ADVANCED SYNTHETIC APERTURE RADAR OBSERVATIONS WITH CLUSTERS OF SAR SATELLITES

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KEYWORDS: Synthetic Aperture Radar (SAR), High Resolution SAR, Interferometric CartWheel, Multi-Baseline Interferometry, Along Track Interferometry, Volume Probing, Satellite Formation Flight

ABSTRACT

This paper provides an overview over the advantages and applications of clusters of SAR satellites. It describes the orbit mechanisms for stable configuration flights and how they have evolved from ERS Tandem to the Interferometric CartWheel. The applications, which are described in detail, are superresolution and polarimetric InSAR volume probing for biomass estimation.

Introduction

The first configuration flight between two SAR Satellites was the highly successful ERS Tandem Mission with ERS-1 and ERS–2. Due to technical constraints the two fly-overs were separated in time by exactly one day. Although this mission has pioneered SAR interferometry the large time separation of one day lead to severe decorrelation effects. This problem was overcome with the Shuttle Radar Interferometry Mission SRTM where the two sensors were linked by a 60m long mast (Suchandt, 2001 and www.dfd.dlr.de/srtm).

In this paper we consider light free-flying SAR platforms, which fly in a formation and work in strong cooperation. Such clusters of sensors have several applications and advantages over single, highly advanced, heavy and expensive satellites. The advantages are as follows:

- **Graceful Degradation**
  In case of a significant failure not the overall system will breakdown. The loss of one satellite will cause only 1/n degradation of the overall performance. This situation is similar to a hologram, where a local damage does not cause a hole in the image but only degrades the overall image quality.
  If one microsatellite fails it may be replaced by a new one at any time. Satellites, which are aged, can be replaced by samples of a new generation. On the other hand if an important part of a highly sophisticated satellite fails the overall system has to be replaced, which may interrupt the operations and is much more expensive. The strategy to overcome this problem with expensive satellites is to integrate redundant parts (which makes the satellite even more heavy) and to perform intensive simulations and qualifications and tests prior to launch (which increases the cost significantly).

- **Series Production**
  It can be cheaper to build a series of small, light and simple satellites than to build only one big, heavy and highly sophisticated satellite.

- **Reconfigurable to Different Applications**
  The cluster of SAR microsats could be configured at least for the following applications:
  - high resolution SAR (superresolution) with an along track orientation
  - surface motion measurements (along track interferometry) with an along track orientation
  - multi-incidence angle observations with a cluster distributed in along or across track
  - DEM generation, biomass and ice monitoring with a CartWheel (across track interferometry and polarimetry)

These advantages have led in the United States to the TechSAT21 initiative (AFRL, 1998). In the next chapter of this paper an overview about SAR satellite configuration flight is given. This is followed by a description of the possible applications and missions.

Stable Configuration Flight – From ERS-Tandem To The CartWheel Concept

In order to compare radar images very precisely using the technique of radar interferometry, a relatively small difference of points of view is required. To establish this baseline, many combinations are possible. The most obvious and relatively cheap is to use the same satellite twice, waiting for it to come back in about the same position (i.e. within the requirement of similarity of the points of view). The early development of space borne radar interferometry was based on this method. In this case, the interferometric signal is made of four components that must be discriminated by careful analysis: (1) residual orbital errors which create parallel fringes across the interferogram, (2) topographic signal of which amplitude is modulated by the across-track separation of the spacecrafts, the combined atmospheric delay typical of each scene datum are also contributing (3). Finally (4), any displacement of the ground occurring between the times of the data takes is printed in the interferogram. The time elapsed between the acquisitions, which is responsible for the two last components of the interferometric signal, might cause some loss of signal clarity (loss of coherence) because the elementary targets on the ground have an opportunity to change. This opportunity is generally all the larger that the time elapsed is long. The minimal time elapsed is the orbital cycle of the satellite, which is generally long (35 days for most of the lifetime of the ERS satellites). With the advent of ERS-2, ESA’s second radar satellite, identical to ERS-1 as far as the radar is concerned, a new possibility was exploited, **the tandem**.

The principle is very simple, each satellite follows its nominal 35-day cycle orbit, but the two satellites are shifted by one day. From the ground, everybody sees ERS-1, then ERS-2 after one day, then again ERS-1 after 34 additional days. The mission is very interesting because the reduced time separation is a key factor for improving coherence. The elementary targets do not have as much time to evolve. Another great success of this mission was the mapping of relatively quick moving targets such as glaciers. One single day was the ideal time lapse to record the displacement fringes correctly: a full 35-day interval would make them unreadable due to the accumulation of a 35-times larger displacement. Another advantage of the tandem is the ability to maintain a very small difference of point of view. Two factors contribute to this possibility. Firstly, the two satellites face about the same conditions of solar activity and atmospheric braking. Their trajectories evolve in a parallel way and their relative trajectory is very stable. Secondly the orbit corrections can be phased. When a satellite drifts close to the limit (i.e. one kilometre from the nominal track), it is kicked back on track by a corrective impulse. In order to reduce the frequency of the correction, the impulse is strong enough to send the satellite close to the limit on the other side (still one kilometre from the nominal track). The satellite then drifts back slowly. If the second satellite is fired at the same time, regardless on whether it had yet reached the limit, it can remain very close to its companion. Offsets of 50 or 100 meter were achieved routinely in the tandem mission. The offset has sometimes been made greater purposefully in order to increase topographic sensitivity.

