An Extended Staring Spotlight Mode Enabled by Concurrent Imaging

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***Abstract*—Synthetic Aperture Radar imaging is characterized by the well-known trade-off between acquired area and resolution. Larger swath widths are obtainable by methods such as ScanSAR, which yields a sizeable area at the cost of a degraded azimuth resolution. Conversely, other techniques such as the Staring Spotlight limit the coverage, increasing the resolution of the observed scene. In this paper, we propose a novel imaging mode where, by using Concurrent Imaging as a support technique, we can double the azimuth length of Staring Spotlight acquisitions without degrading the resolution.**

***Index Terms*—synthetic aperture radar, azimuth resolution, beam direction, antenna gain, earth observation, pulse repetition frequency, staring spotlight, stripmap, TerraSAR-X, concurrent imaging**

I. Introduction

The design of Synthetic Aperture Radar (SAR) acquisitions is characterized by the assessment of multiple trade-offs, especially regarding coverage and resolution. The use of Stripmap imaging (SM), for instance, allows wide swaths to be obtained, at the cost of limiting the integration time to a smaller value, when compared to Spotlight approaches.

The Staring Spotlight (ST) mode has higher azimuth resolution, as all the points in a given scene are illuminated for a longer duration. The integration time is limited only by the steering of the antenna. The available steering angle in practice is constrained by the size of the antenna elements in azimuth direction and the resulting grating lobes. These lobes tend to increase the amount of ambiguous power received by the radar, finally limiting the achievable resolution. Nevertheless, a high azimuth resolution is still achieved due to the increased illumination time compared to a Stripmap acquisition. However, the antenna steering leads to the size of the image on the ground being limited and smaller than that of Stripmap acquisitions.

With the use of a recently proposed technique, which is called Concurrent Imaging [1], we send pulses to different scenes on the ground, acquiring multiple different images simultaneously. This allows a SAR instrument to receive signals from regions that are distant from one another or using modes with different resolutions over the same area.

The new contribution of this paper is the proposal to image regions adjacent in flight direction with very high resolution. Hence, this paper discusses the possibility of an *Extended Staring Spotlight* (EST). EST utilizes Concurrent Imaging as a support technique to juxtapose two scenes in azimuth, both with the same elevation angle. This enables the generation of a combined image with twice the azimuth length of a traditional ST acquisition and the same azimuth resolution.

II. Concurrent Imaging

What we refer to as *Concurrent Imaging* was firstly introduced as *Discrete Stepped Strip* in [2], and a similar discussion is further developed in [1]. The core of the technique is to alternate the transmit pulses to different scenes on the ground. Each scene is tied to a specific acquisition mode.

Currently, all the uses of Concurrent Imaging have only two modes operating simultaneously. Both modes 1 and 2 image different areas on the ground and receive their signals periodically within their respective echo windows. Fig. 1 depicts the concurrent mode in action.

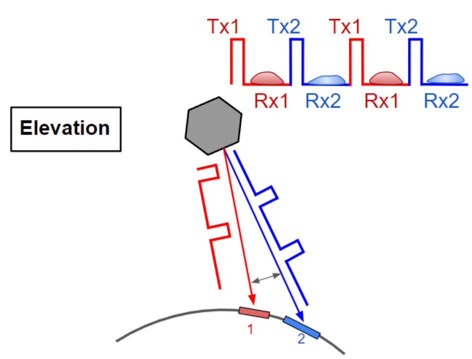

Fig. 1. Depiction of a concurrent acquisition. The antenna points towards scene 1 for a Tx 1 pulse, then it points to scene 2 for a Tx 2 pulse. The echoes are also captured with the matching antenna pattern.

A concurrent acquisition of two different areas may be done with the scenes in various configurations - with distinct azimuth or elevation positions. Naturally, the timing analysis must allow such configuration - no transmit nor nadir interferences - and the returning power from ambiguities on the ground must be low.

III. Extending the Staring Spotlight

ST acquisitions provide a high azimuth resolution, but the azimuth length of the imaged scene is limited by the half-power beamwidth (HPBW) of the antenna. In order to increase the size, the technique used should change to Sliding Spotlight (SL) or Stripmap. Regardless of the chosen approach, the resolution of the acquisition would deteriorate.

A different approach that would conserve azimuth resolution and increase image size is to make two consecutive ST acquisitions - the first mode acquiring the first half of the extended image and the other mode doing the same for the second half.

