GEOSYNCHRONOUS SAR FOR TERRAIN & ATMOSPHERE WITH SHORT REVISIT (GeoSTARe)

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ABSTRACT

GeoSTARe would be a mission combining the continuous view capabilities from geostationary orbits of super-continental areas with the all-day, all-weather imaging capabilities of Synthetic Aperture Radar. It would complement Copernicus Sentinel-1 bringing the repeat time from days down to hours.

In that, it would provide novel and unique observations. The well proven potentials of Radar in sensing roughness, deformations, and moisture, combined with the short time to get any image, from minutes to an hour, and the immediate data download and exploitation (thanks to the geostationary orbit) makes GeoSTARe a game changer in those fields where hourly-to-daily monitoring is a must.

1. OVERVIEW

GeoSTARe's will target:

- land: providing early detection of landslides, estimation of floods, soil moisture changes, crop growth;
- hazards: volcanic activity, prequels and sequels of seismic and aseismic motions;
- infrastructure deformations: roads, railways, bridges, dams and mines stability, permafrost;
- oil and gas: underground gas storage, carbon capture and storage ;
- snow cover: snow mass and melting, Snow Water Equivalent estimation;
- meteorology: estimation of columnar water-vapor maps continuously from space to provide accurate Numerical Weather Predictions.

The observed area could have a footprint from hundreds up to a thousand kilometers wide, set using either mechanical or electronic steering (or both), anytime, and anywhere within a continent.

Performances in terms of area covered, resolution and image time would be scalable, depending of the power available on-board and the antenna size, and expandable in a constellation of multiple mini-satellites, each of them transmitting and receiving, attaining metric resolution with sub-hourly revisit opening new perspectives for security and civil protection. In the case of an independent satellite, rather than a system hosted on a Communication Satellite (COMSAT), tiny changes of the eccentricity of the orbit could expand the width of the real antenna to be covered, thus trading azimuth resolution with signal to noise ratio, so that multiple passes could be combined into highly resolved features of the terrain, if stable.

The applications proposed would rather benefit the public sector, like emergency responders, interior Ministries or Meteorological Services. However, land-use, agriculture, infrastructure deformation monitoring would be of a strong economical interest, at a later development stage, for mining, public works and oil and gas industry.

GeoSTARe present maturity is the result of six years of studies after the proposal of a "GEOsynchronous SAR for Atmosphere and Terrain" in the frame of the 8th ESA Earth Explorer, that, while not selected, still achieved a very high ranking and was recommended for further studies.

The quasi-geostationary SAR can be thought as a special case of the geosynchronous SAR, first proposed in literature in [1], and then studied in Europe [2], USA [3], and China[3]. The demonstration of the first Chinese geosynchronous satellite has been approved in Project 'Civil Space Infrastructure' by the Chinese Government. Compared to the geosynchronous, the quasi geostationary SAR achieves continuous imaging of the same area (in place of 24-hours delay revisit) and sacrifices the continental coverage, while still retaining the continental access. Furthermore, it uses less power and more mature technologies.

2. MISSION OBJECTIVES

GeoSTARe continuous imaging capabilities with millimeter sensitivity to Line Of Sight path changes will extend the successful outcomes of past LEO-SAR missions by addressing a whole range of phenomena whose dynamics can be measured starting from hours, while the revisit span could be years.

For some applications GeoSTARe is unique, providing a measure that cannot be achieved otherwise on that time-space resolution (tens-to-hundreds of meters in time and minutes to hours in space) and regional or subcontinental scale.

This is the case of the spatial distribution of water vapor in the atmosphere, soil moisture, hydro-geological and geophysical phenomena such as landslides, seismic events, volcanic activity, and infrastructure dynamics.

