Multiple PRI Technique for Concurrent Imaging Mode using TerraSAR-X

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***Abstract*—The concurrent imaging mode using TerraSAR-X is a technique that allows the acquisition of two images in a single flyover. It brings high versatility and can double the image output rate. These benefits are of great interest as there is a long revisit time for spaceborne SAR systems. One of the main drawbacks is the use of high pulse repetition frequencies (PRFs), which causes ambiguity issues and timing limitations. Therefore, knowing and improving the quality of the imaging mode is desired. This paper presents a quantitative analysis of its global availability. Moreover, a technique named multiple pulse repetition intervals (PRIs) is proposed to improve the coverage of the imaging mode while maintaining its ambiguity performance. Further simulations are presented, confirming the benefits of the technique, culminating in a vast global availability for the concurrent mode.**

***Index Terms*—TerraSAR-X, concurrent imaging, staring spotlight, stripmap, synthetic aperture radar, Earth coverage, availability**

I. Introduction

The various SAR systems in space can retrieve images by using dedicated acquisition modes. The Stripmap (SM), Staring Spotlight (ST) and ScanSAR modes are currently the most renowned and used modes [1]–[3]. The typical trade-off between the modes is the compromise of scene size for spatial resolution. For example, the Staring Spotlight mode of TerraSAR-X can deliver a resolution of up to 25 cm and a scene of roughly 4 km x 3.7 km, while the ScanSAR mode manages to bring a swath width in the order of 100 km but with a resolution of around 20 m [4]–[6].

One of the main limiting factors of spaceborne SAR systems is the long revisit time. For instance, the satellite TerraSAR-X, the object of analysis in this study, has 11 days of revisit time [7]. Consequently, if one desires to acquire over two nearby regions with different acquisition modes, then up to 11 days have to be waited. A good but expensive solution is to deploy multiple satellites at different orbit positions in order to reduce the revisit time. However, another possibility has been presented in [8], [9], where it is introduced and validated by experimental acquisitions a concurrent imaging technique that enables the acquisition of two images in a single flyover.

An important benefit of the concurrent imaging mode is the fact that it can already be applied to the current generation of SAR systems and does not require any additional cost. The idea behind acquiring two images at the same time is to interleave the modes of each image in a pulse-to-pulse manner, as depicted in Fig. 1.

In order to achieve satisfactory performance in terms of azimuth resolution and ambiguity levels, a fairly high pulse repetition frequency (PRF) must be used. Details on the performance levels and the processing technique of the concurrent imaging mode can be found in [9]. The use of such high PRFs leads to the main limitations of the mode, namely degraded ambiguity levels and reduced scene size in range.

Given that the pulse repetition interval (PRI) is the inverse of the PRF, the proposed mode operates at relatively low PRIs compared to the operational values for the radar. The reduction of the PRI results in a shorter receive echo window. The consequence is a limitation in the swath width of the acquisition. Besides, the low PRI also causes the ambiguity regions in range to be closer to the target. For the PRF range under analysis – 5 kHz to 6.7 kHz – the first ambiguity starts to appear within the main lobe of the elevation antenna pattern. This effect leads to stronger range ambiguities.

As each mode is only used in every other pulse, the actual sampling rate is only half the acquisition PRF. The sampling rate of each mode is named effective PRF. Therefore, when analyzing ambiguity in azimuth, the effective PRF must be the one considered. The low effective PRF leads to strong ambiguities in azimuth as ambiguous targets once again appear within the main lobe of the azimuth antenna pattern. There is a clear trade-off between the strength of the ambiguities and the scene size when choosing the most appropriate PRF. Due to these strong constraints, the proposed mode is expected to have limited availability rates without dedicated optimization measures. This paper aims to study how vastly the mode can be used around the globe and then propose and evaluate techniques to improve the concurrent mode availability.

