SCIENTIFIC OBJECTIVES OF THE INTERFEROMETRIC CARTWHEEL

Report for the CNES. Prof. Michel Kasser, february 2001.

A. Introduction

The Interferometric Cartwheel (ICW) will provide a world-wide DTM of metric precision (of the order of 1 meter, for a 20 meters mesh) and exhaustively covering the world. We may here recall that topographies of Venus and March are currently known better than those of the terrestrial emerged surfaces (and, of course, of those that are immersed…). A metric level precision is in view in none of the projects currently discussed in space agencies, to the exception of niches such as CRYOSAT. The major scientific perspectives of this project are underlain therefore by two large domains of applications :

- The production in some months of mission of a very precise world DTM comes upstream of most domains of research in Earth sciences,

- The temporal variability of such DTM on chosen zones by an all weather method is very attractive, but is to validate again, and it is the other essential aspect that proposes this project.

We present here some immediate scientific applications of this project, set up by a group of french scientific specialists from various disciplines. The paragraphs that follow are given as examples, and do not form a complete list, that would be besides difficult to limit considering the number of domains in which the DTM are useful, but also considering the considerable difference between this device and the classical space radars (so that all applications are not yet foreseen).

Many proposed applications have different levels of scientific interest depending on the frequency used (which is of course the frequency of the active radar satellite escorted by an Interferometric Cartwheel). As a last preliminary remark, one should note that at the present level of reflection, it appears that lower frequencies (the L band) would be scientifically preferred to higher ones (e. g. band C), as they open the possibility either to go deeper into dry grounds, either to penetrate better through moderate density canopies, or even to try to compute a new vegetation index based on the 3D volumetric response of trees. But these points are not yet well documented and will no more be detailed here.

B. Geophysics, geology,

Numerous studies require to use a precise topography of the studied zone for the exploitation of different geophysical or geological data acquired on the ground, by airborne or by satellite means. This point is always delicate because the topography is often known only locally by the cartographic documents whose projection and geodesic system are frequently local systems, and whose transformation parameters are rarely very well known. In certain regions, only a very low precision and of low definition topography (global files to 30" mesh for example) can be available.

We will propose now the main applications for which it is indispensable to use a precise DTM and the degree of precision required to perform the considered studies. We will mention also the researches that will be driven if high precision and high definition DTM are available at different times, allowing to monitor the temporal evolution of the topography.

B.1. Geophysical and geological studies requiring the knowledge of a precise topography.

We will study academic or applied problems, and also contributions to seismic and volcanic risk assessment, and slopes instabilities.

B.1.1. Knowledge of the internal structure: gravimetry and electromagnetism.

The gravimetric studies allow, by the calculation and the inversion of Bouguer anomalies, to identify variations of density in the basement. Applications are numerous and depend from the scale of the survey achieved and from the precision of the measures. They go from the deep interfacing cartography to the fine modelling of the internal structure of geophysical objects (volcanoes, seismic zones,…). The anomalies of Bouguer are obtained from precise measures of the spatial variations of the density (obtained by terrestrial, airborne or spatial methods) while applying corrections that depend (i) of the altitude of the point of measure and (ii) of the local topography that influences to the first order the value of the measured density and must be corrected carefully. Considering the present precision of field gravimeters and of the positioning achieved, the factor limiting the final precision of the anomalies of Bouguer is the knowledge of the relief around points of measure. It is therefore fundamental to use precise digital terrain models, and the most precise available if the measures are done in a zone presenting strong slopes.

Typically, for a survey of the anomaly of Bouguer to the scale of a region of some thousand of km^2, it is necessary to use DTM with a 10 m precision with a 50 m mesh. For dense gravimetric surveys at the level of active zones, it is necessary to use a metric precision DTM with a mesh of 10-20 m.

In electromagnetism, the DTM are essential for all types of magnetic or electric ground prospections. These methods of survey require a mean density of measures of 25 m along of identified axes. These axes must be marked perfectly in relation to the topography of the land since one tries to put in electric or magnetic anomaly relation with the geological accidents that are associated there. Besides, as in gravimetry, the DTM is indispensable to eliminate the inherent topographic effects to these ground surveys.

