



Rapid-Repeat SAR Imaging of the Ocean Surface: Are Daily Observations Possible?

Benjamin Holt and Jeffrey Hilland

The fine resolution of synthetic aperture radar (SAR) yields exciting views of the two-dimensional ocean surface and its interactions with the atmosphere, long waves, and currents. However, the high data rates and power required to achieve this fine resolution limit the available swath widths and hence the temporal and spatial sampling of the ocean surface, in turn limiting SAR ocean observations to periodic “snapshots” rather than synoptic, frequent views. The wide swath capability of Radarsat and Envisat enhance ocean sampling, reducing it to a few days. The dynamics of many important ocean and atmospheric processes have shorter timescales, however, and may require an entirely new satellite concept to be adequately captured. We examined two different satellite SAR mission concepts with the goal of achieving daily ocean observations. The first concept was for a mission with increased swath width using a single antenna flown at a higher than normal altitude. The second considered using a spacecraft carrying two antennas in a more conventional orbit. Trade-offs between the two missions are discussed. (Keywords: Ocean surface, SAR, Satellite design.)

INTRODUCTION

Imaging of the ocean surface with a synthetic aperture radar (SAR) provides unprecedented detail in views of the ocean’s short wave field as it responds to interactions with the atmosphere, longer waves, and currents. Useful and often intriguing space-based ocean radar imagery has been obtained for more than 2 decades, starting with Seasat in 1978. Seasat was followed by the Shuttle Imaging Radar (SIR) flights in 1984 and 1994, and this decade has seen Russia’s ALMAZ-1 (1991–1992); the Japanese Environmental Resources Satellite (JERS-1) mission (1992–1998); the continuing missions of the European Space Agency (ESA) European

Remote Sensing (ERS-1/2) satellites (1991–present), and the Canadian Space Agency’s Radarsat-1 (1995–present). Key results on coastal processes (mesoscale circulation, surface and internal waves, slicks, and bathymetry) and sea ice using SAR have been widely published (e.g., various special issues of the *Journal of Geophysical Research Oceans* have appeared: volumes 88(C3) in 1983, 93(C12) in 1988, 99(C11) in 1994, 103(C4) in 1998, and 103(C9) in 1998). Currently, interest in examining the atmospheric processes detectable on the ocean surface is growing, particularly in mesoscale wind fields and boundary-layer features.

(Several related articles appear elsewhere in this issue.) Acquisition of ocean imagery will continue into the next decade with the launches of at least three satellites carrying SARs: ESA's Envisat in 2000, Canada's Radarsat-2 in 2002, and Japan's Advanced Land Observing Satellite (ALOS) in 2002.

However, many of the ocean processes, particularly the air-sea interactions of interest for radar imaging, have temporal and spatial scales that are largely undersampled by all of these SAR missions. These missions provide periodic "snapshots" rather than the more desirable frequent and synoptic views of the ocean surface that are needed to capture its dynamics. This undersampling means that the utility of SAR for ocean studies has not yet been even closely optimized. Our study is an attempt to answer the following question: Can a SAR mission be designed to provide observations of the ocean surface that more nearly match the spatial scales and temporal dynamics of the ocean surface and air-sea interactions, as needed for both science and operational requirements? We considered scenarios where either one or two SAR antennas are carried on a satellite platform.

VIEWING THE OCEAN SURFACE

As illustrated in Fig. 1, the timescales of ocean physical processes extend from minutes to years, and length scales range from meters to 1000 km.¹ Imagery from SAR provides key data on ocean swell, internal waves, mesoscale circulation including fronts and eddies, and a wide range of atmospheric processes. Data on atmospheric processes include measurements of

wind speed and direction, detection of atmospheric roll vortices and turbulence, and identification of the extent and structure of storms and rain cells. Even the processes with relatively longer timescales, such as fronts, eddies, and gyre circulations, may fluctuate over a period of a few days or even less. In terms of operational interests, ship monitoring (to observe both fishing and traffic), detection of natural and anthropogenic slicks, identification of icebergs, and sea ice navigation are perhaps best done with SAR imagery.

