Exploring new solutions for large areas and long linear structures monitoring: INSAR from satellites and LIDAR from UAV

Remy BOUDON, Philippe REBUT, Didier BOLDO, Gaël VERDUN and Coline BROTHIER, France

Key words: Photogrammetry, Lidar, INSAR, satellites, UAV, UAS, dikes, landslides, monitoring, subsidence, sinkholes, Engineering Survey, Deformation measurement, Remote sensing, Risk Management

SUMMARY

The Synthetic Aperture Radar Interferometry (INSAR) uses multi-temporal image data acquired by SAR satellites as they fly over land on their polar orbit. It aims to estimate for each pixel of the radar images the phase difference between two acquisitions in order to quantify a variation of distance and therefore a displacement on natural (rocks, buildings ...) or artificial targets (reflective corners). INSAR is one of the techniques explored since 2009 by EDF to improve and optimize the supervision of its infrastructures. Thanks to collaboration with the French research laboratory GIPSA-Lab of Grenoble INP and through studies carried out with the leading companies in the field, the limits of use and the level of uncertainty are better understood today.

From a lower but still aerial point of view, Lidar embedded in UAV may offer interesting monitoring system to cover long linear of structures such as dikes. For now, the survey monitoring of such structures is carried out by classic methods, most often by direct levelling. These methods do not allow detection of local subsidence such as sinkhole which would appear between two levelling points. These are usually detected by the regular visual inspection. On limited sections of a few hundred meters, static Lidar (Laser scanning) can possibly be used to ensure an exhaustive coverage of the whole surface of the structure. But this quickly becomes very heavy to implement on longer distances, reason why, experiments and developments are carried out at EDF to evaluate monitoring survey using Lidar embedded on fixed wing UAV to cover long linear in full autonomy. Developments concern, on one hand, the carrier and the embedded sensors and, on the other hand, the post-processing tools adapted to the detection of these localized defects without introducing too many constraints for global geo-referencing. The final objective is to get a simple and fast UAV system that can easily be operated to support inspection and monitoring works and help for early detection of anomalies.

This paper proposes to present various experimentation results given by these two complementary technologies – Satellites INSAR and LIDAR UAV – at EDF in the framework of infrastructures monitoring.

Exploring new solutions for large areas and long linear structures monitoring: INSAR from satellites and LIDAR from UAV

Remy BOUDON, Philippe REBUT, Didier BOLDO, Gaël VERDUN and Coline BROTHIER, France

1. INTRODUCTION

The Synthetic Aperture Radar Interferometry (INSAR) uses multi-temporal image data acquired by SAR satellites as they fly over land on their polar orbit. It aims to estimate for each pixel of the radar images the phase difference between two acquisitions in order to quantify a variation of distance and therefore a displacement on natural (rocks, buildings ...) or artificial targets (reflective corners).

It is an increasingly used technique for the monitoring of infrastructures, mining and tunnelling operations, gas storage tanks, LNG platforms ... It has the advantages of not requiring active instrumentation on site, to be less sensitive to weather conditions, and to allow for an overall vision thanks to its coverage of very large areas (several tens of km²). With current satellites and future space programs, this technique offers long-term service guarantee. Moreover, thanks to the radar data archived since the 1990s and when sites are suitable, this technique can make it possible to reconstitute a posteriori deformation in areas of interest.

INSAR is one of the techniques explored since 2009 by EDF to improve and optimize the supervision of its infrastructures. Thanks to collaboration with the French research laboratory GIPSA-Lab of Grenoble INP and through studies carried out with the leading companies in the field, the limits of use and the level of uncertainty are better understood today.

From a lower but still aerial point of view, Lidar embedded in UAV may offer interesting monitoring system to cover long linear of structures such as dikes. For now, the survey monitoring of such structures is carried out by classic methods, most often by direct levelling. These methods do not allow detection of local subsidence such as sinkhole which would appear between two levelling points. These are usually detected by the regular visual inspection. On limited sections of a few hundred meters, static Lidar (Laser scanning) can possibly be used to ensure an exhaustive coverage of the whole surface of the structure. But this quickly becomes very heavy to implement on longer distances.

Reason why, experiments and developments are carried out at EDF to evaluate monitoring survey using Lidar embedded on fixed wing UAV to cover long linear in full autonomy. Developments concern, on one hand, the carrier and the embedded sensors and, on the other hand, the post-processing tools adapted to the detection of these localized defects without introducing too many constraints for global geo-referencing. The final objective is to get a simple and fast UAV system that can easily be operated to support inspection and monitoring works and help for early detection of anomalies.

This paper proposes to present various experimentation results given by these two complementary technologies – Satellites INSAR and LIDAR UAV – at EDF in the framework of infrastructures monitoring.

2. EXPLORING INSAR from SATELLITES

2.1 General technology principles

Radar satellites allowing INSAR processing from the images they acquire, are located on polar orbits at approximately 700 km off height.

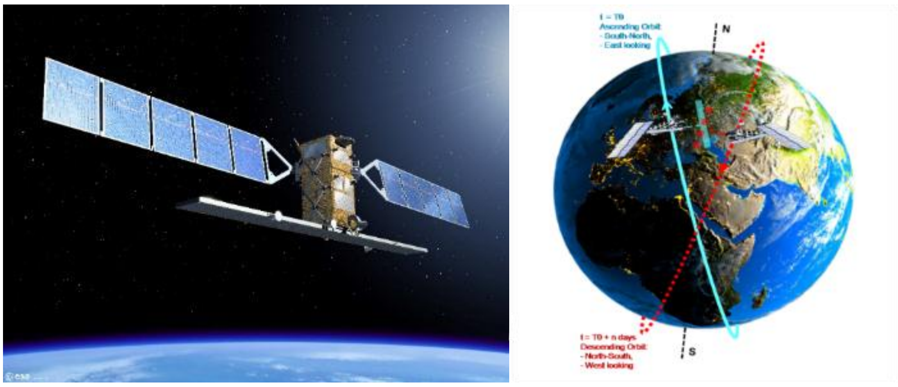


Figure 1: SENTINEL satellites – ascending and descending orbits

Thanks to satellites movement and radar aperture, ground images collected cover large area from tens to hundreds of km on two modes, ascending and descending.