Let us note also that several programs of global cartography of the ground density and its variations versus the time from space will be achieved during the next decade (projects CHAMP, GRACE and GOCE). It is clear that data on the field of density produced by these spatial missions will not be able to be analyzed in term of structure or mechanical behavior of the lithosphere at large scale only if one uses an equivalent quality information on the topography. The availability of a global DTM of homogeneous precision - and moreover of high precision - is the indispensable condition to the realisation of these studies.

B.1.2. Determination of geoidal anomalies on a given zone.

The knowledge of density anomalies allows to calculate the shape of the geoïd provided that one uses a precise topography. This information is useful for studies of structure and also to transform classical leveled altitudes to GPS altitudes. Indeed, altitudes obtained by GPS are expressed in relation to an ellipsoid of reference, whereas the classic leveling data are heights on the geoid. The passage of a system to the other can be either performed by the simultaneous observation of GPS and classical measures (very difficult and at least very costly to do practically), either by the calculation of anomalies of the geoid from available gravimetric data, a precise DTM and some geodetic points measured simultaneously by the two methods. The need to provide data compatible between leveling observations collected in the past and present GPS data is necessary to preserve the vertical movement history since the beginning of measures. On numerous seismic provinces, leveling data are available since several decades (more than one century in France), and the knowledge about how to convert these altitudes precisely on the ellipsoid allows to preserve the old data use for studies of long-term ground movements. The system conversion to the present one has also a very large importance for surveyors and professionals of the topography and GIS.

B.1.3. Measure of ground deformations by radar interferometry.
Studies of ground deformation, for example after an earthquake, are based on geodetic data use (GPS, leveling,…) and besides since some years on the interpretation of SAR interferograms. The calculation of SAR interferograms requires an initial DTM whose precision conditions the quality of interferometric pictures generated. The requested precision for the DTM is 3 to 5 m with a mesh of 20 to 40 m to exploit the largest number possible of images while generating all combinations susceptible to interfere.

B.1.4. Modelling of deformation fields.
Deformations on a seismic region or a volcanic structure result from the mechanical response of the medium to a source of perturbation (variations of pressures in a magmatic reservoir, opening of an igneous crack, displacement on a fault plane,…). The understanding of the considered phenomena requires an evaluation of the features of this source of disruption and implies an available model. To take in account a faulty topography in the model may drive to erroneous parameter values (for example, over-evaluation of the volume variation, bad evaluation of the fracture slope) or even a non-adequacy of the model to the given problem. Indeed, the presence of a meaningful topography influences the strain field inside the medium and modify limit conditions of the problem. An interpretation of deformation fields without consideration of the topography is generally too imprecise to be useful.

B.1.5. Zoning of the volcanic risk.
During a volcanic eruption, products (lava streams or pyroclastic out-flows) get most often their way in a manner closely bound to the topography. According to their ejection speed and their viscosity, the products will be canalised by the more or less high topographies. In the case of lava streams, a preventive calculation of out-flows requires a DTM of precision 1 to 2 m with a mesh of 5 to 10 m. Due to their high kinetic energy, the calculation for pyroclastic out-flows requires a lesser precision, of the order of 5-10 m. In short, the assessment of the risk of lahars and/or secondary pyroclastic out-flows from recent deposits require a very good knowledge of the thickness of these deposits, of the order of 1-2 m.

B.1.6. Survey of the flank destabilizations on the volcanic buildings.
Many volcanoes had in a more or less recent past one or several episodes of massive downfall of their flank (a fraction to several tens of cubic kilometers). The destabilizations of flank have some devastating effects, on the one hand laterally by the controlled explosions that they can generate when the saturated lands of pressurized water and various gas gets suddenly in surface but also by the avalanche of debris that they produce. When the volcano is situated on an island, these debris avalanches can reach the sea quickly and provoke important tsunamis. These phenomena often represent catastrophic events and play a major role in the volcanic building evolution. It is therefore necessary to identify them in the past history of volcanoes.

A quantitative geomorphology analysis (calculations of slopes, curvatures,….) can contribute in search of the past events (horseshoe-shaped structure scar of the head of the slip, modification of the hydrographic network, deposits with a morphology in blocks,…..) : it requires a metric precision DTM with a mesh of 10 to 20 m.

B.1.7. Survey of slope instabilities.

