Towards an Operational Spaceborne System for High-Resolution Current Measurements in Coastal Areas

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***Abstract* – Along-track interferometric synthetic aperture radar (along-track InSAR) is a new technology for imaging surface current fields from airborne or spaceborne platforms with accuracies of 0.1 m/s or better, spatial resolutions on the order of 10 to 1000 m, and swath widths of up to more than 100 km, depending on platform and instrument parameters. This is particularly attractive for the mapping and monitoring of current fields in coastal areas. The SRTM experiment on a Space Shuttle in early 2000 offered a first chance to demonstrate current measurements by InSAR from space. Although the SRTM configuration was not well suited for current measurements and the coverage of the ocean was very limited, some images of coastal scenes exhibit clear signatures of typical surface current patterns, which have been found to be in good agreement with theoretical predictions and to resolve current variations on spatial scales of about 1 km. The German satellite TerraSAR-X, which will be launched in 2005, will offer similar current measuring capabilities. Concepts for more specific, further optimized InSAR missions for oceanic applications are currently under investigation. We give an overview of these developments.**

I. INTRODUCTION

The concept of direct current measurements from airborne or spaceborne platforms by along-track interferometric synthetic aperture radar (along-track InSAR) was first proposed in [1]. The along-track InSAR technique exploits the fact that the phase of microwave backscatter from a moving target changes with time at a rate determined by the line-of-sight (radial) target velocity component. This effect corresponds to the Doppler shift in frequency. Two complex synthetic aperture radar (SAR) images of a scene which are acquired with a short time lag on the order of milliseconds exhibit phase differences proportional to the time lag and to the Doppler shift of the signal. Accordingly, the phase differences can be converted into target velocities, resulting in an image of the surface current field. To obtain two images with a short time lag, the InSAR antennas must be separated by some distance in flight (along-track) direction.

Early experiments with an airborne along-track InSAR system of the NASA Jet Propulsion Laboratory were carried out during the late 1980s. First InSAR-derived currents from the 1989 Loch Linnhe experiment were found to deviate significantly from in-situ data [2]. This discrepancy could be attributed to effects of surface wave motions and of the hydrodynamic modulation of the waves by the spatially varying currents, which had to be taken into account in the data interpretation. Doing this adequately in later projects, American and German scientists obtained good agreement of airborne InSAR-derived current fields with data from an HF radar [3] and with in-situ data from ADCPs and results of a numerical circulation model [4], respectively.

Numerical InSAR imaging models, such as the one described in [5], permit a theoretical analysis of the dependencies of InSAR signatures of current features on parameters such as the radar frequency, incidence angle, and the time lag between the two SAR images. This time lag, which is determined by the along-track antenna separation and the platform velocity, is a particularly crucial parameter: It must be sufficiently long to obtain significant phase differences between the two SAR images, but sufficiently short to avoid decorrelation of the backscattered signal and to avoid ambiguity problems if the velocity range of interest is mapped into a phase interval of more than 2π. At X band (about 10 GHz), ideal InSAR time lags should be on the order of 2-4 ms, corresponding to an effective antenna separation of 14-28 m at a typical spaceborne platform velocity of about 7000 m/s. For detailed discussions on the theoretical aspects of current measurements by along-track InSAR, see [5] and [6].

A spaceborne along-track InSAR would provide direct current measurements at the high spatial resolution and coverage known from conventional SAR systems, such as the ones on ERS-1 / ERS-2, RADARSAT-1, and ENVISAT. Due to the limitation to surface current measurements, SAR interferometry would rather complement than substitute the interpretation of altimeter data in open-ocean applications, where depth-averaged currents at horizontal resolutions of a few kilometers can be derived from measured surface elevations and slopes. Another limitation arises from the fact that single-beam InSAR systems are sensitive to a single line-of-sight velocity component only. To obtain fully two-dimensional current fields, data from at least two overpasses with different look directions must be combined. Altogether, along-track InSAR measurements appear to be most attractive for applications in coastal areas, where high resolutions are particularly valuable, surface currents do not deviate much from depth-averaged currents, and one-dimensional measurements are sufficient for many purposes. In contrast, the capabilities of radar altimetry are very limited in coastal areas. In-situ instruments or ground-based remote sensing systems such as HF radar may be superior to InSAR for some applications, but they require complex infrastructures and cannot be deployed easily in arbitrary test areas.

A first demonstration of current measurements by spaceborne along-track InSAR could be performed from a Space Shuttle during the Shuttle Radar Topography Mission (SRTM) in early 2000 [7]. We present some results in the following section. In section III we discuss the current measuring capabilities of the German satellite TerraSAR-X, which will be launched in 2005. An outlook to future spaceborne InSAR concepts with improved sensitivity and spatial resolution and with the capability to provide two-dimensional measurements during a single overpass, is given in section IV.

