MirrorSAR: A Fractionated Space Transponder Concept for the Implementation of Low-Cost Multistatic SAR Missions

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Abstract

This paper introduces a new fractionated radar concept that offers the potential to significantly reduce the costs of future multistatic SAR missions. The key idea is based on a radical simplification of the receiver satellites by limiting their main functionality to a kind of microwave mirror (or space transponder) which redirects the incoming radar echoes to one or more transmitters. There, the routed signals are coherently demodulated using the same local oscillator that was used before to generate the radar pulses. This MirrorSAR concept not only saves the hardware for coherent demodulation, data storage, downlink and digital control within the receiver satellite, but also avoids the need for a bidirectional phase synchronization link between the transmitter and receiver, as it is currently employed in TanDEM-X. As the requirements for the receiver satellites are significantly reduced in this approach, it becomes possible to use low-cost platforms such as those currently being developed in the NewSpace context and to scale their number without any cost explosion. This will ultimately pave the way for novel remote sensing applications like multi-baseline SAR interferometry and single-pass tomography.

1 Introduction

Multistatic SAR missions open the door to a new dimension of radar remote sensing [1], [2], [3]. One example is multibaseline cross-track interferometry for the generation of high-resolution digital elevation models with decimeter-level height accuracy. A second example is single-pass tomography for the three-dimensional imaging of semitransparent volume scatterers. Further examples are multiangular backscatter measurements for speckle reduction, improved scene characterization and super resolution. Multistatic SAR missions offer moreover promising perspectives for advanced vector deformation monitoring and 3-D velocity measurements of moving objects, the extraction of tropospheric water vapor and ionospheric delays in high turbulence as well as the retrieval of ocean surface currents and topography together with their short- and long-term evolution over time.

Despite these widespread opportunities, only one bistatic SAR system has yet been deployed in space. The main reason for this imbalance between opportunities and investment are the complexities and costs associated with bi- and multistatic SAR systems. Important cost drivers are the duplication of hardware for the reception, storage and downlink of radar data, the increased launch volume and mass for the deployment of multiple satellites, the necessity of additional hardware for accurate phase synchronization and the need of a high downlink capacity to transfer the radar data from multiple satellites to the ground. To tackle these challenges, we have developed the new SAR system concept MirrorSAR, which has the potential to significantly reduce the hardware and downlink requirements for future bi- and multistatic SAR missions [4].

2 The MirrorSAR Concept

The MirrorSAR system architecture comprises a set of spatially separate transmit and receive satellites, as shown in Figure 1. A key feature of MirrorSAR is the use of a fractionated SAR system approach where scene illumination and spatial sampling of the scattered radar wavefront are performed by distinct platforms. At the same time, MirrorSAR aims at a radical simplification of the receiver satellites. This is achieved by reducing their main functionality to a transponder-like routing of the radar echoes from the passive receivers to the active transmitter(s), as illustrated by red arrows in Figure 1. Since the receiving satellites act as mere space relays, they require neither fully equipped radar receivers (including their coherent down-conversion, digitizing and timing devices) nor expensive data storage and downlink systems. This radical simplification will in turn reduce their mass, power, accommodation and control demands, supporting the use of small low-cost platforms.

The decoupling between the Tx and Rx paths opens moreover the door for independent hardware optimization of both the high-power transmitter and the low-power receiver. The receiver design may, for example, benefit from the opportunity of a stable thermal environment without heating from the transmitter amplifier. A constant low temperature is in turn well suited to ensure a low noise figure in the receiver front-end, together with stable operating conditions without phase and amplitude drifts. The transmitter design may, on the other hand, benefit from the opportunity of using longer transmit pulses or even a frequency modulated continuous wave (FMCW) illumination, which reduces the peak power requirements