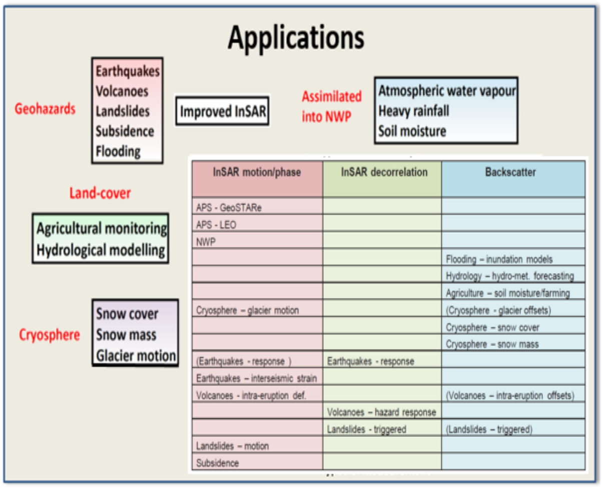

Figure 1 – Summary of GeoSTARe applications, ordered by measurable.

GeoSTARe will achieve two main scientific objectives [5]:

a. *To generate a guaranteed sub-daily series of radar observations to measure rapidly developing surface events such as river floods, landslides, earthquake damage and lava flows, and to monitor the stability of objects on earth.*

Current and future LEO-based radar constellations can achieve occasionally two measurements in the same day, but not with the same viewing geometry and not every day. GeoSTARe will enable two images per day with constant geometry to be acquired from the matching halves of the apparent daily motion created by the eccentric orbit. This capability means that applications requiring rapid response and with short lifetimes (e.g. emergency events) can be addressed in a way that guarantees systematically an useful product. Moreover, many assets on ground, such as dams, dikes, and general infrastructure can be efficiently monitored for safety and stability to prevent catastrophic events.

b. *To exploit the trade-off given by variable radar return signal integration times in various retrievals of water such as field-scale soil moisture and* ***km-scale water vapor*** *as an input to Numerical Weather Predictions.*

The availability of lower (higher) azimuthal resolution within shorter (longer) integration times through tiny changes of the geosynchronous orbit allows imaging with a wide range of options of time and space resolution. Some applications may require maximal resolution (e.g. 5 m, in the case of independent satellites) acquired over a long period (e.g. 8 hours), others will require a coarse image (e.g. 2 km) acquired over as short an interval as possible (e.g. 20 minutes). The former may be targeting a surface that is relatively stable over that period, the latter a surface that is liable to lose coherency. Processes affected by the diurnal cycle can be addressed in this way.

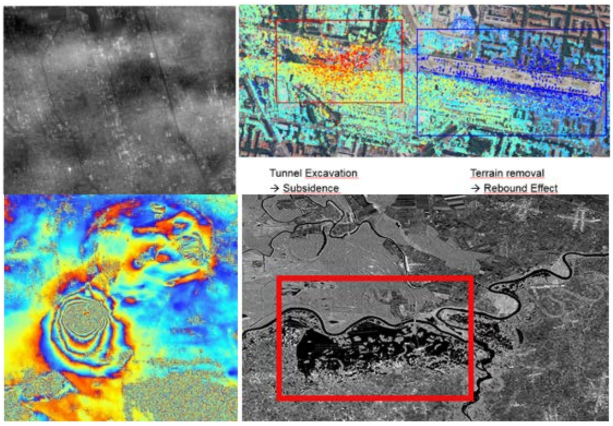

Figure 2 – Example of applications. Top left: a water vapor map, superposed to the Radar amplitude; right: infrastructures deformations estimated by PSInSAR, bottom left: SAR interferogram showing subsidences in a mine. Images courtesy of TRE. Bottom right: flooding by Sentienl-1 SAR backscatter (courtesy of ESA).

3. PRODUCTS & APPLICATIONS

GeoSTARe would exploit amplitudes, multi-polarimetric, interferometric phases and coherence to bring SAR applications, that reached maturity in decades of space-borne SAR data, to daily revisit. A summary of GeoSTARe applications is provided in Figure 1, and some examples are shown in Figure 2. Such applications addresses four of the five Living Planet domains: Atmosphere, Cryosphere, Land surface and Solid Earth, while GeoSTARe products could add value to present Copernicus services: Land Monitoring, Atmosphere Monitoring, Emergency Management and Security.

4. MISSION CHARACTERISTICS

Two concepts are suitable for GeoSTARe implementation:

#1 a *C-band fully polarimetric,* either single beam, COMSAT hosted, or multiple beam stand alone mini-satellite.

