Concepts and Applications of Multi-statitc MirrorSAR Systems

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***Abstract*—The paper describes the basic components of MirrorSAR and explains how bi- and multistatic SAR acquisitions are achieved by shifting only minimal functionality to the receive satellites. It shows that synchronization is not required or reduced in complexity by a MirrorLink. The MirrorLink forwards the ground reflected radar signal from the receiving satellites in a space transponder manner to the transmit satellite. Several options for the MirrorLink are discussed. In MirrorSAR, a number of satellites enable the acquisition of dual- or multi-baselines in a single-pass. The paper discusses several application examples where MirrorSAR eases the overall system complexity, the data acquisition and improves the SAR product quality. An interferometric SAR application example is discussed in more detail.**

Keywords—Synthetic Aperture Radar (SAR), MirrorSAR, Multiple Baselines, Synchronization, MirrorLink.

I. Introduction

As is generally the case in Earth observation, new Synthetic Aperture Radar (SAR) mission concepts increasingly involve swarms of satellites with fractionated functionalities. The most obvious division of a single SAR satellite's function is the separation into transmit and receive satellites.

Up to now, the synchronization of the local oscillators on-board the transmitting and receiving satellites has been an issue that is addressed, for example, by exchanging synchro-nization pulses before, after and between the radar signal pulses of the actual acquisition [2]. This introduces quite a high complexity. Additionally, radar pulses extracted from the synthetic aperture degrade in principle the signal quality.

Distributed SAR systems will have demand for a high bandwidth data exchange between the individual swarm or formation satellites. Optical Inter-Satellite-Links (ISL) can provide huge bandwidths that allow handling a network of many SAR satellites. As discussed in the paper, MirrorSAR proposes an analog optical ISL that eases synchronization issues at high bandwidth capacity.

In interferometric SAR and other SAR applications, the generation of data products requires often the acquisition of several baselines. For example in TanDEM-X [2], global acquisitions with two different baselines were carried out in a sequential manner. Formations of smaller SAR satellites allow the acquisition of multiple baselines in a single-pass. MirrorSAR is very well suited for this approach because it allows very simple and inexpensive receive satellites.

A first solution for a safe orbit concept that provides baselines along the orbit was demonstrated in TanDEM-X by the application of Helix orbits [8]. The example of a global Digital Elevation Model (DEM) acquisition by means of interferometric SAR is investigated in detail. SAR tomography, which is used, for example, for forest biomass estimation, will also be discussed in more detail. These examples are based on interlaced Helix orbits.

Section II provides an overview about MirrorSAR. Section III discusses the functionality of the receiving satellites that is reduced to space transponders only. Section IV presents several options for the MirrorLink. Section V provides MirrorSAR application examples.

II. MirrorSAR Mission Concept

MirrorSAR [1] is a multistatic SAR mission concept in which the radar receive antenna is relocated to a separate receive satellite (Rx), but the radar signal receive chain including down conversion, A/D conversion, mass storage and data downlink remains on the transmit satellite (Tx).

Fig. 1 illustrates the principal radar signal flow in a MirrorSAR formation with only one Tx and one Rx satellite. The Tx satellite emits the radar signal to the ground scene to be acquired. Due to the bistatic acquisition geometry, there is no reduction of the swath width caused by transmit interferences, e.g. [7]. The ground reflected radar echoes are received by the Rx satellite's radar antenna and forwarded to the Tx satellite via an analog MirrorLink that preserves the signal phase. On-board the Tx satellite the down conversion is performed using the identical oscillator that has been used for the radar signal generation. This principally overcomes the synchronization usually required in bi-static SAR systems. After digitization and mass storage, the acquired radar data are down linked to the ground station.

Another integral part of the MirrorSAR concept is the simultaneous acquisition of several Rx baselines. This enables, for example, highly accurate and robust SAR interferometry, e.g. [2]. Large and small baselines are available in one single-pass. Fig. 2 illustrates a MirrorSAR formation with one Tx and three Rx satellites. The Tx and one Rx satellite fly the same orbit with an along-track separation. The other two Rx satellites fly Helixes around the Tx orbit in close formation with the first Rx satellite. The Helix orbit concept has been demonstrated with two satellites in close formation by the TanDEM-X mission [2].

