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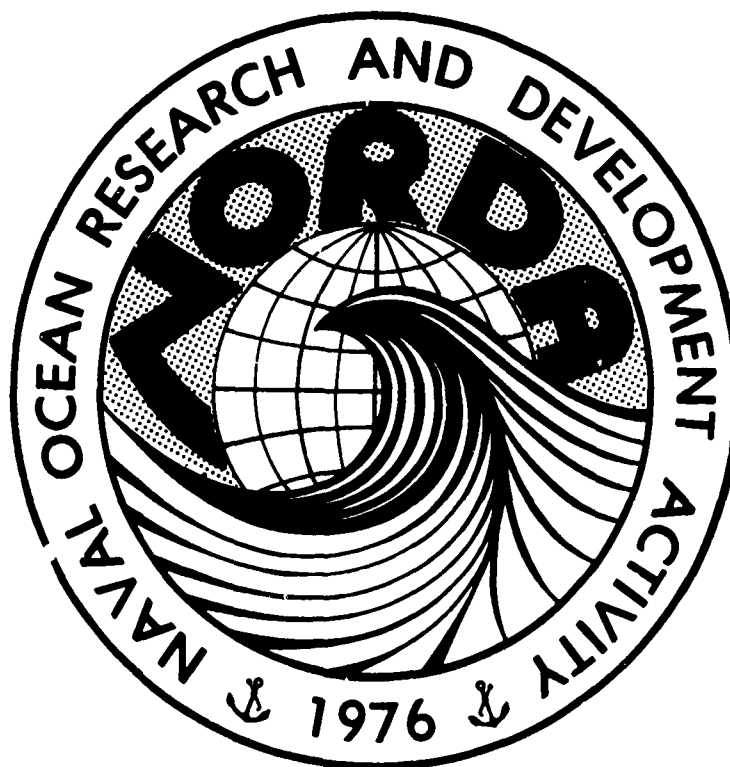
NORDA Technical Note 226

Naval Ocean Research and
Development Activity
NSTL, Mississippi 39529



A Position Paper: Mesoscale Oceanography from GEOSAT

ADA132292



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August 1983

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PREFACE

Just prior to the release of this position paper, the workshop recommended in section 5 was held at NORDA on 20-22 July 1983. The workshop, entitled "Oceanography from GEOSAT," was attended by about 70 members of the Navy, NOAA, NASA, and the academic oceanographic community. The consensus of the attendees was amazingly uniform: the opportunity posed by an Extended, Exact Repeat Mission for GEOSAT (as proposed within this paper) is unique and of critical importance to attempts to gain an understanding of the oceanic mesoscale. The topographic opportunity afforded by the nominal 18 month GEOSAT mission is very limited for all purposes except the primary GEOSAT mission of marine geodesy. Attendees said that the best way of meeting the goals of the secondary oceanographic mission for GEOSAT is to allow unfettered accomplishment of the primary geodetic goals initially, with the secondary oceanographic goals accomplished during the extended, exact repeat mission.

A comprehensive report on the recommendations of this workshop is due in September, 1983. At this point I must add that during the workshop, the technical feasibility of an extended, exact repeat mission was re-examined in a smaller working group session. It was agreed that the technical ease with which such an extended mission could be accomplished, as well as the near certainty of a long-lived GEOSAT (barring any catastrophic failures), necessitates that planning for such an extended mission proceed without delay.

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ACKNOWLEDGEMENTS

This project was funded by Program Element 61153N, Herb Eppert, Jr., Program Manager.

A Position Paper: Mesoscale Oceanography from GEOSAT

1. Introduction

The satellite altimeter represents the only viable platform for obtaining topographic information over oceanic regions of appreciable size in near real time. Plans call for the U.S. Navy's operational use of mesoscale dynamic topography as derived from satellite altimetry by the end of the 1980's, when the Navy Remote Ocean Sensing System (NROSS) and NASA's Ocean Topography Experiment (TOPEX) will fly with radar altimeters. In the interim, the best way to prepare for the operational, as well as valid research use of NROSS/TOPEX altimetry is by using GEOSAT altimetry as effectively as possible. Given its present orbital configuration GEOSAT is expected to yield only a marginal capability for the recovery of mesoscale dynamic topography. In this position paper I present the justification for this strong statement and, more importantly, conclude with a rational, cost-effective solution to the problems presented by the present orbital configuration: the Extended, Repeat Orbit Mission for GEOSAT.

The prime GEOSAT mission is the collection of global sea surface topography at a cross-track spacing of approximately 5 km. These global data will be averaged to compute a mean sea surface topography in order to approximate¹ the long wavelength components of the marine geoid for OP-0211 (Trident Program). The required track spacing necessitates that the groundtracks laid down by the GEOSAT altimeter do not exactly repeat.

The present nominal orbit, with a nodal period of 6043.6 secs, meets this non-exact repeating criterion. As we see later, all possible deviations from this nominal orbit have a fundamental near repeat period of 3 days. This means that

¹This mean topography differs from the true equipotential surface (geoid) in that the former contains topography arising from mean ocean currents and any residual time-variable circulation that has not been adequately averaged.

successive groundtracks are always spaced nearly 1000 km apart at the equator, while every 3rd day the grid of groundtracks nearly closes. The distance by which the groundtrack on the 3rd day misses an exact closure defines the important temporal and spatial sampling scales relevant to obtaining either a synoptic (snapshot) or a statistical sampling of the mesoscale topography. In order to meet the objectives of the secondary mission for GEOSAT, which is oceanography, we must optimize the orbital strategy to minimize temporal and spatial aliasing of the mesoscale topography. Two important considerations severely limit any attempt to obtain mesoscale topography from data collected during the initial 18-month geodetic mission of GEOSAT. These are:

(1) The non-repeating pattern of groundtracks leads to severe contamination of the mesoscale dynamic topography by the marine geoid and,

(2) The severe temporal undersampling of non-stationary mesoscale fields associated with the slow fill-in of groundtracks does not allow for synoptic realization of the mesoscale topographies.

