# WITTEX: An Innovative Multi-Satellite Radar Altimeter Constellation
## *A Summary Statement for the High-resolution Ocean Topography Science Working Group*

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**Abstract** WITTEX consists of multiple radar altimeters on individual satellites in the same orbit plane. Earth rotation separates their respective measurement tracks on the surface. In the monostatic version (co-located transmitter and receiver), each satellite generates one track, at nadir, as is standard in pulse-limited ocean altimetry. The nadir altimeters would have two frequencies (to mitigate ionospheric path delays) and a three-frequency radiometer (to estimate wet atmosphere propagation delays). Delay-Doppler techniques would be used to reduce each instrument's power and mass requirements, increase measurement precision, sharpen along-track resolution, and reduce the minimum stand-off distance from land. In the bistatic version (transmitter and receiver located respectively on neighboring satellites), an additional track would be generated at the midpoint on the surface between the satellites. Like nadir altimetry, the bistatic geometry supports natural measurements, in the sense that the sea surface heights are derived from the minimum of the waveform's range history. (This is in distinct contrast to the off-nadir geometry of a wide-swath altimeter, which is an un-natural measurement since surface heights must be extracted from a continuously increasing range history.) The bistatic altimeters need to have only one frequency. In general, a WITTEX-bistatic constellation of n satellites would generate 2n-1 surface tracks. All nadir and bistatic data will support wind speed, significant wave height, and sea surface height measurements with conventional algorithms and TOPEX-class accuracies. The co-planar satellites could be launched cost-effectively from one vehicle. Their sub-satellite tracks would be separated in proportion to their inter-satellite orbital spacing. At maximum latitudes their tracks coincide, so their respective height measurements can be cross-calibrated routinely. Data from a WITTEX constellation would support measurement of both components of the surface gradient, and would open a variety of beneficial solutions to the time/space sampling trade-off. In the future, in addition to a continuing altimeter in the Jason orbit, an operational WITTEX deployment is recommended. If nadir-viewing only, it would consist of five co-planar satellites in a Geosat orbit. These would produce five tracks at ~30 km separations at low latitudes. A WITTEX-bistatic configuration would maintain the same coverage with only three satellites. The cost of a WITTEX constellation, including all satellites, their altimeters, and their launch, is predicted to be less than the corresponding costs of TOPEX/Poseidon.

### Introduction

Coordinated multiple nadir-sensing altimeters have long been acknowledged to offer the only way to achieve significant improvement in temporal and spatial topographic sampling of the global oceans, while simultaneously maintaining height accuracy (NASA, 1987; Rapley et al., 1990, Koblinsky et al., 1992; Fu et al., 1998; Greenslade et al., 1997; Jacobs et al., 1999; LeTraon and Dibarboure, 1999; Tapley et al., 1994; Stammer and Dieterich, 1999). In spite of their appealing and substantial science value, however, multiple satellite solutions have always been considered to be unrealistic, because their costs were perceived to be prohibitive (Fu et al., 1998; Koblinsky et al., 1992; NASA, 1999). The cost barrier can be substantially reduced, however, if the altimeters can be deployed simultaneously with only one launch vehicle, and if each individual satellite is sufficiently small and low cost. As outlined below, delay Doppler altimeters in a nadir-viewing WITTEX constellation should meet both conditions.

It is normally assumed that one altimeter generates height data along its track at nadir, so that "the number of altimeters" is equivalent to "number of tracks." However, there is a fundamental distinction to be made. The essential attribute for applications is the number of tracks along which accurate height measurements can be obtained, not the number of satellites. Mid-way between the nadir tracks from two altimeter satellites there is another track that could be generated, if the satellite pair was equipped with a bistatic radar. (In this context a bistatic radar is one in which the transmitter is on one satellite, and the receiver is on the other.) It can be shown that the measurement accuracies realized in the bistatic mode are comparable to those in the nadir mode, to first order (Raney, 2001). If nadir and bistatic altimeters are combined, n satellites would generate 2n-1 measurement tracks on the surface. We denote such a constellation WITTEX-bistatic.

In the descriptions that follow, it is assumed that all WITTEX configurations would complement an ongoing TOPEX-class measurement series.