#2 a *dual-frequency L* (full-pol) + *X*, COMSAT hosted or stand-alone, with a wide L-band beam and a SPOT fine resolution in X band, positioned within the wide L band coverage [6].

COMmunication SATellites hosting compatibility limits the eccentricity to 8×10^{-4} to keep the host within the ±0.1° pointing for Earth. Such eccentricity impacts the azimuth resolution and is assumed here for performance evaluation. The other relevant element in driving GeoSTARe performances is the total power. In the table we assume to limit the mean power to 750 W in the dual-beam L+X configuration, that corresponds to 2 KW absorbed – well within capabilities of a modern mini-satellite. Performances are summarized in Table 1.

Table 1 – GeoSTARe concepts and performances

		C-band 5.4 GHz	L-band 1.257 GHz	X-band 9.6 GHz
Polarization		VV	FULL (VV)	VV
Ground Range resolution	m	20	100	5
Bandwidth	MHz	10	2-80	40
Azimuth resolution: coarse (30')	m	120	570	75
fine (7 hours)	m	10	35	5
Swath (az × rg)	km	3×(400×900)	1500×3000	200×360
Mean power	W	3×150	500	250
Antenna diameter	m	5	6	
NESZ	dB	-14...-20	-19...-26	-16...-22
SNR	dB	0...6.8	-1.2...+6.5	3...9
BITRATE	Mbit/S	18	3	70
PRF		200	40	350
Power Flux on ground	mW/km²	4.5	1	24

4.1. Concepts and TRL

One possibility is a single frequency C-band system, with a 5 m reflector illuminated by an active array. This system – heritage of Italian Cosmo-SKYMED and compact SAR [7], could scan multiple beams, accessing simultaneously several areas, say within 1°, as shown in Figure 3. The number of beams, three in the figure, can be increased by reducing the resolution, or by increasing the total power. Moving the pointing from one area to another, to cover the area in Figure 3, or even further extra European continent, can be done within minutes by mechanically steering the reflector.

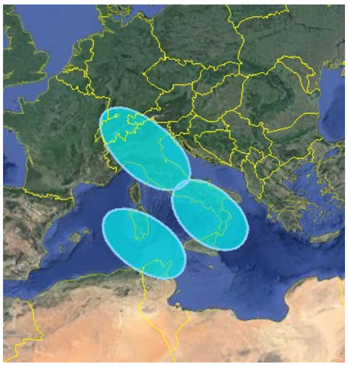

Figure 3 – Example of coverage achieved by three quasi-simultaneous (assuming electronic beam steering) C-band beams over Italy.

The second possibility is a dual-beam-dual-frequency L WIDE + X SPOT. The SPOT X-band beam can be repositioned within the coverage of the L wide beam. The L beam provides water vapor maps for meteorological forecasts and to compensate the X-band atmospheric phase screen, besides measuring soil moisture over a quite wide area. X band provides high accuracy over stable areas (urban, rocks, bare soil) with a resolution up to 3×3 m in 7 hours.

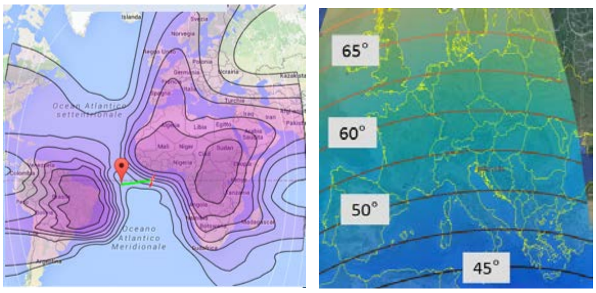

Figure 4 – Left: example of the super-continental access achieved by a commercial COMSAT satellite (Eutelsat 8 West B), from "satbeams". Right incidence angles over Europe by a geostationary satellite located at 10° longitude.

For both concepts the access would be continental (or super-continental), as shown in Figure 4 (left).
The L+X band has been studied within the frame of ESA GeoSTARe activity [5]. That concept, shown in Figure 8, exploits a dichroic surface for allowing a flexible pointing of the X band while keeping the WIDE L beam fixed. The TRL is not higher than 4 for the lack of space qualified power source in L and X band. However, they can be developed following the on-going activity in C band for METOP-SG [8]. The payload mass in the order of ~250 kg.

