A Geosynchronous Synthetic Aperture Radar; for Tectonic Mapping, Disaster Management and Measurements of Vegetation and Soil Moisture

S. N. Madsen, Wendy Edelstein, Leo D. DiDomenico, and John LaBrecque*
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109
*NASA Headquarters

***Abstract-* A geosynchronous synthetic aperture radar (SAR) with an orbit inclination of 50–65° can provide daily coverage of all of North and South America. Longitudinally, the width of the mapped area would be on the order of ±50° at the Equator, somewhat more at the most northern/southern latitudes. Within the area mapped, very good temporal coverage can be obtained –up to several mappings during the 12 hours per day where the satellite is in the "right" hemisphere. This would be a key capability in relation to disaster management, tectonic mapping and modeling, vegetation and soil moisture mapping, and for operational and semi-operational requirements. A constellation of geosynchronous satellites could provide global coverage.**

I. Science and Applications

A geosynchronous SAR, with its fine temporal resolution, would overcome the limitations of current imaging systems, allowing dense interpretation of transient phenomena as GPS time-series analysis with a spatial density several orders of magnitude finer. Unique visibility into Earth surface dynamics would be provided. Our understanding of tectonics, earthquakes and other crustal processes is presently limited by a lack of data and lack of models that reflect the true physics. As the physical models are largely data-driven, a geosynchronous SAR for 3-d deformation measurements will drive new insight into the space-time behavior of processes related to earthquakes and volcanic eruptions. With observations taken every few hours, time series of rapidly evolving phenomena, such as pre-eruptive volcano dynamics, would be a major advance in predictive capability, improving modeling potential as well as civil protection. Pre-seismic deformation, one of the most elusive aspects of earthquakes, could be addressed with such a system.

Fine temporal sampling is essential for disaster management, e.g. of flooding, fires, landslides, hurricanes, and earthquakes. Using a fairly long wavelength (e.g. L-band) changing water boundaries caused by storms or flooding could be monitored in near real time. Interferometric correlation would similarly allow near-real-time mapping of surface changes caused by earthquakes, volcanic eruptions, mudslides, or fires.

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Monitoring vegetation changes due to human or natural disturbances and the dynamics of vegetation recovery is important to understanding the global carbon cycle. Radar systems provide a capability to map the dynamics of land cover and land use change. The sensitivity of radar to the vegetation structure and moisture content makes it the preferred instrument for monitoring vegetation recovery and the carbon sequestration process.

Soil moisture is a key factor in defining the characteristics of the hydrological cycle. The consistent measurement of soil moisture on both temporal and spatial scales is extremely important for understanding land surface processes. The large temporal and spatial variability of soil moisture has made this a difficult parameter to measure by remote sensing. Active microwave sensors are considered the most promising sensors for estimating soil moisture on a global scale. The required spatial resolution of 1 km or better on the global scale, makes active microwave systems better suited than passive microwave radiometers (limited to greater than 10 km resolution).

All the above applications require a high temporal measurement frequency (1-2 days) to determine process dynamics and more permanent changes.

II. The Geosynchronous SAR Concept

A geosynchronous SAR concept has previously been presented by Tomiyasu [1]. In Earth body fixed coordinates, the orbit of an idealized geosynchronous satellite in a zero eccentricity orbit with an equatorial crossing at zero longitude and an inclination I) is given by

$$\vec{r}_{sat} = r_G \begin{pmatrix} 1+\left(\cos i - 1\right)\ \sin^2 \omega_G t \\ \left(\cos i - 1\right)\cos\omega_G t\ \sin\omega_G t \\ \sin i\ \sin\omega_G t \end{pmatrix} \tag{1}$$

where the angular velocity is $\omega_G = 2\pi / T_s = 72.92 \cdot 10^{-6}$ and $r_G = \sqrt[3]{GM_E / \omega_G^2} = 42164\,\text{km}$ is the geosynchronous radius. The satellite velocity is easily derived from (1).

Assuming an inclination of 50°, the satellite velocity, v_{sat}, will range from 1100 m/sec at the equator to 2600 m/sec at the most northern point corresponding to a nadir velocity of 166 m/sec to 393 m/sec. The Doppler bandwidth is given by

$$f_D = \frac{2 v_{sat} \cos\phi_{squint}}{L_{ant}} \approx \frac{2 v_{sat}}{L_{ant}} \tag{2}$$

thus, for a 30 meter antenna, the minimum pulse repetition frequency (PRF) would be in the range 75 to 175 Hz. The fractional azimuth bandwidth variation over the orbit is much larger than for sun synchronous orbits. For our initial considerations we assumed a PRF of 200 Hz and required a mapping capability from 10° to 50° degrees angle of incidence, corresponding to slant ranges from 35875 km to 37785 km and ground ranges from 945 km to 4820 km off the nadir point. As iso-range and iso-Doppler lines becomes progressively parallel when mapping in the direction of motion, we exclude areas on the ground from our coverage assessment, in case the line from the nadir point to the target forms an angle of less than 30° relative to the ground track.

