A Photonics-Enhanced Bistatic High-Resolution Wide-Swath Synthetic Aperture Radar System Concept

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Abstract

This paper presents a novel concept for implementing a gapless high-resolution wide-swath (HRWS) bistatic synthetic aperture radar (SAR) system using photonics in conjunction with the MirrorSAR concept. MirrorSAR is a bi- or multi-static SAR concept where the platforms are separated in transmit and receive. The simplified receive satellites, acting as space transponders for the echo signal, have highly reduced weight, size and power requirements leading to lower costs. This MirrorSAR setup can be used for gapless HRWS imaging when illuminating the swath by a wide-angle high duty-cycle chirp and a high pulse-repetition frequency while the receiving platform generates multiple beams to collect the echos. Here, photonics can replace many system functions, including the optical beamforming networks (OBFN) allowing for the generation of multiple wideband beams without a significant impact on the receive platform computation and memory requirements. The OBFN outputs are multiplexed on the same channel using wavelength-division multiplexing and transferred back to the transmit platform via a free-space optics (FSO) link, where the beams are demultiplexed and coherently downconverted and digitised. An example architecture of such a system with the spectrum at selected points is presented assuming a phase shifter Blass matrix based OBFN in conjunction with a phased-array-fed reflector. Aside from additional discussion on optical frequency comb generation, beamforming network options and the FSO link, it is also shown how the concept can be straightforwardly expanded into a multistatic SAR constellation. Finally, an outlook is provided on further simulations and performance calculations required to evaluate the concept.

1 Introduction

Synthetic aperture radar (SAR) is a well established technique for radar remote sensing and has been widely used for Earth observation for over 40 years [1]. One of SARs most valuable assets is the ability to acquire high-resolution images of the Earth surface independent of weather conditions, clouds or sunlight illumination. Despite being a well established remote sensing technique, modern demands on wider coverage with more frequent acquisitions without a reduction of resolution drives the development of further performance enhancement and new concepts [2]. In conventional SAR there is a trade-off between swath width and azimuth resolution brought upon by the minimum-antenna-area constraint [3]. There have been developments of several techniques to circumvent this trade-off where one example includes utilising multiple simultaneous directed beams to collect the echoes of several pulses traversing the ground, so called multi-beam scan-on-receive (SCORE) [4][5][6][7]. Another technique for expanding the swath is f-scan, where the dispersive properties of the antenna or beamforming network is exploited to compress the echo window of each pulse, which allows for a wider swath [8][9]. A more radical solution is the spatial separation of the transmitter and receiver in a bistatic system. The separation decouples the transmit duty cycle from the swath width enabling a much longer or even a frequency-modulated continuous-wave (FMCW) signal cast over an ultra-wide swath [10][11]. Additionally, the acquired swath lacks gaps since the transmit events do not interrupt the receiver operation.

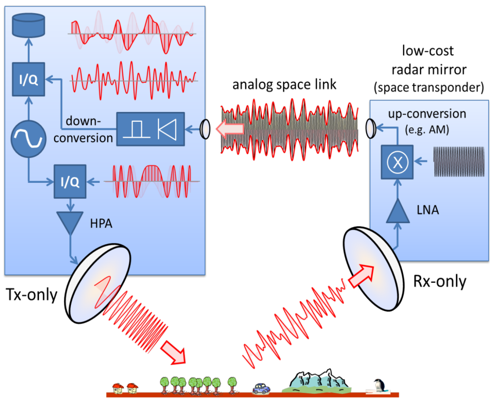

Figure 1 The basic concept of MirrorSAR [11]. The Tx-only platform transmits a chirped radar signal while the Rx-only platform acts as a simple transponder receiving, amplifying and returning the signal over an amplitude modulated (AM) free space link.

In this paper a concept for implementing a high-resolution wide-swath (HRWS) system using a bistatic MirrorSAR configuration is presented, where the beamforming and inter-satellite signal and data transfer are implemented utilising the optical domain. In Section 2 the concept of MirrorSAR and how it can be used for HRWS SAR imaging is presented. In Section 3 the role of photonics in enabling the HRWS MirrorSAR operation is explained with an example system architecture and a discussion on the various optical components and architectures. Finally, Section 4 summarises and discusses the main findings presented in the paper and provides an outlook on further simulations and performance calculations required to evaluate the concept.