## WITTEX

WITTEX is named in honor of Emil Witte who was the first to discover (1878) the geostrophic current equation. It also is an acronym for Water Inclination Topography and Technology Experiment. The two-dimensional geostrophic current can be derived if two orthogonal components of the surface height gradient can be observed hence WITTEX. To date, satellite radar altimeters have been able to measure only the along-track component. WITTEX would overcome that limitation with a constellation of three or more co-planar small-satellite radar altimeters (Fig 1). The satellites are spaced apart by several hundred kilometers. Their sub-satellite tracks are laterally separated because of the Earth's rotation. At a given latitude, measurements occur within minutes of each other, so that the cross-track surface gradient can be measured as well as the usual along-track gradient. Track separation may be adjusted during mission operations by selection and maintenance of the inter-satellite spacing. Thus, measurement of the two-dimensional surface gradient can be optimized during a single flight mission. The sea surface height (SSH) data are free of off-nadir errors, since all measurements enjoy the accuracy inherent to pulse-limited geometry. Since all WITTEX satellites are co-planar, their surface tracks coincide at their latitude extremes. Height data from all measurements should agree at these points; WITTEX constellations are self-calibrating.

A WITTEX constellation can be tuned to favor dense spatial coverage, relatively tight temporal coverage, or other priorities. A change from one scenario to another would require a few days. Using the Geosat 17-day orbit as a reference (~800 km altitude, 108-degree inclination, ~17-day repeat, and 160 km equatorial track separation), consider four three-satellite possibilities (Fig 2). One could also envisage operational five-track coverage (Fig. 3) which could be realized either by nadir instruments alone or by a bistatic configuration.

*SCENARIO I*, *High spatial resolution* (~200 km orbital spacing): Each triplet of sub-satellite orbit tracks would be 24 km wide, and span less than 1 minute. This arrangement would support measurement of both the along-track and the cross-track surface gradients at about the same resolution.

*SCENARIO II, Uniformly dense spatial coverage* (~900 km orbital spacing): Each triplet of tracks would have a time spread of about 4 minutes, and all adjacent tracks would be ~50 km apart at the equator. This spacing is nearly optimum for observing oceanic eddy fields and surface energy transport (Stammer and Dieterich, 1999).

*SCENARIO III*, *High temporal resolution* (~2600 km orbital spacing): This arrangement would place each succeeding altimeter's track on top of the spatially adjacent one. This would generate three- and six-day revisit cycles, in addition to the normal 17-day Geosat cycle. An alternative version of this scenario would space the satellites ~5200 km apart, resulting in effective six- and twelve-day repeat cycles within each 17-day base cycle. Frequent revisit is desirable to observe the evolution of large-scale features, such as El Niño.

*SCENARIO IV, Site-specific coverage* (controlled spacing): Given that one of the altimeters would be dedicated to a fixed exact-repeat mission, the others in the constellation could be moved as required upon command. This would allow a user to shift the altimeters' tracks to pass over an area of particular interest, which would have scientific, military or natural hazard applications. With two roaming satellites, any given site could be covered by both an ascending and a descending pass. This guarantees at least one cross-over and more frequent coverage at the site of interest. Alternatively, the satellites could be timed to generate four cross-overs that would bracket the site. Finally, this scenario could be tuned to provide much-needed spatial data to upgrade existing bathymetric surveys.

*SCENARIO V, an operational constellation of small, nadir-viewing satellites* (~460 km orbital spacings). Five altimeters in a Geosat orbit would produce ~30 km inter-track spacing near the equator, and near-simultaneous coverage (<5 minutes time spread) by each set of five nadir tracks. The next adjacent set of five tracks would occur three days later (or earlier). This time/space coverage is nearly ideal for observation of mesoscale eddy fields (Jacobs et al., 1999), surface energy transport (Stammer and Dieterich, 1999), and geostrophic current vectors (Greenslade et al., 1997; Stammer and Dieterich, 1999), none of which can be observed directly by present means. This scenario provides better temporal and spatial coverage as well as greater on-orbit redundancy, at relatively small marginal cost over a constellation of fewer satellites.

## WITTEX-Bistatic

The same track coverage portrayed in Fig. 1 could be generated by only two satellites if the center track were illuminated in a bistatic mode. A bistatic radar is one for which the transmitter and the receiver are located separately, in this case on different widely spaced satellites. The bistatic sea surface height measurement can be shown (Raney, 2001) to sustain accuracies comparable to those of the nadir mode. The bistatic measurement focuses on the specular point between the transmitter and the receiver. The specular point is located at the minimum radar range between the two satellites, and its forward reflection (towards the receiver) is very strong. Note that knowledge of the precise range or incident angle of the specular point is not required, since the sea surface height is contained in the minimum range observed in the reflected signal. The Doppler properties of reflections from the neighborhood of the specular point are equivalent to those at nadir, so that all advantages of the delay-Doppler paradigm (outlined in the following section) carry over to the bistatic case. In general, n satellites equipped with nadir and bistatic altimeters would generate 2n-1 accurate measurement tracks on the surface.