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II. InSAR-Derived Currents from SRTM

The main objective of the Shuttle Radar Topography Mission (SRTM) in February 2000 was the generation of high-resolution, high-precision topographic maps of the Earth's land surfaces with a single-pass, dual-frequency (C and X band) cross-track InSAR on the Space Shuttle "Endeavour" [7]. The cross-track InSAR technique exploits phase differences between complex SAR images acquired from different perspectives for topographic measurements. The cross-track antenna separation of SRTM was 60 m. For technical reasons, there was an additional along-track separation of 7 m, which resulted in an effective time lag of about 0.5 ms between the two InSAR images. An artist's view of the SRTM configuration in space is shown in Fig. 1.

Fig. 2 shows an X band SRTM phase image (Fig. 2a) and the corresponding amplitude image (Fig. 2b) of the Dutch "Waddenzee" area between islands in the North Sea and the Dutch mainland. The total test area size is 70 km x 70 km; the pixel size of the phase image is 100 m x 100 m; it was obtained by averaging over 4 x 4 pixels of a standard SRTM data product. Due to the combined antenna separations in cross-track and along-track direction, the phases can be interpreted in terms of surface elevations and / or line-of-sight velocities: At an incidence angle of 55° and a platform velocity of about 7500 m/s, a phase interval of 2π corresponds to a height range of about 175 m or a horizontal velocity range of about 38.5 m/s. Assuming that the whole Waddenzee area was covered with water at the time of the SRTM overpass (which is confirmed by the homogeneous signatures in the SAR amplitude image of Fig. 2b) and that there are no water level variations by several meters within the test area, a conversion of the InSAR phases into horizontal velocities appears to be appropriate.

After some data processing and masking of land areas, we obtain the InSAR-derived line-of-sight current field shown in Fig. 3. It exhibits pronounced flow patterns with overall current variations by about 2 m/s.

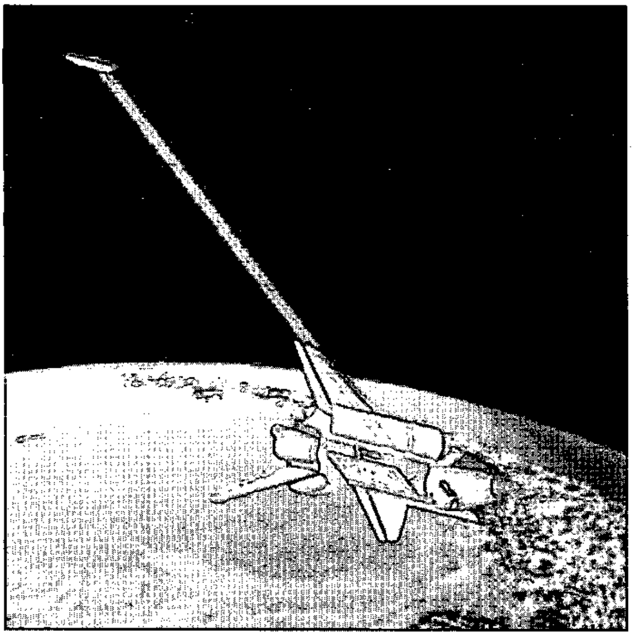
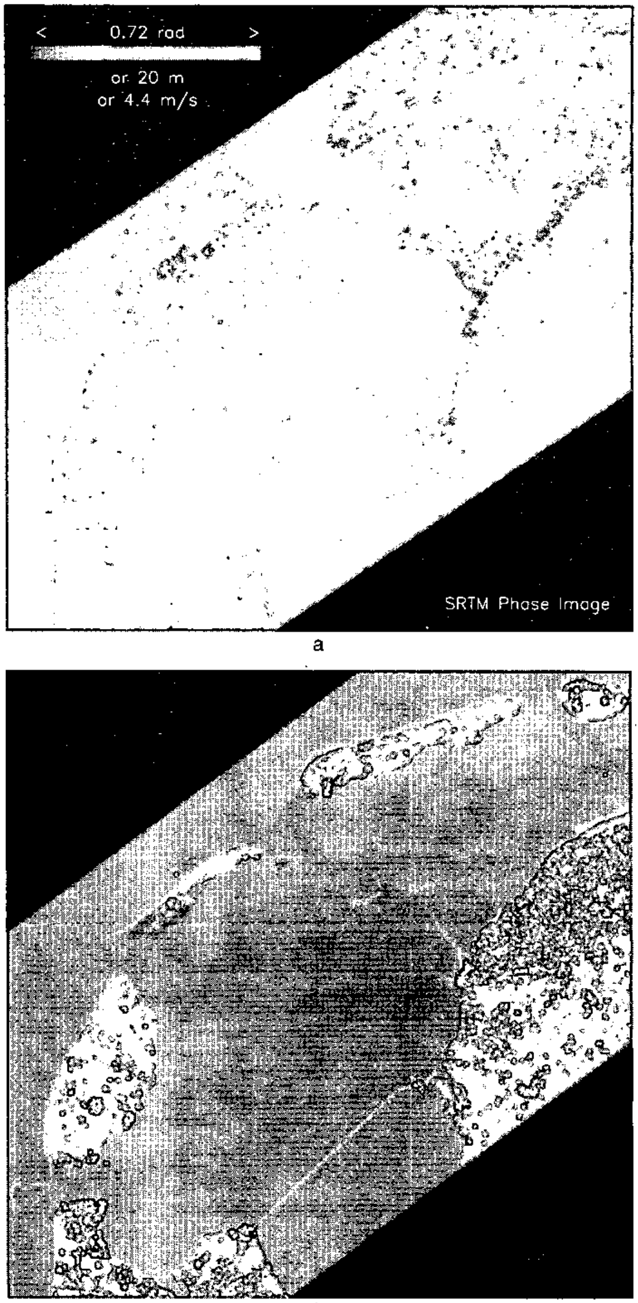


Fig. 1. Artist's view of the SRTM configuration (from NASA / JPL website).



a

b

Fig. 2. X band SRTM phase image (a) and amplitude image (b) of the Dutch "Waddenzee" (70 km x 70 km) acquired on 15 February 2000, 12:34 UTC. The radar look direction is towards northwest; north is at the top of the images.

