PRELIMINARY PERFORMANCE ANALYSIS AND DESIGN FOR A DISTRIBUTED P-BAND SYNTHETIC APERTURE RADAR

Giovanni Alberti, and Giancarmine Fasano

Consortium for Research on Advanced Remote Sensing Systems (CO.RI.S.T.A.)
Via J.F. Kennedy 5, 80125 Naples, Italy
email: alberti@unina.it, g.fasano@unina.it
web: www.corista.unina.it

Marco D'Errico

Department of Aerospace and Mechanical Engineering, Second University of Naples
Via Roma 29, 81031 Aversa (CE), Italy
email: derrico@unina.it

Stefano Cesare, and Gianfranco Sechi

Thales Alenia Space Italia S.p.A., Business Unit Optical Observation & Science
Strada Antica di Collegno 253, 10146 Turin, Italy
email: stefano.cesare@thalesaleniaspace.com, gianfranco.sechi@thalesaleniaspace.com

Mario Cosmo, Roberto Formaro, and Quirino Rioli

Agenzia Spaziale Italiana
Viale Liegi 26, 00198 Rome, Italy

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ABSTRACT

This paper focuses on a new concept for spaceborne P-band radar implementation, that is distributed SAR based on formation flying. This approach can in principle allow to overcome physical constraints that limit the performance of monolithic SARs, leading in the P-band case to huge antennas and hard swath/resolution trade-offs. The proposed SAR is based on a larger transmitting satellite and a set of lightweight receiving-only platforms. This architecture also allows for multi-mission capabilities. In particular, in the P-band case forests observation and biomass estimation can be in theory combined with interferometric ice sounding. Payload concept is clarified, and a preliminary performance analysis in terms of ambiguity and coverage is proposed.

1. INTRODUCTION

This study deals with a spaceborne P-band mission based on an innovative distributed architecture. This mission was considered in the Phase A study for an Earth Observation Mission based on Satellite Formation funded by the Italian Space Agency (ASI). The study has been conducted under the coordination and leadership of Thales Alenia Space Italia (TAS-I), and CO.RI.S.T.A. has been in charge of assessing the scientific applications and defining the payload architecture.

Low frequencies and P-band are widely considered of high interest from a scientific point of view, in particular for biosphere and bioclimatology studies, glaciology, and geophysics.

However, in spite of its scientific value a spaceborne P-band radar poses significant technological challenges, which are mainly connected to the necessity to use huge antennas (order 100 m^2) because of requirements on power and ambiguities. Moreover, a traditional implementation of the sensor has some strong limitations in view of the scientific applications. For example, full polarization (which is believed to be necessary to correct Faraday rotation) leads to double the radar Pulse Repetition Frequency (PRF) for given azimuth ambiguities. As a consequence, swath has to be reduced to keep acceptable values of ambiguities in range. From the application point of view, this has a dramatic effect since

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global coverage (for biomass estimation) and low revisit time (to keep a reasonably low time de-correlation and enable application of interferometric techniques) pose contradicting requirements to orbit design and it is hard to find an acceptable compromise.

A distributed SAR allows to overcome these constraints by exploiting the enhanced sampling capability of the system [1-4]. Basically, it is comprised of a number of cooperating antennas which are able to gather the radar signal sent by one of them and reflected by the Earth surface, so that global system PRF depends on effective PRF and on the number of satellites. The system is based on accurate positioning and synchronization among all the satellites which fly in formation.

The paper gives an overview of options and trade-offs for the distributed system, focusing on the payload related aspects. In particular, first of all scientific applications of P-band, observation requirements, and critical aspects related to a classical "monolithic" implementation of the sensor are described. Then, distributed payload concept is clarified and details about the distributed SAR performance are provided. Different sensors architecture are traded-off against each other to find a good compromise between number of satellites, antennas dimensions, global system performance. Finally, considerations on the possibility to combine biomass estimation and interferometric ice sounding in a (unique) formation flying mission are presented.

2. P-BAND SAR DATA APPLICATIONS AND PERFORMANCE REQUIREMENTS

Low frequencies are widely considered of high interest from a scientific point of view, in particular for biosphere and bioclimatology studies, glaciology, and geophysics. The two main applications considered in literature are forest areas classification and biomass estimation, and ice sheets sounding and subsurface analysis.