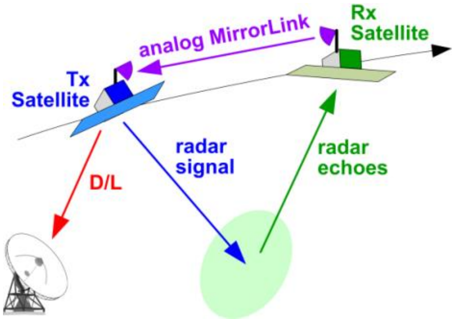

Fig. 1. MirrorSAR principle radar signal flow.

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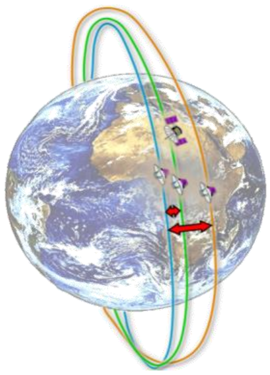

Fig. 2. Single-pass multiple baselines. MirrorSAR system example with one Tx and three Rx satellites that provide small and large baselines.

III. Rx Satellite as Space Transponder

Fig. 3 (a) provides a block diagram of a fully functional Rx satellite for bistatic SAR operation. Apart from the complete SAR receive chain from Rx SAR antenna to down link, a synchronization of the local oscillators (LO) of the Tx and Rx satellites is required. In the block diagram, the TanDEM-X synchronization approach is presumed that is based on synchronization pulse exchange. The Rx satellite receives the Tx pulses of the Tx satellite via a separate synchronization antenna, and the Rx satellite transmits synchronization pulses derived from its own LO that is used for down conversion towards the Tx satellite. As both satellites receive radar pulses based on the LOs of the other satellite, the oscillators' differential phase noise and frequency deviation can be compensated on-ground [3].

Fig. 3 (b) shows the block diagram for the space transponder like Rx satellite of the MirrorSAR mission concept with phase preserving MirrorLink. As is discussed in the next section, the radar signal echoes received from ground modulate the amplitude of an optical or a very high frequency radio signal. All the receiving chain including A/D-conversion is located on-board the Tx satellite. The simple and cheap construction of the Rx satellite is especially interesting as several Rx satellites are foreseen within the MirrorSAR formation in order to provide several single-pass baselines.

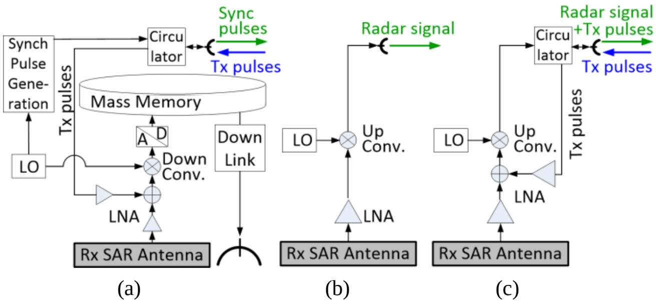

Fig. 3. (a) Fully funtional Rx satellite for bistatic SAR operation. (b) MirrorSAR Rx satellite with phase preserving MirrorLink. (c) MirrorSAR Rx satellite with non phase preserving MirrorLink.

In case that a phase preserving MirrorLink is not available due to cost or space qualification reasons, the Double MirrorLink [1] option is discussed in the next section. It is based on the reception of Tx pulses by the Rx satellite. Fig. 3 (c) shows the additional functionality on-board the Rx satellite that would be required in that case. The Tx pulses are added to the radar signal received from ground before up conversion to the carrier frequency of the MirrorLink.

IV. MirrorLink Possibilities

There are several possibilities to realize a MirrorLink. Depending on technological maturity or for cost reasons, one of the following variants may be the best choice. In principle, however, an optical link appears to be the technically best solution.