Reference currents for a validation of the SRTM results could be obtained from RIKZ / RWS, The Hague, Netherlands, where the circulation model KUSTWAD for the Waddenzee area has been developed [8]. The KUSTWAD dataset which is available to us contains 14 current fields for one tidal cycle in March 1995. That is, the model has not been applied to the specific scenario at the time of the SRTM overpass, but to another scenario five years earlier. However, the agreement between measured and simulated current fields should usually be good at the same tidal phase.

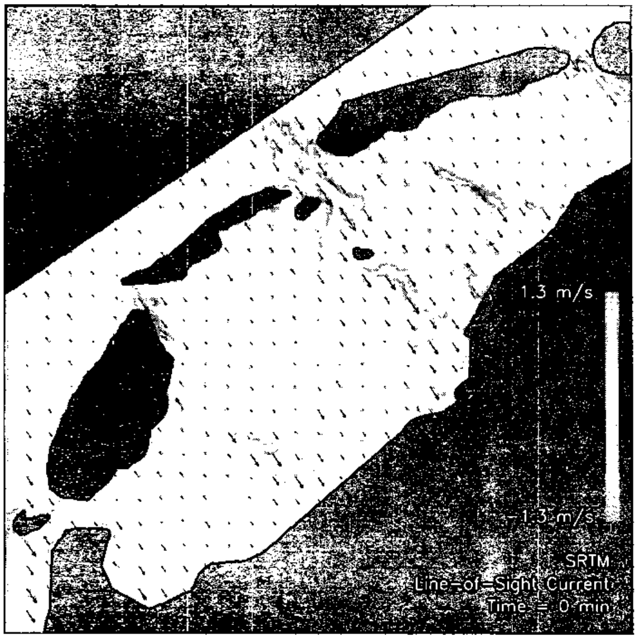


Fig. 3. Line-of-sight current field in the test area as derived from the SRTM data of Fig. 2a; only datapoints with valid currents from SRTM and KUSTWAD (see Fig. 5) are shown.

Fig. 4 shows the bottom topography of the KUSTWAD model in the test area. Some similarities between the flow patterns of Fig. 3 and the bathymetric layout are obvious. Fig. 5 shows the component in SRTM look direction of the KUSTWAD current field with the shortest time lag from the tidal phase at the time of the SRTM overpass, which took place 3:16 hours before high water in West-Terschelling: The KUSTWAD current field corresponds to a tidal phase 20 minutes earlier. The actual and the KUSTWAD-derived SRTM line-of-sight current field appear to be well correlated.

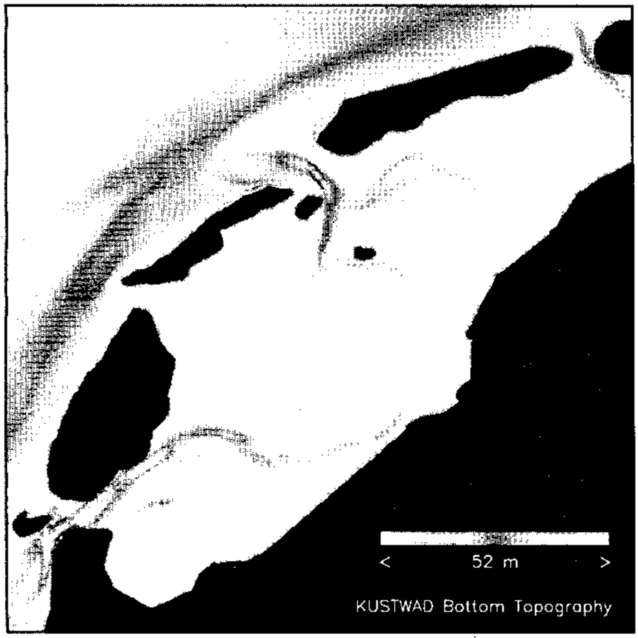


Fig. 4. Bottom topography of the circulation model KUSTWAD in the 70 km x 70 km "Waddenzee" test area.

