Trends for Spaceborne Synthetic Aperture Radar for Earth-Observation

Márcio Martins da Silva Costa[1] e Angelo Passaro[2]
[1]Technological Institute of Aeronautics, ITA, Praça Mal. Eduardo Gomes, 50, Vila das Acácias, 12228-611, São José dos Campos – SP, Brazil
[2] Institute for Advanced Studies (IEAv), Trevo Cel Aviador José Alberto Albano do Amarante, nº1, Putim, 12228-0011, São José dos Campos – SP, Brazil

***Abstract* — SAR satellites have been increasingly used in the last years. Nowadays, the main challenge is to combine high-resolution with large swath in order to acquire more data with more resolution in a shorter time. Several proposals have been considered in order to achieve this objective. This paper summarizes the trends on Spaceborne SAR systems that promise to overcome the current challenges.**

***Keywords* — Spaceborne SAR, Synthetic Aperture Radar, Remote Sensing.**

I. INTRODUCTION

The ability of monitoring large areas with high resolution images, independent of daylight, vegetal and cloud coverage, smoke, and weather conditions, gives to SAR system advantages over optical sensors. The SAR also has the ability to penetrate in vegetation and soil .

The cost associated to Spaceborn SAR are relatively high, however the coverage and the huge amount of data generated by this sensors are of considerable importance in Defense and for civilian activities, mainly in countries with continental dimensions, such as Brazil, China, and Canada [1]–[6].

In fact, the use of SAR satellites has growing in the last years. Several missions are already operational and there are at least 10 new missions to be launched in the next 5 years [1], [7], [8].

Nowadays, there is a considerable effort to optimize geospatial data collection, boosting the development of new SAR technologies [9].

The information obtained after the processing of SAR data are valuable for several civilian applications, such as the systematic monitoring and analysis of [1], [10], [11]:

a) deforestation, forest biomass change, forest height, vertical forest structure (applications in biosphere);

b) volcanic activities, earthquakes, landslides, plate tectonics (applications in geo/lithosphere);

c) ice cover and mass change, soil moisture, flooding, ocean currents, water level change (applications in hydro/cryosphere), among others.

SAR data have also several applications in Defense providing, for instance [8], [10]–[12]:

a) capacity to access, manipulate, analyze, and manage spatially reference data for mission planning in Geographic Information Systems (GIS);

c) operational environment awareness;
d) monitoring of borders;
c) surveillance of ship traffic;
d) detection and surveillance of targets, among others.

Until 2014, all conventional spaceborne SAR systems have used a planar antenna. In general, a few path of T/R elements are employed to steer the antenna beam towards the swath area [8], [13]. This approach limits the acquisition of SAR images combining high-resolution and wide-swath coverage. The SAR process involves the use of the Doppler shift generated by the relative movement to the ground. If the goal is to have a high-resolution in azimuth, the Doppler bandwidth must be higher on the receiver of the SAR. This implies in to increase the Pulse Repetition Frequency, PRF. However, if the PRF is increased, the echo window length is reduced in order to avoid the interference between consecutive pulses of the reflected signals. This implies in to reduce the swath width. In other words, with conventional technologies it seems that it’s not possible to have high-resolution and wide swath at the same time [1], [14].

In this paper the trends for Spaceborne SAR for Earth-observation is presented. The new technologies explored now attempt to overcome this limitation, allowing to combine high-resolution with large swath.

II. CONVENTIONAL SPACEBORNE SAR DESIGN

The geometry of conventional spaceborne SAR is illustrated in Fig. 1:

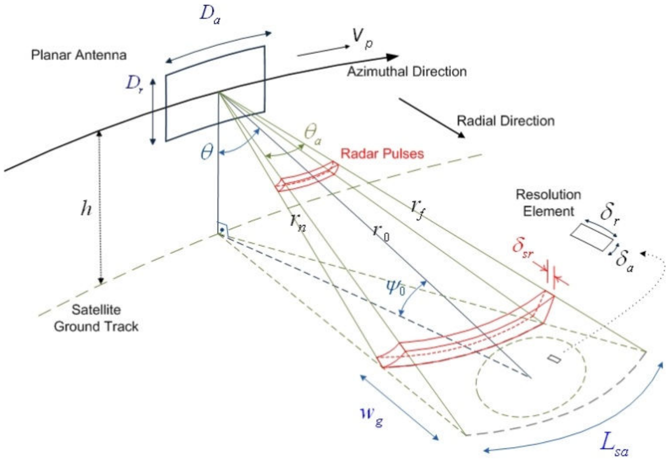

Fig. 1. Geometry of conventional spaceborne SAR.