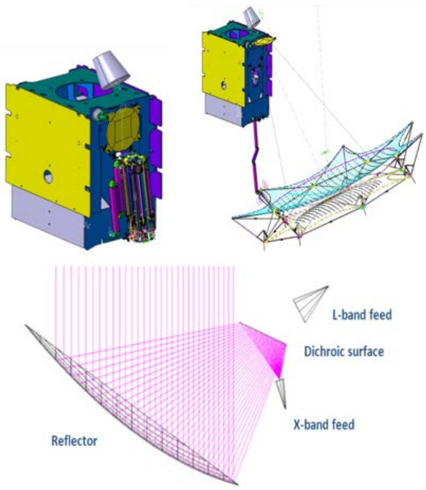

Figure 5 – Dual-band-dual-frequency, single reflector concept. Left: L+X concept. Left: stowed, middle deployed; right: geometry from [5]

The C band concept can be hosted either on a COMSAT or on a stand-alone mini-satellite. The concept shown in Figure 6 is derived from Thales Alenia Space Italy, named compact-SAR [7]. It exploits an active array to illuminate a wide reflector, achieving electronic beam steering. In a change with respect to the original compact SAR, the C band would be used in place of X. Moreover the mini-satellite, fitting into Vega launcher, is to be transferred from LEO orbit to GEO by electric propulsion. This would be achieved in 166 days, assuming a power of 6 kW and using 256 kg of mass. The TRL is pretty high, as exploiting an existing platform (PRIMA-S), an on-going development for the antenna, and C band active T/R modules from Sentinel-1. The advantages of this solution stay in the extreme flexibility and the possibility of trading anytime spatial resolution for signal to noise ratio, say using multiple passes to retrieve extremely high resolution details.

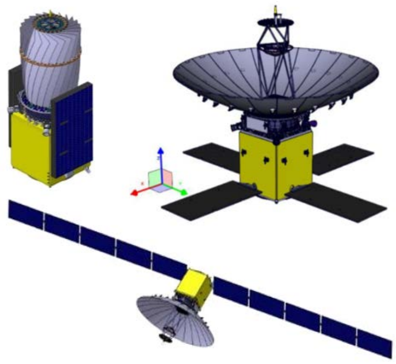

Figure 6 – C band system as stowed in VEGA launcher (left), deployed (mid) and operating, right.

4.1. Architecture, ground segment & calibration

The architecture of a geosynchronous SAR is summarized in the elements of Figure 7: the satellite, with its Radar payload and the downloading of acquired and digitized data, the ground segment for data acquisition, processing and dissemination (including programming and mission control), and the calibration structures, composed of a network of active calibrators in fixed positions and always in view of satellite. The scheme of a calibrator is on the right: they are inexpensive repeaters whose primary role is to provide precise position to allow for estimation of orbits, clock drifts etc., – in the short term.

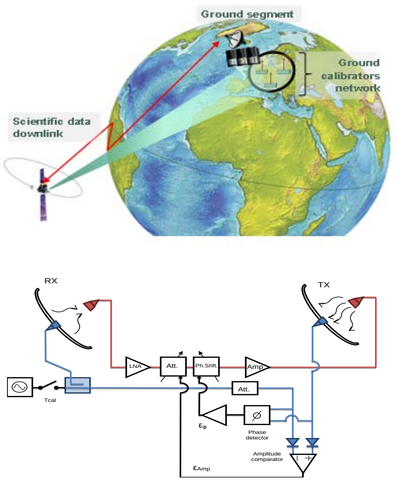

Figure 7 – Top: GeoSTARe architecture. Bottom: scheme of an active calibrator.

The ground segment architecture, in Figure 8, is quite general and common to most LEO-SAR systems. The Level-1 data processing, in the block diagram in Figure 9 is instead quite different with respect to any mission so far developed. In fact, one single image is the result of 15’ to 7 hours acquisition, data corresponds to 2-30 Giga complex samples (in the best case of 15’), that far exceeds the LEO SAR, where a single image is acquired in less than one second.
The Level-2 processing, shown in the same figure, exploits algorithms quite similar to those developed in Italy since 2000, like SqueeSAR [9] and SBAS [10].

