Waveform-Encoded Synthetic Aperture Radar: Image Quality Assessment Using Satellite Data

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Abstract—Synthetic aperture radar (SAR) remote sensing is very attractive for the systematic observation of dynamic processes on the Earth’s surface since it allows high resolution imaging independent of weather conditions and sunlight illumination. Waveform-encoded SAR is a novel SAR concept based on pulse-to-pulse variation of the transmitted waveform that allows focusing the nadir echo and the range ambiguities and suppressing them through a multi-focus post-processing. However, the assessment of the ambiguity suppression performance for such a system is not trivial, as the processing involves a non-linear thresholding and blanking approach. This work proposes a novel methodology, which exploits real TerraSAR-X data to accurately simulate the effect of the range ambiguity on the useful signal and allows for a quantitative assessment of the image quality of a waveform-encoded SAR. The analysis considers different waveform variation schemes (namely up- and down-chirps and cyclically shifted chirps) and a contrast-minimization technique for threshold selection, whose performance is compared to the best achievable one (i.e., the optimum threshold). The results of this work further highlight the potentialities of the waveform-encoded SAR concept and allow accounting for its ambiguity suppression capability in the design of a SAR system.

Index Terms—Synthetic aperture radar (SAR), range ambiguities, pulse-to-pulse waveform variation, matched filter, multi-focus post-processing, contrast minimization, optimal threshold, local ambiguity-to-signal ratio.

I. INTRODUCTION

Synthetic Aperture Radar (SAR) is a very attractive remote sensing technique for the systematic observation of dynamic processes on the Earth’s surface, as it allows high-resolution imaging independent of weather conditions and sunlight illumination. SAR is typically characterized by a side-looking geometry and transmits electromagnetic pulses with high energy downward to the surface at a given pulse repetition frequency (PRF) in order to collect the backscattered signals in a sequential order. After interacting with the surface, the returning echoes are coherently sampled, i.e., the radar retains their amplitude and phase, providing an effective long “synthetic” antenna which allows improving the spatial resolution of the overall system [1]–[5].

As a consequence of the SAR pulsed operation and side-looking geometry, some undesirable echoes corresponding to preceding or subsequent transmitted pulses and propagating back from targets different than the imaged ones, can arrive at the radar simultaneously with the echoes of interest: these are nadir returns and range ambiguities. The returns coming from the nadir, i.e., the closest point of the Earth’s surface to the radar, can be stronger than the desired echoes because of the specular scattering process, and strongly corrupt the quality of the SAR image [6], [7]. Moreover, a further source of degradation is represented by range ambiguities: while nadir returns only affect limited regions of the SAR images (bright stripes at given ranges), range ambiguities typically corrupt large regions of them [2].

In order to cope with nadir returns and range ambiguities, an innovative, recently patented concept, waveform-encoded SAR, has been investigated, based on pulse-to-pulse variation of the transmitted waveform [8]–[13]. The ambiguous signal, i.e., the range ambiguity or the nadir return, can be thus smeared as a consequence of the pulse or range compression operation, if different and “orthogonal” waveforms are employed on transmit. As a result, it appears as a noise-like disturbance rather than slightly-defocused artifacts and some ambiguous energy is suppressed, if the PRF of the system is larger than its processed Doppler bandwidth, similarly as in a staggered SAR system [14]. However, the ambiguous signal, despite it is smeared and therefore less visible, still contributes to the background noise, thus limiting the retrieval of information from SAR data.

The proposed technique allows suppressing (not only smearing) nadir returns and range ambiguities through a multi-focus post-processing. As sketched in Fig. 1, the raw SAR data of the total signal, corresponding to the superposition of useful and ambiguous signals, are firstly focused using a filter matched to the ambiguity, so that the ambiguity results to be correctly focused and properly located, while the imaged target is smeared over range and azimuth, as a consequence of the pulse-to-pulse variation of the transmitted waveform. It can be noticed that the range ambiguous signal contains more pixels with higher intensity compared to the useful one because of a proper focusing, despite the total energy is lower. As a consequence, the range ambiguity can be significantly attenuated using a thresholding and blanking approach, with a negligible corruption of useful signal, which results to be only minimally affected, if the threshold is properly selected. An effective criterion for threshold selection can be obtained by minimizing the image contrast (defined as the ratio of the standard deviation of the intensities to the mean of the
intensities [9], [15]): as the threshold decreases, the image contrast also decreases as a consequence of removal of strong and focused ambiguity features; once the ambiguous signal has been removed, if the threshold decreases even more, the image contrast increases because of significant removal of useful signal. The latter focused SAR data are then transformed back into raw data through an inverse focusing operation and are finally focused again using a filter matched to the useful signal, obtaining a focused SAR image where the range ambiguity is strongly attenuated with a negligible corruption of the imaged target. The proposed multi-focus post-processing can be repeated to suppress higher orders of the ambiguities.

The assessment of the ambiguity suppression performance for such a system is not trivial, as the processing involves a non-linear thresholding and blanking approach. This work proposes a novel methodology, which exploits real TerraSAR-X data to accurately simulate the effect of the range ambiguity on the useful signal and allows for a quantitative assessment of the ambiguity suppression capability for a typical L-band system.

II. METHODOLOGY FOR PERFORMANCE ASSESSMENT

The proposed methodology for performance assessment is based on the simulation of raw SAR data (Fig. 2) of a scene, where useful and ambiguous signals are superimposed, and for a specific system with given parameters (in this case we simulate the data for an L-band SAR system). For simplicity, only one range ambiguity is assumed to be superimposed to the useful signal. In order to reproduce the backscatter variation, the backscatters of different portions of an X-band TerraSAR-X image acquired over the Greater Munich area are used. Specifically, four portions of fixed size, i.e., 4096 x 4096 pixels, have been extracted from the TerraSAR-X data, corresponding to different typical features of a SAR image, i.e., Lake Starnberg, the Munich urban area, a forest, and a town (Germering), in order to separately simulate the useful and ambiguous signals (the complex backscatters of the range ambiguity have been amplitude-scaled in order to simulate reasonable levels of ambiguity, with different ambiguity strengths). This methodology allows simulating both a conventional SAR (without waveform variation) and a waveform-encoded SAR just changing the transmitted waveforms.

