Current status about the development of an Italian airborne SAR system (MINISAR)

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ABSTRACT

MINISAR is a compact airborne interferometric SAR potentially suitable for many applications but mainly finalized for the production of technical topographic maps and monitoring the evolution of landslides events and assessing their extension and risk area. The program is co-funded by the Italian Ministry for Education, Universities and Research (M.I.U.R.)
The hardware consists in an airborne X-band radar, able to obtain a resolution less than a meter (because of a 280 MHz stepped chirp signal) and an altimetric accuracy less than 7 meters. Such an accuracy derives from an equivalent 1.5 meters baseline and the high gain antennas that let MINISAR to use a transmitted power of only 80 W. The system will be mounted on board of a small platform and it is thought to have future development for unmanned platform.
Data will be processed using a chirp scaling algorithm in order to obtain the two Single Look Complex (SLC) images which can be then processed to obtain high accuracy Digital Elevation Model (DEM).

Keywords: Airborne SAR, SAR interferometry, hazard management

1. INTRODUCTION

Among natural hazards, it is especially for floods and landslides that airborne SAR systems can play a key role mainly for their capability to provide prompt and wide observation day and night and all-weather. The goal is not only to investigate the damages but also to give warning, evaluate the risk and prevent catastrophes.
To this aim essential information arise from accurate topography of the area in addition to the possibility to monitor small movement of control points on ground with high degree of precision (of the order of 1 cm or less). Essentially, it is what classical and differential airborne SAR interferometry can offer.
In this framework it can be found the rationale that puts the Italian Ministry for Education, Universities and Research (M.I.U.R.) to partially fund the MINISAR project devoted to the design, develop and test an innovative airborne interferometric SAR sensor. The Consortium for Research on Advanced Remote Sensing Systems (CO.RI.S.T.A.), a non profit research organization formed by three University of South Italy (Napoli and Bari) and two main Italian industries of aerospace (Alenia Spazio and Laben), is responsible of the whole definition and development of the radar. The other partner of the initiative, consortium Technapoli, is in charge of the activities for developing applicative software that complete the research project.
Currently the system is under integration and its first flights are scheduled within the summer of 2004.
MINISAR will be validated with respect two main applications such as the production of technical topographic maps and the monitoring of the evolution of landslides events and the assessment of their extension and risk area.
Particular efforts have been devoted to limit dimension and weight to allow installation on board of a small platform but without sacrifice performance. In addition some design choices have been preferred (digital chirp synthesis, stepped-frequency) in order to make the system as flexible and expandable as possible. In fact, this is considered the first prototype for a further miniaturization of the sensor to allow its installation on board of unmanned platforms.
Finally, this will be the first operative airborne SAR system in Italy, totally defined and developed by Italian team.

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2. SYSTEM DEFINITION AND PERFORMANCE

In order to define the main system parameters and to assess its performance, a dedicated software tool in MATLAB language has been developed. This routine, through graphical interfaces, includes a set of classical equations that relate the main parameters for SAR systems in order to make suitable trade-off among then and to evaluate the impact directly on the expected performance.

Typically, starting from the required resolution along range and azimuth imposed by the application and antenna characteristics fixed by mechanical and realization reasons, the software tool is able to evaluate the impact of each parameter, such as the transmitted bandwidth and power, pulse duration and repetition frequency on system performance evaluated by means of achievable swath, signal to noise ratio (SNR) and signal to ambiguity ratio (ASR). Results of such analysis are shown in Table 1, where the main system parameters are reported. Some comments follow.

First of all, two main operative modes are foreseen, called narrow and wide since they differ in the achievable swath, accomplished by means of two operative altitudes (3000 and 5000 meters). In order to maintain the same SNR level, different pulse lengths are implemented (18 and 30 μsec) while the transmitted peak power is left unchanged to a very low value (80 W).

The SNR, in case of extended targets, is evaluated by the following relation:

$$SNR = \frac{P_{av} G^2 \lambda^2 \sigma_0 \rho_{gr} \rho_{az} T_i}{(4\pi)^3 R^4 KTF} \qquad (1)$$

where P_{av} is the transmitted averaged power, G is the antenna gain, λ is the used wavelength, ρ_{gr} and ρ_{az} are the ground range and azimuth resolutions, T_i is the system integration time, R is the target distance, KTF is the system thermal noise density and σ^0 is the surface backscattering coefficient.