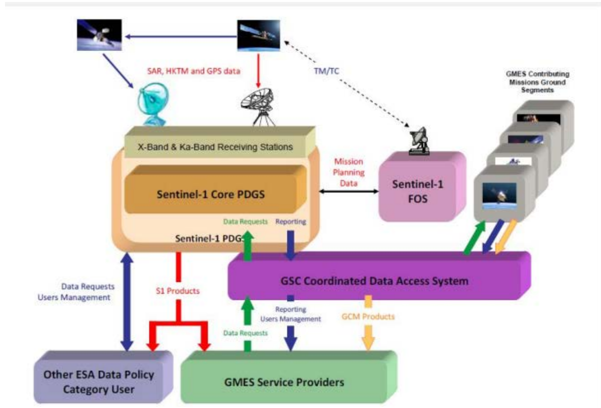

Figure 8 – Sentinel-1 Ground segment architecture. Most of the element could be re-used, by changing processors.

4.1. End to end demonstration

The geostationary SAR was first proposed in 1995 and since then has undergone many studies and demonstrations. A first concept demonstration was achieved by using a HOTBIRD illuminator in [11]. A quite better refined demonstration of the same principle, that is using a geosynchronous illuminator and on ground receiver, has been carried out by the Bejing Institute of Technology [4], shown in Figure 10. The 20-m resolution, S-band, bistatic SAR image of the moon, achieved by exploiting Arecibo Observatory Planetary Radar as transmitter and the Green Bank Telescope as a receiver, shown in the same figure demonstrates the capability of focusing at distances even 10-times larger than the geostationary orbit – see also [12]. At last, the result of an end-to-end GeoSTARe L-band demonstration is shown in the same figure, compared to the original ALOS PALSAR image [13]. The additional noise, due to the much longer distance, is evident in the lake, and measurable in the SNR map in the same figure. A further end-to-end simulation of GeoSTARe images achieved in L band, at different synthetic aperture time is shown in Figure 11.

5. PERFORMANCE

Geostationary SAR is unique in providing instantaneous access, on demand, within super-continental coverage.

More than that, the staring capabilities would provide an observational asset not otherwise achievable. The coverage shown in Figure 3 on the right, is 400 km × 900 km wide and can be achieved each 12 hours in C band, at 20×10 m resolution and with 450 W mean power. It would require 12 days of the Sentinel-1A and B constellation, each sensor using similar power and delivering a resolution of 20×5 m.

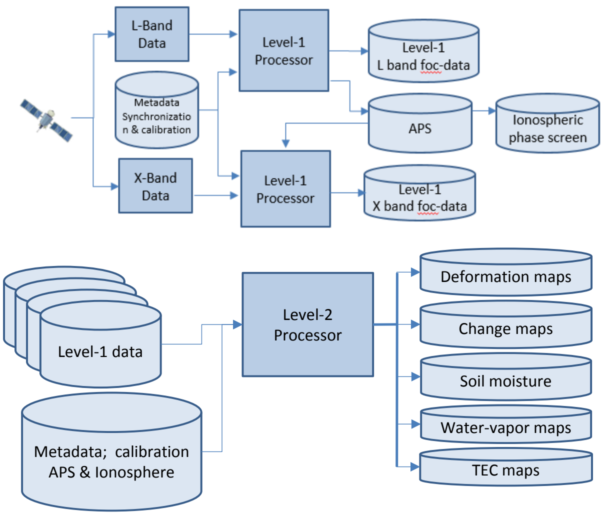

Figure 9 – Block scheme of the level-1 (top) and level-2 (bottom) SAR processors.