Considering forests, a P-band spaceborne radar can be considered as a unique instrument to provide global coverage of both boreal and tropical forests with the possibility of biomass estimation up to limits which are unachievable using higher frequencies, like C-band or L-band, because of signal saturation [5-7]. This information is of great importance with respect to the requirements of the terrestrial carbon cycle scientific community, filling a gap in the data requirements for coupled models of the Earth System. The main reason why low frequency radars can help to retrieve forest biomass, also monitoring disturbances and flooded forests, is that at P-band the penetration into the canopy is important and the scattering comes principally from large scattering elements (trunks and large branches) where most of the above-ground biomass is stored. Thus, P-band backscattering is connected to the so called "woody" biomass, whereas leaf biomass can be estimated by other sensors (electro-optical or higher frequency SARs). Much literature deals with inversion techniques to retrieve biomass information from P-band backscatter ([5-8]).

The strong contrast at P-band between forests and unforested areas should also allow to realize accurate forest and deforestation maps, contributing to estimate the rate of deforestation and re-growth in tropical areas. Moreover, P-band measurements can give information on forest inundation.

As for P-band ice sounding applications, they are based on the fact that P-band radiation is capable of penetrating ice up to depths of a few kilometers. Thus, a spaceborne P-band sensor in theory can provide a global 3D mapping of the whole Antarctica with subsurface information on ice thickness, glacial topography, and internal layering. It is worthwhile noting that knowledge of these parameters is at the moment limited to a few areas and has been gained by means of airborne or ground-based low frequency radar sensors. On the other hand, improvement of Antarctica subsurface knowledge would be very important in the framework of climate and sea level studies, due to the key role played by dynamics of large ice sheets.

This application has already been considered in preliminary studies [9] supposing to use a nadir pointing synthetic aperture radar. This is due to the necessity to suppress the surface clutter which is present in the received signal together with the internal layers echoes.

However, recent studies [10] focused on the possibility to use a cross-track interferometer to remove surface clutter preserving basal echoes, so as to generate a 3d model of the bedrock and a global mapping of ice thickness. This measurement technique has the potential to be applied in a distributed sensor framework.

3. PAYLOAD CONCEPT AND SYSTEM ARCHITECTURE

Forests observation and biomass estimation can be achieved by a side-looking P-band SAR. In this case, the distributed payload is based on a linear formation made up of a number of satellites moving on the same trajectory with respect to an Earth-fixed reference frame. Thus, all the satellites have the same ground track. This can be obtained by separating the satellites in true anomaly and in right ascension of the ascending node, as shown in [11].

The basic concept of distributed SAR is to enhance azimuth sampling capability without impacting range ambiguities. This is why performance limits of monolithic SAR systems can be overcome. The multi-platform payload is comprised of a number of cooperating antennas able to receive the radar signal sent by one of them and reflected by the Earth surface, so that global PRF depends on effective PRF and the number of satellites. In particular, in ideal conditions global PRF is directly proportional to Nsat. Azimuth ambiguities depend on global PRF, while range ambiguities depend on effective PRF. Of course, the system relies on accurate positioning and synchronization among all the satellites which fly in formation. In fact, along-track positioning is related to uniformity of azimuth sampling. Moreover, each antenna is relatively small and by itself relatively useless, whereas the combined processing of all the received signals leads to high observation performance.

The distributed SAR concept could be theoretically achieved by two different configurations, which can be defined as multi-monostatic and multistatic.
In the multi-monostatic system, each antenna is transmitting/receiving its own signal in proper positions along the orbit. The main advantage of the multi-monostatic configuration is that tight real time control of the formation is not necessary. In fact, in this case azimuth sampling accuracy is connected to the choice of transmission instants, so accurate real time knowledge (not control) of relative position is required. However, since each antenna has to receive only its transmitted signal 3dB beams in azimuth must not intersect (neglecting side-lobes). Thus, given the large 3dB angles corresponding to relatively small antenna dimensions at P-band, required along-track distances should be of the order of 200 km. Of course, this poses major problems in determination and control of relative position and attitude.
The problem can be faced in different ways. However, if transmitted signal has not to be modified the only possible solution is that the different apertures receive the same transmitted signal (multistatic configuration). The main drawback of this architecture is that location of phase centers depends on satellites along track distance, so that accuracy in real time relative position control is strictly connected to uniformity in azimuth sampling.
In a multistatic architecture, along track baseline between satellites is flexible and can be chosen according to the following equation:

$$\Delta x_i = \frac{2V}{PRF}\left(\frac{i-1}{N_{sat}} + k_i\right), \qquad (1)$$
$$i \in \{2,3,\ \ldots, N_{sat}\},\ k_i \in Z$$

where:

V : spacecraft linear velocity (about 7.580 km/s);
PRF : Pulse Repetition Frequency (for each transmitted polarization);
N_{sat} : number of receiver spacecrafts;
k_i : an integer coefficient;
Z : relative integer number set.

