French Space Agency Activity and Goals Concerning Interferometry

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ABSTRACT

The potential of radar interferometry has been recognised, at CNES, a few years ago, but our first large scale experimentation only took place since the launch of ERS1. Our action in radar interferometry is categorised in three areas:
- Product definition and validation; we developed a software package which allows an automatic (but supervised) production of the "interferometric product", a three channel (amplitude, phase, coherence) output from the raw data pair with a throughput compatible with our goals. This product was tested by a company specialised in digital elevation model (DEM) reconstruction under CNES contract. The software package is being modified for its inclusion into receiving stations
- Scientific investigation support; a major point is that interferometric products can be interpreted with a very limited radar background. This encourages a wide diffusion by primary production centres to various scientific users. We are currently supporting more than ten French or foreign laboratories or companies by providing interferometric products on one or several test sites to each of them.
- Development of new applications; global activities such as Earth crustal motion monitoring or glaciers moves, as well as potentially hazardous phenomena (landslides, volcanoes, ground depression) may represent a major driver of future projects. CNES therefore took a particular care in choosing test sites and cooperations in order to develop in house understanding of these. A few examples of these activities will be presented in details. We will also put the emphasis on the work done on the assessment of the displacements caused by an earthquake.

All these activities are driven by the ultimate goal of assessing precisely the interest of adding an imaging radar to the SPOT family of satellites toward the end of the century and fine tuning the mission features of this satellite.

BACKGROUND

Radar interferometry has been demonstrated almost twenty years ago (ref. 1), but was actually pioneered by Jet Propulsion Laboratory scientists (ref. 2) using SEASAT and SirB data. A few points are very specific of radar interferometry and should be stressed:
- the potential of radar interferometry is quite clear and can be understood readily. The program at CNES was decided in 1985 following a paper study indicating the possibility of crustal moves monitoring (ref. 3). Actual small moves detection was achieved using SEASAT data (ref. 4) on a relatively flat topography. Unlike amplitude data, the information content of interferometric product can be easily understood by non radar specialists as it is purely geometric. The potential user population is therefore very wide. Along the same line of thoughts, one could notice that interferometric product may be expressed in units of the international system (S.I.), that is in metre, which is unique in the remote sensing field.
- the actual potential of the technique and particularly the percentage of success with respect to the surface nature and to the time elapsed between the data takes are very poorly known. The geometric conditions for coherence are, however, quite easy to compute (ref. 5,6).
- Another requirement of radar interferometry is phase unwrapping, which will not be discussed in detail (ref. 7,8). Phase unwrapping may not, in our opinion, be as critical as it is often thought of. In many occasion it can be bypassed, when, for instance, a rough digital elevation model (DEM) exists on the site which features a r.m.s. error of less than the altitude of ambiguity (i.e. the difference of elevation which causes one fringe). Similarly, in the case of multi-date acquisitions, close interferometric pairs may give the rough DEM which could be used to unwrap the more difficult pairs. Anyway, there seems to us to be little prospect of fully

automated unwrapping process (i.e. no human check at all, whatever the site and the quality of the data). We therefore think of phase unwrapping as a mix of more or less sophisticated algorithms associated with very ergonomic interactive software tools.

The two first points we exposed (number of users and unknown percentage of success) call for a very large set to be explored in order to serve a large number of users and to meet a wide range of experimental situations. One may therefore fear that local experiments (ref. 9,10,11) do not provide the kind of global verification which is required. These experiments are nevertheless very useful for punctual performance assessment and technical validation.

We decided to deal with these constraints first by establishing a large basis of co-operation with dedicated professionals (industrialists or scientists). The list of the test sites and their main features are given in figures 1 and 2. Second, although the technique is not operational, we were forced to organise the production on a rather large, seem-operational scale. This approach appeared very fruitful later on. In the case of the study of Los Angeles earthquake, the 35000 square kilometres we analysed are hardly sufficient to in-

Name	*Cooperation*	*#scenes*	*surface (km2)*	*Application*
Ukraine	ISTAR	2+2	14,000	DTM
Ukraine	CNES	50	315,000	Platform stability
Ukraine	CNES	50	315,000	Surface changes
Landers	GRGS	12	35,000	Co-seïsmic moves
Sardinia	ESA, ISTAR	2x0.5	5,000	DTM
Bern	ISTAR	2	14,000	DTM
Turkey	IPGP,LGST	6	20,000	Faults
Etna	IPGP	3	4,700	Volcanic crisis
Nice	ISTAR	6	14,000	DTM
Nice	IPGP	5	14,000	Landslide
Le Boulc	BRGM	9	14,000	Landslide
Flevoland	ESA	2	2,500	Processor validation
Kisthym	-----	2	14,000	DTM
Romania	CNES	9	40,000	Radargr. + interfero.
Spitsberg	Polarinstitutt	12	14,000	Ice motion
Bretagne	LGST	10	14,000	Surface change

Total: 125 scenes; 540,000 km^2

Fig. 1 - Interferometric test sites under investigation.