The paper is structured as follows. In Section II, the concept of imaging targets at disjoint areas is introduced. The terms availability, overlapping and non-overlapping areas of interest are defined, followed by a first quantitative analysis of the global availability of the mode. Section III proposes a technique named multiple PRIs that brings efficiency and flexibility to the mode. The global availability improvement achieved by the proposed technique is discussed in Section IV. Finally, Section V concludes the paper.

II. Multi-Target Imaging

The concurrent imaging technique was originally thought to acquire a high-resolution Spotlight patch within a larger Stripmap scene, namely SM/ST acquisition. Due to its simple

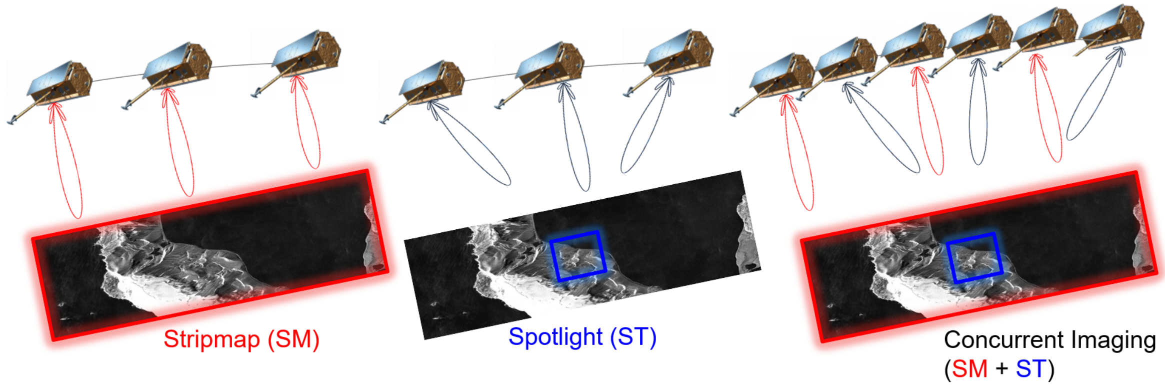

Fig. 1. Illustration of the concurrent imaging mode operation by interleaving pulses of each mode. The image depicts a possible application of the mode in which SM and ST pulses are interleaved. Other combinations for the concurrent mode are also possible.

mechanism of interleaving pulses, new and more diverse applications were made possible. For instance, targets that are even hundreds of kilometers apart can be imaged simultaneously. An echo timing analysis and a proper antenna pattern selection are essential to achieve this more extensive imaging. Having the ability to acquire over disjoint regions, a SM/SM concurrent acquisition is also feasible and of great interest. Fig. 2 illustrates the multi-targeting potential of the mode, in which every two yellow strips can be fully imaged at once. The strips in this example cover an incidence angle range from 19° to 65°, representing a span of 720 km, and the range scene size of the individual swathes decreases in length from 40 km for steep incidence angles to 16 km for shallow incidence angles. The extension in azimuth of each strip has not been depicted as it depends on the imaging modes being applied. Apart from specific satellite restrictions, a Stripmap acquisition could have, theoretically, an unlimited extension, while a Spotlight would be only a couple of kilometers long.

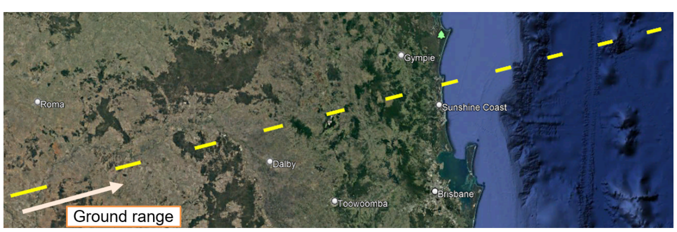

Fig. 2. Illustration of every possible target for a concurrent imaging acquisition over Queensland, Australia, using a PRF of 6088 Hz.