Instabilities of slopes represent one of the natural risks currently the more expensive and most murderous on the globe. This generic term includes landslides, the muddy streams, the torrential lavas, falls of block... The reduced size of these phenomena (about ten meters to some kilometers) requires the use of remote sensing tools of very high resolution.

A metric precision DTM with a mesh of 10 to 20 m on potentially unsteady sides would be an extremely precious tool for the morphological analysis while facilitating the detection and the quantification of the characteristic structures of instability zones (summit steepness, frontal pads of slip foot, cracks rears). These information allow to better characterize the phenomenology of the slip. Besides, the gravity being the main motor of movements, a precise knowledge of the topography is a fundamental data for the development of numeric models of the slip dynamics.

B.1.8. Appreciation of the degree of seismic fault activity.

Satellite or airborne imagery have allowed to make some considerable progress in the identification of steepness and other morphological tracers of active faults in the seismic regions. This identification from satellite data most often allows to identify localization and the geographical extension of faults, but gives an information not very precise on their movement, in particular for the small structures. Ground surveys are often undertaken to measure the accumulated movement at the same time as the one correspondent to the last seismic events. A DTM of a precision of 1 m with a mesh of 5 to 20 m would allow a very meaningful improvement in this domain. Such a DTM would allow, beyond the simple cartography of sismogenous active structures, to quantify the displacements cumulated on several seismic cycles (typically on a window of time of a few 10 000 to 100 000 years), giving access to the "long term" degree of activity of these structures (essential parameter concerning parasismic engineering, founded currently on a sampling on a window of 35 year time to 1000 years corresponding respectively to the instrumental and historic sismicity).

Indeed, the degree of fault activity affected by the fast movements (typically superior to 1 mm/an) is rather shown by shifts of passive markers (mountainous foreheads, deviations of rivers..), localized close to the accident. The degree of activity of slower and/or not emerging in surface faults are especially shown by dynamic markers, and in particular by the hydrographic network. One analyzes the migration of disruptions bound to the recent activity, with more important spatial wavelengths than in the previous case.

B.2. Studies exploiting the temporal variability of precise DTM.

B.2.1 Large topographic modifications (setting up of streams, pyroclastic deposits, landslides).

The possibility to get repeated DTM of high precision allows to value the site and the volume of products produced on the terrestrial surface (streams of lava, pyroclastic deposits,…) or out of place (landslides). In the case of volcanoes, the frequent update of DTM at the time of the setting up of new streams is indispensable if one wants to maintain a predictive capacity for the following streams (cf. 2.B.1.5). After a setting up of pyroclastic deposits on an exploding volcano, the comparison of two DTM of high precision obtained before and after the event could allow to know the zones more exposed to the re-mobilization of these unsteady and deposits, susceptible to be driven under shape of lahars at the time of the first rainy episodes occurring after the eruption (case of the eruption of the Galungung in 1982 or Pinatubo in 1991 for example). The seismic regions are also subject to important topographic variations during earthquakes : on the one hand the co-seismic distortions themselves can reach some meters for earthquakes of magnitude 7 to 8 ; on the other hand, earthquakes are very often accompanied, especially in tropical region, of landslides.

In the case of slope instabilities, the acquisition of a DTM several times would offer the possibility to do some extremely useful mass balances for the monitoring and possibly the prevention of crises in the potentially unsteady zones.

B.2.2. Cartography of damages after an earthquake.

A precise DTM to 1 m with a mesh of the order of 20 m would allow to raise very precise maps of damages after an earthquake. In the same way after an earthquake having provoked destructions in urban zones, a differential survey of the urban DTM (mission of demonstration) can provide very quickly a fine localization of the destructions, in particular while using the possibility of ambiguity resolution brought by the third satellite.

B.2.3. Monitoring of deformations of anthropic origin.

Numerous zones of mining extraction, gas or oil, provokes subsidences can affect some very extended zones, sometimes even generating real messes (mines of Lorraine for example). The precise and regular monitoring of such zones must bring some useful answers concerning civil security, and it is advisable to make a demonstration of it on a probation basis. The advantage in relation to the classic radar interferometry is the capacity to identify and to measure some brutal and pluri-metric movements.

B.2.4. Monitoring of the erosion.