2 The HRWS MirrorSAR Concept

MirrorSAR is a bi- or multistatic SAR concept first presented in [11][12] where the main idea is to allow one of the platforms, the primary satellite, to handle the high power radar transmitter, on-board processing and data downlink, while one or multiple secondary satellites handle the reception of the low power radar echo, potential beamforming and the routing of the signal back to the primary satellite. The concept is illustrated in Fig 1, with a very simple receive platform that amplifies and re-routes the signal back to the transmitter satellite, acting like a low-cost radar mirror or space transponder. The signal is then demodulated, digitised, subjected to potential on-board SAR processing, compressed and stored in the primary satellite before down-linking the data. In order to avoid a dedicated synchronisation link between the platforms the received radar echo can be modulated on a carrier using amplitude modulation (AM). This ensures that any unknown phase originating from the receive satellite local oscillator (LO) is cancelled during the demodulation process.

The main benefit of this setup is the reduced weight, size and cost of the secondary satellites since they now require no downlink communication system, a reduced radar receiver with no memory requirements and no dedicated synchronisation link. This minimizes the power demands and simplifies the thermal design. The transmit satellite benefits from less losses and a more efficient illumination due to the lack of transmit-receive modules or circulators and the extension of the transmit waveform reducing peak power requirements.

As mentioned in Section 1, the separation of transmit and receive to different platforms decouples the duty cycle from the achievable swath width, while also enabling HRWS operation without imaging gaps since the transmit events no longer interrupt the receiver. In order to achieve a high azimuth resolution in this configuration, a long chirp (or even FMCW) with a sufficiently high pulse repetition frequency (PRF) is used to avoid azimuth ambiguities due to the shorter antenna length. Given a wide swath, multiple echoes will now traverse the ground simultaneously, requiring multiple antenna beams to separate them as illustrated in Fig. 2. Using this setup, an ultra-wide swath with high azimuth resolution can be achieved through a mode similar to the common stripmap mode. Worth noting is that to match a very high azimuth resolution in the range direction a signal chirp with a sufficiently high bandwidth would need to be used to maintain a balanced resolution

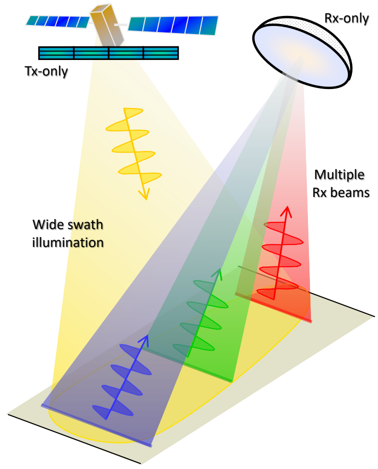

Figure 2 HRWS operation for a bistatic MirrorSAR system. The primary satellite illuminates the ground with a wide beam utilising a high PRF with a high duty cycle while the secondary satellite collects the data with several receive beams.

cell. This, together with the multiple channels created by the beams, represents a challenge on the analog space link between primary and secondary satellites.

3 Photonic HRWS MirrorSAR

To facilitate the described HRWS imaging setup and still maintain the benefits of a lightweight, simple and low power secondary satellite, while also enabling multiple channels to be transferred without any unknown residual phase, a photonics-enhanced system is suggested. The optical domain has the ability to support a large number of channels with a very large bandwidth [13], which is crucial to transfer the multiple parallel ground echo signals across the analog space link. This can be done via optical frequency comb generation (OFC) and wavelength-division multiplexing (WDM). The idea is to let each receive analog beam signal occupy a separate part of the optical spectrum enabling them to use the same analog space link without interference. This can readily be combined with the wideband operability of photonic beamforming (PBF).

A system concept employing PBF, WDM and a free-space optics (FSO) link is illustrated in Fig. 3 with the accompanying radar signal spectra at crucial parts of the architecture shown in Fig. 4. The primary satellite transmits the wide beam to image the swath while the secondary satellite collects the echo in multiple elevation channels. At point Ⓐ in the receiving satellite, an OFC is generated with a number of optical frequency lines proportional to the number of simultaneous beams required to image the swath. At point Ⓑ, the received radio frequency (RF) signal of each channel then modulates the amplitude of the generated OFC. The AM frequency lines are then fed into an optical beamforming network (OBFN) that applies the appropriate beamforming weights to each RF signal spectrum with a number of outputs equal to the number of used frequency lines. The exact configuration of this OBFN will

