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DOI
10.1109/IGARSS.2017.8126908

Publication date
2017

Document Version
Final published version

Published in
2017 IEEE International Geoscience and Remote Sensing Symposium: International Cooperation for Global Awareness, IGARSS 2017 - Proceedings

COMPANION SAR CONSTELLATIONS FOR SINGLE-PASS INTERFEROMETRIC APPLICATIONS: THE SESAME MISSION

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ABSTRACT

This paper provides a compact overview of SESAME, a mission concept in which two receive-only small Synthetic Aperture Radar (SAR) satellites flying in close formation would allow single-pass interferometric observations using Sentinel-1 as transmitter.

Index Terms— bistatic, companion missions, Synthetic Aperture Radar

1. INTRODUCTION

There is an increasing interest in distributed or fractionated mission concepts for Earth Observation (EO) that seems to follow a general technological trend. In the case of SAR missions, however, there is a clear measurement-technical rationale leading to distributed mission concepts: formation flying multistatic SAR systems allowing single-pass interferometric acquisitions with arbitrarily large baselines. The scientific and economic value of this type of missions have been amply demonstrated by the TanDEM-X mission [1].

Probably, the first worked out companion mission concept was the interferometric Cartwheel [2]. In contrast to TanDEM-X, whih features two fully capably almost identical SAR systems, the Cartwheel system would have consisted of a set of of three formation-flying receive-only spacecraft accompanying ENVISAT. Similar mission concepts include, for example, PICOSAR and SAOCOM-CS [3].

This paper presents an overview of SESAME (SEntinel-1 SAR Companion Multistatic Explorer), a mission proposal in response to ESA's Earth-Explorer 9 call. SESAME would extend the capabilities of Sentinel-1[4] by adding a pair of close formation-flying receive-only spacecraft in order to enable single-pass interferometric observations, as illustrated in Fig. 1.

The SESAME mission is dedicated to the observation of land surface topography, topographic change and bio-geophysical parameters in order to advance the scientific understanding and modeling of dynamic processes of the geosphere and biosphere. The observations focus at processes that are associated with distinct temporal changes of shape and elevation of land surfaces and ice bodies, as well as forest height and biomass. Available topographic databases with (near) global coverage are lacking the capability to capture and quantify key features as required for studying dynamic processes that are shaping and transforming the land surfaces, ice bodies and vegetation cover. The SESAME mission will be able to fill this critical gap by providing repeat acquisitions of precise, spatially-detailed elevation data over land surfaces including ice covered areas and forests.

The primary SESAME objectives respond directly to specific challenges of ESA's Earth Observation Science Strategy for Cryosphere, Solid Earth and Land Surface, exploiting the Single-Pass Interferometric SAR (SP-InSAR) capability of the mission.

2. MISSION ARCHITECTURE

As illustrated in Fig. 1, in SESAME's system concept two receive-only C-band radar satellites fly in close formation relative to each other, and at an along-track distance of roughly 200 km with respect to Sentinel-1 C or D, which is used as a transmitter of opportunity.

2.1. TOPS mode and the dual companion solution

The use of Sentinel-1 as illuminator has a number of advantages, like a very high orbit duty cycle or a unified mission control. However, it also imposes several constraints. A major challenge is the standard use of the TOPS acquisition mode [5]. The first consequence, which we will address later, is the need to follow the azimuth scanning performed during TOPS acquisitions.

A more subtle issue is the reduced Doppler bandwidth with respect to a stripmap acquisition. An along-track separation, B_{AT}, between two receiving spacecraft results in an instantaneous Doppler shift given by

$$f_{\mathrm{D}} = K_r \cdot \tau_{\mathrm{AT}} \approx K_r \cdot \frac{B_{\mathrm{AT}}}{2 \cdot v_{\mathrm{orb}}}, \tag{1}$$

where K_r is the Doppler rate and v_{orb} the orbital velocity. For Sentinel-1's Interferometric Wide Swath (IWS) mode, the processed Doppler bandwidth is in the order of $340\,\mathrm{Hz}$, which, substituting in (1), means that the along-track separation between the two receivers has to be much smaller (in our mission analysis we set a factor of $1/3$) than $2.5\,\mathrm{km}$. While the TanDEM-X experience shows that the resulting relative orbit control requirements can be comfortably met in a scenario with identical spacecraft, they would be nearly impossible to meet in a heterogeneous formation. Thus, without entering into additional programmatic or mission safety considerations, compatibility with TOPS acquisitions naturally leads to a two-satellite solution.