In the next two sections I present details of problems arising from these considerations. In Section 4 I suggest a simple way to overcome the problems: the extended, exact repeat orbit mission for GEOSAT (the GEOSAT-ERM to coin an acronym).²

²One should take careful note of the fact that I do not show much concern on the lack of a boresighted microwave radiometer on GEOSAT (used for water vapor pathlength corrections). This is based on careful analysis of the SEASAT Scanning Multifrequency Microwave Radiometer (SMMR) data, which indicates a fairly low amplitude correction (15 to 20 cm rms at spatial scales likely to interfere with oceanography). More importantly, there is a distinct frequency mismatch between high frequency atmospheric water vapor variability (periods of order several days) and the much lower frequency variability of the mesoscale ocean (periods of order several months). Thus, I feel that the mesoscale variability data obtained from a repeat orbit, as suggested later, would be subject to only a slight increase in the effective instrument noise floor due to fluctuations in atmospheric water vapor content.

One may question the relationship between my proposal for an extended, exact repeat orbit mission for GEOSAT and on-going plans for altimeters to fly on NROSS and NASA's TOPEX. I shall review issues relating to the effective use of the planned altimeter on NROSS in a future position paper. It is likely that atmospheric drag will be a more severe limitation on the effective use of the NROSS altimeter than is the case for GEOSAT's minimal drag. Funding for NASA's TOPEX, while presently somewhat more secure than in the past, remains uncertain. Thus, an extended GEOSAT mission with the satellite flying in an exact repeat orbit may represent the greatest opportunity for use of the satellite altimeter as a platform for global observation of the oceanic mesoscale. In any case, this unrecognized opportunity is certainly the most cost-effective and returns the quickest results.

2. Problems arising from Non-Repeating Orbits

Spatial variations in the topography of the ocean surface arise from three³ major sources:

- (1) Spatial undulations in the geoid,
- (2) Geostrophically (or quasi-geostrophically) balanced currents, generally associated with mesoscale circulation features and,
- (3) Externally forced topography, such as oceanic tides or atmospheric pressure loading.

Table 1 summarizes typical topographic amplitudes and spatial wavelengths for each of these signals. Notice that the amplitude of typical geoid undulations can completely mask the much weaker topography of the mesoscale ocean. Consider local geoid gradients which can involve changes of order 10 to 100 centimeters amplitude in only a few kilometers spatial distance. Such large geodetic gradients are

³ Additionally, the temporal mean, basin-scale general circulation of the ocean results in topographies of 1-10 centimeters amplitude variation over 10^3 - 10^4 kilometers horizontal scale. Observation of this basin-wide setup is not possible with GEOSAT (primarily due to present limitations in the Doppler tracking TRANET system) and remains a goal unique to NASA's proposed TOPEX mission.

Table 1. True sea surface topography consists of three components:

SOURCE	AMPLITUDE	SPATIAL SCALE
GRAVITATIONAL EQUIPOTENTIAL SURFACE (GEOID)	10^4 cm	10^3 km
TIDES	10 to 10^2 cm	10^3 km
GEOSTROPHIC OCEAN:		
BASIN/INTERMEDIATE SCALES	1 to 10 cm	10^3 to 10^4 km
MESOSCALE	10 to 10^2 cm	10^2 km

associated with major bathymetric features. The problem of cleanly separating the signal of dynamic topography from that of the geoid is in some regions equivalent to a signal to noise ratio of 1:100.

In Section 4 we see how a grid of repeating groundtracks allows for straightforward removal of the geodetic signal. During the initial 18-month GEOSAT mission the non-repeating nature of the altimeter groundtracks requires that independent reference surfaces, used to model the geoid, be subtracted from the raw topography in order to obtain mesoscale topographies (in the form of a residual). It must be emphasized that such a brute force approach to the computation of residuals is merely a stop gap measure.⁴ Plans call for the regional use of "NAVOCEANO hybrid surfaces or "geoids". Unfortunately, these reference surfaces exist in only limited regions⁵ and even in these limited regions may not have adequate spatial resolution (5 minute grid) to accommodate sharp geodetic features like seamounts (though the survey design attempts to accommodate seamounts). A critical limitation associated with these "geoids" is that purely geodetic information, as collected by shipboard gravimetric survey, is inherently of high spatial frequency ($>10^{-2} \text{ km}^{-1}$). Hence, SEASAT altimetry is blended with the gravimetric data to provide information on intermediate and longer scales. Thus, these surfaces are hybrids and any attempt to compute mesoscale topography as a residual will rely essentially on the computed difference between a GEOSAT data track and a SEASAT data track. There are no fully adequate reference surfaces against which to cleanly compute mesoscale

⁴The most appropriate oceanographic use of the satellite altimeter is observation of changes in topography. In this respect the altimeter functions much as a bottom-located inverted echo sounder that collects a time sequence of changes in thermocline depth, but is difficult to calibrate in absolute units. Flying in a orbit that lays down exactly repeating groundtracks allows for this most effective use of the altimeter.

⁵Present plans allow for the computation of useful topographic residuals for mesoscale analyses in a region that only covers an area equal to one-third of one percent of the global coverage that would be possible during the extended; repeat orbit mission.

topographies⁶. While the problem of simple detectability might be addressed with this differencing approach, it may not be possible to compute the desired dynamic topography from such an approach. In order to make full use of the potential of satellite altimetry the U.S. Navy ultimately desires dynamic topography as input to numerical and climatological oceanic models.

