitable for InSAR, a correlation or certain degree of similarity in the surface properties must exist between corresponding pixels of the two image acquisitions. This is quantified by the coherence image. Due to a higher signal to noise ratio, usually brighter pixels represent good correlation statistics, whereas darker pixels express lower correlation.

Point Target Analysis (PTA) is one of the approaches amongst InSAR techniques that uses radiometrically stable scatterers for detection and processing of coherent information from multiple SAR acquisitions. Point-like targets offer good correlation over time, making it possible to estimate deformation rates at measurement locations over long term series InSAR dataset when natural ground properties such as vegetation, humidity, soil properties, and deformation rate changes influence the backscattered signal phase.

3.2 Artificial targets or corner reflectors

Trihedral corner reflectors (Figure 4), although they have been used for over 50 years for radiometric and position referencing, are now being used as point target for interferometry. These corner reflectors are phase coherent pass to pass and thus can be used to measure the position changes of the underlying scene (e.g. active slopes). These aluminum trihedral corner reflectors offer four advantages: i) they are simple devices to manufacture; ii) they have large radar cross sections for their physical size; iii) they have wide angular acceptance angles; and iv) they are reasonably easy to deploy (C-CORE 2006).

Such corner reflectors have been installed on unstable slopes in Canada to monitor movement, including sites in the Mackenzie River valley (Thunder River, Couture et al. 2007), northern British Columbia (Buckinghorse, Hawkins et al. 2007); Alberta (Little Smoky River, Froese et al. 2008; 2009); and southern Yukon, C-CORE 2007).

The following section describes the deployment of corner reflectors at the Gascons site to accompany the development of a long-term monitoring program and to fulfil the objectives related to a better understanding of causes and consequences of slope movement.

Figure 4. Photo of a corner reflector (CR1) installed at the Gascons site. A D-GPS antenna is temporarily

installed on the corner reflector to measure its exact location.

4 DEPLOYMENT OF CORNER REFLECTORS

4.1 Location selection

Strategic locations for the corner reflectors at the Gascons site were based on the extent of the unstable rock slope, the distribution of open fissures, the identification of key compartments or zones thought to be more prone to displacement, the landslide processes and potential direction of movement, and the location of complementary, ground-based geotechnical instrumentation. Their locations were also dictated by measuring relative slope movement along two main perpendicular axes within the unstable area, and by comparing measured displacement with adjacent stable zones.

A total of eight corner reflectors were installed in October 2009 as part of extensive field campaign dedicated to characterizing the site and installing monitoring devices. Two of the corner reflectors (CR1, CR2) were deployed in areas located outside the unstable area (Figure 5), and therefore these corner reflectors are considered as stable reference targets. Corner reflector CR1 is installed in an opening within the forested sector. It is located northeast of the unstable area along the western margins of the opening, but far enough from an adjacent abandoned garage to avoid any interference of the garage with the radar signal. The second stable corner reflector, CR2 (Figure 6), is mounted on the roof of a small utility bunker located about 50 m from the western slide limits and within the limits of the right-of-way of the railway (Figure 5).

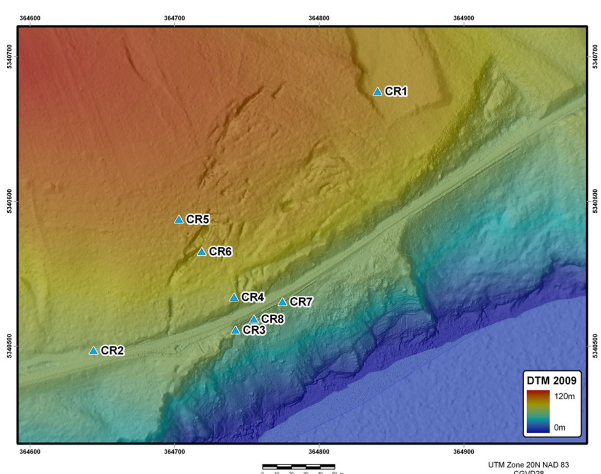

Figure 5. Map showing location of the eight corner reflectors installed at the Gascons site. DEM results from lidar survey performed in late fall 2009 (source: LIDAR survey, U. Laval).