Lacq	ELF	*	14,000	Subs. from gas extr.
The Nether.	ELF	*	14,000	Subs. from oil extr.
Gardanne	BRGM	*	14,000	Subs. from mining
Pinatubo	LGST	*	14,000	Volcanic crisis
Caucasus	CNRS	9	40,000	Faults
Papua-N.	ISTAR,SPOT.	8	50,000	DTM
France	IGN	15	30,000	DTM mosaïc
Guyana	LGST	2	14,000	Equato. forest
Colobrieres	LGST	5	14,000	Geologic surf. change
China	GRGS	*	*	Faults

Acronyms of the laboratories and firms:

LGST	Laboratoire de Géologie Structurale et Télédétection
GRGS	Groupe de Recherche en Géodésie Spatiale
IGN	Institut Géographique National
ISTAR	Imagerie Stéréo Appliquée au Relief
BRGM	Bureau de Recherches Géologiques et Minières
IPGP	Institut de Physique du Globe de Paris

Fig. 2 - Interferometric test sites to be studied.

clude the area were displacements were significant. Another advantage of having large surface is the possibility to lock very precisely the orbits of the interferometric pair. The precision of this technique is directly proportional to the surface involved. An operational approach is also time-saving for the subsequent step of the industrialisation of the procedure, which is currently under way.

Figure 3 gives the organisation of the interferometric software we developed. It is somewhat difficult to assess precisely the effort which was put on this software since some of it is not specifically devoted to interferometry (such as PRISME, our general purpose correlator). However, radar interferometry has been mostly developped by three people in two years (i.e. six man-year). The associated funding has been moderate: 50000 US$ per year. This does not take into account the travel budget nor the computing costs. The processing was done on a VAX8250 computer associated with a MP32 array processor (by FPS) rated at 18 MegaFlops. This system has recently been replaced by a DECα workstation, for a total cost of 90000 US$.

APPLICATIONS

All the applications listed in figure 1 and 2 will be predictably successful. The only remaining unknowns are the percentage of scenes where the coherence is kept, the nature of targets which loose coherence (the status of equatorial forest is still uncertain in this regard) and the amount of artefact which will be brought by small moves in DEM computation. Like any advance in metrology, radar interferometry is likely to reveal small moves which have gone unnoticed so far, especially if they are not associated with unpleasant events.

It is, however, theoretically possible that another field opens to radar interferometry, we would call this "phasimetry" and define it as any phase change which cannot be explained by small moves, unperfected orbital tuning nor topography. If we look at the way the phase of a pixel is built, the position of the scatterers is critical. If we imagine that a surface is made of identical scatterers, it is clear that changing each scatterer into a different type of scatterer would not destroy coherence if the positions of the scatterers remain unchanged. Moreover, if we change not only the scatterers, but also their positions by a constant vector, the coherence will, again, be preserved. This kind of situation may very well occur in agricultural targets: on one day the main contribution to the reflectivity may come from a part of the plant and, one week later, by another part of the plant, while the position of the plant does not change and the distance from the first reflecting part to the second reflecting part is constant for all the plants in a pixel.

TECHNICAL PROCEDURE

In the scheme of figure 3, the raw data are first checked and concatenated into a single large volume raw data set. This is an essential condition to the building of a large surface data base. Segments of up to 3000 km of ERS1 raw data have been processed this way. The data are then channelled into a phase preserving correlator developed at CNES (ref.12). Alternate solutions are available for phase preservation (ref. 13,14). The correlator allows the production of low resolution data as well as more standard products (SLC, FDP, etc...). In the case of an interferometric processing, the two images of the pair will be very economically processed into low resolution products which will enter a correlation and modelling process resulting in a considerably improved relative orbital model with a typical precision of less than one metre. The initial model comes from restitued or predicted orbits.

The modelling also indicate, at a very early stage of processing, whether a given pair will meet the baseline condition necessary for proper fringe quality and allows the retrieval of the bulk of the fringes due to the relative orbital positions (ref. 6), which is automatically done if the ellipsoid correction option is selected in further interferometric processing. Another feature of the processor allows the choice of the output geometry of the image. Once the accurate orbital model is obtained, the image pair raw data may be reprocessed to high resolution single-look complex co-registered images which may be directly combined into the interferometric product, generally a multi-look, three channel image: mean amplitude, fringes corrected to the ellipsoid and coherence (ref.15). The advantage of this is clear if a multi-look interferogram is required. The saving in disk space is then considerable. The interferometric product may also be injected into a DEM comparison processor where the fringes induced by topography will be computed using the improved orbital model and subtracted from the actual interferogram. A further step of orbital model refinement takes place at this stage: we count the residual fringes at four points of the image where no terrain move is expected. This counting results in the final orbital model, with a typical precision of one centimetre. This step of fringe counting could be automated since orbital fringes are very regular (automatic fringe counting is only experimental right now). This model is combined again with the DEM and provides an interferogram where the phase results from:

- terrain motion
- possible surface phase changes
- inaccuracies in the DEM
- noise

The DEM may turn the interferogram or any product in the same geometry, such as coherence or amplitude, into a map co-ordinate geometry (geocoded product).