ISBN 978-3-8007-4636-1 / ISSN 2197-4403

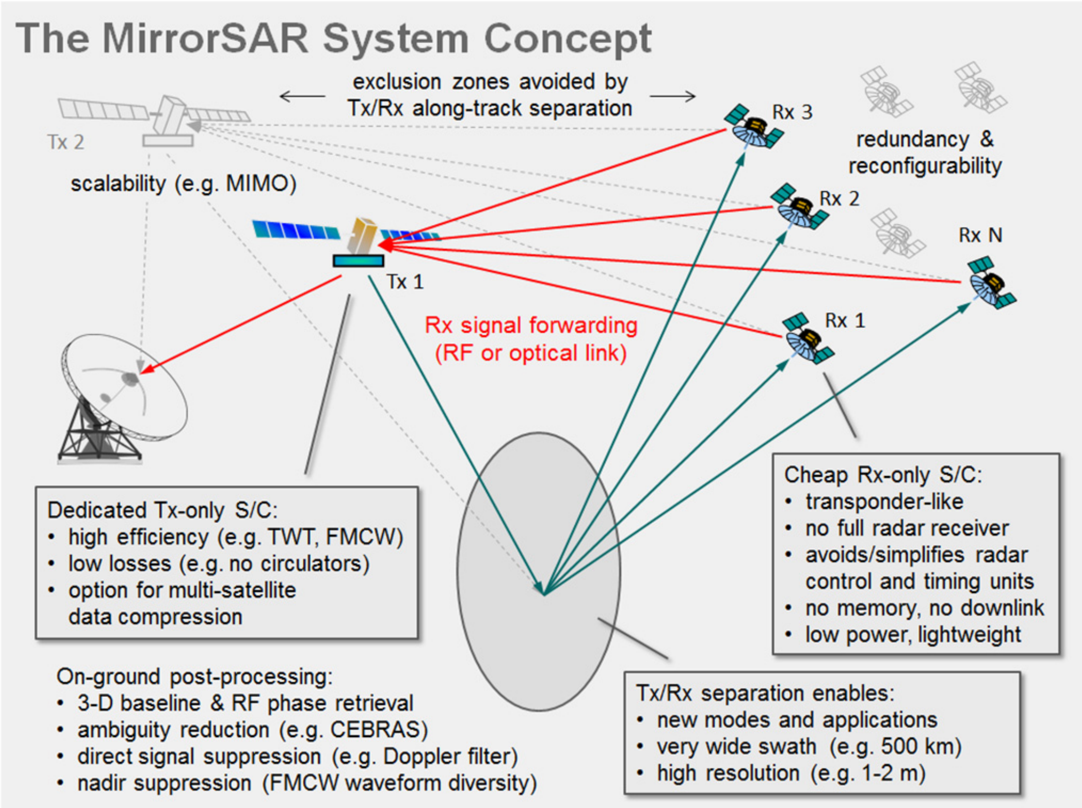


Figure 1: Illustration of the MirrorSAR concept. The scene is illuminated by one or more transmitter satellites. The scattered radar waves are then spatially sampled by multiple receivers that route their recorded signals to the transmitter. The transmitter satellite in turn coherently demodulates and combines the multiple forwarded signals, before the relevant information is transferred to the ground.

and thus has the potential to significantly simplify the high-power amplifier and its associated power supply chain. Moreover, hardware such as switches, circulators and limiters, which are typically required for amplifier protection and Tx/Rx signal isolation, can be avoided together with their associated losses.

MirrorSAR can hence be regarded as a promising technique for the implementation of affordable yet high-performance multistatic SAR missions, benefiting from the growing number of small low-cost platforms that are becoming increasingly available through numerous NewSpace initiatives.

Several additional opportunities make such a configuration even more attractive for future developments. First, the separation between the transmitter and receiver satellites enables a new approach to image ultra-wide swaths with very high resolution, thereby overcoming an inherent limitation of conventional monostatic SAR systems [5]. Second, the system capabilities can be scaled by adding multiple transmitters, which pave the way for the implementation of powerful MIMO-SAR modes. Last but not least, the joint availability of all receiver signals in a centralized node offers new opportunities for efficient data compression, as the multistatic radar signals from close satellite formations are typically characterized by a high degree of mutual redundancy.