The problem with this method is that it is not feasible for a nominal ST acquisition. For the second mode to start its imaging, the first must finish steering the antenna from $+\alpha_{\text{lim}}$ to $-\alpha_{\text{lim}}$, with α_{lim} being the steering limit for the azimuth angle. However, to acquire the second scene with full azimuth resolution, the second mode would also need to start its steering from $+\alpha_{\text{lim}}$ to $-\alpha_{\text{lim}}$ as well, pointing the antenna to a region that is not juxtaposed with the first half of the intended extended image. This would lead to a sizable gap between the two acquired scenes, making it impossible to acquire two juxtaposed scenes in order to create an extended, continuous one.

To avoid this, instead of starting a second ST acquisition after the first finishes, we use Concurrent Imaging to let both modes operate simultaneously.

In the literature, the use of concurrent modes has been limited to the extraction of two Stripmap images in different spots on the ground, or a joint acquisition of Stripmap and Staring Spotlight to better visualize a small but detailed region within a wide area [1].

However, we could exploit this technique to enhance existing Spotlight modes for a given target area. By selecting the second scene to be juxtaposed to the first one, in the azimuth direction, while both areas are kept at the same incidence angle in elevation, an extended acquisition mode is possible. In particular, we may image both scenes in a Staring Spotlight mode (ST), producing an Extended Staring Spotlight (EST).

It was hypothesized in [3] to be possible to acquire two different areas jointly in this manner, although the conditions required and the process of acquisition were not further developed. In this paper, we design a method for extending the Staring Spotlight coverage, while also investigating its performance, showing that it can be done for multiple concurrent pulse configurations and for a wide range of incidence angles.

An EST acquisition leverages Concurrent Imaging by having the antenna to periodically send a pulse to the first half of the extended scene (Mode 1), and then another pulse to the second half (Mode 2). This process is finished when both scenes have azimuth antenna angles outside the steering range.

It must be noted that, at the beginning of the EST imaging, the second mode is not active - no pulses are sent to the second half of the extended scene. Conversely, at the end of the process, the first half is not acquired, while the second half is. This is done to prevent sending pulses to any of these areas if their azimuth antenna angles are outside the steering range.

In this paper we will use TerraSAR-X parameters as reference, for which the steering angle limit is $\alpha_{\text{lim}} = 2.2°$.

The acquisition walkthrough is:

1) When the antenna angle from the satellite to the first scene center is in range for ST imaging, start ST acquisition in Mode 1.
2) While still acquiring the first scene, when the antenna angle to the second scene center also enters ST azimuth angle range, start the concurrent ST acquisition of the second scene.
3) The acquisition of scene 1 ends when the azimuth angle of the satellite with respect to its scene center reaches the lower limit of -2.2°. The imaging of scene 2 is still ongoing.
4) Finally, the second scene reaches the lower steering limit, ending the imaging process.

The imaging scheme is concisely depicted in Fig. 2.

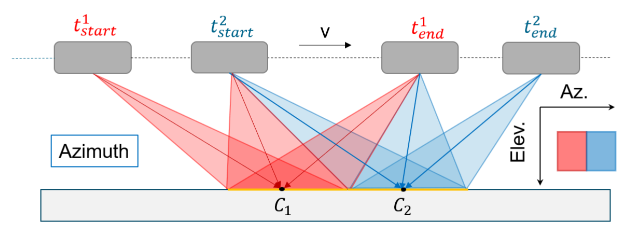

Fig. 2. The complete process of an Extended Staring Spotlight (EST) acquisition. The second imaging mode begins its ST amidst the first mode, and the first imaging mode ends amidst the second one.

This extended mode doubles the azimuth coverage of the acquisition, as two juxtaposed scenes are obtained. In addition, it maintains azimuth resolution, as the integration time of all points in the two scenes is the same as in the conventional ST.

From a timing perspective, it could be argued that this method reduces the swath width of the extended scene. Since two pulses must be sent concurrently, the PRF must be doubled, reducing by half the available echo window for each scene. This is the main trade-off of EST, where the available echo window is halved in order to double the azimuth coverage. However, the received signals of ST acquisitions usually have low duration in the echo window, as their swath widths are not large enough to occupy it completely. Hence, the reduction in the available echo window does not necessarily impact the swath width of the extended image.