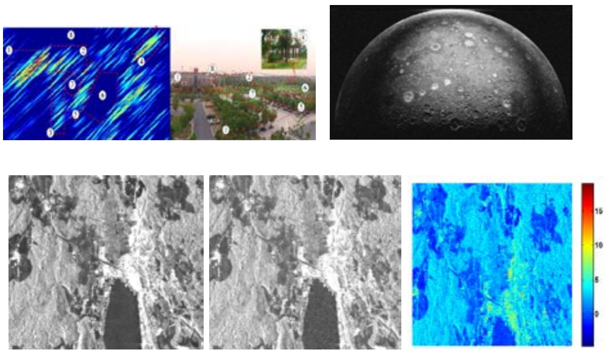

Figure 10 – Top, left and middle: geosynchronous SAR demonstrations by exploiting the Chinese Beidou inclined geosynchronous satellite orbit (IGSO) navigation satellites as illuminator of opportunity [4]. Top right: bistatic SAR image of the moon from Earth [Image by Bruce Campbell, National Air and Space Museum, Smithsonian Institution]. Bottom left: original ALOS L band image, middle: end-to-end demonstration of GeoSTARe image (8-hours acquisition); right: SNR map (dB) [12].

It is worthy to mention that resolution, images area and image time are closely related to the transmitted power. Just taking the mini-satellite example in Table 1, one could bound the product of the transmit power, P_t, the image time, T_I , the resolution cell size, A_{res}, and the swath size, A_{swath} to the following value:

$$P_t \times T_I \times \frac{A_{res}}{A_{swath}} = 150\,W \times\ 1\,h \times \frac{60\ \times\ 20\ m^2}{400\ \times 900\ km^2}$$

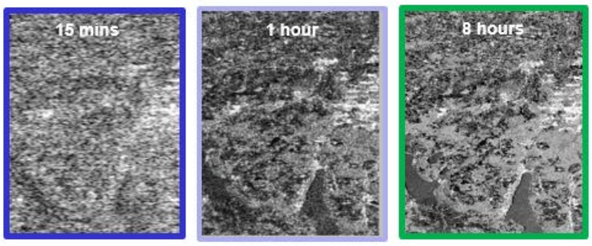

Figure 11 – End to end demonstration of GeoSTARe products (amplitude, L-band) processed at different resolutions by exploiting quick-looks, from [12].

That is 300 Mpixels could be imaged in one hour by exploiting 150 W. A welcome and unique feature of a GeoSTARe is that all the parameters above are not to be fixed in pre-launch, but can be tuned dynamically during each acquisition.

6. EVOLUTION

A single geostationary SAR could represent the base of an evolution into swarm configurations, where the addition of further satellites configured in MIMO (all transmitting and all receiving) would reduce the image time and improve the resolution [14].
An example is given in Figure 12, that compares a single satellite with a two satellites configuration. In the first case, in one hour only a maximum of 15% of the complete antenna aperture can be covered, leading to a resolution degraded by a factor 7. Moreover, an almost null aperture (1% of the full synthetic aperture), occurs twice in every day, for about three hours, during the time spent at the extremes of the orbit span, see Figure 12.
The addition of a cooperative satellite (possibly hosted on second COMSAT), properly phased in orbit, as shown in Figure 13, would improve the aperture to 40% of the full, giving a resolution better by of a factor 2.5, an additional SNR gain of a factor 1.6, and would still allow for a 5% synthetic aperture in the worst case. However, the major advantage would be to bring the interferometric revisit from 12 hours down to one hour, that would decriticize the impact of Atmospheric Phase Screen and decorrelation, allowing for the use of X band [15]. It is shown in [16] that a swarm of 6 mini satellites could provide a sub-hourly image access time with a metric resolution, day-and-night-all-weather, not possible with any other sensor.

7. LIMITATIONS

The limitation of a geostationary SAR comes partly from the fixed viewing angle, partly from the equatorial placement and partly from the long integration time.
The first two elements accounts for a latitude-locked incidence angle, that increases with latitude. At 65° the incidence is close to 70°, creating long shadows and

sensing mostly horizontal surface deformations and surface roughness variations (that reduces moisture sensitivity). Nonetheless, there could be some user TV-SAT antenna to be exploited as targets of opportunities [2], that would be quite bright at low wavelength, like X band.