A. Acquisition Availability

The possibility of acquiring over multiple regions with the concurrent mode leads to questioning whether a given set of targets on Earth can be simultaneously imaged. The concept of *availability* arises as the solution. Therefore, one can say that a concurrent acquisition is *available* if any two targets on Earth's surface respect both timing and ambiguity constraints for a selected PRF.

A limiting factor on TerraSAR-X is that the antenna pattern of reception must be the same as the previous transmission due to commanding restrictions. Consequently, there must be an even number of traveling pulses at the moment of reception of each mode. Studies are being carried out to bypass this limitation. Besides, the echoes from each target must arrive at the antenna when the radar is in reception mode with the proper antenna pattern. Receiving while the system is in transmission mode is not possible due to the high difference in power, and the Nadir echoes must be avoided due to their strong backscatter profile [10], [11].

The following subsections present a more detailed numerical analysis of the availability in specific scenarios.

B. Availability for Overlapping Areas

A potential scenario is when both targets are within the same region of interest. Illustratively, they can be considered to be part of the same yellow strip from the multiple ones depicted in Fig. 2. In order to obtain a quantitative measurement of the Earth coverage, a specific target and the minimum required scene size of each mode must be specified. Considering the initial idea of a Spotlight patch within a Stripmap scene, the timing constraint is reduced to only analyzing the SM acquisition, as the ST one is much shorter in range and within the same region. In addition, the SM scene is required to be 30 km wide symmetrically around the simulated point target. Situations in which one imaging area is entirely within the other are named *overlapping areas*.

The simulation described here considers one hundred thousand uniformly distributed random points on the Earth's surface. For each of them, the satellite orbit and available PRFs are checked in terms of timing and ambiguity constraints. The acquisition is judged as being available if both the timing is feasible without transmit or Nadir interference and the predicted ambiguity levels are below a predefined threshold. Concerning the scene center incidence angle, in the *full performance* scenario the target must be between 20° and 45°, while in *data collection* the constraint is loosened to between 14° and 60°.

Due to the TerraSAR-X orbit being sun synchronous, there is a higher fly-over rate for targets at higher latitudes [7].

Therefore, one can expect targets near the equator to have the lowest availability. Fig. 3 depicts the availability rate for the scenarios described, i.e., random targets with a 30 km symmetric scene and proper PRF for a concurrent imaging. The figure shows that the probability of a target being available increases towards higher latitudes. In Fig. 4, the data collection range is considered, and the latitude is fixed to zero to obtain a roughly worst-case result. The available targets are shown in green, while those in red are not available given the constraints imposed.

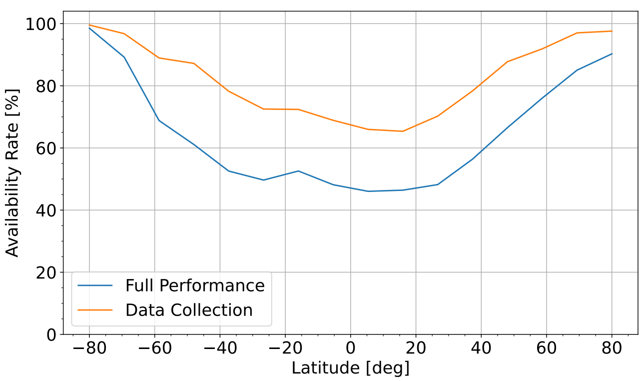

Fig. 3. Availability rate in terms of latitude for the overlapping concurrent mode. The plot represents the probability of a random point at a certain latitude to be accessible for a 30 km/5 km SM/ST concurrent acquisition. SM scene must extend at least 15 km to far and near range to obtain a 30 km symmetrical scene.