For an acceptable acquisition with the use of EST, one must properly choose three parameters: a ground incidence angle θ_{i} for the scenes, a PRF value, and an η_1 fraction of PRI to be reserved for Mode 1 and the rest ($\eta_2 = 1 - \eta_1$) of the PRI for Mode 2 [4].

IV. Methodology

In order to verify the feasibility of the Extended Staring Spotlight and optimize its performance, the timing for a given incidence angle and the ambiguity levels must be studied for multiple PRF and η values. If some interference is detected, or the ambiguity power is too high, this angle must be deemed not suitable for an EST acquisition. If none of these occur, EST imaging is considered feasible for that particular angle.

The methodology is detailed in the following subsections. The results and plots were generated by means of simulation considering the TerraSAR-X parameters [5].

A. Timing Analysis

For a target scene to be suitable for an acquisition of any technique, the received signals must fit the echo windows. If the swath width is too large, the received signal of the whole strip may interfere with the transmit pulse. Another possibility is for the received signal to arrive with some nadir interference, infecting the image with spurious power.

When it comes to EST, the usage of Concurrent Imaging leads to two different scenes being obtained within the same PRI. Hence, we need to ensure that the two Rx signals do not arrive with any overlapping. Fig. 3 displays a transmission diagram with no Tx nor nadir interferences, which is the first necessary condition for a successful acquisition.

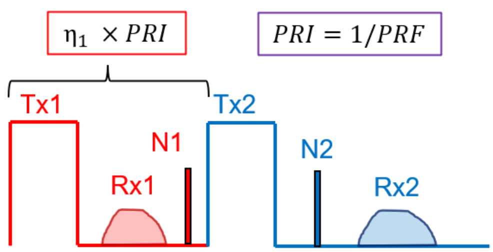

Fig. 3. Schematic representation of the transmit and receive events of a viable concurrent imaging. The transmission modes are given in red (mode 1 - Tx 1) and blue (mode 2 - Tx 2), and the received signals of each pulse have matching colors (Rx 1 and Rx 2). A successful concurrent acquisition has each acquired scene fitting within two consecutive Tx pulses (echo windows), without any overlapping with each other and neither with any nadir signal (N1 for Nadir coming from Tx 1 and N2 for Tx 2).

If none of these previous interferences occur, then the acquisition is feasible from a timing perspective.

From a design point of view, it is necessary to obtain the configuration parameters that achieve a feasible acquisition, which in this context relates to finding all the pairs (η_1, PRF) where no interferences happen. Fig. 4 displays a map where all possible sets of (η_1, PRF) for a specific EST acquisition are shown. The map is obtained by computing all of the echo times for each set and checking for interferences.

The next step in the process is to evaluate the ambiguity power levels. For each specific pair that accommodates both scenes from a timing perspective, the ambiguity power is

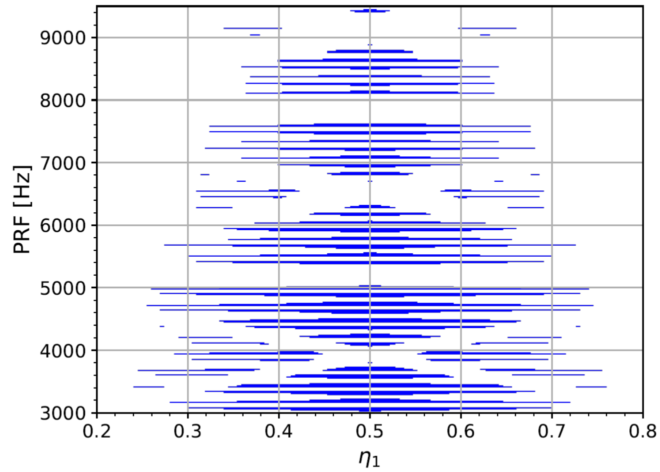

Fig. 4. Map of all possible pairs of (η_1, PRF) where an EST acquisition is possible (in blue). This extended scene has both scenes (modes 1 and 2) with 5 km of swath width, aligned in elevation and juxtaposed in azimuth, at an incidence angle of 27°.

calculated, extracting both the range ambiguity-to-signal ratio (RASR) and the azimuth ambiguity-to-signal ratio (AASR). If the ambiguity levels are too high, exceeding a predetermined threshold, this specific pair is excluded.

