INSAR ASSESSMENT OF PIPELINE STABILITY USING COMPACT ACTIVE TRANSPONDERS

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ABSTRACT

This study examined the use of a network of 7 prototype Compact Active Transponders (CATs) to measure ground and pipeline motion in an area subject to landslides in northern Italy. The results showed that two of the CATs, located at the center of the study area, experienced higher rates of line-of-sight (LOS) motion than the others. The spatial variation in the LOS motion rates could indicate that the central section of the slope moved at a higher rate, most likely in a westward and down-slope direction during the study. In addition to the InSAR measurements, GPS campaigns provided four epochs of motion measurements. Despite technical and environmental challenges, the study demonstrated the potential use of CATs to remotely map and monitor ground and structure motion.

1. INTRODUCTION

The construction of oil and gas pipelines in remote, inaccessible and challenging environments increases susceptibility to ground stability hazards. Landslides and mass movements; subsidence and uplift due to oil, gas and water abstraction and enhanced recovery; underground mining activities; fault creep and rupture; and volcanic deformation, can put pipeline integrity, and therefore operations and the local environment, at risk.

To detect early warning signs of these hazards and reduce the risk of damage, the stability of the ground surface around the pipelines is traditionally monitored with ground based technologies such as GPS surveys, slope inclinometers, tiltmeters, accelerometers, strain gauges and thermistors [1]. The ability to remotely monitor pipeline movement and movement of the ground in or over which the pipeline and associated structures are installed, without the need for expensive, time-consuming and potentially dangerous field work, would be an advantage to pipeline operators and engineers.

This paper presents the results of an 18-month research and development project carried out by Fugro NPA and eni gas & power division to assess the performance of CATs to monitor active landslide movement and its impact on a buried oil pipeline, during a 10-month measurement campaign.

1.1. InSAR Technique

Interferometric Synthetic Aperture Radar (InSAR) is a remote technique that has been successfully used to measure motion resulting from a number of different ground motion mechanisms in pipeline areas [2, 3]. The authors have extensive experience using differential InSAR (DifSAR) and time series techniques such as Persistent Scatter InSAR (PSI). There are also many examples in the literature of both differential InSAR and PSI being successfully used to measure landslide motion [e.g. 4, 5, 6], although time series techniques are generally more successful at identifying to landslide motion signals.

In order to use the techniques described in the previous examples, there are a number of conditions that must be met. To obtain results using DifSAR, a high level of signal coherence is required, which limits the types of terrain to typically arid, non-vegetated areas. The PSI technique requires a high density of naturally occurring point targets, which are present in a large stack of SAR images. These are typically man-made structures such as buildings, and are known as persistent scatterers (PS).

1.2. Artificial Reflectors

In areas that either lack suitable ground cover conditions for DifSAR or have a low distribution of PS, artificial reflectors can be used [7, 8, 9]. Networks of artificial reflectors are typically deployed over small (<1 km^2) areas. These can either be used as part of a larger PSI study incorporating naturally occurring point targets or limited to the reflector network itself. Advantages of this technique are that measurements can be made at specific known points remotely and without frequent visits to the site. Also, a number of sites may be contained within the same SAR image footprint which presents users with further opportunities for optimisation and cost savings. There are, however, a number of possible factors that may affect the ability of artificial reflectors to establish ground motion at a particular site. These include the terrain, the topography

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and geometry of the site in relation to the satellite, the required measurement point density or resolution and the characteristics of the motion e.g. linearity and magnitude.

1.3. Compact Active Transponders

The studies discussed above make use of Corner reflectors (CRs); passive trihedral metallic reflectors which act as PS. Compact Active Transponders (CATs) have been co-developed by Fugro NPA as an extension to the artificial reflector concept. CATs (Fig. 1) are active radar reflectors, about the size of a shoe-box, designed to provide a strong response to an over passing Synthetic Aperture Radar (SAR) satellite. CATs are capable of responding to multiple satellite beam modes, unlike CRs which are somewhat limited to predefined beam modes on installation. They are also smaller and unobtrusive and as a result are therefore less likely to be stolen or vandalized. They are designed to be phase stable to within 1 mm [10].