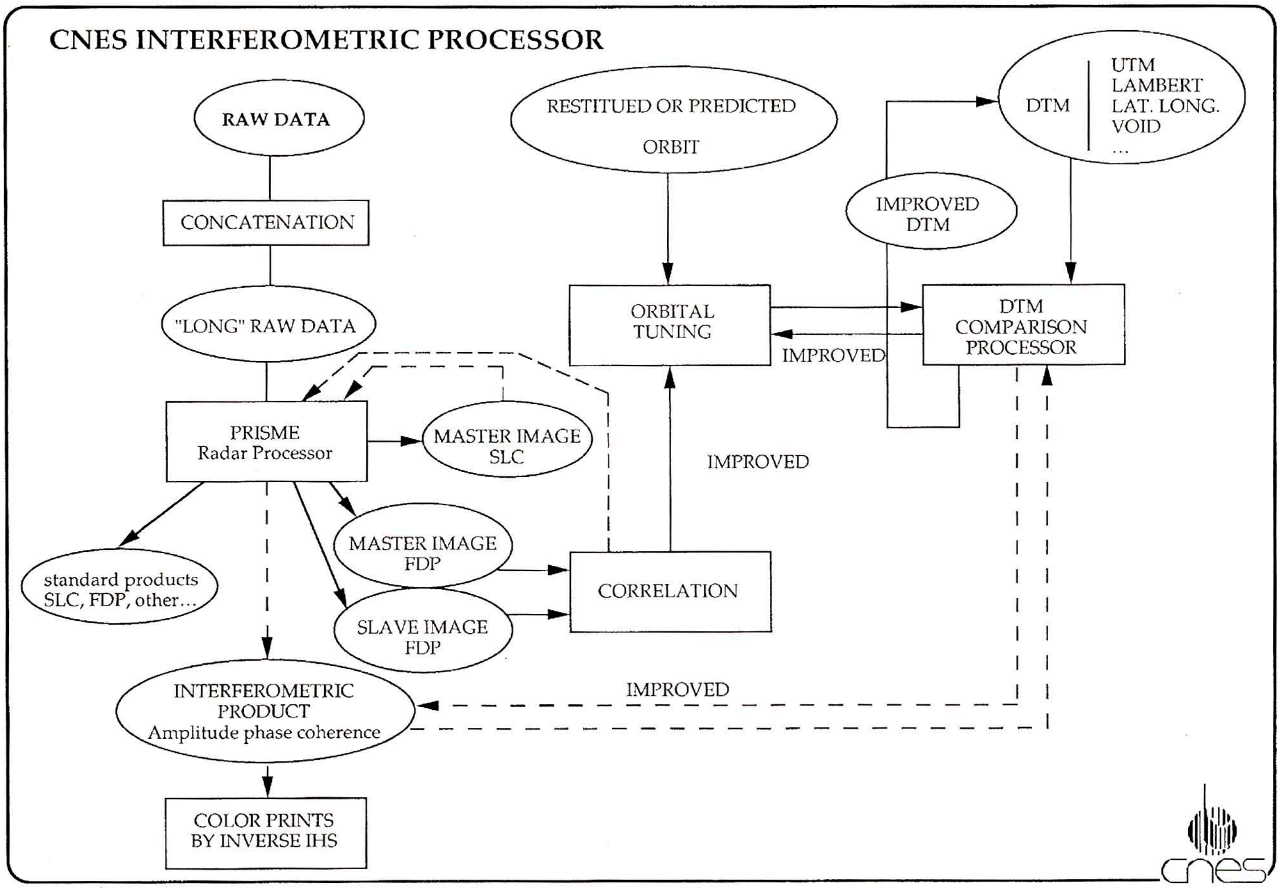

Fig. 3 - CNES interferometric processor.

This software is now mature and may accept several DEM formats (figure 3). A feed-back allowing the interferogram to react on the DEM in order to improve it will be experimentally implemented. We hope this kind of algorithm will further reduce the need for phase unwrapping.

FIRST REAL WORLD STUDY: COMPARISON OF SPOT AND ERS1 DEM's

A major field of interferometry application is digital elevation modelling. Optical stereoscopy has proved to be very useful for DEM extraction and is therefore the reference to which other competing methods have to be compared. Together with a company experienced with DEM computations from SPOT stereo-pairs, ISTAR, we compared SPOT DEM and radar interferometry DEM. The comparison could not only apply to ERS1 data, but also to ALMAZ, J-ERS1 and SirB data, since our interferometric product share the same format wherever the SAR data come from.

The study was to compare not only technical performance of the product, but also its ability to be merged into the operational tool of a leading industrialist in the field of DEM computation. The result concerning these two aspects has been satisfactory and interferometry is similar to stereoscopy with this regard (ref. 16). Some artefacts that have to be removed after visual inspection, such a time changing agricultural fields, demand the same tools. The need for phase unwrapping has not been recognised as a major challenge is this study.

It is difficult to compare the technical performance of the products, since it depends critically on the orbital geometry for both techniques. Radar interferometry could be credited of a small advantage with this respect, but the four sites where DEM's have been produced cannot be considered as a large enough statistical basis.

Three of the sites are technically depicted in the interferometric situation sheets of figure 4, 5 and 6. The work has not yet been completed on the fourth site (Nice). Image 1 shows the DEM computed over Sardinia by SPOT, as compared to image 2, where it has been computed by ERS1 (Data from Sardinia have been obtained through the "fringes" group managed by the European Space Agency). The results are very similar. Optical and radar DEM's are

Gennargentu

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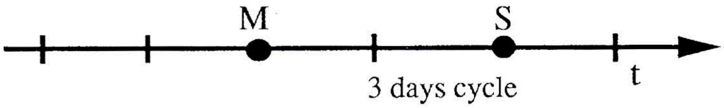

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14000 Formats

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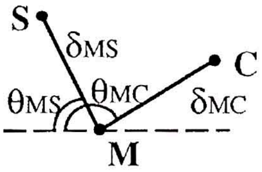

Δ Master to	Δt	δb	θb	δe	θe	Quality of Fringes	Altitude of ambiguity			
							NRb	FRb	NRe	FRe
Slave	6 d	168 m	183°	136 m	189°	Good	-46 m	-73 m	-59 m	-97 m
Compl.										