The same equation holds in the multi-monostatic case without the factor two and considering signal transmission instants.
In this study, it is supposed to have a multistatic architecture with a separate transmitting-only antenna. In particular, one (larger) mother spacecraft works as the transmitter. The linear formation is made up by receiving-only microsatellites, with low weight receiving-only antennas.
This leads to the possibility of optimizing transmitter and receivers separately, avoiding transmit interference problems, and enabling larger PRF flexibility. Moreover, a higher RF peak power can be used to improve Noise Equivalent Sigma Zero. From the application point of view this scenario is more suitable for a multi-objective mission.

4. DISTRIBUTED SAR PERFORMANCE ANALYSIS

Given the principle of the system, different choices are possible regarding the number of receivers, the antenna dimensions both for the transmitter and the receivers, the processed Doppler bandwidth. Basically, increasing the number of satellites the following results are obtained: for given ambiguity requirements, effective PRF decreases, ground swath increases, data rate for the single satellite can increase or decrease as it depends on effective PRF but also on desired swath. On the other hand, a larger number of satellites can be used to improve range and ambiguity performance, while keeping adequate data rates and swaths.
Given a look at the P-band antenna realization technologies, it comes out that a possible choice consists in using, as the basic transmitting/receiving units, patches of a diameter of 44 cm, separated by a distance of the order of 0.8 λ (wavelength is about 69 cm) . In the following, possible choices about the number of receiving satellites and the antenna dimensions are analyzed considering this patch configuration.
From system engineering point of view, it is very interesting to evaluate the possibility of reducing the number of adopted patches, and so the antenna dimensions. In this case a large number of satellites is needed to gain satisfying performance. Combining small receivers with a larger transmitter antenna guarantees a good compromise between system complexity and performance.
For example, assuming a transmitter antenna of 9 X 3 patches (azimuth X range), it comes out that acceptable resolution and ambiguities are achieved in a 130 km swath using 4 rather small receiving antennas (3 X 3 patches). Or course, performance improves if 6 or more receivers are considered.
In the considered case, transmitting antenna physical dimensions are of the order of 4.8 m X 1.6 m, while receiving antennas are of the order of 1.6 m X 1.6 m.
Achievable performance for this configuration is summarized in Table 1 as a function of the number of receiving satellites (4, 6, 8). It is important to underline that full quad polarization has been considered in all the calculations. As anticipated earlier satisfying performance is achieved also with 4 or 6 satellites due to the azimuth radiation pattern of the large transmitting antenna.
In the case of 6 receiving antennas ambiguity performances are reported in figure 1 and figure 2 as a function of global system PRF, while figure 3 outlines radar data rate for a single receiver spacecraft.
It is important to note that these calculations were performed considering as a requirement an azimuth resolution of about 35 m with 8 looks. As a consequence, processed Doppler bandwidth is a fraction of the maximum bandwidth achievable by the small antennas.

Sat number (receivers)	4	6	8
Patches (range X azimuth)	3 X 3	3 X 3	3 X 3
Physical dimensions Rx antenna (m, range X azimuth)	1.5 X 1.5	1.5 X 1.5	1.5 X 1.5
Optimal effective PRF (for each pol.) (Hz)	≈ 700	≈ 566	≈ 425
RAR (dB)	-10 -17	-14 -25	-26 -32
AAR (dB)	-10	-15	-15
Data rate for the single sat (Mbit/s)	150	170	135
Swath achievable without impacting RAR (km)	130	180	200
Off-nadir angle (average) (°)	25	25	25

Table 1 - SAR performances for 4.8 m X 1.6 m Tx antenna, 1.6 m X 1.6 m Rx antennas and variable number of satellites

