International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

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Spectrum requirements for spaceborne synthetic aperture radar applications planned in an extended allocation to the Earth exploration-satellite service around 9 600 MHz

RS Series

Remote sensing systems

International Telecommunication Union

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R RS.2274

Spectrum requirements for spaceborne synthetic aperture radar applications planned in an extended allocation to the Earth exploration-satellite service around 9 600 MHz

1 Introduction

There is a growing demand for very high resolution pictures produced by synthetic aperture radars (SAR) operating in the Earth exploration-satellite service (EESS) (active). This image resolution needed for global environmental monitoring can only be achieved by correspondingly transmission bandwidth. Resolution **651 (WRC-12)** invites ITU-R to conduct studies addressing options for the extension of the EESS (active) allocation in the band 9 300-9 900 MHz by up to 600 MHz anywhere within the frequency ranges 8 700-9 300 MHz and/or 9 900-10 500 MHz.

Report ITU-R RS.2178 describes in detail the essential role and global importance of radio spectrum use for Earth observations and related applications in general. In addition, the information on applications provided in this Report concentrates particularly on the description of applications of spaceborne SAR requiring high resolution information to less than 0.3 m. This desired resolution can only be achieved if a chirp transmission bandwidth of 1 200 MHz is available. Such a bandwidth requires an extension of the current EESS (active) allocation by 600 MHz. Such a high resolution will enable unprecedented features for long-term (4d, i.e. 3d space dimensions and one time dimension) global monitoring as well as for environmental monitoring and land-use purposes.

It is to be recognized that the allocation to the EESS around 9 600 MHz combines the advantage of a largest possible bandwidth at the lowest possible frequency regarding propagation conditions. Much lower frequencies cannot provide this large bandwidth, while much higher frequencies increasingly suffer from worsening propagation conditions.

Very high resolution mapping and monitoring is required by the below applications that stipulate a substantial socio-economic benefits:

– Disaster relief and humanitarian aid actions require ad hoc access to up-to-date geo-information, comprising remote areas of the globe. Airborne imaging is very often limited by remoteness of the area to be observed and cloudy weather conditions. Today’s radar satellites are too limited in resolution to allow adequate infrastructure damage assessment (and consequently a rough estimate of the number of affected people) to assist first responder activities. Likewise, the identification of trafficable roads, landing strips or suitable spaces to set up first aid or refugee camps is limited by the resolution of today’s radar sensors.

– Safety of energy supply: to ensure sustainable oil and gas production, these sites need to be carefully monitored in terms of management of the extraction. In addition, vast pipeline networks require monitoring in terms of their integrity to avoid – or at least to detect – leakages and severe environmental pollution. For this, reliable and weather independent monitoring is required.

– Cadastre: for city management and agricultural planning. Countries in the tropical region suffer particularly from substantial cloud coverage. Some of these nations face rapid built-up areas growth, and land cover and land use change. In addition, the growth of settlements and industry in quickly growing conurbations benefits from timely monitoring in support of spatial planning and associated public infrastructure programs. All require an affordable, reliable and weather independent mapping capacity.

For the above-mentioned applications, given the object characteristics to be observed, a resolution below 20 cm is required. Satellite technology around 9-10 GHz is well suited to meet this need, provided that a transmission bandwidth of up to 1 200 MHz can be applied. Airborne SAR sensors can also achieve the required resolution, but not efficiently over large areas and for very long time observations.

The Report comprises two main sections. The first section provides the mathematical description of the relation between the transmission bandwidth and the achievable pixel resolution with a SAR. The second part concentrates on the need for new Earth observation applications enabled by high-resolution information.

2 Relation of SAR performance and used transmission bandwidth

2.1 EESS SAR characteristics

A SAR is a coherent spaceborne side-looking radar system which utilizes a satellites flight path to emulate an extremely large antenna or aperture electronically, and that generates high-resolution remote sensing imagery.

In principle, the SAR is a phased array antenna. But, instead of using a large number of parallel antenna elements, SAR uses one antenna element in time-multiplex. The different geometric positions of the antenna elements are the results of the moving platform.

The satellite travels forward in the flight direction with nadir pointing beneath. The microwave beam transmits obliquely at right angles to the flight direction illuminating an area called swath referring to the strip of the Earth's surface from which data is collected by side-looking radar. The longitudinal extent of the swath is defined by the motion of the aircraft with respect to the surface, whereas the swath width is measured perpendicularly to the longitudinal extent of the swath.

It is the width of the imaged scene in the range dimension. Range refers to the across-track dimension perpendicular to the flight direction, while azimuth refers to the along-track dimension parallel to the flight direction.

Over time, individual transmit/receive cycles (at pulse repetition time, PRT) are completed with the data from each cycle being stored electronically. The signal processing uses magnitude and phase of the received signals over successive pulses from elements of a synthetic aperture. After a given number of cycles, the stored data is recombined to create a high resolution image of the terrain being over flown.

The principles of SAR can, for example, be found in the NOAA SAR Marine User's Manual [1], "A Mathematical Tutorial on Synthetic Aperture Radar" [2] or "An introduction to Synthetic Aperture Radar (SAR)" [3].

2.1.1 Range resolution

A radar self-illuminates an area by transmitting RF pulses which are reflected from the target area and collected by the radar receiver. By measuring the time difference between pulse transmissions and their reception, a radar is able to determine the distance, i.e. range or slant range, of the reflecting object. The range resolution of a radar system is its ability to distinguish two objects separated by some minimum distance.

The range resolution for radars with real aperture or synthetic aperture is the same. To distinguish between two targets which are separated by a distance d, d must be so wide that the reflected radar waves do not overlap.

Consider, that a radar signal with a pulse width τ is reflected by two targets separated by a distance d. The radar signal needs the time $t = \frac{d}{c}$ to bridge the gap between the two targets before and after the scattering at the second target. Thus, the path length difference is $2d$. The reflected signals do not overlap at the radar receiver if the path length difference is bigger as the pulse length $c \cdot \tau$:

$$2d - c\tau \geq 0$$

Therefore, the range resolution or the minimal distance to distinguish between two targets is:

$$d = \frac{\tau \cdot c}{2}$$

Because, the bandwidth BW is the reciprocal of the pulse width $\tau = \frac{1}{BW}$, the term can be written as follows:

$$\delta_{AT} = d = \frac{c}{2BW}$$

As the range resolution δ_{AT} becomes finer, the pulse width gets smaller and the transmission bandwidth increases. Therefore, the achievable range resolution is directly only dependent on the transmitted signal bandwidth.

This term would lead to a "slant-range" resolution of 12.5 cm for a bandwidth of 1 200 MHz. To obtain the relevant image resolution, the slant-range resolution needs to be projected onto the ground. This projection is strongly dependent on the incidence angle, under which the scene is acquired. In addition, a spectral weighting in the SAR processor needs to be considered, which is needed to suppress artefacts in the image.

Under the assumption of a moderate weighting (Hamming-Window 0.8), the existing 600 MHz spectrum would allow for a resolution < 30 cm only at large incidence angles (> 50°). Towards the near end of the access range, the bandwidth demand increases, reaching 1 200 MHz at 30° incidence angle:

$$\delta_{GR} = d = \frac{c}{2BW \cos\psi} \frac{1}{\rho}$$

where:

δ_{GR}: ground resolution

Ψ: grazing angle

ρ: ratio due to the Hamming window used in SAR (e.g. 0.8).

Therefore, the ground resolution for a bandwidth of 1 200 MHz varies from 19.1 to 45.7 cm for grazing angles between 35 and 70 degrees, respectively.

EESS SAR transmits linear frequency modulated (FM) "chirps" by varying the transmission frequency linearly over a frequency range which determines the RF transmission bandwidth used by the system. Chirp length and slope depend on the required range resolution, the pulse repetition frequency (PRF), and the available radar technology.

2.1.2 Azimuth resolution

In the direction orthogonal to the radar beam, called cross range, azimuth, or along track, a SAR uses aperture synthesis to improve its spatial resolution.

Consider a spacecraft illuminating a target. The axes of a coordinate system are given as follows: the y-axis is pointing along the flight path of the spacecraft, the x-axis is perpendicular to the flight path and the z-axis is the height. The aircraft will fly parallel to the y-axis with the speed v and will illuminate a target at the ground for a time T. The range between the spacecraft and the target as a function of time is given by:

$$R \cong \sqrt{x_0^2 + (y_0 - vt)^2 + h_0^2}$$

$$t \in \left[-\frac{T}{2};\frac{T}{2}\right]$$

for $L << R$. With a fixed starting point:

$$R_0 = \sqrt{x_0^2 + y_0^2 + h_0^2} \text{ and } \cos\theta_0 = \frac{y_0}{R_0}$$

R can be expanded by using the Taylor series expansion to:

$$R \cong R_0\left(1 - \frac{vt}{R_0}\cos\theta_0 + \frac{v^2t^2}{2R_0^2}\sin^2\theta_0\right)$$

Assuming the reflected and received signal at the spacecraft as:

$$e = KA \cdot \cos(\omega_0(t - \tau))$$

where:

K: a constant

A: amplitude of the transmitted signal

τ: time delay which is a function of range: $\tau = 2\frac{R}{c}$.

Substituting $\frac{1}{c} = \frac{2\pi}{\lambda \cdot \omega_0}$ and inserting the expression for R, changes the cosine-term to:

$$\omega_0(t - \tau) = \omega_0 t - \frac{4\pi R_0}{\lambda} - \frac{4\pi vt}{\lambda}\cos\theta_0 + \frac{2\pi v^2 t^2}{R_0\lambda}\sin^2\theta_0$$

Using the definition of an instantaneous frequency:

$$f = \frac{1}{2\pi} \cdot \frac{d}{dt}\omega_0(t - \tau)$$

this leads to the following term:

$$f = \frac{\omega_0}{2\pi} + \frac{2v}{\lambda}\cos\theta_0 - \frac{2v^2 t}{R_0\lambda}\sin^2\theta_0$$

The first term is the transmitted frequency f_0, the second term is the Doppler shift associated with the angle θ_0 and the third term represents the change in Doppler shift due to the forward motion of the spacecraft.

The instantaneous frequencies for two different targets in the same distance R_0, but separated in azimuth by a distance d will be:

$$f_1 = f_0 + \frac{2v}{\lambda}\cos\theta_0 \qquad \text{and}$$

$$f_2 = f_0 + \frac{2v}{\lambda}\cos\theta_0 - \frac{vD}{R_0\lambda}\sin\theta_0$$

since the time to cover the distance between both targets is:

$$t = \frac{D}{2v\sin\theta_0}$$

This results into an observed frequency shift of:

$$\Delta f = f_1 - f_2 = \frac{vD}{R_0\lambda}\sin\theta_0$$

The synthetic array length L is given by the total time the spacecraft is illuminating the target T and the velocity of the spacecraft: $L = vT$. Thus, the array length of the SAR is the distance the spacecraft travels while looking at the target. To resolve the two targets, data must be collected for a time $T = \frac{1}{\Delta f}$. With this correlation, we get: $L = \frac{R_0\lambda}{D\sin\theta_0}$. Therefore, the resolution to distinguish between two targets is:

$$SR = \frac{\lambda R_0}{L\sin\theta_0}$$

The spatial resolution of SAR depends on the used radar carrier wavelength, the distance to the targets, the incidence angle and the synthetic array length.