Costa, Márcio M. S., marcio.costa.br@ieee.org; Passaro, A., angelopassaro@gmail.com.

where h is the altitude of the satellite; D_r is the width of the antenna; D_a is the azimuthal direction antenna length; v_p is the velocity of the platform; θ is the look angle; θ_a is the aperture azimuth beamwidth; r_n is the near range; r_0 is the range from the SAR sensor to the target; r_f is the far range; ψ_0 is the grazing angle; w_g is the swatch; δ_{sr} is the slant-range resolution; δ_r is the ground-plane spatial resolution; δ_a is the ground-plane azimuthal direction resolution; and L_{sa} is the synthetic aperture length [14].

The ground-plane azimuthal direction resolution is given by:

$$\delta_a = D_a / 2 \qquad (1)$$

The relation between D_a and *PRF* can be expressed by:

$$D_a = 2v_p / PRF\ , \qquad (2)$$

i.e.:

$$\delta_a = v_p / PRF\ . \qquad (3)$$

The slant-range resolution can be expressed by:

$$\delta_{sr} = c_0 / 2\beta \qquad (4)$$

where c_0 is light speed and β is the transmitted pulse bandwidth.

The ground-plane spatial resolution is obtained by projecting δ_{sr} to the ground plane:

$$\delta_r = c_0 / 2\beta \cdot \cos\psi_0\ . \qquad (5)$$

The several pulses transmitted from space by SAR satellite reach the target in different distances. In order to avoid ambiguity, i.e., the interference between consecutive pulses, a minimum time interval between each pulse is needed. This time interval increases as w_g increases and, consequently, it decreases *PRF*. The relation between w_g and *PRF* is given by:

$$w_g \approx c_0 / \left(2 \cdot PRF \cdot \cos\psi_0\right). \qquad (6)$$

Equations (3), (5) and (6) suggest that high resolution and large swath are conflicting requirements. As a consequence, it would not be possible to design a SAR satellite system providing at the same time high resolution and large swath [1], [3], [14]–[16].

However, several new techniques have been developed recently with the purpose to overcome this restriction.

III. HIGH RESOLUTION WIDE-SWATH (HRWS)

One of the new trends is to employ a planar antenna with digital beamforming (DBF) on receiver in elevation associated with multiple receive channels in azimuth (Fig.2).

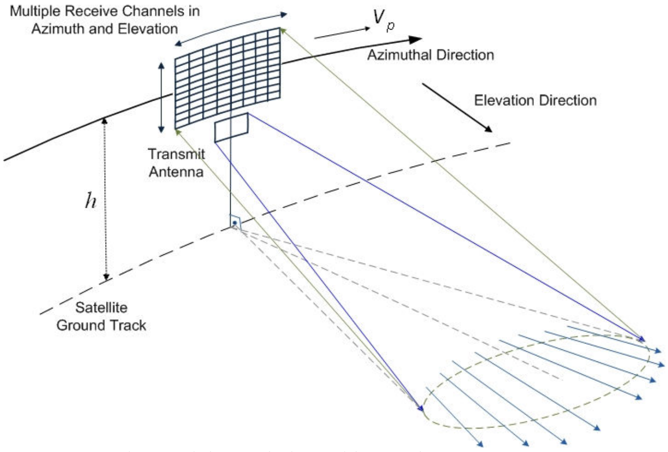

Fig. 2. High Resolution Wide-Swath SAR system.