Another way of obtaining difference of points of view is formation flying of the two or more radar instruments. Again, the easy way to create it is to put the instruments at the extremities of a mast. This was done in the Shuttle Radar Topography Mission (SRTM). The mast maintained mechanically the baseline and the Shuttle attitude control system maintained the desired viewing angle of the instrument. Another way would be to replace the mast by a propulsion system and to force the second antenna (on a free-flyer) into a parallel orbit. However, such a system would not last long as the fuel consumption would be huge. As an example, assume we want to fly permanently with one kilometer across track apart from a free orbiter. Our spacecraft would then rotate one kilometer off the center of the Earth while being distant of about 7000 km, leaving permanently about 1/7000 of the Earth gravity to compensate. This would correspond to an impulse of more than 100 m/s a day. It can, however, be envisioned that a strong electric propulsion system might maintain a 100-m baseline for a couple of years (10 m/s a day). Similarly, vertical separations can be created with similar costs. However, it is more convenient to analyze the way free-flyers can organize themselves.

We assume a moving frame the origin of which flies a certain orbit, and we consider the relative orbits that can be created with respect to this origin.

Noting Z the vertical axis (positive when sticking up), X the velocity axis and Y the horizontal axis perpendicular to the track, hence oriented to the left as seen from the spacecraft, the equations of the orbit of the micro-satellites, relative to the synchronous orbit are written:

$$X = 2R \sin(\omega t + \phi)$$
$$Y = A \cos(\omega t + \psi)$$
$$Z = R \cos(\omega t + \phi)$$

Where R is the vertical radius of the configuration and A a term liked to a possible change of the orbital plane, corresponding to a change of the Equator crossing time (i.e. a slight change of the ascending node longitude). In the pure cartwheel mode, A = 0 and the relative displacement is contained in the vertical plane including the velocity. Form these equations we conclude that:

1) A configuration where the rotation is restricted to a plane perpendicular to the velocity is impossible.

2) A « flat » displacement (Z=0) is also impossible unless it is reduced to the Y-axis. In the case the micro-satellites collide twice an orbit.

In order to obtain stable differences of point of view as well as of acquisition times all along the orbit, several receivers can be placed with different ϕ or ψ. For instance, if three receivers are given a slightly higher eccentricity than the conventional radar satellite they follow, while keeping the same orbital period, they will feature a non-zero R. Slight changes in the longitude of the ascending node can also be added, creating a non-zero A. They describe an ellipse around the orbital position they would have without the additional eccentricity and longitude change. The even distribution of the perigees results in an even distribution of the receivers along the ellipse, which features a horizontal axis twice as long as the vertical one. The longitude change adds a lateral axis. It can be shown that, with three receivers, the horizontal and vertical baselines vary only by 7.5% along the orbit, with respect to their average value, provided we consider the two satellites best positioned for the purpose among the three.

The main advantage of this “CartWheel” (Massonnet, 2001) concept is the geometric stability of the configuration all along the orbit. In a vertical configuration, this stability is obtained for a left as well as a right viewing. By introducing an inclination of the wheel (non zero A), a given incidence can be privileged, which can be interesting for modifying the ratio between the critical horizontal and vertical baselines, therefore adapting it to the parameters imposed by the companion radar.

However, variations of this concept and other configurations have to be further analysed.

Multi-Angle SAR Observations

The multistatic observation angles, which can be achieved by a cluster of SAR satellites, are in particular useful to improve scene classification or target identification. The cluster may be distributed in along track or across track. The latter has the special advantage of forward scattering (Mochia, 2001) resulting in a stronger backscatter signal. The difference in the observation angles can be too large for SAR interferometry, but Stereo-SAR techniques may be applied for the generation of topographic maps.

CartWheel Configuration – The DEM Mission

The application of the CartWheel configuration for the generation of a global digital elevation model (DEM) has been studied in detail by a joint team from CNES and DLR (Mittermayer, 2001a,b, Runge 2001). As an illuminator satellite the Envisat and ALOS have been considered. It was shown that a very accurate global topographic model, with vertical accuracy in the range of one meter could be achieved. The CNES developed MYRIADE microsatellites could be used and the earliest possible launch date is fall 2005 (Martinerie, 2001).

CartWheel Configuration – The Biomass Mission

The digital elevation model derived from the X-band SRTM data represents a shape of the earth surface. In densely vegetated areas this elevation model includes the canopy of the trees because the high frequency microwaves are mainly reflected by the top of the trees. For many applications true ground elevation data are required. In order to penetrate the vegetation a long wavelength like the L-band is required. It would be of great interest to measure furthermore the volume and density of the biomass layer on the earth surface. This can be achieved with polarimetric SAR interferometry (Cloude, 2001). A suitable illuminator satellite would be the Japanese ALOS, a European TerraSAR L-band satellite or the proposed US-Echo satellite.

One of the most exciting possibilities of these configurations is the possibility to map volume scattering through the loss of coherence it causes. This is enabled by simultaneous interferometric observations where a temporal loss of coherence does not occur (like in repeat pass systems). However, unlike SRTM, here we can work with much higher level of baseline (i.e. much closer to the critical value of the baseline). The system allows working with a various level of sensitivity using the flexibility in incidence angle permitted by the illuminator and the pointing of the wheel.

