

A MirrorSAR-based single-pass dual-baseline SAR interferometer for the generation of very high quality DEMs

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Abstract

In this paper we demonstrate that a multistatic Synthetic Aperture Radar (SAR) system consisting of a single-pass dual-baseline interferometer is able to provide Digital Elevation Models (DEMs) with unprecedented quality in terms of resolution and vertical accuracy. Such topographic maps may reach the HRTI-4 standard, with 6 m independent posting and a point-to-point height accuracy of 0.8 m for a 90% confidence interval. Compared to the HRTI-3 DEM from TanDEM-X, this means an improvement by one order of magnitude if one considers both the better height accuracy and the improved spatial resolution.

The present paper provides an efficient and cost-effective implementation of the proposed single-pass dual-baseline SAR mission, based on the recently proposed MirrorSAR concept. It consists of a single transmit-only spacecraft, and three receive-only satellites. Interferometric performance figures are provided for future mission studies where the proposed MirrorSAR-based mission configuration has been employed and refined.

1 Introduction

Enhanced imaging capabilities, increased reliability and flexibility, and support of new scientific applications to understand the Earth dynamics are just some of the features required for next-generation Synthetic Aperture Radar (SAR) missions. In recent years, it has been understood that, in order to satisfy such requirements, it is necessary to move towards distributed SAR systems as a complement to very complex single-platform systems.

Multistatic SAR systems offer a number of advantages and several unique imaging opportunities that arise from the coherent combination of multi-angular scene observations [1]. The scientific and economic value of bistatic and multistatic SAR missions has been amply demonstrated by the German TanDEM-X mission [2], the first and only one bistatic single-pass SAR interferometer in space. Other missions have been proposed in the past like the interferometric Cartwheel concept [3]. In contrast to TanDEM-X, which features two fully capable almost identical SAR systems, the Cartwheel system would have consisted of a set of three formation flying receive-only spacecraft accompanying ENVISAT. Similarly to TanDEM-X, the mission proposal Tandem-L is designed for bistatic single-pass interferometry and repeat-pass coherence tomography [4]. Also, in the last years, SAR mission concepts such as SAOCOM-CS [7] and SESAME [5], proposing respectively one and two companion satellites as extensions to the L-band SAOCOM and the C-band Sentinel-1 missions, have been extensively investigated and supported by the scientific community. Thus it appears very clear the tendency for future SAR missions to deploy distributed SAR systems that own the great potential to enable new scientific applications, advancing the understanding of the intricate dynamics of the Earth system, as well as to demonstrate in space new technologies and imaging techniques.

However, a major challenge for the implementation of such advanced multistatic SAR systems is the cost that arises from the complexity, mass and power demands of the required hardware.

Nonetheless, the newly proposed MirrorSAR concept [8], [9], comprising spatially separated transmitter(s) and simpler and cheaper transponder-like passive receivers, paves the way to future cost-effective fractionated SAR missions.

A possible implementation of the MirrorSAR mission concept consists of a single-pass dual-baseline interferometer that exploits at least three passive receivers, among which two simultaneous baselines are available, and that follow a master transmit-only satellite. With such a SAR mission configuration, the primary product is an ultra-high resolution Digital Elevation Model (DEM), which can be generated thanks to single-pass dual-baseline across-track interferograms, thereby overcoming limitations of single-baseline interferometers like TanDEM-X that need multiple passes to acquire the necessary set of baselines.

In the current paper, first an overview of the general MirrorSAR system and then its implementation in the form of a single-pass dual-baseline interferometer are provided. Then, the expected interferometric performance is shown for some mission studies in which such a mission concept has been proposed. Finally, the unprecedented quality and resolution that can be achieved for global and local topographic products are shown.