In the generalized WITTEX-bistatic configuration, each satellite would host three altimeters: one viewing nadir, and two others, each pointed at the nominal specular point corresponding to the fore and aft neighboring satellites in the constellation. (The end members would require only one bistatic instrument, but it should be cost effective to make all satellites identical. This would support partial on-orbit redundancy, and achieve maximum cost savings through duplicate satellite construction.) The nadir instruments would be as described below. The bistatic instuments would use only one frequency, and would not include radiometers. The necessary atmospheric and ionospheric path-length corrections to the bistatic legs could be interpolated from the nadir instruments, as there always would be sufficient data available from the nadir measurements. (Note that the greatest space and time separations between the bistatic and the nadir propagation paths would be half of the surface track spacing, and within a few minutes coincidence, respectively.) Further, each pair of satellites must communicate with each other, and maintain knowledge of their respective spacings to within a few centimeters. Whereas this is well within the state-of-the-art, it is a requirement in addition to those of a simpler WITTEX constellation. Clearly, each WITTEX-bistatic satellite would be somewhat larger and more complex than the smaller-better-cheaper nadir-sensing WITTEX birds.

Bistatic WITTEX constellations open new possibilities for on-orbit arrangements. We have considered one situation (Scenario VI) that is a step towards maximizing coverage from a multi-satellite configuration. If all specular points were used, including especially those between outlying spacecraft, then four satellites would be sufficient to generate nine (9) surface tracks. In a Geosat orbit, these would have equatorial spacings of only about 18 km. There are two primary down sides to this scenario. Two of the spacecraft would have to be host to three bistatic altimeters in addition to the nadir-viewing instrument. Also, several of the bistatic measurements would be at included angles considerably larger than sixty degrees, and hence their accuracies would be degraded. The most appealing bistatic constellations are those in which only nearest-neighbor specular points are used, as illustrated by the next scenario.

*SCENARIO VII, three-satellite WITTEX-bistatic* (~920 km orbital spacings). Instead of five nadir-sensing altimeters, consider three bistatic (and nadir) altimeter satellites in a Geosat orbit. These would produce the same coverage as Scenario V (Fig. 3), namely, ~30 km inter-track spacing near the equator, and near-simultaneous coverage. Note that the interpolations required for bistatic path length corrections would need to span only 30 km.

## Implementation

One vehicle can launch multiple satellites efficiently into the same orbit plane, if the satellites are sufficiently small. Fortunately, the delay Doppler radar altimeter (DDA) leads to a smaller instrument, and therefore a smaller satellite, than would be possible with the conventional radar altimeter paradigm (Raney, 1998). In addition, altimetry performance is improved. Although the DDA technique requires much less transmitted power, it yields more precise measurements than a conventional radar altimeter even though it has a much smaller along-track footprint (Jensen and Raney, 1998), and it can operate more reliably up to the shoreline. The delay Doppler technique has been proven in airborne demonstrations, supported by NASA's Instrument Incubator Program.

The waveform-generation algorithms of an orbital version would be similar to those of TOPEX, augmented by the delay Doppler paradigm. The waveform data volume from each altimeter will be on the order of twice that of TOPEX; the high-resolution waveforms will be generated at a 27 Hz rate, corresponding to resolved footprints of 250 m in the along-track direction. Waveforms averaged at a 1-Hz rate would have along-track resolution of 6.75 km, regardless of SWH. These waveforms have been shown (by simulation) to have comparable accuracy and approximately half the variance of the corresponding TOPEX 1-Hz SSH, wind speed (WS), and significant wave height (SWH) measurements.

The Earth's equatorial rotation rate of ~450 m/s, combined with a track-repeat tolerance of ~1 km, translates into an along-orbit relative position control requirement of only ~9 km for the nadir WITTEX configurations. Relative spacecraft spacings must be known to centimeters for accurate height measurements from the WITTEX-bistatic array. As is true for all WITTEX scenarios, their respective height measurements coincide at the latitude extremes. This provides a robust basis for cross-satellite relative calibration.

