MiniSAR, an Italian airborne interferometric SAR for environmental monitoring

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ABSTRACT: MiniSAR is a compact airborne interferometric SAR, potentially suitable for many applications but mainly finalized for producing technical topographic maps, for monitoring landslides evolution and for assessing their extension and risk area. Particular efforts have been devoted to limit its dimensions and weight to allow installation on board of a small aerial platform but without jeopardizing 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, it has been designed and assembled in view of future developments for unmanned platforms. The hardware consists in an airborne X-band interferometric SAR, 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 (achieved by adopting half physical baseline, with antennas operating in ping-pong mode) and the high gain antennas, that let MiniSAR to use a transmitted power of only 100 W. The system has been mounted and tested on board of a small platform (Tecnam P92, a JAR-VLA Very Light Aircraft). The antennas are based on a multi-layer uniform array of 32x3, and the antenna interface 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 a Chirp Generation Unit based on an 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). The Frequency Generator Unit (FGU) is the heart of the system since it is the main source of phase noise that 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 switch 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. Some example of images produced by the system will be presented.

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 high resolution, all-time and all-weather observations. 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 (Gens 1996, Rosen 2000). To this end several research teams have been developing and experiencing airborne SAR interferometric systems during recent years (Gray 1993, Zebker 1992, Faller 1995, Brenner 2003, Scheiber 1999, Schwäbisch 1999, Winner 2000).

In this framework the Italian Ministry for Education, Universities and Research co-funded the MiniSAR project devoted to 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 Universities of Napoli and the main Italian aerospace industry (Thales Alenia Space), was responsible of the whole definition and development of the radar. The other partner of the initiative, consortium Technapoli, was in charge of the activities for developing applicative software.

The main applications of MiniSAR are either production of technical topographic maps and monitoring of landslide evolution, including 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 airplane (ultra-light family) 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, need pointed out also by other investigators (Kim 2002).
Finally, this is the first operative airborne SAR system totally defined, developed and operated by an Italian team.

2 RADAR PARAMETERS AND PERFORMANCE

Tables 1 reports the main MiniSAR system parameters while Table 2 shows the main expected performance of the radar. They have been computed by means of a dedicated software tool, which, through graphical interfaces, includes a set of classical equations that relate the main SAR parameters (Ulaby 1986, Curlander 1991). It performs trade-offs among them and evaluates their impact on expected performance.
Typically, starting from the required resolution along range and azimuth imposed by the application and antenna characteristics, 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, basically achievable swath, signal to noise ratio (SNR) and signal to ambiguity ratio.
For example, Figure 1 shows the expected SNR as a function of off-nadir angle for various extended targets.

Table 1. Main system parameters.

Frequency	X-band, 9.65 GHz
Polarization	HH – VV
Chirp bandwidth	4 stepped chirps, 70 MHz each
Sampling frequency	300 MHz
PRF	200 Hz
Transmitted power	100 W
Pulse length	5 µs
Antenna	2
elevation angle	60°
range beamwidth	22°
azimuth aperture	2.2°
baseline length	0.75 m
Aircraft height	1000 m
Aircraft velocity	40-55 m/s
Squint angle	0°

Table 2. Main system performance figures.

Range resolution (1 Look)	up to 0.85 m
Azimuth resolution (1 Look)	up to 0.5 m
Resolution in interferometric mode	3m x 3m (3x6 Looks)
Clutter to Noise Ratio	≥ 14 dB
Peak to Sidelobe ratio	< -13 dB
Ambiguity to Signal Ratio	< -20 dB
Echo dynamic range	20 dB
No. of bits for sample	8 bits
Data Rate	≤ 50 Mb/s
Data Storage	7.3 Gb (about 10 Km strip-map)

As far as the expected interferometric performance are concerned, it is worth noting that the accuracy in evaluating 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 that, by exploiting the Cramer-Rao bound, can be expressed as a function of the number of coherent looks and image coherence, which depends on image SNR (Rodriguez 1992, Li 1990).
The resulting height uncertainties have been computed as a function of the off-nadir and evaluated for point and extended targets. They have been obtained by considering the system parameter of Tables 1 and a SNR of 10 dB for extended target and 15 dB for point target and an uncertainty of few millimeters in the knowledge of each baseline component.
Figure 2 shows the achievable height uncertainty in interferometric mode that results to be compatible with the production of standard topographic map, 1:25000 scaled, that is the main application of the present research project.
Since long baseline gives some problems with 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, which can be easily accomplished by using ultra-light aircraft.
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 adds flexibility to the system that can be easily upgraded to transmit wider bandwidth as well it 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 hundreds of picosec) 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).