2 The MirrorSAR Concept

The innovative MirrorSAR concept has been introduced in [8], and poses the basis for highly efficient and cost-effective fractionated SAR systems. As shown in **Figure 1**, it comprises spatially separated transmitter(s) and receivers. Each receiver satellite simply behaves like

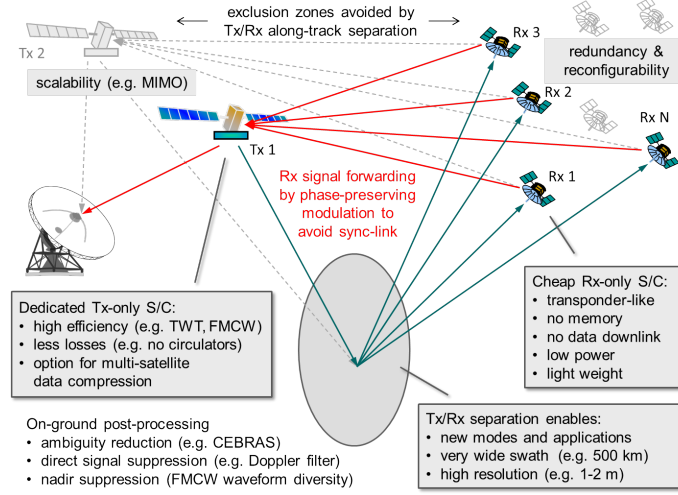


Figure 1: MirrorSAR mission concept consisting of mutually displaced transmitter(s) and passive receivers. The 'mirror-like' receivers simply route the radar echoes to the active transmitter(s): no sophisticated RF hardware, on-board memory and power-consuming downlink capabilities are required at the receivers' side.

a mirror, forwarding the backscattered radar signals towards the transmitter, where the radar echoes are coherently demodulated by using the same oscillator used for radar pulse generation. Given the simplification of the receivers, they do not need to be fully equipped: electronics for the down-conversion, digitizing and timing, on-board memory and downlink are not required. Consequently, weight and cost of the receivers are significantly reduced, allowing for system scalability and higher redundancy levels without cost explosion.

A further breakthrough feature of MirrorSAR is that a phase synchronization link between transmitter and receiver is not needed. Synchronization approaches that, without sacrificing the bistatic and interferometric performance keep the complexity of the MirrorSAR receivers low, are explained in more detail in [9].

A more extensive description of the overall MirrorSAR concept is also provided in [9].

3 Towards Higher Resolution and Higher Accuracy DEMs

3.1 DEM Standards

DEMs are nowadays broadly employed for many commercial and scientific applications but there is still a growing interest from numerous geoscience applications to get always higher quality information about the Earth's surface topography and topographic changes [2] - [6]. Mapping of topography and topographic changes over glaciers, ice caps and ice sheets to estimate changes in volume and mass, monitoring of subsidence and erosion caused by permafrost degradation as well as measuring of the displaced volume associated with landslides, volcanic eruptions, debris flow and mudflows are just some of the possible objectives of interest for the scientific communities [5],[6].

A topographic map is generated exploiting single-pass

across-track interferometry. As shown in **Figure 2**, a variety of air- and spaceborne sensors can provide DEMs. However, different sensors are characterized by specific coverage capabilities and quality of the provided topographic maps. For instance, airborne SAR systems are able to retrieve with very high resolution topographic maps, that are, however, limited to local or regional areas. In **Table 1** the defined standards for DEMs are listed together with the associated resolution and vertical accuracy. The Shuttle Radar Topography Mission (SRTM) was the first spaceborne topographic mission and met the DTED-2 specification. With TanDEM-X [2], the first global DEM has been obtained with a resolution and accuracy according to the HRTI-3 level. To satisfy such a standard requirement, the employed interferometric baselines corresponded to heights of ambiguity in the range of 30 m - 40 m. With ambiguous heights below 30 m it would be even possible to further improve the DEM performance. However, such a smaller height of ambiguity is likely to cause phase-unwrapping problems in the height retrieval. To avoid such difficulties, especially over difficult terrain on local or regional scale, multiple DEM acquisitions with a variety of different baseline lengths have been employed to facilitate phase unwrapping while still meeting the height accuracy requirements. Nonetheless, given the TanDEM-X acquisitions performed at different times, changes of the interferometric phase center due to variations in the environmental conditions or true topography changes have affected the interferometric phase and consequently complicate the final DEM product generation.