Assuming that the system is tuned to a certain fraction of the critical baseline using a given angle of incidence, for instance in the 40° range, it is clear that the equivalent orthogonal baseline will be reduced when working at a lower incidence angle, allowing the exploration of varied percentages of the critical value from the same cartwheel orbital configuration. In reality, volume scattering can be easily understood from a topographic point of view: the elevation of each scattered creates a topographic phase combined with the strength of the scatterer. As a result, the targets from a volume “disagree” on the phase value because they differ in elevation, which results in a loss of coherence. The coherence depends on the amplitude distribution of the scatterers throughout the depth of the altitude of ambiguity (assuming that the depth of volume does not exceed the latter). Working with lower than nominal incidence angles increases both the penetration depth and the altitude of ambiguity: the change in elevation that creates one additional topographic fringe or “contour line”. A collection of various incidence angles from the same orbital separation is thus likely to provide a very sensitive probing tool for vegetation. As for the DEM application, having a third receiver in an intermediate position can further increase the richness of the data.

A major objective of environment sciences is the determination of the three dimensional structure of the vegetation, especially forests, a major parameter for the monitoring of the biosphere. The evolution of forests, which cover a quarter of the land surfaces, is also a key factor of the evolution of the atmosphere as a carbon sink. The three dimensional structure of the forests can reveal changes in height and species as well as damages caused by thunderstorms and other exceptional atmospheric events.

Similarly, the evolution of the icecaps is one of the keys to the understanding of the trends of the climate. The very cold, thus very dry, ice allows substantial penetration by radar waves, especially at long wavelength.

The penetration in deserts can be assessed by comparison of DEMs made from non-penetrating techniques (optical of short-wave radar) and from long wave radar, or by polarimetric InSAR methods as described above. Much better results for archaeological and paleoclimate research can be expected than from the already remarkable SIR-A and SIR–B L-band missions, where dried out riverbeds and even a lost city (Ubar) were detected under the deserts sand (Holcomb, 1998).

The extension of a biomass mission for ice and desert applications would lead to a general **“volume probing mission”** for climate change research.

Let us assume that the specification of the mission is the mapping of all forests surfaces four times a year under two very different incidence angles, continued all through a three-year long nominal mission. During these three years, the Arctic and Antarctic icecaps could also be mapped twice a year, again using two widely separated incidence angles. In the course of the mission, selected test sites could be observed at any occasion, therefore yielding very frequent observations with many different incidence angles. Assuming that the total activity on the test sites will be similar, in terms of acquired surface, to the systematic mapping of forests and ice caps, we can estimate the volume of data to be acquired:

The global surface of forests is 40 million square kilometers. The global surface of ice caps is 14 million square kilometers. The above requirements represent therefore 2*(40*4+14*2) million square kilometers a year, or 376 million square kilometers. With a swath-width of 100 km, it corresponds to a length of 3.75 million kilometers, or the length of about 94 orbits (40000 km per orbit). Since a satellite typically covers 5250 orbits a year, the duty cycle demanded to the system and therefore to its companion radar is 1.8%. If we assume, for instance, that the radar instrument of the companion (the illuminator) works 18% of the time, the mission would draw 10% of its resource, regardless of some scenes being required anyway by companion’s user community.

Super-Resolution by an Along-Track Formation

The achievable azimuth resolution of a SAR depends on the acquired Doppler- (Azimuth) bandwidth or in other words on the length of the synthetic aperture integration time. This bandwidth has sufficiently been sampled with a Pulse Repetition Frequency (PRF). Furthermore the receiving antenna length must not be longer than double of the desired azimuth resolution. The PRF, however, can not be increased without limits. The higher the PRF the smaller becomes the achievable swath and obviously a higher PRF causes a higher energy consumption.

In order to obtain a larger swath a Scan SAR System can be employed, but this reduces the azimuth resolution. To improve the azimuth resolution (by increase of integration time) a Spotlight SAR can be used, but this configuration does not allow to record a continuous data strip in along-track. Beside these disadvantages Scan SAR and Spotlight SAR require expensive and heavy active phased array antennas. (Spotlight SAR can also be realised by mechanical steering of the satellite, but this technique limits the frequency of observations.)

In order to increase the range resolution chirps with high bandwidth have to be transmitted. (To obtain a 1m range resolution typically a 150 MHz range chirp-bandwidth is necessary.)
The losses in the signal to noise ratio due to the necessary wide-band receiver have to be compensated with a higher radiated power.

The method which is introduced here is aimed to relax the requirements for the PRF and the radiated power. The system uses several (n) receiving platforms which fly in a formation in along track as depicted in Figure 1. All receiving satellites look at the same antenna footprint, but due to their separation in along-track and the squinted antenna look-angles they receive different Doppler frequency bands (Fig.2).