How is the ocean sampled from satellites? In general terms (and not including altimetry, which is dedicated to gyre circulation), the primary satellite ocean sensors enable routine monitoring of nearly the entire global ocean every 12 h to 2 days. These include sensors for sea surface temperature and ocean color, which have about 3000-km swath widths with 1-km resolution and provide twice-daily global coverage. Scatterometers for measuring winds have swath widths varying between 500 and 1800 km with resolutions from 25 to 50 km. Passive microwave imagers have viewing parameters similar to those of scatterometers.

As for SARs, those of Seasat, ERS-1 and ERS-2, and JERS-1 have about 100-km-wide swaths set at a fixed-center incidence angle, resolutions on the order of 30 m, and orbital repeat periods generally greater than 3 weeks. The limited 3-day repeat periods of Seasat and ERS-1 were extremely useful for time series studies but resulted in large interorbit coverage gaps. For several months, ERS-1 and ERS-2 were in adjacent 35-day repeat periods separated by 1 day, which also proved quite valuable for ocean studies. Both flights of SIR-C/X-SAR in 1994 had slowly precessing orbits that enabled daily, and to a limited extent twice-daily, observations using the ability to alter viewing angles and direct the antenna (and shuttle) to view both sides of the flight path. But each flight lasted only about 10 days. Finally, Radarsat-1 provides a ScanSAR mode with 300- to 500-km swath widths. This wide swath mode enables imaging poleward of 50° latitude every 2 to 3 days as a result of orbit convergence. Equatorward of 50° latitude, a location can be seen with ScanSAR every 3 to 5 days. Radarsat-2, Envisat, and ALOS will have similar wide swath modes available, with Radarsat-2 providing imaging on one side of the flight path or the other (but not both at the same time!). All of these missions have orbital repeat periods from 10 to 44 days. Even with approximately

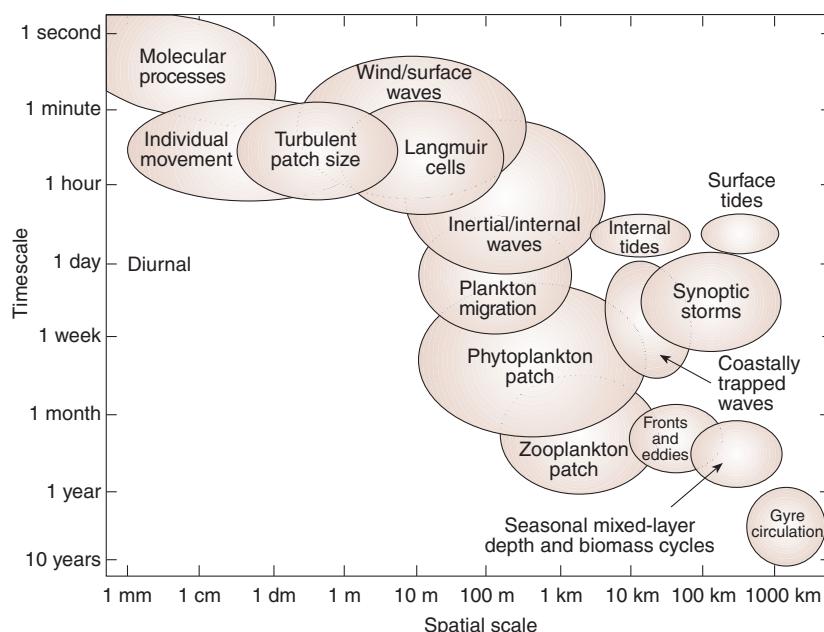


Figure 1. Temporal and spatial scales of key physical and biological processes in the ocean (adapted from Ref. 1).

3-day subcycles, routine ocean sampling will be problematic at these long-duration repeat periods. Coordinating acquisitions to provide routine observations of any given region among sensors with different swath widths, orbital periods, and customer needs will be challenging to say the least.