A direct transponder like solution that just forwards the received ground reflected signal after amplification on-board the Rx satellite to the Tx satellite needs to consider interferences with the radar pulses that are transmitted from the Tx satellite to the ground. This would eliminate one big advantage of the bistatic configuration, which is a larger swath width without this interference limitation.

A. Optical MirrorLink

An optical link provides the radar signal phase with potentially the highest data rate. One possibility to achieve a phase preserving high bandwidth link is to modulate the amplitude of the optical carrier by the radar signal [1]. The exact knowledge of the optical carrier frequency or phase is not required. This option is illustrated in Fig. 4 in its main Tx and Rx satellite MirrorLink functionalities. The function of the Rx satellite is only to receive the radar signal reflected from the ground, and to modulate it onto the optical carrier. The optical signal is sent to the Tx satellite, which means an analog space link for the radar signal. The Tx satellite detects the envelope of the optical signal and performs the down conversion into baseband using the local oscillator from the radar signal generation. Alternatively, it directly samples the signal in the radar frequency band using a coherent IQ demodulator as is shown in Fig. 4.

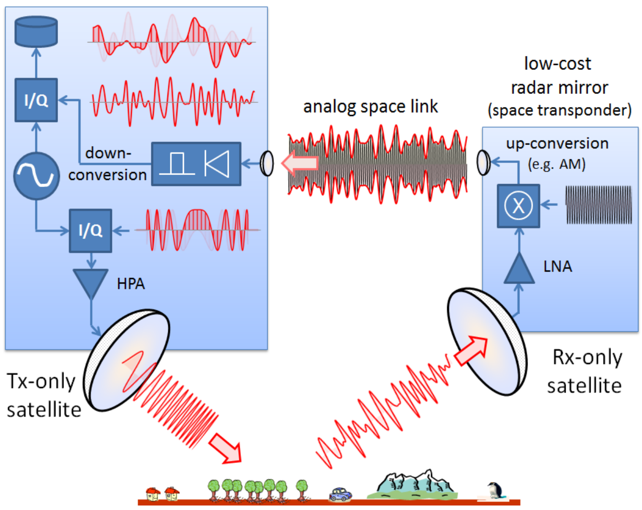

Fig. 4. Main functionalities of Tx and Rx satellites in case of availability of an optical MirrorLink. The function of the Rx satellite is only to receive the radar signal reflected from the ground, and modulates it onto a high-frequency carrier that allows to preserve the radar singal phase, e.g. an optical carrier. Amplitude modulation can be used.

B. High Radio Frequency MirrorLink

Instead of an optical carrier also a high radio frequency carrier can be used for the MirrorLink. The carrier frequency needs to be considerably higher than the radar frequency used. In this case, the exact knowledge of the high frequency carrier frequency or phase is also not required. Nevertheless the link is phase preserving because of the envelope detection.

C. Double-MirrorLink

It is also possible to use a moderately higher radio frequency for the MirrorLink that does not directly preserve the phase of the radar signal. In this case, an additional synchronization between the between the LOs used for up conversion on-board the Rx satellite and down conversion on-board the Tx-satellite is required.

A solution suitable for bistatic operation is the Double-MirrorLink [1]. In contrast to the approach used in TanDEM-X [2], where two fully equipped SAR satellites – both can operate as stand-alone SAR systems with radar signal transmission and reception – are mutually transmitting and receiving radar pulses, the Double-MirrorLink requires only the transmission of the radar pulses from the Tx to the Rx satellite. No transmit pulse generation is required on-board the Rx satellite. Fig. 5 illustrates the principal flow of the Tx pulses that are the synchronization signal.