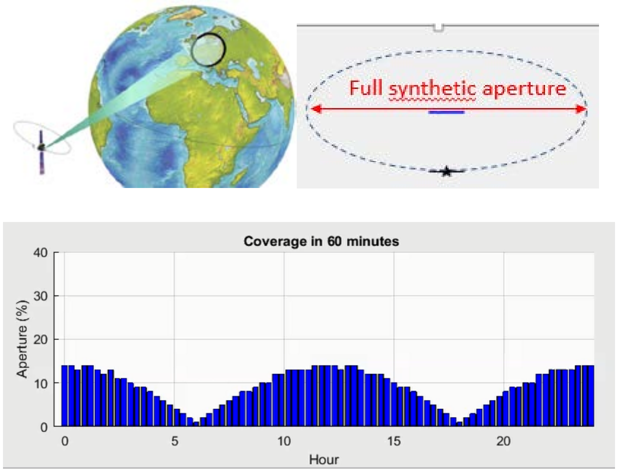

Figure 12 – Single SAR orbit configuration, top left, and aperture (black) achieved in one hour, top right. Bottom: histogram of aperture achieved during 24 hours.

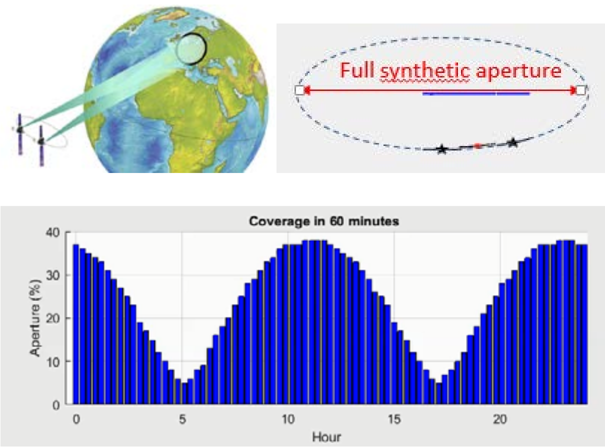

Figure 13 – Twin SAR in bistatic mode. Top left: orbit configuration. Top right: apertures of each of the two real and the virtual satellite in one our. The resulting joint aperture is in blue. Bottom: histogram of apertures achieved during 24 hours.

The long image time, combined with the slow relative motion of a geostationary satellite, 5 m/s at most, causes fast moving targets (water) to disappear from the image and slow moving objects to decorrelate. Vegetation will not be coherent if observed in X band, but not in L or C. Finally, there will be the 25% blind interval mentioned in the previous section.

However, we observed that the evolution into a constellation, starting from just two mini-satellites will remove both limitations above, reducing the image time while increasing the power budget quadratically with the number of sensors, leading to a new generation of very high resolution X band sensors with high sensitivity to small objects and deformations.

Finally, we notice that GeoSTARe signal would be blanked by LEO satellites when they illuminate the same area, since its power flux, typically 1-24 mW/km² is more than three order of magnitude less than LEO-SAR. A LEO SAR travelling at 7 km/s would interfere for two minutes, assuming the 900 km swath. In the case of a single satellite, the orbit should be controlled to place the minimum aperture (see Figure 12) at the LEO-SARs imaging times (typically 9-21 in Europe). In the case of two satellites, a space adaptive notch could be implemented [17]

8. CONCLUSIONS

GeoSTARe is unique in its all-day-all-weather quasi-continuous imaging with millimeter sensitivity to deformations, super-continental access, continuous observations and immediate data download and exploitation.

The need for tiny maneuvers makes it long lasting (up to 15 years), while simplifying the orbit transfer. The system takes fully advantage of slight orbit motion, therefore eccentricities compatible (or if possible larger) than those used in present COMSAT satellites. Moreover orbit height can be periodically tuned to avoid interferences with existent COMSATs.

The system takes advantage from very mature concepts (Radar, Interferometry) yet providing a totally new observational asset. These new observations will enable monitoring of fast evolving fields: water vapor (the unique system providing the required time-space resolution), soil moisture, flooding, soft DEM (landslides, glaciers and snow cover, infrastructure stability) and coherent changes.

First proposed as 8th EE, 2010, it has been extensively studied after ESAC selection recommendation:

"ESAC considers that GEOSAT would be a unique and extremely useful addition to current and forthcoming Earth observation capabilities"

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