3 Synchronization Options

An important aspect of MirrorSAR is bistatic radar signal synchronization. A possible solution is a bidirectional space-to-space link as implemented in TanDEM-X, where the nominal SAR data acquisition is periodically interrupted and radar pulses are exchanged between the two satellites [6]. A joint processing of the recorded pulses then allows a posteriori a mutual phase referencing with an accuracy of 1-2° in X band, which corresponds to a time synchronization accuracy of better than 1 picosecond. The drawback of this solution is that it requires fully-equipped radar transmitters and receivers on each satellite together with their appropriate digital control, data storage and downlink units. In the following, several alternative synchronization options are considered to reduce the complexity of the MirrorSAR receivers without sacrificing bistatic and interferometric performance.

3.1 Phase-Preserving Radar Data Link

In its most simple configuration, the required phase stability might be achieved by limiting the receiver functionality to a mere amplification and re-radiation of the received RF signal (as performed in a classical transponder). This option has, however, the drawback

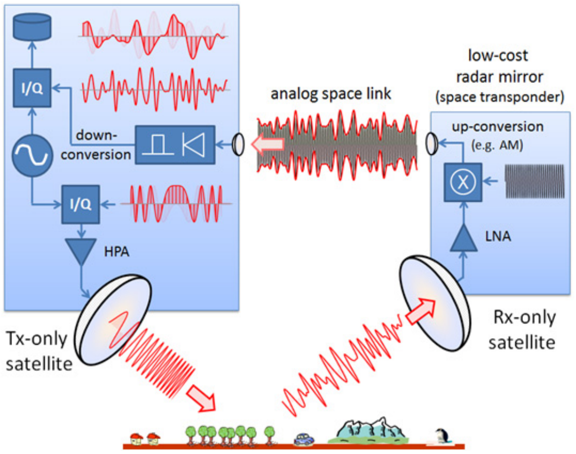


Figure 2: MirrorSAR employs a fractionated SAR approach where the high-power radar transmitter and the low-power radar echo receiver are accommodated on different platforms. The Rx satellite is considerably simplified by reducing its main functionality to a transponder-like routing of the radar signal. To preserve the phase integrity of the radar echo, an appropriate modulation is employed, as illustrated here for the case of amplitude modulation.

that the forwarded signal may be disturbed by the radar echo from the ground. A better solution, which moreover enables the forwarding of multiple channels from each receiver, as well as from multiple satellites, is the use of a modulation that preserves the phase of the routed radar signal and avoids any dependency on the (possibly random) phase of the modulation carrier. As an example, one may conceive that the receiver satellite generates for this purpose a high frequency signal (either microwave or optical carrier) that is amplitude modulated by the radar echo to be forwarded to the transmitter. As illustrated in Figure 2, a simple amplitude demodulation in the transmitter can then recover the time-delayed radar echo without phase disturbance from the high frequency carrier.[1] After this first-stage down-conversion, the routed radar signal is, in a second step, demodulated to baseband by using, e.g., a coherent I/Q demodulator that is driven by the local oscillator of the transmitter. As this oscillator has also been used to generate the transmitted radar pulse, possible frequency and phase drifts are cancelled as in a classical monostatic SAR. Radar echoes from multiple channels within each receiver, as well as from multiple receiver satellites, can then be routed without interference by employing multiple frequencies (or different wavelengths in case of an optical carrier).