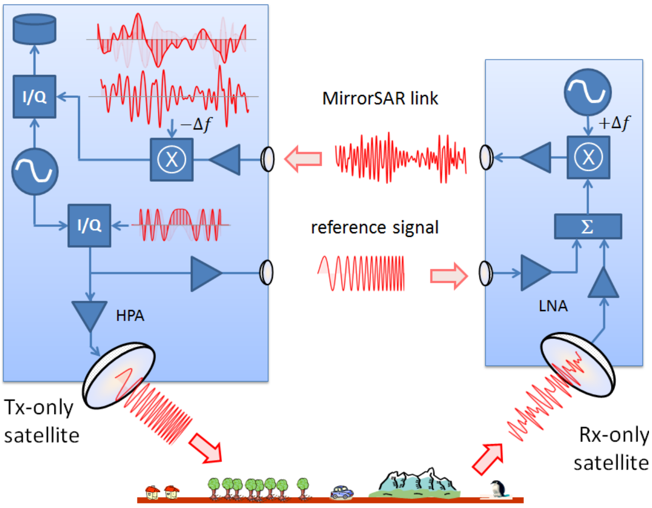

Fig. 5. Double-MirrorLink in its main functionalities of Tx and Rx satellites. It provides a synchronization of the local oscillators used for up and downconversion of the radar signal to the MirrorLink carrier frequency.

The Tx pulses are transmitted as reference signal from the Tx satellite towards the Rx satellite by means of a dedicated low-gain antenna. In Fig. 5, the reference signal is received from the Rx satellite by a dedicated antenna, too. In case that the frequency of the reference signal and the carrier frequency of the MirrorLink allow to use a combined antenna, the MirrorLink antennas on-board the Tx and the Rx satellites can be used for the reference signal transmission, too. As is shown in Fig. 3 (c) for the Rx satellite, circulators need to be added in that case to both satellites.

The reference signal is superimposed to the received ground reflected radar signal on-board the Rx satellite. The resulting signal is frequency shifted by a frequency Δf by means of a coherent mixer and sent back to the Tx satellite via the MirrorLink. There, the frequency shift Δf is reversed before the signal is down-converted; in the figure again by a coherent IQ demodulator. The frequency shifts introduce phase errors, but these are identical in the radar echo signal and the double mirrored reference signal. So the synchronization of the LOs used for the MirrorLink modulation and demodulation on-board the Rx and Tx satellites can be achieved.

V. MIRRORSAR APPLICATIONS

The fractionated concept of MirrorSAR with very little functionality on the Rx satellites and more functionality on the Tx satellite side, predestines this system for building up satellite formations with few Tx and many Rx satellites. An immediately obvious example is multi-baseline SAR interferometry as well as tomography. SAR interferometry is discussed in more detail as already a dedicated study was performed from DLR to investigate the possibilities of MirrorSAR for application in the HRWS mission [4], [6], [7]. Other mission concepts are discussed, too.

Special care needs to be given to the orbit formation concept. Apart from the minimization of the collision risk and providing the required geometrical baselines, the orbit concept needs to ensure the visibility of the MirrorLinks between the Rx satellites and the corresponding Tx satellite(s).

A. Multi-baseline SAR Inteferometry

The discussed MirrorSAR concept consists of HRWS as Tx satellite and 3 Rx satellites. It is illustrated in Fig. 6. The Tx satellite is on a TerraSAR-X orbit, and the 3 Rx satellites are 15 km ahead in along-track direction. The Tx satellite provides an antenna with 6 m length in azimuth and 1.4 m in elevation dimension. The Rx satellites antennas extend 3 m in azimuth and 1 m in elevation dimension. The Tx average power and bandwidth are 2.3 kW and 200 MHz, respectively. The desired global Digital Elevation Model (DEM) has a horizontal posting of 4 m in both azimuth and ground range dimensions. The global coverage is achieved by 12 swaths in elevation with 20 km swath width each. This covers the 240 km total access range that is required at an orbital altitude of 514 km.

An orbit concept was developed based on Helix orbits [8]. The 3 Rx satellites R_1, R_2 and R_3 fly interlaced Helix orbits around a virtual R_0 satellite that is on the Tx satellite orbit but 15 km ahead of it. In order to minimize the beam width of the MirrorLink antennas in the presence of an attitude steering law that is required for Doppler centroid minimization, e.g. [5], it was found to be advantageous that all the Rx satellites should always fly on the same side of the Tx orbits' orbital plane, i.e. always have the same sign in their cross-track baseline w.r.t. R_0 [7]. The resulting orbit concept that provides the required baselines between the Rx satellites is given in Fig. 7 in Earth-fixed geometry.