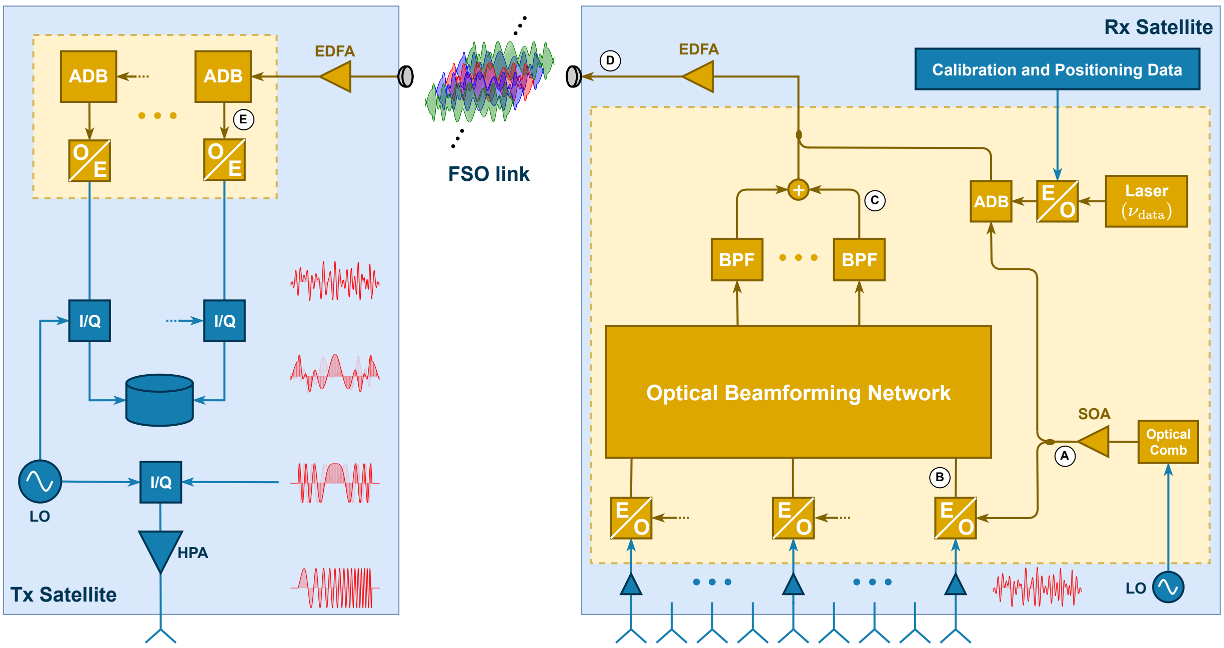

Figure 3 Example concept of a photonics-enhanced HRWS MirrorSAR system. HPA, high-power amplifier; E/O, electro-optic modulator; LO, local oscillator; SOA, semiconductor optical amplifier; BPF, bandpass filter; ADB, add/drop block; EDFA, erbium-doped fibre amplifier; FSO, free-space optics; I/Q, I/Q modulator or demodulator.

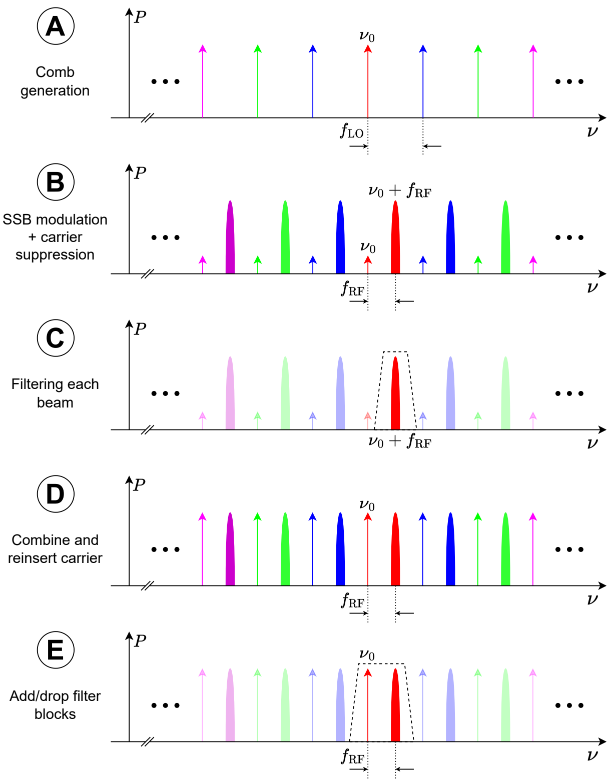

Figure 4 Spectrum at selected points in the photonic MirrorSAR system in Fig. 3. In this example, an OBFN employing phase shifters (PS) rather than true-time delays (TTD) is assumed, which means that the optical carrier is suppressed and re-inserted after the phase shifting to ensure that the beamforming weights are visible in the RF domain. SSB, single-sideband.