The signal is transmitted by a single small antenna that doesn't use DBF. This antenna is designed to illuminate a wide swath with broad bandwidth. The echoes from the scene are received by DBF elements arranged in azimuth and elevation uniform path. The multiple sub-apertures are connected to a specific channel that amplifies, digitizes and records the signal for subsequent sending to the ground station. This technique is known by Scan-on-Receive (SCORE) and it has a good performance on planar scenes. However, mountainous terrains with large gaps reduce the high resolution performance [1], [13], [17]–[19].

The difference between this technique and the traditional stripmap mode lies in the coherent combination of the echo signals at the receiver.

In order to enlarge the swath, HRWS must have a long antenna. This requirement can be a limitation considering the launcher fairings [1], [19], [20].

IV. ULTRA-WIDE SWATH OPERATIONAL MODES

a) ScanSAR with Multiple Azimuth Channels

This technique employs the Burst Mode Operation. This mode allows switching the footprint presented in section III into different sub-swaths (Fig. 3). However, this technique reduces the illumination time per sub-swath. The alternative is to design a Multi-Channel in Burst Mode enabled to increase the time spent in one footprint [1], [19], [21].

According to [1] and [22] this SAR system might be used by ESA (European Space Agency) in the Sentinel-1 replacement. Nevertheless, this concept needs additional research in order to solve challenges like bandwidth variation, large variation on squint angles and different burst *PRF*[19].

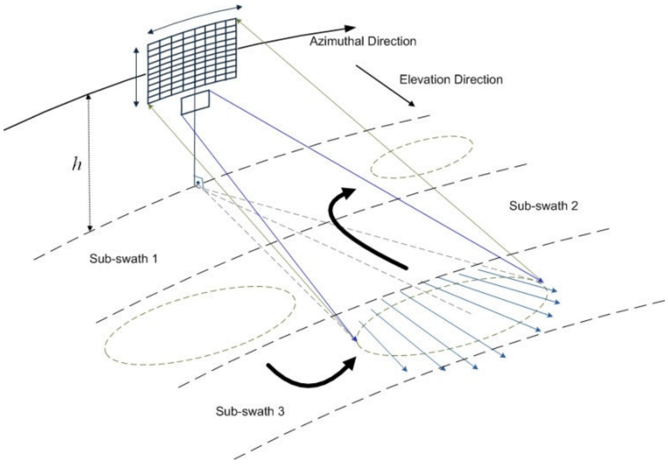

Fig. 3. ScanSAR with Multiple Azimuth Channels.

b) Single-channel SAR with Multiple Elevation Beams

This is an alternative to ScanSAR with Multiple Azimuth Channels operational mode. This approach considers a different path of elements disposed in elevation. The arrangement of elements in elevation faces different swaths that return the echo signal generated by a single transmitting antenna.

The challenge is to cover the blind ranges let between the illuminated swaths. The possible solution can be the use of a constellation where each satellite has different bursts with different *PRF* (Fig. 4) [1], [19].

The other challenge of this mode is the use of a higher SAR antenna, as discussed in Section III.

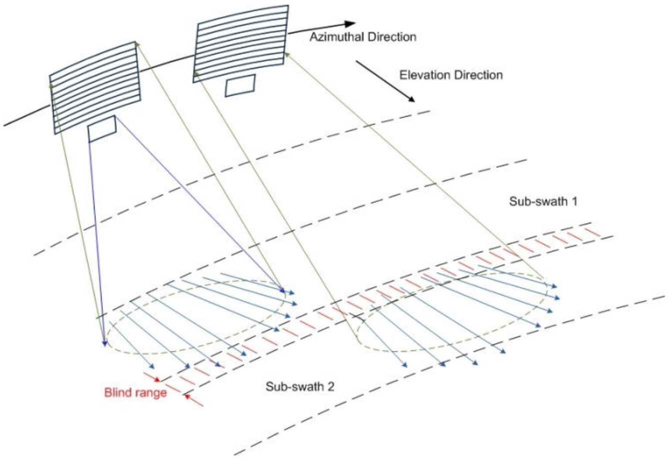

Fig. 4. Single-channel SAR with Multiple Elevation Beams.

c) Digital Beamforming with Reflector Antenna

A promising alternative to overcome the challenge of the higher planar antenna is to employ a deployable reflector antenna (Fig. 5).