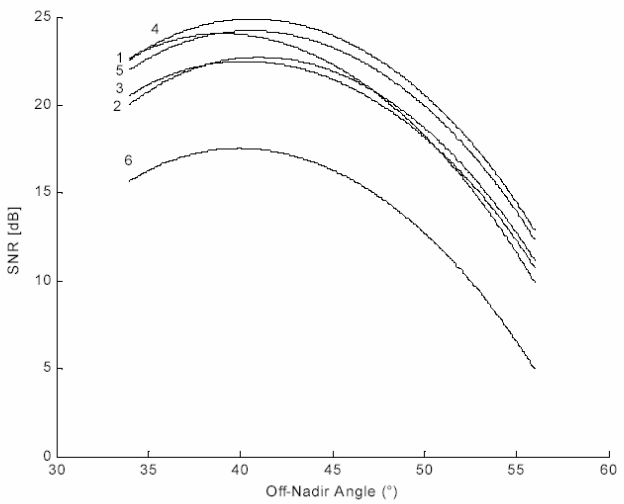

Figure 1. Achievable Signal to Noise Ratio (SNR) as a function of off-nadir angle (1 rock, 2 trees, 3 grass, 4 bushes, 5 short trees, 6 snow)

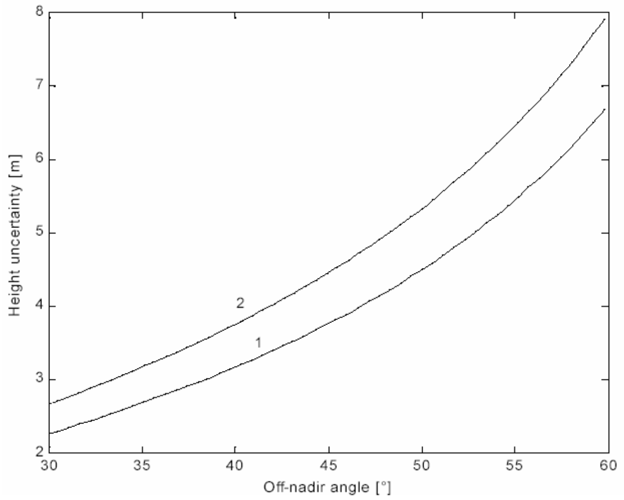

Figure 2. Achievable height uncertainty in interferometric mode as a function of off-nadir angle (1 extended target, 2 point target).

3 SYSTEM ARCHITECTURE

Regarding the hardware configuration, the system has been designed in modular boxes, so that it can be embarked on different, small aircraft.

Its general architecture is shown on Figure 3.

The antennas have been designed by the University of Calabria, Department of Electronic, Information and System in Cosenza (Italy) and their prototype is reported if Figure 4. The configuration is based on an multi-layer uniform array of 32x3 elements.

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 switch among four frequency values each PRI.

A commercial frequency synthesizer 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.

MINISAR is equipped with a dedicated Inertial Navigation System (INS), with an integrated GPS (Global Positioning System) receiver, in order to measure with high degree of accuracy the attitude and position of the sensor.

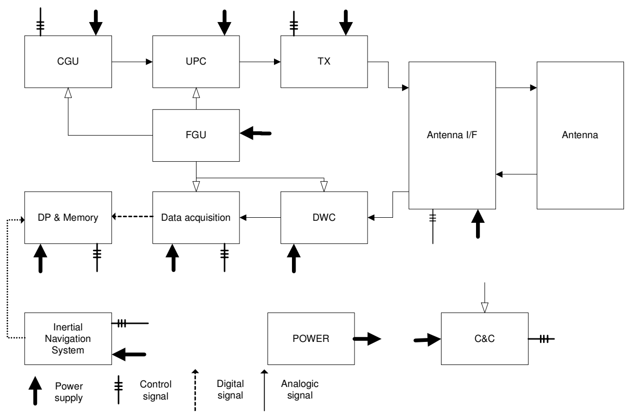

Figure 3. System architecture.