Six other corner reflectors (CR3 to CR8) were installed within the limits of the area affected by slope deformation. These corner reflectors are meant to measure slope displacements in the three sectors (see §2.2) of the site. Four of them (CR3 to CR6) are aligned along a north-south axis, which is believed to be more or less parallel to the main direction of slope movement; whereas three corner reflectors (CR3, CR7, and CR8) are aligned east-west in a direction perpendicular to the slope movement.

Corner reflector CR3 belongs to both alignments and is installed on the southeast facing rock face of the Petit-massif (Figure 7). This is considered the most unstable block among the entire unstable zone.

Figure 6. Photo of corner reflector CR2 installed on the roof of a utility bunker at the Gascons site.

Figure 7. Corner reflector CR3 anchored on a southeast facing rock face of the Petit-massif at the Gascons site.

Corner reflector CR4 is located immediately adjacent to the railway track on top of a 10 m-high railway cut (Figure 8). CR4 is installed upslope of an open fissure that extends beneath the railway bed and towards the Petit-massif.

Two corner reflectors (CR5 and CR6, Figures 9 and 10 respectively) were installed on both sides of a large open fissure (identified as Fissure No. G in Lord et al. 2010 in these conference proceedings) that extends over 55 m from the railway track to the northern tip of the unstable area (Figure 5). It defines the north and northwestern limits of the unstable area. This fissure is about 9 m wide at its maximum and exhibits a graben-like shape with collapsed rock blocks.

Finally, two other corner reflectors (CR7 and CR8) were anchored on two sections of the retaining wall extending 15 m and 35 m east of the Petit-massif. CR7 was installed on one of the vertical iron H-beams at the eastern end of the retaining wall (Figure 11). This section of the retaining wall shows indication of past displacement as shown in Figure 11.

CR8 was anchored to the wooden structure of the western section of the retaining wall (Figure 11). This section of the retaining wall was re-built after the July 23rd, 1998, failure of the rock slope. Protective structures at CR7 and CR8 prevent potential damage caused by plowed snow or falling and bouncing rocks.

Figure 8. Photo of CR4 located on top of the railway cut.

Figure 9. Photo of corner reflector CR5 located on the north side of fissure No.G.

Figure 10. Photo of CR6 located on the downslope side of fissure No. G.

Figure 11. Photo illustrating corner reflector CR7 (foreground) with a D-GPS unit mounted on it. Corner reflector CR8 installed on the retaining wall (left-hand side of the photo) and CR3 anchored on a southeast face of the Petit-massif (background).

4.2 Installation and anchoring of corner reflectors

To ensure phase stability, corner reflectors must be structurally rigid and stable three-dimensionally to allow displacement measurement accuracy of the order of 1 mm. Rigid stainless steel rods are usually fixed obliquely from one leg another to ensure an adequate level of stiffness of corner reflectors (Figures 7, 8, 9, and 10). In addition, the corner reflectors have to be securely mounted on the ground whose motion is to be measured. In the forested sector, felling of trees was required at locations of CR4, CR5, and CR6 in order to obtain an unobstructed view between reflectors and SAR satellites. One full day was required for assembling the eight corner reflectors prior to their installation.

Three main installation scenarios were developed depending on the location of the corner reflectors and ground and infrastructure conditions; therefore, various anchoring systems were developed. All corner reflectors require at least three anchoring points to ensure rigidity and stiffness. The following sub-sections describe the anchoring systems in bedrock, overburden, and on infrastructure.

4.2.1 Anchoring system in bedrock

When bedrock was outcropping or <1 m below the surface, the anchoring system chosen involved 5/8-11" threaded stainless steel rods anchored into the bedrock by drilling 1"-diameter and 12"-deep holes and cementing the rods in place using fast drying glue. Holes were drilled with a portable generator-powered hammer drill. Drilling direction and inclination were dictated by the position and orientation of the corner reflectors. Fine particles from drilling were blown out of the holes before inserting the glue and rods. Three to five holes are usually required: two for the front legs and one to three for the back of the corner reflector. Figure 4 shows a typical installation for a corner reflector anchored in bedrock (CR1).

The anchoring of corner reflector CR3 at the Petit-massif was somewhat challenging as it was installed on a rock face (Figure 7). The installation required the professional services of rock climbers.