3. Problems arising from Orbital Sampling Strategy

Any attempt to synoptically map mesoscale topography with a single, nadir-looking altimeter faces an unavoidable tradeoff between temporal and spatial resolution as shown in Figure 1. Illustrated is the crosstrack equatorial distance (defined here as spatial resolution) between an exact repeating grid of groundtracks that closes in some specified number of days (defined here as temporal resolution). The prime mission of GEOSAT will be accomplished with a nonrepeating orbit with a near repeat in roughly 153 days. Figure 2 illustrates the pattern of roughly 40 km spaced groundtracks laid down in 30 days over the Loop Current/Gulf Stream System during the 18-month geodetic mission.

Very limited knowledge of mesoscale variability (based on Mid Ocean Dynamics Experiment (MODE) and POLYMODE experience) indicates a peak in oceanic activity on time scales of order 10^2 days and space scales of order 10^2 kilometers. Adequate along-track statistical sampling, which reference to Figure 1 indicates might be accomplished with orbits repeating exactly in periods 3-10 days, is important as a research tool for studying the spectra and the geographic/seasonal distribution of mesoscale variability. However, if the altimeter is ever to be used as an operational tool for updating prognostic and diagnostic models⁷, near-synoptic mapping is essential. In most active mesoscale regions such synoptic mapping might be attempted with orbits repeating on periods ranging from 20 to 40 days and lying along the "shoulder" of the curve shown as Figure 1.

⁶Even the final global mean surface computed for the GEOSAT prime mission by the Naval geodetic community will have much too low spatial resolution to constitute an adequate reference surface in many regions of high gravimetric activity.

⁷I must again emphasize that no alternative to the satellite altimeter is forthcoming.

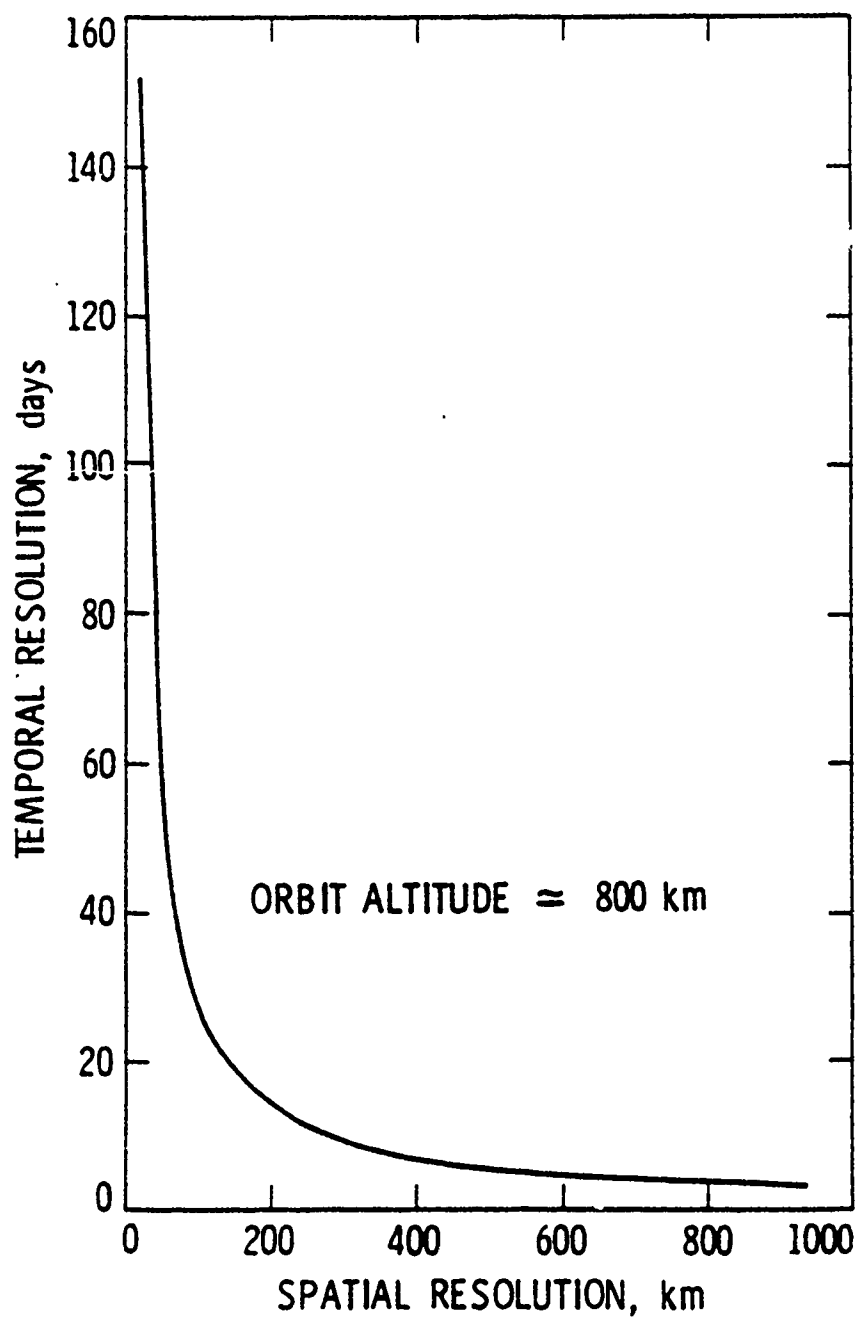


Figure 1. The unavoidable tradeoff between temporal and spatial resolution for the single, nadir-looking altimeter flying in an 800 km altitude orbit. During the nominal or geodetic mission GEOSAT's orbit is approximately that of a 153 day repeat (hence, lying at the extreme upper left end of the curve). Attempts to synoptically map meso-scale topographies could be made from orbits lying along the shoulder of the curve (repeat cycles from 40 to 20 days). Statistical sampling of the oceanic mesoscale is best obtained from orbits along the flatter portion of the curve (repeat cycles from 10 to 3 days). (Figure taken from paper entitled, "Oceanographic Satellite Altimetric Mission Survey" by G.H. Born, D.B. Lame, and J.L. Mitchell)