The ground is illuminated by one active SAR system positioned e. g. in the centre of the formation. The distance between the receiving platforms is adjusted that each satellite receives an adjacent Doppler-band. In a processing system these Doppler-bands can be put together in order to form a wide Doppler-band. Without accounting that the Doppler-bands need some overlap the azimuth resolution can be increased by the factor of n. Furthermore the sampling of the Doppler-band (with the PRF) can be reduced by the factor of n for this multiple-platform system in comparison with a system which generates the wide spectrum with only one antenna.
A „Super-Resolution“ SAR processor with aperture synthesis may work in the following sequence:
a.) A complex SAR image is computed from each channel.
b.) From each spectral overlap region an interferogram is formed
c.) The phase offset (which represents the phase difference between the channels) and the co-registration coefficients are extracted.
d.) A pixel co-registration and a phase offset correction for all channels is applied.
e.) A complex summation of the data sets is performed in order to obtain the super-resolution image.
If a higher radiometric resolution is desired, a traditional look summation of the detected data sets can be applied. For target recognition applications it can be helpful to analyse each look
(which is taken from a different aspect angle) separately.

To achieve the same azimuth resolution (Doppler-bandwidth) with the standard and the multiple receiver configurations the azimuth integration time (or the length of the overall synthetic aperture) must be the same for both systems. But the difference is that the antenna footprint of the standard system must be n-times wider than the one of the multiple receiver system. This requires the use of a n-times smaller (shorter in along-track) antenna and results in a n-times longer target illumination time.

The multiple receiver SAR can be seen as a combination of an array antenna and a synthetic aperture antenna.

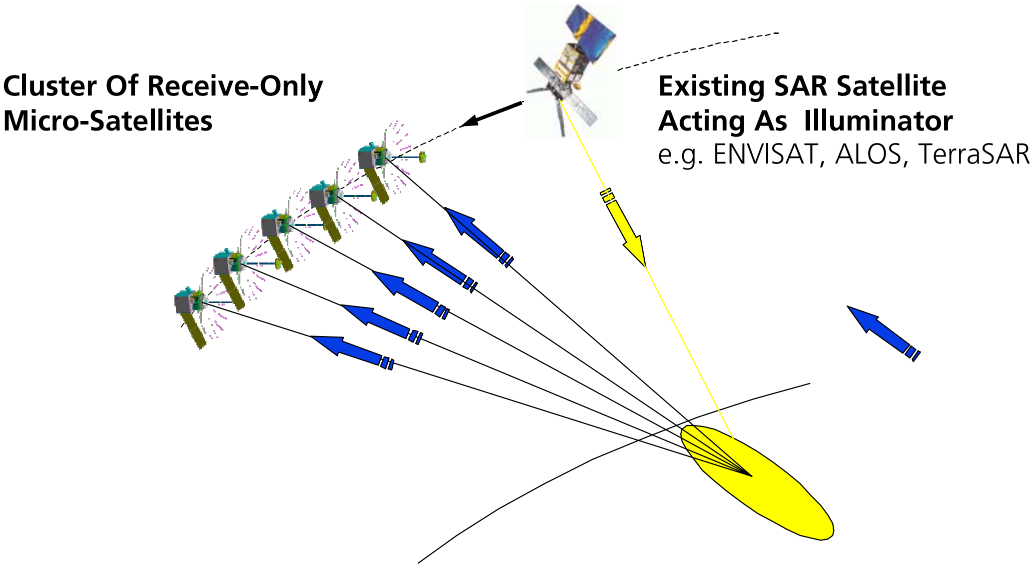


Figure 1: Configuration for superresolution SAR with one illuminator and a cluster of receive only satellites

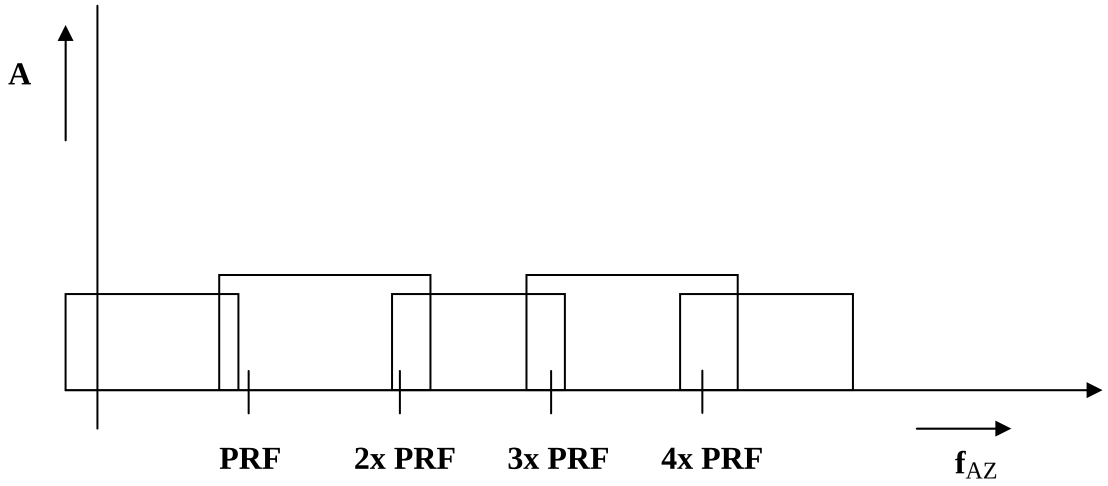


Figure 2: Synthesis of azimuth spectra for superresolution

In summary the **advantages of a multiple-platform system for superresolution** from the radar point of view are:

- **n-times shorter target illumination time**:
  For the imaging of moving scatterer, like the sea surface it is advantageous to use short target illumination times. Long integration times can lead to a blurring of the target. In SAR interferometry a scene decorrelation can appear.
- **n-times lower PRF is possible**
  This is of special importance to wide swath and / or high resolution SARs, because with a standard SAR it is impossible to obtain a wide swath and high resolution at the same time.
- **n-times longer antennas are possible**
  One channel of the multiple-receiver system produces only 1/n of the final azimuth resolution. Therefore, a n-times longer (in along track) antenna can be used. This is a work-around of the fundamental SAR law that the achievable azimuth resolution is limited by half of the antenna length. This is important for the power budget of the radar, because a n-times larger transmit and receive antenna requires a n-times smaller radiated power.
  For the multiple receiver platforms micro-satellites shall be used. Their ability to perform attitude control with large along track structures is limited. Therefore a high resolution system with antennas of up to 6m length may be considered.
- **Distributed illuminator is possible**
  In order to make the system redundant and to distribute the burden of power generation and amplification each satellite can be active and can contribute to a joint illumination of the target.
  No longer is a single high power illuminator required. The power requirement for one microsatellite from the cluster is reduced by 1/n in comparison to a single illuminator.

In the following the distributed illuminator concept shall be investigated in more detail. In general with a bi-static system there are **two approaches for the ground illumination:**

a) **The opportunistic approach with an existing illuminator**

Here we take advantage of an already existing (at the time of the mission) SAR satellite which will have proven its capabilities, like Envisat, ALOS, Radarsat or TerraSAR. The main advantage is that one may benefit from investments which are already done and from the infrastructure which already exist. Beside problems with data rights and safety of the master satellite, which can be resolved in practice, it appears the problem of harmonisation of the time schedule of the missions. Furthermore, the design of the microsatellites which fly in formation with the „illuminator“ have to be adapted to the technical constrains (radar bandwidth and frequency, orbits, air drag, etc.) of the master satellite, which will always leads to some sort of compromises.

b) **The cluster of active SAR satellites**

In this concept each platform consists of a complete SAR satellite including a transmitter. Figure 3 shows this cluster of active SAR satellites in comparison with a standard SAR. Please note that the synthetic aperture has the same length for both systems, while the antenna footprint and the transmitted power per satellite can be much smaller for the high resolution SAR with in the cluster configuration.

The chirp generator of each system can be commanded to generate a certain bandwidth, e. g. the first satellite transmit pulses with a spectrum ranging from 0 to 20MHz, the second transmits a pulse spectrum from 20 to 40 Mhz and so on. The receivers are wideband that they can record the echos of all transmitted signals. The separation of the contributions of each transmitter can be performed in the SAR processor by simple bandpass-filtering (Runge, 1999). Figure 4 shows how the 2D-spectra of the received signal is arranged by the SAR processor. The spectrum of the echo signal received by the satellite in the centre of the cluster configuration appears in blue colour.

This active cluster concept avoids the need of a dedicated illuminator and makes a mission self-contained. It is expected that due to the possibility of series production this concept is the cheaper to realize.

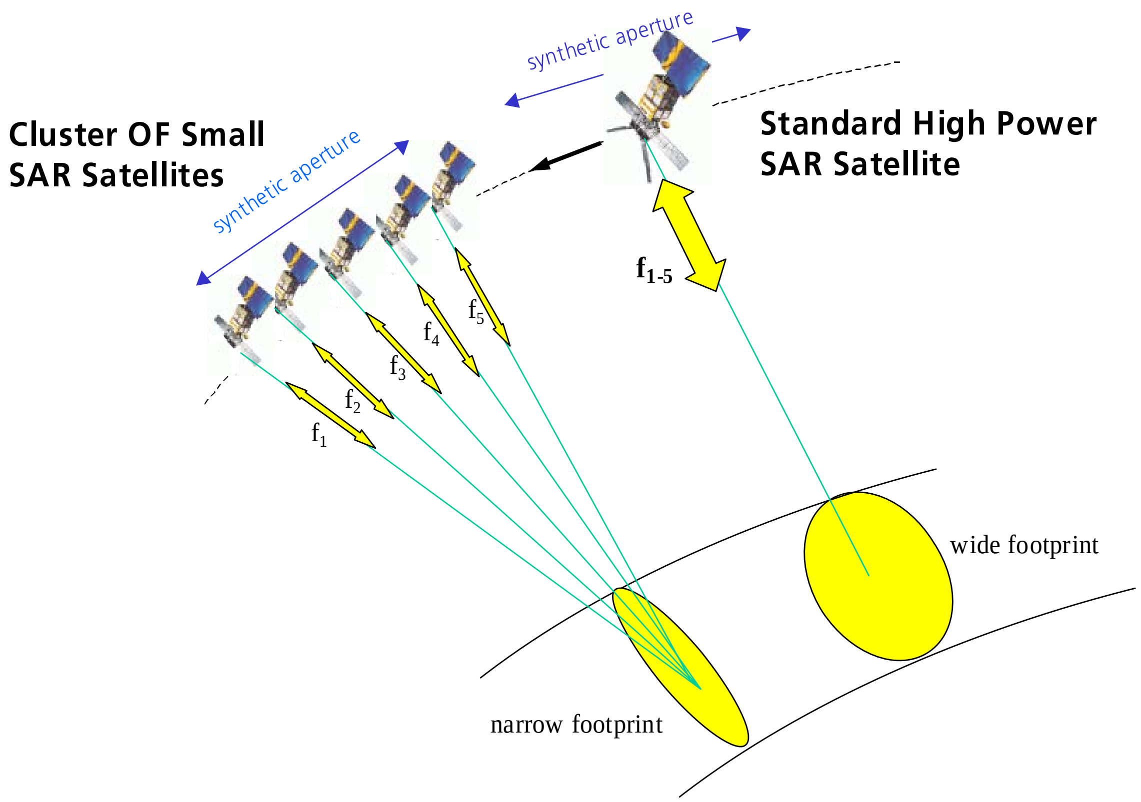


Figure 3: A cluster of active SAR satellites versus a standard high resolution SAR