An implicit assumption of this approach is that the distance between the transmitter and receiver satellites does not change abruptly and can be estimated with sufficient accuracy. The first assumption is justified by Newton's first law, while the required accuracy in the second assumption is to a large degree dictated by the specific application. If only bistatic SAR amplitude images are desired, coarse estimates of the relative position and velocity are sufficient [7]. Single-pass interferometry and tomography will, on the other hand, ask for accurate relative phases and therefore precise position estimates between the involved satellites. Such accurate position estimates are, however, anyway required to avoid phase offsets of comparable magnitude that would otherwise arise from baseline errors. Experience with TanDEM-X shows that a relative position estimation with an accuracy in the order of 1 mm can be achieved based on state-of-the-art GPS technology [3]. This accuracy would already limit the residual phase errors to approx. 1.5°, 6° and 12° in L-, C- and X-band, respectively. Note that these estimates refer to absolute phase offsets and the much more relevant short-time phase variations will be by at least one order of magnitude smaller than these values.

3.2 Double Mirror Synchronization

An alternative solution to achieve the required phase synchronization is illustrated in Figure 3. Here, an additional reference signal is transmitted from the Tx-only satellite towards the receiver by using a dedicated low-gain antenna. This reference signal may be either a copy of the transmitted radar pulse or a dedi-

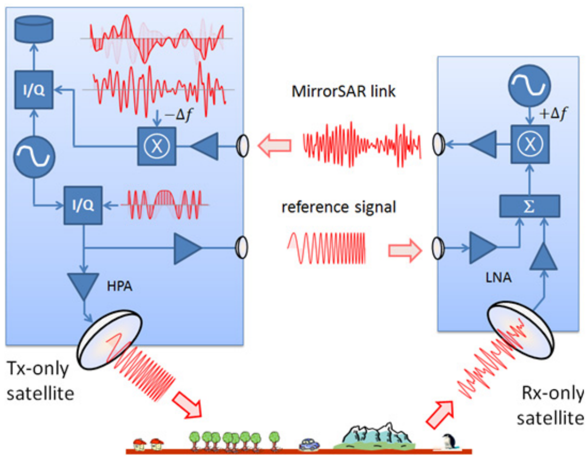


Figure 3: MirrorSAR synchronization by employing a double mirror approach where both the radar echo from the ground and a directly received reference signal are forwarded to the transmitter satellite. Phase errors introduced by the additional single-sideband modulation (+Δ*f*) and demodulation (-Δ*f*) are then compensated on ground by evaluating the superimposed reference signal.

[1] In an optical laser link, the modulation and demodulation can be performed by using a Mach-Zehnder modulator and a photodiode, respectively. This technique is already in widespread use for Radio over Fiber (RoF), where wide-band RF signals are transmitted over an optical fiber link. For MirrorSAR, the fibre would be replaced by a free-space laser link, where, in contrast to a space-to-ground link, the requirements regarding laser power and beam alignment are drastically reduced, as the separation between the Tx and Rx satellites is typically in the order of only 10 km and remains moreover nearly constant.

cated waveform that is coherently derived from the transmitter's ultra-stable oscillator. The signal is then received in the Rx-only satellite by a dedicated antenna[2] and superimposed on the recorded radar echo from the ground. As illustrated, the overlaid signals are jointly frequency shifted by $+\Delta f$ using a coherent mixer and radiated back to the transmitter, where the additional frequency shift is reversed before the signal is down-converted to baseband using the transmitter's local oscillator. The demodulated signal is finally digitized, stored in memory and transferred to the ground. The up-conversion by $+\Delta f$ and the independent down-conversion by $-\Delta f$ will, of course, introduce additional phase errors. These errors are, however, the same for the received radar echo from the ground and the mirrored reference signal. An evaluation of the reference signal enables therefore a compensation of these phase errors.

The synchronization processing requires a separation between the overlaid reference signal and the mirrored SAR data from the ground. For this, the data are first range-compressed and then transformed to the range-Doppler domain. As the distance between the Tx and Rx satellites is almost constant, the direct signal will be characterized by a strong peak close to zero Doppler and at a specific range. A narrow range-Doppler filter can then extract the reference signal with negligible disturbance from the SAR echo. On the other hand, the derived reference signal can also be coherently subtracted from the radar data before performing the SAR image processing.[3]

The double-mirror synchronization option of Figure 3 may be challenged by interference between the radar pulse transmitted to the ground and the much weaker signal transmitted directly to the receiver. As this interference could cause a distortion and phase shift of the reference signal, it is suggested to introduce an additional delay (e.g. via a delay line or, more simply, by a mere cable whose length exceeds the final range resolution). By this trick it becomes possible to mutually separate in the ground processing the unintended direct signal radiated from the main radar antenna and the desired reference signal transmitted via the dedicated space-to-space link. The same approach can be used in the receiver to decouple the reference signal received by its main antenna from the desired signal received by its dedicated space-to-space antenna.