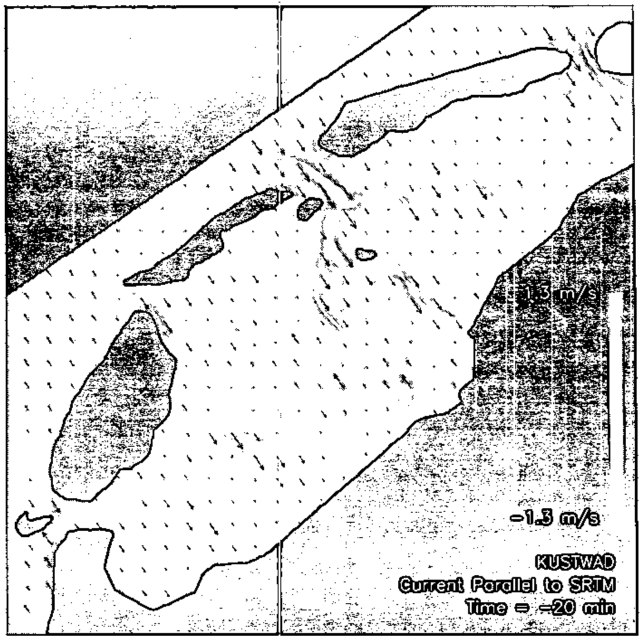


Fig. 5. Same as Fig. 3, but showing the current field as derived from KUSTWAD model results for the tidal phase 20 minutes before the SRTM overpass.

This impression is confirmed by results of a statistical analysis. Fig. 6 shows a scatter plot of the SRTM-derived currents of Fig. 3 vs. the KUSTWAD-derived currents in the SRTM line-of-sight direction of Fig. 5. The correlation coefficient between the two datasets is 0.558, the regression coefficient is 1.011, the rms difference is 0.24 m/s, and the mean difference is 0.02 m/s. In view of the fact that the KUSTWAD model run was not carried out for the particular scenario of the SRTM overpass and that there is a time lag of 20 minutes between the two tidal phases, this is a good result.

To compare spatial variations in the two current fields quantitatively, we have computed correlation and regression coefficients of differences within the two current fields on different length scales. For example, differences between pixels in the SRTM current field which are separated by 1 km were correlated with the corresponding differences between pixels in the KUSTWAD current field to obtain regression and correlation coefficients for variations on a length scale of 1 km. This analysis was performed for distances of 100 m (1 pixel length) to 10 km (100 pixel lengths) parallel and perpendicular to the look direction of SRTM. Results are shown in Fig. 7: They indicate that the correlation and regression coefficients are almost constant down to spatial scales on the order of 1 to 2 km, i.e. spatial scales on the order of the (spatially varying) resolution of the KUSTWAD model grid.

We conclude from these results that the SRTM configuration is basically capable of resolving all variations in the line-of-sight current component in the test area which are relevant to KUSTWAD. This is a quite surprising and encouraging result, since the SRTM configuration was purely designed for topographic mapping over land. To some experts, it did not appear to be suited for current measurements at all. We have access to some more SRTM images of ocean scenes which exhibit interesting signatures. We will try to analyze and publish these data in the near future in order to exploit the potential of SRTM for a demonstration of current measurements by along-track SAR interferometry from a spaceborne platform as much as possible.

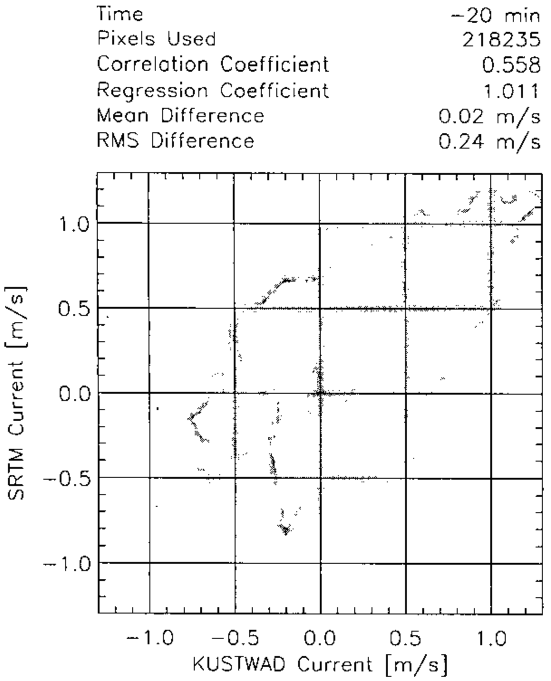


Fig. 6. Scatter diagram showing the distribution of SRTM-derived vs. KUSTWAD-derived current components in the SRTM look direction, as well as corresponding statistical quantities, for the tidal phase 20 minutes before the SRTM overpass.