How do we improve the sampling of the ocean surface with SAR? To first order, the swath width can be increased. For a single spacecraft, this can be done either by increasing the swath width with one antenna or by doubling the coverage with two antennas, each looking simultaneously on opposite sides of the subsatellite track. However, several inherent SAR–ocean sensing difficulties create conflicting design options that must be considered.

Ocean backscatter has increasing sensitivity with increasing frequency, particularly in the relation of backscatter to wind speed.² In general, C band is preferred over L band for most SAR ocean applications. In terms of power, lower-frequency SARs have lower power requirements. For a given signal-to-noise ratio, for example, L band is easier to accommodate on a satellite than C or X bands. Next, ocean backscatter falls off rapidly with increasing viewing angle as compared with backscatter from other surfaces. This results in a comparatively narrow range of viable SAR viewing angles over which the ocean produces backscatter sufficiently above a reasonable noise floor to be detected as signal. Thus, simply increasing the swath width by viewing at higher angles is not feasible for ocean sensing unless the orbital altitude is raised. On the positive side, however, viewing at angles beyond this narrow range improves the detection of ships and icebergs, because the ocean clutter becomes significantly lower than the target returns. The transmitted power required is sensitive to altitude, so

raising the orbit further increases the power requirement. Another consideration for ocean sensing is resolution. A standard trade-off in SAR design is between swath width and resolution, where increased swath width is often achieved with a concurrent reduction in resolution and vice versa. This effect is even more amplified when multiple polarizations are available. Users of SAR data have a natural proclivity for fine resolution and are often reluctant to move to reduced resolutions. Last, going to a reduced resolution (say between 50 and 100 m) also raises the minimum detectable wavelength of surface swell, making the data less useful for ocean wave studies.

SCIENCE REQUIREMENTS FOR A RAPID-REPEAT OCEAN MAPPER

To help guide the design study, we put together “science” and “operations” requirements based on discussions with several colleagues (Table 1). For frequency, C band generally provides better overall detection of ocean features and air-sea interactions than L band, while X band has higher power requirements. Vertical transmit–vertical receive (VV) polarization over the ocean provides more ocean return than horizontal transmit–horizontal receive (HH) polarization.² Calculation of the spatial resolution for science was assisted by Young (see his article in this issue) with an analysis based on examining the turbulent scale of air-sea interactions. The operational resolution was selected to be more conducive to ship detection. The preferred range of viewing angles is 19 to 45°; in contrast, angles higher than 45° may be useful for ship and iceberg detection. A noise equivalent σ_0 of at least –20 dB provides sufficient signal-to-noise ratio for returns at low wind speeds at the larger science angles. For

Table 1. Science and operations requirements for a rapid-repeat ocean mapping SAR.

Science requirements	Operations requirements	Configuration
Mesoscale circulation features: currents, fronts, eddies, internal waves	Ship detection: fishing, traffic Pollution detection: oil slicks Iceberg detection: seasonal in Atlantic	Frequency: C band (5.3 GHz) Polarization: VV Resolution and number of looks: Science: 150 m, 10 or more looks Operations: 50 m, 4 or more looks Incidence angle range: Science: 19–45° Operations: 19–58° Noise equivalent $\sigma_0 \leq -20$ dB
Mesoscale air-sea interactions: wind fields, atmospheric boundary-layer processes		Coverage and repeat orbit interval: Global access within <3 days, consistent viewing geometry, Sun-synchronous orbit

coverage, global access is required. For satellite repeat interval, it is highly desirable to view a point on the Earth with consistent viewing geometry at about the same time each day. For this, we selected a Sun-synchronous orbit.

In addition to correlating better with the shorter-term dynamic processes, wider and more frequent SAR coverage also provides a better complementary data set for use with the other ocean imaging sensors such as the Advanced Very High Resolution Radiometer (AVHRR) and the Sea-viewing Wide Field-of-View Sensor (SeaWiFS). As a result, regional climatic-scale investigations that incorporate SAR will become possible. Of particular value will be studies of the coastal regions to examine the effects of significant climatic events such as El Niño and resulting seasonal variations in weather patterns that alter the coastal environment, both physically and biologically.