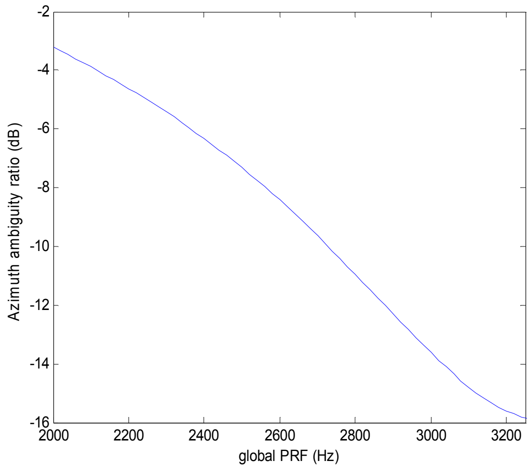

Figure 1 - Azimuth Ambiguity Ratio as a function of global PRF

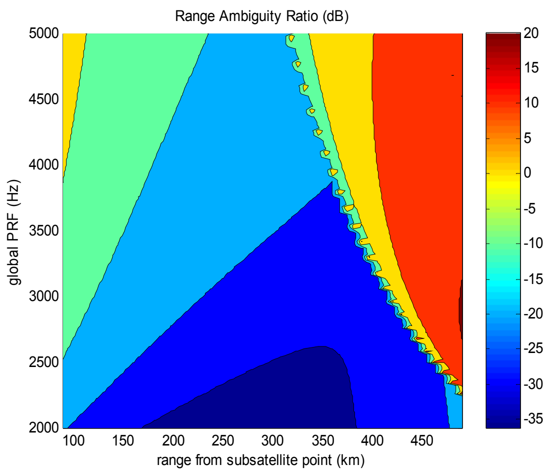

Figure 2 - Range Ambiguity Ratio as a function of global PRF and range from sub-satellite point

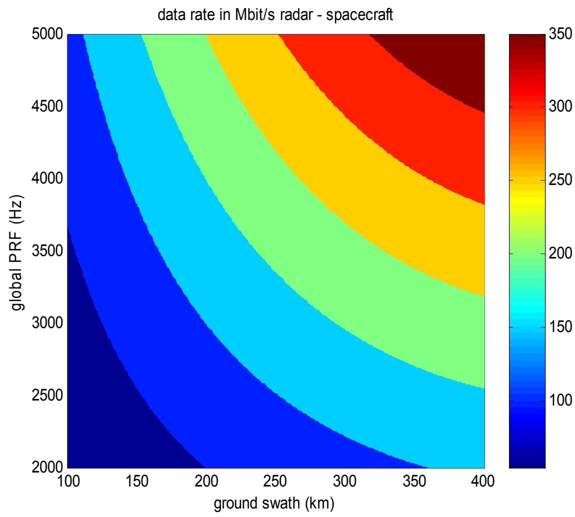

Figure 3 - Data rate from the radar to the spacecraft (single satellite)

If maximum Doppler bandwidth were processed, azimuth ambiguities would be clearly unacceptable. Of course, for the case of 8, or even more for 12 satellites, processed Doppler bandwidth can be increased to improve resolution and/or number of looks without significant consequences on ambiguity performance.

A coverage analysis has been performed on the basis of selected formation orbit (sun-synchronous dusk-dawn at an altitude of about 556 km) to evaluate radar mean orbit duty cycle requested by the application. Starting from a global biomass map based on TURC model, a binary longitude-latitude map of regions of interest has been derived (figure 4). The map has been used with an orbit propagator to estimate orbit fractions useful for the biomass application.

The result is outlined in figure 5, with a mean orbit duty cycle of 10.6 %. Periodicity is due to the considered orbit repetition factor (331/22). Mean orbit duty cycle, among other things, allows to estimate the data volume per orbit generated by the formation.

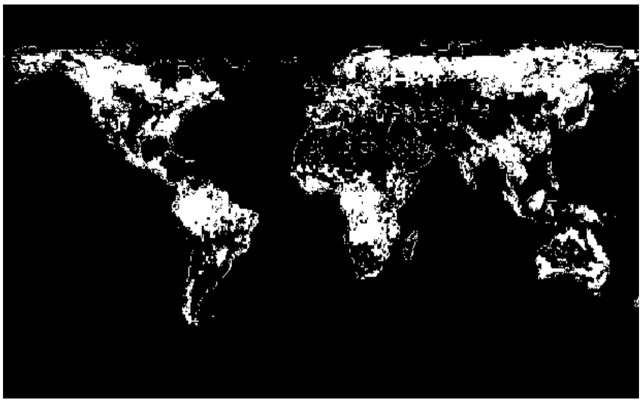

Figure 4 – Binary longitude-latitude map with regions of interest in white

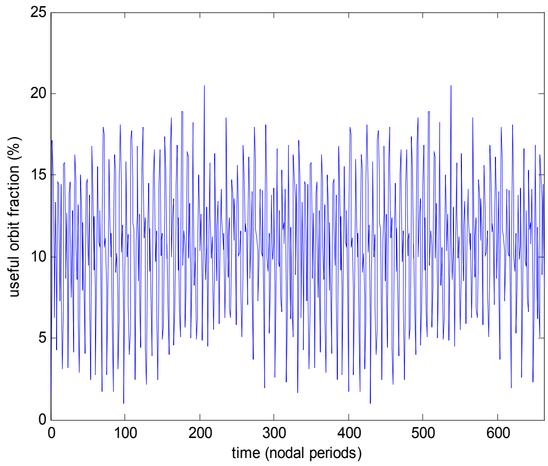

Figure 5 – Useful orbit fraction for biomass estimation during two repetition periods