For $\theta_0 = 90°$, the *SR* is equal to the spatial resolution of a real aperture radar:

$$SR = \frac{\lambda}{D}\cdot R$$

with:

λ: radar carrier frequency

D: antenna diameter

R: target range.

Achieving azimuth resolution comes with a requirement that necessitates the radar to send a pulse each time the radar platform translates half of the along-track antenna length. This condition sets the lower bound of the PRF. The relationship is given by:

$$\frac{\nu}{SR} < PRF$$

Thus, as the along-track antenna length is diminished to improve along-track resolution, the radar must pulse faster. Only one pulse for a given radar frequency can be in the target zone at a time to avoid ambiguity. This condition sets an upper bound on the PRF which is a function of the swath width ($S = R_{far} - R_{near}$) in slant range direction as shown in Fig. 1 and the real (uncompressed) pulse duration, T, resulting in the expression:

$$PRF < \frac{1}{2T + 2(R_{far} - R_{near})/c}$$

More spacing between pulses is required as swath width and/or incident angle increases. Thus, the quest for increased coverage will eventually collide with a desire for improved along-track spatial resolution.

2.1.3 Functionality of SAR systems

A typical space-based, monostatic SAR is shown in Fig. 1. Consider that the SAR transmits pulses while moving along the satellite track. Each pulse travels to the target area where the antenna beam intercepts the Earth and illuminates targets at that location, and the reflected return pulses are in turn collected by the same antenna. A SAR system saves the phase histories of the responses at each position as the real beam moves through the scene and then weights, phase shifts, and sums them to focus on one point target (resolution element) at a time and suppress all others. SAR achieves a very high signal processing gain because of coherent summation of the range-correlated responses of the radar.

In Fig. 1, the antenna beam illuminates the target when the platform reaches position t_1, but not before. It continues to illuminate the target for a distance L_{SA} (synthetic aperture length) until it reaches t_2. The time required to translate the along-track beam through a point target is called the integration or dwell time. The spatial resolution in the along-track direction approaches the physical length of the antenna divided by two. This is, to the first order, independent of the used SAR frequency and the range to target.

Typical dwell or integration time for taking a SAR image is given by

$$DwellTime = \frac{L_{SA}}{V} = \frac{\lambda \cdot R}{V \cdot D_{AT}}$$

with:

V: spacecraft velocity

D_{AT}: along-track (azimuth) antenna diameter.

FIGURE 1

EESS SAR imaging geometry for spot mode of operation

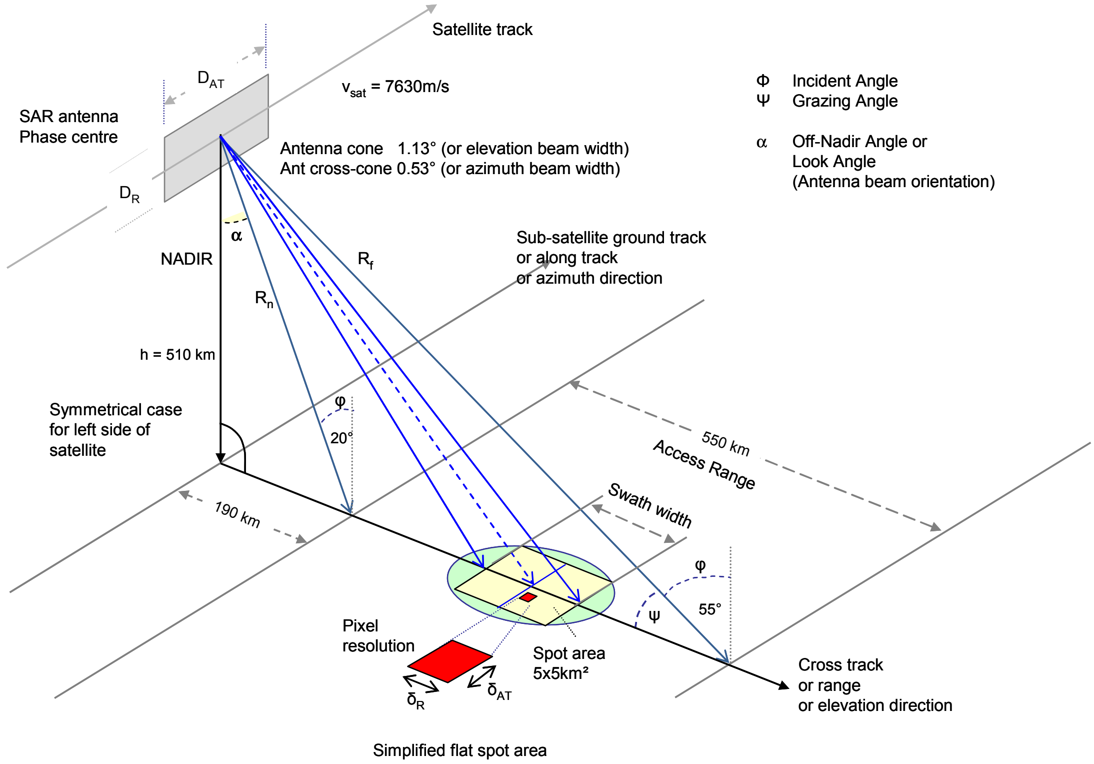


Figure 1 illustrates the imaging geometry of a strip-mapping SAR. The shown length of the synthetic aperture is a function of the beam width of the real aperture.

2.2 RF propagation versus wideband performance of SAR

The justification for an extended frequency bandwidth is driven by the need for a SAR picture at a high-resolution of less than 0.3 m which achieves radar images comparable to high-resolution optical pictures achieved by space-based devices. The bandwidth demand is solely driven by the physical phenomenon and not from the number of systems which should coexist in the band. Transmission periods from EESS SAR sensors are by nature of application limited to short durations of less than 5 s per image taken.

The physical relationship on the correlation between high image resolution and transmission bandwidth of SARs in general was described in the previous section. This capability will support high-precision observations with combined SAR and optical sensor information adding higher value to many monitoring approaches or would make them even possible. For instance, optical systems can add true colours and bio-physical information (through near- and short-wave infrared observations), SAR systems can complement with their precise geolocation, 3d-measurements, surface motion analysis and specific biomass estimate contributions.

It is assumed that only a few SAR missions are expected to use this band and bandwidth. A reason for this is that the different scientific mission tasks require the use of different frequency bands. This is based on mainly two physical properties of the electromagnetic waves: the surface and the atmospheric penetration – both effects directly depend on the used wavelength.

3 Applications for high resolution for EESS SAR

3.1 Trends for the need of higher resolution information in Earth observations

There is a general tendency in environmental and landscape monitoring, in topographic mapping, in construction works, and in disaster management to increase mapping resolution in order to obtain more details for local activities. Hence, the goal is to offer high-end imagery which allows mapping and monitoring from scales 1:25,000 up to 1:5,000, worldwide.

In case that aerial photographs are not available in a repetitive manner or ad hoc (i.e. to regularly update or monitor hot spots (disasters) or larger regions), and for a large area, many application domains do require the highest resolution possible from space. This is mainly due to the fact that for object recognition the size and the shape of a target needs to be known as good as possible, in order to avoid ambiguities. Especially over frequently cloud covered regions (in the tropics and in the higher latitudes) today's EESS SAR technology is capable to provide a level of detail that can serve a multitude of environmental, engineering and planning activities, in sub-meter resolution, as shown in Fig. 2.

FIGURE 2

Example from an airborne full polarimetric X-Band SAR colour composite at 37 cm resolution

Forested area and land cover classification in an airborne Full Polarimetric Color Composite (37cm resolution, Red= HH Green= HV Blue= VV, NESZ -43dB)

The image allows identifying individual trees, forest stand structures and tree height, logging roads, buildings, roads, heterogeneities in agriculture land and further built-up/man-made infrastructure. Such information is needed worldwide for instance for ecological studies and landscape management, forest monitoring (e.g. illegal logging or forest degradation processes), crop forecast and pest management in agriculture, topographic mapping, spatial planning, etc.

The sensitivity of the X-Band frequency for surface changes allows using such imagery for disaster impact assessment, as supportive tools for disaster management, identification of stable permanent scatterers for surface motion monitoring and general change detection monitoring (using signal intensity and/or coherence). There are three SAR measurement principles. SAR polarimetry (intensity), SAR interferometry (phase), and SAR radargrammetry are the key measurement principles applied supporting:

– precise topographic and cadastral 2D and 3D data capture;
– precise satellite geodesy for 3D and 4D mapping and surface motion monitoring;
– sensitive change detection indication.

3.2 Applications for wideband SAR

Major science and technology, and socio-economic areas supported include, among others:

– radar methodology research (e.g. polarimetry, satellite geodesy);
– Earth Sciences (Glaciology, Geology, Climatology, Oceanography, Meteorology);
– food security policies and forecasts;
– law enforcement (e.g. environmental regulations, civil security, disaster preparedness);
– humanitarian aid and relief measures.

The following application examples are based on a combination of SAR measurement principles and give a more detailed overview over the advantages of a SAR resolution below 0.3 m.

3.2.1 National mapping and cadastre

Strategic topographic base mapping and map update at national scales (1:200,000 to up to 1:5,000) is an increasing demand, especially to foster economic development (FAO). The trend goes to larger scales (i.e. 1:25,000 – 1:5,000) which means higher resolution. This precision is of great importance for rapid mapping of large areas (in comparison to air-borne technologies) and improves land-use planning based on current data. Updating land related information is important to record changes of ownership and division of property in a timely fashioned manner for documentation.

High resolution satellite images provide a historical record of areas where traditional land surveying approaches are time consuming and require a lot of efforts. For example, it is very difficult to do cadastral survey in remote areas especially in mountain areas when the weather is harsh. Cadastral mapping is a pre-condition for property transfer, public infrastructure development and local/national taxing. Today, this is a major blockage towards commercial investment in infrastructure, agriculture, industry in many countries, as local or airborne surveys are not affordable on a regularly basis and cannot keep track of the speed of actual changes.

Especially in tropical regions VHR SAR imagery can improve mapping and map-updates for larger scale mapping due to the weather independency.

3.2.2 Public protection and disaster relief (emergency)

Case studies of the UN-SPIDER demonstrate Earth observation capabilities all along the disaster management cycle (mitigation, preparedness, response and recovery) and particularly the importance of high resolution radar in order to provide, for instance, damage assessment maps, earthquake 3D damage visualisation, oil spill detection, flood maps.

Today, all Earth observation data sources are used in case of disaster events in the frame of the UN International Charter. SAR data proof to be especially useful under cloud covered conditions, but come to an end of their applicability for local assessments of settlements and infrastructure, as their resolution is still limited today.

Especially the identification of infrastructure integrity, including damages on buildings, transportation networks (roads, railways, pipelines, power lines), or dams, and the assessment of landslides hazards and their monitoring requires very high resolution (VHR) imagery. Here, precise mapping at very high resolution, intensity and coherence change detection, and permanent scatter interferometry can support the identification of relevant features.