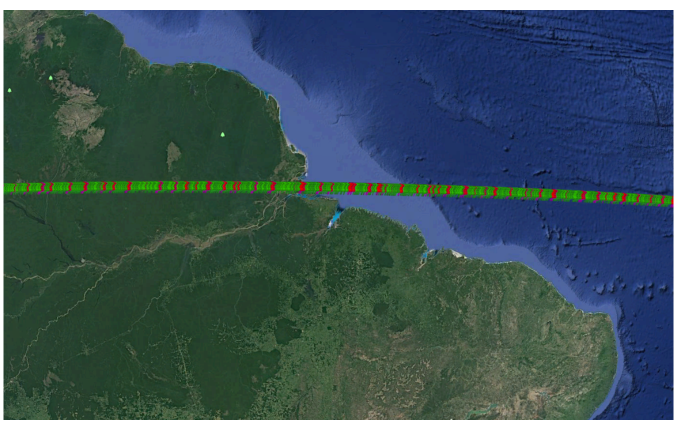

Fig. 4. Available targets at latitude zero are depicted in green, whereas areas which are not accessible with the concurrent imaging technique are depicted in red. A symmetrical 30 km/5 km SM/ST overlapping scenario and the data collection incidence angle range are considered.

The results obtained show that even at low latitudes, the availability remains at least above 65%. This represents great Earth coverage, and the mode can be considered to be widely available. The only exception would be for highly sensitive acquisitions in terms of ambiguities, e.g., regions with high contrast in backscatter, like cities close to the sea. In these cases, the concurrent mode at the actual state of development could degrade the images. These specific situations, however, have not been considered in the simulations. A more generic approach (PRF between 5 kHz and 6.7 kHz) was taken based on the operational PRF range of the satellite [5].

C. Availability for Non-overlapping Areas

The applications in which the regions of interest are at different yellow strips, according to Fig. 2, are named *non-overlapping areas*. Earth coverage statistics can be similarly obtained by availability simulation. For non-overlapping areas, other scenarios are analyzed. Not only SM/ST but also SM/SM acquisitions are investigated. The first scenario is a 30 km Stripmap scene combined with a 5 km Spotlight one. As a second case, two 20 km Stripmap scenes are considered.

The simulation considers two targets randomly placed at the equator separated by a distance of up to 250 km. Every fly-over resulting in an incidence angle between 14° and 60° is considered. Then, the available on-board PRFs are checked in terms of timing and ambiguities constraints. The targets must only be within the required swath width, and this represents a looser restriction compared to the symmetrical scene in the previous simulation. Besides, the latitude has been fixed to zero to obtain a worst-case scenario. Figs. 5 and 6 depict the availability for the SM/ST and SM/SM simulations, respectively. Twenty thousand random targets were simulated.

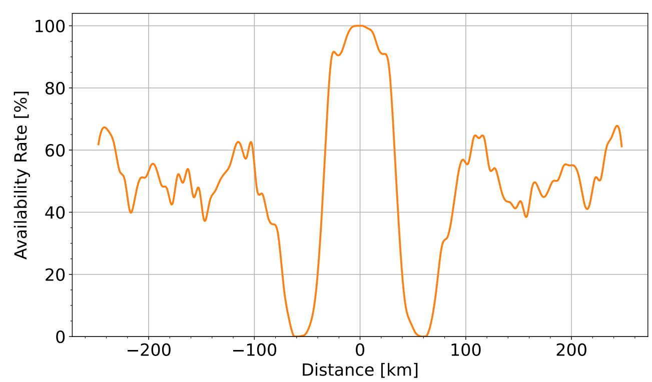

Fig. 5. Availability rate in terms of the distance between the targets for non-overlapping concurrent imaging acquisitions. The plot depicts the probability of two random points on the equatorial line to be accessible in a 30 km/5 km SM/ST concurrent acquisition.

The non-overlapping simulation represents a generalization of the overlapping one, as for distances near zero both acquisitions would be on the same yellow strip (Fig. 2), i.e., within the same area of interest.. However, since here the targets must not necessarily be in the scene center, the availability climbs to 100% for overlapping areas. When the distance is between 40 km and 60 km, the availability drops down to zero. This effect is mainly caused by the fact that reception cannot take place while the radar is transmitting.