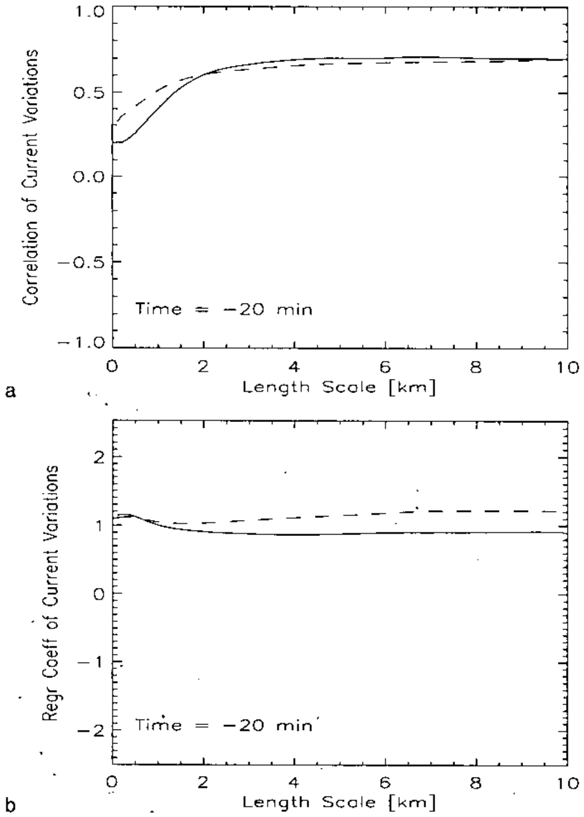


Fig. 7. Correlation (a) and regression coefficient (b) of variations in the SRTM and KUSTWAD currents at different spatial scales parallel (solid) and perpendicular (dashed) to the SRTM look direction.

III. THE TERRASAR-X MISSION

Fig. 8 shows an artist's view of the German satellite TerraSAR-X, which is scheduled for launch in late 2005. The X band (9.65 GHz) SAR antenna of TerraSAR-X can be electronically divided into two segments of 2.4 m length to obtain separate receiving antennas for fully polarimetric measurements and, experimentally, for along-track interferometry [9]. The effective along-track InSAR time lag will be 0.17 ms, i.e. 1/3 of the effective time lag of SRTM and only about 1/20 of the ideal InSAR time lag at X band (see section I). Accordingly, the sensitivity of TerraSAR-X to small current variations will be quite low. Furthermore, the normalized radar backscattering cross section (NRCS) of the ocean surface at low wind speeds can be below the relatively high instrument noise level of about −19 dB. However, TerraSAR-X will have a relatively high single-look resolution of 3 m × 3 m in stripmap imaging mode (swath width: 30 km), which permits averaging over many pixels to reduce noise at reasonable spatial resolutions. We will show by an analysis of simulated data products that the current measuring capabilities of TerraSAR-X in split antenna mode will be similar to the ones of SRTM in the "Waddenzee" test case discussed in section II.

The conventional and interferometric SAR imaging of ocean scenes can be simulated by the numerical model suite M4S of the University of Hamburg [5]. Starting from an input current field and mean wind vector, M4S computes the spatially varying surface wave spectrum in the test area, converts the mean current and wave spectrum at each grid point into a Doppler spectrum, and maps the contributions to the backscattered signal with different Doppler shifts to the appropriate pixels in the SAR / InSAR intensity and phase images according to SAR / InSAR imaging theory. Also the characteristic noise statistics for given instrument and data processing parameters and for the computed NRCS of the ocean and coherence of the backscattered signal can be simulated to obtain realistic realizations of intensity and phase images as they would be obtained from a real SAR / InSAR.

For a model validation and for a comparison of the current measuring capabilities of TerraSAR-X and SRTM, we have carried out simulation runs for the scenario of the SRTM overpass of the "Waddenzee", using the current field from the KUSTWAD model in combination with a realistic wind speed of 5 m/s from west and instrument parameter settings of SRTM and of various modes of TerraSAR-X.