3.2 Improvements with Single-Pass Dual-Baseline Interferometer

The above mentioned limitations of single-baseline systems can be overcome by a single-pass dual-baseline interferometer. In this way three simultaneous acqui-

sitions are available and two interferograms can be generated out of them, where no decorrelation due to changes within the scene and environmental conditions affect their quality and mutual consistency. Furthermore, the availability of two baselines allows exploiting the large baseline to achieve global digital elevation models with unprecedented accuracy and resolution, according to the HRTI-4 standard, without facing phase unwrapping problems thanks to the small baseline, well suited to minimize the coherence loss from strong volume scatterers and to resolve phase ambiguities in the DEM generation process. A possible single-pass dual-baseline interferometric system based on the MirrorSAR concept is sketched in **Figure 3**. A dedicated illuminator is 10-20 km away from the constellation of receive-only satellites. Taking Rx_1 as a reference, the other two receivers fly with different baselines following an helix around the Tx_1 orbit. Let us assume Rx_2 flying with a large across-track baseline, approximately of 1 km with respect to Rx_1 , while Rx_3 is separated by Rx_1 of a smaller baseline, in the order of 150 m - 200 m. As it will be shown in the following, such a system is able to provide DEM products with excellent relative and absolute height accuracy.

Another possible approach could use two similar baselines, with the advantage of producing differential interferograms with large height of ambiguity for solving phase unwrapping and as well to improve the height accuracy [9].

	Spatial Resolution	Relative Vertical Accuracy
DTED-1	90 m x 90 m	< 20 m
DTED-2	30 m x 30 m	< 12 m
HRTI-3	12 m x 12 m	< 2 m
HRTI-4	6 m x 6 m	< 0.8 m
HRE-4	4 m x 4 m	< 2 m

Table 1: DEM standards: required spatial resolution and 90% point-to-point confidence level vertical accuracy

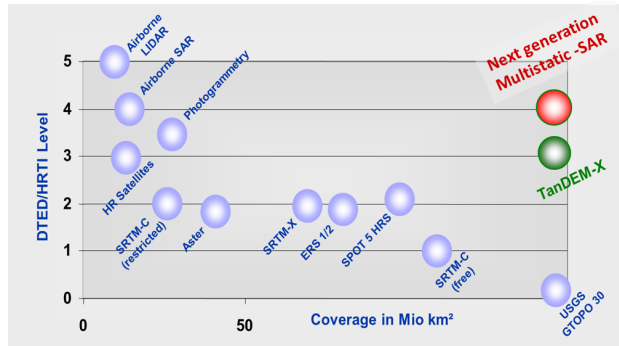


Figure 2: DEM standards of several sensor technologies, differing for height accuracy and coverage capabilities

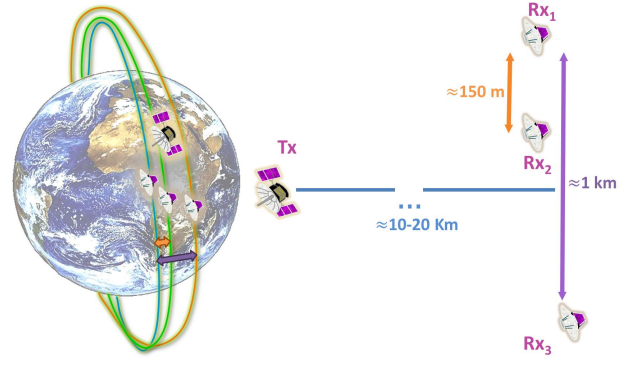


Figure 3: Satellites formation and baselines

3.3 Interferometric Performance Estimation

This section investigates the interferometric performance achievable with the proposed MirrorSAR single-pass dual-baseline interferometer, employed in the frame of different mission studies. The key factors influencing the interferometric performance are the coherence and the number of looks [10]. The total coherence γ_{tot} is the result of different contributions:

$$\gamma_{tot} = \gamma_{system} \cdot \gamma_{quant} \cdot \gamma_{rg} \cdot \gamma_{az} \cdot \gamma_{temp} \cdot \gamma_{vol} \quad (1)$$

where γ_{system} is the coherence loss due to the combined contribution of thermal noise and ambiguities, γ_{quant} is due to quantization, γ_{rg} and γ_{az} represent, respectively, the baseline and the relative Doppler spectra shift decorrelation, while γ_{vol} and γ_{temp} are, respectively, related to the volume and temporal decorrelation. The temporal decorrelation is negligible since the acquisitions are made in single-pass and the quantization coherence does not represent a limiting factor as it is larger than 0.98 when 4 bits are used for block-adaptive quantization. Furthermore, the relative spectral and Doppler shift are mitigated by common-band filtering and the main effect is the loss of resolution turning into a reduction of the number of independent looks. Concerning γ_{vol} , it has been neglected in a first analysis.

The interferometric phase error can be derived from the probability density function of the phase difference between the two interferometric SAR channels which is a function of the number of looks and of the coherence [13]. From the standard deviation of the interferometric phase σ_ϕ , the standard deviation of the height error σ_h can be easily computed from the relation:

$$\sigma_h = \frac{\sigma_\phi \cdot h_{amb}}{2\pi} \quad (2)$$

in which h_{amb} is the height of ambiguity, inversely proportional to the across-track baseline. Alternatively, the height error can be expressed as the 90% point-to-point confidence interval. In case of errors with independent Gaussian distributions, the 90% point-to-point height error Δh error may, for a large number of looks, be approximated by $\Delta h = 1.65 \cdot \sqrt{2} \cdot \sigma_h$, where the factor

1.65 (sigma) is due to the assumption of a Gaussian error distribution and $\sqrt{2}$ accounts for the two independent random variables and allows the conversion from single-point to point-to-point error.

4 DEM Performance Analysis for Future SAR Missions

4.1 IRIS

IRIS is a Ka-band multistatic SAR interferometric system proposal submitted in response to ESA's mission call for Earth Explorer 10 with the goal to measure static and dynamic topography, focused on the cryosphere [6].

The IRIS mission will consist of a 3 or 4 - Rx satellites flying a helix formation on a LEO sunsynchronous orbit with optimized baselines varying between several tens of meters and several hundred meters to fulfil the mission scientific objectives.

Thanks to the availability of two (or even three) baselines, the redundancy in the observation may be used for i) enhancing the sensitivity to topography by increasing the largest baseline, ii) enhancing the robustness to unwrapping errors by increasing the largest height of ambiguity, and iii) providing further observables for interferometric calibration. Furthermore, over some target areas (e.g., sea ice), IRIS will allow for the separation of topography and motion, yet with enhanced accuracy and robustness.

A dual/triangular-baseline IRIS allows for a robust recovery of topography, helps improve temporal sampling, performance, robustness, mission duration, upgrade and scalability and fully delivers the expected science. Last but not least, a multi-baseline IRIS offers the potential for experimental acquisition geometries targeting exploratory observations such as atmospheric sensing, model-based tomography (e.g., for agriculture, very dry snow, dry soil), or local ocean observations (e.g., 2-D Doppler Centroid anomalies).

The driving mission requirement for the system is to provide global coverage over land within 1 year, subject to spacecraft simplicity and instrument design to fit within the EE10 budget. A combination of 25 km swath and 6 minutes operation per orbit is considered suitable for the task. More specifically, a preliminary approach consists of covering the 25 km area by illuminating two separate sub-swaths of 12.5 km each, which can be achieved by appropriate mechanical pointing of the antenna radiators, at possible incidence angle of 30, 40, or 45 degrees. The preliminary timeline shows that we can cover with a repeat orbit of 14 days (using a orbit height of around 583 km) most of the cryosphere areas of interest in about 3 months, while still aiming for yearly global mapping. **Table 2** shows the preliminary IRIS system requirements.