4.2.2 Anchoring system in overburden

When the overburden thickness exceeded 1 m, the developed anchoring system involved the use of 9/16"-diameter stainless steel rods that have an internal threaded hole (3/8"-18) on each end and are approximately 48" long. Threaded rods are inserted into the ends so that several rods can be joined. Those rods were driven into the ground using a sledge hammer until refusal. The system used took into account of potential frost heave. Thus the rods were inserted into frost pipes made of ½" diameter schedule 44 steel water piping. Hawkins et al. (2007) described the design of the frost pipe. Such design was used for corner reflectors CR5 and CR6 (Figures 9 and 10). Plastic winged-tubes were also used as frost pipes (at CR4 only, Figure 8). Pulling tests were also performed once the rods had been driven in the ground to verify the quality of the anchoring system.

4.2.3 Anchoring systems on infrastructure

Three corner reflectors (CR2, CR7 and CR8) required special anchoring systems specifically designed to accommodate their installation on the in-place infrastructure, either the utility bunker (CR2) or the retaining wall (CR7 and CR8).

The installation of CR2 was facilitated by a stainless steel plate mounted on the roof of the utility bunker. 5/8-11'' threaded stainless steel rods bolted into that plate were used as front and back legs for CR2 (Figure 6). In this case no additional reinforcement rods were required to ensure stiffness and stability of CR2.

The same technique was used to anchor CR8 on a wooden platform mounted at the base of the westernmost section of the retaining wall (Figure 11).

Finally, corner reflector CR7 required a unique anchoring design as the back of the corner reflector was attached to a vertical steel H-beam, whereas one side was anchored into horizontal 6x6" wooden creosoted beams (Figure 11). Rigidity was found sufficient with only three anchoring points; the external side of the base of the corner reflector did not require any anchoring.

4.3 Orientation and inclination

In order to maximize the quality of the backscattered radar waves, the symmetrical axis of the corner reflectors should point toward the looking view of the SAR satellite, both for azimuth and elevation pointing. Consequently, the bottom edges of the corner reflectors were aligned to the azimuth 10° and their bases were tilted up by a 19° angle relative to horizontal.

4.4 D-GPS measurements

The corner reflectors were surveyed with Novatel dual frequency GPS with site occupations between 3 and 22 hours in length (Figure 4). A local survey monument was used for differential corrections. The survey marker position was determined using NRCan PPP (Precise Point Positioning) with an absolute accuracy of 1 cm. The 3D sigma relative accuracy of the reflector positions was better than 1 cm for all reflectors. Three old benchmarks were surveyed with similar accuracy except one with 2 cm accuracy due to overhead obstructions.

4.5 360° photography

Panoramic photos using a Nikon D300 with a 10.5 mm Nikkor lens and a Nodal Ninja Ultimate R10 panoramic head were taken at five reflectors and three benchmarks. These photos taken at known locations will be used to identify small changes in the site between field visits.

5 RESULTS - SAR IMAGES ACQUISITION

Since the installation of the corner reflectors, RADARSAT-2 SPOTLIGHT SAR data are acquired routinely over the site. InSAR requires that the data be acquired on the same relative orbit which occurs every 24 days. Table 1 presents the acquisition series for the two SPOTLIGHT modes SLA-19 and SLA-76. This SAR database will continue to grow every 24 days up to the end of the monitoring program.

Table 1. RADARSAT-2 acquisitions for the two SPOTLIGHT modes.

SLA-19	**SLA-76**
2009-11-07	2009-11-03
2009-12-01	2009-11-27
2009-12-25	2009-12-21
2010-01-18	2010-01-14
2010-02-11	2010-02-07
2010-03-07	2010-03-03
2010-03-31	2010-03-27
2010-04-24	2010-04-20
2010-05-18	2010-05-14
2010-06-11	2010-06-07

Figure 12 shows the stack average of all SLA-76 already acquired. By their bright intensities, the corners reflectors can be easily identified (highlighted by green circles) and confirm that they are well aligned with the incoming radar waves. To be statistically accurate, the PTA-InSAR technique requires at least 20 SAR scenes. With the coming spring and summer acquisitions, it will be possible to begin the PTA-InSAR analysis.