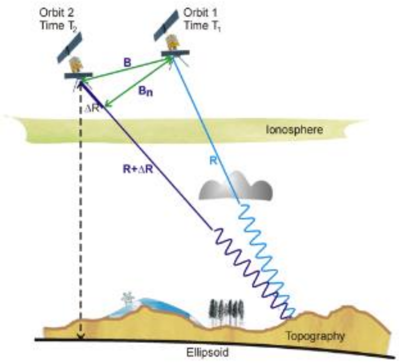


Figure 2: multi-temporal acquisitions – radar images ground coverage

INSAR processing consists in detecting points which reflect properly radar signal in the images, and then observe the evolution of the common ones in the series of images. Points may be natural: rocks or buildings, concrete or metallic structures… or artificial corner reflectors fit for purpose.
The treatment requires to take into account many parameters: satellite position, site topography (approximate DTM), atmospheric effects… in order to deduce effective site displacements of interest.
Displacements are evaluated in differential from a reference point on a stable area which needs to be found in the images, both in terms of radar response and movement.

Figure 3 gives example of INSAR study typical deliverables.

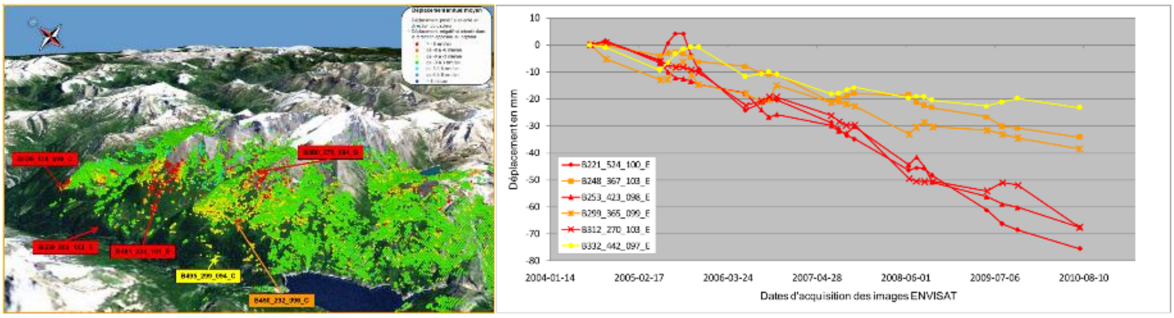


Figure 3: example of INSAR study deliverables

2.2 Implementation

Main radar satellites missions concern environment and security fields. Acquisition programs are defined by their sponsors: Spatial Agencies, Research Organizations, Civil Security… Once archived, radar images become available for purchase or free download.

There are archives available on various laps of time (satellites lifetime) since approximately 1992, in different radar frequency bands, line of sight angles and image resolutions: ERS, Envisat, Radarsat, TerraSAR-X, Cosmo-Skymed, PAZ, Alos, Sentinel… Actual space programs give a visibility till 2020-2025.

Constellations (mono or multi-satellites) allow to find time frequency acquisition on a given site from a period of one month to a few days.

It is possible to ask satellite operators to acquire images on your site of interest in “best effort mode” which means that they may realize these acquisitions if their satellites are available and on a voluntary basis, hoping you will buy these archive afterwards.

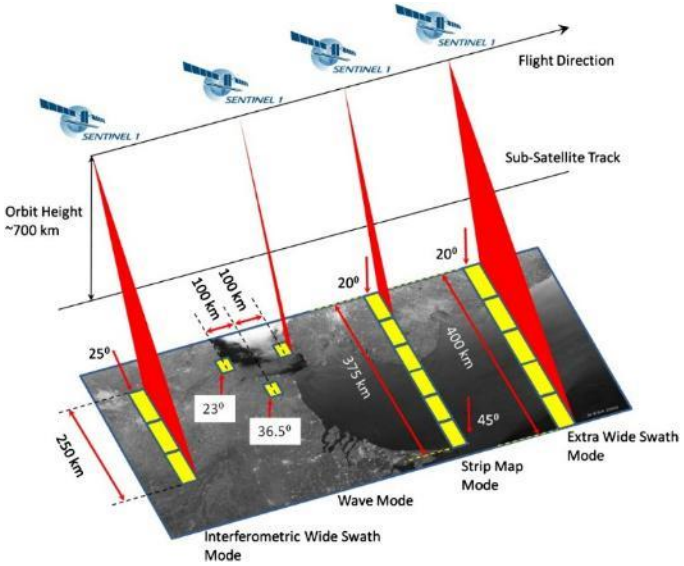


Figure 4: example of acquisition modes of SENTINEL 1

A SAR image can be seen as a two dimension matrix made of pixel covering variable surface of land from ~1x1m till ~20x20m or ~20x40m depending on resolution and geometric configuration.

The Line Of Sight (LOS) is globally located on a vertical plane East-West. It is along this LOS and solely along this LOS that distance measurement is done. In other words, INSAR do not allow to measure displacements perpendicular to LOS. Moreover, the sensitivity of INSAR measurements to ground movements clearly depend on the geometric configuration of the site of interest (orientation, slope) and the direction of expected displacements.