Each WITTEX nadir altimeter has two frequencies and an on-board water vapor radiometer (WVR), similar to the TOPEX design. The bistatic radars need have only one frequency. The DDA approach, combined with recent advances in spacecraft technology, leads to substantial miniaturization for either the nadir or the bistatic altimeters. The mass of each nadir WITTEX satellite is predicted to be less than 100 kg. This is about one-third that of Geosat Follow-On. The nominal mass objective for each WITTEX-bistatic satellite is less than 200 kg.

The cost estimated for either a five-satellite WITTEX-monostatic constellation or a three-satellite WITTEX-bistatic constellation (including their payloads and launch into a Geosat orbit) is less than the counterpart costs for TOPEX/Poseidon. Although there are only three satellites in the bistatic configuration of Scenario VII, each is more complicated than the nadir-viewing WITTEX spacecraft. Nevertheless, the total cost of the bistatic version could well be substantially less than that of a five-track nadir WITTEX configuration. WITTEX-monostatic would require five two-frequency altimeters with WVRs, as opposed to WITTEX-bistatic, which would require only three two-frequency altimeters with WVRs. In addition, two bistatic single-frequency altimeters would be required, augmented by inter-satellite communications and distance measurements. The operational costs of WITTEX-bistatic should be less. For example, precision orbit determination would be required for only three satellites, rather than five.

## WITTEX-Wide

WITTEX-Wide would be a constellation of three co-planar radar satellites, except that the center satellite (DD2 in Fig 1) would be a DDA and a wide-swath altimeter (Rodriguez et al., 2001), rather than a nadir-sensing instrument alone. From a TOPEX-class orbit, the JPL multi-beam altimeter concept would generate SSH data at ~15-km postings across a swath approximately ±100-km centered on nadir. In the WITTEX-Wide concept, two co-planar altimeters (DD1 and DD3), one leading and one trailing the wide-swath altimeter, would create parallel tracks to each side of the swath's center line. If DD1 and DD3 were separated from the wide-swath altimeter by about 1200 km along their orbit, the resulting cross-track nadir spacings would be about 75 km at the equator. The set of three satellites in such a WITTEX-Wide constellation would pass each observation neighborhood within five minutes of each other.

Although appealing in principle, a wide-swath altimeter has several disadvantages that have to be overcome before it might live up to its promise. These disadvantages include: (*i*) a large sensitivity to errors in satellite roll knowledge, (*ii*) an inherent inability to measure SWH off-nadir, (*iii*) an inherent dependence on extrapolations (and, at low wind speeds, sensitivity to the relative direction of wave propagation) for off-nadir em-bias corrections, (*iv*) a lack of direct measurements to correct for wet atmosphere delays in the off-nadir channels, (*v*) a lag of many days before cross-track and along-track height measurements can be reconciled at their intersections, (*vi*) a progressive trend toward parallel tracks as the measurement latitude approaches the plane of inclination, thus frustrating the roll correction algorithm, (*vii*) a necessity to develop and qualify new analysis algorithms, and (*viii*) a relatively costly approach that may not readily be configured to support operational reliability and on-orbit redundancy.

WITTEX-Wide could help to offset many of these disadvantages. Inherently accurate pulse-limited heights from "the outrigger" altimeters would provide continuous roll- and path-length-corrected height data that could be used as reference profiles to reduce systematic errors from the wide-swath off-nadir measurements. However, these benefits, like the effectiveness of the wide-swath correction algorithm itself, decrease monotonically (to zero) as latitude increases towards the altimeters' inclination.

## On Natural Height Measurements

The great virtue of a pulse-limited radar altimeter is that the measurement objective, sea surface height, is measured directly (subject of course to path length corrections and precision orbit determination). That is, the radar range of interest is the minimum range observed in the ensemble of signals reflected beck to the radar. There is no need to establish the precise neighborhood giving rise to the reflection, nor to the angle of incidence relative to the radar. Nadir is by definition the closest point to the altimeter, and any change in sea surface height is manifest as a corresponding change in the minimum range to that point. This may be denoted a *natural measurement*.