In the analysis of catchment areas, the quantification of the regional erosion needs different parameters than can be deduced from a DTM : slope, difference of lithology, difference of land use, etc… Through several precise DTM on a zone data one may monitor catastrophic erosion phenomena (landslides, transfers of mass and remobilisations). Otherwise it becomes possible to do a dynamic monitoring of dune systems, and probably also of pergelisols.

As the mission does not foresee to provide a global differential DTM, applications identified in sections B.2.1, B.2.2, B.2.3 and B.2.4 will be achieved on the selected sites (to be defined).

C. Hydrology.

Potentially, the Interferometric Cartwheel appears as a solution to a problem of accessibility of the topographic measure, indispensable to the development of hydrology, from the small to the large scale. In particular, needs are important for both weak and strong slope areas.

The hydrology models the continental component of the water cycle. The precipitations (rains, snows) migrate in and to the surface of the ground, and so constitute the origin :

- of resources in waters of catchment areas (necessary to agriculture, etc.),
- of the floodings, the most import ant natural risks in terms of damages for many countries.

Paths borrowed by these precipitations, and notably their partitions between infiltration and run-off, depend from the streamlined features of the grounds (infiltration) and from the catchment areas topography (run-off and lateral out-flows in the first meters of grounds).

In a physical modelling, measures of altimetry must be thus sufficiently precise to allow to take in account phenomena of concentration of surface out-flows in linear network (an aggravating factor of floods) and the lateral redistribution of water in the first layers of the ground (impact on the evaporation and therefore on balances).

But a catchment area is constituted of slopes whose characteristic scale is not function of the size of the basin. The physical modelling of hydrologic processes requires an altimetric precision that does not decrease with the size of the basin studied.

To date, most hydrologic studies concentrated on catchment areas of relatively modest size. Aerial missions and/or national organisms could provide the necessary DTM (often with a lot of difficulty in developing countries).

But henceforth the hydrology develops itself to become also large scale hydrology. Indeed, (i) the quantification of the local impacts of possible climatic changes on the resource in waters and risks of floodings, and (ii) the coupling between the meteorological forecastings and hydrologic (to meso-scale and continents scale) to short and mean terms, are some of the fundamental and recent questions that are asked to the hydrology.

They require an approach at a very large scale, coupled to the atmospheric and oceanographic modelings.

With a more exploratory and demonstrative point of view, it will be interesting to test the capacities of the Interferometric Cartwheel for :

- the measure of the level of the free surface all the long of the large streams. These levels are indeed a fundamental importance in the modelling of the stream hydraulics since they give access to slopes of out-flow energy. The assimilation of energy slopes calculated thanks to measures of the Interferometric Cartwheel in the hydraulic models can let thus hope for an improvement of the modelling of the large stream hydraulics, that is for example first importance in the climatic modelling.

- the measure of the content in superficial ground water. An interesting interaction active/passive with the project of SMOS satellite is to consider, since this one provides the same variable with a temporal repetitivity of the order of the day, but with a spatial resolution very loose, of the order of 50 km. Procedures of disintegration of the SMOS data before assimilation in hydrologic models are therefore necessary. The Interferometric Cartwheel could provide some complementary data, that is to say with a very precise spatial resolution but a weak temporal repetitivity, that could be assimilated directly in hydrologic models, and that would allow also to validate procedures of disintegration of the SMOS data.

D. Oceanography

One of the main problems of oceanographers is the lack of data in the sea. Sea campaigns are very costly, they allow to cover only restricted zones of the ocean, and in short they don't allow to collect synoptic data. The utilization of satellites represents a considerable progress in this respect. They allow a global cover, of almost synoptic way. The mass of data thus obtained can be used for the direct monitoring of the oceanic structures, and to be assimilated in the numeric models, allowing to limit their drift.

Currently, satellites essentially provide two types of information to oceanographers. By their passive measures, they allow to calculate the "radiance" of oceans. In the visible domain, it allows to map the color of water (and so for example to the primary activity) ; in the infra-red domain, one can reach the temperature of surface. Altimeters allow to measure the sea level by an active measure. Their precision is better than 5 cm for the Topex/Poseidon satellite. These measures are currently the only oceanic information of dynamic nature provided to us by satellites (another technique, the SAR imagery, has still some processing problems). It is in this domain that can intervene the Interferometric Cartwheel.