Figure 1. Compact Active transponder (CAT installed on mounting structure.

2. STUDY DESIGN

The trial site is located near Campomorone, north of Genoa, Italy (Fig. 2). The site is traversed by a sub-surface oil pipeline that was decommissioned by eni refining & marketing division due to landslide risk. It therefore yielded a safe environment to monitor the hazard and its interaction with the pipeline structure.

The groundcover primarily consisted of small woodland and long grass. The pipeline section (12 inches in diameter and approximately 500 m in length) was buried at varying depths but was exposed at regular intervals to accommodate extensometer monitoring equipment (Fig. 3). The pipeline route was marked by a clearing through the woodland except in areas where the terrain became too steep. In these areas the location of the pipeline was indicated by white marker posts. The access permission on site and maintenance of vegetation during the trial was secured by eni refining & marketing division.

Before deployment of the CAT units, the suitability of the trial site, the subsequent design of the CAT network and the satellite acquisition plan needed was carefully assessed. A legal prerequisite was to secure a radio transmission license prior to operating the CAT equipment. Fugro NPA secured a short-term research & development license with the Ministry of Communication in Rome, Italy for the duration of the study.

Figure 2. Map of the Campomorone trial site including the location of the 12 inch diameter pipeline (white dashed line) and CAT locations; red icons represent CATs fixed to the pipeline, blue icons represent CATs fixed to the ground. North is left of the page. Background is orthorectified Quickbird imagery. Insert: Regional map showing location of trial site (white star). Image sourced from Google Earth.

Fig. 3. A section of the pipeline corridor of looking north along the slope profile.

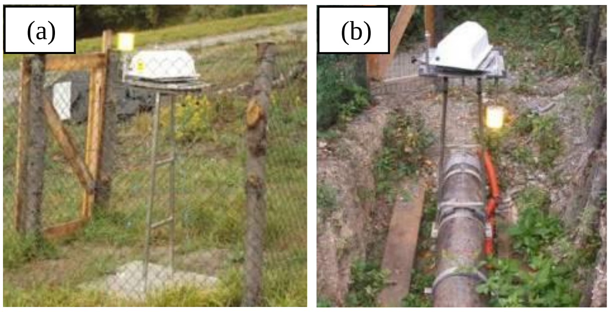


Fig. 4. CAT mounting structures: (a) for ground deployment. CAT 8 is shown. (b) for pipeline deployment. CAT 3 is shown.

The pipeline transects an approximately west-facing slope, which is ideal for InSAR as the available SAR satellites available for this study (Envisat and Radarsat-1) have a low sensitivity to north-south motion. The CAT deployment locations were constrained by:

a. the location and orientation of the exposed sections of pipe;
b. the optimal location of measurement points required to capture landslide motion;
c. an adequate line-of-sight (LOS) to SAR satellites in ascending and descending orbit modes;
d. the avoidance of signal interference between individual CATs and local 'natural' point targets;
e. the minimisation of interference from vegetation.

In June 2008, a network of seven CATs was deployed (marked on Fig. 2). Three CATs (1, 3 & 4) were anchored to the pipeline, one CAT (CAT 2) was deployed directly next to the pipeline and the remaining three CATs (5, 6 & 7) were deployed in the vicinity of the pipeline. Two CATs (5 & 6) were located along the slope profile; the third (CAT 7) was located further away from the slope to be used as a motion reference.

The nature of the study called for an innovative mounting design that would allow a CAT device and GPS antenna to be co-located and fixed to the ground or pipeline structure. The mounting structures were designed, engineered and patented by eni (Fig. 4). The structures were either anchored to the pipeline or to plates on the ground allowing for the CAT devices to be levelled and aligned to true north.