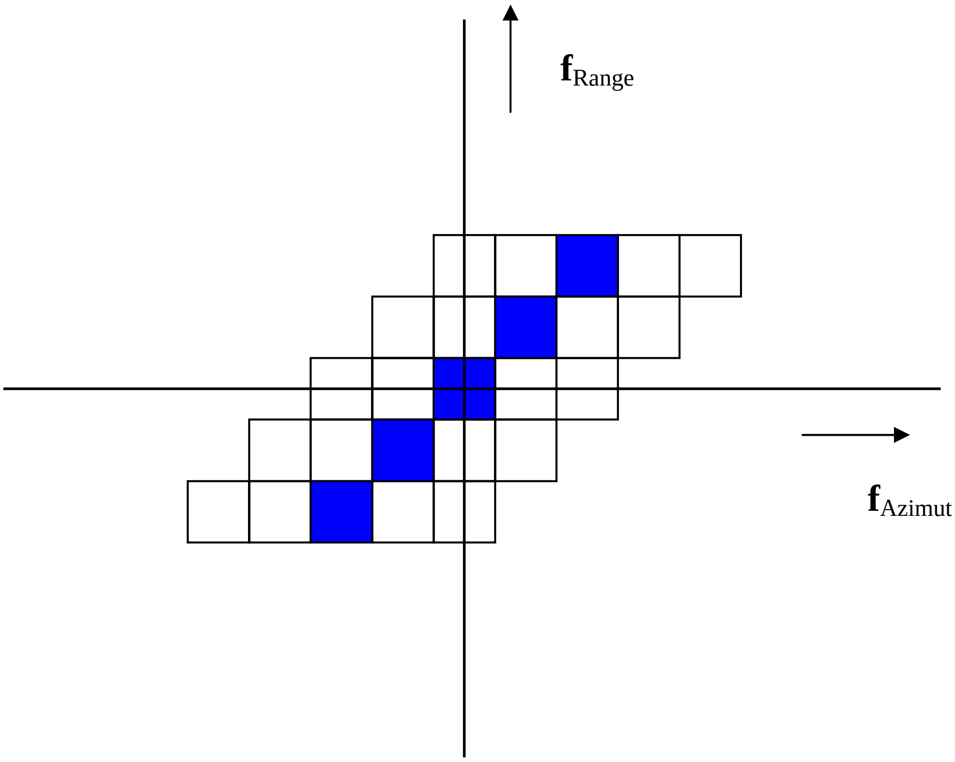


Figure 4: Assembly of 2D-raw data spectra of the active cluster SAR

The Along Track Configuration – The Ocean Currents Mission

The idea to detect and to measure the speed of ocean surface currents with along track interferometry (ATI) dates back to the 80ties of the last century (Goldstein, Zebker 1987). Measurements with aircrafts have been performed by JPL (Carande, 1994) and later by DLR and the Aerosensing company. In comparison with across track interferometry the technique has not become very popular yet because only few results have been published up to now.

The ATI uses two antennas separated in flight direction. Such system acquires two data sets from the same position but with the time lag Δt. If the scatterer is stationary the two data sets are identical (save from noise) and the interferometric phase would be zero (Bamler, Hartl 1998). If a scatterer moves in the direction of the line of sight with v_{range} the interferometric phase φ_{ATI} will be:

$$\varphi_{ATI} = 360^\circ \frac{2 \cdot \Delta t \cdot v_{range}}{\lambda}$$

In order to measure two velocity components squinted dual beam radar has been proposed (Frasier, et. al. 2001). Care has to be taken at the interpretation of the measurements because corrections for the wave motion have to be applied (Romeiser, Hirsch, 2001). Therefore, the wave height and direction has to be derived from the SAR image first (Bao, Schulz-Stellenfleth, 2001).

The sensitivity of the system is governed by the wavelength λ of the radar, the radar signal to noise ratio and the ATI baseline length. The latter one, however, can not be increased without limits because the ocean surface decorrelates quiet fast! According to (Romeiser, Thompson, 2000) the decorrelation time using the L-band is only 50ms. Therefore, the two satellites in the along-track formation must not be separated further than about 400m and the satellite operators will require very precise position measurements. Probably a sort of distance meter has to be installed on the satellites. For X-band radar the decorrelation time is even smaller and the two antennas may be connected by a boom or mounted on the International Space Station.

ATI is the only remote sensing technique that has the potential to provide maps of ocean currents at better than 20 km resolution. The principal existing technique is altimetry (like Topex and Jason), which with coarse across-track resolution (typically 250 km) and along-track resolution (about 20 km) is limited to mapping sea level variations resulting from tides, and from mesoscale and large scale geostrophic currents. An additional satellite-based technique consist of using sequences of infrared images to map the advection of frontal features, but this is limited to cloudless areas and to areas where sufficient thermal gradient exist, and therefore is not of general application. Land-based techniques such as HF and VHF doppler radars require heavy infrastructure and have only local coverage.