B. Ambiguity-to-Signal Ratio

For a given set of (η_1, PRF), it is desirable to know certain parameters related to image quality. The most relevant when it comes to EST is the ambiguity-to-signal ratio (ASR), which comprises the sum of the power that comes from both azimuth and range ambiguities. More importantly, it is necessary to extract the worst value of ASR throughout the whole image. The worst case is an important parameter, as it can be compared with a predefined quality threshold to determine if the scene complies with the minimum performance requirements for a given pair (η_1, PRF) - no point in the scene will have an ASR above a given upper limit, making it a reliable metric to extract.

Part of this assessment is to obtain the RASR of all points of the image on the ground.

1) Range Ambiguities: Fig. 5 displays the RASR distribution throughout a scene imaged by an Extended Staring Spotlight acquisition when using a specific pair (η_1, PRF) $= (0.5, 5000$ Hz). For each point on the scene, a RASR value is associated [6], and the worst case is extracted.

This analysis is repeated for every valid pair in the map of available PRFs in Fig. 4, extracting the worst RASR values of each set and mapping them back to their respective sets on it, producing the RASR map, depicted in Fig. 6.

2) Azimuth Ambiguities: The same procedure is applied for the AASR: for every pair (η_1, PRF) of the map on Fig. 4, the AASR is calculated for all the points on the image acquired, extracting the worst value of the scene. Afterward, this value is mapped to the respective pair on the PRF map, producing the map of worst-case AASR for each (η_1, PRF) pair.

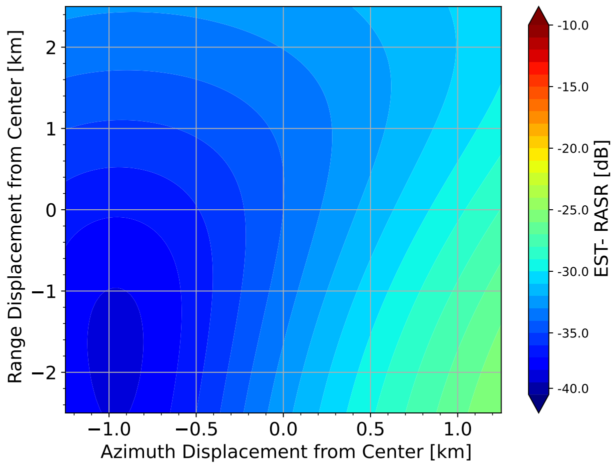

Fig. 5. RASR distribution throughout the scene of mode 1 (first half of the extended image) of an EST acquisition, for $\eta_1 = 0.5$, PRF $= 5000$ Hz, $\theta_i = 27°$, 5 km swath width by 2.5 km azimuth length for each scene mode. This picture refers to the RASR distribution of the first half of the extended image, as indicated by the diagram on the right side.

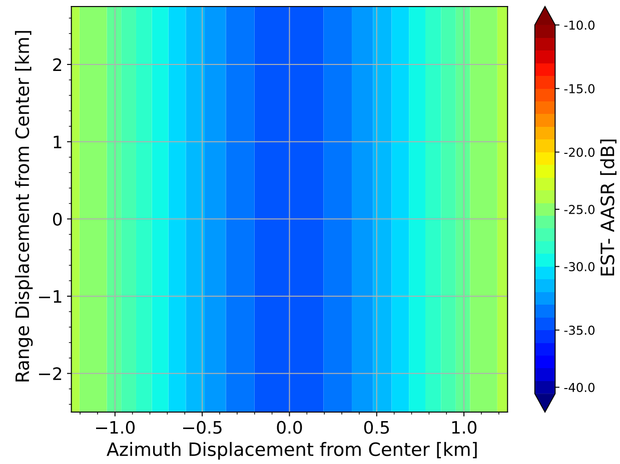

Fig. 7. AASR distribution on the ground, for the scene imaged by mode 1 in the extended area made by the two scenes (modes 1 and 2), juxtaposed - for $\eta_1 = 0.5$ and PRF = 6500 Hz, and for $\theta_i = 27.0°$.