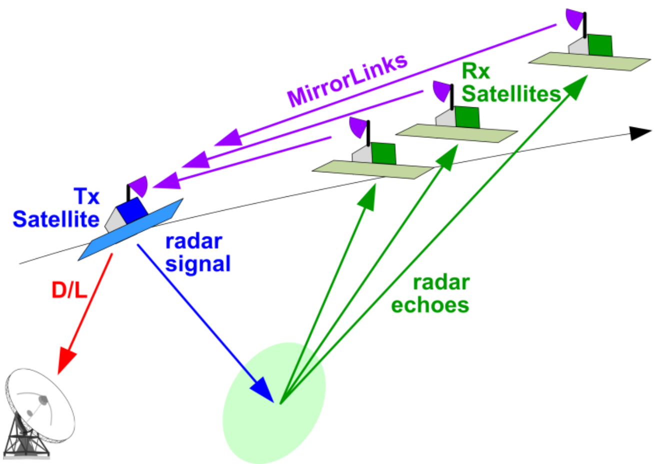

Fig. 6. MirrorSAR configuration with HRWS as Tx satellite and three small Rx satellites for the acquisition of a global DEM.

Fig. 7 shows on the left hand side the Rx baselines between R_0 on the reference orbit and R_1, R_2 and R_3 on the Helix orbits. The orbit geometry is defined by the maximum values of along-track, cross-track and radial Rx baselines that are indicated by the horizontal lines in the plot. After conversion into Earth-fixed geometry, the cross-track baselines show a small bias that cannot be compensated [7]. From the Rx baselines to the virtual satellite Rx_0, the available interferometric baselines can be derived. Fig. 7 shows on the right side the smallest baseline between R_1 and R_2 and the largest baseline between R_1 and R_3.

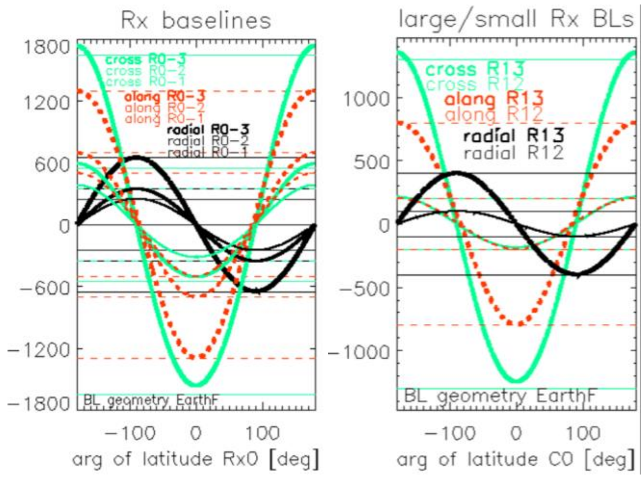

Fig. 7. (left) Baselines in [m] of the Rx satellites w.r.t. the virtual satellite position R_0. These along-track, cross-track and radial baselines describe the Helix orbits in Earth-fixed geometry. (right) The resulting smallest and largest baselines in [m] between R1 and R2, and between R1 and R3, respectively.

Fig. 8 shows the resulting height error across the 240 km total access range, expressed in incidence angles from 30° to 48.8°, and as a function of target area latitude. The height error is a 90% point-to-point error [2]. The height performance derives from the larger baseline R_{13}. The smaller baseline is required to assure the quality of the interferometric phase unwrapping. For example, in the TanDEM-X mission two complete global acquisitions with different baselines were required to achieve the height performance of better 2 m at a posting of 12 m x 12 m. The MirrorSAR concept discussed in this section provides at least the same height performance at a posting of only 4 m x 4 m.