The heritage of the successful employment of these antennas in telecommunication satellites enhances the trend to implement this technology in modern SAR systems.

These antennas are made with advanced light graphite-epoxy composite which has low sensitivity to space thermal variations.

The gain of the antenna allows to improve the signal-to-noise rate, using a lower transmission power. This feature reduces considerably the power requirement, usually between 3,000W and 5,000W for traditional planar systems, to levels about 1,000 W [1], [14], [19], [23]–[27].

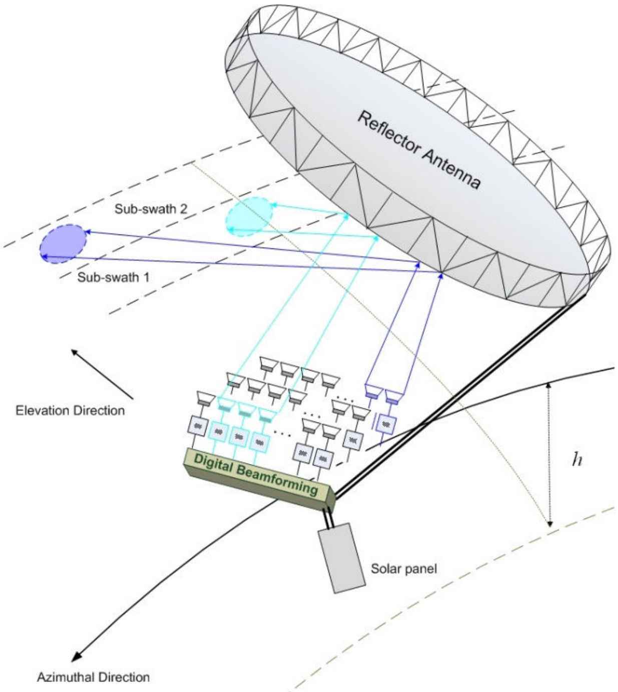

Fig. 5. Digital Beamforming with Reflector Antenna.

The antenna focuses the scene reflecting the signal transmitted by a set of feed T/R elements. This set depends on the swath that will be illuminate. The signal echoes back to the antenna and are registered through the feeds switched as receivers. Along azimuthal direction the beams are swept in order to cover the entire scene [23], [24].

This concept was introduced by NASA/JPL (Jet Propulsion Laboratory) and DLR during Tandem-L/DESDynI projects researches [1].

d) Rotating Reflector Antenna

This concept was introduce by NASA/JPL in the mission named Soil Moisture Active and Passive (SMAP).

This approach does not use a DBF technology. A single feed is pointed to the antenna that has a rotation rate about 13.0 to 14.6 rpm. The footprint has a swath about 40 km. However, the rotation along track, associated to processing algorithms, allows covering a 1.000 km of swath (Fig. 6).

The satellite was launched January, 29th 2015 and the intensive period of calibration and validation is expected to be finished at April, 27th 2016[26], [28], [29].

One of the advantages of this project is to cover a large area in a few days. The entire planet can be mapped at least four times faster than with the use of the present technology [28].

One of the difficulties to implement this technology is the spin of the antenna. The attitude of the satellite must be controlled when the rotation starts, in order to prevent displacement of the provided orbit [20].

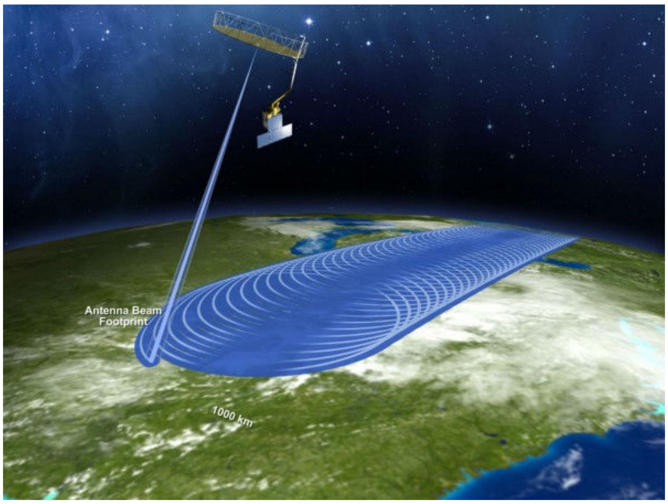

Fig. 6. SMAP Mission Illustrative concept. Available at <http://news.sciencemag.org/> and [26]. Access:July 10th.