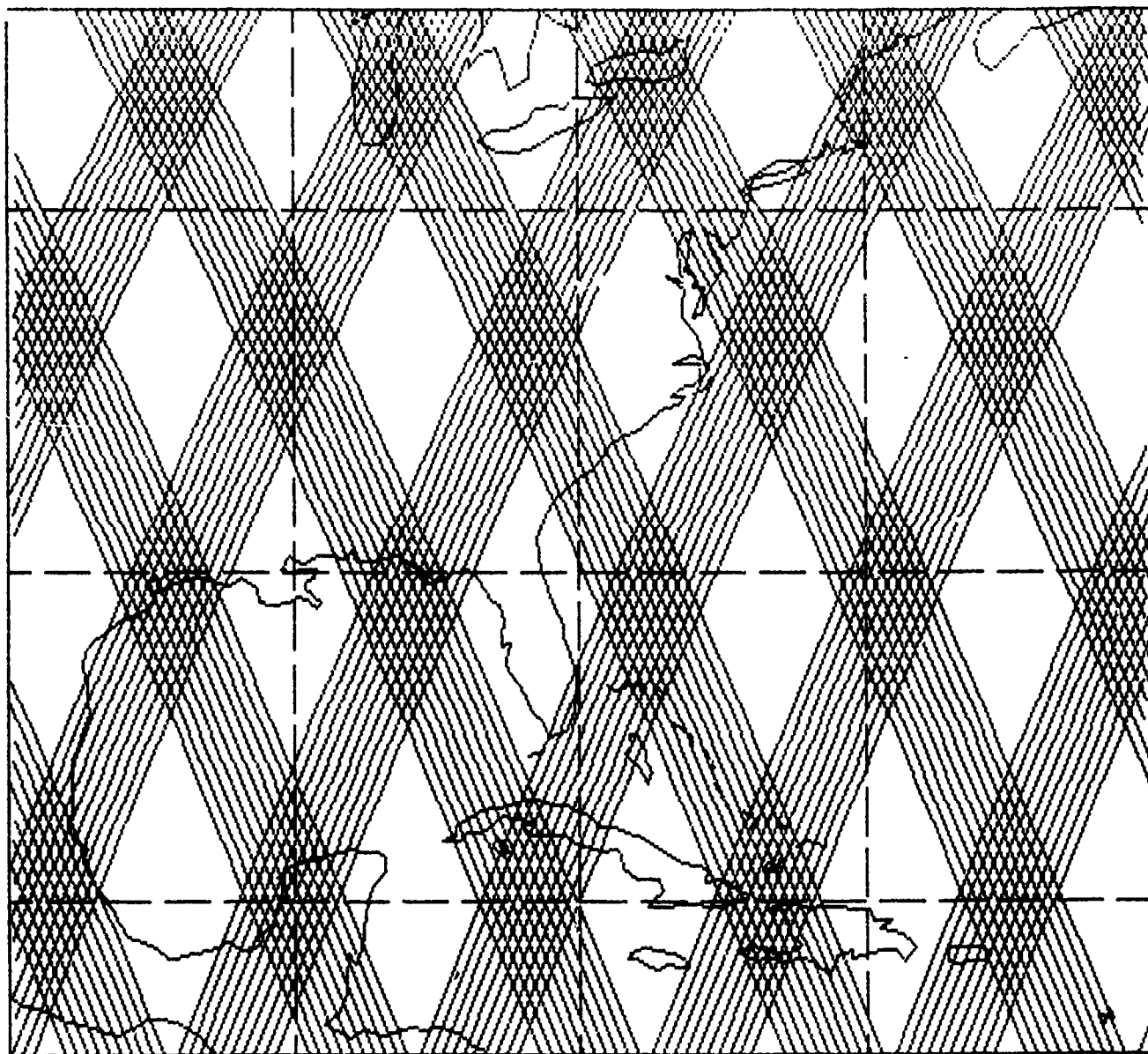


Figure 2. GEOSAT ground track coverage over the Loop Current-Gulf Stream System as accumulated in 30 days during the nominal geodetic portion of GEOSAT's mission. (Courtesy of Dr. Zack Hallock, NORDA)

The groundtracks laid down during the nominal 18-month GEOSAT mission severely undersample in time, while they more than adequately sample in space. This means that attempts to synoptically map a non-stationary mesoscale field will often meet with failure due to movement of the mesoscale features during the period over which the satellite lays down its groundtracks. The resulting topographies will be hopelessly smeared and the result is analogous to a snapshot of a moving object with a much too slow shutter speed.⁸

Figures 3 and 4 illustrate rather poignantly the "smearing" effects of this temporal undersampling. Figure 3 depicts the topographic field of four stationary mesoscale eddies⁹ as mapped from computer simulated passes of GEOSAT over the region during a 75 day period. These 75 km radius, simulated eddies might be considered representative of non-interacting western boundary current rings. Notice that the GEOSAT groundtracks are spaced tightly enough (at approximately 40 km equatorial spacing) to spatially resolve these features, thus to detect them. However, if the eddies are given typical phase velocities of 5 cm/sec to the southwest the temporal undersampling of the initial GEOSAT orbit leads to terrible distortion of the topographies (see Fig. 4) and to false detection (i.e., "seeing" two eddies when there is really only one). Dr. Zack Hallock (NORDA) has run a large number of such computer simulations and finds that if a field of typical boundary current meanders is to be sampled, the problems of temporal aliasing are insurmountable if one must depend entirely upon a single, nadir-looking altimeter (often there will be no alternative).