In addition, ad hoc situational mapping (topographic and thematic information) for the disaster cycle can be generated at larger scales required to support operational and tactical relief measures in the field.

3.2.3 Environmental monitoring

In the context of monitoring climate change at an international level as well as at a local scale, International agencies and national government’s environmental agencies utilize topographic or thematic maps with detailed spatial resolutions for environmental monitoring with respect to “land cover” and “land use” changes (e.g. forests, agricultural fields, open spaces, nature reserves) and the development of the surrounding (e.g. urban sprawl). There are also concrete objectives in tracking deforestation, monitoring agricultural resources and water supply.

The unique change detection capabilities of X-Band VHR imagery can be used to assess degradation pattern (e.g. in the framework of REDD+ – Reduction of Emissions from Deforestation and Forest Degradation) and to monitor local forest activities, e.g. from illegal logging, mining, defoliation (from pests or pollution), etc.

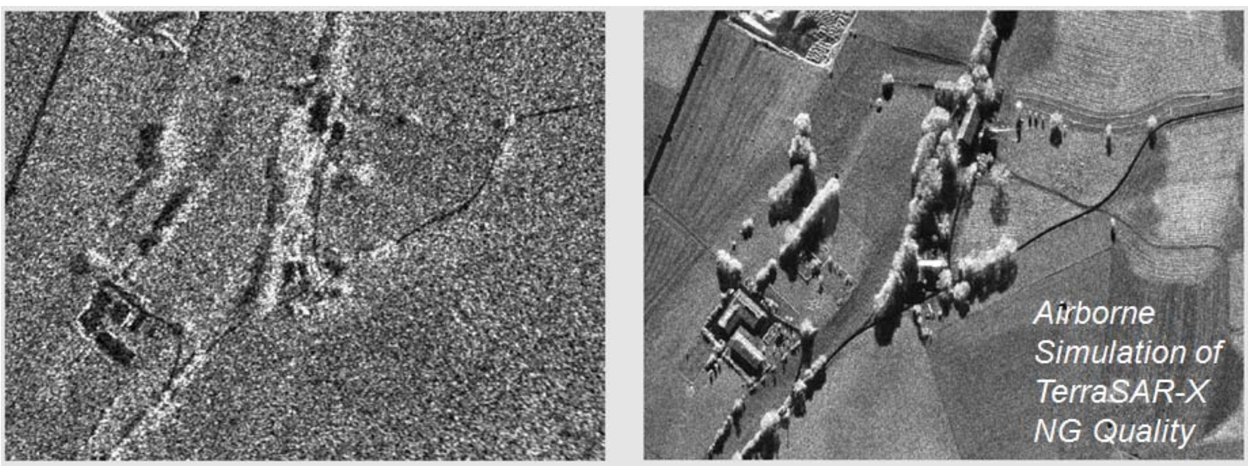
As part of multi-stage national inventories, degradation monitoring requires an identification of single trees removed from systematic very high resolution sampling areas (see Fig. 3). This is indispensable for reliable national and regional assessments, early warning and control, as required by REDD+ countries, donors and the evolving carbon market.

Changes affecting small islands such as water infiltration or coastal subsidence are also major signs of climate change. Here, the general tendency is to move much stronger towards local conditions and, thus, demanding higher resolution imagery.

As the national implementation of international environmental policies usually requires monitoring at fixed milestones, cloud independent information provided by SAR can support timely reporting.

FIGURE 3

Example for single tree identification with high-resolution SAR (Airborne simulation of 1 m vs 0.25 m resolution)



3.2.4 Food security

Food security observations and forecasts, forest management and precision agriculture benefit from pest monitoring through measurements of defoliation (interferometric or radargrammetric measurement – dual pol or quad pol) based on area frame sampling schemes. Again, very high resolution is required in order to detect subtle change in vegetation density/coverage.

As part of multi-stage inventories that are using wall-to-wall mapping from other earth observation sources, such very high resolution measurements enable to set-up precise statistics from national to local levels.

3.2.5 Maritime safety and security applications

Maritime security and safety is of utmost importance today. As shipping traffic is growing rapidly, pressure on the safety and security of maritime operations is increasing likewise. In addition to the rising likelihood of accidents and associated environmental damages at sea, ship traffic is more and more threatened by piracy attacks. Besides that, increasing illegal activities at sea borders, like smuggling, drug trafficking, illegal fishing and immigration, additionally demand for enhanced situational awareness.

In support of international conventions, illegal ship traffic or fisheries can be monitored in near real time (NRT). SAR satellite-based maritime surveillance services play a key role in open ocean surveillance and help to overcome existing shortcomings. Due to their capability to provide detailed and timely information on vessel traffic over vast areas on a global basis within one shot, they effectively complement existing monitoring systems.

VHR X-Band imagery has the potential to effectively complement MR wide swath data, typically being used for scanning of large areas for suspicious targets, by:

– detection of small vessels typically being used for piracy, smuggling, illegal immigration, etc.;
– gathering of detailed information on suspicious targets being detected in large area scanning;
– classification of vessels;
– identification of suspicious activities in ports and at beaches being potential starting points for illegal maritime activities (early warning, intelligence information, etc.).

3.2.6 High precision Sea-/River dike and dam monitoring

The monitoring of sea and river dikes is a specific case of infrastructure monitoring. The proper performance of sea and river dikes plays a more important role also in the context of global warming and related sea water level rise or heavy rain events and resulting flooding. Dikes are on the one hand endangered by man-made activities (e.g. oil- and gas production along the coastline) or by natural effects like improper construction with evolving cavities included.

Water reservoirs are subject to surface movements as there is on the one hand a strong load on the reservoir dams due to varying water content in the reservoir. On the other hand, a varying water level in the reservoirs could cause severe landslides along the coastline of the water reservoirs. If a landslide turns into a sudden “rock fall” into the water reservoir, this could result in local tsunamis, which could endanger local people and infrastructure in the water reservoir area.

SAR sensor’s resolution plays an important role with regard to measurement pixel resolution: The higher the spatial resolution the higher also the pixel density along sea and river dikes – an example comparison between C-Band data and high resolution X-Band SAR data is shown in Fig. 4.

FIGURE 4

Effect of SAR sensor's spatial resolution and wavelength on persistent scatterers interferometry (PSI) point density and distribution – Left: C-Band result (20 m); Right: SAR in StripMap (3 m) (© GoogleEarth)

The relevant service to be offered from remote sensing data is the derivation of maps and datasets which show the surface movement situation along but also in the wider area of the dikes or dams of water reservoirs. Surface movement rates as well as individual time series of surface movements are delivered.

The following benefits can be stated:

– The spaceborne approach of surface movement monitoring has the advantage of generating a wide area overview along the dike structures, allowing a reduction of personal inspection or terrestrial monitoring. This is especially valid, if a large network of dams/dikes needs to be monitored (e.g. in the case of the Netherlands).

– A potential collapsing of dikes in the case of a flooding event could be predicted by the identification of areas along the dike with slow vertical or horizontal movements through the wide area overview. Identified parts of the dike, which can be considered as "critical" need then further inspection, terrestrial monitoring or even reconstruction.

3.2.7 Landslide monitoring (land subsidence and uplift)

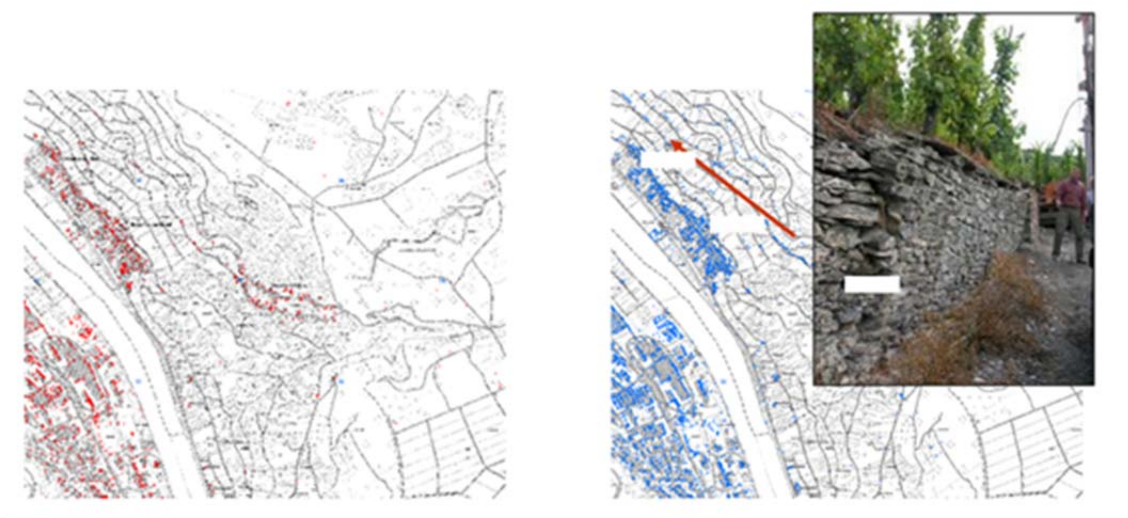
This application is important for any type of infrastructure, which is aligned along slopes in rough terrain (e.g. roads, pipelines), local settlements or even urban agglomerations on specific slopes or at the bottom of the valley beneath the slope. Landslides are occurring due to instable layers nearby the surface and/or weak interfaces between underground rock and surface soil layer. Gravity forces these layers towards the bottom of the valley, while interfaces strongly support any kind of movement into the direction of the bottom of the valley.

The relevant service to be offered from remote sensing data is the derivation of maps and datasets which show the surface movement situation in the area of slope, which is known for instabilities. Surface movement rates as well as individual time series of surface movements are delivered. In the case of sparse or insufficient point density (e.g. in agricultural or more vegetated areas) corner reflector interferometry is offered.

The use of high resolution SAR data as input can enable also smaller objects in the area to “act” as measurement pixel. Figure 5 shows an illustrative example – smaller stone walls along maintenance area appear as measurement pixels in High Resolution Spotlight data whilst they are not present in the StripMap data.

FIGURE 5

Effect of SAR sensor’s spatial resolution on PSI point density and distribution – Left: StripMap (3 m); Right: High Resolution Spotlight (1 m)



The following benefits apply:

– surface movement monitoring by using spaceborne SAR sensors could strongly support in continuous update of the slope movement information;

– instable slopes could be identified using the wide area overview;

– landslide could also be characterized through the high resolution of SAR data.

