Synchronization Signal Interference Analysis for Tandem-L

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Abstract

Tandem-L is a highly innovative mission concept with two radar satellites with reflector antennas to acquire data for Earth system science. The bi-static acquisitions require a synchronization of the satellites which will be ensured by exchanging radar pulses via synchronization antennas. The synchronization signal can additionally reach the SAR antenna. This paper analyzes the impact of the synchronization signal on the SAR antenna. Also, the SNR of the synchronization link is investigated to determine an acceptable trade between the synchronization SNR and low interference on the SAR antenna for different synchronization antenna orientations.

1 Introduction

Understanding the global dynamics of different Earth system processes in the geosphere, biosphere, cryosphere, and hydrosphere is of fundamental importance for various scientific research fields. Tandem-L is a proposal for a unique mission to monitor these processes on Earth in order to contribute to urgent questions in Earth system dynamics [1]. The mission is comprised of two L-band synthetic aperture radar (SAR) satellites (further called TL1 and TL2) flying in a close formation. Digital beam forming capabilities are implemented in the system to allow high-resolution wide-swath imaging. In addition, a reflector antenna is required and used to increase the coverage and the sensitivity of the system. Tandem-L products will, for example, provide global forest heights and structure maps and based on that, biomass estimates. Another utilization is the accurate monitoring of geologically active areas like volcanoes or seismic zones.

For certain products, e.g. forest height and the creation of a digital elevation model, bi-static acquisitions are needed. These require a synchronization of the local oscillators in the two satellites which will be ensured using additional synchronization signals exchanged via dedicated synchronization antennas. Due to the formation it is also likely that the signals from the synchronization antennas reach the SAR antenna (see **Figure 1**). Since the received SAR pulses are faint signals, a low noise amplifier (LNA) is needed in the receive chain. In order to protect this LNA from damage the SAR front-end is equipped with a limiter. Triggering this limiter would result in a loss of received SAR pulses and thus has to be avoided. Therefore, the power received by the SAR antenna transmitted by the synchronization antennas will be analyzed here.

Another important parameter to note is the signal-to-noise ratio (SNR) of the synchronization link, which determines the quality of the phase referencing during on-ground processing. The optimal case would be a **high SNR** between the synchronization antennas and at the same time a **low interference** on the SAR antenna caused by the synchronization signal. For an optimal trade between these two measures, different synchronization antenna orientations are investigated in the following.

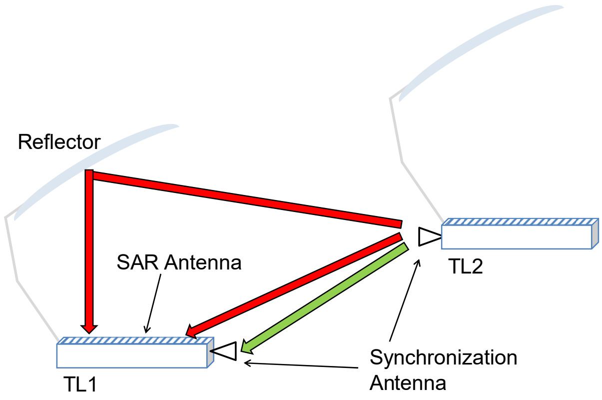

Figure 1 Schematic illustration of the Tandem-L system with possible paths for the synchronization antenna transmission. The green arrow shows the intentional path from one synchronization antenna (black triangle) to the other. The two red paths are potential paths from the synchronization antenna to the SAR antenna.

The paper gives a brief overview of the satellite system and the important components for the analysis in Section 2. In Section 3 the gain values used for the antennas and the calculation of the received power and the SNR are presented. In the subsequent Section 4 the corresponding results are shown. The final section includes a conclusion and the outlook for future work.

2 System Description

2.1 Coordinate System

This subsection is used to clarify the coordinate system for following plots and calculations. The used Cartesian coor-

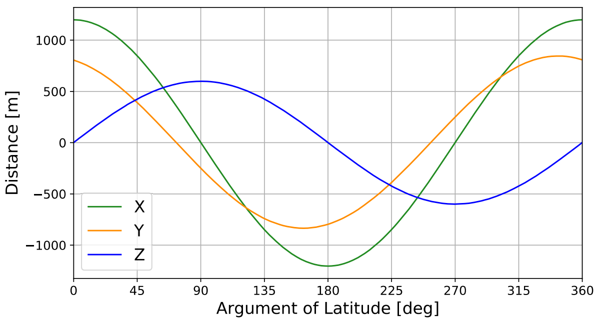

Figure 2 The relative position of TL2 as seen from TL1 in one example orbit with a horizontal baseline of about 850 m plotted in Cartesian coordinates.

dinate system is chosen to be satellite centered. TL1 is selected as the origin. The Z-axis is perpendicular to the SAR array and points away from Earth, the X-axis is in flight direction and the Y-axis completes a right-handed coordinate system. The resulting spherical coordinate system is oriented in the way that flight direction of TL1 corresponds to $\phi = 0°$ and $\theta = 90°$.