be discussed later. At each of the OBFN outputs an optical bandpass filter selects the AM RF signal spectra, now representing one beam each, creating the spectrum at point Ⓒ. Now the beams, encoded on separate parts of the optical spectrum, can be multiplexed onto the same channel along with any additional positioning, calibration or other data that need to be transferred to the primary satellite. This is also where the original optical carrier is re-inserted, if needed, which depends on the type of OBFN. The amplified signal with the spectrum at point Ⓓ is then sent to the primary satellite via an FSO link. At the primary satellite, the signal is amplified once more to counteract any losses over the FSO link and then fed into a suitable demultiplexing network. In this example an array of add/drop blocks acts as demultiplexers and selects the spectrum containing each beam and feeds them into separate photodetectors where point Ⓔ shows the spectrum of the signal fed into one of the photodetectors. At this demodulation step any unknown phase originating from the laser(s) or the secondary satellite LO is cancelled and each beam is now available in the RF domain for demodulation and digitisation using the LO of the transmit satellite. Since this LO has been used for generating the transmitted radar signal, any phase or frequency drifts are then cancelled in this demodulation step, as is the case for a conventional monostatic SAR.

3.1 Optical Frequency Comb Generation

There are several ways to generate a suitable OFC for the purposes of the concept laid out above [14]. However, since the number of receive beams required is relatively low (<10) so is the number of frequency lines, which argues for a less complicated comb generation scheme. As

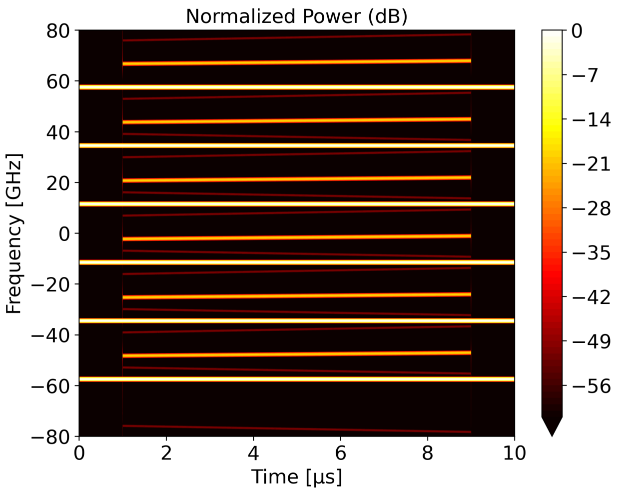

Figure 5 Short-term Fourier transform of a 6-tone comb modulated with a chirp signal. Single-sideband modulation is used, where the sideband is clearly visible next to each comb line. The second order harmonics can also be seen in both sidebands of each tone.

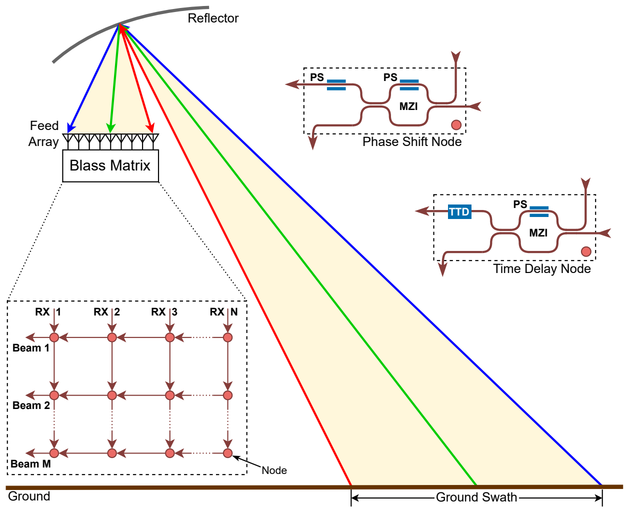

Figure 6 Phased-array-fed reflector (PAFR) in conjunction with a Blass matrix network, with two different node suggestions. PS, phase shifter; TTD, true-time-delay; MZI, Mach-Zehnder interferometer.