FIGURE 6

Example of EESS SAR based slope monitoring in Central Germany including corner reflector installations – Intensity image of the acquisition

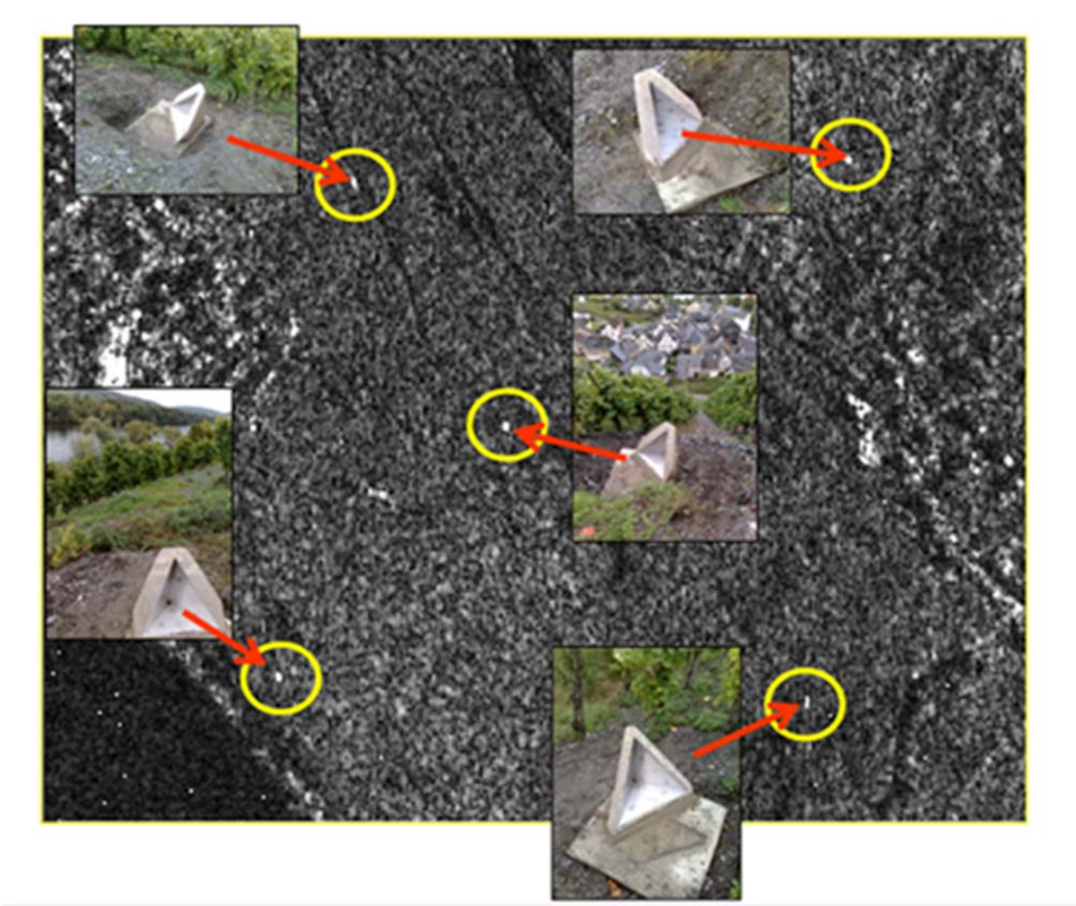
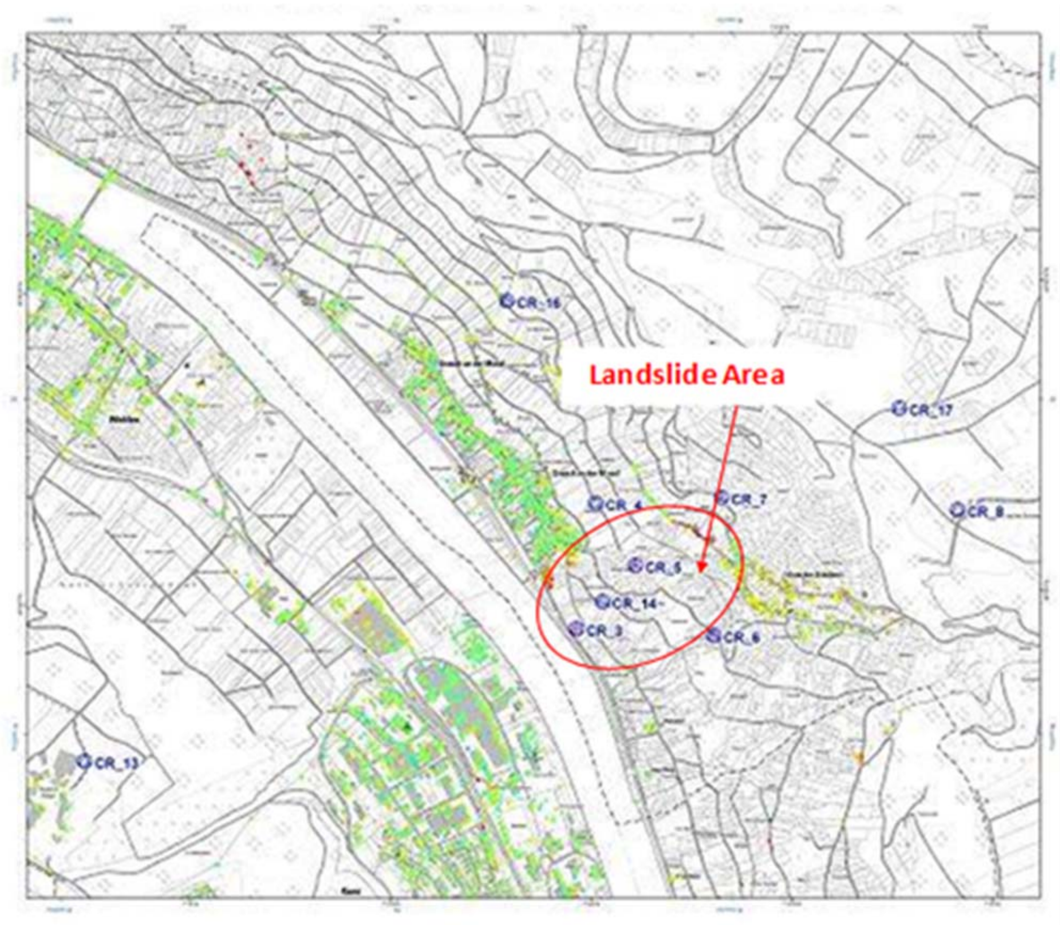


FIGURE 7

EESS SAR based slope monitoring in Central Germany including corner reflector installations – Intensity image of the acquisition

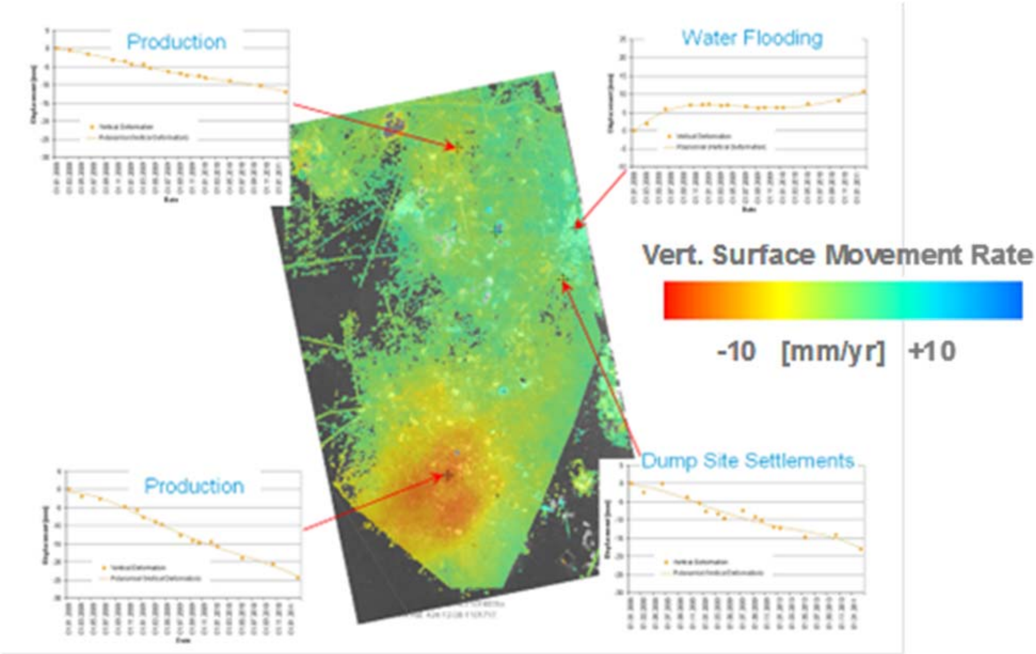


3.2.8 Oil- and gas exploration monitoring

Oil- and gas production triggers a decrease of pore pressure and thus a compaction within the deeper rock formation (e.g. porous sand stone). This compaction transfers to the surface through the overburden and finally results in subsidence with rates in the order of several millimetres up to centimetres per year. Main factors influencing the amount of production related subsidence are production rate, the depth of the production formation, the application of potential stimulation techniques (i.e. injection of water, steam, which is supporting pore pressure and thus counteracting subsidence) and geomechanical parameters of the overburden. A typical example is shown in Fig. 8.

FIGURE 8

Surface displacement map for Burghan oilfield in Kuwait and selected times series of surface displacements



The relevant service to be offered from remote sensing data is SAR-based surface movement monitoring resulting maps and datasets showing the surface movement situation in the wider area of the oil- or gas field. Surface movement rates as well as individual time series of surface movements are delivered.

The following benefits can be stated:

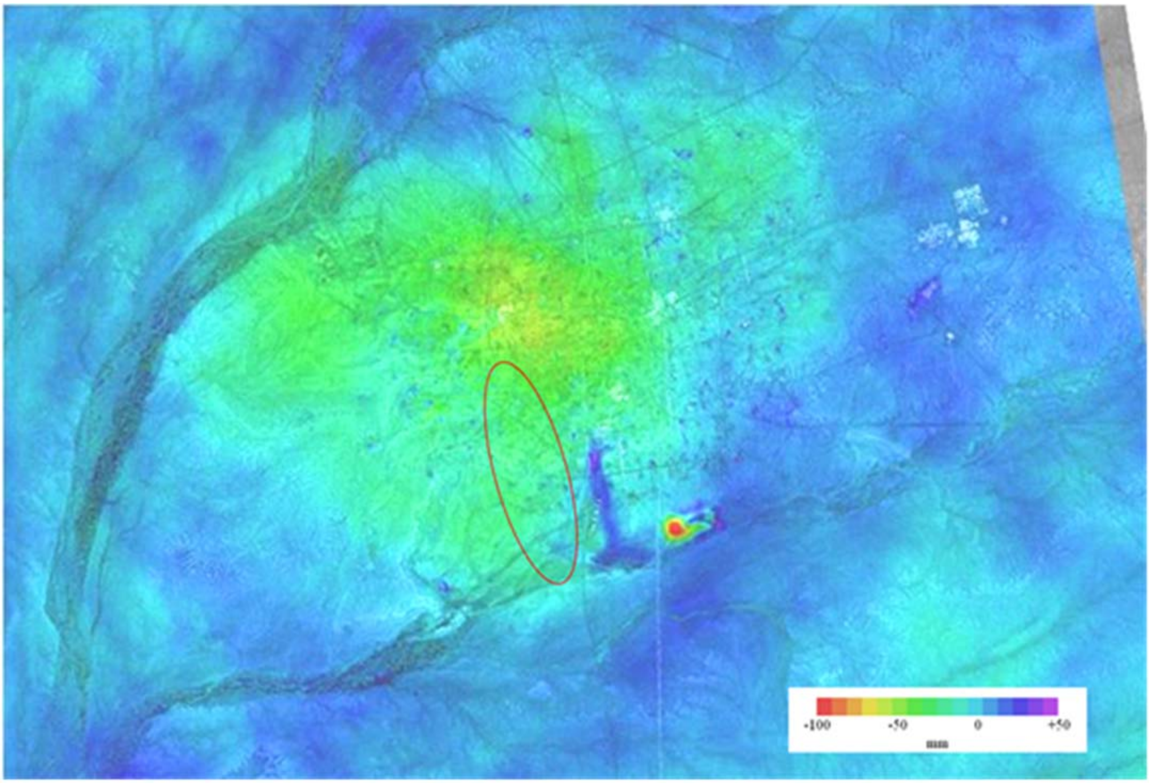
– Visualization of the spatial behaviour of surface movements and thus also steeper horizontal gradients of surface movements allows the identification of pressure compartments restricted by underground fault structures with restricted permeability; reservoir engineers can thus be supported in specific decisions for the optimization of production, e.g. the localization and operation of injection and production wells [4] [5]. The higher the resolution of the input SAR source, the more measurement pixels can be expected making it possible to also detect smaller pressure compartments. Furthermore, so-called spatial phase unwrapping can be supported by having a higher measurement pixel density allowing to quantify also stronger gradients in surface movements.