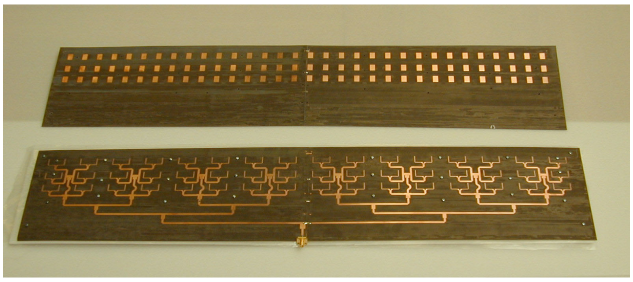

Figure 4. MiniSAR antenna layout.

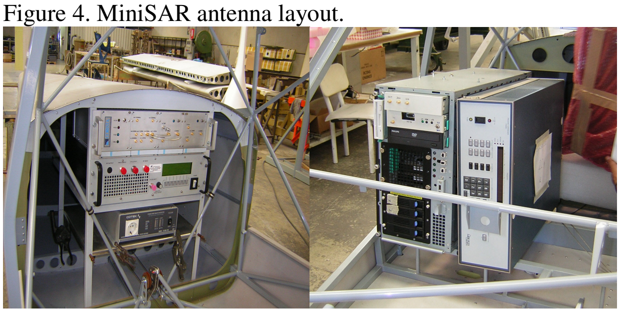

Figure 5. MiniSAR installation during aircraft assembly.

Furthermore, MINISAR is totally autonomous from the point of view of power supply since it is equipped with a series of battery that are able to assure about half hour of full operation.

MiniSAR has been installed on-board a P92-JS Very Light Aircraft (Tecnam s.p.a. property) whose final assembly has been done simultaneously to radar positioning and fixing, as shown in Figure 5.

The radar subsystems positioning has been organized in the following way:

- UPC/DWC unit, TWT unit, antenna front-end, inverter, inside aircraft fuselage, behind pilot seat (see Fig. 5 on the left);
- inside the cabin there are Data processing & A/D Conversion unit and Frequency Generation unit, which are fixed to the structure, on the left of the pilot, in place of the passenger seat (see Fig. 6);
- on the fuselage the are the two left-looking antennae.

The final MiniSAR layout is shown in Figure 7.

Figure 6. MiniSAR subsystems in place of the passenger seat.

Figure 7. MiniSAR final layout.

4 DATA PROCESSING

From the software point of view, 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). In particular, for image compression a chirp scaling approach has been preferred (Moreira 1994), due to its phase preserving properties obtained without data interpolation. To compensate motion errors the Phase Gradient Autofocus (PGA) algorithm has been implemented (Eichel 1989).

Different methods for unwrapping the interferometric phase difference have been implemented (Goldstein 1988, Giglia 1994).

During 2006 and 2007 some data campaign have been performed, aimed to test and calibrate the system and the processing chain. The selected test area is located on Monte Verna plain near Capua in South Italy. The terrain has a mean altitude of 480 m and presents various cultivation as well as hills, caves and Volturno river.

Some examples of the obtained images are reported in Figure 8, 9 and 10 compared with an optical version extracted from GoogleEarth^{TM}.

5 CONCLUSION

MiniSAR is the first operative airborne SAR system totally defined, developed and operated by an Italian team. It has been developed by Consortium for Research on Advanced Remote Sensing Systems (CO.RI.S.T.A.), co-funded by the Italian Ministry for Education, Universities and Research.

The main applications of MiniSAR are either production of technical topographic maps and monitoring of landslide evolution, including 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 airplane (ultra-light family).

MiniSAR flew during 2006 and 2007 over a test site in south Italy by gathering a great amount of interferometric and by producing several high resolution images.