Table 1. Data used during the study.

Satellite	Orbit	Track	LOS*	Number of images
Envisat	Descending.	480	21°	9
Envisat	Descending	208	25°	7
Envisat	Ascending	387	45°	9
Radarsat-1	Ascending	n/a	45°	6

* LOS at CAT locations.

GPS surveys were provided for measuring the geographical location of the CATs. During the installation stage the ellipsoid heights of the CAT mounted devices were measured using GPS processing.

The CAT units were programmed to respond to the required satellite overpasses. The Envisat satellite was programmed to obtain SAR images every orbit cycle (35 days) for both ascending and descending passes for the 10-month study period. In addition Radarsat-1 was programmed for the descending pass (24-day cycle. Descending mode images were deemed optimal given the slope characteristics. The SAR sensors on both of the satellites have programmable beam modes with different look angles. The beam modes were chosen to maximise the resolution and the strength of the response and minimise the effects distortions due to the steep topography. The data acquired for this study are shown in Tab. 1.

3. InSAR PROCESSING

It was not necessary to process all possible interferometric combinations of SAR images; the longest term interferograms (the first to the last date) and the shortest-term interferograms (one cycle, e.g. 24 or 35 days) were processed. The sum of these would enable a check on the phase unwrapping of the long-tem interferograms. This would enable both rapid and slow motion to be sampled (as the motion characteristics were unknown at the start of the project). This left 50 interferograms, out of a possible 94. The high perpendicular baseline of some of the interferograms prevented the accurate co-registration required for InSAR processing, leaving 41 interferograms for analysis.

In order to carry out an assessment of the phase differences, the Signal-to-Noise Ratio (SNR) of the CAT responses above that of the background clutter must be above a certain level. Where the CAT responses could not be identified above the background clutter no phase value, and therefore no motion measurement, was recorded.

The contribution to the interferometric phase from the topography was estimated and removed using the GPS measurements in WGS84 system (height range: 366.457 – 413.436 m). The high accuracy of the height measurement means errors due to topography will be negligible. The phase contribution due to different orbital positions at different acquisition times was estimated and removed using the knowledge of the satellite orbits. Inaccuracies in these estimates can cause residual, slowly varying (and usually linear) large-scale phase trends in the interferograms. If the interferograms are partially coherent, then the phase trends can be estimated and removed; however, due to the small area of the trial site, any remaining residual trends should be minimal. Differences in the atmospheric water vapour distribution across the trial site between images dates can cause a contribution the phase measurement. Small-scale variations in atmospheric water vapour typically have length scales of ~1 km. The errors due to atmospheric variations should therefore be minimal across the trial site (target size ~0.5 km).

4. GPS PROCESSING

Measurements from five GPS campaigns were collected using two Leica Geosystem receivers and processed by eni refining & marketing division's Physical Chemistry Department and made available to Fugro NPA. Measurements were collected in September and November 2008 and February, April and July 2009, giving four epochs of motion measurements. The equivalent LOS motion was calculated from the East, North, Up (ENU) coordinates. Estimates of uncertainty for the GPS measurements were calculated for each survey using the propagation of variance method, and projected into the LOS. The GPS measurement uncertainties are smaller for the later surveys, since a greater number of baselines were measured.

5. KEY RESULTS AND DISCUSSION

5.1. Assessment of controlled movement

To ensure the correct functioning of the CAT hardware, a controlled movement test was performed. CAT 4 was tilted by between 5° and 8° in a westerly direction on 30th September 2008 and returned to the horizontal on 16th October 2008. If the phase centre of the CAT is assumed to be at its center, this equates to a LOS motion of between +13 and +16 mm for Envisat track 387 and Radarsat-1 interferograms, and +11 and +19 mm for Envisat track 480 interferograms. Acquisitions on Envisat track 208 did not begin until after the tilt test. The effects of the CAT 4 tilt activity, which simulated a displacement towards and then away from the satellite, can be clearly seen within Fig. 5.