– Performance of stimulation efforts in context with Enhance Oil and Gas Recovery (EOR/EGR) could be monitored a shown in Fig. 9. Stimulation efforts could be optimized as these measures very often counteract against production related subsidence sometimes yielding reduced subsidence or even uplift (see case study "In Salah CO2 monitoring"). The higher the resolution of the input SAR source, the more measurement pixels can be expected making it possible to also evaluate spatially restricted effects of EOR/EGR measures on the surface and thus better control of underground operations.

– Oil- and gas fields operators could be supported by identification of failing oil- and gas field infrastructure; it can either be identified, if production wells are not performing as expected, e.g. due to the existence of non-identified fault structures and resulting so-called pressure compartments – these can be resolved by laterally non-consistent subsidence; it can also be identified, if e.g. well casings of water injection wells are broken so that water is injected in shallow layers near below the surface instead of being injected into the deep formation – water in the shallow layers causes swelling e.g. of clay and thus uplift on the surface in extent mainly restricted to a smaller area around the wells. Higher density of measurement pixel density would allow the detection of smaller extended effects of failures and would also support spatial phase unwrapping for the determination of also stronger surface movement amplitudes.

FIGURE 9

Surface Displacement Map from Oman oil field – Spatially restricted surface uplift (red ellipse) is strongly correlating with the location of a failing well (broken well casing); water meant for injection into the deep formation is injected into shallow layers resulting in surface uplift (Ref. 6)



– Potential damages on oil- and gas field infrastructure (e.g. pipelines, processing plants) can be avoided by identification of stronger subsidence areas; counteractions could be much earlier initialized (e.g. reduction of production, water and steam injection into the relevant area); damages on pipelines or processing plants do not just generate high costs for material but could also result in major stand-by times for production, which is the major impact.

– An environmental impact could be reduced by spaceborne surface movement monitoring: Stronger subsidence related to production (e.g. of decimetres or even metres over years) could result in stronger change of the ground water table; ground water flow directions could change significantly or the ground water table could rise to shallow parts of the surface, strongly influencing the growth and health of vegetation; in the worst case, ground water table could rise even generating flooded areas – this could cause severe impact on vegetation but also in infrastructure; the proper wide area monitoring of surface movements could help to better predict these influences and to take countermeasures in advance (e.g. reduction of production, water and steam injection into the relevant area).

– In many countries, the operators of oil- and gas fields have finally legal obligations concerning the monitoring of the impact of their operations; production related surface movements could have the strongest impact on the environment as such, very often, the monitoring of surface movements is mandatory; the potential of having a wide area overview on surface movements can very much complement information from terrestrial monitoring of surface movements.

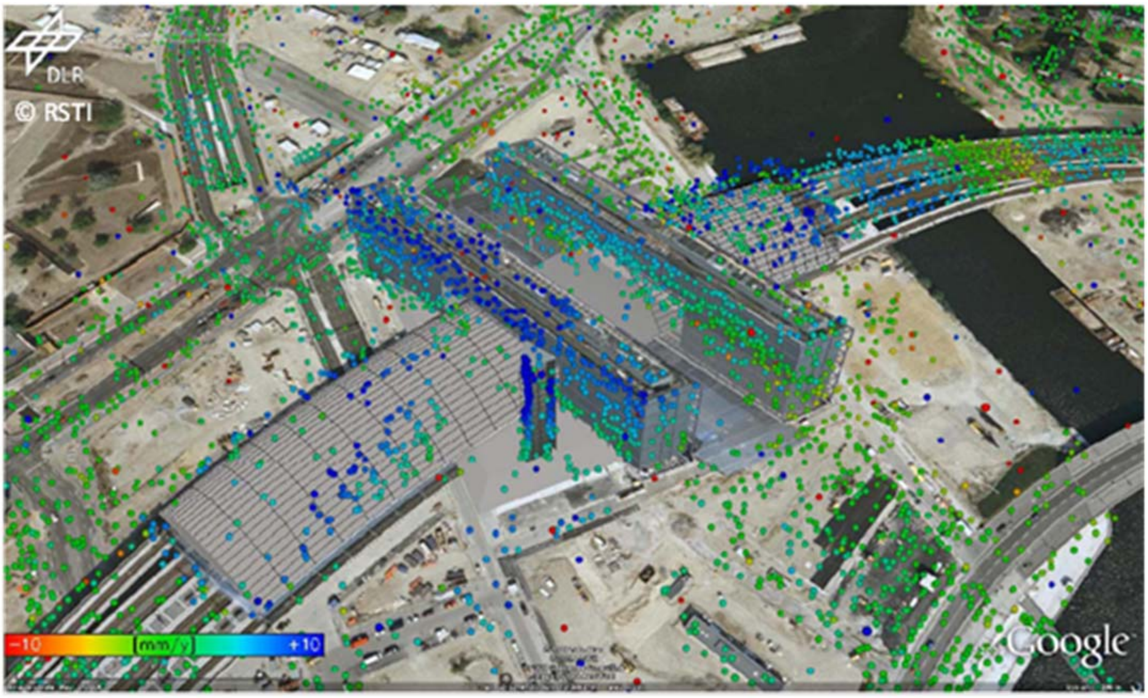
3.2.9 Infrastructure and civil engineering and construction site monitoring

As interferometry can monitor surface motion induced by construction work, very high resolution (VHR) X-Band imagery can be used for urban monitoring, for instance to estimate illegal or informal buildings construction, as well as to monitor urban development and urban sprawl. With a high revisit time, space-borne imagery allows short-term monitoring of construction sites, of the surrounding infrastructure and environment (e.g. potential land use change) in an unbiased and reliable way.

X-Band radar imagery can support the monitoring of buildings and infrastructure. The identification of interferometric permanent scatterers (i.e. objects which are not subject to major changes but may show dislocations over time e.g. due to subsidence or thermal expansion or contraction) is facilitated with increasing resolution. This means that much more details on surface movements (subsidence or uplift) can be localized which directly can be used to measure stress on constructions. VHR provides increased measurement capabilities: monitoring of single and smaller buildings is only possible for large buildings. This can therefore contribute to the monitoring of world cultural heritage.

FIGURE 10

SAR Interferometry showing minor deviations of building structures over one year (Main Station, Berlin, Germany)

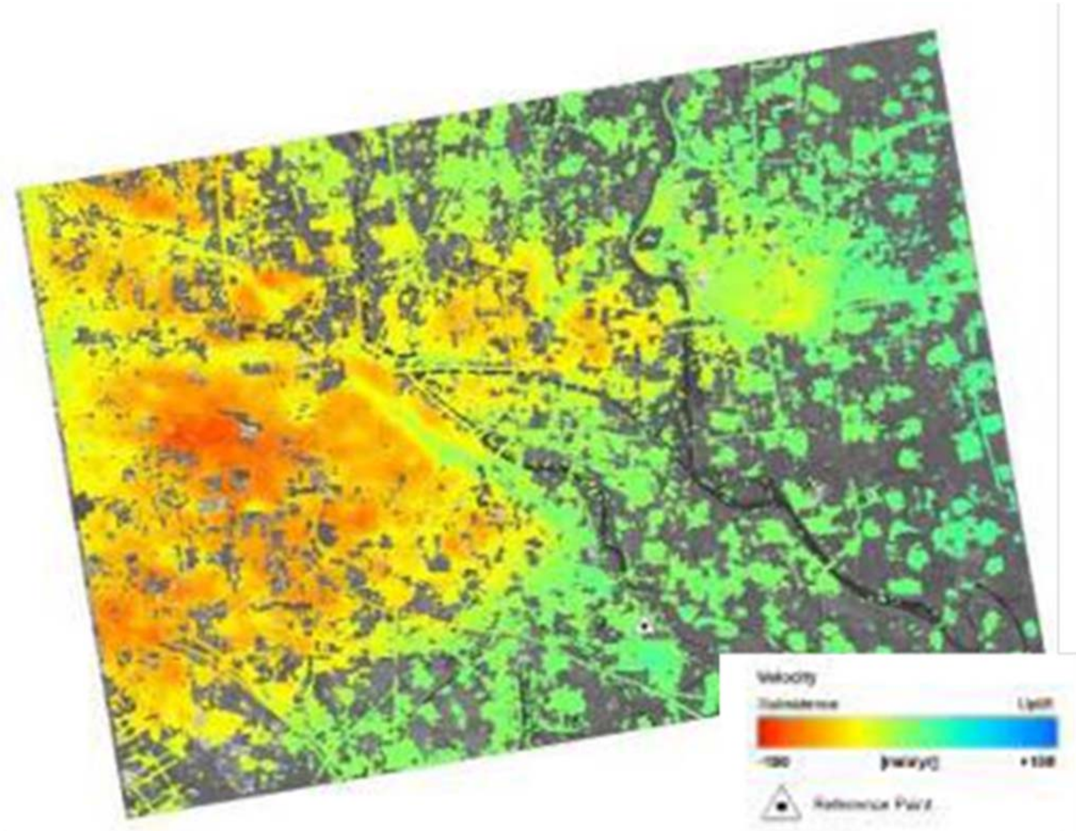


Surface infrastructure (e.g. roads, buildings, industrial facilities) are directly linked to the surface due to their foundation. As such, these installations are directly affected, if the ground moves for different reasons. Beside the already above-mentioned sources of surface movements (oil- and gas production, mining, oil- and gas storage), further sources need to be considered.

First of all, the extraction or also the injection of groundwater is very often related to surface movements (subsidence and uplift, respectively). This is happening for different reasons: On the one hand, sediments (e.g. clay soil) have different volume depending on the level of humidity – the more humid sediments are the higher are their volume. Furthermore, the groundwater level plays an important role due to buoyancy. The higher the groundwater level increase in a certain time period is the more levels of the underground are affected by buoyancy and thus stronger uplift can be expected in [6], [7], and [8]. An example for subsidence caused by ground water extraction is shown in Fig. 11.