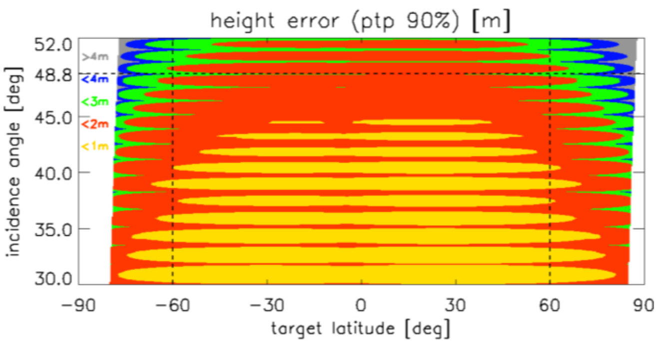

Fig. 8. Height error derived from large R_{13} baseline.

B. SAR Tomography

The application SAR tomography provides a 3D reconstruction of the individual scatterer distribution. It can resolve the vertical structure of semi-transparent media, for example ice covered surfaces or forest canopies. The layover problem in urban areas can be tackled. In SAR tomography a complementary SAR aperture is created by combination of several acquisitions taken from different passes with different altitudes that create different radial baselines.

Fig. 9 shows the resolution dimensions of a tomographic acquisition. The slant range resolution is defined by the range bandwidth and azimuth angle resolution by the azimuth aperture. The third dimension, the elevation resolution is given by the tomographic aperture that is created from several acquisitions that have radial baselines with respect to each other. The Helix orbit concept can be further developed to provide such radial baselines. In the figure, for a dedicated orbit position several satellites are shown with different along-track, cross-track and radial baselines. It should be kept in mind that the baseline lengths vary along the orbit. As it has been discussed above for multi-baseline interferometry, an interlaced Helix orbit concept allows for visibility of the MirrorLinks.

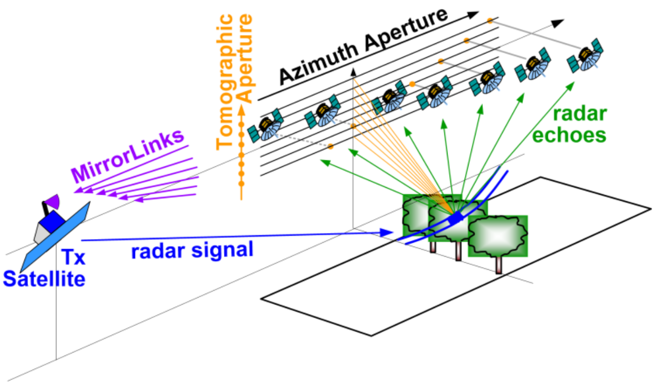

Fig. 9. Tomographic MirrorSAR. The two-dimensional resolution of SAR range delay and azimuth angle from the azimuth aperture is complemented by the tomographic angle from the tomographic aperture. A multi Helix oribt concept allows the visibility of the MirrorLinks in presence of several Rx satellites.

C. Floating SAR

Another possible application for the MirrorSAR approach is Floating SAR [9]. Floating SAR describes and combines several swarm satellites in the radial dimension in order to build up a distributed antenna in elevation composed of the small antennas of the individual swarm satellites. The name *Floating* is intended to indicate a constant variation in the satellites' relative position as all swarm satellites fly their own and different orbits. In the previous section for SAR tomography, also the radial dimension is required. Orbit concepts developed for one of these applications could also be useful for the other.

In [9], the example Floating SAR geometry of Fig. 10 was calculated. One Tx satellite with 8.5 m^2 antenna surface in combination with 20 Rx satellites, each with 0.8 m^2 antenna surface achieves a swath width of 50 km at an resolution of 1 m in X-band for an 514 km orbit.

From the 20 Rx satellites with varying radial separation, an equivalent elevation antenna is synthesized with 6.5 m antenna elevation height and a phase center separation of the individual satellites' antenna elements of 0.46 m. Applying on-ground SCORE, e.g. [10], provides the 50 km swath width at a resolution of 1 m.