While these techniques have been used to study several categories of ocean processes, there is a lack of high resolution (i.e. 100-200 m scale) studies of ocean flows, in particular in the fields of air-sea interactions and surface layer circulation and in coastal processes. ATI-SARs are the only instruments capable of advancing studies in these fields. Main applications are:

- mapping of coastal processes, erosion processes, pollution
- ship routing / manoeuvres in high current areas (with strong tides)
- basic studies on air-sea interactions (heat transfer, etc.)
- seasonal weather forecasts
- study of El Nino phenomenas

The following two key requirements may be posed to ATI mission data products:

- spatial resolution: 200 m
- velocity range: from 0.02 m/s up to 4 m/s

Further analysis has to show whether these performance requirements can be reached with illuminator satellites like Envisat or ALOS.

The SRTM Along Track Interferometry Example

In the following the SRTM antenna configuration is taken as an example for a spaceborne ATI. The system was designed for across track interferometry which was performed with a 60m boom. Due to mechanical constrains the canister for the boom and the secondary antenna was mounted with a 7m offset to the main antenna in the Space Shuttle cargo bay. This created a small along track baseline Δx which is long enough to detect and measure very fast tidal currents close to coasts. For the special case of SRTM along track interferometry the along track time lag is:

$$\Delta t = \frac{\Delta x / 2}{v_{Shuttle}} = \frac{3.5\,m}{7500\,m/s} = 0.46\,ms$$

(Only half of the antenna separation has been accounted here because of single pass interferometry.) The relation between the measured interferometric phase φ_{ATI} and the radial velocity v_{range} is (with λ=3.1 cm):

$$\varphi_{ATI} = 360^\circ \cdot 0.030\,\mathrm{s/m} \cdot \mathrm{v}_{range}$$

As an example the motion of a scatterer of 1 m/s corresponds to a phase of 10.8 degrees. (In the DEM a strong target moving with 10 m/s (36 km/h) would produce a 108 degree interferometric phase, which corresponds to a (108/360 * 180 m) 54 m height error due to this motion.)

Strong tidal currents reach up to 10 knots (about 5m/s) and have been detected with the X-SAR / SRTM. Figure 5 shows an example in the Waddenzee at the Dutch coast. Figure 5a depicts the orientation of the data take from southwest to the northeast. The radar look direction was from southeast and the Shuttle heading was northeast.

Figure 5b represents the amplitude image showing in the south the Afsluitdijk of the Ijsselmeer. The islands from left to right are Texel, Vlieland and Terschelling. Also some small islands like Noorderhaaks between Den Helder and Texel and Richel as well as Griend between Vlieland and Terschelling are clearly visible. The image was taken at Feb. 15th 2000 at 12h34 UTC. This was nearly at high tide. In the phase image (Fig. 5c) the strong currents between Den Helder and Texel and Vlieland and Terschelling are clearly visible. It shall be pointed out that only the velocity component in across track is imaged.