The Envisat (track 387) interferogram which bridged the tilt activity (spanning 31/08/08 to 05/10/08) resulted in a LOS displacement of 13.6±1.9 mm. The interferogram which bridged the return-tilt activity (spanning 05/10/08 to 09/11/08) resulted in a LOS displacement of -9.8±1.7 mm, whilst the Radarsat-1 interferogram which bridged the return-tilt activity (spanning 02/10/08 to 26/10/08) resulted in a LOS displacement of -9.5±1.8 mm. The LOS displacement measurements for CAT 4 were in line with the theoretical expectations.

After the period of the tilt experiment Fig. 5 shows that that CAT 4 appears to be relatively stable.

5.2. Spatial Variation in Motion Measurements

In ascending orbit modes, CAT 1 and 2 experienced the most LOS motion (e.g. Fig. 6, CAT 1), with CAT 2 to a lesser extent than CAT 1 whereas CATs 3, 4, 5 and 6 are predominantly stable (e.g. Fig. 7, CAT 6). These measurements could indicate a higher rate of LOS motion associated with the central section of the slope.

Examination of the Envisat descending mode interferograms appears to corroborate that CATs 1 and 2 are experiencing the highest LOS motion rate (e.g. Fig. 8, CAT 1), showing motion away from the satellite. The combination of motion towards the satellite in ascending LOS and motion away from the satellite in descending LOS could indicate that the CATs are undergoing a combination of downward and westward motion. However, there is the possibility that the data points are affected by motion ambiguities (See section 5.3). If this was the case, then the motion of CATs 1 and 2 could be stable in descending mode. This would bring the results in line with the GPS data. Unfortunately, only CATs 1, 6 and 7 are visible in the Envisat descending track 480 interferograms, making corroboration of this very difficult. In some circumstances information from the two LOS motion vectors can be used to estimate the relative proportions of westward and downward motion. An estimate of total motion magnitude, *d*, can only be obtained from a single LOS measurement if assumptions are made about the motion azimuth and the angle between slope motion and a level plane. If both ascending and descending measurements are available these can, in principle, be used to resolve the LOS measurements into vertical and east-west components of deformation.

This requires ascending and descending measurements over the same timeframe. For CATs 1 and 2, the measurements from tracks 387 and 208 showed a relatively constant direction and rate of LOS motion. Although the measurement dates differ and the descending measurements span a shorter period of time, the relatively constant motion rate enables an estimate to be made of the equivalent descending motion which would have been observed over the period covered by the ascending measurements.

For CAT 1, ascending track 387 showed LOS motion on the order of +40 mm over the 280 days of measurements, and descending track 208 showed on the order of -60 mm over 208 days (the equivalent of -80 mm over 280 days). Taking into account the relative incidence angles, these can be approximately resolved to give a motion of the order of 105 mm down-slope, at an angle of approximately 23° from horizontal.

For CAT 2, ascending track 387 showed LOS motion on the order of +20 mm over the 280 days of measurements, and descending track 208 showed on the order of -35 mm over 245 days (the equivalent of -40

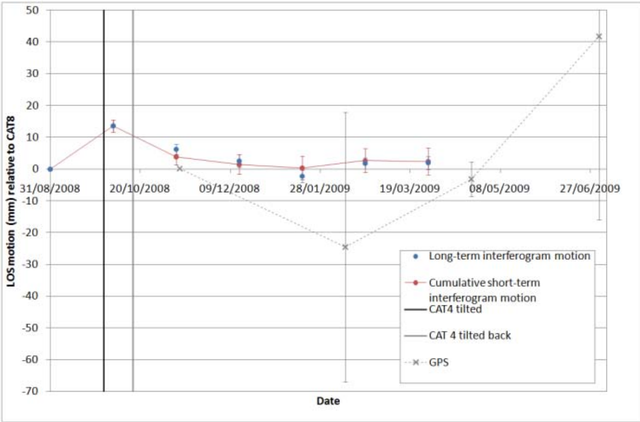


Figure 5. Results from InSAR analysis for Envisat track 387, CAT 4. The LOS displacement is shown. The blue dots represent the long-term interferograms. The red dots represent available measurements from the short-term interferograms. Each previous point is used as a baseline for the motion period so all short-term interferograms in the chain must be available. The GPS results projected into radar LOS are also shown.