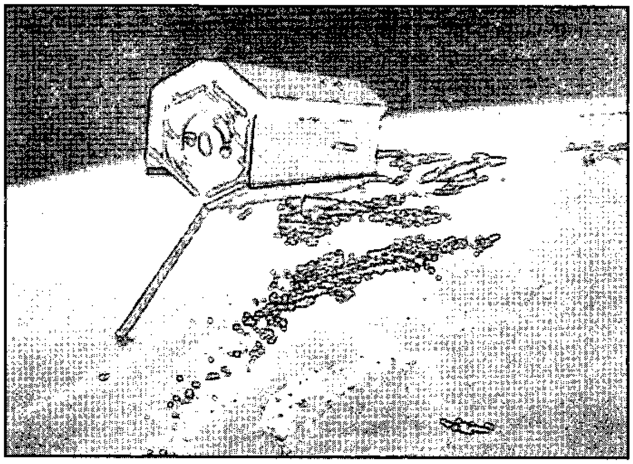
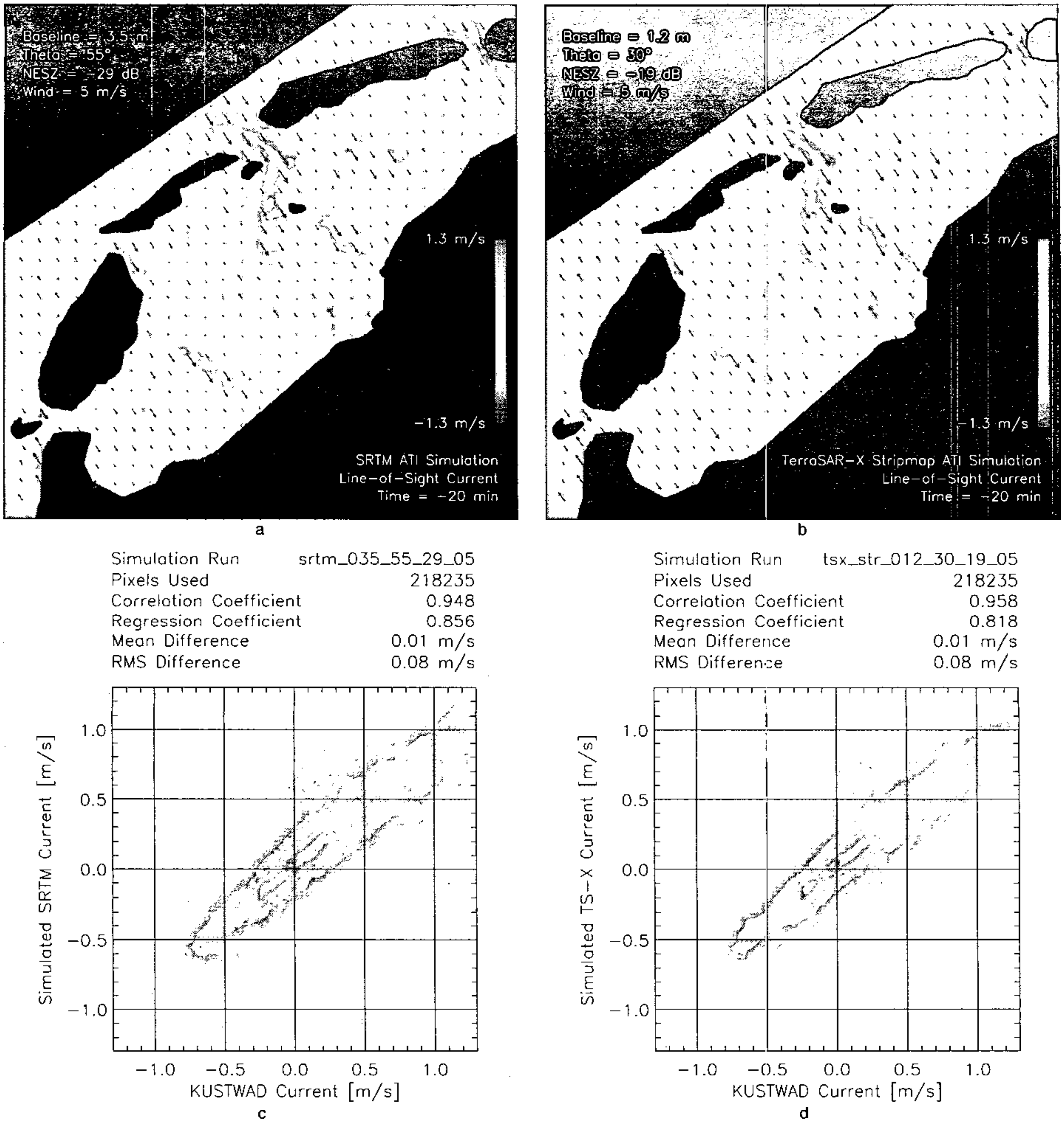


Fig. 8. Artist's view of TerraSAR-X (from Astrium website). The SAR antenna is the light gray panel facing downward; it is 4.8 m long.

Fig. 9a shows a simulated SRTM-derived current field, which was obtained by processing a simulated SRTM phase image with realistic noise statistics with the same methods that had been applied to the actual SRTM data to obtain the current field of Fig. 3. Fig. 9b shows a simulated TerraSAR-X data product for the same scenario and (for comparability) the same swath. This simulated TerraSAR-X data product is very similar to the simulated SRTM data product. Results of a statistical analysis are shown in Figs. 9c and 9d.

The agreement between the actual SRTM data product (Fig. 3) and the simulated one (Fig. 9a) is quite good, indicating that the M4S model produces realistic results. The correlation of both simulated data products with the KUSTWAD currents is much better than in the case of the actual SRTM data (Fig. 6). We believe that this can mainly be attributed to differences between the KUSTWAD current field and the actual current field at the time of the SRTM overpass, which have not been taken into account in our simulations.



a

b

Simulation Run	srtm_035_55_29_05
Pixels Used	218235
Correlation Coefficient	0.948
Regression Coefficient	0.856
Mean Difference	0.01 m/s
RMS Difference	0.08 m/s

Simulation Run	tsx_str_012_30_19_05
Pixels Used	218235
Correlation Coefficient	0.958
Regression Coefficient	0.818
Mean Difference	0.01 m/s
RMS Difference	0.08 m/s

c

d

Fig. 9. Simulated InSAR-derived line-of-sight current fields for the SRTM swath in the "Waddenzee" scenario and statistical diagrams; (a) SRTM simulation result; (b) TerraSAR-X stripmap mode simulation result; (c) distribution of SRTM simulation results vs. KUSTWAD currents and statistical parameters; (d) distribution of TerraSAR-X simulation results vs. KUSTWAD currents and statistical parameters.

Aside from this systematic difference between the actual SRTM data product and the simulated data products, we note a slightly better correlation between the simulated TerraSAR-X-derived currents and the KUSTWAD currents than between the simulated SRTM-derived currents and the KUSTWAD currents. This indicates that TerraSAR-X in split antenna stripmap mode will be capable of providing current measurements at a quality similar to the quality of the SRTM result which has been shown to be quite reasonable in section II.