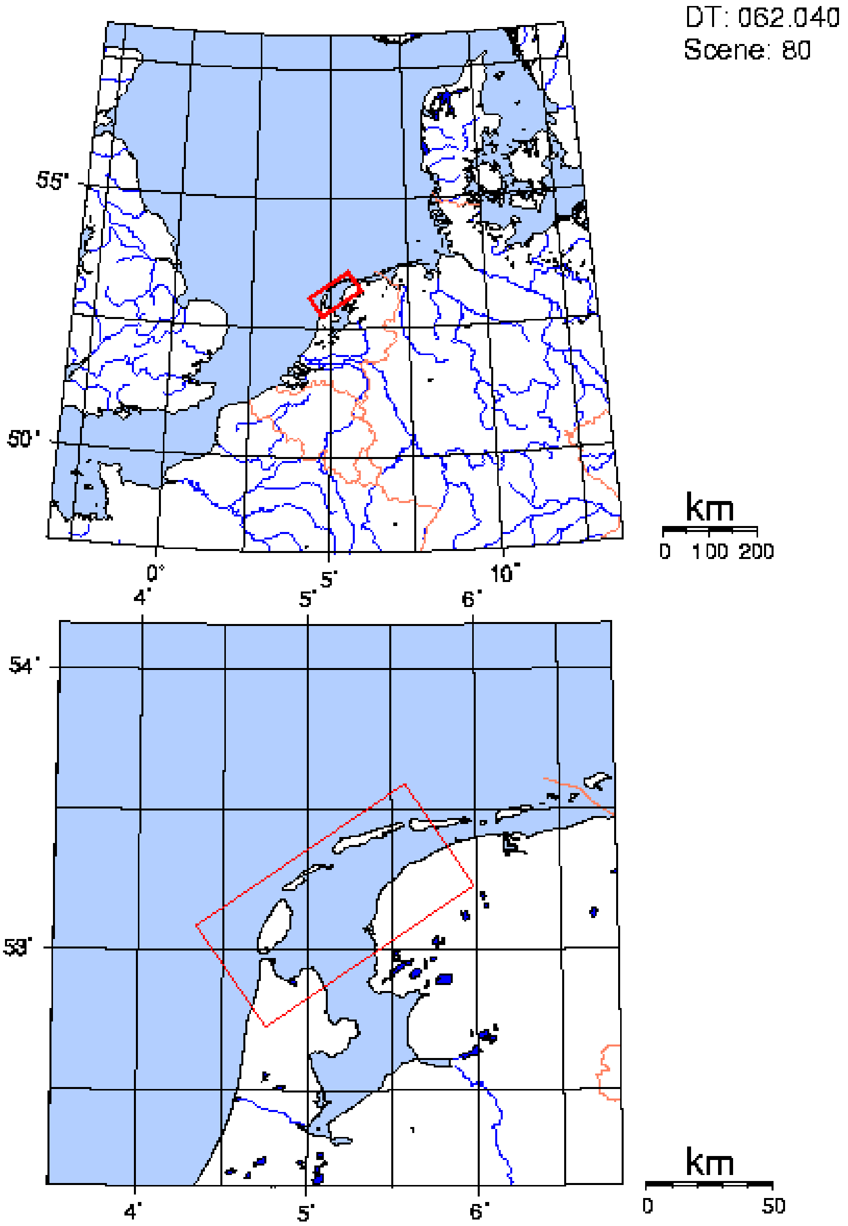
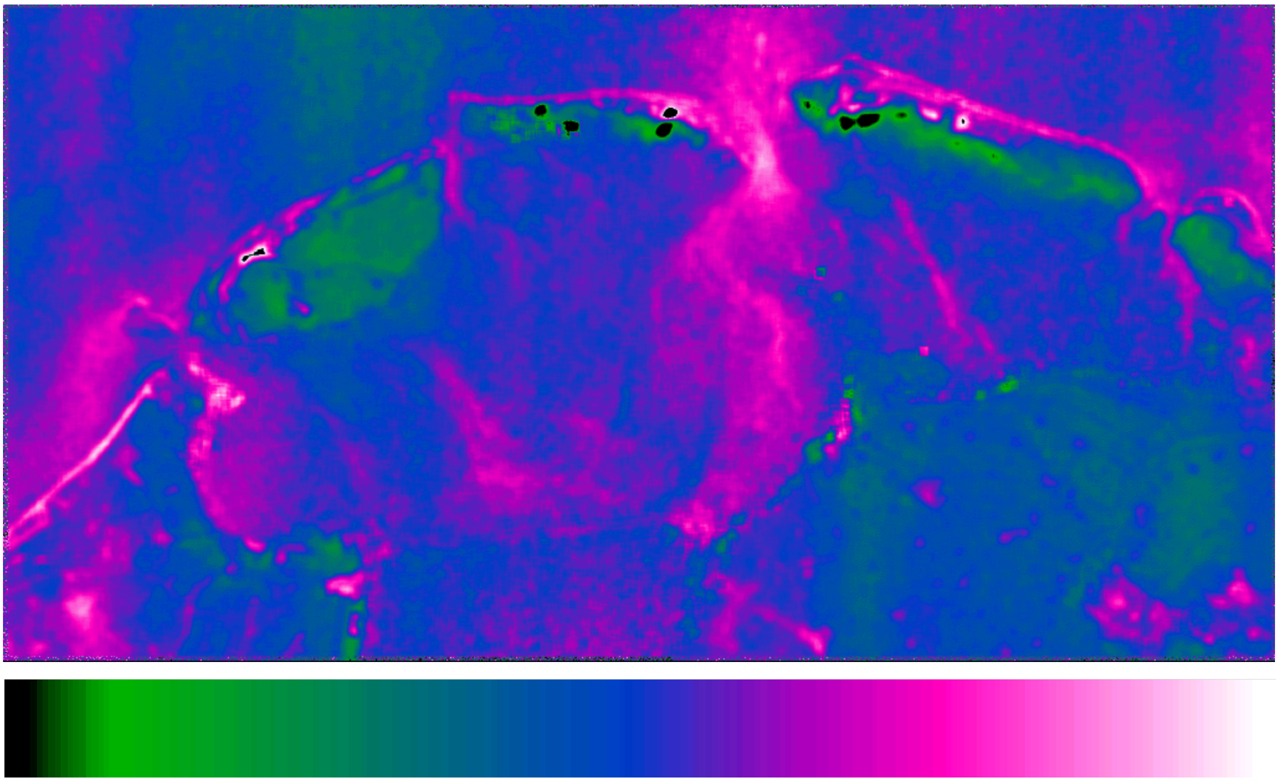


Figure 5a: Orientation and location of the X-SAR / SRTM data take DT062.040.

Figure 5b: X-SAR / SRTM geocoded amplitude image of the Waddenzee in the Netherlands



Colour coding:
black: -21°(-2.0 m/s) blue: 0° (0 m/s) white: +21° (+2.0 m/s)

Figure 5c: X-SAR / SRTM phase image of the Waddenzee in the Netherlands

The interpretation of the SRTM interferograms is difficult because due to the additional across track baseline not only motion but also elevation causes a phase shift. In the interferogram shown in Fig5c it was tried to minimize this effect by subtracting an artificial interferogram inversely generated from an existing digital elevation model with a 1km lateral spacing. Therefore, the land in Fig.5c shows some difference between this model and the SRTM elevation model and should not be interpreted here.

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