Ultimately, the objective use of satellite altimetry for diagnosis and prognosis of dynamics and subsurface thermal structure of active mesoscale fields depends upon

⁸One should also note that the slow "fill-in" of a region by the satellite's groundtracks is inconsistent with the present requirement for a daily mesoscale feature demonstrational product from GEOSAT. Timescales associated with both track fill-in and with changes in the mesoscale topography are more typically weeks, not days.

⁹It is crucial to appreciate that the lack of an adequate reference surface, as discussed in Section 2, in general precludes obtaining such a contour map from GEOSAT during the initial 18-month mission except in isolated regions with useful residuals obtained in an area less than one percent of the global area over which residuals from the GEOSAT-ERM could be computed.

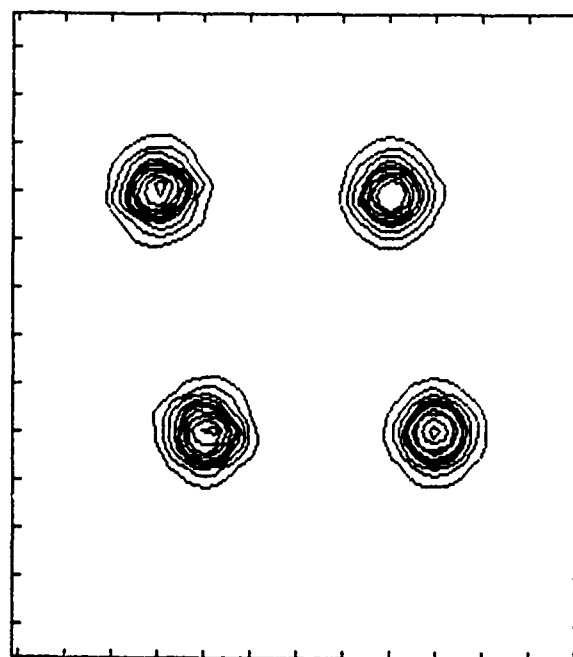


Figure 3. Contoured field of surface topographies associated with four stationary mesoscale rings. These computer simulated rings have an approximate e-folding radius of 75 km and peak central amplitude of 1 dynamic-meter. The rings have been sampled by 75 days of accumulated GEOSAT altimetry (geodetic orbit) and then objectively mapped. (Courtesy of Dr. Zack Hallock, NORDA)

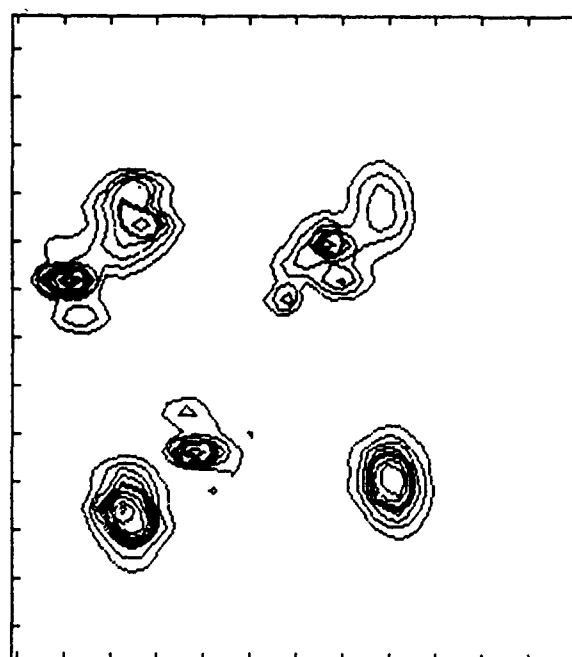


Figure 4 The same four rings as illustrated in Figure 3 and as sampled by GEOSAT during the nominal, geodetic mission. The "smearing" results because the rings are now no longer stationary, but have been given a realistic phase velocity of 5 cm/sec to the southwest. (Courtesy of Dr. Zack Hallock, NORDA)

the assimilation of altimeter observed topography into numerical circulation models. Dr. John Kindle (NORDA) has run several studies attempting to simulate the ingestion of GEOSAT observed topographies into a regional circulation model. In these attempts the long-lasting errors associated with the ingestion of the improperly sampled altimeter data can be quantified. Figures 5 and 6 show the residual error expressed in terms of the regionally normalized rms error in depth of the main pycnocline as a function of time from the initial ingestion of GEOSAT sampled topography. The ill-effects of this improperly sampled data (as illustrated in Figure 5) reside for over 150 model days, severely limiting the usefulness of the model as a prognostic tool. On the other hand, a faster repeating orbit, such as the 21-day repeat orbit used to produce Figure 6, leads to much less noisy predictions. Studies such as these will help in defining the most appropriate repeat cycle for the extended mission's orbit.

The design of a proper mesoscale sampling strategy depends upon the nature of the frequency/wavenumber response of the mesoscale ocean. This response is expected to be different in different regions of the global ocean. The specification of a suitable sampling strategy for several regions of Navy interest (e.g., Northwest Atlantic) is being addressed. One attractive possibility is a 20-day exact repeating orbit. The same nonstationary eddy field simulated in Figure 4 is shown as sampled by a 20-day exact repeating orbit in Figure 7. Notice that the problems of temporal undersampling have been alleviated for the most part. Even more importantly, changes in topography observed from such an exactly repeating orbit are completely free of geoid contamination. The satellite groundtracks for a 20-day exact repeating orbit are shown in Figure 8 (which may be compared with Figure 2).

In the next section I present a simple, straightforward (and extremely cost-effective) proposal for overcoming the limitations associated with oceanographic utilization of altimetry. This proposed scheme would provide an otherwise unexpected wealth of useable mesoscale altimetry to the U.S. Navy in sufficient time to prepare for the meaningful use of both NROSS and TOPEX altimetry.