Figure 8. Example of MiniSAR images (oprtical image on top extracted from GoogleEarth).

Figure 9. Example of MiniSAR images (oprtical image on top extracted from GoogleEarth).

Figure 10. Example of MiniSAR images (oprtical image on top extracted from GoogleEarth).

6 REFERENCES

Gens, R., and van Genderen, J.L., 1996, *Review article SAR interferometry-issues, techniques, applications*. Int. J. of R. Sens., 17, 1803-1835.

Rosen, P.A., Hensley, S., Joughin, I.R., Li, F.K., Madsen, S.N., Rodriguez, E., and Goldstein, R.M., 2000, *Synthetic Aperture Radar Interferometry*. Proc. of the IEEE, 88, 3, 333-382.

Gray A. L. and P. J. Farris-Manning, *Repeat-pass interferometry with airborne synthetic aperture radar*, IEEE Trans. G. R. Sens., 31, 180–191, 1993.

Zebker H. A., S. N. Madsen, J. Martin, K. B. Wheeler, T. Miller, Y. Lou, G. Alberti, S. Vetrella, and A. Cucci, *The TOPSAR interferometric radar topographic mapping instrument*, IEEE Trans. Geosci. Remote Sensing, vol. 30, pp. 933–940, Sept. 1992.

Faller N. H. and E. H. Meier, *First results with the airborne single-pass DO-SAR interferometer, IEEE Trans. Geosci. Remote Sensing*, vol. 33, pp. 1230–1237, Sept. 1995.

Brenner A. R., Ender, J. H. G., 2003, *Very Wideband Radar Imaging with the Airborne SAR Sensor PAMIR*, IGARSS'03, ISBN 0-7803-7930-6.

Scheiber R., A. Reigber, K. P. Papathanassiou, R. Horn, S. Buckreuß, and A. Moreira, *Overview of interferometric data acquisition and processing modes of the experimental airborne SAR system of DLR*, in Proc. IGARSS'99, Germany, 1999, pp. 35–37.

Schwäbisch M. and J. Moreira, *The high resolution airborne interferometric SAR AeS-1*, in Proc. 4th Int. Airborne Remote Sensing Conf., Ottawa, ON, Canada, 1999, pp. I-540–I-547.

Winner C., Siegmund R., Schwäbisch M., Moreira J., *Generation of High Precision DEMs of the Wadden Sea with Air-*

borne Interferometric SAR, IEEE Trans. on Geoscience and Remote Sensing, 38, 5, 2234-2245, 2000.

Kim S., A. Pergande, J. Hughen, *Low Cost Ka Band SAR/ISAR for UAV Applications*, IEEEAC paper # 1366, 2002.

Ulaby F.T., Moore, R.K., and Fung, A.K., *Microwave remote sensing*, Boston: Artech House, Inc., 1986.

Curlander J.C., and Mc Donough, R.N., *Synthetic Aperture Radar,* New York: J. Wiley & Sons, 1991.

Rodriguez E., Martin, J. M., *Theory and design of interferometric synthetic aperture radars*, IEEE Proceedings, Vol. 139, No. 2, April 1992.

Li F.-K., and Goldstein, R.M., *Studies of multi-baseline spaceborne interferometric synthetic aperture radars,* IEEE Trans. On Geoscience and Remote Sensing, 28, 1, 88-97, 1990.

Moreira A., Yonghong Huang, *Airborne SAR processing of highly squinted data using a chirp scaling approach with integrated motion compensation*, IEEE Trans. on Geoscience and Remote Sensing, Volume 32, Issue 5, 1994.

Eichel P. H. and C. V. Jakowatz, Jr., *Phase Gradient Algorithm as an Optimal Estimator of the Phase Derivative*, Opt. Lett., 14, 20, 1101-1103, 1989.

Goldstein R. M., H.A. Zebker, C.L. Werner, *Two dimensional phase unwrapping*, Radio Science, 23, 4, 717-720, 1988.

Ghiglia D., L. Romero, *Robust two-dimensional weighted and unweighted phase unwrapping that uses fast transforms and iterative methods*, Journal of Optical Society of America, Vol 11, No 1, pp 107-117, January 1994.