2.2 Flight Formation

The formation flown by the two satellites is assumed to be helix-like, similar to the TanDEM-X mission [2]. The helix can be described by a vertical baseline (B_{V}) and a horizontal baseline (B_{H}). The B_{V} has its maximum close to the Earth's poles and its minimum at the equator. The opposite is the case for the B_{H}. It will be varied in an interval from 0.8 km up to 19.9 km [3]. **Figure 2** shows the position of TL2 for one orbit around the Earth with a B_{H} of about 850 m in Cartesian coordinates. The argument of latitude (AoL) describes the position of the satellite system in relation to Earth starting at the equator. The northern and southern most points near the poles correspond to 90° and 270° AoL.

2.3 Instrument

A possible design of the SAR antenna consists of 35×3 (elevation×azimuth) patch element doublets [4]. These patches are driven by transmit/receive modules. In the receive chain there will be a LNA. To protect this LNA from too high received signal power a limiter will be placed in front of it. If the signal exceeds a threshold the limiter will trigger and interrupt the current flow towards the LNA. This would lead to a number of rejected pulses and needs to be avoided. For bi-static operation, a synchronization of the two satellites is needed [1]. To compensate for different oscillator phase drifts [5] during on-ground processing, the satellites will exchange radar pulses with each other. This will be achieved by additional small low-gain antennas on both satellites with a circular polarized signal. Six small antennas will be placed on each satellite in order to ensure an omni-directional coverage, as it is the case for the TanDEM-X mission [2].

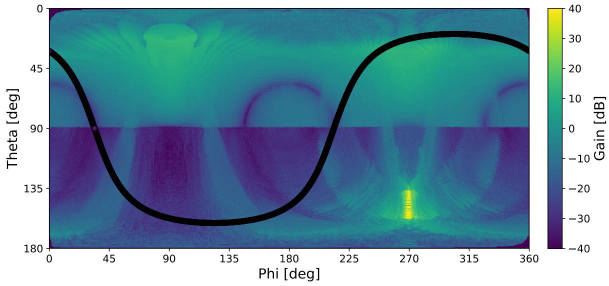

Figure 3 SAR antenna far-field gain envelope map. The clear difference between the upper ($\theta > 90°$) and lower ($\theta < 90°$) half of the plot is seen because the satellite body is shielding the radiation in the lower half. The high gain at $(\phi, \theta) = (270°, 135° - 160°)$ is the result of the reflector focusing the beams. The black line marks distinct positions of TL2 from one orbit as seen from TL1.

3 Methods

The goal of this study is on the one hand to check the level of the received signal power by the SAR antenna transmitted from the synchronization antennas. This signal path is further called *sync-SAR* (red arrows in Figure 1). On the other hand, the orientation of the synchronization antennas shall be optimized. For this purpose, it is important to look at the SNR between two synchronization antennas. This signal path is denoted as *sync-sync* (green arrow in Figure 1) in the following.

3.1 SAR Antenna Gain

To compute the received power for the path *sync-SAR* the SAR receive antenna gain is required in 3D. For this analysis, the three azimuth doublets of each elevation row are combined in an elevation patch-line. The far-field gain map for each elevation patch-line is evaluated on a sphere around the whole satellite including the reflector. Then the envelope is obtained by taking the maximum gain values among all 35 elevation patch-line gain maps for every point on the evaluation sphere. The resulting gain map of the whole SAR antenna is shown in **Figure 3**. The blockage of the satellite's corpus is the reason for the clear separation of the plot at $\theta = 90°$. The reflector's shadow is seen as darker areas in the upper part of the figure ($\theta < 40°$). The black line illustrates the position of TL2 for one orbit traveling around TL1 in spherical coordinates. It marks the gain values taken for the SAR antenna for this exemplary orbit. The remaining structures which can be seen in the plot are most probably caused by simulation artifacts and interferences.