IRIS will be able to provide extraordinary accurate and unique products such as (i) topographic maps with $100 \times 100 \text{ m}^2$ posting and better than 10 cm height accuracy over permafrost areas globally at yearly rates, over

mountain and outlet glaciers and ice caps twice a year, (ii) local maps of sea ice topography $5 \times 5 \text{ m}^2$ posting and better than 2 m height accuracy at weekly rates, (iii) a global DEM of the planet with $5 \times 5 \text{ m}^2$ and better than 1.85 m height accuracy at yearly rates.

4.2 EarthCon

The MirrorSAR concept as a dual-baseline cross-track interferometer with three receiver satellites and one dedicated transmitter has been proposed in the Earth-Con study. It was a Phase 0 study by the German Space Agency for future formations and constellations of miniaturized SAR satellites for new remote sensing applications. Thanks to the use of a FMCW illumination with a power of 500 W in X-band, and just by employing a single SAR mode with fixed incident angle of 40° for a swath width of 20 km, an excellent performance is achievable: one global DEM acquisition in less than 5 months and nearly bimonthly coverage of the Polar Regions with unprecedented resolution and accuracy. Such a system would benefit from a ground resolution of 1.5 m in both range and azimuth, a NESZ below -20 dB, as well as excellent range and azimuth ambiguity-to-signal ratio (better than -24 dB).

In **Figure 5** a comparison of the global performance achieved with TanDEM-X (top) and that expected for the new proposed mission concept (bottom) is shown. In both cases, the height errors are expressed as 90% point-to-point errors. When comparing the two systems it is possible to clearly observe the improvement of a factor approximately 10 between the TanDEM-X and the proposed EarthCon mission considering the relative height accuracy and the 2D geometric resolution. Indeed, with the proposed configuration for the EarthCon study, the DEM quality satisfies the HRTI-4 level with a posting of 6 m and point-to-point relative vertical accuracy better than 0.8 m which translates into a single-point height standard deviation better than 0.35 m. Such a performance, that can be even improved combining multiple acquisitions during the mission life, enables also highly accurate DEM differencing products, which are also of great interest for the scientific community. It is also worth stressing the unique global mapping capability of the proposed mission, achievable in less than 5 months, thanks to separation of Tx from Rx's. This, compared to the fact that the global DEM obtained with TanDEM-X has been generated after almost three years of mission, due to the necessity of passing multiple times over some more critical areas makes the final mission performance even more remarkable.

4.3 HRWS with 3 MirrorSAR Companions

Another ongoing mission, currently in the Phase A, is the planned German High-Resolution Wide-Swath (HRWS) X-band SAR mission. The mission concept is based on the monostatic satellite HRWS, operating in X-band with different acquisition modes and which also behaves as an illuminator for three passive companion satellites, with

Parameter	Value
Center Frequency	35.75 GHz
Resolution (az. and rg.)	1.5 m
Incident Angle	40°
Swath Width	25 km
Avg. Tx Power	620 W
NESZ	-17 dB
Orbit Height	583 km