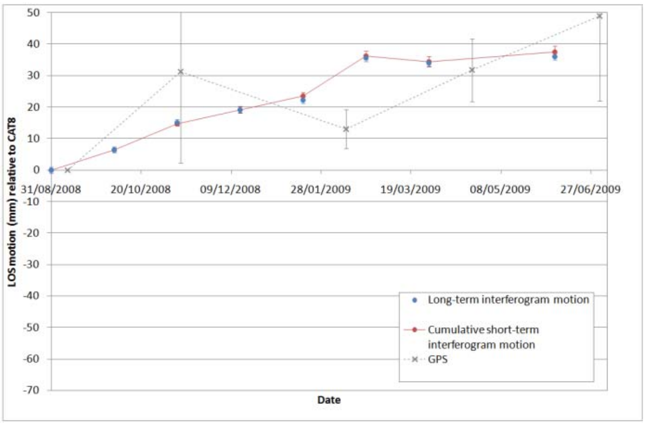


Figure 6. Results from InSAR analysis for Envisat track 387, CAT 1. The LOS displacement is shown. The blue dots represent the long-term interferograms. The short term interferograms are plotted (red dots/lines) where possible. The previous point is used as a baseline for the motion period so all short-term interferograms in the chain must be available. The GPS results projected into Radar LOS are also shown.

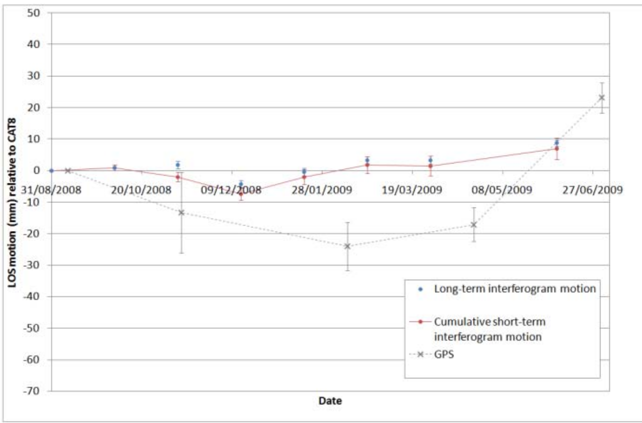


Figure 7. Results from InSAR analysis for Envisat track 387, CAT 6. The LOS displacement is shown. The blue dots represent the long-term interferograms. The short term interferograms are plotted (red dots/lines) where possible. The previous point is used as a baseline for the motion period so all short-term interferograms in the chain must be available. The GPS results projected into Radar LOS are also shown.

mm over 280 days). These can be approximately resolved to give a motion of the order of 55 mm down-slope, at an angle of approximately 23° from horizontal. These measurements assume approximately constant rates of motion for the descending LOS measurements, and neglect the possibility of a small component of north-south motion potentially present in the LOS measurements due to the slight deviation of the satellite tracks from a north-south direction.

However, the motion direction (westward and southward with an angle of 23°) is compatible with that which could be expected given the characteristics of the site.

5.3. Comparison with GPS measurements

The September 2008 GPS campaign data are considered a baseline for the GPS, relative to which the three epochs of motion are considered (with the exception of CAT 4, where data were not obtained in September 2008). This date coincides with the start of the InSAR measurements only for Envisat track 480; the remaining three tracks have start dates which are significantly offset from the start of GPS measurements. Coupled with the coarse temporal sampling of the GPS data, this makes comparison between the GPS and InSAR datasets challenging.