2.2. Formation flying and mission phases

For a single-pass interferometry observation concept, one of the most fundamental parameters is the height of ambiguity,

$$h_{\mathrm{amb}} = \frac{\lambda_0 \cdot R \cdot \sin\theta_{\mathrm{inc}}}{B_{\perp}}, \tag{2}$$

which is proportional to the carrier wavelength λ_0, the slant-range to the target, R, and the sine of the angle of incidence, θ_{inc}, and inversely proportional to the cross-track perpendicular baseline, $B_{\perp}$.

Formation flying provides the opportunity to dynamically reconfigure the observation geometry in order to optimize this h_{amb} for specific scenarios. At the same time, it introduces an unwanted latitude dependence. With SESAME, these two aspects are addressed by organizing the mission in two periodically alternating phases.

First, a *polar phase* designed to provide the desired heights of ambiguity in the polar regions. Due to vanishing horizontal baselines at high latitudes, these large cross-track baselines need to be implemented though a vertical separation (introduced via a differential orbit eccentricity, Δe).

By virtue of the Clohessy-Wiltshire equations, a relative vertical motion results in a twice as large relative along-track motion. Consequently, considering (1), vertical baselines in the order of $1\,\mathrm{km}$ over polar regions imply vanishing common Doppler bandwidths at more meridional regions. Large Δe values are expensive in terms of the formation maintenance budget (Δv).

These two problems will be mitigated during *non-polar phases* by reducing the vertical separation and re-

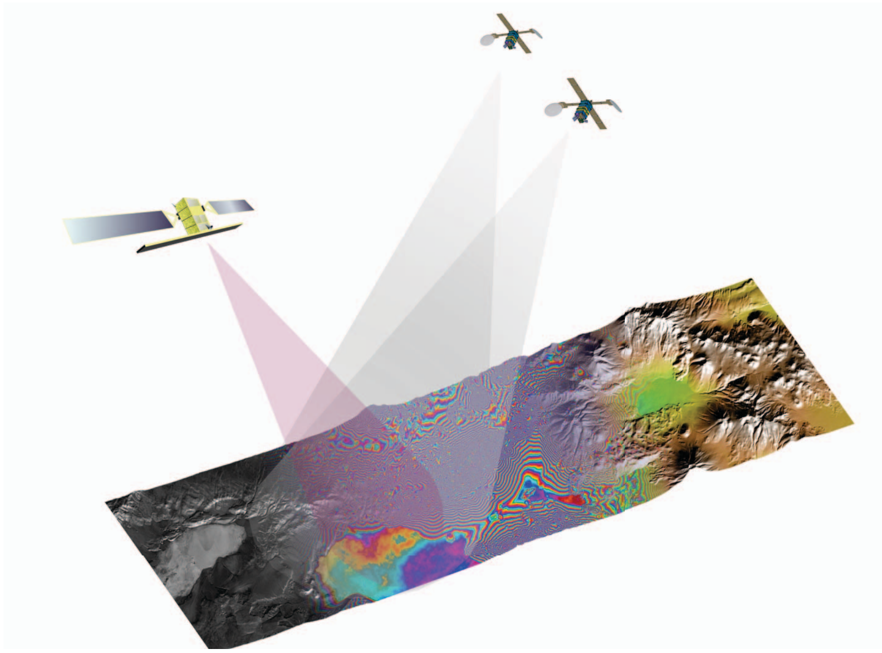


Fig. 1: Artist illustration of SESAME system concept.

lying, primarily, on small differences in the longitude of the ascending node ($\Delta\Omega$) to provide horizontal baselines. In addition, small differential inclinations (Δi) will be used to obtain a linear progression of this $\Delta\Omega$ to provide baseline diversity with a low Δv cost.

Fig. 2 shows the timeline of heights of ambiguity resulting from our current formation timeline for 360 days (30 Sentinel-1 repeat cycles) of operations for the first IWS subswath (steepest indicent angle).