Finally, we would like to discuss possibilities to obtain two-dimensional current fields from TerraSAR-X. The restriction to one-dimensional current measurements in the line-of-sight direction can be a serious shortcoming, since many applications require the knowledge of fully two-dimensional surface current fields. In areas like the Waddenzee one can try to derive the missing current component from the measured one and the known bottom topography, using a high-resolution model such as KUSTWAD. In the general case this will not always be possible. However, one can combine currents measured during ascending and descending overpasses of a test area statistically to obtain, for example, mean two-dimensional current fields for different tidal phases.

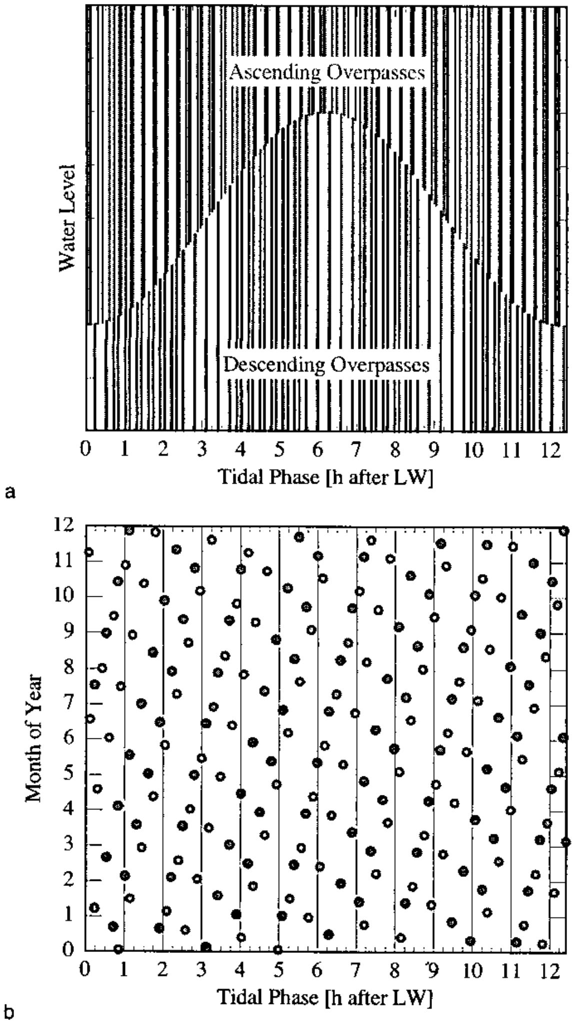


Fig. 10. Coverage of the tidal cycle in the Waddenzee by ascending and descending TerraSAR-X overpasses within a period of one year; (a) total coverage; (b) coverage at different times of the year.

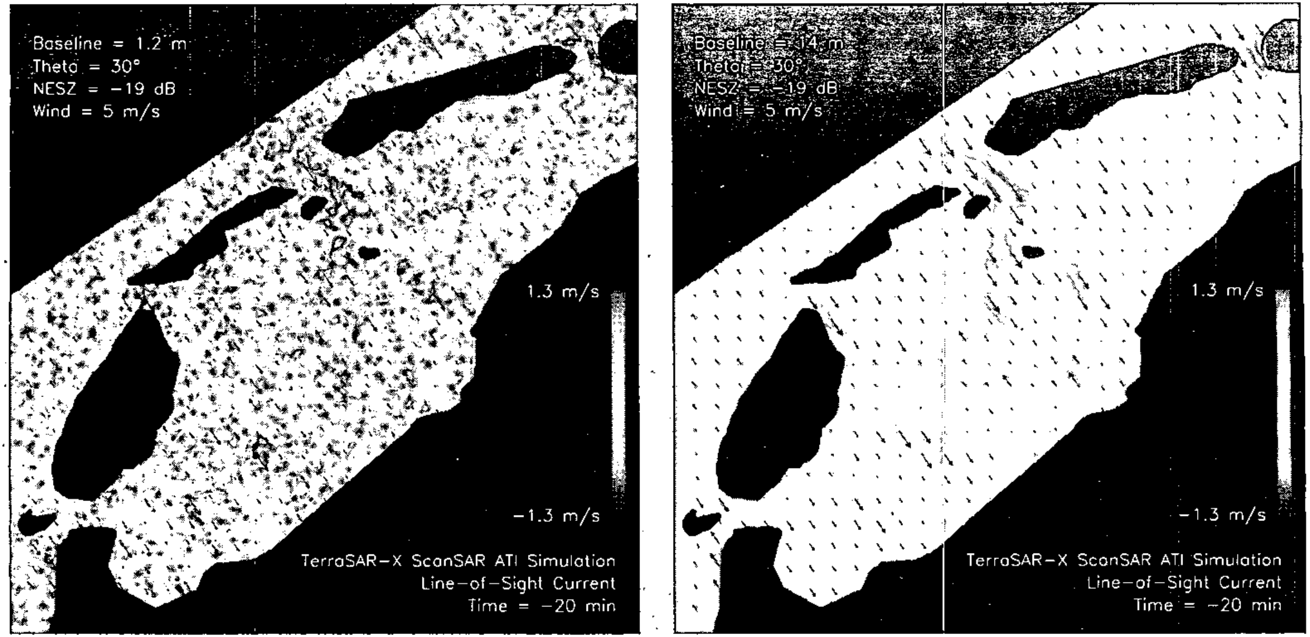
In the Waddenzee area, there will be three ascending and three descending overpasses within one 11-day repeat cycle of TerraSAR-X. Fig. 10a shows the corresponding sampling of the tidal cycle which can be obtained within a period of one year. The coverage of the tidal cycle is quite dense and uniform. It should be possible to obtain good estimates of the mean two-dimensional current field for each hour of the tidal cycle from such data. To avoid an aliasing of seasonal effects such as, for example, a dominant sampling of flood currents during winter and of ebb currents during summer, also the seasonal coverage of the data at different tidal phases should be as uniform as possible. Fig. 10b shows that this will be satisfied. TerraSAR-X data can thus be used, for example, for the generation of current atlases for coastal areas of interest, showing two-dimensional current fields for different tidal phases at spatial resolutions on the order of 1 km