An approximate and subjective comparison is possible if a linear deformation rate is assumed over each GPS epoch, and used to take into account the offset at the start of the epoch under consideration. However, given the large difference in motion magnitude and direction seen between the two GPS epochs, this assumption of linear motion is highly unlikely to be robust, and therefore the comparison may only be considered a first-order approximation of the fit between the two datasets.

In general, there is an encouraging fit between the GPS and InSAR measurements, to within the levels of uncertainty for the two datasets. However the GPS data show, in many cases, a large magnitude of motion, and a large change in motion magnitude and direction between two epochs. The GPS data have large uncertainties relative to the InSAR data, however if the CATs are indeed experiencing this degree of motion there will be implications for the resolution of unwrapping ambiguities.

To provide a fair comparison between the InSAR and GPS techniques, the unwrapping ambiguities in the InSAR data were considered in isolation, without reference to the GPS results. Consequently there are cases where ambiguities in the InSAR data could potentially be resolved differently in order to result in a better fit to the GPS data. For example, Fig. 9 shows a case where an ambiguity has been resolved by assuming a minimum deformation; adding an ambiguity adjustment gives a higher motion rate, but a better fit to the GPS data.

There are also cases where the InSAR data show consistently small motions over a number of epochs, and it is unlikely that large ambiguities are present, for example, measurements for CAT 6 in Envisat track 387 (Fig. 7) consistently shows deformation measurements of a few millimetres. In cases such as these, where the InSAR measurements are well-constrained and unwrapping ambiguities are unlikely, it is probable that the relatively higher uncertainties and coarse temporal sampling of the GPS data are responsible for any mismatch.

6. CONCLUSIONS

The InSAR trial revealed the necessity for more regular SAR image acquisitions (acquired in ascending and descending mode, and at multiple look angles). Across the Campomorone trial site, a site which appears to be experiencing non-linear ground and pipeline motions, both CATs and GPS struggled to perform optimally, especially given that the reference (CAT 8) also experienced motion. In this respect the trial was extremely useful and helped to define the limits of both technologies. The CAT 4 tilt activity, which simulated a displacement to the unit by altering its LOS to the satellite, was useful in that it demonstrated the effects of displacing the CAT unit. The artificial displacements towards and away from the satellite that occurred on 30th September 2008 and 16th October 2008 can be seen clearly, and actual movements detected by InSAR were in line with theoretical expectations.

CATs 1 and 2 were anchored to pipeline and experienced the most LOS motion in ascending orbit modes. The spatial variation in the motion rates could indicate that the central section of the slope moved at a higher rate, exhibiting westward and downward motion of the pipeline. Fig. 10 shows indicative low and high magnitude (cumulative) CAT motions. The image indicates that a high risk section of slope may exist between CATs 1 and 2. CAT 1 is estimated to have moved down-slope by approximately 105 mm over 280 days, and CAT 2 is estimated to have moved down-slope by approximately 55 mm. An angle of slope of around ~23^{o} is estimated in both cases. CATs 3, 4, 5 and 6 are predominantly stable in ascending orbit modes. It would appear that a number of CATs are showing a down-slope motion that could be attributed to a change in slope morphology/pipeline position.

Using a higher repeat period of SAR image acquisition may achieve better results. The C-band satellite Sentinel-1 due to be launched in 2013 has a repeat period of 12 days. TerraSAR-X, launched in June 2007, has a repeat period of 11 days (one third that of Envisat)