4. A Proposal: The Extended, Exact Repeat Mission for GEOSAT (GEOSAT-ERM)

The severe limitations on the use of GEOSAT altimetry for obtaining critical information on the oceanic mesoscale, as discussed in the previous sections, could be remarkably overcome by maneuvering GEOSAT into a properly selected, exact

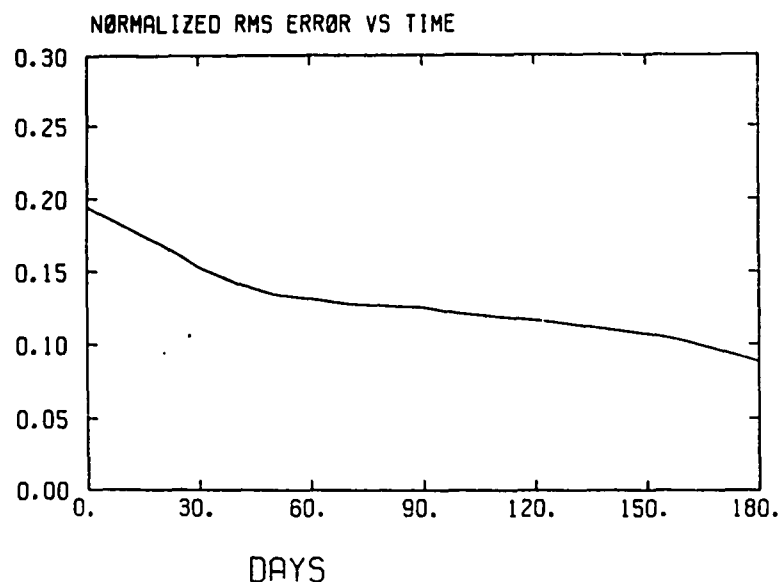


Figure 5. Normalized RMS error in pycnocline height anomaly as a function of time after initialization of an oceanic numerical model with simulated GEOSAT data as sampled from an orbit approximating the nominal or geodetic orbit. This particular regional model is used to simulate the circulation in the Gulf of Mexico. In western boundary current regions, where rings are typically smaller than those in the Gulf, the RMS errors are likely to be higher. (Courtesy of Dr. John Kindle, NORDA)

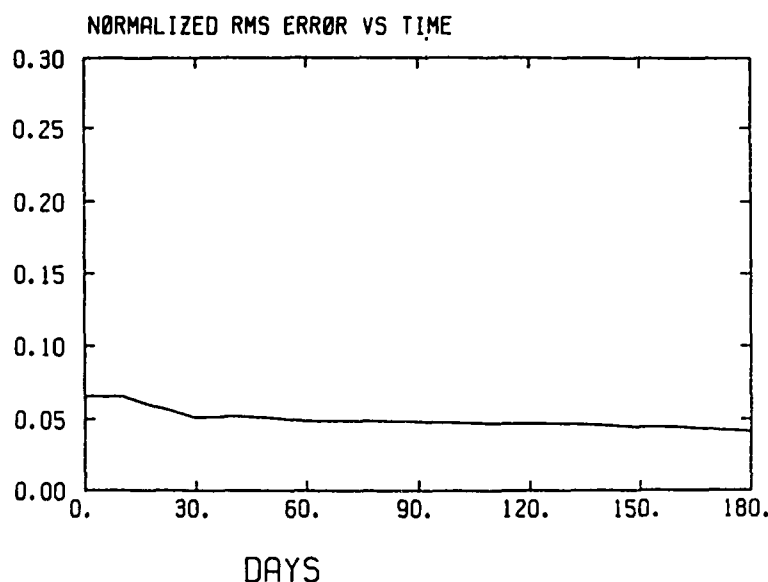


Figure 6. Normalized RMS error as in Figure 5 after initialization with topography sampled from a hypothetical 21-day repeat orbit. While such an orbit seems to adequately resolve the large eddies of the Gulf of Mexico, it is likely that in other regions smaller eddies may not be adequately resolved. (Courtesy of Dr. John Kindle, NORDA)

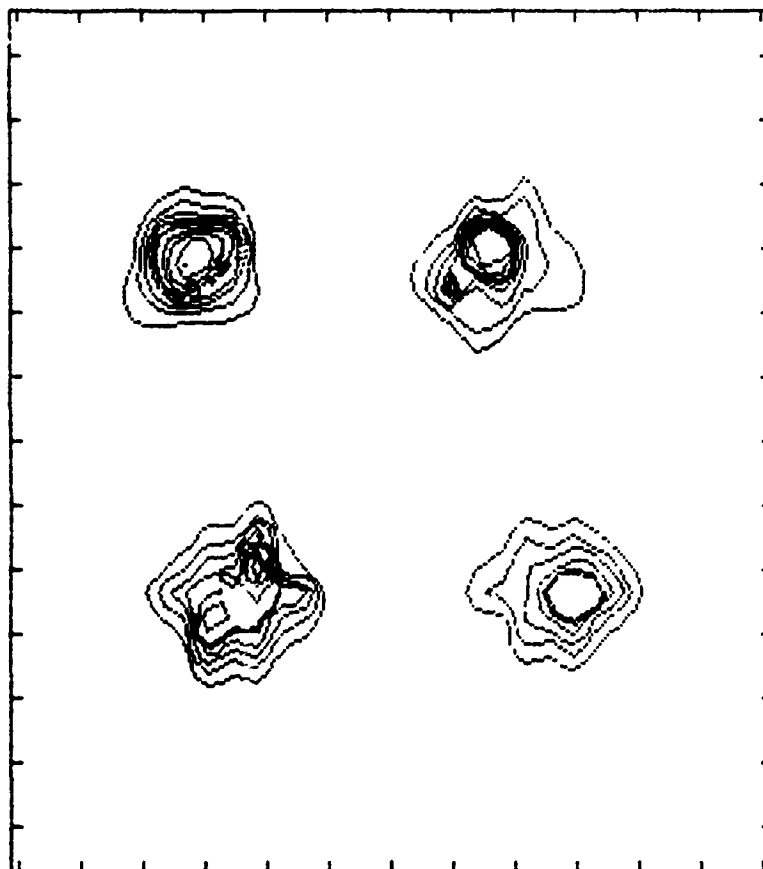


Figure 7. The same non-stationary rings as illustrated in Figure 4 as sampled from a 20 day repeat orbit. The much faster fill-in of satellite groundtracks alleviates much of the smearing evidenced in Figure 4, while the wider spaced ground tracks are still adequate to map the ring.