IV. FUTURE DEVELOPMENTS

The along-track InSAR capability of TerraSAR-X in split antenna mode is a low-cost add-on to a conventional spaceborne SAR mission, which should be considered as an experimental mode. It will be useful for a demonstration of the technique, but the short antenna separation and the high instrument noise lead to a relatively low sensitivity. Furthermore, the capacities for data acquisition in split antenna mode will be quite limited. The full potential of along-track SAR interferometry from space can not be exploited with such systems. However, we hope that the availability of InSAR-derived current fields from TerraSAR-X and results of some pilot studies on the basis of these data will trigger some interest in the oceanographic community and lead to a positive feedback between a growing demand for InSAR data for oceanic applications and an implementation of improved spaceborne InSAR systems. Designs for such future systems exist and can be implemented within timeframes of a few years.

A major improvement will result from an increase of the InSAR time lag, thus the along-track antenna separation. At X band it can be achieved by mounting one of the two antennas on a deployable boom. Results of ongoing feasibility studies indicate that a boom of up to about 28 m length could be installed on a TerraSAR-X follow-on satellite without major design changes. This would result in an effective time lag of 2 ms and a drastical reduction of the noise level of InSAR phase images. In stripmap mode (30 km swath width), spatial resolutions of measured current fields on the order of 100 m could be obtained. Alternatively, the ScanSAR mode of TerraSAR-X with a swath width of 100 km at a reduced pixel size could be used to measure current fields with a resolution of about 1 km and extended spatial coverage. In split antenna mode, the quality of the ScanSAR data would not be sufficient for current measurements at reasonable resolutions. The improvement of the data quality with an increased antenna separation is depicted in Fig. 11, which shows simulated InSAR-derived current fields in ScanSAR mode for the split antenna setup (Fig. 11a) and the boom setup (Fig. 11b).

At lower radar frequencies, where longer time lags are required (the ideal InSAR time lag is roughly proportional to the radar wavelength), a formation flight of two or more independent platforms would be more appropriate. An example of a proposed formation flight configuration is the "Interferometric Cartwheel" with three small "slave" satellites with receiving antennas following a conventional "master" satellite [10]. Such configurations are particularly attractive for certain land applications of SAR interferometry, but they can also be used for current measurements.



a b

Fig. 11. Simulated TerraSAR-X ScanSAR mode data products for the "Waddenzee" scenario; (a) split antenna configuration, effective time lag = 0.17 ms; (b) proposed dual antenna / boom configuration, effective time lag = 2 ms.

Finally, the problem of obtaining two-dimensional current measurements with a single overpass could be solved by using a dual-beam InSAR system with two different look directions, as discussed in [11]. However, this concept requires specific hardware components and data processing methods and is unlikely to be implemented on a spaceborne platform in the near future.

V. CONCLUSIONS

We have presented an overview of the principles, the potential, and the limitations of oceanic current measurements from space by along-track InSAR. A first demonstration of the feasibility of this technique could be performed with data from the SRTM mission. Despite unfavorable system parameters, the SRTM data resolve current variations off the Dutch coast down to scales on the order of 1 km, which is a quite good and encouraging result. Simulation results indicate that the German satellite TerraSAR-X, which will be launched in 2005, will offer similar current measuring capabilities. Further improvements can be obtained with increased along-track antenna separations. Various concepts of InSAR systems with an antenna on a deployable boom or several small satellites in a formation flight configuration have been proposed for this purpose and could be implemented within a few years.

At this stage of the development, the dissemination of the potential of spaceborne InSAR and an involvement of potential users of operational data products in upcoming projects are quite important. We hope that this paper makes a useful contribution to the promotion of this promising technique.

ACKNOWLEDGMENTS

We would like to thank our colleagues Karin de Jong and Jur Vogelzang from Rijkswaterstaat, The Hague / Delft, Netherlands, for providing the KUSTWAD current fields for this study and for the fruitful informal collaboration on this subject.

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