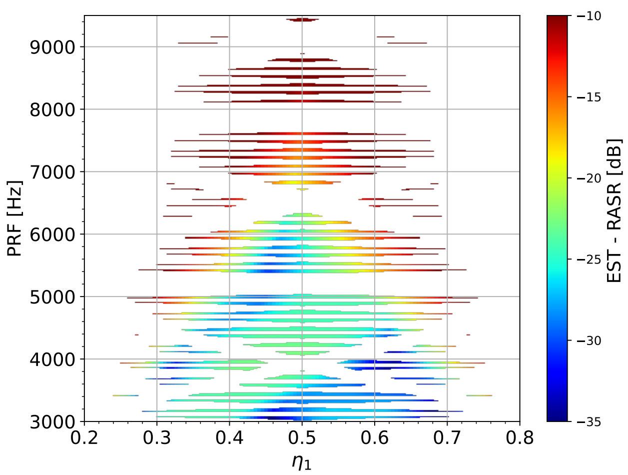

Fig. 6. Map of the worst RASR values (dB) for each available (η_1, PRF) pair in Fig. 4, for an extended scene at 27° incidence angle of 5 km. The range ambiguity power gets higher as the PRF increases.

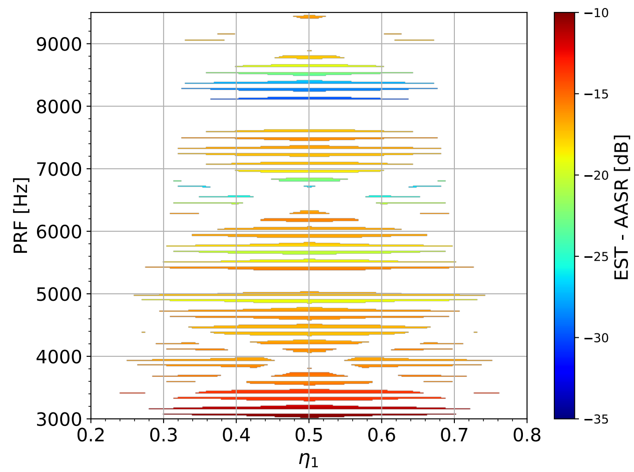

Fig. 8. Map of the worst AASR values (dB) for each available (η_1, PRF) pair in Fig. 4, for an extended scene at 27° incidence angle of 5 km. The azimuth ambiguity power tends to lower as the PRF increases.

Fig. 7 displays the distribution of AASR throughout the first half (mode 1) of the extended scene, for another given pair of $(\eta_1, \text{PRF}) = (0.5, 6500 \text{ Hz})$, and Fig. 8 displays the PRF map with the worst AASR values of this half scene mapped to it.

C. Optimal Value

After obtaining the worst values of RASR and AASR, for each set on the PRF map, their sum is computed as ASR. It is necessary to find which pairs minimize the total ambiguity power coming from the ground, regardless of the nature of the ambiguity. Hence, both sources are added as a total amount of interfering power, which must be kept at a minimum.

This produces an ASR map, similar to those previously shown - but now, the pairs of the map whose ambiguity values do not meet a minimum threshold value of quality are excluded. For this paper, -17 dB of ambiguity threshold is considered of reasonable quality. Looser values as -15.5 dB are considered acceptable, though not ideal. This is due to the fact that systems such as TerraSAR-X consider acceptable acquisitions whose ambiguity levels are -20 dB for RASR and -17 dB for AASR - and both individual thresholds, when added, result in a -15.5 dB ASR upper limit [5].

Fig. 9 presents this filtered ASR map, where only the pairs whose maximum ground ASR does not exceed the -17 dB threshold are shown.

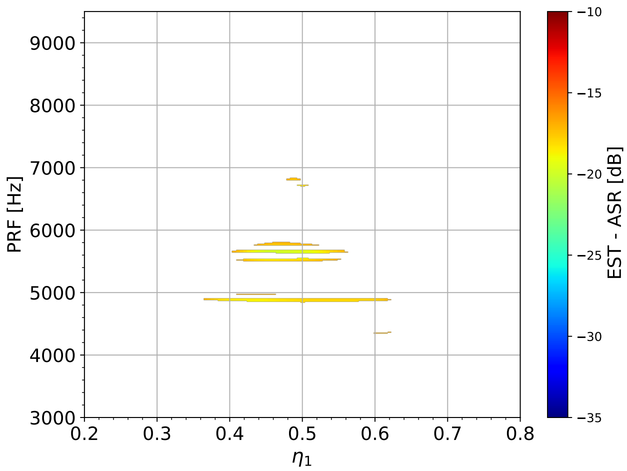

Fig. 9. ASR map, displaying the sets of (η_1, PRF) whose ASR values do not exceed -17 dB, and their respective values. It is notable that very few sets meet the threshold, compared to all the sets present in the PRF map in Fig. 4.