Fig. 5 shows an approximately 50% availability for distances greater than 100 km for 30 km/5 km SM/ST acquisitions. The low availability is caused mostly by the limited number of PRFs that enables the acquisition of a 30 km scene because of the limited echo window length for high PRFs.

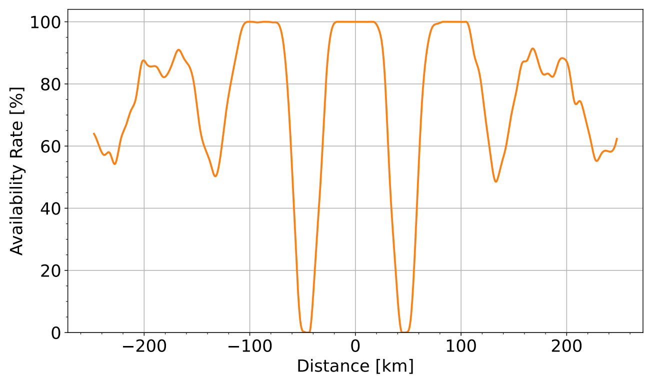

Fig. 6. Availability rate in terms of the distance between the targets for non-overlapping concurrent imaging acquisitions. The plot depicts the probability of two random points on the equatorial line to be accessible in a 20 km/20 km SM/SM concurrent acquisition.

Fig. 6 represents the reduction from 30 km to 20 km and even considers another 20 km scene instead of 5 km. The shorter swath leads to looser timing constraints and more possible PRFs and it results in a better availability oscillating between 50 and 100%.

III. Multiple PRIs Technique

In concurrent acquisitions, the reception alternates between the modes. For a fixed PRI, the echo window length of each mode is the same and must be long enough to accommodate both scenes. Maximizing the swath width in Stripmap acquisitions is usually desired. Taking a SM/ST concurrent acquisition as an example, the SM echo window is totally utilized to maximize the swath width. Conversely, the ST echo window has very poor use of the time domain, as only roughly 5 km are being imaged. Fig. 7 depicts this bad use of time as the ST echo window is not completely used. Keeping the effective PRI constant, increasing the SM echo window, and reducing the ST echo window would greatly benefit the time domain use efficiency. The effective PRI can be obtained by the sum of the individual PRIs: $T_{\text{PRI,eff}} = T_{\text{PRI,SM}} + T_{\text{PRI,ST}}$.

To concurrent SM/ST acquisitions, the multiple PRIs idea can be summarized by

$$T_{\text{PRI,SM}} = \frac{T_{\text{PRI,eff}}}{2} + T^*, \tag{1}$$

$$T_{\text{PRI,ST}} = \frac{T_{\text{PRI,eff}}}{2} - T^*, \tag{2}$$

where T^* represents the exchange of time duration between the echo windows of the modes.

The idea of increasing the echo window of one mode by reducing the other can be seen as each mode having a different PRI. This section proposes and evaluates the multiple PRIs idea. The main objective is to achieve gains in flexibility, efficiency, and availability in concurrent imaging acquisitions. The improvement is not restricted only to SM/ST, but to any possible combination.

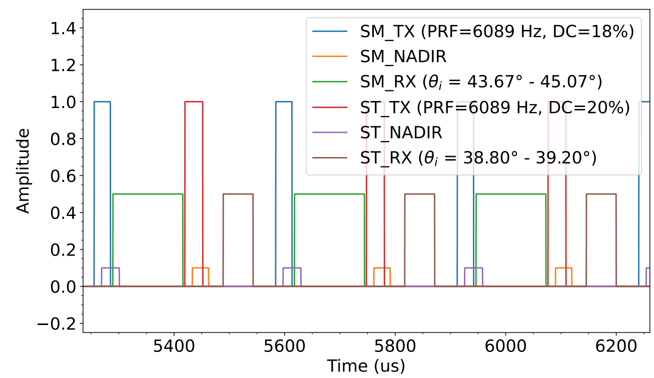

Fig. 7. Signals in time for a fixed PRI acquisition. Amplitude values are for illustration only. The figure shows that the ST echo window is not completely used, representing a less efficient system.