This last parameter is evaluated by using the following relation[1]:

$$\sigma^0(\vartheta) = P_1 + P_2 \exp(-P_3\vartheta) + P_4 \cos(P_5\vartheta + P_6) \qquad (2)$$

being ϑ the off-nadir angle and where the $P_1 \ldots P_6$ parameters are function of either terrain kind, operative frequency and polarisation. In Figure 1 are shown the achievable values of SNR as a function of the off-nadir angle for various surface model, for the chosen polarisation (HH) and for both the operative modes. The goal of 10 dB is well reached within the whole swath for both the operative modes, except a fraction of the swath in the wide mode in presence of snow.

Therefore, the choice of a small transmitted power (80 W) seems surely suitable, that makes the system more compact and light with less demand of power.

	Narrow	Wide
Operative frequency	X-band, 9.65 GHz	
Polarization	Linear HH	
Transmitted bandwidth	4 x 70 MHz	
Sampling frequency	300 MHz	
Nominal aircraft velocity	70 m/s	100 m/s
PRF	210 Hz	300 Hz
Nominal off-nadir angle	45°	
Antenna elevation angle (3dB)	22°	
Antenna azimuth angle (3 dB)	2.2°	
Nominal altitude	3000 m	5000 m
Nominal slant swath	3600-5365 m	6100-8900 m
Ground Swath dimension	2200 m	3900m

	Narrow	Wide
Baseline length	1.5 m	
Transmitted power	80 W	
Pulse duration	18 μs	30 μs
Range resolution (1 Look)	0.85 m	
Azimuth resolution (1 Look)	0.5 m	
Nominal interferometric resolution (slant rg x azimuth)	0.85m x 1.5m (3 Look)	2.5m x 3m (18 Look)
Signal to noise ratio	≥ 10 dB	
Ambiguity Signal Ratio (ASR)	< -20 dB	
Signal dynamic	20 dB	
Number of bit per sample	8 bits	
Data Rate	≤ 50 Mb/s	≤ 118 Mb/s
Data Storage (10 Km strip)	7.3 Gb	12.2 Gb

Table 1: main system parameters

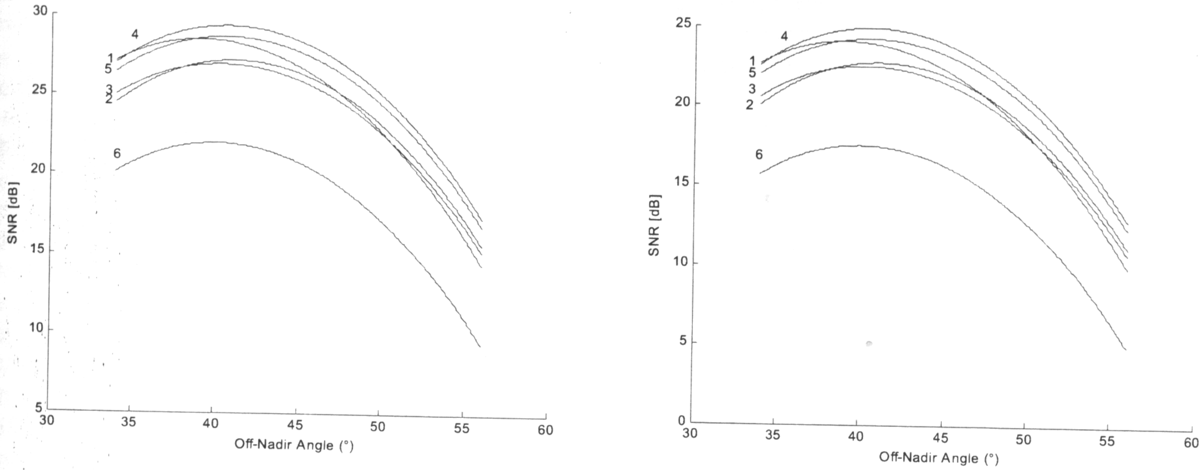

Figure 1: achievable SNR as a function of off-nadir angle for various kind of terrain (1 rock, 2 trees, 3 grass, 4 bushes, 5 short trees, 6 snow). Narrow mode on the left and wide mode on the right

The signal to ambiguity ratio is evaluated by using the classical definition reported in the following[2]:

$$ASR = \frac{\sum_{m,n\in I\ m\neq 0, n\neq 0} \int_{f_{dc}+m\cdot PRF-\frac{B}{2}}^{f_{dc}+m\cdot PRF+\frac{B}{2}} G^2\left[\alpha\left(f,\tau+\frac{n}{PRF}\right),\beta\left(f,\tau+\frac{n}{PRF}\right)\right]\frac{\sigma^{\circ}(\psi)}{R^3\sin\psi}df}{\int_{f_{dc}-\frac{B}{2}}^{f_{dc}+\frac{B}{2}} G^2[\alpha(f,\tau),\beta(f,\tau)]\frac{\sigma^{\circ}(\psi)}{R^3\sin\psi}df} \tag{3}$$