FIGURE 11

Surface movement monitoring result from Beijing, China; Strong surface movements can be delineated caused by underground ground water extraction

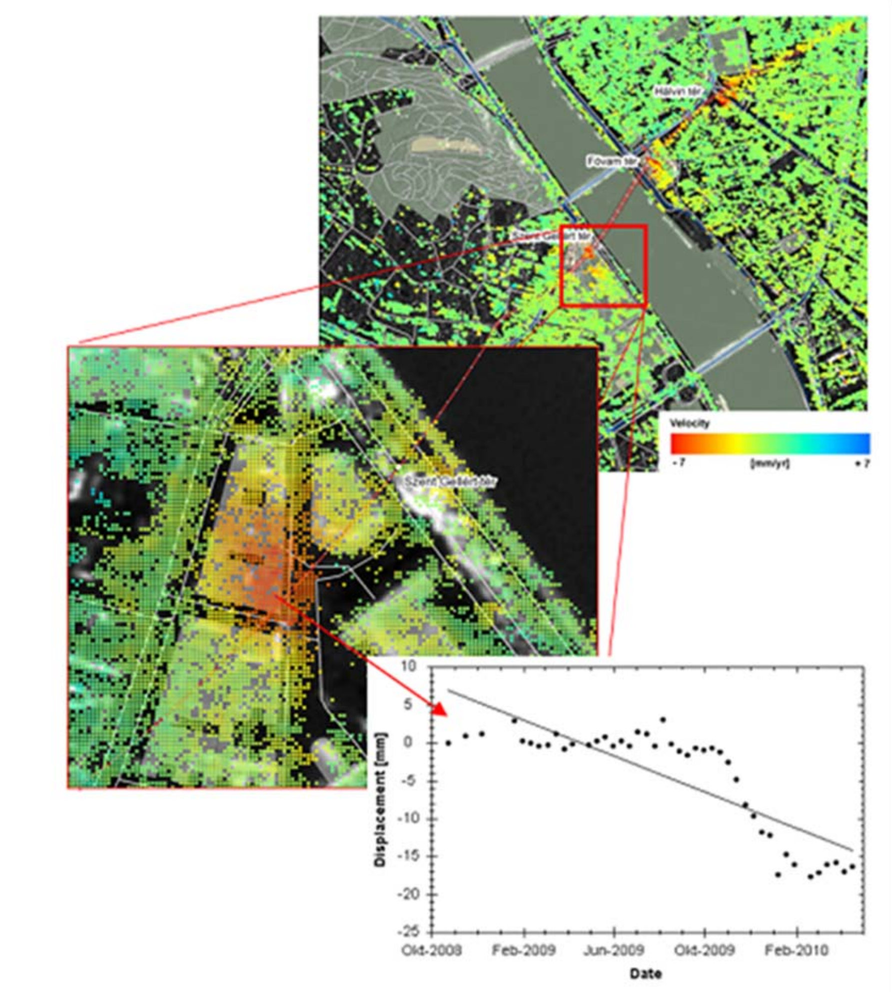


Second, underground construction (subway construction, underground parking lots, tunnels) work very often creates surface movements – either due to related creation of underground cavities, while having insufficient cavity support (e.g. wooden or steel pillars) or due to necessary ground water pumping, in order to make underground construction possible.

The reasons and effects are quite comparable to underground mining. Nevertheless, there is a major difference: Due to strongly different depths of the source, the extent of related surface movements is quite different. Whereas surface movements which are related to underground mining are widely extended, surface movements related to underground construction in shallow depths are basically very restricted in their extent. Especially in the latter case as such high resolution SAR sensors need to be favoured for monitoring in order to also reveal these small extended surface movements and relate them to underground construction.

FIGURE 12

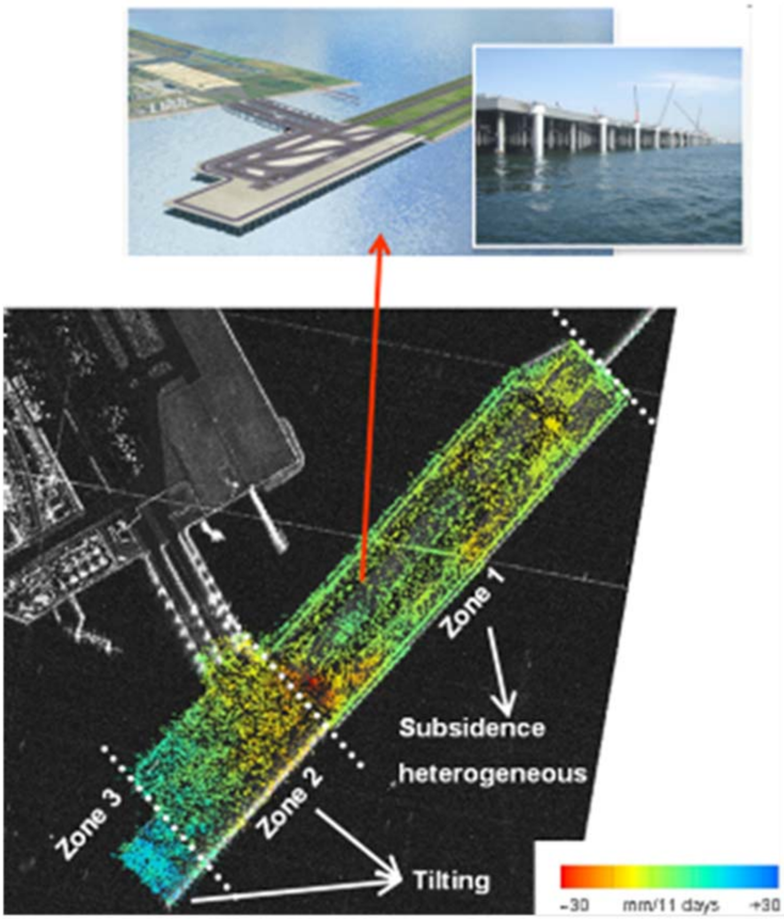
Top-PSI analysis in the wider area of a subway construction site in Budapest on base of 43 TSX satellite data sets between October 2008 and April 2010; Centre – focused SBAS analysis in the area of Station Scent Gellerért tér on base of 8 TSX satellite data sets between 28/08/2009 and 05/04/2010; Bottom – sample time series of surface displacements showing the highly non-linear displacements induced by temporarily restricted time of construction



Another reason for the movement of surface infrastructure is their construction on unconsolidated soil, e.g. relevant in the case of intensive cut- and fill operations on hills and valleys in the countryside or in the case of construction on reclaimed land along the water side of the sea, lakes or rivers.

FIGURE 13

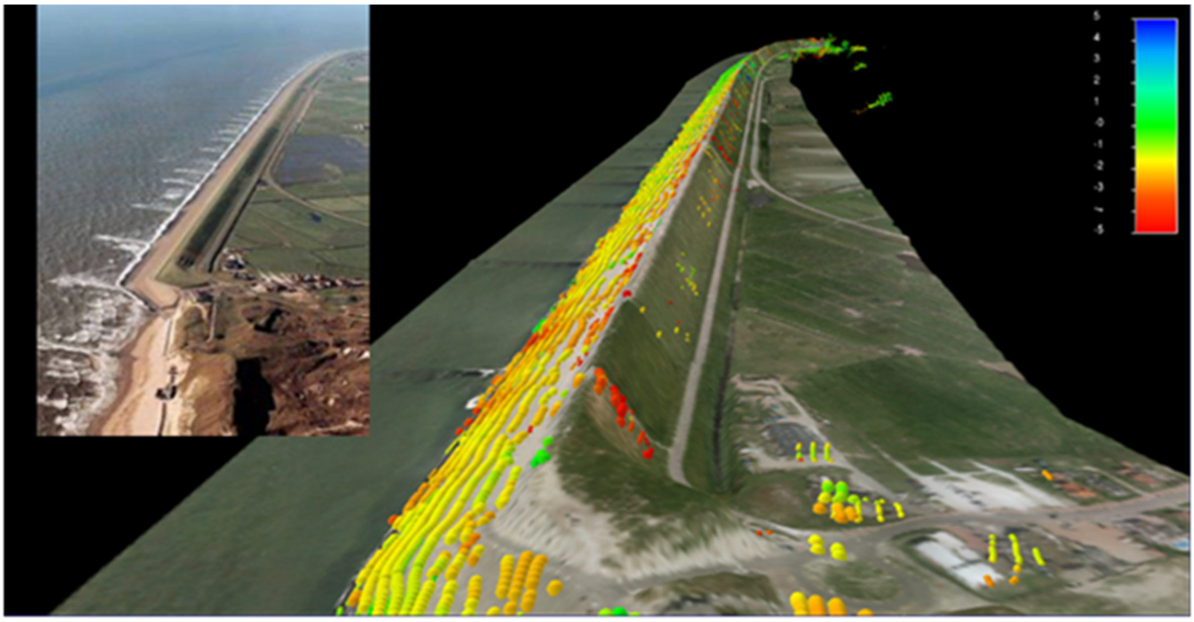
Surface movements of a new runway at an airport in Asia – documented by SAR radar interferometry



The relevant service to be offered from remote sensing data is SAR based surface movement monitoring maps and datasets which show the surface movement situation in the wider area of relevant infrastructure. Surface movement rates as well as individual time series of surface movements are delivered. These can be correlated with known information on location and time of activities (e.g. construction, ground water pumping).

FIGURE 14

Dam monitoring at the North Sea Coast



The following benefits can be stated:

– The wide area overview on surface movements allows the identification of non-predicted "hot spots" of surface movements in an area surrounding, e.g. underground construction. Terrestrial surveying grids could be focused on these hotspots and could thus be optimized – including a cost-saving potential. Higher density of measurement pixel density would allow the detection of smaller extended hot spots for guiding additional terrestrial surveying.

– Spaceborne surface movement monitoring based on "historic data" could act as a backup for terrestrial surveying and can serve for verification purposes, which is typically also achieved by contracting independent surveying companies. As above, a higher resolution of used SAR sensor would allow also the detection of smaller anomalies.

– Furthermore, the payment of necessary compensations could much better be controlled with regard to the justification of payments: Payments do just need to be triggered, if damage is really caused by underground construction work. The relevant decision could be supported by spaceborne surface movement monitoring based on the spatial and temporal behaviour of the surface movement signal – it must be related to the known location and time of activities influencing the underground (e.g. groundwater pumping, underground tunnelling). A higher density of measurement pixel would give a higher reliability of results on individual building stage with regard to potential compensation requests.

3.2.10 Applications in the science & technology research domain

SAR technology and SAR image interpretation are still very young scientific disciplines and offer good synergy opportunities with other scientific fields like meteorology.

As an example, VHR SAR imagery in the X-band domain is especially suited for the identification of subtle surface changes (e.g. defoliation of trees by pests, degradation pattern in savannah and open forests (where optical imagery has severe problems due to signal saturation)), and in tropical regions. The same is true in urban regions where illegal buildings and urban sprawl demand VHR imagery for change detection and object recognition. Here, science is working, as well, towards more sensitive means for change interpretation, e.g. in the framework of spatially disaggregated socio-economic models.

On-going investigations strive for further automation of the map generation process. Currently, a large amount of the mapping is done manually by interpretation experts. Increased dimensionality, i.e. polarimetric X-band data, will enhance automated classification accuracies.