Table 2: IRIS system requirements

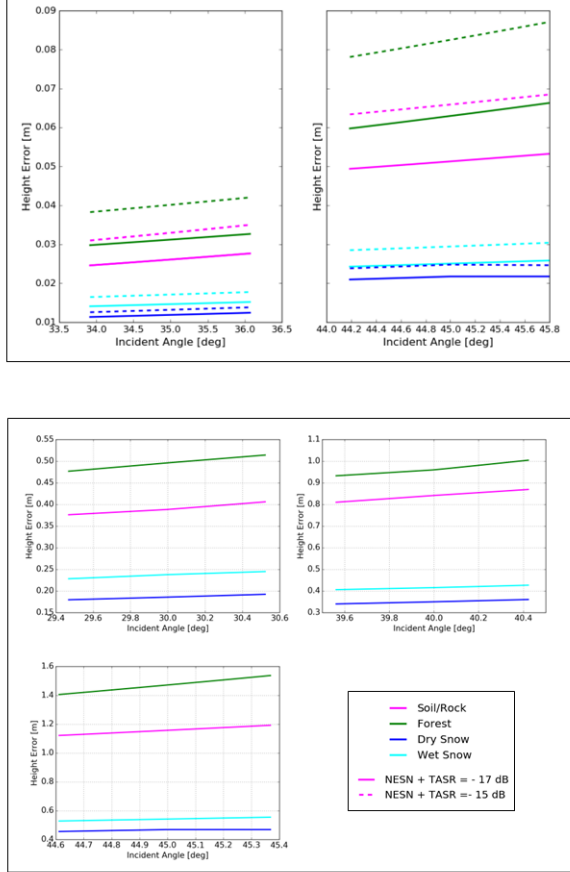


Figure 4: (Top) Height accuracy computed for the 12.5 km swaths at 35 and 45 deg incidence for 4 representative terrain types, two NESZ+TASR combinations, posting of $100 \times 100 \text{ m}^2$ and a perpendicular baseline of 400 m. (Bottom) DEM accuracy for the 12.5 km swaths at 30, 40, and 45 deg incidence and posting of $5 \times 5 \text{ m}^2$ and an NESZ of -17 dB.

the aim to generate high-resolution digital elevation models. The mission requirements focus more on regional and local DEMs while the global DEM is left as secondary mission objective, demanded with a posting of $4 \times 4 \text{ m}^2$.

The achievable performance is shown in **Figure 6**. The performance is expressed in terms of height accuracy within the HRWS (corresponding incidence angle vari-

ation on the x - axis). Furthermore the height accuracy is shown for all the possible latitudes within the grey band and the performance at latitude 0° and 80° are highlighted and shown respectively in red and green. This height accuracy is achievable in one single pass. The availability of multiple acquisitions enables improvement of the performance.

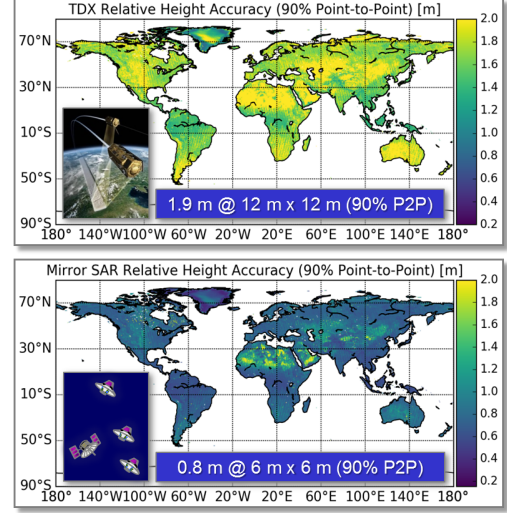


Figure 5: Global performance in terms of height error [m] achieved by TanDEM-X (top) and the proposed MirrorSAR single-pass dual-baseline system (bottom).

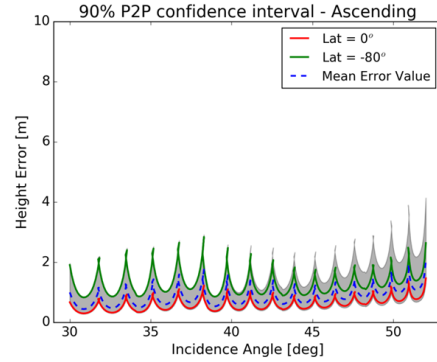


Figure 6: Local performance for a DEM posting of 4 m achievable by the HRWS and MirrorSAR companion mission

5 Conclusions

The high potential of a single-pass multi-baseline interferometric SAR system to acquire within a single global coverage an ultra-high quality DEM, according to the outstanding standards HRTI-4 or HRE-4, has been extensively demonstrated by means of the interferometric performance predictions for the considered Ka- and X-band systems. The simultaneous availability of two different baselines provides a very high accuracy and simplifies the phase unwrapping problem. A single-pass dual-baseline SAR mission can be employed in the future

in a very cost-effective way thanks to the exploitation of the MirrorSAR concept, which ensure the low cost and weight, redundancy and reconfigurability of the mission.

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