where f_{dc} is the value of Doppler centroid, B is the Doppler bandwidth and $\alpha(f,\tau)$ and $\beta(f,\tau)$ are the elevation and azimuth angles as a function of Doppler frequency and delay return time. The foreseen values as a function of the off-nadir angles are shown in Figure 2, that confirms that ASR can be kept below –20 dB in any cases.
As far as the expected interferometric performance, it is worth noting that the terrain height is mainly a function of baseline components, attitude angles, slant range, platform altitude and interferometric phase difference. Therefore, by supposing independent error causes, each previously mentioned parameter contributes to the total height uncertainty with its variance multiplied by the derivative of height with respect the considered parameter.
For extended target, main role is played by the variance of phase difference σ_{Φ}^2 that, by exploiting the Cramer-Rao bound, can be expressed as a function of the number of coherent looks N_L and image coherence γ, such as:

$$\sigma_{\Phi}^2 = \frac{1}{2N_L}\frac{1-\gamma^2}{\gamma^2} \tag{4}$$

where the image coherence can be expressed as a function of image SNR and system parameters, through α [3]:

$$\gamma = \frac{|\alpha|}{1+SNR^{-1}} \tag{5}$$

Figure 3 shows the resulting height uncertainty as a function of the off-nadir angle for both the operative modes and evaluated for point and extended targets. These results have been obtained by considering the system parameter of Table 1 and a SNR of 10 dB for extended target and 15 dB for point target and an uncertainty of 1 mm in the knowledge

of each baseline component. In narrow mode a maximum uncertainty of 5 m is reached while in wide mode additional about 2 m are loosen. In both cases the reached height uncertainty is compatible with the production of standard topographic map, 1:25000 scaled, that is the main application of the present research project.
Since the baseline of 1.5 m gives some problems with the small aircraft where this system has to be installed on, a transmitting ping-pong mode has been implemented. In this case each antenna transmits and receives a pulse alternatively, like done in satellite multi-pass interferometry. This is equivalent to have the same performance with half the baseline.
Another peculiar characteristic of this system is that the transmitted bandwidth of 280 MHz is achieved by 4 chirp signals of 70 MHz of bandwidth each, that are generated consecutively and translated in X band by means of 4 slightly different frequency values. Therefore, more precisely, the system works as a stepped-chirp radar. This is done for two main reasons: on one hand this working mode adds flexibility to the system that can be easily upgraded to transmit wider bandwidth, on the other hand this allows the use of more precise chirp generator devices able to assure high degree of phase linearity. This advantages are partially compensated by stronger requirements on timing system that should assure an high degree of accuracy (on the order of 1 nsec) on the starting time of each transmitted chirp. Taking into account also the ping-pong mode, totally 8 chirp signals have to be transmitted each pulse repetition interval (PRI).

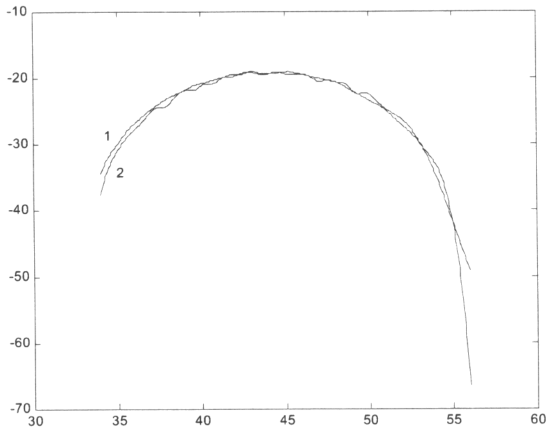

Figure 2: achievable ASR as a function of off-nadir angle (1 narrow mode, 2 wide mode)