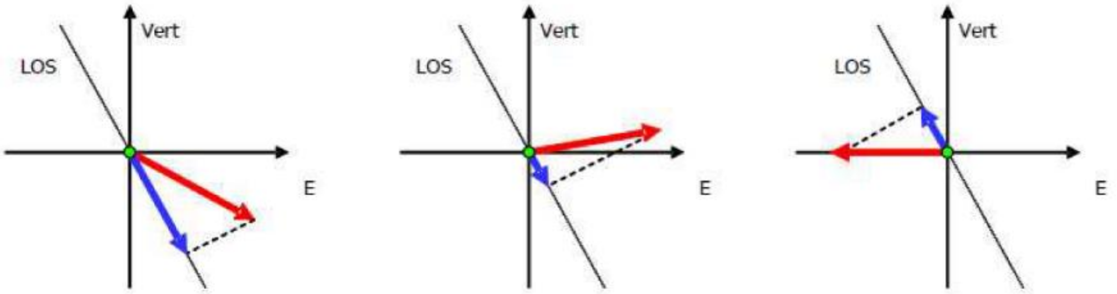


Figure 5: sensitivity of INSAR measure along LOS (blue) to actual displacement (red)

There are also limitations due to distortion effects (layover) and shadow effect which may reduce actual ground coverage of radar images, in particular in mountains/valleys.

Finally, it is important to consider ground nature itself: vegetal cover is not suitable for radar reflection, as snow and water: forest, field… will not offer natural points for INSAR and images acquired when snow is present will not be workable. Naked mineral soils, rocks and urban areas will be much better covered. However, same reflection points have to be found in the series of images processed: i.e. construction sites on evolution may not offer many INSAR points.

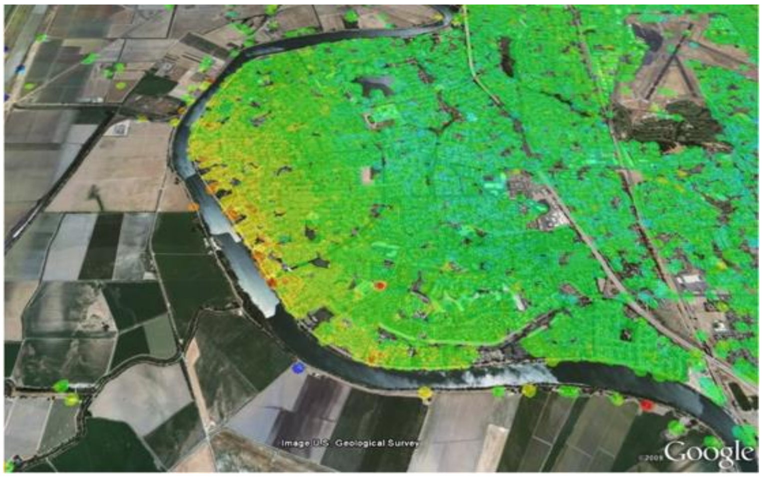


Figure 6: example of INSAR results: fields vs urban area

By combining INSAR processing of the same area seen in 2 acquisition modes, ascending and descending, it may be possible to measure 2D displacements in a vertical average plane formed by the LOS in each of the modes (i.e. vertical and East-West displacements, North-South displacements can not be measured), provided that the point measured is exactly the same. This is rarely the case for natural points. On the other hand, it is possible to envisage associating two reflecting corners with the same physical point, each oriented towards a mode.

Figure 7: survey point equipped with corner reflector for two modes

2.3 Accuracy

Displacements measured by INSAR are relative displacements with respect to the point fixed in the images. However, a site presents in general many stable zones that can corroborate this hypothesis of fixity. It is therefore common to speak of "absolute" displacements of an area or structure in its environment.

The accuracy of INSAR displacements depends on several parameters:

- the number of images available, with a minimum of 20 exploitable images being recognized as a reasonable basis,
- the extent of the site studied, which determines the distance separating it from the fixed point and therefore the part of errors from atmospheric corrections,
- the geometrical configuration of the site and therefore its sensitivity to LOS distance measurement,
- the wavelength used,
- soil characteristics and quality of detected echoes (signal to noise ratio),
- the quality of the software chain and know-how in terms of parameterization (thresholds for the detection of points, method for correcting topographical effects, atmospheric effects, etc.)
- the precision of the DTM...

As with many other technologies, it is therefore difficult to announce exact accuracy values that would be applicable to all INSAR studies.

It is, however, possible to give some orders of magnitude to fix ideas:

Constellation	Resolution (ground pixel size)	Uncertainty in plan view	Frequency band	Uncertainty along LOS
ERS 1 et 2	20x20m	±20m	C	±5mm
ENVISAT	20x20m	±20m	C	±5mm
ALOS	40x40m	±40m	L	±10mm
COSMO-SkyMed	3x3m	±3m	X	±3mm
TerraSARX	2x2m	±2m	X	±2mm

Figure 8: differential LOS uncertainty with respect to a fixed point a few kilometers away

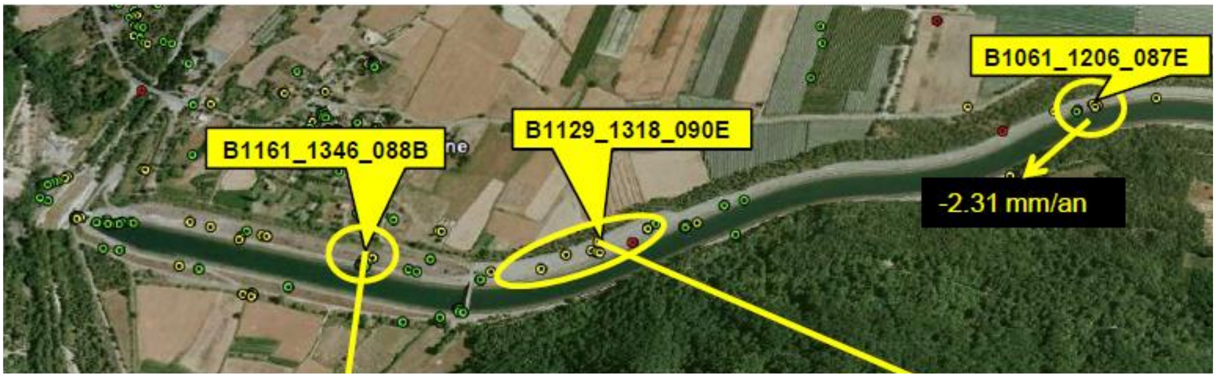
It should also be noted that, as for other measurement techniques, it may be advantageous to have independent control means on the ground: GNSS or Topographic measurements on a number of points equipped with corner reflectors for example.