such, electro-optic frequency comb generation using one or two dual-arm driven Mach-Zehnder modulators (MZM) in series or parallel would be sufficient. A single MZM is capable of producing a comb with high efficiency and out of band rejection with up to 3 equal power tones, while a second MZM in series allows for up to 9 equal power tones with similar performance [15]. The power of the output comb can be adjusted by changing the output power of the feeding laser or by using an optical amplifier at the output of the generated comb. The frequency spacing achievable is tied to the bandwidth of the modulators. As an example, if one would need to generate six simultaneous beams in the X-band, six frequency lines with 23 GHz spacing could be employed, where the frequency spacing is chosen so that overlap between the RF modulated sidebands is avoided. This can be realised with two cascaded MZMs where the first generates 2 tones with a 34.5 GHz spacing while the second generates 3 tones per input tone with 23 GHz spacing. The resulting comb is visible as the bright lines in Fig 5. This would require an MZM with a bandwidth of 34.5 GHz or more, which is readily available on a number of different material platforms [16].

Any modulating RF signal would treat the lines of the generated OFC as independent sources. Fig. 5 shows the comb modulated by an X-band chirp signal with 1.2 GHz bandwidth. A single-sideband modulation is used, where the sideband is clearly visible next to each comb line. The second order harmonic is also visible at both sidebands of each comb line, but not overlapping any of the RF or carrier information, due to the carefully chosen OFC spacings.

3.2 Beamforming Network Options

For the exact configuration of the OBFN there are many options starting with the choice of phase shifters (PS) versus true-time delays (TTD). The ultra-wide swath coupled with a high chirp bandwidth would require TTD operation in order to avoid excessive degradation of the antenna beams in a planar array (PA) antenna. However, the complexity of the receive satellite would be increased employing TTDs that function over the bandwidth of the generated OFC. A simpler solution is a phased-array-fed reflector (PAFR) in conjunction with an optical Blass matrix network, which is illustrated in Fig. 6 and has already received some development and promising solutions [17][18]. The setup allows the same BFN to be employed for several beams with minimal overlap due to the mapping of different angle-of-arrivals to a smaller subset of feed elements. For the given example, each node of the Blass matrix contains a coupler and a PS. This means that the carriers in the OFC modulated by the RF echo need to be suppressed and re-inserted again after the OBFN for the phase shifts to be visible in the photodetected signal. For this operation to function without an introduced phase uncertainty, the optical paths of the channels must be equalised and have the same temperature. This is possible if all paths are housed on a temperature controlled photonic integrated circuit (PIC) marked as the yellow shaded area in Fig. 3 [19]. The PAFR reduces the effects of beam squint as compared to a PA, but if TTD is still needed the nodes of the Blass matrix can be equipped with, e.g. ring-resonator-based optical filters that ensure continuously tunable time delays over the spectrum of the selected beam [20][21].

3.3 Free-Space Optics Link

FSO links have been used for many years in various space applications including low earth orbit (LEO) to LEO, geostationary earth orbit (GEO) to LEO and satellite to ground links [22]. Therefore, there already exist many commercial options for compact high performing optical transceivers for inter-satellite links [23]. However, it is still important to ensure that the FSO link connecting the platforms does not induce too high losses or degrade the optical phase coherency beyond performance specifications.

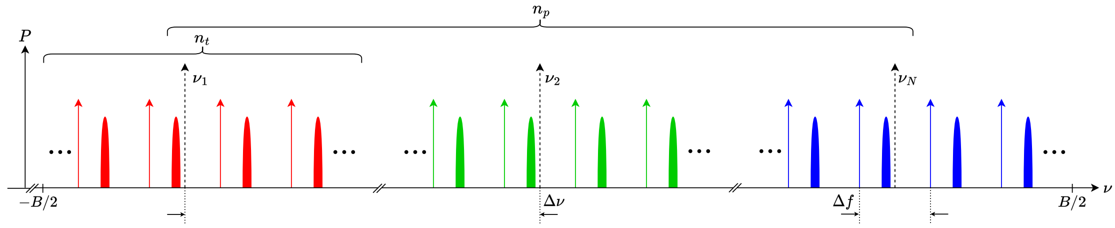

Figure 7 Optical spectrum used by a multistatic Photonic MirrorSAR constellation.