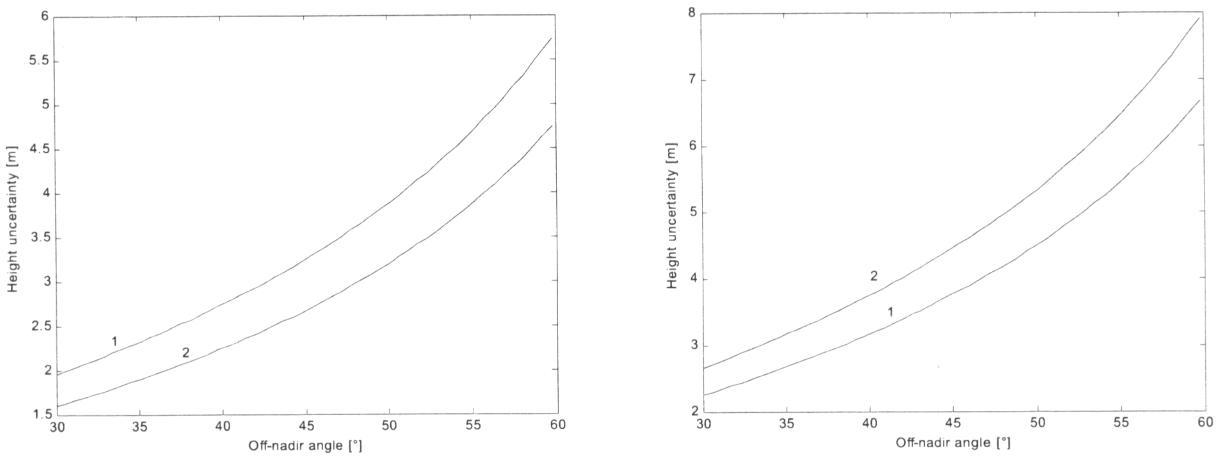

Figure 3: achievable interferometric height uncertainty as a function of off-nadir angle (1 extended target, 2 point target). Narrow mode on the left and wide mode on the right

3. HARDWARE DESIGN

The system can be thought to be composed by several module as shown in Figure 4.
The antennas have been designed by the University of Calabria, department of Electronic, Information and System in Cosenza (Italy). A first prototype has been already released, while the actual pair of antenna will be ready in September 2003. A configuration based on an multi-layer uniform array of 32x3 elements has been selected.
The antenna interface (I/F) sub-system is constituted by WR90 guidelines, circulator and ferrite switches for implementing ping-pong transmission mode.
The chirp signals to be transmitted are digitally generated by the Chirp Generation Unit (CGU). This is based on AD9852 component, a highly integrated synthesizer that uses advanced Direct Digital Synthesis (DDS) technology, coupled with an internal high-speed, high-performance (12 bit) Digital-to Analog Converter (DAC). This component allows the generation of chirp signal with bandwidth up to 150 MHz. It is mounted on board of a card provided directly by ANALOG company and it will be controlled by an additional card realized by CO.RI.S.T.A. based on PIC microcontrollers.
The Frequency Generator Unit (FGU) is the heart of the system since it is the main source of phase noise that mainly affects the interferometric performance of the radar. It provides the frequencies for the digital sub-systems and, mainly, those needed for the up and down conversion of chirp signal. Since the stepped frequency mode of the system, the FGU unit should be able to switches among four frequency values each PRI. A commercial frequency synthesizer provided by Comstron-Aeroflex company will be used.
The Up-Conversion (UPC) and Down-Conversion (DWC) units are responsible for up and down translation of the chirp signal before transmission and after reception in addition to accomplish the needed amplification and filtering. These two units have been realized by using COTS (Commercial Off-The-Shelf) components.
The TX sub-system is constituted by a commercial mini TWT that amplifies up to 120 W the X-band signal before transmitting it to the antenna. It is a commercial instrument in a 19'' rack configuration. As mentioned before, the low level of transmitted power is one of the peculiar characteristic of the system.