Fig. 4 - Interferometric situation of Sardinia.

also very similar over Ukraine. A less successful example can be found with Bern, where the fringes were visible, but poor in quality. Only a rough DEM can be computed (image 3). Such a DEM would, however, be very valuable for preliminary phase unwrapping of a more adequate pair.

SECOND REAL WORLD STUDY: LANDERS EARTHQUAKE

The Landers earthquake of June 28, 1992 (magnitude 7.3) presented a surface rupture over 75 km. It was followed 3 hours later by the Big Bear earthquake (magnitude 6.4). No surface rupture was reported for this later event. The area is very well surveyed by conventional geodetic tools. The fault itself has been detected using space borne SPOT data taken before and after the quake (ref. 17). The precision of this technique of image correlation is about $1/10^{th}$ of a pixel or one metre.

The location of the earthquake has been imaged on four separate dates by the ERS-1 satellite in 1992: April 24, July 3, August 7, and September 11 and provided a unique opportunity to verify the feasibility of mapping crustal moves by interferometry (ref. 18). Among the three pairs spanning the earthquake date, the April 24 - August 7 pair provides optimum conditions for image correlation because it has the shortest baseline (126 m horizontal, 60 m vertical) and best met the "coherence condition" required for interferometry. With the geometry of this pair, a difference of altitude of 72 m creates one topographic fringe. The interferogram presents good fringes despite the record 105 days elapsed between the data takes. This quality may be at-

Berne

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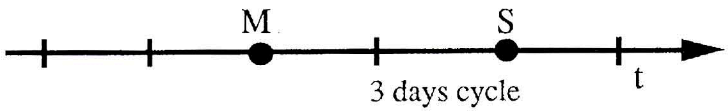

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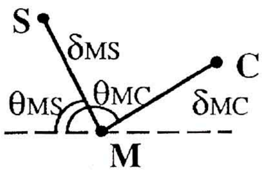
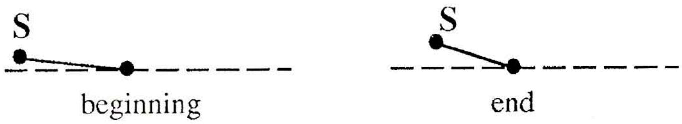




Δ Master to	Δt	δb	θb	δe	θe	Quality of Fringes	Altitude of ambiguity			
							NRb	FRb	NRe	FRe
Slave	6 d	74 m	6°	52 m	18°	Poor	107m	172 m	170 m	236 m
Compl.										

Fig. 5 - Interferometric situation of Bern.

tributed to the exceptional stability of the reflecting surface on this mostly desert area. Another pair which does not span the earthquake (July 3, August 7) and where in principle no move occurred, has been used for error budgeting. Given the larger orbital difference (496 m horizontal, 22 m vertical), this latter pair is 4.5 more sensitive to altitude than the first one. We processed 70000 formats to high resolution complex images for each data takes, the length of the observed region was thus 275 km. We also kept partially correlated pixels in range. The sides of the swath are therefore of degraded quality but the resulting image is 125 km wide, which is beneficial to fringes counting and allows in turn a better orbital tuning.

We applied the above described procedure and we injected a DEM of southern California, computed by USGS and provided by JPL (Dr T. Farr). The DEM turned into a fake radar image (image 4) which allowed us to "lock" the orbital geometry of the radar image of August 7 (image 5), taken as a reference for slant range geometry. This was done by the above described "orbital tuning" correlation and modelling tool.

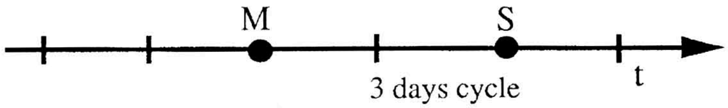
A fake interferogram was then produced by taking into account the DEM and the relative orbital positions derived from the correlation residuals of August 7-April 24 images. Due to limited precision of the correlation (a few hundredth of a pixel), up to ten fringes caused by non-perfect orbital tuning remained in the real interferogram, once the fake interferogram had been subtracted from it.

The relative orbital model was then refined in order to minimise fringes at far-field, where no earthquake bound move was assumed.

The new fake interferogram obtained using both the DEM

Ukraine

Date of acquisition :



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30000 Formats

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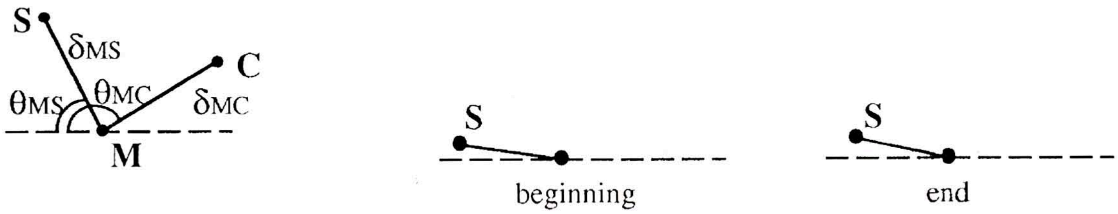

Δ Master to	Δt	δb	θb	δe	θe	Quality of Fringes	Altitude of ambiguity			
							NRb	FRb	NRe	FRe
Slave	6 d	70 m	9°	64 m	11°	Good	110 m	180 m	-120 m	-192 m
Compl.										

Fig. 6 - Interferometric situation of Ukraine.

and the corrected orbital tuning was subtracted from the actual interferogram obtained from April 24-August 7 pair, leading to the differential interferogram.