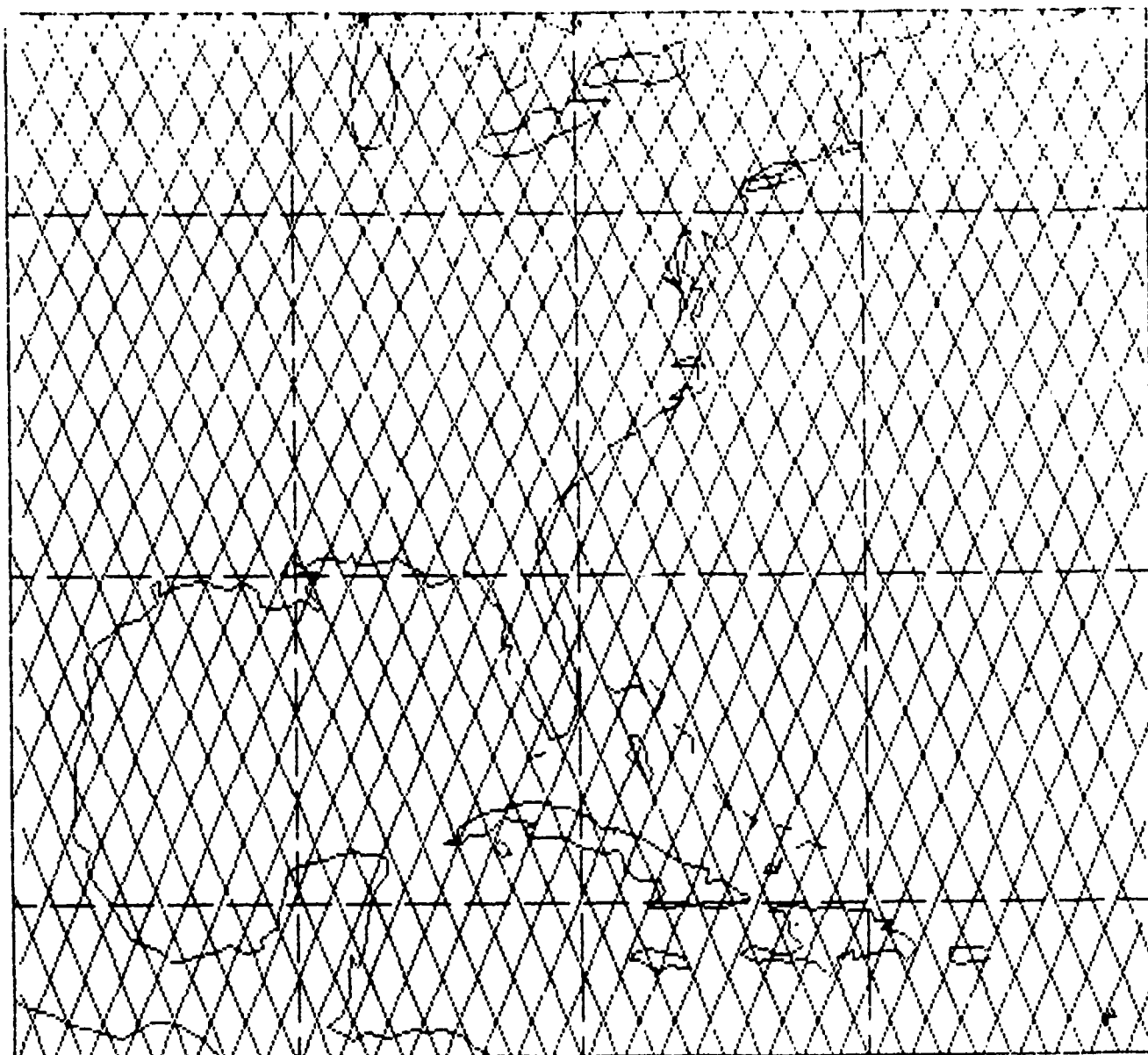


Figure 8. Hypothetical GEOSAT groundtrack coverage over the Loop Current-Gulf Stream System as accumulated in 20 days with the satellite flying in an exact repeating 20 day orbit. Such an orbit could be attained at the end of the relatively brief nominal mission with the expenditure of only about 6 lbs. of propellant.

repeating orbit at the end of the nominal 18-month geodetic mission. The mechanisms for overcoming these limitations are simply:

(1) The exact repeating nature of the groundtracks would allow the computation of an ensemble averaged topography along the track. Individual pass by pass differences against this ensemble average then represent the critical temporal fluctuations in topography. Hence, the bulk of the mesoscale topography, which is temporally fluctuating, can be separated cleanly from the geoid on a worldwide basis.¹⁰

(2) The selection of an orbit with wider groundtrack separation and a higher temporal sampling frequency would allow for a near-synoptic realization of topographies in some active mesoscale fields. Thus, to a large extent the sampling problems associated with the initial GEOSAT data could be overcome.