2.3. Acquisition scenario

SESAME's acquisition scenario is, of course, primarily constrained to following that of Sentinel-1. It is further limited by the formation dependent common Doppler availability. In order to cap the data volume and to simplify the instrument, our baseline scenario is to acquire only one Sentinel-1 subswath at a time. Different subswathes will be acquired, as required, in different passes.

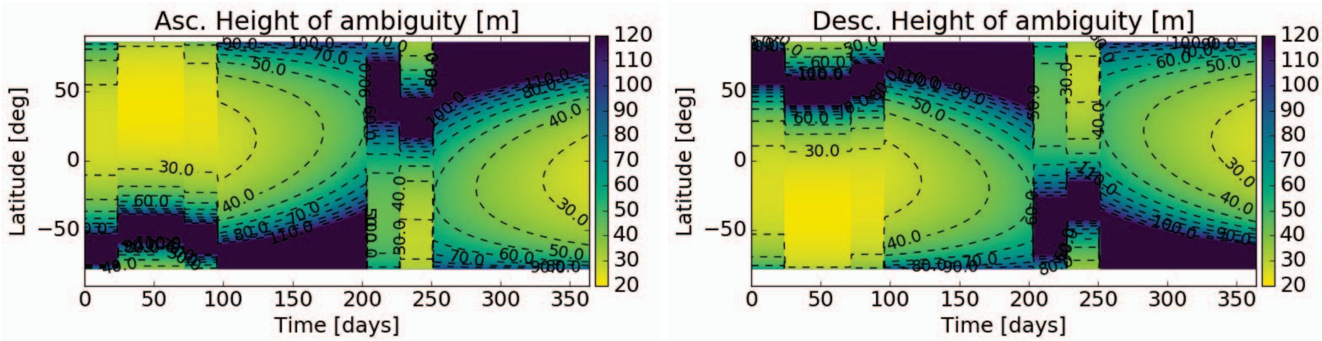
Our preliminary one year acquisition timeline includes: An 8 cycle (96 days) northern polar phase, where first and third subswath ascending orbit acquisitions would be interleaved in order to provide, primarily, incident angle diversity; A 10 cycle (120 days) regular phase dedicated primarily to boreal forests, and solid earth ascending orbit acquisitions associated to natural hazards and non-polar glaciers; A shorter 4 cycle (48 days) southern polar phase; A second 10 cycle non-polar phase providing, primarily, complementary descending acquisitions over most regions of interest.

With this acquisitions plan, the daily orbit duty cycle remains below $7\,\%$, while daily data volumes stay under a $2.5\,\mathrm{Tbit}$ for both spacecraft combined.

3. SPACE SEGMENT

The space segment consists of two 200 kg class spacecraft carrying a receive-only radar payload. A recurring challenge in the design of companion SAR payloads is to solve the conflict between the need to provide adequate ambiguity suppression, which requires large antennas, and the the promise of a light-weight and low-cost system.

For SESAME, this is addressed by the use of two small (in the order of $1\,\mathrm{m}^2$) antennas spaced approxi-



(a) Ascending

(b) Descending

Fig. 2: Heights of ambiguity timeline as a function of latitude for 30 repeat cycles.

mately 4.5 m in flight direction. This yields an comb-like azimuth pattern with a mainlobe that has, approximately, the same beamwidth as that of Sentinel-1, but which is flanked by a series of grating-lobes. These grating-lobes are, however, suppressed by the transmit pattern. The narrow mainlobe implies that SESAME must follow the azimuth beam steering introduced by TOPS. The current baseline is to acquire the echoes received by both antennas, and do this azimuth steering on the ground using Doppler-dependent Digital Beamforming. Altogether leads to an Azimuth Ambiguity to Signal Ratio of around $-18\,\mathrm{dB}$, which is about $7\,\mathrm{dB}$ better than what would be achieved using a single short antenna with the same total area.

SESAME will use a two-way link for mutual synchronization. System-level synchronization with Sentinel-1 is not required, since phase errors introduced on the transmit side are common to both receivers and cancel out in the resulting interferogram.

4. OUTLOOK

This paper has provided a brief overview of the SESAME mission, highlighting some salient technical aspects. Our current analyses show the technical feasibility and adequate overall performance of the mission.

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