A. *Modified Timing Diagram*

The typical method to determine the PRFs that respect timing constraints is the timing diagram [2], also known as diamond diagram. Given the target position by its incidence angle (θ_i), the satellite height and the duty cycle (DC), the timing diagram as shown in Fig. 8 indicates the PRFs in which there are neither Nadir nor transmission (TX) interference.

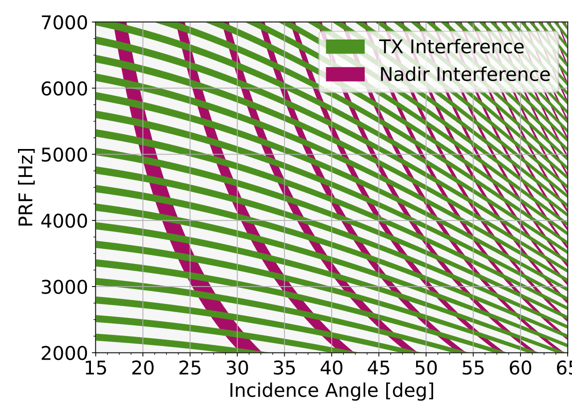

Fig. 8. The timing diagram for a platform height of 519 km and a transmit duty-cycle of 18%. The green areas indicate transmit interference, and the purple regions indicate nadir interference. The usable PRF and incidence angle combinations in which both interferences are avoided are shown as diamond-shaped white areas.

In the case of the concurrent mode with different PRIs, a more generic approach is required as there is one extra degree of freedom. The modified timing diagram presented in Fig. 9 is proposed for the concurrent imaging mode with multiple PRIs. Customarily when designing an acquisition, one or more targets on the Earth's surface are predefined. Fixing the incidence angle of a target and the duty cycle for each mode, the modified timing diagram indicates every possible PRF combination that respects the timing constraints. Effective PRFs lower than 2.5 kHz are discarded as they result in unsatisfactory azimuth ambiguities. Interference with the Nadir echo and the radar transmission are depicted in purple and green, respectively. Available PRF combinations are the remaining white regions.

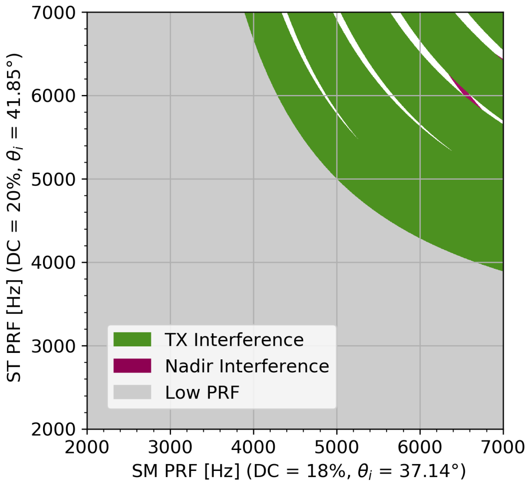

Fig. 9. The modified timing diagram for an orbit height of 519 km. The green areas indicate transmit interference, the purple nadir interference and the gray low performance PRFs. The usable PRFs combination in which both interferences are avoided are depicted by the white areas. Each axis represents one acquisition mode attached to a duty cycle and a target.

To assess whether a PRF combination respects the timing constraints for an extensive scene, multiple modified timing diagrams must be checked for the whole incidence angle range of interest. This extra dimension of simulation directly results from the additional degree of freedom imposed by the use of different PRIs in each mode.

B. Swath Width Evaluation

Plotting multiple timing diagrams and checking one by one is not a very practical approach. Given two targets and a PRF combination, however, each scene maximum swath width is a fixed value that can be obtained from the timing analysis.