V. FINAL CONSIDERATIONS

The future of the Spaceborne SAR systems is promising. Several missions are already launched and there are at least 10 new missions to be launched in the next 5 years[1], [7], [8].

The use of reflector antennas has a potential to cover large areas in short time. The first mission using this technology was already launched and there are new projects upcoming in the next years [26], [30].

DBF arises as a good solution to allow for SAR missions with high-resolution and large swath simultaneously. A very interesting alternative to DBF is the usage of rotating antennas with just one feed.

Ongoing researches in other areas, not mentioned in this work, the experience and results of SMAP mission, and the development of projects that use DBF will drive the trends of Spaceborne SAR Systems.

REFERENCES

[1] A. Moreira, P. Prats-iraola, M. Younis, G. Krieger, I. Hajnsek, and K. P. Papathanassiou, "A Tutorial on Synthetic Aperture Radar," *Geoscience and Remote Sensing Magazine, IEEE*, no. 1, pp. 6 – 43, 2013.

[2] M. S. M. Costa and D. Fernandes, "Análise do Emprego de uma Constelação de Pequenos Satélites SAR em Vigilância Marítima .," in *XVI Simpósio de Aplicações Operacionais em Áreas de Defesa - XVI SIGE*, 2014, pp. 90–95.

[3] G. Franceschetti and R. Lanari, *Synthetic Aperture Radar Processing*. Boca Raton, FL: CRC Press, 1999.

[4] I. H. Woodhouse, *Introduction to Microwave Remote Sensing*. Boca Raton, FL: Book, CRC Press, 2006.

[5] R. Schröder, J. Puls, I. Hajnsek, F. Jochim, T. Neff, J. Kono, W. R. Paradella, M. M. Q. Da Silva, D. M. De Valeriano, and M. P. F. Costa, "MAPSAR: A small L-band SAR mission for land observation," *Acta Astronaut.*, vol. 56, no. 1–2, pp. 35–43, 2005.

[6] D. Entekhabi, E. G. Njoku, P. E. O'Neill, K. H. Kellogg, W. T. Crow, W. N. Edelstein, J. K. Entin, S. D. Goodman, T. J. Jackson, J. Johnson, J. Kimball, J. R. Piepmeier, R. D. Koster, N. Martin, K. C. McDonald, M. Moghaddam, S. Moran, R. Reichle, J. C. Shi, M. W. Spencer, S. W. Thurman, L. Tsang, and J. Van Zyl, "The soil moisture active passive (SMAP) mission," *Proc. IEEE*, vol. 98, no. 5, pp. 704–716, 2010.

[7] "Satellite Missions Directory - Earth Observation Missions - eoPortal," 2015. [Online]. Available: https://directory.eoportal.org/web/eoportal/satellite-missions. [Accessed: 13-Mar-2015].

[8] A. Moreira, "A Golden Age for Spaceborne SAR Systems," in *Microwaves, Radar, and Wireless Communication (MIKON), 2014 20th International Conference on*, 2014, pp. 1–4.

[9] M. Younis, A. Patyuchenko, S. Huber, and G. Krieger, "High Performance Reflector-Based Synthetic Aperture Radar -A System Performance Analysis -," in *Radar Symposium (IRS), 2010 11th International*, 2010, pp. 1–4.

[10] James B. Campbell, *Introduction to Remote Sensing*, 4th ed. New York, NY: The Guilford Press, 2007.