STUDY OPTIONS

The two study options we considered for a single spacecraft included using one or two antennas to achieve increased swath coverage. These configurations guided the mission and radar design. We describe each approach, discuss the resulting design configuration, and show examples of the approximate coverage from several orbital repeat intervals.

The selection of the orbital height and swath width is an iterative process. To aid in this, we used a simple graphical approach to approximate swath geometry at the equator and at 30° latitude for different repeat intervals over a fixed distance (longitude). The fixed distance was determined by the following approximation. Using a radius of 6378 km, the circumference of the Earth is about 40,074 km. We assumed the nominal number of orbits per day to be 14 regardless of orbit height (more like 13 at 1300–1500 km) for graphical simplicity. At the equator, the separation between adjacent orbits is then about 2860 km (25.7° of latitude). At 30° latitude, the separation is reduced to about 2300 km. A complete mapping at one viewing orientation with an 800-km swath requires 3.5 days at the equator or 3 days at 30° latitude. There is increasing overlap poleward of 30° that further reduces the sampling interval, but this was not included. We used the standard Sun-synchronous orbit inclination of about 98°. From orbital tables, more specific altitudes were then selected that corresponded to suitable repeat intervals.

Concepts for a One-Antenna Design

To improve coverage with a single antenna while maintaining the constrained range of viewing angles for ocean sensing, the orbit must be higher than the

typical altitude of 800 km used by several space-based SARs (ERS, Radarsat, Envisat). With viewing angles of 19 to 45°, a swath width of about 800 km is achievable at an orbital altitude of about 1400 km. From orbital tables, repeat intervals of 1 to 5 days are available between altitudes of 1319 and 1496 km. Figure 2 shows example coverage plots with an 800-km swath at 2- and 3-day exact repeat intervals. The 3-day coverage provides about 85% complete coverage at the equator and complete coverage at 30° latitude. The 2-day repeat coverage is incomplete at 30°, and the 4-day repeat (not plotted) provides complete coverage at the equator with considerable overlap at 30°. We selected the 3-day repeat option, which can be achieved at an altitude of 1368 km. The subsequent radar design is shown in Table 2, which includes the Radarsat-1 ScanSAR wide design for comparison.³

The positive aspects of this design are that it uses one antenna and matches the general requirements. We assumed that the antenna is an active phased array. Also, the design is in consonance with Radarsat-1 and thus is technologically within the state of the practice for instrument implementation. It should be noted that this is a feasible design for the given mission design environment. A fixed bandwidth slightly larger than that of Radarsat-1 provides the operational resolution required. We used a 5% duty cycle, which results in a DC power draw from the spacecraft bus about twice that of Radarsat-1. This power requirement is well

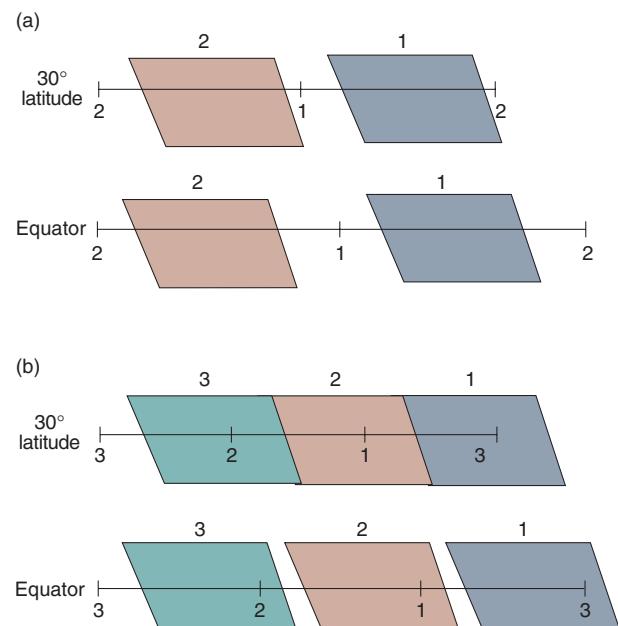


Figure 2. Approximate coverage of a one-antenna rapid-repeat mapper with an 800-km swath (ascending orbits only, right-looking) at the equator and at 30° latitude: (a) 2-day exact repeat orbit; (b) 3-day exact repeat orbit. The axis lengths represent 2860 km (equator) and 2300 km (30° latitude). The orbit repeat day is indicated by the numerals on the axis and corresponding swath. Table 2 lists further details of this design.