To show its interests, let's see what more precisely the altimeters provide to us. In the absence of a precise knowledge of the geoid, the utilization of the level that they measure is possible only under the shape of an anomaly in relation to a mean level, calculated through measures of the satellite on several passes. These measures are usable of direct way for the monitoring of anomalies (waves, whirlwinds), and as data of assimilation in the numeric models. Otherwise, while considering an hypothesis of geostrophy (the gradient of pressure is balanced only by the Coriolis force), they allow to reach anomalies of surface speed normal to traces, with a precision of the order of 10 cm/s.

Inshore, a certain number of supplementary obstacles appear. The presence of strong gradients of topography and the proximity of continents reduce the precision of the measure of the level. On the other hand, altimeters stop to work when they pass above the Earth, and need a certain distance to hang up, that is to provide measures all over again when above the sea. Globally, one appraises that altimetric measures are not usable less than 25 km (at least) of coasts. The problem of the tide correction is there more crucial than in open sea (because tides are more important there). In short, the hypothesis of geostrophy used there to reach anomalies of speed is less valid.

The Interferometric Cartwheel would bring information of different nature from those provided by altimeters, since it would measure the absolute speed of surface currents directly. To this consideration, it presents a certain interest, for the direct monitoring of any type of oceanic phenomenon (and not only of anomalies), and for the assimilation of data as well. On the other hand, it would seem that it would not have limitations that the altimeters meet to the neighborhood of coasts, which would allow to get data even in the inshore regions. The requisite precision to be exploitable is given by the spatio-temporal oceanic phenomenon scales : for open ocean, some tens of kilometers and the order of ten days ; for the inshore ocean, of the order of 10 km and some days. In any case, currents are the order of about some tens of cm/s.

E. Utility and needs for applications in glaciology.

E. 1 The polar caps.

The polar caps contain 99% of the fresh water stocked at the surface of the Earth. Their role is the one of a cold pole, frozen water mass reserve, more or less important according to the climatic periods, that intervene directly on the variations of the ocean level. Two scientific survey themes can use Interferometric Cartwheel :

- the survey of the present variations of thickness of ice and their contribution to variations of the mean level of oceans. Indeed, this thematic is usually treated by radar altimetry, but the altimetry presents a limit when slopes of surfaces are too important (~1°). The altimetry allows thus to follow 80% of the polar cap surface, but proves to be unfit to the monitoring of the inshore regions. The monitoring of inshore regions is yet primordial to close the balance of mass because these are the regions that react the most quickly to a change of climate.

- the survey of the dynamics of the polar caps and their capacity of reaction to a climatic change on a longer term. Two quantities are useful for this thematic, the precise topography and the field of surface speeds of ice out-flow that both are accessible with the Interferometric Cartwheel.

The Interferometric Cartwheel can serve as demonstrator in the setting of the first thematic, and to provide a precise topography of reference for other missions, either of the same type or either based on different techniques (for example the Laser altimetric missions). The second thematic can be satisfied by this only mission for the objective of precise topography for the survey of the dynamics as well as for the measure of out-flow speeds, by interferometry.

E. 2. The sea ices.

The ices of sea provide an important strain of the high latitude climate to the yearly and inter-yearly scale. They regulate the exchanges between oceans and atmosphere and store the energy as latent heat. The extent of the sea ices is now supervised in operational mode with the help of many instruments of AVHRR type. But then, an important unknown parameter that the Interferometric Cartwheel can allow to measure is the thickness of these sea ices, directly reliable to a quantity of energy. The used method would be based on the measure of level difference between the free ocean and the frozen ocean in the surroundings of "water holes" (so-called method of the "free-board").

The Interferometric Cartwheel can serve as demonstrator in the setting of this thematic and possibly as tool for local studies of short duration.

E. 3. The glaciers.

The alpine glaciers constitute excellent witnesses of the present variations of climate. It is advisable to study their shrinking, but also their instability by monitoring their balance line (bound to the shape of the glacier). The set-up of a topography of these glaciers is a first step that can serve as basis for a temporal monitoring, it is also an useful data to test the state of stability as well as to force the numeric models of drains of the glacier.