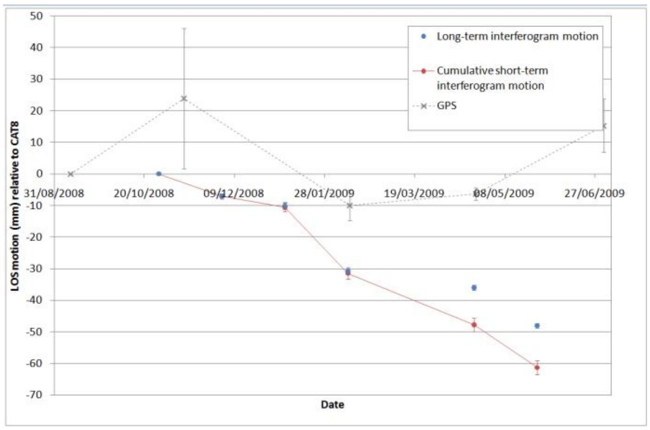
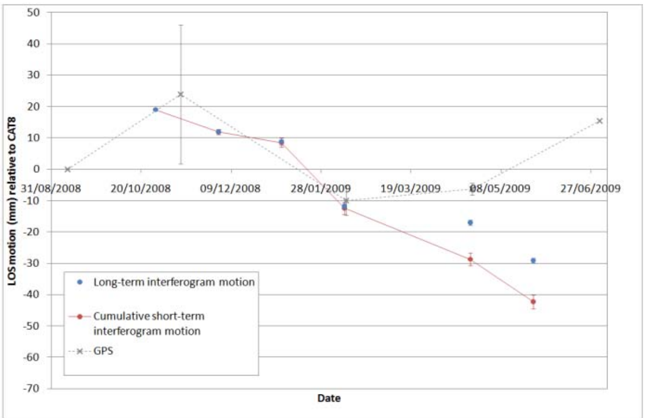


Figure 8. Results from InSAR analysis for Envisat track 208, CAT 1. The LOS displacement is shown. The blue dots represent the long-term interferograms. The short term interferograms are plotted (red dots/lines) where possible. The previous point is used as a baseline for the motion period so all short-term interferograms in the chain must be available. The GPS results projected into Radar LOS are also shown.



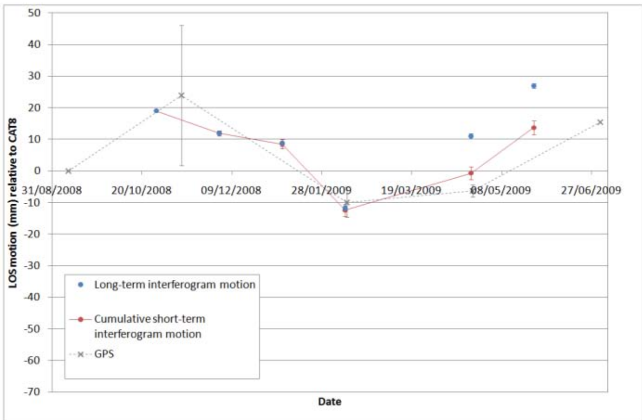


Figure 9. (top) CAT 1 measurements for Envisat track 208, with the InSAR data displaced so the start date corresponds approximately with the GPS. The second image (bottom) shows the same data with a +28 mm unwrapping ambiguity adjustment on 21/04/2009 and a +56 mm adjustment on 25/05/09, to give a better fit to the GPS measurements.

but with a 15 mm ambiguity instead of 28 mm (more than half that of Envisat).

This trial service was an excellent demonstration of the capability of artificial reflector InSAR using prototype CAT technology, across what is now known to be an extremely challenging active landslide site for both the InSAR and GPS technologies. The trial has proven the ability of artificial reflector InSAR to detect subtle ground and pipeline movements, thereby reducing the need for frequent ground based survey campaigns. Groundcover, topography and rate of ground motion have pushed, and in some instances exceeded the capabilities of both technologies, and bought a number of challenges to light which must be overcome in order for CATs to become commercially viable.