A lower PRF is expected to provide larger scene sizes, as the available echo window is longer. This approximation, however, is not always true as there are interference events that can eventually fall inside the receive echo window. This effect is visible for an exemplary concurrent acquisition in which the Stripmap mode has a duty cycle of 18% and images a target at an incidence angle of 37.14°. In comparison, the Spotlight has a DC of 20% and images a target at an incidence angle of 41.85°. In this scenario, the PRF combination 5 kHz in SM and 7 kHz in ST results in a 30 km swath width for the SM acquisition. Reducing the SM PRF to 4.4 kHz reduces the swath to only 12 km, as a Nadir echo appears in the receive echo window. Fig. 10 summarizes the SM swath width for the available PRFs obtained in Fig. 9.

The swath width is one additional performance parameter that can be used to define the optimum PRFs. Its application widely varies based on the acquisition. For SM/SM acquisitions, the swath width of both images can be summed to

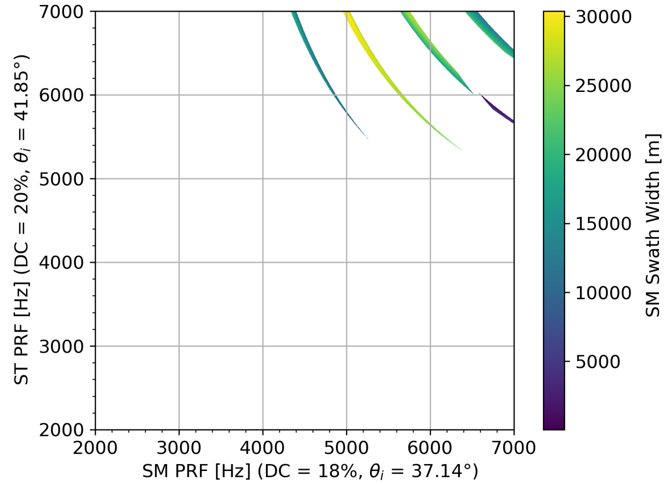

Fig. 10. Stripmap swath width in meters for multiple PRIs concurrent acquisitions. The SM mode utilizes a duty cycle of 18% and images a target at an incidence angle of 37.14°.

maximize the total scene extension. A minimum scene size for each image may also be defined. In summary, the swath width analysis greatly depends on the desired imaging performance, being the main factors the required scene size of each mode and the available PRFs.

IV. Global Availability Improvement

The proposal of having different echo window durations for each mode leads to a more efficient and flexible use of the time domain. Consequently, certain acquisitions that are not feasible with fixed PRIs may become realizable with different PRIs. A global availability improvement is expected in concurrent acquisitions using multiple PRIs. This section aims to analyze the effect of multiple PRIs on the Earth coverage of the concurrent imaging mode using TerraSAR-X. The improvement in availability for the same two scenarios presented in Section II-C is investigated.

A. 30 km/5 km SM/ST Concurrent Acquisition

The first scenario of analysis is a concurrent acquisition comprised of one 30 km Stripmap and one 5 km Spotlight scene separated by a distance of up to 250 km. This represents the original scenario to which the concurrent imaging mode was designed. Besides, these scene sizes are approximately the standard values for operational acquisitions. Therefore, managing to perform this sort of acquisitions would be ideal. Using fixed PRIs, the availability for this set of constraints was discussed in Section II-C and is depicted in Fig. 5. A 50% percent average availability was observed, so improvement is definitely required. The use of multiple PRIs leads to a great improvement all over the distance range. Fig. 11 portrays the improved results.