3.2 Synchronization Antenna Gain

The gain map of the synchronization antennas, similar to the SAR antenna gain in Figure 3, is needed for both study goals. Several orientations of the synchronization antennas are analyzed. This is done in order to see which configurations will yield the best outcome in terms of a high SNR

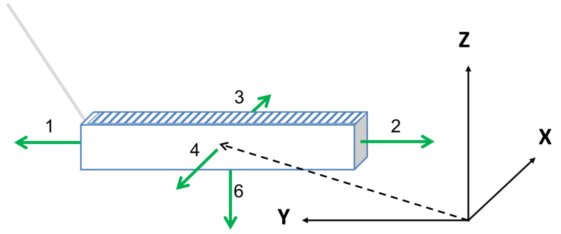

Figure 4 Schematic illustration of one possible orientation of the synchronization antennas, oriented along surface normals of a cube. The 5th antenna would be placed on top of the reflector because it should point in the opposite direction antenna 6. The dashed arrow shows the true origin of the coordinate system, which is shifted for clarity.

for *sync-sync* and still a low power received by the SAR antenna. One possible pointing of the antennas is to orient them along surface normals of a cube as shown in **Figure 4**. This case is further called *cube normals*. The second orientation is similar to the *cube normals* but the antennas are rotated by 45° around the Z-axis. The origin of the coordinate system is in the middle of the cube as illustrated in the figure. This configuration is called *cube rotated*. The third option is defined by evaluating the spherical angles (ϕ, θ) for all foreseen baselines (BLs), i.e. under which the satellites will see each other for all considered B_{H}. This is done because there are areas in the $\phi - \theta$ plane where TL2 is never seen by TL1. Based on that the pointing of each antenna is adjusted to cover the most prominent angles. This orientation is further called *formation based*.

From the pointing of an antenna, the off-boresight angle can be obtained. This angle is used to calculate the synchronization antenna gain by a polynomial function obtained for the TanDEM-X mission [5]. The resulting gain values are normalized with respect to an off-boresight angle of zero. Adding the maximum gain at boresight $g_{\max}$ from **Table 1** to the given value, returns the absolute gain of the synchronization antennas.

3.3 Power Calculation

The received power P_{rx} needs to be calculated for both study goals. It is calculated with the following equation:

$$P_{\mathrm{rx}} = \frac{P_{\mathrm{tx}} \cdot G_{\mathrm{tx}} \cdot G_{\mathrm{rx}} \cdot \lambda^2}{(4\pi)^3 \cdot r^2}, \tag{1}$$

where P_{tx} is the power of the transmitted pulses which for *sync-sync* and *sync-SAR* comes from the synchronization antenna. G_{tx} and G_{rx} are the gain values of the transmit and receive antenna. The wavelength of the transmitted signal is denoted by λ and r is the distance between the two antennas. To obtain G_{tx} the transmit losses L_{tx} need to be considered in the gain calculation described in the previous part (Section 3.2). For the *sync-sync* path G_{rx} is obtained similarly with the difference that the receive losses L_{rx} and also a polarization loss L_{pol}, which originates from the circular polarization of the transmitted wave, are added. All used values can be seen in Table 1. In the case of *sync-SAR* G_{rx} is extracted from the gain map shown in Figure 3.

Table 1 Parameters assumed for the analysis. The temperature T_{n} used for the noise density is the antenna noise temperature.

Parameter	Value
Wavelength λ	0.238 m
Gain at boresight $g_{\max}$	10 dBi
Output power P_{tx}	42 dBm
Transmit losses L_{tx}	-4 dB
Receive losses L_{rx}	-4 dB
Polarization loss L_{pol}	-3 dB
Pulse width τ	$15 \cdot 10^{-6}$ s
Noise figure NF_{rx}	3 dB
Noise density δ_{n} ($T_{\mathrm{n}} = 290$ K)	-174 dBm

The relative position of the two satellites determines which value to take from the whole map.

3.4 Signal-to-Noise Ratio

The synchronization system is required to accurately compensate the phase drift of the oscillators. Therefore, the SNR is only relevant for *sync-sync*. It can be calculated by dividing the signal power P_{s} by the noise power P_{n}. The pulse compression will lead to an additional gain for the signal power which can be determined by

$$P_{\mathrm{s}} = P_{\mathrm{rx}} \cdot \tau \cdot \Delta\omega, \tag{2}$$

where P_{rx} is the power of the signal without pulse compression obtained by (1), τ is the pulse width, and $\Delta\omega$ is the bandwidth. The noise power P_{n} is calculated by:

$$P_{\mathrm{n}} = \delta_{\mathrm{n}} \cdot \Delta\omega \cdot NF_{\mathrm{rx}}, \tag{3}$$

where δ_{n} is the noise density and NF_{rx} is the noise figure of the receiver. The SNR can then be calculated by the ratio of (2) and (3).

$$\mathrm{SNR} = \frac{P_{\mathrm{rx}} \cdot \tau}{\delta_{\mathrm{n}} \cdot NF_{\mathrm{rx}}} \tag{4}$$

The calculation of the received power (1) for *sync-SAR* and the SNR (4) for *sync-sync* is performed for all relative positions of the satellites during a sweep of the B_{H} from 0.8 km to 19.9 km.