Table 2. One-antenna design for a rapid-repeat ocean mapping SAR.

Characteristics	Ocean mapper	Radarsat-1 ScanSAR wide
Frequency band/polarization	C/VV	C/HH
Altitude	1368 km	800 km
Swath width/number of sub-beams	800 km/8 sub-beams	520 km/4 sub-beams
Resolution/number of looks		100 × 100 m/8 looks
Science	150 × 150 m/28 looks	
Operations	50 × 50 m/12 looks	
Antenna dimensions	16.5 × 1 m	15 × 1.5 m
Incidence angle	24–52°	20–49°
Data rate	60–97 MB/s	105 MB/s
Bandwidth	20 MHz	11, 17 MHz
Noise equivalent σ_0	< –21 dB	–20 dB
Azimuth ambiguity	< –15 dB (boresight)	–22 dB
Range ambiguity	< –21 dB	–18 dB
Peak transmit power	6.0 kW	5.5 kW
Average DC power	572 W	280 W

within the capability of buses being provided by the commercial satellite industry but could be reduced to about 350 W, resulting in a noise equivalent σ_0 of approximately –19 dB.

Many design choices are possible to further optimize this design. For example, the azimuth ambiguity performance could be improved by lengthening the antenna. The duty cycle could be reduced to lower the power demands. A constant bandwidth was used for all sub-swaths, resulting in a constant-slant range resolution. The bandwidth could be varied to obtain constant resolution in ground range. Other design choices must be made, such as the amount of beam overlap required, which reduces the resolution in the overlap area. However, further design trade-offs are beyond the scope of this study.

The difficulties in this design are primarily attributable to the mission design, which requires large area coverage (wide swath) and a short repeat cycle. To mitigate the incidence angle effects, we chose a higher altitude. This altitude requires radiation hardening to protect the instruments and the system from exposure to higher radiation levels and more single-event upsets than would be experienced at more benign altitudes around 800 km. The wide swath is achieved through the use of eight ScanSAR subswaths, which makes processing and calibration complex. While the orbit and swath provide complete coverage every 3 days (assuming the use of descending passes to fill in equatorial gaps), which is far better than any other

current or near-term space-based SAR, the orbit and configuration do not really meet the central theme of near-daily observations. The use of a second satellite in a duplicate orbit offset by 1 day would enable a second complete mapping with 1- and 2-day separations.

An alternative concept to a low Earth orbiting mission is to use a geosynchronous orbit having an altitude of 35,768 km with an inclination greater than 0°. The well-known geostationary Clarke orbit⁴ has an inclination of 0°. The inclined orbit provides a ground track that nutates relative to the surface of the Earth, providing the required relative motion to form a synthetic aperture.⁵ The low velocity relative to Earth provides a long beam dwell time compared with low Earth orbiting missions. The geosynchronous orbit has a period of approximately 24 h. Given a left-looking SAR geometry, coverage over the eastern and western coasts of North America can be achieved daily with two satellites, each at an 80° inclination with different ascending nodes (Fig. 3). The geosynchronous orbit enables wide swath coverage (in this case approximately 540 km) over a narrow range of incidence angles with a single beam and a short revisit time. Because numerous communications satellites operate in equatorial orbits, the commercial launch and satellite industry has a large technology base from which to draw for an ocean mapping mission operating from geosynchronous orbit. However, orbital slots in geosynchronous planes may be limited, and the possibility of collisions with