The Interferometric Cartwheel can serve as demonstrator for this thematic, but also for basis of a long-term monitoring. A limit of application may be foreseen for glaciers with too high slopes or in too narrow valleys.

F. Applications of bistatic measure.

Upstream of the different thematics, the principle of the measure opens perspectives on the utilization of the radar observation of targets (amplitude image). Bistatic information not only gives us the retrodiffusion of the active satellite, but also the diffusion in the passive sensor direction, according to the different angles. One has access therefore to an angular information on the function of diffusion of the surface overflown in every pixel (σ_0, $d\sigma_0/d\theta$).

As the absolute calibration of microsatellites is not a nominal objective of the Interferometric Cartwheel, these studies should be driven using relative calibrations.

The constraint is then stronger to separate effects of roughness of surface from dielectric constant effects. This formulation is general and must be specified for every type of surface. For example, the humidity of surfaces, the saltiness of the sea ice, rates of accumulation on the polar caps...

G. Utilization in GIS (Geographical Information Systems)

The more and more comfortable accessibility to the spatial or aerial pictures under digital shape always recalls the problem of the geometry of these pictures in order to transform them rigorously in metric documents, superimposable to maps and allowing land management (orthophotographies, pictures SPOT level III, etc…). Among the essential data that miss in very detailed imagery, the DTM constitute today an essential stake. Among applications that will be much more easy if the presented project works at once, we will only mention some examples :

- orthorectification of digital aerial pictures, avoiding a large part of the present processes of photogrammetric restitution. The obtained orthoimages often form the basic layer of urban GIS, and regularly the layer of updating information basis as well.

- fine urban environment description to simulate to best the optimal localization of cellular telephony emitters.

- works of institutional cartography, that require considerable surfaces of DTM. The national needs evolving towards more and more detailed scale (in France the IGN completes a topographic data base of one meter precision for example on all the country), the needs in fine altimetry don't stop increasing.

- in short, many technical domains require a good access to such a DTM : agriculture, environment, forests, hydrologic and geological risks, etc…

H. Principle of the measure according to missions.

The primary mission is the production of a data game allowing the calculation of a global digital model (DTM) of the Earth, the calculation being achieved to the demand. The probationary missions concern 1) the exploration of the ultimate potential in very precise DTM (sub-metric), 2) the test of capacities of inshore current measure, or even in open sea, by interferometry along of the trace selecting a small impact angle in the range allowed by the emitting radar, different of the one of the reference mission, 3) the analysis of the physical behavior of the bistatic picture radar and 4) the test in real size, and in simultaneous receipt, of the super-resolution in distance and in azimuth. One will be able to foresee to set-up the "wheel" with a maximal spacing, in primary mission end, in order to test (1) and (4) or to adjust it to a compatible temporal gap with the "navy" target life span to achieve (2). The half-second of the §1 corresponds to a mean horizontal basis of about 3.3 km, therefore to a vertical basis of 1 km. Let's note that the mission doesn't have no objective of calibration bound to the amplitude image.

The proposed mission will be constituted therefore of at least two distinct phases :

1) a long phase of operational topography, with a weak spacing and an objective of global cover of emerged lands. One minute of work by orbit for a span of 70 to 100 km large products typically 30000 km^2 and there are 5000 orbits per year, but all won't be usable. This phase will display a moderate topographic sensitivity, for example of 40 m by fringe, and will work practically on any type of slope.

2) a shorter phase with a maximal sensitivity, where the spacing is equal to 70% of the critical bases. This phase will allow the test of the improvement of the resolution of a factor 1.7 in the two directions. It will also allow locally to get interferograms of high sensitivity thanks to a weaker ambiguity altitude.

Let's give the necessary size orders now. Let's imagine to exploit ALOS to the resolution corresponding to 28 MHz of sampling and under 45° incidence, at least in the setting of the main mission. For applications on the ocean, the incidence will be 23°. These incidences will be preserved for ENVISAT, but with the strip of frequency of 16 MHz of this satellite. In the two cases, the constellation could be 150 km before the monitoring satellite, which removes all collision risk in case of manoeuvres.

Conclusions

The interferometric cartwheel has many scientific goals of top level importance, at least the ones based on the capability to provide DTMs.

But there are probably many other topics that could be envisioned, but for which no simulations have yet been performed.