The analysis considers two waveform variation schemes. The first scheme consists of cyclically shifted chirps [8], [9], i.e., an example of short-term shift-orthogonal waveforms [16] proposed in [17]:

$$s_k(t) = e^{j\frac{2\pi}{B} t - t_k - \tau \left( \left\lfloor \frac{t - t_k - \tau}{\tau} \right\rfloor + 1 \right)}$$

(1)

where \(\tau\) is the chirp duration, \(B\) is the chirp bandwidth and \(-\tau/2 \leq t_k \leq \tau/2\), is the cyclical shift of the chirp waveform. In more detail, the sequence of waveforms proposed in (1) repeats periodically every \(B\) pulses, during which \(\tau\) and \(B\) are kept constant while varying the shift \(t_k\) from pulse-to-pulse, according to the following quadratic law [8], [9]:

$$t_k = \frac{k(k+1)}{2B} - \tau \left\lfloor \frac{k(k+1) + B\tau}{2B\tau} \right\rfloor, k = 0, ..., 2B\tau - 1$$

(2)

The second scheme consists of up- and down-chirp alternation [18]. This kind of sequence, i.e., only two waveforms, allows...
suppressing, as well as smearing only odd range ambiguities, i.e., echoes corresponding to an odd number of preceding or subsequent transmitted pulses.

III. PERFORMANCE MEASUREMENTS

In order to quantitatively assess the performance of the contrast minimization technique for threshold selection, a total error $E_{\text{tot}}$ can be evaluated after focusing matched to the useful signal as a function of thresholds and with reference to the ambiguity-free image, by exploiting the separate knowledge of useful and ambiguous signals within the simulation. In particular, it can be decomposed into two separate components: the residual ambiguous signal $u_{\text{amb}}$ and the removed useful signal $u_{\text{sign,ref}} - u_{\text{sign}}$, where $u_{\text{sign,ref}}$ and $u_{\text{sign}}$ denote the focused useful signal assuming a conventional SAR without waveform variation and a waveform-encoded SAR with a multi-focus post-processing, respectively:

$$E_{\text{tot}} = \sum |u_{\text{amb}}|^2 + \sum |u_{\text{sign,ref}} - u_{\text{sign}}|^2$$

(3)

The minimization of the total error, i.e., optimal threshold, can be used as best reference for performance assessment, as it allows for the best trade-off between ambiguity suppression and removed useful signal. However, it cannot be obtained in practice, but only within a simulation context, as the useful and ambiguous signals are required to be separately available. In addition to the ambiguity suppression achievable with the optimal threshold, the ambiguity suppression achieved using the threshold which leads to contrast minimization has been evaluated.

IV. RESULTS

Using the desired L-band system parameters and for a 10-dB amplitude scaling of the range ambiguous signal (this is an extreme case, as generally far less stronger ambiguities are expected), Fig. 3 shows the resulting corruption on Lake Starnberg due to the range ambiguity with reference to the ambiguity-free image (Fig. 3(a)). Specifically, Fig. 3(b) refers to a conventional SAR system without waveform variation, while Fig. 3(c) and (d) show the image quality improvement of a waveform-encoded SAR with the sequence of waveforms of (1) and (2) in case of mere waveform variation and multi-focus post-processing, respectively. It can be noticed that the improvement is striking.

The achievable ambiguity suppression due to contrast minimization depends on the scene and the local ambiguity level: the higher the range ambiguity level, the better the ambiguity suppression capability. In order to quantify the ambiguity impact on the imaged target for a conventional SAR system without waveform variation, the local ambiguity-to-signal ratio (i.e., $RASR_{\text{local}}$) has been considered, defined as:

$$RASR_{\text{local}} = \frac{\sum |u_{\text{amb,ref}}|^2}{\sum |u_{\text{sign,ref}}|^2}$$

(4)

where $u_{\text{sign,ref}}$ and $u_{\text{amb,ref}}$ denote the useful and ambiguous signals, respectively, after focusing using a filter matched to the desired signal. Moreover, different scenarios have been simulated, in order to better understand the ambiguity suppression capability of the waveform-encoded SAR concept for different scenarios. However, contrast minimization leads to a worse image quality, i.e., higher total error, for low local ambiguity-to-signal ratios as a consequence of significant removal of useful signal, despite a further range ambiguity suppression is achieved compared to the mere waveform encoding. As a result, the performance of the contrast minimization method depends on the local ambiguity-to-signal ratio, while the performance has been proved to be almost independent from the scene.

V. CONCLUSION

Waveform-encoded SAR allows suppressing (not only smearing) range ambiguities by continuously changing the transmitted waveform and by implementing a multi-focus post-processing with a thresholding and blanking approach. This paper proposes a methodology for assessing the performance of a waveform-encoded SAR through simulations based on real TerraSAR-X data. The resulting image quality improvement is significant, especially for high local ambiguity-to-signal ratios, and the system performance has been demonstrated to be almost scene independent. The results of this work further highlight the potentialities of the waveform-encoded SAR concept and allow accounting for its ambiguity suppression capability in the design of novel low cost SAR systems. Finally, azimuth phase coding of transmitted pulses could be considered as an alternative or in combination with waveform encoding [19], [20].
REFERENCES