The same virtue carries over to bistatic measurements of sea surface height. That is, the radar range of interest is the minimum range observed in the ensemble of reflected signals available to the radar. Just as in nadir altimetry, for bistatic height measurements there is no need to establish the precise neighborhood giving rise to the reflection, nor to the angles of incidence or reflection relative to the radars. The specular point is by definition at the minimum reflected range between the two satellites, and any change in sea surface height is manifest as a corresponding change in the minimum range of all rays reflected from the neighborhood of that point. Thus, a WITTEX-bistatic height is also a *natural measurement.*

The situation is very different for any scheme that would attempt to measure sea surface height through backscatter gathered in a side-looking geometry. The wide swath altimeter is one example of such a geometry. In the side-looking case, extraction of sea surface height from radar range data requires that the angle from the radar to the ocean's surface be known, indeed, very well known. Radar range increases monotonically with time, and with incident angle. There is no minimum in the range data that would firmly establish the height measurement point. If very accurate sea surface heights are required, then extremely accurate knowledge is required of the incident angle at the point of measurement. Height measurements in a side-looking geometry is by definition a problem in triangulation, rather than a minimum distance along a straight line. Triangulation introduces new uncertainties, and these induce new sources of sea surface height error. We consider triangulation to be an *un-natural measurement* if accuracy is required.

Being an un-natural measurement, wide swath altimetry starts with a fundamental disadvantage. This disadvantage can never be fully overcome. As acknowledged by its most ardent proponents (Rodriguez et al., 2001), there is no way to meet the angle knowledge requirement by direct means. The tolerances fall approximately two orders of magnitude beyond current hardware capabilities. Thus, the implied systematic errors in off-nadir height measurements must be met by indirect methods. Those methods include extensive temporal and spatial averaging. This averaging in effect is a low-pass filter. The end product of height fields may well have data postings at relatively close spacings and reduced variance, but only those signals that pass through the averaging filter will be portrayed.

## Conclusions

At present there are no means in place to observe vector velocity fields over the oceans. A WITTEX constellation would be the first and perhaps the only feasible means to meet this requirement. Estimates of kinetic energy, Reynolds stresses, mean and meandering flows of the world's oceans would become a routine observation. These estimates would contribute to accurate modeling of $CO_2$ atmosphere-ocean exchange as well as the long-term modeling of large-scale dynamic effects such as El Niño.

Mesoscale ocean phenomenon (~50-100 km) are both spawned by and can drive the mean flow. Oceanic rings, western boundary current meanders, and deep ocean eddies are important in modifying not only the dominant flow over much of the ocean but in affecting the geochemical, chemical and biological oceanography. Eddy fields transport, entrap, and disperse chemicals, dissolved substances, nutrients, small organisms and particulate matter, and are central to the oceanic energy exchange processes.

The WITTEX concept, either the nadir-viewing WITTEX-monostatic or WITTEX-bistatic, is an elegant response to these and other long-standing needs in precision oceanic altimetry. In contrast to other means of generating coverage, it is inherently accurate, and self-calibrating. WITTEX offers a flexible, capable, unique, and cost-effective approach that would significantly advance the state-of-the-art of satellite radar altimetry.

Ten years from now we could be poised to implement a nearly ideal yet affordable multiple satellite solution in response to the altimetric requirements delineated by the oceanographic and geodetic science communities. In subsequent decades, the paradigm for operational ocean topographic measurements should be radar satellite constellations.

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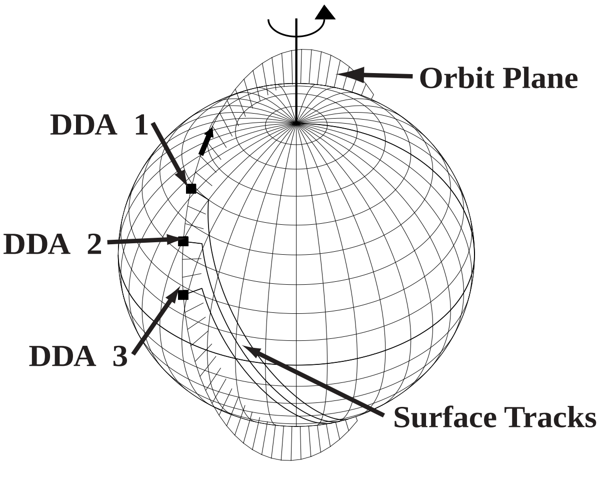