4 Results

The SNR for the *sync-sync* path and the received power for the *sync-SAR* path are compared for the different orientations of the synchronization antennas. In **Table 2** one can see the three orientations described in Section 3.2 with the corresponding minimal SNR and maximal received power values calculated over the whole B_{H} interval.

The lowest SNR value is obtained for the largest distance between TL1 and TL2, because of their inverse dependency ($\mathrm{SNR} \propto {}^{1}/{}_{r^2}$). The biggest separation occurs in Y-direction. Only the *cube normal* orientation has antennas

Table 2 Comparison of the results of the minimal SNR for the *sync-sync* path and the maximal power received for the *sync-SAR* path.

Orientation	**Sync-Sync** SNR	**Sync-SAR** Received Power
Cube normal	52.9 dB	-2.76 dBm
Cube rotated	44.04 dB	-2.76 dBm
Formation based	42.41 dB	-3.41 dBm

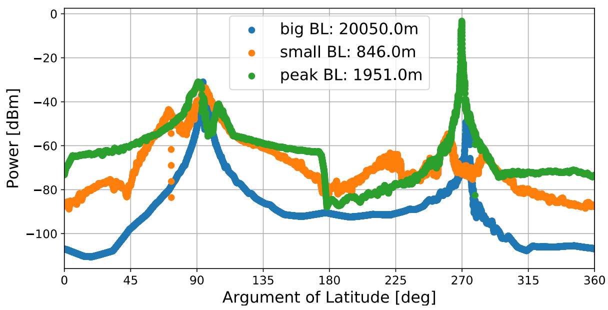

Figure 5 Exemplary received power for *sync-SAR* with the *cube normals* orientation. The peak BL is the one where the maximal received power is calculated.

pointing directly in that direction. This results in the fact that this orientation has the best SNR value. Since *cube rotated* has the same received power value as *cube normals* but smaller SNR it will not be considered further in the future.
For the *formation based* configuration, the SAR antenna receives the lowest power. It does not yield the best SNR although it was chosen based on the formation. This can be explained by the fact that in this analysis only the viewing angles were considered and not the relative distance.
An exemplary simulation result can be seen in **Figure 5**. Here the received power for *sync-SAR* in the *cube normals* orientation is shown for three B_H values. The smallest and largest BLs are colored in orange and blue. The green data is the orbit where the highest received power was calculated. It shows that the peak is at about 270° AoL near the south pole. This peak occurs for all considered orientations. At this position, TL2 is below TL1. Thus, the synchronization signal which has the highest impact on the SAR antenna, reaches the antenna indirectly over the reflector.
The limiter used in the TanDEM-X mission has a threshold of 20 dBm, i.e. signals with a lower power level can pass the limiter with almost no attenuation, stronger signals are depleted [6]. The calculated received power for *sync-SAR* is well below this threshold for all orientations. Hence, the dominating factor for choosing a synchronization antenna orientation is the SNR for the *sync-sync* case, with the *cube normals* as the optimal result.
Future investigations are to find a minimal SNR value where the synchronization is still possible and to optimize the antenna orientation.

5 Conclusion

Synchronization of the on-board oscillators is a crucial issue for bi-static SAR systems. In order to evaluate the effects on the system the received power for *sync-SAR* as well as the SNR for *sync-sync* signal paths were calculated. For this purpose, the synchronization antenna gain map was derived for multiple pointing configurations. The calculation also included first estimations of possible losses regarding the signals. The flight formation was taken into account by calculating the received power and the SNR for B_H values varying from 0.8 km to 19.9 km. With these values, the correct gains for the SAR and the synchronization antennas were obtained from the corresponding gain maps.
The performed analysis showed that the orientation with the lowest received power for *sync-SAR* is the *formation based* configuration. The other two synchronization antenna orientations yielded a higher power value but with a better SNR rating for the *sync-sync* path. A further insight was that the received power for *sync-SAR* is not a limiting factor. Hence, *cube normals* is chosen as the optimal antenna orientation among the analyzed ones.
Future investigations will include the analysis of a minimal SNR with which the synchronization is still possible.

6 Acknowledgment

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7 Literature

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