Image 6 shows the differential interferogram after it has been put in the cartographic reference of the DEM.

Together with the phase image, a coherence image was produced. Coherence is the third channel of the interferometric product we designed (ref. 15) and is nothing else than an average of the complex correlation coefficient of the two co-registered complex images of the pair. This image (image 7) is bright where the target structures have been well conserved. On may notice areas of high topography where the coherence is low. The striking feature of image 7 is found in the vicinity of the surface rupture, which appears very clearly as a banana shaped region on the right-hand side of the image. Our hypothesis is that, unlike the loss of coherence caused by a variation of the geometric point of view, the actual stretching of the pixels in this area, due to the mechanical action of the quake, caused the loss of coherence.

For comparison, a theoretical displacement field was computed by geophysicists of GRGS (Groupe de Recherche en Géodésie Spatiale), who were associated with us in this study (G. Peltzer and K. Feigl). The contribution of this field to the range was computed by projection on the target-radar axis. The pattern of fringes is very similar in the modelled and observed fields, as it can be seen on the close-up on image 8. The resemblance is striking for the Landers quake, where the surface rupture was a good input for the modelling process. The big bear quake, with no surface rupture, was much less successfully modelled. It appears as a family of circular fringes at the bottom of image, hardly detectable in this rather incoherent region.

This indicates that radar interferometry is at least as good as more conventional measures in a very well documented case, but actually much more powerful in general.

Another, less spectacular proof of the validity of this interferometric measurement can be found in the error budget. The July 3-August 7 pair should not exhibit any moves (post-seismic moves are typically $1/100^{th}$ of co-seismic moves). We processed this pair using the same method and found an error related to topography amounting to 1,5 fringe. Since the altitude of ambiguity of this second pair is 16 metres, we infer that the error in the DEM in on the order of 25 metres, where the "official" error is 30 metres (G.Peltzer, from USGS).

The error inferred on the April 24-August 7 pair, taking into account that it is less demanding in altitude accuracy, is 9 millimetres.

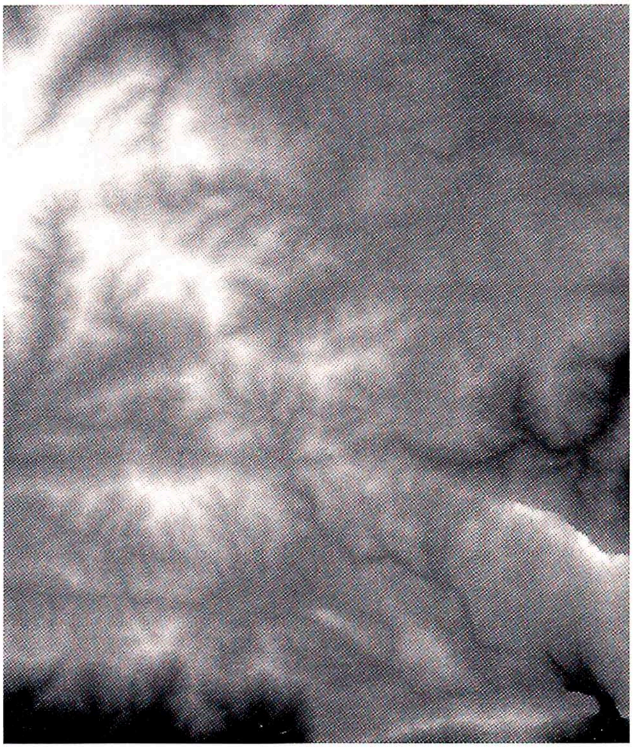

Image 1 - DEM of Sardinia computed by ISTAR (F. Perlant) using interferometry applied with "fringe group" ERS1 data.

Image 2 - DEM of Sardinia computed by ISTAR (F. Perlant) using SPOT stereoscopy.

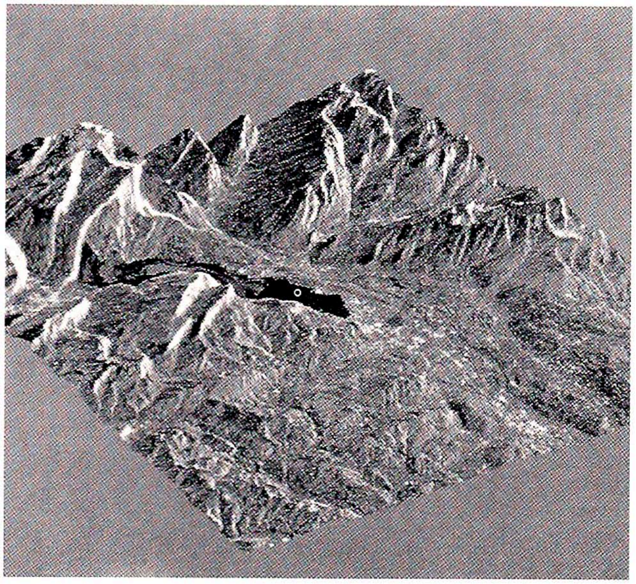

Image 3 - Perspective view of a rough DEM of Bern area computed by ISTAR (F. Perlant) using interferometry with ERS1 data acquired in Toulouse. This is an example of poor quality interferometric DEM. This product could be used for phase unwrapping of better data.