[2] The synchronization and MirrorSAR space link antennas could, in principle, be combined in a single antenna by using a circulator.

[3] The subtraction creates a narrow gap in the Doppler spectrum for a specific range that has only a minor effect on the focused SAR image. If necessary, one could further reduce this impact by varying the PRI and/or the Tx waveform, which will distribute the same loss among multiple range cells. This technique has not only been suggested as a suitable means to suppress the direct signal in bistatic SAR systems, but recently also as promising technique to suppress the nadir echo in monostatic SAR images [8].

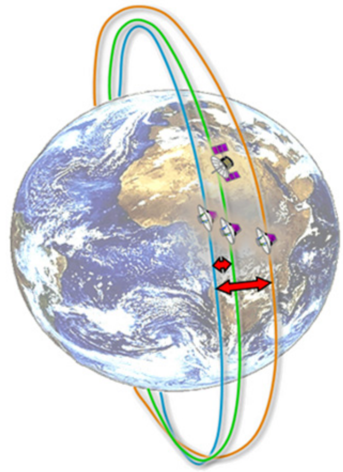


Figure 4: Dual-baseline MirrorSAR interferometer for generating highly accurate digital elevation models.

4 MirrorSAR Mission Examples

The MirrorSAR concept has been proposed, evaluated and refined in several mission studies, which are summarized in the following sections (see also [9]).

4.1 EarthCon

EarthCon was a Phase 0 study initiated and supported by the German Space Agency to analyze and develop innovative concepts for future formations and constellations of miniaturized SAR satellites serving novel remote sensing applications. In our search to reduce the costs of multistatic SAR missions by new and possibly disruptive technologies and techniques, we proposed the MirrorSAR concept as a promising means to lower the complexity of the receiving satellites by limiting their functionality to a minimum, namely the spatial sampling of the radar echo's wavefront and the forwarding of the associated radar signals towards the transmitting satellite.

As a first possible embodiment of MirrorSAR, we proposed a dual-baseline cross-track interferometer with three receiver satellites and one dedicated transmitter using 150 MHz FMCW illumination with a power of 500 W in X-Band (cf. Figure 4). Both the transmitter and the receiver satellites were equipped with deployable reflector antennas and, to keep the system as simple as possible, we employed only a single SAR mode with a fixed incident angle of 40° and a limited swath width of 20 km. This swath width is compatible with one global DEM acquisition in less than 5 months and a nearly bimonthly coverage of the Polar Regions. The chosen incident angle is moreover regarded as a good compromise between SNR maximization and layover/shadow minimization in view of the generation of a global digital elevation model (DEM) with unprecedented resolution and accuracy. A performance analysis revealed that such a system can achieve 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 ratios in combination with a 3 m reflector antenna that is illuminated by an appropriately designed single-channel feed (cf. Figure 5).[4]

Regarding DEM generation, such a MirrorSAR system is well suited to achieve a point-to-point height accuracy below 0.8 m for a 90% confidence interval and an independent posting of 6 m x 6 m. If compared to the specification of the WorldDEM of TanDEM-X, this corresponds to an improvement by a factor of 10, if one considers the product of the height accuracy and the spatial resolutions. To achieve such a performance, the height of ambiguity has to be in the order of 20 m, which corresponds to a perpendicular baseline of approximately 700 m. Note that this baseline length is still less than 5% of the critical baseline for the chosen bandwidth of 150 MHz. To avoid problems with phase unwrapping, we suggested a dual-baseline satellite formation with three receiver satellites that fly in a triple Helix configuration similar to the trinodal pendulum suggested in [2]. This configuration enables a fixed and optimized baseline ratio, thereby supporting stable phase unwrapping.