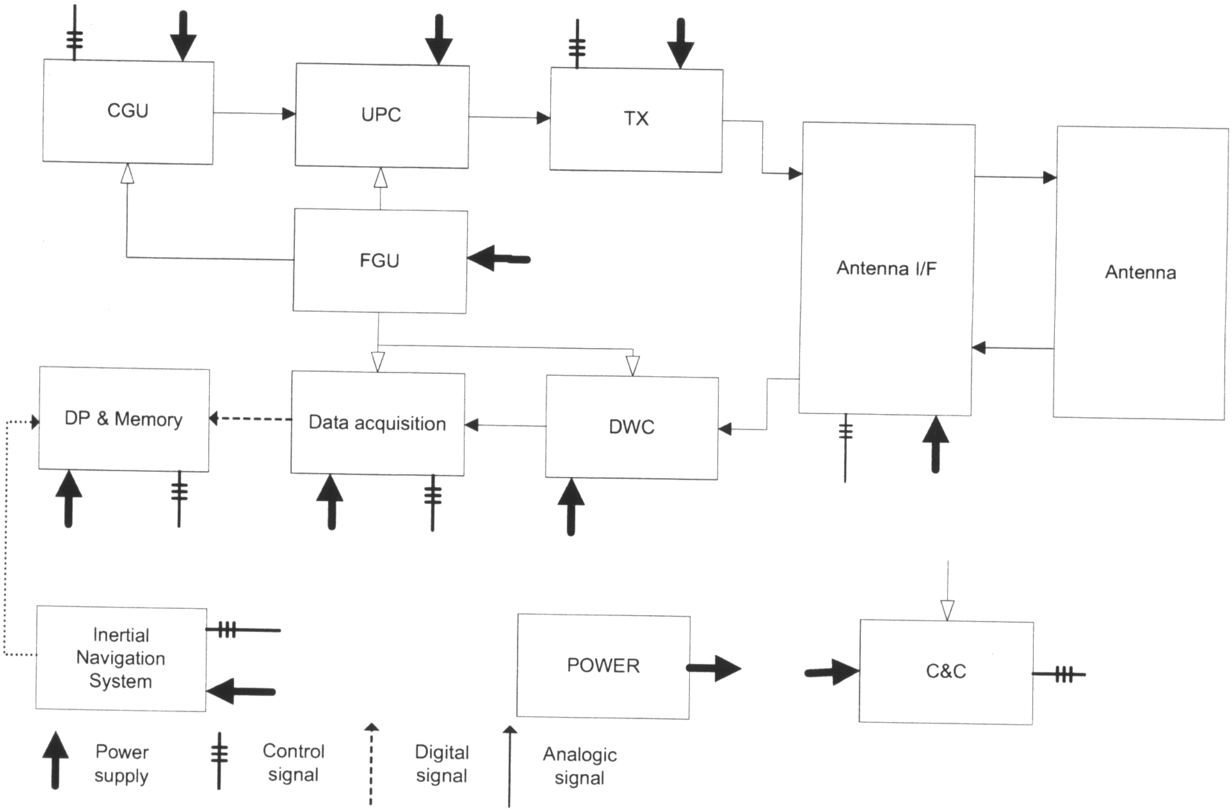

Figure 4: System architecture

The received signals coming through the two interferometric channels are acquired and digitized by two Analog-to-Digital (A/D) converters based on a MAXIM component (Max104), that is able to manage sampling frequency up to 1 GHz. The synchronization and interface needed are assured by two commercial cards equipped with VIRTEX II FPGA by Xilinx. The choice of FPGA will allow a great flexibility in the implementation of the chosen synchronization architecture.
The unit Data-Processing and Memory (DP & Memory) is devoted to the formatting of data coming from the receiving channels and the inertial navigation system and to their storing. The formatting is still implemented by the FPGA cards while all data will be stored by using normal disks controlled by a PCI card, the Streamstor PCI-816XF2 of Conduant, that is able to support up to 160 Mbyte/sec of data rate trough two output ports in FPDP format.
The radar will be controlled and commanded by a dedicated unit (C&C) by means of a graphical and friendly software interface. It will be possible to set all the operative parameters of the radar and configure the measuring mode.
MINISAR will be equipped with a dedicated Inertial Navigation System (INS) in order to measure with high degree of accuracy the attitude and position of the sensor. The selected INS unit is the model H-764G with embedded GPS, produced by Honeywell, Sensor and Guidance Products. Data provided by this sensor will be used for correcting and geo-referencing applicative products and for studying additional techniques for compensating motion errors in SAR interferometric images.
Finally, MINISAR will be totally autonomous from the point of view of power supply since it will be equipped with a series of battery that will assure about half hour of full operation.
The units devoted to radio-frequency have been already integrated and tested, while the remaining digital sub-systems will be ready within the end of 2003. During the first months of 2004, the whole system will be installed on board of a Partenavia P68 aircraft to perform its preliminary calibration flights within the summer.

4. DATA PROCESSING

A complete interferometric SAR processing chain has been developed at CO.RI.S.T.A. starting from raw data to the production of Digital Elevation Model (DEM). The processing software has been tested by using airborne data from previous campaigns performed with different sensor[4]. In particular, for image compression a chirp scaling approach has been preferred[5], due to its phase preserving properties obtained without data interpolation.
To compensate motion errors the Phase Gradient Autofocus (PGA) algorithm[6] has been implemented, while further improvement are expected by using also data coming from the dedicated navigation system of MINISAR.
Different methods for unwrapping the interferometric phase difference have been implemented[7,8].

5. CONCLUSIONS

Consortium CO.RI.S.T.A. is developing a new compact airborne interferometric SAR (MINISAR) in the framework of a research Italian project co-funded by the Italian Ministry for Education, Universities and Research (M.I.U.R.)
In this paper the main considerations that have driven the design of the system have been outlined and its expected performance presented.
The hardware architecture has been showed and the main components that will constitute the radar have been indicated.
Currently the system is under integration and the schedule foresees its installation on board of the selected aircraft within the summer of 2004. Preliminary calibration flights will follow.

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