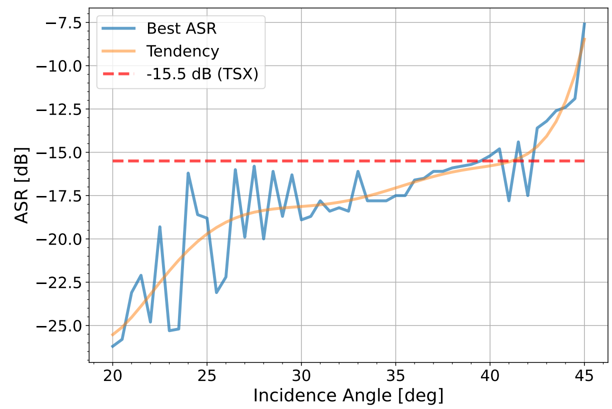

Fig. 10. ASR as a function of the incidence angle for an extended scene of 5 km of swath width by 2 × 2.5 km azimuth length. The blue curve contains the extracted values of ASR for each angle by simulation, and the red dashed line marks the quality threshold of -15.5 dB.

The amount of pairs whose ambiguity power is acceptable is low compared to the number of pairs where acquisition is feasible from a timing perspective. However, as long as at least one exists, the EST imaging is possible. Among the filtered pairs, the optimal pair for the simulated acquisition is picked, which for an extended scene of 5 km swath width by 2×2.5 km azimuth length and an incidence angle of $\theta_\text{i} = 27.0°$, is (η_1, PRF)$=$ $(0.48, 5680$ Hz$)$. Nonetheless, we set $\eta_1 = 0.5$ to distribute the ambiguities evenly azimuth-wise, as 0.48 is the optimal value for minimizing ASR in the first half of the extended scene, but not for both halves.

V. General Results

The processes discussed in Sec IV. are repeated for multiple incidence angles from 20° to 45°, at a step of 0.5°. This interval was chosen using TerraSAR-X as reference, as this is its full-performance interval.

Fig. 10 displays ASR values simulated for the scenario of an Extended Staring Spotlight of two scenes juxtaposed in azimuth, each 2.5 km of azimuth length, and both with 5 km swath width, with each value on the plot being the optimal ASR extractable, each with a distinct set of (η_1, PRF) parameters. As the incidence angle increases, the PRF used tends to decrease as well.

The plot shows a clear upward trend as the incidence angle of the acquisition increases, which is expected, although the simulated values are highly volatile in the first half of the incidence angle range. This oscillatory behavior is derived from the AASR contribution to the total ambiguity power. For small incidence angles, the RASR contribution to the ASR is low, even for high PRFs. On the other hand, the AASR contribution barely changes with the incidence angle, but is expected to decrease for higher PRFs. In the case of Staring Spotlight, this descent is not linear - the value of AASR oscillates substantially, especially for high values of PRF. This means that for low incidence angles, the higher values of PRFs will extract the optimal performance, as the increase in RASR with PRF is not sufficiently relevant - hence, AASR dominates ASR behavior at low incidence angles. However, for higher incidence angles, the RASR increase with PRF becomes dominant, so lower PRFs are needed for an acceptable acquisition - and for lower PRFs, the behavior of AASR is significantly less volatile. This is the reason why the latter half of the ASR performance curve in Fig. 10 is more stable.

Regardless of the behavior, all incidence angles until 40° maintain ambiguity power below -15.5 dB, and most angles below 35° have ASR under -17 dB (with some care for oscillation).

The results of Fig. 10 show that an EST imaging mode is feasible for most incidence angles with reasonable ambiguity levels.

VI. Further Possibilities

A. Extended Sliding Spotlight

An extended image could be acquired employing Sliding Spotlight (SL), instead of ST. The main difference of the SL acquisition from ST is on the steering of the antenna, as the focus where the antenna points towards - the rotation center - is below the ground. The result is a broader scene acquired, but with a deteriorated azimuth resolution. By using SL acquisition with Concurrent Imaging in the same fashion, an Extended Sliding Spotlight (ESL) could be achieved, resulting in a broader extended scene, with a higher azimuth resolution than Stripmap, although not as high as what is obtainable with an ST or EST acquisition.