**Figure 1.** Three-satellite nadir-viewing WITTEX Constellation.

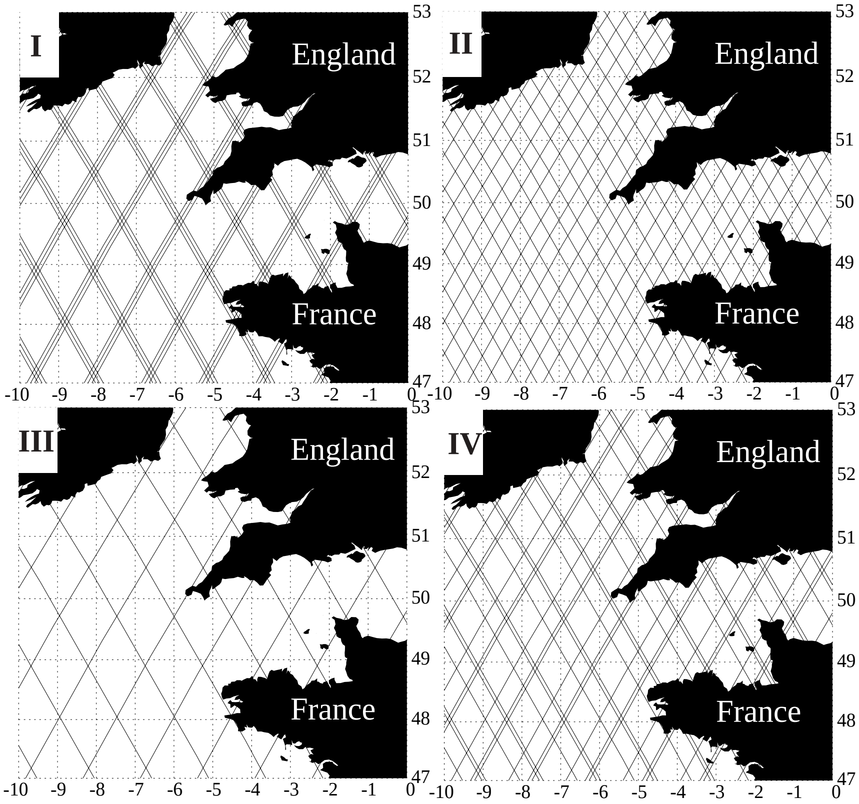

**Figure 2.** Four three-satellite nadir-viewing WITTEX scenarios.

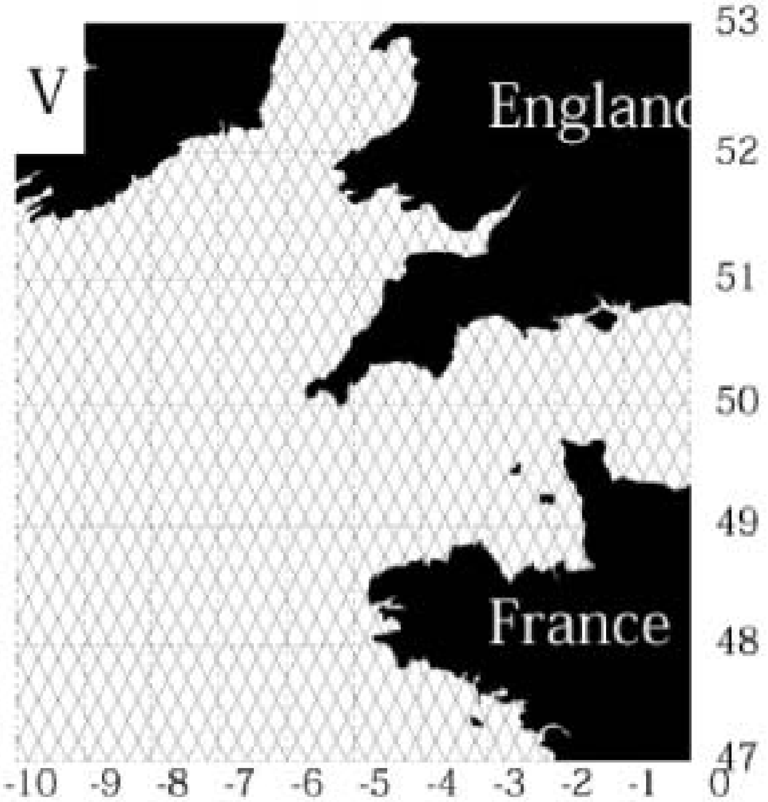

**Figure 3.** An operational five-track pattern from Geosat orbit.