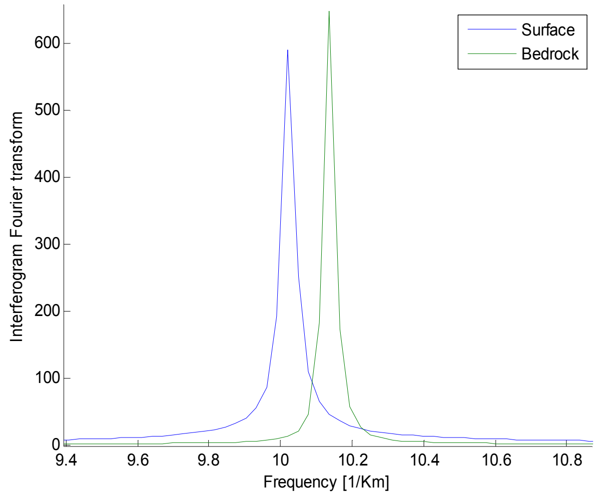

Figure 6 - Interferogram Fourier transform (By=50 m, Bz=3500 m, swath of 30 Km, bedrock depth of 3700 m)

5. DISTRIBUTED SAR FOR ICE SOUNDING

The distributed implementation of P-band SAR has also the potential to combine biomass estimation with ice sheets sounding, applying as mentioned earlier an interferometric technique [10].

This possibility relies on the fact that the mother satellite can be put in a cartwheel-like configuration [12] in order to gather interferometric data. In other words, over ice it is sufficient to add a classical monostatic SAR image generated by the mother satellite to make an interferometric pair with the other SAR image made by the bistatic SAR linear formation.

Therefore ice sheet sounding seems compatible with biomass estimation through the formation flying concept. The main difference in the two applications (besides resolution, PRF and swath, which is much smaller than before) is in the off-nadir angle that for the ice sheet sounding should be decreased significantly. Bedrock echo can be separated from ice surface return on the basis of the separation of spatial frequencies in the interferogram.

Figure 6 reports interferogram Fourier transform for ice surface and bedrock with 50 m of horizontal baseline and 3500 m of vertical baseline. The separation of the two frequencies allows for surface clutter cancellation.

An ambiguity analysis has been performed also for this configuration leading to acceptable results.

From the orbital point of view, required relative motion can be obtained at orbit poles by means of a slight difference in eccentricity (order 10^{-4}) and inclination (order $10^{-4\circ}$) between mother and children satellites. Figure 7 outlines horizontal and vertical baseline components as a function of latitude.

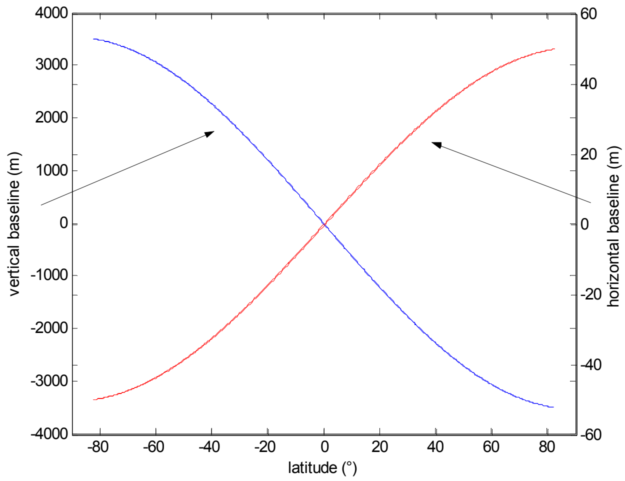

Figure 7 - Horizontal and Vertical Baseline as a Function of Latitude

6. CONCLUSIONS

This paper presented a feasibility study on a P-band Synthetic Aperture Radar based on a multi-platform architecture. It was shown how can formation flying allow to overcome intrinsic limitations of monolithic P-band SAR systems. The basic principle is to improve the azimuth sampling capability without impacting range ambiguities. Such a system is based on accurate positioning and synchronization among all the satellites which fly in formation.

The main advantages are in terms of enhanced swath, reduced mass and complexity for the satellites, enhanced flexibility and multi-mission capability. Preliminary numerical results show achievable ambiguity and resolution performance as a function of the number of receiving satellites. Adopting a mother transmitting satellite and small receiving-only children platforms is a good compromise between system complexity and performance. Moreover, this architecture allows to perform interferometric ice sounding if the mother satellite can work as a receiver too and the off-nadir angle is decreased significantly. In this case, a cartwheel-like relative motion is needed between the mother and the children satellites.

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