Exploiting Formation Flying for Earth Science: P-band Distributed Synthetic Aperture Radar

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APPLICATIONS

BIOMASS: 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 [1-5]. This information is of great importance with respect to the requirements of the terrestrial carbon cycle scientific community, filling a crucial 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 [1-4]. The strong contrast in 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. In order to achieve these observations, a traditional side looking synthetic aperture radar has to be used. It is worth noting that swath and repetitiveness play a key role in this application, since reducing revisit time on observed forests allows to better estimate vegetation evolution and the effect of factors such as fires and floods.

Mission requirements for a spaceborne P-band SAR aimed at forest observation and biomass retrieval are summarized in the following:

- global coverage of land areas below 80N and above 80S every ≤ 25 days. 25 days are required for enabling repeat pass interferometry. Of course shorter revisit times are better.
- the local time of observations must be selected in order to avoid strong ionospheric effects (phase scinitillation and Faraday rotation). A dawn-dusk orbit (or similar orbits, like 4am – 4 pm) should be a good choice
- full polarimetry should be necessary for ionospheric correction
- incidence angle not much less than 30°
- spatial resolution at most 50 m X 50 m (with 4 looks or more)
- swath width of at least 110 km to meet the revisit time requirement with incidence 30°. More would be better.
- NESZ of -30 dB (low backscatter at P-band)

ICE SOUNDING is 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 can provide a global 3D mapping of the whole Antarctica, with subsurface information on ice thickness, glacial topography and internal layering. It is worth noting that knowledge of these parameters is at the moment limited to a few areas and has been acquired 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 had already been considered in preliminary studies [7] where it was supposed to make use of 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 [8, 9] 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 can be used in a distributed sensor approach, as it will be shown in the following.

CONCEPTS

For fulfill requirements for biomass retrieval, a preliminary design based on a single satellite gives a "theoretical" antenna size of 4.5 x 22 m2 that, with an uniform illumination, allow to reach -13 dB of AAR (Azimuth Ambiguity Ratio) and about -40 dB of RAR (Range Ambiguity Ratio) over about 80 Km of ground swath. The achievable NESN (Noise Equivalent Sigma Nought) is about -37 dB with 500 W of transmitted peak power on 20% of duty cycle. The needed PRF is 655 Hz over which two pulses in different polarization should be transmitted in order to allow the full polarization mode.

The problem of having so large antenna can be overcome by exploiting the concept of distributed SAR in order to enhance the sampling capability of the system. Basically, it is made up by a number of cooperating antennas which are 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.

The basic idea consists in dividing the azimuth dimension of the original antenna among different satellites that will work with a reduced PRF. The sampling points of the original SAR system over the orbit are achieved by the satellites in an interleaved way and the original Doppler spectrum is reconstructed by the processing allowing to reach the original azimuth resolution.

This is the SAR TRAIN concept.

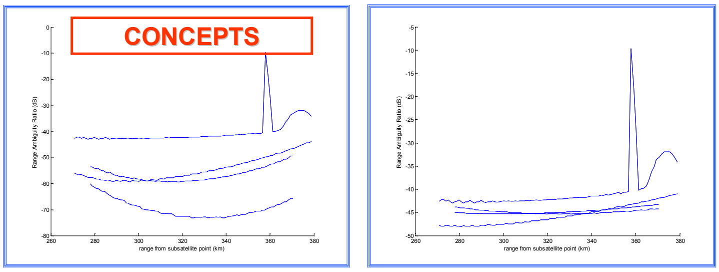


Figure 1 – RAR for a single satellite SAR system and for SAR train (Nsat = 2,3,4). The figure on the left refers to an antenna dimension along the range of 4.5 m, while that on the left the dimension has been reduced to 2.25 m, 1.5 m and 1.125 m.

The advantages are numerous:

1) each satellite works with a reduced PRF given by $PRF_i = \frac{PRF}{Nsat}$. After the processing the AAR is the same but the RAR increases significantly (see Figure 1, left side);
2) the improvement in the final RAR can be exploited for reducing the antenna size in the along range dimension at the expenses of antenna gain. This can be balanced by increasing the averaged transmitted power by exploiting the larger pulse interval allowed by the reduced PRF. In this way the NESN can be kept low or even equal to the original system (see Figure 1, right side);
3) the increasing of averaged transmitted power directly causes an increase of power demand for each satellite, if multi-monostatic configuration is used. In this operative mode each antenna is transmitting/receiving its own signal (see Figure 2, left side), so that tight real time control of the formation is not necessary. In fact, azimuth sampling accuracy is connected to the choice of transmission instants, so accurate real time knowledge (not control) of relative position is only required. In the multistatic configuration (see Figure 2, right side) the different apertures receive the same signal transmitted by one satellite, so that the uniformity in azimuth sampling is achieved by real time relative position control among the formation. If the role of transmitting source is switched among the satellites along the orbit the total averaged power demand of the system can be distributed among the components of the formation. The final result is that, by using standard techniques of fly-formation control, it is possible to reduce significantly the amount of averaged power for each satellite, allowing an implementation on micro or nano platforms;
4) finally, the overall measurement scenario can be completed by adding one mother spacecraft working as the transmitter and forcing the linear formation to work only as receiving stations. This, from one side, allow a further reduction of weight and size of each satellite and also permits to maintain the same overall performance with a lower number of receiving system. On the other side, by considering a cartwheel configuration for the mother satellite, it is possible to open the door to several interferometric application (along and across-track) for a large number of application including ice sounding;
5) for the mother satellite, it is possible to open the door to several interferometric application (along and across-track) for a large number of application including ice sounding

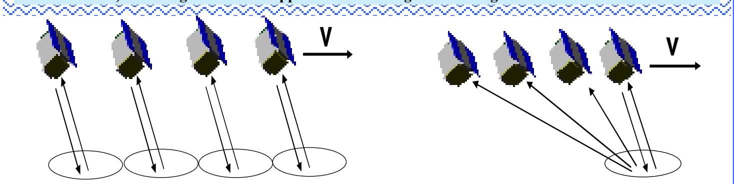
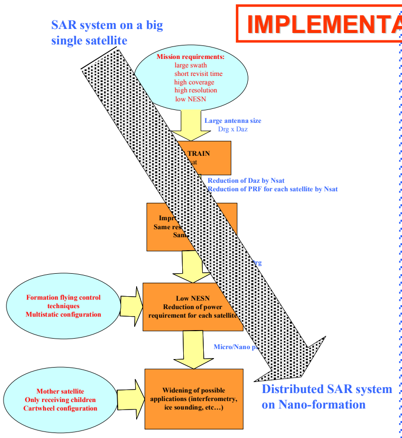


Figure 2 - Multi-monostatic (left side) and multistatic configuration (right side)

IMPLEMENTATION

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

Sat number	4	6	8	12
Patches (range X azimuth)	3 X 3	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	1.5 X 1.5
Optimal effective PRF (for each pol.) (Hz)	≈ 700	≈ 566	≈ 425	≈ 450
RAR (dB)	-10 -17	-14 -25	-26 -32	-21 -28
AAR (dB)	-10	-15	-15	-18
Data rate for the single sat (Mbit/s)	150	170	135	160
Swath achievable without impacting RAR (km)	130	180	200	220
Off-nadir angle (average) (°)	25	25	25	25

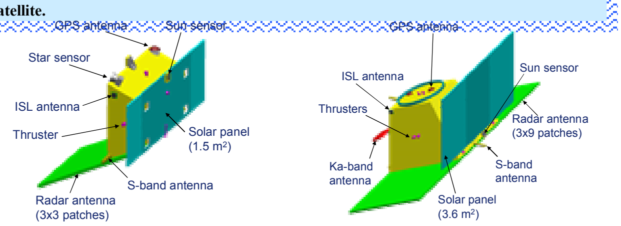


The satellite defined for implementing the distributed SAR in P-band is based on small platforms specifically equipped for the formation flying and including innovative technologies for the payload and subsystems aimed to the reducing the dimensions and the on-board resource demand. The configurations chosen allow for a deployment of a 1 mother + 4 children satellite formation with a single VEGA launch. The radar in P-band employs a lightweight planar array antenna with printed patches, RF power amplification provided by Solid-State Power Amplifier components and miniaturized Tx/multiRX chains.

The formation flying makes use of the Global Navigation Satellite System in differential mode for the determination of the relative satellite position to better than 5 cm, and proportional cold-gas thrusters for the formation geometry control.

The children satellites route the collected radar measurements to the mother satellite through an inter-satellite link (ISL) based on the WiFi protocol. The same ISL is used for exchanging the navigation data among the satellites. The mother satellite is in charge of transmitting the science data to ground through a Ka-band system utilizing a digital modulator. The data are stored on flash based mass memories. The on-board data handling is a fully integrated/modular network with system on chip processing modules, layered software architecture and networking protocol.

The estimated overall mass is 430 kg for the mother satellite and 180 kg for each children satellite.



Configuration of the mother spacecraft (left) and of the children spacecraft (right)

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