Also the use of persistent scatterer interferometry in construction work e.g. to identify constructions under stress (e.g. bridges, roofs, roads, energy lines, power plants) does offer a new dimension for scientific studies which, at present, suffers from insufficient spatial resolution.

Persistent scatterer interferometry is needed to enable monitoring of critical plants, e.g. chemical plants, and sites in terms of subtle changes (e.g. subsidence or uplifting), on-going or interrupted construction works and site traffic.

3.2.11 Law enforcement

Besides monitoring the implementation of environmental regulations (see environmental monitoring), the sensitive change indication in terms of land use/land cover or associated infrastructure (e.g. airstrips, roads) can support the identification of illicit framing and other non-regulated man-made activities.

These may include growth indications for informal settlements around major conurbations or illegal trafficking near border areas by identifying new vehicle tracks or frequently used foot-paths.

3.3 SAR applications (need for continuity and improvement of SAR images)

Quoting Report ITU-R RS.2178, “One can improve prediction of the Earth system only through comprehensive, systematic Earth observation. Observing what is happening today and analysing what has happened in the past, is the key to understanding and predicting what will happen in the future”.

Current X-band EESS SAR satellites provide Earth observation images by using centre transmit frequencies around 9 600 MHz.

Future SAR systems are conceived to provide continuity of service, with improved performances, thus extension of the current allocated frequency band around 9 600 MHz would allow to:

– Large re-use of existing technology developed for currently flying EESS satellites.
– Valorize the existing images, also through interferometric applications (e.g. system like Cosmo-SkyMed and TerraSAR-X catalogues totally consists currently (2013) of more than 600,000 standard images) [10].

3.4 Benefits of EESS frequency extension of 1 200 MHz around 9 600 MHz

Satellite Remote Sensing is a relatively cheap and rapid technology of acquiring up-to-date information over large geographical areas, even at variable scales, and is also the only practical way to obtain information from inaccessible regions.

Report ITU-R RS.2178 quotes that: "One can improve prediction of the Earth system only through comprehensive, systematic Earth observation. Observing what is happening today and analysing what has happened in the past, is the key to understanding and predicting what will happen in the future".

During the 90s, the World Bank estimated that an efficient warning system could decrease the impact of natural disasters by 240 billion dollars. In 2011 the total amount of disaster estimated by natural and industrial disasters was 365 billion dollars. As stated by the World Disaster Report issued by the Red Cross in 2012: "…the number of people reported affected by natural disaster (209 million) in 2011 is the fourth lowest of decade, but is much higher than the minimum of 2006 (147 million). In 2011, almost 70 per cent of people reported affected were victims of floods".

The same year, the total number of people reported killed by total natural disasters (Drought/food insecurity, Earthquake/Tsunamis, Extreme temperatures, Floods, Forest/scrubs fires, Insect manifestation, Mass movements, Volcanic eruptions, Windstorm, Industrial and miscellaneous accidents) were about 37,000. The total number of people reported killed by total natural disasters in the decade 2002-2011 were 1,240,000; in the same decade, the total number of people affected by the above-mentioned phenomenon were almost 2,690,000.

Worldwide emergency management and disaster relief: concept has evolved from pure post-accident activities to prevention, preparedness and mitigation of crisis, focusing on the role of pre-crisis activities too, in order to avoid or mitigate the consequences of a disaster.

Such a principle requires multi-temporal acquisition of basic information to compute vulnerability and assess impact and consequences for mankind. SAR spotlight mode with an adequate bandwidth ensures very high resolution, with substantial socio-economic benefit in the field of: Emergency management and disaster relief, Safety of energy supply and Cadastre.

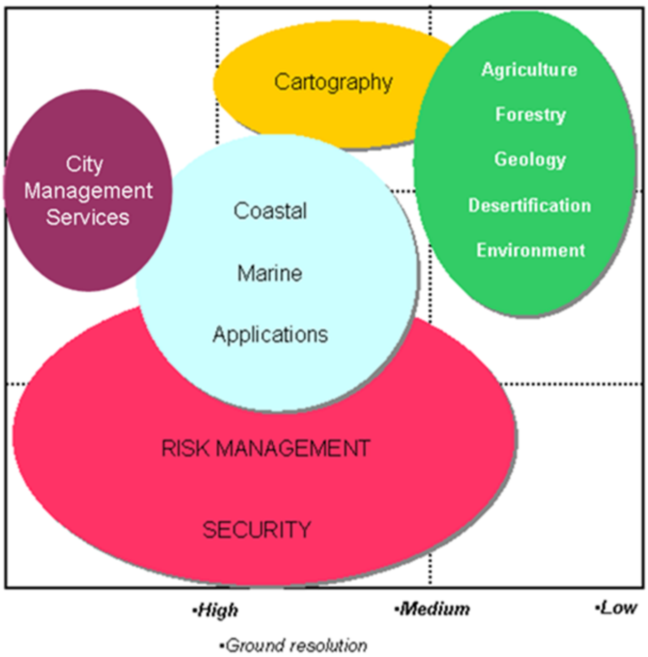
In fact, very high resolution is essential to support prevention, emergency and mitigation work plans for natural stricken centres and inhabited locations, stricken historic and artistic heritage, road network and industry location. Fast growing cities are densely packed, so in case of a hazard event, more people will be also affected by indirect impacts, such as epidemics following disruption of water supply. Rapid urbanization in many parts of the world implies that the number of cities and the urban population living in areas where natural hazards occur will be growing.

Recent reports quote that the population in large cities exposed to tropical cyclones increases from 310 to 680 million between 2000 and 2050, and exposure to severe earthquakes from 370 million to 870 million (World Bank 2010). Reducing disaster risk in urban areas is therefore a pressing challenge for city, state and national governments.

The general distribution of potential hazard risk is generally well known. Many hazards are also recurrent and so there is general awareness of risk, but what is often lacking is operationally relevant and publicly available risk information guaranteed by the needed revisit time and ground resolution, as shown in Fig. 15.

FIGURE 15

Ground resolution requirements in different application fields



The provision of very high resolution data from space has been recently issued by optical satellites (0.8 to 0.41 m at nadir), and improved spatial resolution from optical satellites are still to come even in most cases image acquisition is precluded by clouds and lack of sun illumination. SAR is a complementary space technology, only able to provide whole repetitive coverage of Earth, independent of weather conditions and sun illumination. X-band SAR data (the first from Space) acquired in 1994 during two Space Shuttle missions (X-SAR/SIR-C) demonstrated the ability of 9 600 MHz centre frequency to observe, monitor and assess environmental processes, providing scientists highly detailed information on natural environmental changes and consequences of human activity.

In 2007 COSMO-SkyMed X-band SAR (9 600 MHz centre frequency) and TerraSAR-X (9 650 MHz) confirmed the valuable support of X-band (around 9 600 MHz) to study the Earth with very high spatial resolutions.

X-band SAR constellations have supported many humanitarian emergencies providing images of natural and environmental disasters to International Institutions and humanitarian organizations (see Figs 16 to 21) for example. In May 2008, during the Myanmar flooding caused by the cyclone Nargis, during the Guan-Xian flooding in China and in Haiti after the hurricanes Hannah and Ike. In 2010, current SAR systems have acquired data for several days and allowed to monitor the Deepwater Horizon oil spill drilling in the Gulf of Mexico after rig explosion. In March 2011, after the Japan earthquake and consequent tsunami causing about US$ 200 billion economic losses, more than 3 000 linear km in Stripmap mode along the Japanese Eastern coast from Hachinohe down to Tokyo were acquired and about 200 images were delivered to the Japan Aerospace Exploration Agency (JAXA).

The possibility “to view when needed” led to initiatives to monitor vulnerable areas. “Geohazard Supersites” is an initiative of the geohazard scientific community aimed to make sets of geophysical data, as complete as possible, for the international scientific community in some selected areas of the globe to better understand major geophysical hazards such as earthquakes and volcanoes.

Geohazard Permanent Supersites (Supersites) are single sites or extended areas of highest priority to the geohazards community in which active single or multiple geological hazard caused by single or multiple sources poses a threat to human population and/or critical facilities.

Supersites are subject to investigations aimed at broadening the scientific understanding of the causative geological processes narrowing down the uncertainty in hazard and risk assessment. They are located in geologically active regions. Information from SAR, GPS crustal deformation measurements, and earthquakes are provided in the spirit of Group for Earth Observation (GEO), ESA, NASA and the National Science Foundation (NSF). The easy access to Earth science data will allow advance scientific research, ultimately leading to reduced loss of life from natural hazards. In the future very high resolution SAR will allow to address vulnerability and impact analyses.

Up to December 2012 more than 300,000 COSMO-SkyMed X-SAR standard images of the Earth have been acquired. The data have proven invaluable for tracking ground deformation and surface change, for instance, at Kīlauea volcano, in Hawaii Islands, in the frame of Geohazard Supersites project. The Cosmo-SkyMed database has been utilized in 2009 to map ground deformation velocity in the area of L'Aquila comparing data acquired before and after the earthquake. The movement of single points on a vast territory was computed with the Persistent Scatterers Interferometry (PSI) technology.

Key advantages of PSI are:

– global outlook of the deformation phenomena occurring in wide areas thanks to the capability to use individual features, like structures and buildings;

– sensitivity to small deformations, which in terms of deformation velocity are in the region of 1 mm/yr;

– periodic data acquisitions provided by the space-borne SAR sensors;

– availability of huge historical SAR archives.

The use of a common transmission band between new and old generations of SAR systems shall ensure continuity of products in particular when systems had an actual temporal overlap of operations.

FIGURE 16

ILU modified (interferometric land use modified) of Haiti

Big differences (in red) in backscattering between pre- and post-event images (Source: Italian Space Agency).
Red: Absolute value of the difference between the pre- and post-SAR detected amplitude (26.04.2009 – 15.04.2009).
Green: Mean value of the difference between the pre- and post-SAR detected amplitude (26.04.2009 – 15.04.2009).
Blue: Interferometric coherence (26.04.2009 – 15.04.2009).