In the following paragraph, examples of INSAR studies carried out with one of the leading companies of the field: TRE ALTAMIRA are presented.

2.4 Examples

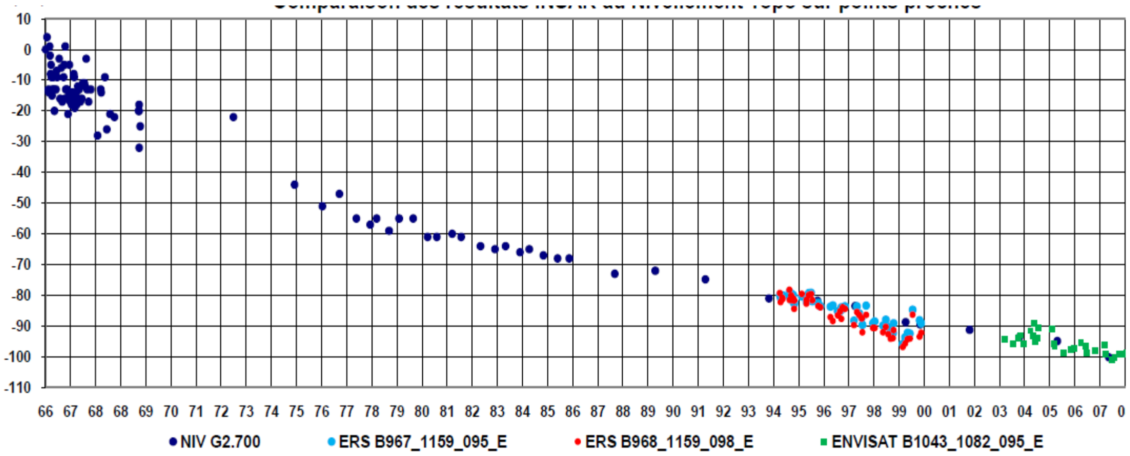
2.4.1 Water Channel – Archive: descending ERS1/2 & Envisat from 1995 to 2010

Extract of the deliverable:



Main outcomes:

- just few points detected on the linear, due to changes on towpath during acquisition period and the low resolution of the images
- but comparisons to leveling results on closest points are interesting as shown on the figure below:



2.4.2 Dam site – Archive: descending ERS1/2 & Envisat from 1995 to 2010

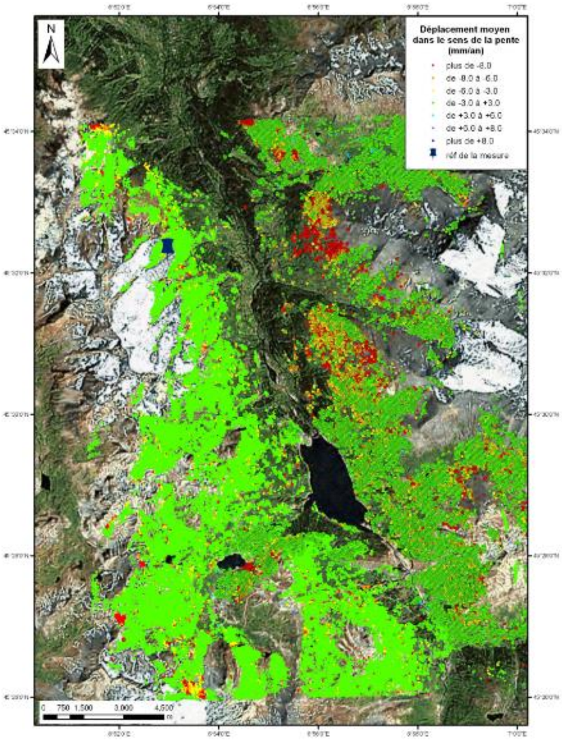
Extract of the deliverable:

Main outcomes:

- interesting number of points detected on dam surface,
- few point show aberrant evolutions,
- overall stability confirmed on dam and left abutment on the period, but inappropriate reference point chosen on the dam itself.

2.4.3 Dam site – Archive: ascending & descending Envisat from 2004 to 2010

Extract of the deliverable:

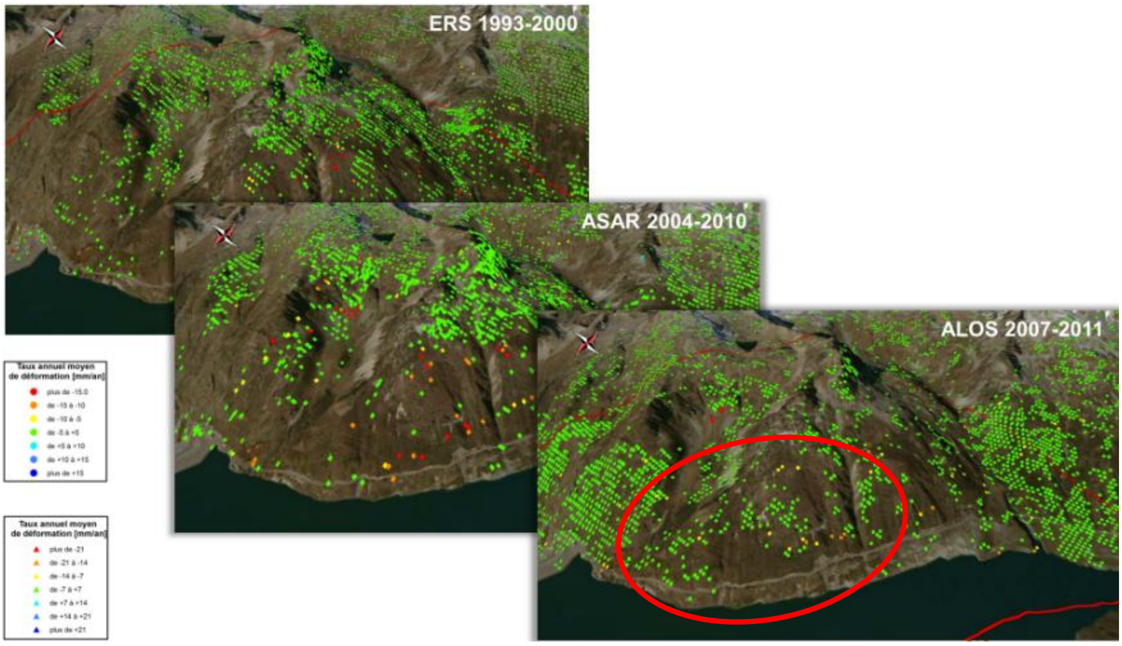


Main outcomes:

- order of magnitude of right bank side consistent with the one observed on dam site,
- help the established geological diagnosis (large-scale sliding on the right bank), despite the presence of several moraine zones (therefore surface displacements)
- however, no point detected on dam structure in the valley

2.4.4 Landslide site – Archive: ascending ERS1/2 & Envisat from 1993 to 2010 and Alos from 2007 to 2011

Extract of the deliverable:



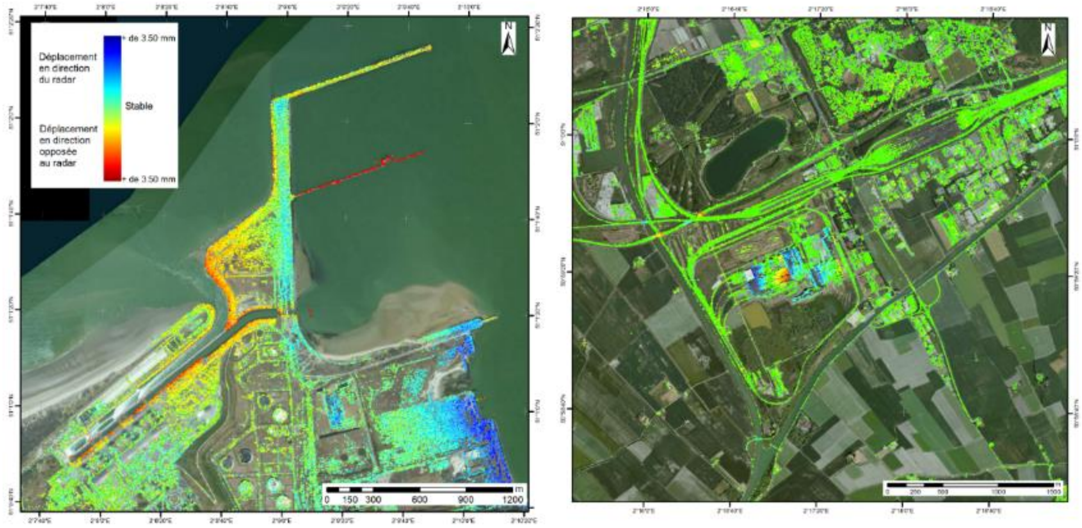
Main outcomes:

- very few points detected in the area of interest: due to vegetation (Alos in L band gives better results) and snow reducing number of available images,
- comparison with GNSS ground measurement quite tricky.

2.4.5 Industrial site – Archive: 50 images ascending Cosmo-Skymed from 2012 to 2013

The challenge of this particular study was to evaluate on a seaside site both tidal and thermal effects and compare to observations made by classical survey means (GNSS and Total Station).

Extract of the deliverable:



Main outcomes:

- tidal (left) and thermal (right) effects (of few mm) have been detected on seaside structure and buildings. They accurately corroborate survey measurements if we consider them as vertical only,
- this study shows the high density of points detected in such industrial areas with high resolution images (Cosmo-Skymed) compared to previous examples.

2.5 Conclusions

Spaceborne INSAR (synthetic aperture radar interferometry) is an interesting monitoring technique due to several reasons: does not require an active instrument mounted at the test site, is not very sensitive to weather conditions, is a relatively long-term guaranteed service with quite frequent revisit times and may allows a posteriori reconstruction of the measurements history for a given site if an archive of SAR products is available and if site configuration is suitable. The INSAR technique is widely employed for large scale monitoring of general subduction movements, resource recovery exploitations (oil, gas and mining), but also of urban area subject to various disturbances (e.g., water pumping, tunneling and general underground construction work).

The accuracy of INSAR measurements is compatible with the monitoring requirements if performed by qualified personnel.

But it is worth mentioning that the INSAR technique provides only displacements along the line of sight of the satellite, and hence a displacement that is perpendicular on this direction cannot be measured. This fact generates some limits of the INSAR technique by making its applicability and interpretability of the results dependent on the geographical configuration of the envisaged site.

Moreover, in the case of water-dams and other hydraulic structures, there are additional factors that can limit the sensibility or even the applicability of INSAR: vegetation and snow cover, visibility of the site from a given satellite orbit (e.g., a deep valley may be partly or completely shadowed in a SAR image) or other geometric distortion effects, i.e., lay-over, foreshortening, which depend on the chosen orbit and the geometrical configuration of the site.

For a given acquisition geometry, artificial scattering centers can be created on the site of interest using corner reflectors. These reflectors have to be carefully designed and set out to ensure high reliability, which can lead to significant in situ instrumentation costs.

Finally, the INSAR technique requires relatively complex signal processing chains (without real-time capability) and there are only few dully qualified INSAR service providers. Besides, a certain number of images acquired from the same satellite constellation are necessary to start an analysis over a given site.