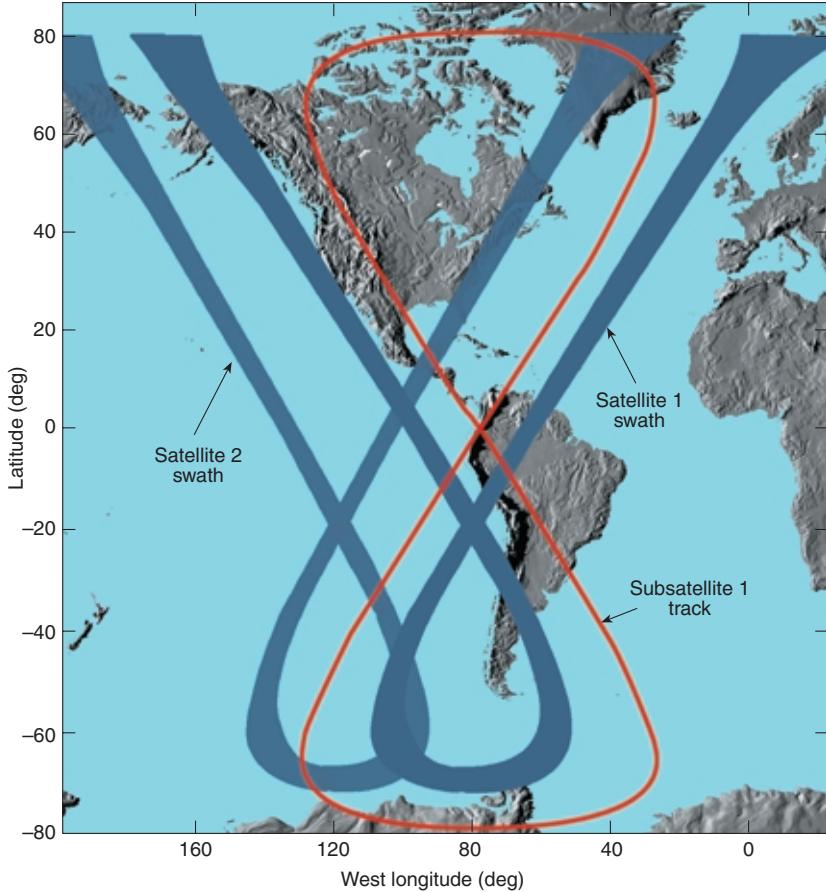


Figure 3. Coverage over a 24-h period for two satellites, each with a 560-km swath, placed in geosynchronous orbit at 35,768-km altitudes and inclinations of 65°. The ascending nodes for the orbital tracks of the two spacecraft are 240° and 280°E (includes spacecraft nadir trace).

satellites in the equatorial plane must be thoroughly analyzed. The disadvantages compared with the low Earth orbiting mission are that a large aperture and additional power are required to achieve sufficient signal-to-noise ratio.

Concept for a Two-Antenna Design

Next we examined a scenario where two antennas are carried on opposite sides of the same spacecraft in low Earth orbit. This configuration essentially mirrors Radarsat and Envisat in terms of single-antenna performance and coverage but provides double coverage similar to the one-antenna design just described. Also, it does not require a higher altitude and could operate at a more conventional altitude near 800 km. But what about the orbital design? In our graphical display, we examined two antennas with 400- and 500-km swaths and repeat cycles of 3 to 6 days. Because of better coverage as well as subcycle coverage, we selected 500-km swaths for the study.

For two 500-km swath antennas (Fig. 4), the 3-day exact repeat provides nearly complete coverage at 30°, but the swaths have nearly complete overlap at the

equator, with considerable gaps! A 5-day exact repeat provides complete coverage at the equator and considerable overlap with adjacent swaths. At 30° latitude, this repeat results in three sets of sliding 2-day and two sets of 3-day near-repeat subcycles. The 4- and 6-day exact repeat orbits are less desirable because the subcycles are less useful. For the two-antenna design, we selected the 5-day exact repeat orbit with two 500-km swaths. The orbital tables indicate that an exact 5-day repeat occurs at an 819-km altitude. The results of this design are shown in Table 3, again with the Radarsat-1 ScansAR wide design listed for comparison.