The standard radar equation can be used to calculate the received radar power and the signal-to-noise-ratio (SNR). It is noted, that to get a similar performance from varying ranges, e.g. a low Earth orbit or from the Lagrangian points, it is necessary to keep the factor

$$\frac{P_t A_{\mathrm{ant}}^2}{\rho^3} \qquad (3)$$

constant (P_t is the transmitted pulse power, A_{ant} is the antenna effective receive area, coefficient, ρ is the slant range). As the pulse repetition frequency (PRF) must be high enough that the Doppler bandwidth of the radar is sufficiently sampled, and on the other hand, the PRF must be low enough that range ambiguities do not show up within the range swath illuminated by the antenna, the antenna area must exceed

$$A_{\mathrm{ant}} \geq 4\rho\lambda \tan\theta \frac{v_{\mathrm{sat}}}{c} \qquad (4)$$

(λ wavelength, θ angle of incidence, c speed of light.) Considering practical antenna illuminations, typically the minimum geometric antenna size would be 50% larger. In the case of a geosynchronous orbit mapping out to 45° it is seen that the minimum antenna areas for L-band is 480 m^2.

III. System Considerations

Based on on-going technology studies, and the above requirements, we propose a 30 m diameter antenna, with ±7° of electronic beam scanning in both elevation and azimuth. The symmetry axis of the antenna will be pointed at nadir such that the beam scanning allows targets from nadir out to 50° angle of incidence to be accessed, while at the same time allowing the beam to point forwards, sideways or backwards.

We assume 20 kW of DC power is available and 15kW of L-band RF power is transmitted at a 20% duty cycle. Given the 200 Hz PRF and a 20% duty cycle, the transmitted pulse-length is 1 millisecond. The noise figure and total system losses are both assumed to be 3 dB. Assuming a backscatter coefficient of –20dB(m^2/m^2), the received power at the maximum range is –118dBW. If we require a signal-to-noise-ratio of 10 dB, we calculate the bandwidth, $B = 18.8\,MHz$, and the resolution this system supports is

$$\Delta g = \frac{c}{2B\sin\theta} = 10m \qquad (5)$$

In the near range (θ = 10°) the conversion from slant range to ground range would lead to a 45 m ground range resolution. In the near range, the range would be shorter, improving the SNR by 2.5 dB, and at the same time the backscatter level will be significantly larger than at 50°. Thus the bandwidth could be increased to 80 MHz, again providing a ground range resolution of 10 m. The 30 m antenna diameter would support a 2 m azimuth resolution due to the curvature of the orbit ($D_{\mathrm{ant}}/2 \cdot r_E/r_G$). The data would thus be 10 m resolution at 5 independent looks, which would be a superior spatial resolution, compared to present space borne SAR systems.

IV. Coverage and Operations

Given a longitudinal node crossing of 72° West, the daily coverage was calculated. In figure 1 green shows areas mapped from 3 different aspect angles in a single day, with a geometry which supports a 3-d displacement measurement accuracy of 10 times the line-of-sight error or better, yellow indicates two aspect angles, and red indicates one. Assuming a 35 m horizontal resolution at a signal to noise ration of 10 dB and 60-looks at L-band, the line-of-sight error (ignoring atmospheric perturbations) would be 1.2 mm and the 3-d vector error would thus be less than 1.2 cm in the green areas.

The range of the geosynchronous SAR would allow it to be operated in a number of modes. The potential modes include:

A 600 km *strip mapping mode* providing one swath, supporting a 10 m resolution with multiple looks (~5),

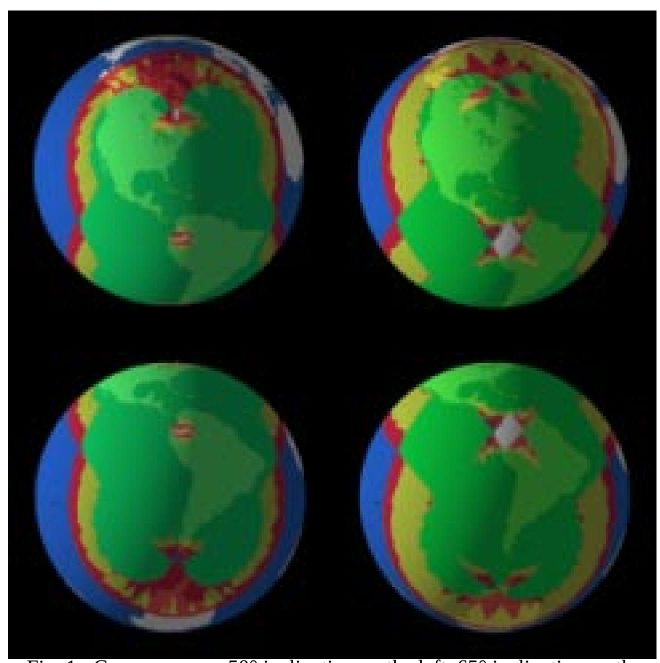

Fig. 1. Coverage map, 50° inclination on the left, 65° inclination on the right. Green indicates 3-d mapping, yellow 2-d and red 1-d mapping.

and would be suited for high resolution mapping.