INSAR technology should not be seen as a replacement of classic topographic techniques (e.g., leveling, tachometry, GNSS, LIDAR, photogrammetry…), but rather as a complementary monitoring method. Compared to in situ sensors, satellites INSAR monitoring may provide:

- an overall picture of the studied area (a SAR image can cover areas from tens to hundreds of km), which facilitates the analysis of the site along with its surroundings (e.g., the evolution of a landslide placed on the banks of a reservoir during a drainage of the dam or the early detection of possible instable areas that require precise in situ monitoring with classic techniques);
- monitoring of hard-to-reach areas due to security reasons;
- an optimization of the frequency of measurements over all the available monitoring systems, adding regular INSAR monitoring while spacing out topographical monitoring for example;
- the ability to possibly recreate, a posteriori, the history of deformations;
- and finally an improvement in: behavioral diagnosis of an infrastructure ; site status evaluation before, during and after works/events ; aid in the understanding of geological phenomena…

3. EXPLORING LIDAR from UAV

3.1 Context

Monitoring of long linear of earth dikes or channel is classically realized by means of:

- geometric levelling on points spaced every 25 or 50 m,
- laser scanning on specific areas when required,
- piezometers profiles spaced every 25 or 50 m,
- leakage follow-up when possible,
- and above all, regular visual inspection.

Today, only regular visual inspection together with leakage follow-up when available allow for detection of local subsidence such as sinkhole which may appear between survey points or outside scanned area, as a consequence of internal erosion.

Figure 9: possible consequence of internal erosion

It is a major challenge to find a measurement technique which would allow for early detection of such phenomenon or a fast inspection after special event (flooding, seismic…) on these long linear structures of tens of km.

In parallel to fiber optics developments which are already largely tested at EDF and have a great potential for structures where it can be implanted, photogrammetry and in particular Lidar boarded in UAV appear to be survey techniques also able to challenge this objective: they both allow for an integral coverage of the structure surface while UAV could make it easy to implement on the long linear concerned. Various ongoing experimentations and developments at EDF are exposed hereafter.

3.2 Local experimentation on dam site

The earth filled dam presented above has a downstream facing made of arranged stones. It presents local deformations as a consequence of both settlement and slight movement toward downstream of the dam.

It is monitored with classical geometric leveling for altimetry and geodetic network for planimetry. Ten years ago, this system has been improved using a static Lidar to cover its entire downstream face in order to detect eventual local deformations.

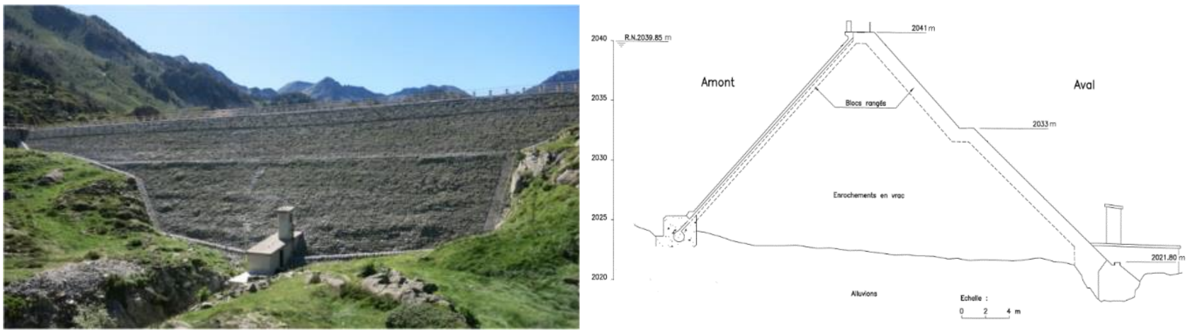


Figure 10: dam downstream face and main profile

Comparison of Lidar surveys at 5 years interval has clearly made possible to identify areas still in evolution (maximum displacement around 1 cm per year). It has proven the interest of such “surface survey” to monitor non-monolithic structures.

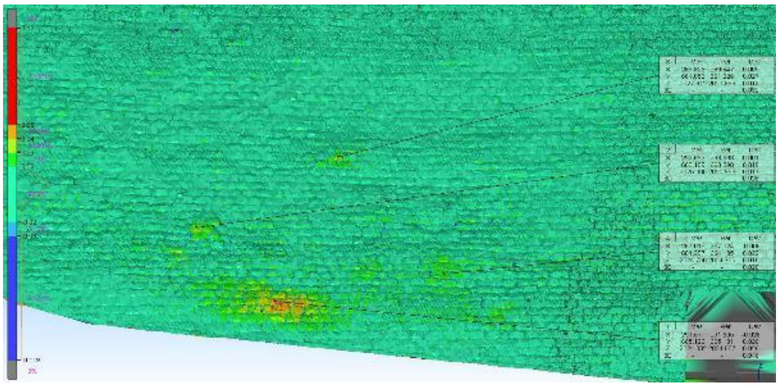


Figure 11: Lidar change detection deliverable

This site has been chosen to test a photogrammetric survey from UAV implemented at the same time as the laser scan survey in 2013. At that time, no effective Lidar was yet available on UAV.

Figure 12: UAS tested and static Lidar

With a particular attention paid on camera calibration, flight plan, images overlap, ground control points and post-processing procedure, interesting results have been obtained: a standard deviation between DTM of ±1 cm with a maximum offset of 3 cm:

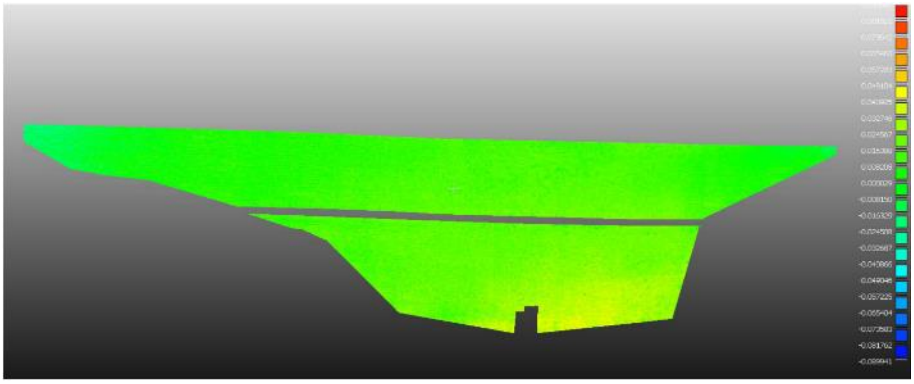


Figure 13: offsets between DTM from photogrammetry and static Lidar

It has also produced interesting deliverables: classic orthophoto mapping but also merging with deformation mapping which make sense for visual inspections as shown on the figure below:

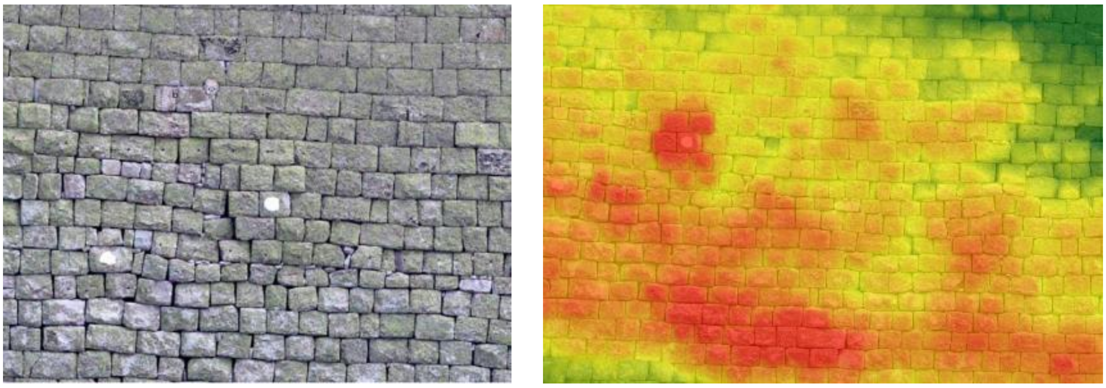


Figure 14: classic orthophoto mapping and merge with deformation mapping

However, such favorable surface for photogrammetry techniques, without any vegetation is actually rare on long dikes.

3.3 Local experimentation on dike mockup

In order to focus on sinkhole early detection, another photogrammetric experimentation have been performed in 2014 on a mockup of an earthfill dam.

Figure 15: dam mockup and jacks system

The mockup have been equipped with an internal box system allowing to gradually simulate a collapse in the body of the dam in order to create a sinkhole on the surface. Materials used in the construction of the dam and on the crest are much closer to real dikes, but still without any vegetation and not so representative of most of dikes. But objective was to evaluate in good conditions detection thresholds of such phenomenon and also to test a specific camera for such applications: the Phase One IXU 150.

In fact, two technics have been tested: fiber optic in the body of the dam and photogrammetry from UAV. A reference survey being insured by static Lidar located on a tripod close by and displacement sensors in the body of the dam.

Figure 16: Phase One IXU and UAV tested

12 flights have been done corresponding to collapse increments ranging from 2 mm at the beginning to 2 cm when sinkhole became clearly visible on the surface till a maximum of 12 cm.

Figure 17: sinkhole appearance

In this particularly favorable configuration and thanks to an important number of control points around this limited area, a deformation from 3 mm amplitude on the surface have been detected by both UAV surveys and static Lidar.

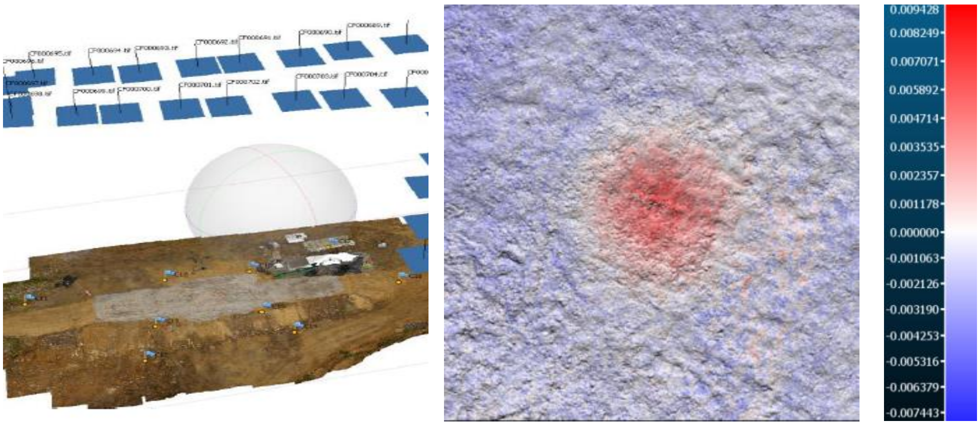


Figure 18: flight plan sinkhole appearance on survey comparisons

3.4 Real dike experimentation

In order to transpose these technics to real case, two main constraints needs to be taken into consideration: the vegetation very often present on dike faces, and the distance to cover tens of km.

Through a partnership with the French railway company SNCF, a test of a prototype made of Lidar boarded on a fixed wing UAV is ongoing. The Lidar is the RIEGL VUX1 specifically developed for such application. The UAV is the new DELAIRTECH DT26X.

Figure 19: RIEGL VUX1 and DELAIRTECH DT26X

Lidar penetration may solve part of the vegetation problem, whereas fixed wing UAV allow to cover long distance in full autonomy. A 1 km dike site have been chosen to test this very promising UAS.

Figure 20: 1 km dike site for testing

Again, in order to simulate sinkhole defaults we wish to detect, a buried box system have been specifically designed:

Figure 21: the sinkhole simulator

Unfortunately, the first survey scheduled in November 2016 have been postponed because of adverse weather conditions. They will take place in June 2017.

3.5 Dedicated algorithm development

Another main constraint to cover long distances is the geo-referencing of surveyed point cloud either from photogrammetry or Lidar systems. Geo-referencing requires ground control points (GCP) measured by other survey means and/or a very effective – and expensive – GNSS/IMU package for trajectory. Extrapolation of GCP ratio used on limited test sites would undermine cost-effectiveness of such system for long dikes.

To address this issue, EDF with its partner the SERTIT have launched in parallel of previous experimentation the development of dedicated algorithms which would allow for localized default detection even if global geo-referencing is approximate or impacted by “low frequency” bias. These bias may come from GNSS/IMU drift while computing a Lidar trajectory or geometric drift while building 3D photogrammetric model of such linear object.