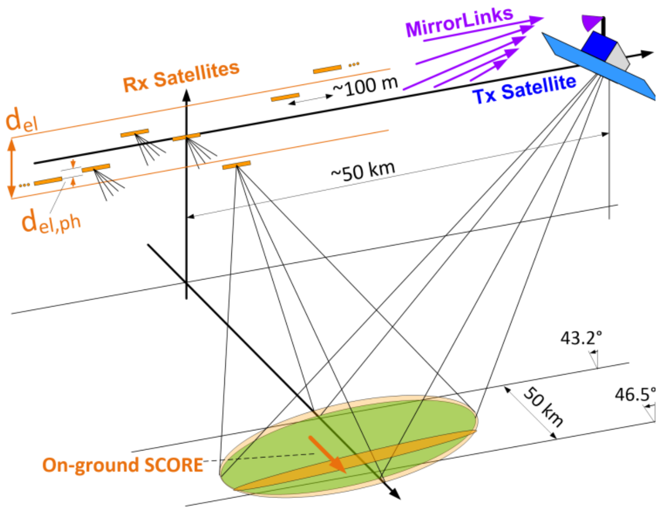

Fig. 10. Floating SAR example system applying MirrorSAR. From 20 Rx satellites with floating inter-satellite radial position, an equivalent Rx antenna is calcualted.

A first concept to provide the small radial distances between the individual Rx satellites in a save formation is to fly several Helix orbits around the reference orbit defined by the Tx satellite. Each Rx satellite flies a small radial and along-track Cartwheel ellipse [11] around a dedicated virtual satellite on the reference orbit. The dedicated virtual satellites of the different real Rx satellites have along-track distances of about 100 m to each other. This concept is illustrated in Fig. 11.

An additional cross-track component that is known from Pendulum orbits [8] completes the orbits in Fig. 10 and Fig. 11 to Helix orbits. In Fig. 9, the cross-track component is hinted. It is required for formation safety reasons and to ensure visibility for the MirrorLink.

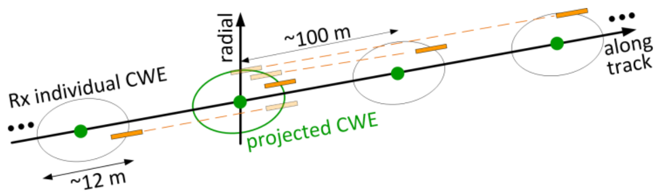

Fig. 11. Floating SAR example system applying MirrorSAR. From 20 Rx satellites with floating inter-satellite radial position, an equivalent Rx antenna is calcualted.

VI. Discussion

The paper discussed the two main components of the MirrorSAR concept. First, the shift of the SAR receive antenna to separate Rx satellites while keeping the digital SAR receive chain on-board the Tx satellite, and second, the single path multi-baseline concept.

The space transponder like function of the Rx satellites goes along with several advantages. The same local oscillator is used for the radar signal generation and for the radar signal demodulation. This overcomes or at least eases the synchronization usually required in bistatic SAR systems. At the same time, the advantage that in bistatic systems the transmit pulse interferences does not need to be included into the echo window timing is kept, which results in increased swath widths.

The single-pass multi-baseline approach reduces the acquisition time for large area interferometric or tomographic acquisitions and at the same time improves the DEM or tomogram qualtiy due to the non-existent temporal decorrelation between the individual data takes.

Several variants for the realization of the MirrorLink were discussed. The most favoured one is an optical link that is, e.g., amplitude modulated by the radar signal. This ensures a phase preserving MirrorLink without the need of additional synchronization means. However, if not available, another MirrorLink synchronization approach has been discussed that is advanced compared to TanDEM-X as the radar pulses need only to be transmitted unidirectional from the Tx to the Rx satellites.

For sure, SAR interferometry and SAR tomography are applications that profit to a great amout from the new MirrorSAR technique. An example related to interferometry has been discussed that improves the already high quality DEM of TanDEM-X by a factor of 9, i.e. improvement of both horizontal postings from 12 m down to 4 m. Among others, SAR tomography and Floating SAR greatly benefit from the MirrorSAR concept. Further research work needs to be invested in optical links for high bandwidth space-to-space data transmission, and into orbit concepts for many Rx satellites in close formaiton. For sure, Helix orbits are a good starting point.

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