The positive aspects of this design are that the instrument and system mirror satellites already in operation. Although power must be sufficient to operate two antennas, providing adequate power is less problematic than going to higher altitudes and may be solvable operationally rather than requiring key design development. Also, the 5-day exact repeat provides both satisfactory coverage and improved subcycle sampling frequency. If a second satellite were implemented,

it is likely that the orbits could be moved to a 3-day repeat orbit. By using a duplicate orbit with an offset equatorial nodal crossing, the second platform could map the equatorial gaps with a one-orbit offset in time and also provide overlapping coverage at 30° latitude. There would then be complete coverage every 12 to 24 h by taking into account the descending passes. A 3-day repeat orbit is available at a 774-km altitude.

In addition to transmitting with two antennas on a single platform, other negative aspects of the design are that it likely costs more than a single-antenna design, even with radiation hardening, and that it requires packaging of two antennas into a single launch vehicle. We note that Russia's ALMAZ-1 carried two antennas, so such a concept has already been flown in space (albeit with heavy launch capabilities required). For packaging into a Delta-2-scale launch vehicle, the problem might be solved with inflatable antennas, which are being studied. Here the antennas are launched in a rolled-up configuration and then deployed as thin membranes stretched across lightweight inflatable structures. The mass density of these antennas is a factor of 3 lower than that of

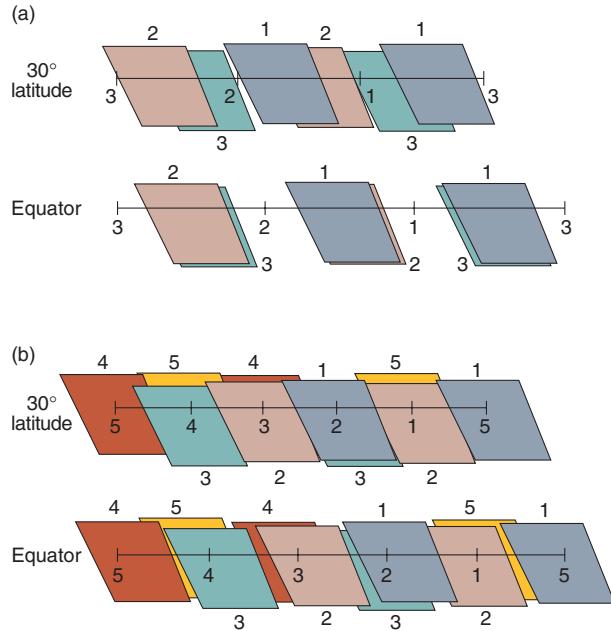


Figure 4. Approximate coverage of a two-antenna rapid-repeat mapper with two 500-km swaths, one on each side of the spacecraft (ascending orbits only) at the equator and at 30° latitude: (a) 3-day exact repeat orbit; (b) 5-day exact repeat orbit. The axis lengths represent 2860 km (equator) and 2300 km (30° latitude). The orbit repeat day is indicated by the numerals on the axis and corresponding swaths. Table 3 lists further details of this design.

conventional honeycomb designs; thus, the launch constraint becomes the shroud volume and not necessarily the vehicle lift capacity. A key unknown for inflatable antennas, which will require on-orbit testing to verify, is the survivability of the membranes and structure in a space environment.

SUMMARY

We have identified feasible system and orbital designs for a SAR ocean mapper. These designs are better optimized to the spatial and temporal dynamics of ocean processes and air-sea interactions than any past, present, or currently planned space-based SAR mission. The single-antenna SAR design described has an 800-km swath and is feasible in a 3-day repeat orbit at a 1368-km altitude. The configuration provides nearly complete coverage at the equator while maintaining favorable ocean viewing angles. A second satellite in a duplicate orbit offset by 1 day would further improve the repeat interval, reducing it to 1 or 2 days. Another single-antenna option is a satellite in geosynchronous orbit. With this configuration, two spacecraft could provide daily coverage of the North American coastal areas. Although it suggests an intriguing alternative, the geosynchronous option is severely limited in terms of global coverage. The two-antenna design works favorably at an altitude of 819 km; it has two 500-km swaths in a 5-day exact repeat orbit with 2- and 3-day subcycles. Although this configuration is attractive, a second satellite offset by one orbit would improve the sampling frequency, reducing it to 12 to 24 h.