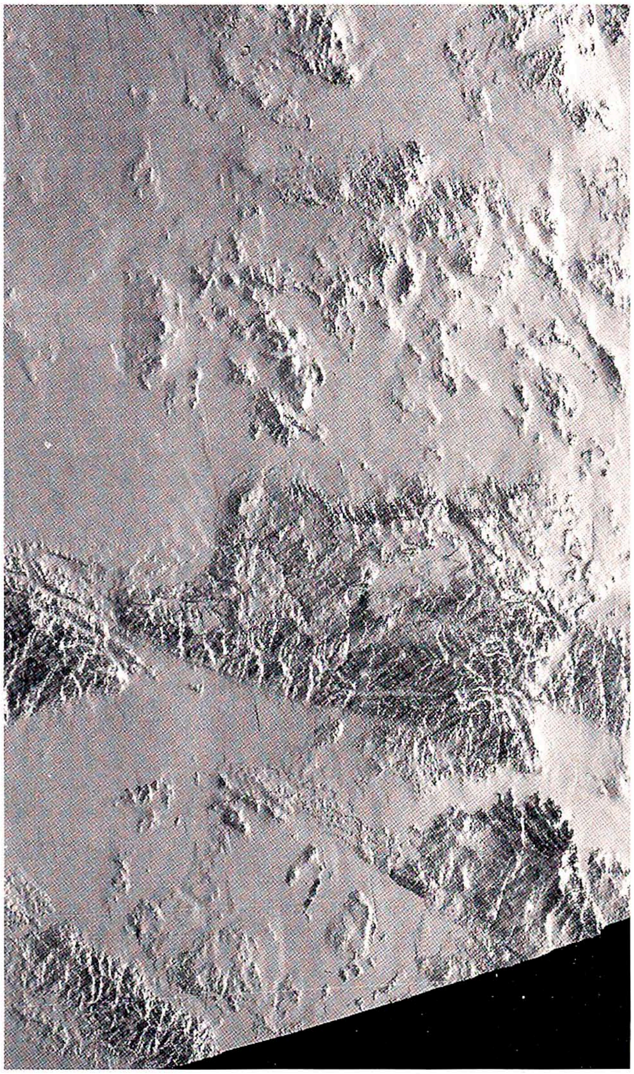

Image 4 - Simulated radar image computed from USGS DEM of Southern California. This image is used to lock the orbital model of actual ERS1 data.

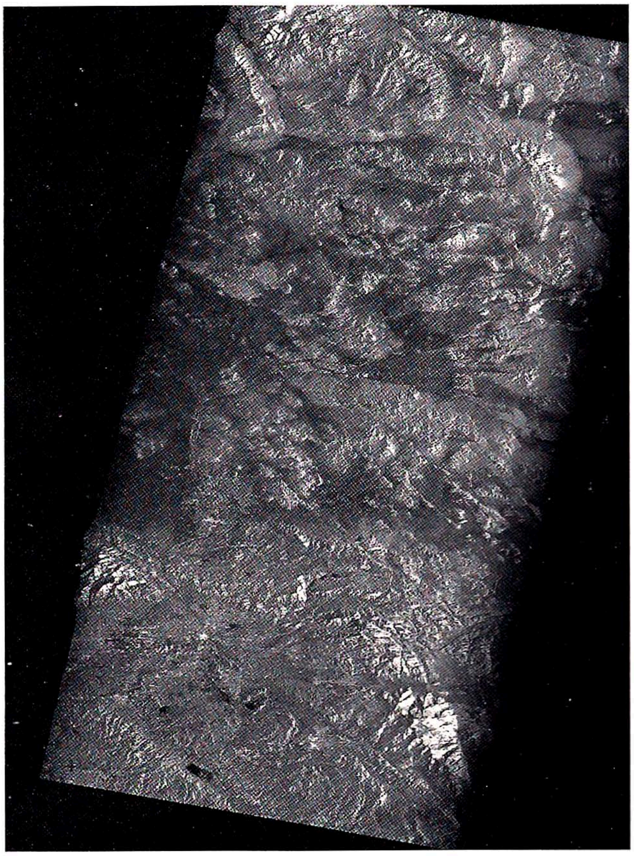

Image 5 - Geocoded image of the Los Angeles - Death Valley area. The data have been acquired by ERS1 on August 7, 1992

A PROSPECT: CLASSIFICATION OF AGRICULTURAL FIELDS

Differential interferometry effects over agricultural surfaces have been obtained by JPL (ref. 4) using SEASAT data. These effects were attributed to soil swelling following irrigation. We decided to study these effects using ERS1 data with the goal of assessing the usefulness of interferometric products for crop classification. By interferometric product we understand not only "non topographic" phase differences, but also additional information such as coherence.

We adopted a statistical approach requiring that a lot of agricultural fields be studied with an as small as possible effort. We chose a simple scheme which does not require a digital elevation model of the area being studied. This scheme is what we would call "opportunistic differential interferometry", where a flat topography and/or exceptionally close orbits allow an easy removal of orbital fringes because the "altitude of ambiguity" is larger than the range of altitudes which can be found in the area.

We therefore selected a suitable area, mostly used for agriculture, and located between the coast of Black Sea (Ukraine) and the northern part of Gulf of Botnia (Sweden, Finland). The length of this segment of ERS1 data is more than 3000 km and the swath width of 125 km. We did not keep the whole length of the segment and obtained an area of 315.000 km^2. Eliminating the phase pattern implied by the orbital situation readily produces large surfaces where differential effects are obvious (image 9) and cannot be explained by topography, given the altitude of ambiguity.