In addition, a rotation center beneath the ground leads to a narrower antenna steering range, potentially resulting in less ambiguity power when compared to EST, since the effect of grating lobes would be weaker.

B. Continuous Staring Spotlight

The existence of two different modes of acquisition enables the possibility of *scene hopping* - by reducing the steering span of each ST mode to its HPBW, one could turn off a first mode, which looks to a first scene of interest, and turn it on again, but looking to a third scene further than the second one, yet juxtaposed to it, and repeat this process for the second mode to be turned off and turned on into a fourth one. When repeated indefinitely, this would create a *Continuous Staring Spotlight* (CST), where the azimuth length of the acquired image could be as large as desired, while still maintaining a fixed size for the swath width. Fig. 11 depicts this mode in action.

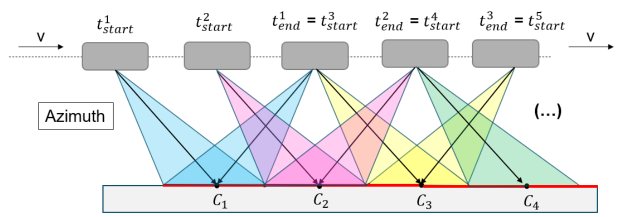

Fig. 11. Continuous Staring Spotlight acquisition. With a limited steering span of twice the HPBW of the antenna, the radar acquires the first and second scenes concurrently as in EST, but when the first scene is finished, a third one, juxtaposed to the second, starts being imaged. When the second scene is done, a fourth one, juxtaposed to the third, will begin as well, and this process continues indefinitely.

Of course, this comes with its limitations. Since the steering span of the antenna would be smaller, this heavily impacts resolution. We estimate this mode could have twice the azimuth resolution of a conventional Stripmap acquisition, at the cost of halving its swath width.

One positive aspect of CST is that the impact of ambiguities would be far smaller than in EST, as the steering span of the antenna angle would be narrow (-HPBW, HPBW), limiting the effect of grating lobes.

C. Complete Continuous Staring Spotlight

The main limitation with CST is the fact that the acquisition must use a narrow steering span for the antenna beam angle, which reduces the integration time of all points of the image and, hence, the azimuth resolution. However, if more modes could be used in the Concurrent Imaging technique - not just two - the steering angle range could be increased. While *scene hopping*, instead of imaging just two scenes, multiple scenes could be juxtaposed and concurrently acquired. Each additional mode adds $\frac{\text{HPBW}}{2}$ to the steering span upper and lower angle limits $(-\alpha_{\text{lim}} - \frac{\text{HPBW}}{2}, \alpha_{\text{lim}} + \frac{\text{HPBW}}{2})$. This would lead to a higher resolution, while keeping the indefinitely long azimuth length of the CST. With enough concurrent modes, this method could achieve the steering angle span of an ST acquisition, providing the same level of azimuth resolution.

This acquisition technique would be a *Complete Continuous Staring Spotlight* (CCST), since it would have to leverage multiple concurrent modes in order to complete the steering angle range of an ST acquisition. For TerraSAR-X, in order to achieve a complete steering span, the CCST technique would need to operate 16 concurrent modes.

This is not practical for multiple reasons. The first one is the intricacy of operating more than two concurrent modes. The second reason is the fact that PRF must increase proportionally to the number of modes used, requiring embedded SAR hardware to work with PRF values of dozens of thousands of hertz, also leading to strongly degraded swath widths. Finally, ambiguity power would also scale accordingly to the number of modes used, potentially leading to a poor quality image.

D. Further Improvements

Many refinements could be done to the core implementation of the methodology proposed. A particular point for improvement is the algorithm implemented to extract the sets of pairs (η_1, PRF) that enable an EST acquisition. It does not consider the possibility of nadir interference filtering [7], which if implemented could provide a wider collection of pairs and better performance.

VII. Conclusion

The technique of Concurrent Imaging can be used to acquire two different scenes within the same PRI. By juxtaposing these two scenes in azimuth while both maintain the same incidence angle, we can acquire in Staring Spotlight both these scenes as two halves of an extended one. This Extended Staring Spotlight (EST) leads to twice the azimuth length of a conventional ST, while potentially maintaining swath width, doubling the area of the image.

The EST acquisition can be done with reasonable ambiguity levels throughout most incidence angles and with multiple configurations of PRF and η_1. This makes it a feasible technique to extract larger areas of the ground while keeping very high azimuth resolution.

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