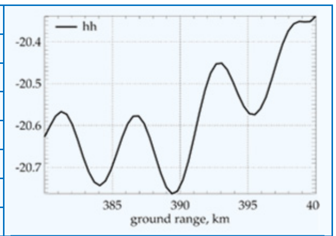
Two different approaches could be chosen to select the optimum baseline ratio (cf. Figure 6). The first and more straight-forward option is using a small and a large baseline with, for example, a baseline ratio of five or even larger. This choice has the advantage that the small baseline is also well suited to minimize the coherence loss from strong volume scatterers like tall forests [10]. The second option is to follow the dual-baseline phase unwrapping approach developed for TanDEM-X, where two single-pass interferograms acquired with similar baselines have been used to produce a differential interferogram with a large height of ambiguity [6], [11]. If transferred to the dual-baseline interferometer, this would imply the availability of a third and even larger baseline that could be used to improve the height accuracy. In any case, the simultaneous acquisition of multiple baselines avoids errors from temporal phase center variations and non-optimum baseline ratios that challenged phase-unwrapping in TanDEM-X [11].

4.2 MirrorSAR Companions to HRWS

Another embodiment of MirrorSAR, which builds up on the developments from the previous section, is based on the idea to add three MirrorSAR satellites to the planned German High-Resolution Wide-Swath (HRWS) X-band SAR mission. The aim is to acquire again high-resolution digital elevation data, and the corresponding mission proposal is currently in a Phase A study. The main difference to the dedicated

[4] This conservative performance calculation assumes a single fixed beam and an appropriately designed feed to provide a tapered illumination of the reflector. By using a receiver system with multiple beams or the frequency scan technique described in [12], the transmit power could even be reduced below 200 W while keeping the same NESZ.

Parameter	Value
Frequency	X-band
Orbit Height	500 km
Bandwidth	150 MHz
Swath Width	20 km
Incident Angle	40°
Reflector Size	3 m
Tx Power	500 W
Losses	5 dB
NESZ	< -20 dB
RASR	< -24 dB
AASR	< -25 dB
HoA Large B.	20 m
DEM Posting	6 m x 6 m
Height Accuracy	0.8 m (90% P2P)



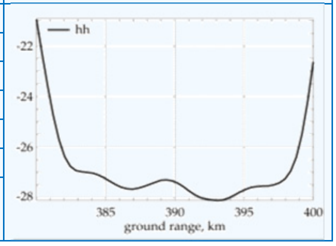


Figure 5: Performance of a MirrorSAR dual-baseline interferometer in X-band. Right column shows NESZ (top) and total ambiguity-to-signal ratio (bottom).

illuminator approach from EarthCon is the reuse of the multi-channel HRWS satellite for radar illumination. This approach has the following advantages:

- cost saving, as no dedicated transmitter satellite has to be developed and launched;
- only minor modifications are required for the HRWS satellite, as it is already equipped with powerful memory, downlink, and multichannel radar receiver hardware.

Disadvantages associated with this solution are:

- joint operation of two SAR missions with different objectives may cause conflicts;
- orbits for MirrorSAR companions are dictated by HRWS orbit. As HRWS is optimized for a short orbit repeat cycle, a wide range of incident angles has to be covered. This impacts DEM performance and complicates the MirrorSAR satellite design;
- global DEM acquisitions are challenged by the limited orbital duty cycle of HRWS.

The current implementation baseline for the MirrorSAR satellites foresees planar antennas with an aperture size of 3 m x 1 m. For the platform, a reuse of the OneWeb satellites is considered, which can provide dramatic cost savings from mass production.