We chose a night segment for our experiment. Although we processed typically one hundred interferograms from ERS1, which cannot be considered as a very good statistical basis,

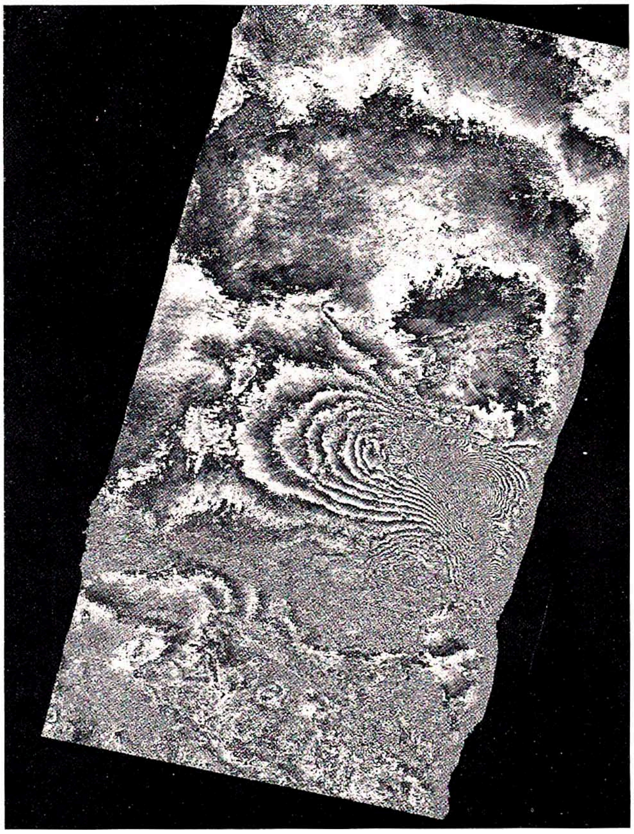

Image 6 - Non topographic phase difference showing earthquake bound moves. This product is geocoded, each fringe represents a satellite oriented move of 28.3 mm.

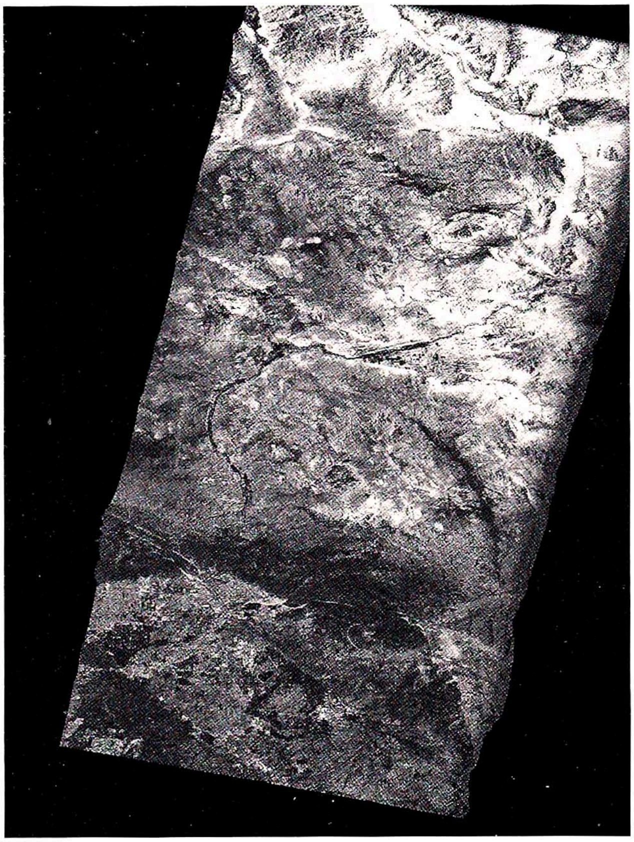

Image 7 - Geocoded coherence image of the same region.The surface rupture is clearly noticeable through the induced loss of coherence (banana shaped feature on the right-hand side).

we observed that data acquired by night tend to be more coherent than data acquired by day. This makes sense if we assume that the vegetation state repeats itself more closely by night than by day, due to a more stable energetic situation. More than 350 agricultural units were extracted from the test site. For each field, the powers of the two images were computed, as well as coherence and non geometric difference of phase. The coherence in addition to the powers shows a big classification potential. This is only indicated by the statistical behaviour of the data since no ground truth has been performed yet. The phase difference shows also a classification potential, alone or combined with the coherence. Further studies and ground truth campaigns will be required to know what is actually classified and to what extend it is useful in the more general problem of crop identification and yield assessment.

CONCLUSION

The availability of ERS1 data is the first large scale opportunity to test interferometric concepts. However, the extensive radar know-how and the computing power and complexity needed for taking full advantage of interferometry are not available to most of potential users of the interferometric technique. That is the reason why French Space Agency decided to define an interferometric product and to organise its production from ERS1 raw data on a limited scale. The product proved to be a good interface with our industrial partners. Following a feasibility study with ISTAR, DEM computation from interferometric product has been included into a product list. We hope that the market will now rise for this kind of product, and will allow us to refine our production schemes and to enter fully operational status.