The availability increases and oscillates between 50% and 100%. However, some plateaus can be seen at 100%, while 50% is only seen for a much lower amount of distances. Given that the simulation was run for targets at the equator

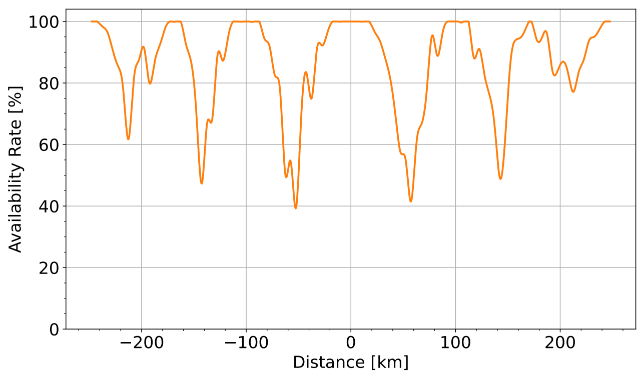

Fig. 11. Improved availability rate in terms of the distance between the targets for non-overlapping concurrent imaging acquisitions. The plot depicts the probability of two random points on the equatorial line to be accessible in a 30 km/5 km SM/ST concurrent acquisition with multiple PRIs.

and two operational modes were performed simultaneously, the availability is acceptable.

B. 20 km/20 km SM/SM Concurrent Acquisition

The second scenario of analysis is a concurrent acquisition comprised of two 20 km Stripmap scenes separated by a distance of up to 250 km. Using fixed PRIs, the availability for this set of constraints was discussed in Section II-C and is depicted in Fig. 6. The use of multiple PRIs leads to great improvement all over the distance range, and Fig. 12 portrays the improved results.

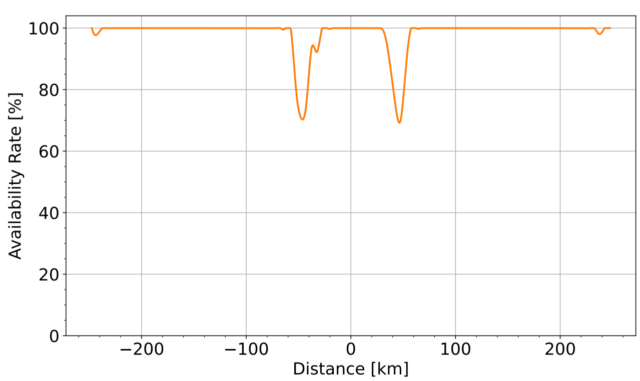

Fig. 12. Improved availability rate in terms of the distance between the targets for non-overlapping concurrent imaging acquisitions. The plot depicts the probability of two random points on the equatorial line to be accessible in a 20 km/20 km SM/SM concurrent acquisition with multiple PRIs.

The improvement is clear, as, for most distances, there is a 100% availability rate. The worst-case occurs for targets separated by approximately 40 km, in which the availability drops to a minimum of 70%. Considering that this result represents worst-case scenario around the globe, i.e., at the equator, the concurrent imaging mode with multiple PRIs has an almost 100% availability for anywhere on the globe when two 20 km Stripmap acquisitions are desired for targets up to 250 km apart.

V. Conclusion

In this paper, the concurrent imaging mode introduced in [9] is analyzed in terms of its global coverage. As the mode brings great versatility and an increased image output rate, developing methods to increase its availability is of great interest. The multiple PRIs technique is introduced and shown to bring significant improvements in the global coverage of the mode. By exchanging reception time duration between each mode, more flexibility and time efficiency were obtained. A quantitative analysis of the availability improvement confirmed the benefits of the technique. Finally, almost 100% availability was obtained for two 20 km Stripmap acquisitions. Very high availability was also obtained for a 30 km Stripmap and 5 km Spotlight concurrent acquisition.

The concurrent imaging mode extrapolates the initial design of the satellite. Therefore, not being able to perform it with nominal performance to all targets and orbit segments is expected. So as to allow for an imaging in all cases, a relaxation in the user requirements would need to be considered. Then, one could consider splitting the transmit signal bandwidth, reducing not only the range resolution but also the range ambiguities. In azimuth, the processed bandwidth could be reduced to achieve better ambiguity performance. This would also lead to a trade-off in azimuth resolution. By reducing the resolutions and improving the ambiguities, a more relaxed scenario in terms of PRF selection is achieved, leading naturally to a higher global availability.

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