Encouraging results have been obtained testing first developments on the dam case presented in §3.2. A new point cloud have been re-computed using only two approximate GCP. The processing consists in a segmentation of the point cloud to best fit the reference one.

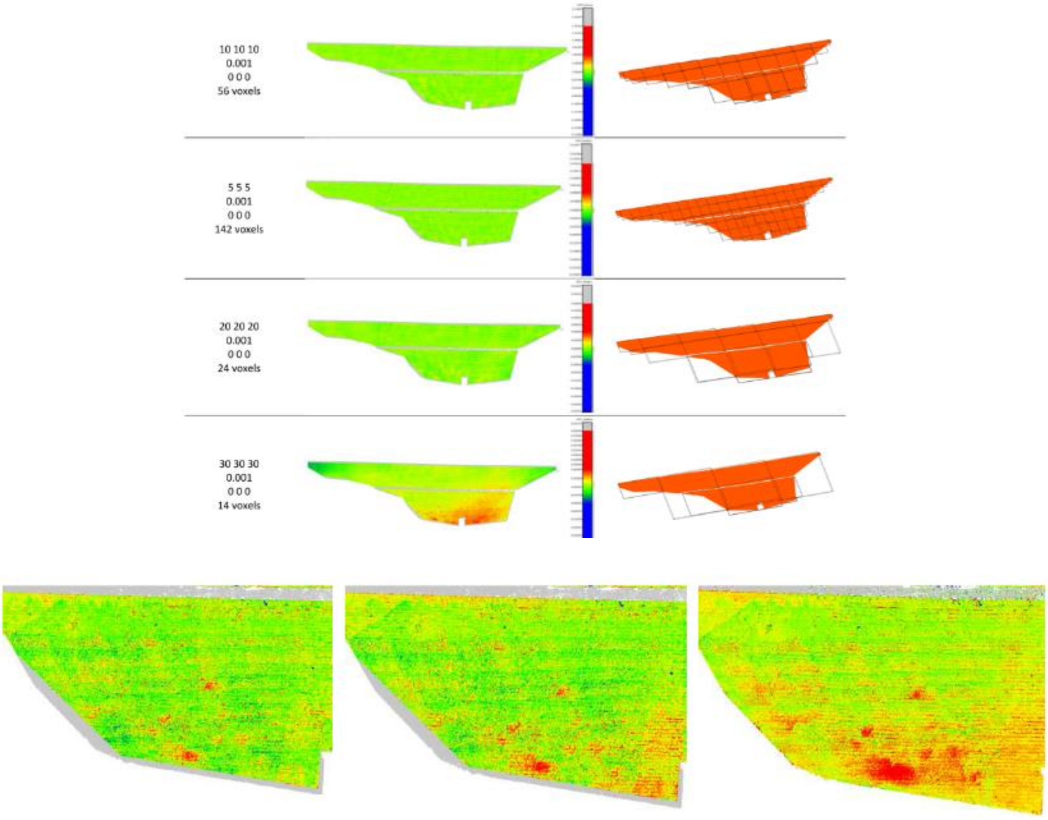


Figure 22: testing different bestfit solutions to challenge static Lidar results

Adjusting segmentation parameters allow to find the best solution which, in that case, detect almost 80% of default observed by static Lidar.

An aerial Lidar simulator has also been developed in order to determine, in theory, the best equipment to be used.

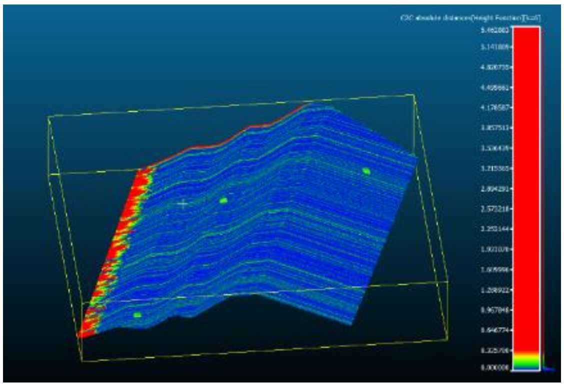


Figure 23: airborne Lidar simulator

Today, these algorithms are being improved and will be tested on real data from the expected experimentation on the real dike.

3.6 Conclusions

Work on a dedicated UAS for dikes monitoring based on Lidar measurement is a challenge for which each component need to be fine-tuned and fit for purpose: localized sinkhole early detection.

As well as INSAR, it represents a complementary tool for mechanical behavior monitoring. It will not replace classical survey tools such as levelling for absolute foundation settlements evaluation for example.

With the continuous innovation on size, weight and performance of sensors and UAV, such UAS could integrate in fine other sensors for visual and thermal inspection, subjects for which developments are also ongoing at EDF.

Finally, their integration in actual monitoring procedure and organization (survey frequency) shall be anticipated to converge to an optimal realistic competitive solution.

REFERENCES

Evolution of survey engineering for dam monitoring
25ème Congrès ICOLD, Stavanger - Norvège, Juin 2015
Rémy Boudon, Gérard Geffraye, Philippe Rebut, Jérôme Sausse, Jean-Paul Fabre

Technologies Topographiques innovantes pour la mesure de déformation d'ouvrages hydrauliques
Colloque CFBR, Chambéry - France, Novembre 2012
Rémy Boudon, Sandra Berni, Fifamè Koudogbo, Anne Urdiroz

La surveillance des ouvrages à EDF
Revue XYZ N°128 de l'Association Française de Topographie, Septembre 2011
Rémy Boudon, Michel Trouillet

Topographie pour les digues & ouvrages en enrochements par porteur drone
Congrès SHF, Paris - France, Avril 2015
Rémy Boudon, Philippe Rebut, Didier Boldo, Arnaud Durand

CONTACTS

Remy BOUDON – EDF
12 Rue Saint Sidoine
69003 LYON FRANCE
Tel. +33 6 47 69 67 67
Email: remy.boudon@edf.fr
Web site: edf.fr