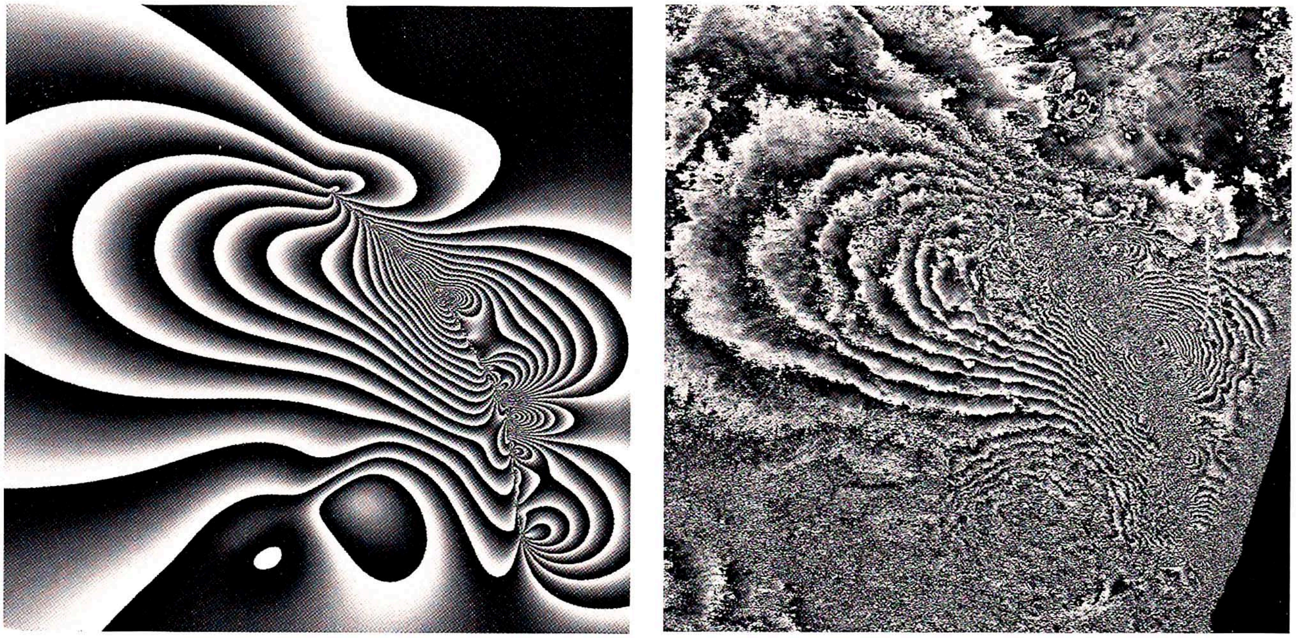

Image 8 - Close-up of the earthquake region comparing actual interferometric results with geophysical modelling (performed by GRGS in Toulouse).

The work performed on the Landers earthquake site in differential interferometry, validated by geophysical modelling (G. Peltzer and K. Feigl), indicates clearly that operational use of the technique is feasible. The work was performed with available orbits and with the actual topography of the site, which reaches more than 3000 metres at some places. The size of the processed site provides a clear visualisation of the moves which occurred during the quake. Since this study is an end to end manipulation from radar raw data to validation with other sources of information, it validates all the technical choices we made.

Many other differential interferometry sites, currently under study, will benefit by the experience gained working with these data. We will now orient our scientific studies toward phase and coherence based classification techniques. The prospect of these is still remote, but the pay-off could be very interesting if it opens the field for agricultural monitoring by an all-weather technique which works on short periods of observation.

Our feeling is that the technique is now mature enough for large scale experiments devoted at predicting or monitoring natural hazards. We are ready to participate to this kind of program. The experiments may also begin to deliver clues for future radar mission optimisation. It will now be impossible to ignore interferometry in synthetic aperture mission design.

The work at the French Space Agency will continue on the test sites mentioned in figure 1 and 2. Interferometric products will be made available on a commercial basis through a cooperation between CNES and SPOT-IMAGE, which is one of the official ERS1 data providers. This commercialisation activity is expected to require a lot of effort due to the remaining technical challenges of radar interferometry and the unknowns of this completely new market. On a technical

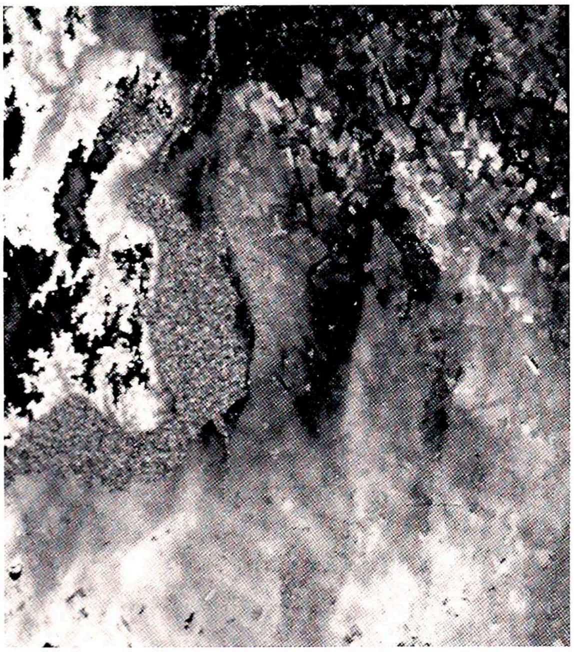

Image 9 - Example of opportunistic differential interferometry in Ukraine. Phase variations associated with agricultural units are common in the upper, right-hand region of the image.

point of view, the emphasis will be put on absolute calibration of interferometric products on very large regions, on the potential use of interferometry for crop classification and on the preliminary design of a radar mission devoted to interferometry, using the experience which has been gained over the past two years.

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