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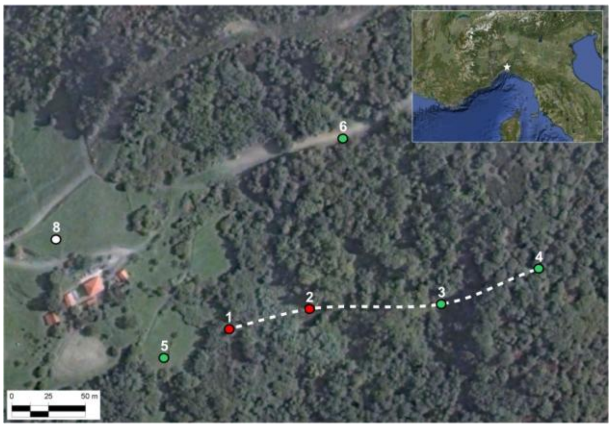

Figure 10. Ground motion risk map for the Campomorone trial site. Map shows the location of the 12 inch diameter pipeline (white dashed line) and CAT locations; the white icon represents the reference CAT, green icons represent CATs with a low motion magnitude, red icons represent CATs with a high motion magnitude. Area surrounding CATs 1 and 2 is deemed to be high risk. North is left of the page. Background is orthorectified Quickbird imagery. Insert: Regional map showing location of trial site (white star). Image sourced from Google Earth.

REFERENCES

[1] Pinnacle Technologies. (2010). Keeping an eye on the pipeline: displacement monitoring with InSAR. http://www.pinntech.com/pubs/CS/CS05_RD.pdf, last accessed 26 October 2010.

[2] Sircar S., Power, D., Randell, C., Youden, J. & Gill, E. (2004). Lateral and subsidence movement estimation using InSAR. *Proc. of the 2004 IGARSS, 20-24 September, Anchorage, Alaska, USA*, **5**, 2991–2994. [doi: 10.1109/IGARSS.2004.1370325]

[3] Singhroy, V., Couture, R., Alasset, P.-J. & Poncos V. (2004). InSAR monitoring of landslides on permafrost terrain in Canada. *Proc. of the 2007 IGARSS, 23-28 July 2007, Barcelona, Spain*, 2451 – 2454. [doi: 10.1109/IGARSS.2007.4423338]

[4] Colesanti, C., Ferretti, A., Prati, C. & Rocca, F. (2003).Monitoring landslides and tectonic motions with the Permanent Scatterers Technique. *Engineering Geology*, **68** (1-2) 3-14. [doi: 10.1016/S0013-7952(02)00195-3]

[5] Hilley, G. E., Burgmann, R., Ferretti, A., Novali, F. & Rocca, F. (2004). Dynamics of slow-moving landslides from permanent scatterer analysis. *Science*, **304** (5679), 1952-1955 [doi: 10.1126/science.1098821]

[6] Berardino, P., Costantini, M., Franceschetti, G., Iodice, A., Pietranera, L. & Rizzo, V. (2003). Use of differential SAR interferometry in monitoring and modelling large slope instability at Maratea (Basilicata, Italy). *Engineering Geology*, **68** (1-2)**,** 31-51. [doi: 10.1016/S0013-7952(02)00197-7]

[7] Singhroy, V., Murnaghan, K. & Zhang, J. (2009). InSAR monitoring of landslides using RADARSAT. *Proc. of the 2009 IGARSS, 12-17 July 2009, Capetown, South Africa*, 2451 – 2454. [doi: 10.1109/IGARSS.2009.5416925]

[8] Ye, X., Kaufmann, H. & Guo, X.F. (2004). Landslide monitoring in the Three Gorges area Using D-InSAR and corner reflectors. *Photogrammetric Engineering & Remote Sensing*, **70** (10), 1167–1172.

[9] Froese, C.R. (2004). Characterising complex deep seated landslide deformation using corner reflector InSAR (CR-InSAR): Little Smoky landside, Alberta. *Proc. 4th Canadian conference on Geohazards, 20-24 May 2004, Quebec, Canada*, 288-294.

[10] Haynes, M., Smart, S. & Smith, A. (2005). Compact active transponders for operational SAR interferometry applications. *Proc. of the 2004 Envisat & ERS Symposium, 6-10 September 2004, Salzburg, Austria.*