FIGURE 17

Flooded areas map (in red) in Myanmar after the Cyclone Nargis obtained with COSMO-SkyMed Data

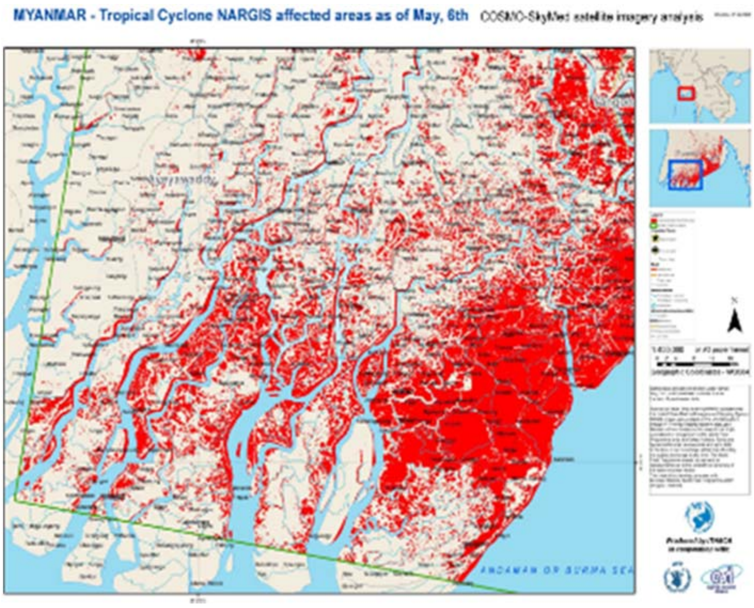
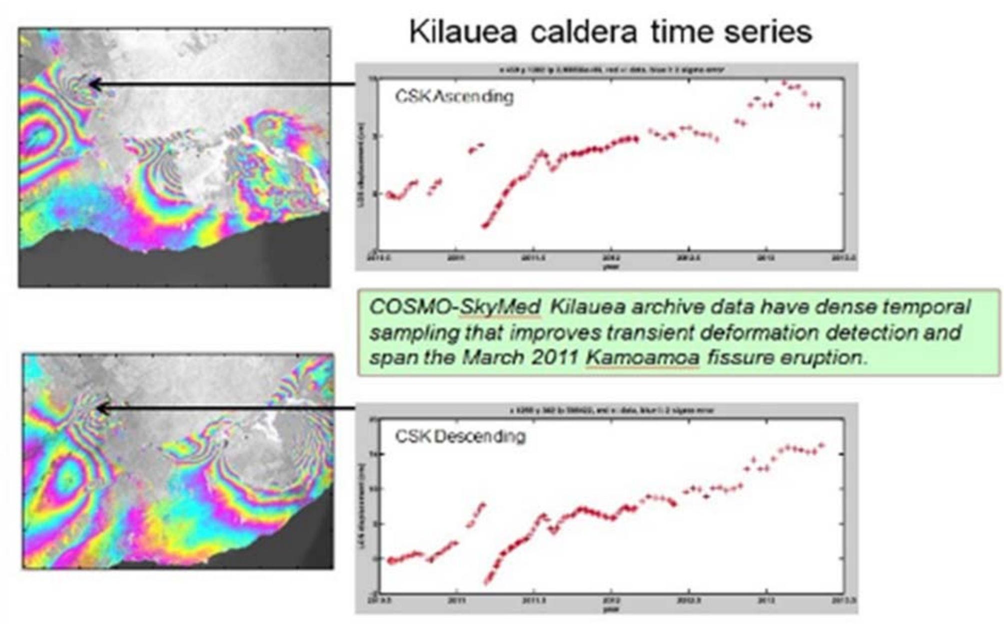


FIGURE 18

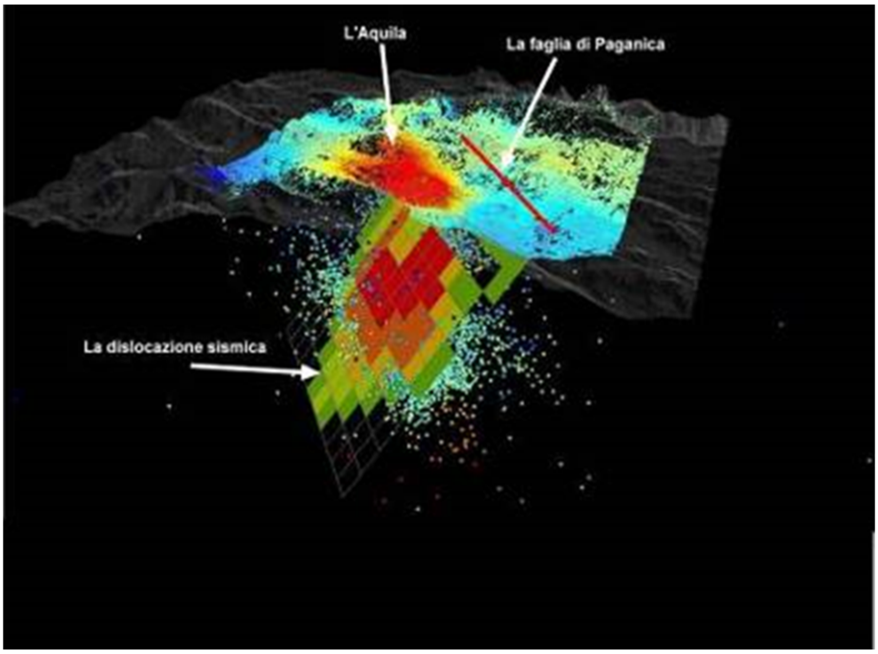
Geohazard supersites surface deformation time series for Kilauea for both the ascending and descending COSMO-SkyMed tracks from 2010.5 through mid-May 2013, with evidence of the March 2011 Kamoamoa fissure eruption



Images kindly provided by P. Lundgren (JPL).

FIGURE 19

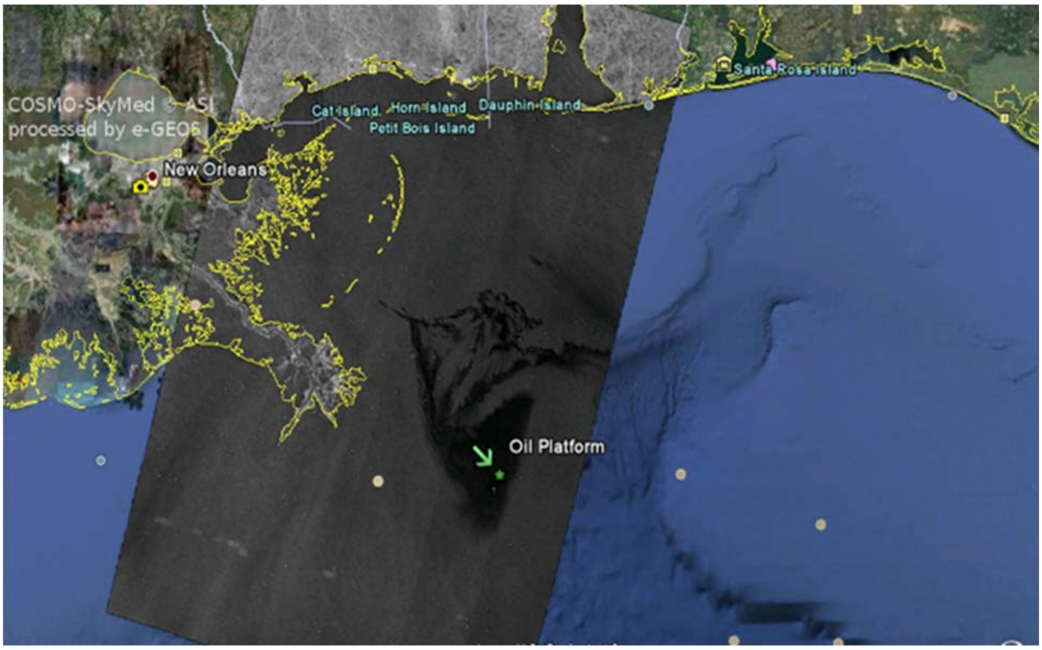
L’Aquila Earthquake



The fault plane obtained from the computed model starting from COSMO-SkyMed data is shown. The fracture plane has a dip of about 50° towards the SW and passes under L’Aquila city. During the earthquake, the Earth crust block located SW from the fault plane slided downside for a maximum slip of 90 cm at 4 km-depth, produced the ground subsidence pattern shown in the figure by red color. The max seismic dislocation corresponds to the maximum displacement in the COSMO-SkyMed LOS (–25 cm).

FIGURE 20

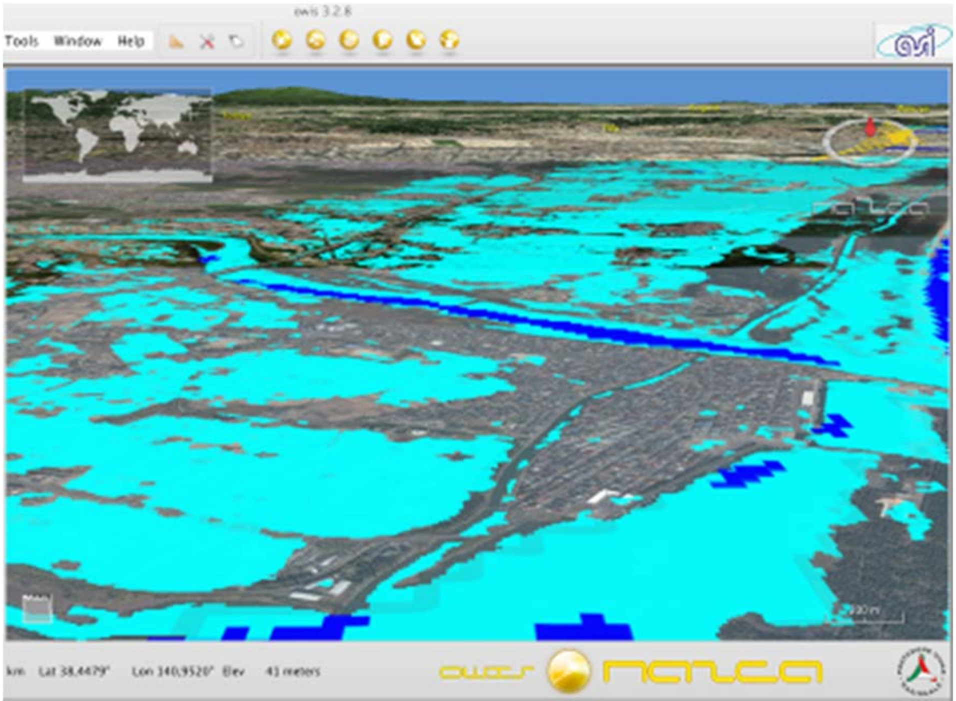
Deepwater horizon oil spill drilling in Mexico Gulf after BP rig explosion



Source: COSMO-SkyMed ScanSAR Wide image – Incidence angle 54° – Ascending orbit, right looking, Polarization: VV. Acquisition time: April 29, 2010 12:09 UTC.

FIGURE 21

Image of flooded area in Japan after tsunami (12.03.2011)



Source: COSMO-SkyMed.

4 Conclusions

This Report shows a high diversity of applications which demonstrate the need for very high resolution observations.

Continuity with the centre of present EESS allocation (9.6 GHz) guarantees comprehensive, systematic Earth observation and multitemporal analyses to support understanding of changes as demonstrated in Report ITU-R RS.2178 as "One can improve prediction of the Earth system only through comprehensive, systematic Earth observation". Observing what is happening today and analysing what has happened in the past, is the key to understanding and predicting what will happen in the future. In addition, Resolution **673 (WRC-07)** *considering d)* considers "that Earth observations are also used to obtain pertinent data regarding natural resources, this being particularly crucial for the benefit of developing countries".

Very high resolution SAR spotlight modes with bandwidth centred at 9.6 GHz would be most desirable for applications which fulfil substantial socio-economic benefit for all mankind.

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Abbreviations

EOR/EGR	Enhance oil and gas recovery
PRF	Pulse repetition frequency
PRT	Pulse repetition time
PSI	Persistent scatterers interferometry
REDD	Reducing sources of carbon emissions in the Tropics (UNFCCC)
SAR	Synthetic aperture radar
VHR	Very high resolution