[11] U. S. N. G.-I. Agency, "Geospatial Intelligence (GEOINT) Basic Doctrine," p. 51, 2006.

[12] J. Publication, "Geospatial Intelligence in Joint Operations," no. October, 2012.

[13] M. Younis, S. Huber, A. Patyuchenko, F. Bordoni, and G. Krieger, "Performance Comparison of Reflector- and Planar-Antenna Based Digital Beam-Forming SAR," *Int. J. Antennas Propag.*, vol. 2009, pp. 1–13, 2009.

[14] L. J. Cantafio, *Space-based Radar Handbook*. Norwood, MA 02062: Artech House Radar Library, 1989.

[15] John C. Curlander and Robert N. McDonough, *Synthetic aperture radar — systems and signal processing*, vol. 29, no. 1. Hoboken, NJ: John Wiley & Sons, Inc, 1992.

[16] N. Gebert, "Digital Beamforming on Receive : Techniques and Optimization Strategies for SAR Imaging," vol. 45, no. 2, 2009.

[17] F. Bordoni, M. Younis, E. M. Varona, N. Gebert, and G. Krieger, "Performance Investigation on SCAN-ON-RECEIVE and Adaptive Digital Beam-Forming for High-Resolution Wide-Swath Synthetic Aperture Radar," in *International ITG Workshop on Smart Antennas*, 2009, pp. 114–121.

[18] C. Fischer, E. A. Friedrichshafen, and C. Heer, "Development of a High-Resolution Wide-Swath SAR Demonstrator," in *Synthetic Aperture Radar (EUSAR), 2010 8th European Conference on*, 2010, pp. 1166–1169.

[19] G. Krieger, M. Younis, N. Gebert, S. Huber, F. Bordoni, A. Patyuchenko, and A. Moreira, "Advanced Concepts for High-Resolution Wide-Swath SAR Imaging Multi-Channel ScanSAR Mode," pp. 524–527, 2010.

[20] W. J. Larson and J. R. Wertz, *Space Mission Analysis and Design*, 3th ed. Dordrecht: Microcosm Press, 2005.

[21] N. Gebert, G. Krieger, and A. Moreira, "Multi-Channel ScanSAR for High-Resolution Ultra-Wide-Swath Imaging," pp. 3–6.

[22] C. Schaefer, C. Heer, and M. Ludwig, "Advanced C-Band Instrument Based on Digital Beamforming," pp. 1–4.

[23] T. Freeman, P. Rosen, B. Johnson, R. Jordan, and Y. Shen, "DESDynI A NASA Mission for Ecosystems , Solid Earth and Cryosphere Science," 2008.

[24] a. Freeman, G. Krieger, P. Rosen, M. Younis, W. T. K. Johnson, S. Huber, R. Jordan, and a. Moreira, "SweepSAR: Beam-forming on receive using a reflector-phased array feed combination for spaceborne SAR," *IEEE Natl. Radar Conf. - Proc.*, no. 818, 2009.

[25] W. a. Imbriale, S. S. Gao, and L. Boccia, *Space Antenna Handbook*. John Wiley & Sons, Inc., 2012.

[26] "SMAP Handbook."

[27] Z. Liangbo, L. Jie, Z. Changjiang, and W. Zhenxing, "Considerations of spaceborne SAR system design," in *Radar Conference 2013, IET International*, 2013, vol. 251, pp. 1 – 6.

[28] M. D. Stegman, "SMAP antenna feed radome: Design, development, and test," in *IEEE Aerospace Conference Proceedings*, 2011, pp. 1 – 14.

[29] "SMAP: Timeline." [Online]. Available: http://smap.jpl.nasa.gov/mission/timeline/. [Accessed: 10-Jul-2015].

[30] A. Moreira, I. Hajnsek, G. Krieger, K. Papathanassiou, and M. Eineder, "Tandem-L: Monitoring the Earth's Dynamics with InSAR

and Pol-InSAR," in *Proc. of "4th Int. Workshop on SCience and Applications of SAR Polarimetry and Polarimetric Interferometry - PolInSAR 2009,"* 2009, no. April, pp. 26–30.