Reza et al. found in [24] that there were no losses significant enough that they could not be compensated by a commercial space-grade erbium-doped fibre amplifier (EDFA), given a less than 10 km platform separation and including propagation, mispointing and FSO transceiver losses. The lack of atmospheric effects in an inter-satellite link means that the only impact on phase coherence is the motion of the two platforms. Since the relative motion between two satellites is lower than 1 m/s and the relative instantaneous positions can be known to single millimetre accuracy using state-of-the-art GNSS technology, as in the TanDEM-X case, one could argue that it would be straightforward to compensate the small Doppler frequency shift induced, either in the transmit satellite on-board signal processing or in the ground post-processing [12][25].

3.4 Expansion to a Multistatic System

The expansion to more than one receive platform to enable interferometric capabilities is fairly straightforward. In order for the signals not to overlap in the FSO inter-satellite link, the beams from each satellite could be separated spatially, which is possible due to the narrow beam divergence of the FSO terminals ($\theta_{\text{div}} \propto \lambda/D_{\text{aperture}}$). Alternatively, the generated OFCs could occupy different parts of the spectrum, which simply means that the lasers on the Rx platforms need to have a wavelength separation of about 1 to 2 nanometres or more (optical C-band). The primary satellite is then able to separate the signals from each beam generated across the constellation via WDM as normal. An expansion of the demultiplexing network as well as a larger memory and signal processing capability in the primary satellite would of course still be required for handling the increased number of channels and data. The total optical bandwidth processed by the system and occupying the FSO link can be described by

$$B = n_t \Delta f + (n_p - 1)\Delta\nu, \tag{1}$$

where n_t and n_p is the number of tones in each OFC and Rx platforms in the constellation, while Δf and $\Delta\nu$ is the OFC tone frequency spacings and platform laser frequency spacings. The spectrum is illustrated in Fig. 7. As an example, if there are 3 Rx platforms employing 4 beams each with 23 GHz spacing, as previously assumed, the results is an optical frequency span of 276 GHz or more. If the X-band is used with the maximum $B_{\text{rf}} = 1.2$ GHz, the total RF bandwidth would be $B_{\text{rf}} n_t n_p = 14.4$ GHz.

In a bistatic system where only the amplitude information is desired, only a rough estimation of the phase is necessary, but in a multistatic system with interferometric data a much more stringent requirement on phase accuracy is necessary. Therefore, expanding to a multistatic system demands that the relative position and velocity of the platforms are accurately estimated, as well as any effects on the phase within the receive satellite platform.

The employment of TanDEM-X shows us that single-baseline SAR constellations enable accurate global digital elevation models (DEM), along-track interferometry for traffic and ocean monitoring, polarimetric SAR interferometry for vegetation characterisation and more [26]. Extention to a multiple baseline constellation would enable several additional capabilities, including multi-baseline cross-track interferometry, single-pass-tomography, and possibilities to reduce impact of speckle, improve scene characterisation and enable super-resolution [27].

4 Conclusion and Outlook

An innovative architecture for realising an HRWS bistatic MirrorSAR system capable of multistatic expansion has been presented. The inclusion of microwave photonics enable receive satellites in the MirrorSAR system to maintain a reduced weight, size and power consumption despite multiple beams on receive, multiple channels and a high bandwidth. The OBFN can generate multiple beams without a large impact on the processing and memory requirement of the receive satellites, while also enabling the multiple beam output channels, optimally separated in wavelength due to the OFC carrier, to be transferred over a single channel optical inter-satellite transmission link. The FSO link supports the transfer of a large amount of data over a single channel and enables a demodulation process that ensures coherent operation in SAR constellations. Furthermore, the mass and volume reduction enables the launch of more receive satellites and paves the way for new SAR modes and applications.

To ensure the viability of the concept, calculations on phase noise, stability, and biases need to be performed to evaluate the coherence of the system. This means that the impact on the phase from all the optical components must be characterised, including lasers, amplifiers, electro-optic modulators, filters, FSO links and opto-electronic demodulators. Since optical components have a significant temperature sensitivity, performance variation over temperature also needs to be investigated. Additionally, a more concrete design example of a photonics-enhanced bistatic MirrorSAR constellation will be developed with a detailed assessment of the SAR performance.

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