A *scan-SAR mode* supporting coverage of 4000 km swaths on either side of the nadir track, at 50 m resolution. This mode would provide daily continental coverage.

A *3-beam scan-SAR mode* supporting aspect angles of 45° forward, broadside, and 45° backwards of 2800 km swaths on both sides of the nadir track to provide 3–d displacement mapping of extended areas in a single day.

A *spotlight SAR mode* where the beam is locked on a single target area for extended periods of time. This mode would be suitable for disaster management.

A total system bandwidth capability of 80 MHz allows stepped frequency operation of the instantaneous bandwidth (e.g. limited to 18 MHz because of SNR limitations and data rate) from day to day within that 80 MHz band. For targets that exhibit sufficient correlation for interferometry, such sub-bands can be staggered coherently. Thus in the far range a total bandwidth of 80 MHz could be build up over 6 days from individual maps utilizing 18 MHz of instantaneous bandwidth, to provide single look imagery with 2.5 m ground range resolution and 2 m azimuth resolution.

The critical baseline for a geosynchronous repeat-pass InSAR system at L-band is approximately 90 km in the near range (worst case). Thus decorrelation due to lack of orbit maintenance is not considered a problem. A much stricter requirement is found by requiring that an inaccuracy of 100 m in estimating the targets height should not contribute more than 2 millimeter to interferometric displacement measurements. In the near range (again worst case) the 2 millimeter displacement error per 100 m height error translates into a maximum orthogonal baseline of 125 m, which means that precise orbit maintenance is of the essence.

V. TECHNOLOGY

Using technologies currently being studied to obtain a 30-meter diameter antenna with ±7° electronic scanning in both azimuth and elevation will likely involve inflatables or mesh antenna technologies. Using inflatable structures to deploy lightweight membrane antennas can achieve antenna mass densities of 2 kg/m^2. The required 20 Kwatts of total DC power can be supplied by current high performance satellites. Over the next 10 to 20 years an increase of at least 50% would be expected benefiting from advances being made in solar array technologies. For instance, the current state-of-the-art in solar arrays achieve 100 Watts/kg, such as the Lightweight Flexible Solar Array technology currently being developed by NASA. 20 Kwatts of DC power can be supplied by current high-performance satellites.

Beyond current technology, we imagine inflatable antennas using flexible membrane apertures embedded with membrane T/R modules. A large antenna aperture can then be shared with the solar array using thin-film solar cell technology, similar to what is currently being developed by NASA. For far-out missions, we propose to exploit this dual-use technology to combine the radar antenna and the solar array function on one lightweight structure. We can expand on this notion by eliminating the inflatable structures, which is considered current state-of-art for deploying flexible membranes, since the majority of the mass is located in the support structure and required inflation system. One could imagine using the internal stresses of a spinning antenna to rigidize it, replacing the structure with small ballast masses to maintain the membrane tension. The ballast masses could be small microthrusters providing attitude control. Since the antenna will be spinning, the T/R modules required for the agile beam pointing can also be used for beam compensation of the spinning antenna as well as to correct for phase distortion due to antenna flatness changes. Nano-spacecraft technology can be used for telecommunications, guidance, navigation and control.

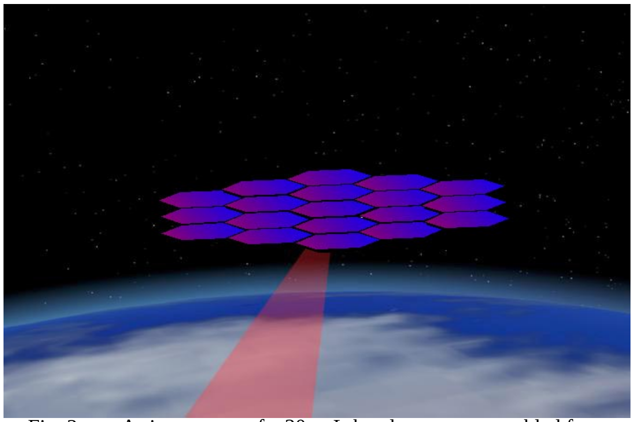

Fig. 2 Artist concept of a 30 m L-band antenna assembled from hexagon elements.

Another concept to achieve very large antenna apertures use a reconfigurable, autonomous SAR, e.g. an array of hexagonal elements, which can be assembled in space to form arrays of differing geometries. The same basic antenna element can be manufactured in large volumes on the ground and then be assembled for the final application in space. These reconfigurable antenna elements would be completely self-contained each with spacecraft avionics and solar arrays. These hexagonal panels could be rigid, but they could in principle be implemented using flexible materials as well.

ACKNOWLEDGMENT

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REFERENCES

[1] K. Tomiyasu, "Synthetic aperture radar imaging from an inclined geosynchronous orbit," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 21, pp. 324-328, 1983.