4.3 IRIS

A third example is IRIS, which has been submitted in response to ESA's mission call for Earth Explorer 10 [13]. IRIS is dedicated to repeated high-resolution DEM acquisitions with special emphasis on the Polar Regions. To minimize penetration into ice, the short wavelength provided in Ka-band has been chosen. Challenges in close formation flight can be mitigated by using the aforementioned technique of synthesizing a small baseline interferogram from two large baseline acquisitions (cf. Figure 6). This option has the further advantage that an additional large baseline is available to improve the height accuracy.

ISBN 978-3-8007-4636-1 / ISSN 2197-4403

5 Discussion

In this paper, we presented the novel concept of a microwave mirror (or space transponder) for the implementation of future bistatic and multistatic SAR systems and missions. MirrorSAR employs a fractionated radar architecture that minimizes the complexity, weight and power demands of the receiver hardware. The drastically reduced payload requirements enable in turn the use of small low-cost platforms that were previously considered unsuitable for high-resolution radar remote sensing.

The new opportunities offered by MirrorSAR are of even higher interest, as the space sector is currently facing dramatic changes like the numerous initiatives launched under the heading of NewSpace. Prominent examples are the present developments of OneWeb and SpaceX to deploy megaconstellations of small satellites in low Earth orbit with the aim to bring internet to every corner of the globe, both at a competitive price and without the delays imposed by geostationary communication satellites. To this aim, automated serial production and new ways for satellite testing will be used to dramatically reduce the costs of each individual satellite to less than 1 M€.

In view of these developments, it is electrifying to think about using such NewSpace platforms also for SAR imaging. To preserve their tremendous cost advantages, it is, however, necessary to keep the required platform adaptations as small as possible. As the complexity of the proposed radar transponders is pretty low if compared to fully equipped companion SAR satellites, MirrorSAR can be considered as an enabling technology for high-resolution radar remote sensing to benefit from the ubiquitous developments of small low-cost platforms and the associated transformation of the space sector. If necessary, it would even be possible to further fractionate the multistatic SAR system by separating the radar transmitter from the radar demodulator, storage and downlink system. In a similar vein, one may also distribute the transmitter on two or even more platforms to become compatible with a dedicated low power platform [14].

An important aspect related to the use of such low-cost platforms is their reliability. For illustration, we may consider the dual-baseline interferometer from Section 4. Assuming a required reliability of 0.9 for the availability of all three receiver satellites, the reliability of each of them has to be as large as 0.97. This is a pretty high value, especially in view of many NewSpace programs. On the other hand, by deploying not only three but four receivers, the required reliability for each receiver can be reduced from 0.97 to 0.87 without losing the capability for dual-baseline interferometry. Taking into account the associated cost savings for each individual satellite, the latter option can ultimately become the more cost-effective solution. It also has the attractive side effect that a fourth satellite is available, which provides additional information about the scattered radar signal. This information can then be used either to improve the DEM accuracy by acquiring interferograms with even larger baselines or to demonstrate new modes such as layover resolution or even single-pass tomography.

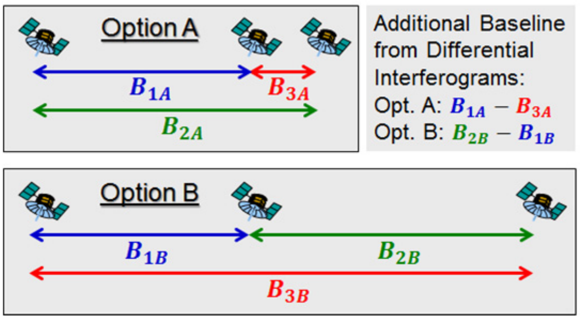


Figure 6: Comparison of two formation flying options for unambiguous DEM generation with small and large baselines. Phase unwrapping is supported in Option A by the short physical baseline B_{3A}, while it is performed in option B by following the TanDEM-X approach where a short baseline $B_{2B} - B_{1B}$ is synthesized from the differential interferogram between B_{2B} and B_{1B}.

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ISBN 978-3-8007-4636-1 / ISSN 2197-4403