6 DISCUSSION AND CONCLUSION

NRCan in collaboration with partners has deployed corner reflectors for application of InSAR at several sites in western Canada (Couture et al. 2007; Froese et al. 2008; 2009; Hawkins et al. 2007). However, the deployment of corner reflectors at the Gascons site is the first of its kind in eastern Canada by NRCan. It is only the second deployment on an unstable rock slope. This site is as challenging as the others as the ground conditions were not uniform and required diverse and non-traditional design of the anchoring systems.

This site also offers multiple environments for corner reflector locations, from clean, well-exposed bedrock to vegetated surfaces.

The application of InSAR techniques at the Gascons site also benefits from the deployment of traditional and new geotechnical monitoring instruments (Locat et al. 2010; Danisch et al 2010). The presence of these ground-based instruments will help in validating the displacement results obtained from InSAR and facilitating their interpretation. Comparison of monitoring data from PTA-InSAR and ground-based measurements can be performed as soon as a sufficient number of SAR scenes is acquired. Preliminary results should become available in fall 2010.

The high resolution digital elevation model (DEM) of the site obtained from lidar surveys, which was carried out after the deployment of corner reflectors in fall 2009, has led to a much better assessment of the distribution of open fissures in the forested sector (Sector II) and the identification of large displaced zones, especially in the north-east zone of Sector II. Thus, the installation of additional corner reflectors is envisaged during the fall 2010 in order extend the monitoring to newly identified potentially moving blocks and contribute to a better characterization of the displacement mechanisms destabilising the rock slope.

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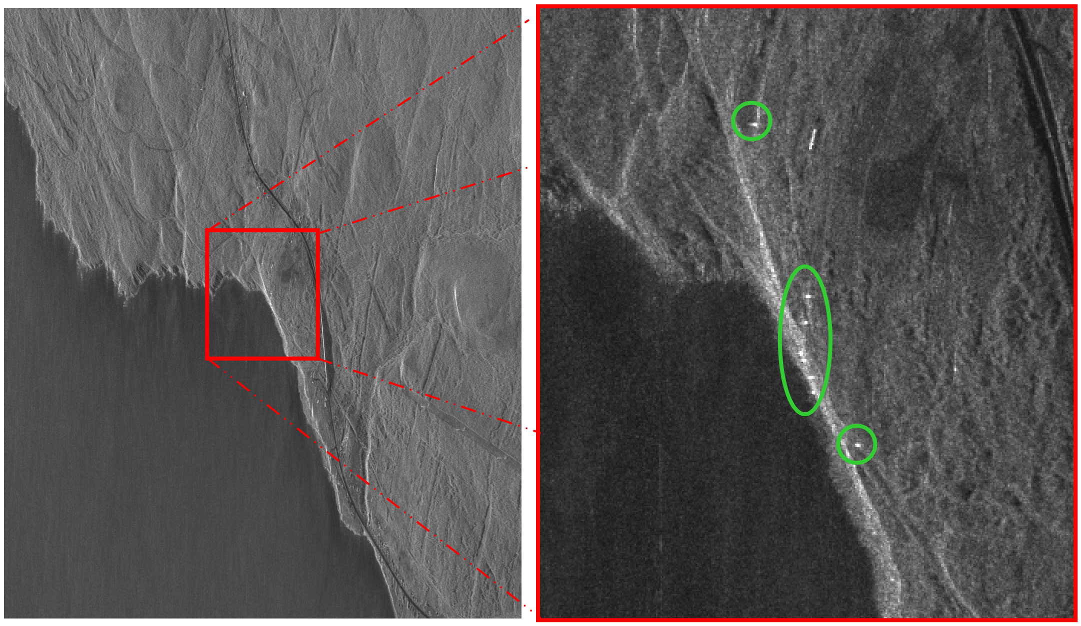

Figure 12. RADARSAT-2 SPOTLIGHT SLA-76 SAR stack averaged data in slant range geometry acquired over the Gascons site (Left). Right figure zooms on site where corner reflectors are circled in green. RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates ltd. (2009) – All Rights Reserved RADARSAT is an official mark of the Canadian Space Agency.

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