With rapidly advancing technology directed toward reducing mission costs by flying lightweight SAR antennas and electronics, and hence lightweight spacecraft, such a dedicated SAR mission will become increasingly feasible economically within the next several years. Perhaps most practically, these requirements and this system approach can be merged satisfactorily with another dedicated mission, for example a land

Table 3. Two-antenna design for a rapid-repeat ocean mapping SAR.

Characteristics	Ocean mapper	Radarsat-1 ScanSAR wide
Frequency band/polarization	C/VV	C/HH
Altitude	819 km	800 km
Swath width/number of sub-beams	2 × 500 km/5 sub-beams	520 km/4 sub-beams
Resolution/number of looks	150 × 150 m/60 looks Science Operations	100 × 100 m/8 looks
Antenna dimensions	16.5 × 0.5 m	15 × 1.5 m
Incidence angle	21–48°	20–49°
Data rate	56–102 MB/s	105 MB/s
Bandwidth	20 MHz	11, 17 MHz
Noise equivalent σ_0	< -18 dB	-20 dB
Azimuth ambiguity	< -16 dB (boresight)	-22 dB
Range ambiguity	< -18 dB	-18 dB
Peak transmit power	3.6 kW	5.5 kW
Average DC power	455 W	280 W

mapping mission. To improve the science justification, regional climate-oriented studies are needed that incorporate SAR synergistically with other ocean sensors. To improve the operations justification, successful demonstrations are needed including, for example, the incorporation of wind measurements into wind forecast models and the ability to detect and apprehend vessels fishing illegally within restricted waters.

REFERENCES

- ¹Dickey, T. D., "The Emergence of Concurrent High-Resolution Physical and Bio-Optical Measurements in the Upper Ocean and Their Applications," *Rev. Geophys.* **29**(3), 383–412 (1991).
- ²Unal, C. M. H., Snoeji, P., and Swart, P. J. F., "The Polarization-Dependent Relation Between Radar Backscatter from the Ocean Surface and the Surface Wind Vector at Frequencies Between 1 and 18 GHz," *IEEE Trans. Geosci. Remote Sens.* **29**(4), 621–626 (1991).
- ³Luscombe, A. P., Ferguson, I., Shepherd, N., Zimcik, D. G., and Naraine, P., "The RADARSAT Synthetic Aperture Radar Development," *Can. J. Remote Sens.* **19** (4), 298–310 (1993).
- ⁴Clarke, A. C., "Extra-Terrestrial Relays: Can Rocket Stations Give World-Wide Radio Coverage?" *Wireless World*, p. 306 (Oct 1945).

⁵Tomiyasu, K., "Synthetic Aperture Radar Imaging from an Inclined Geosynchronous Orbit," *IEEE Trans. Geosci. Remote Sens.* **GE-21**(3), 324–328 (1983).

ACKNOWLEDGMENTS: We wish to acknowledge Diane Evans and Rod Zeiger for supporting this study; Robert Beal, Johnny Johannessen, and Anthony Liu for input on the science requirements; Tony Freeman, Jakob van Zyl, and Jo Bea Way for comments on design options; and John Crawford for orbital information. This work was supported by the National Aeronautics and Space Administration through a contract with the Jet Propulsion Laboratory, California Institute of Technology.

THE AUTHORS

BENJAMIN HOLT, the corresponding author, is with the Ocean Science Element, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. His e-mail address is ben@pacific.jpl.nasa.gov.

JEFFREY HILLAND is with the Radar Science and Engineering Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. His e-mail address is jeffrey.e.hilland@jpl.nasa.gov.