The practicality of such an extended, repeat orbit mission technically hinges on the answers to two questions:

(1) Do best available estimates of survival probabilities for GEOSAT make such an extended mission worth considering?

(2) Given the amount of Freon-14 gas likely to remain onboard at the end of the nominal 18-month mission, what are the possible exact repeat orbits into which GEOSAT could be maneuvered?

Appendix 1 provides detailed answers to both these questions; the summary answers are respectively:

(1) Best estimates of probability of survival decay to the 50% level at the end of approximately 3 1/2 years (thus, potentially allowing for a 2-year extended mission). Estimated probability of survival to the end of the 18-month geodetic mission is approximately 75% (see Figure 9).

¹⁰ Ultimately, the problem of obtaining absolute topography must be addressed as well. This will require adequate in-water measurements and gravimetric survey. Specification of the requirements for solution of this problem are now being addressed as part of the ONR sponsored NORDA Special Focus Program in Altimetry.

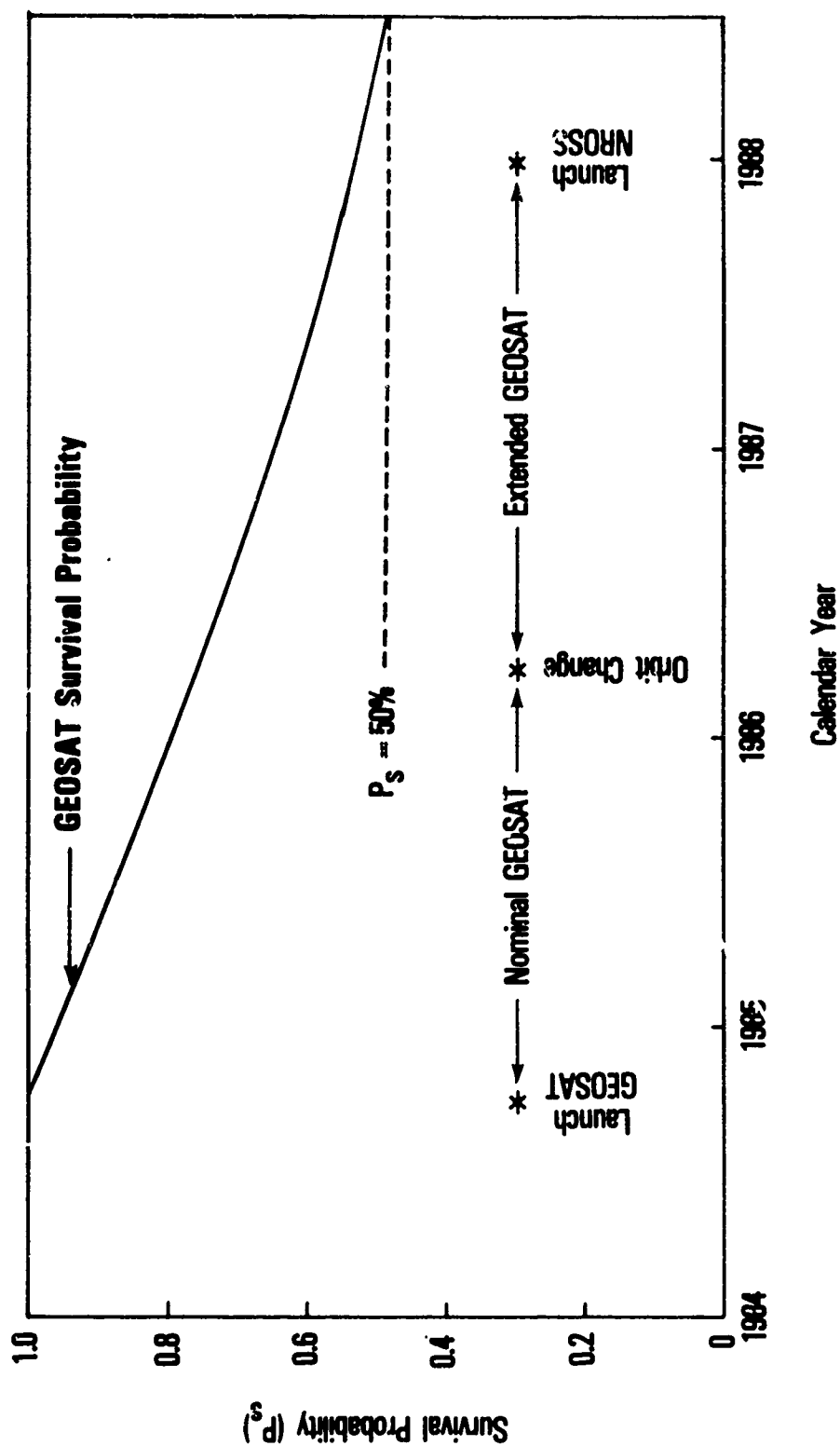


Figure 9. GEOSAT survival probability through the late 1980's. Notice that an extended, exact-repeat orbit mission for GEOSAT might lead directly into the launch of NROSS in 1988.

(2) There are a wide range of exact repeat orbits easily within the window provided by the nominal anticipated 36 lbs of Freon-14 onboard at the end of the initial 18-month mission. For example, the exact 20-day repeat orbit used to generate Figure 7 (the groundtracks of which are shown in Figure 8) can be attained with the expenditure of only approximately 6 lbs of gas. Additionally, the minimum in the solar cycle expected in the 1986-87 time period (exactly coinciding with the proposed extended mission) allows the realistic anticipation of very low atmospheric drag rates (perhaps lower than 1 meter/day), thus requiring a minimum amount of satellite maneuvering to maintain the repeat groundtracks to within 1 to 2 kilometers.¹¹

Fiscally, the extended repeat orbit mission allows the U.S. Navy acquisition of a unique wealth of global mesoscale information at a comparatively miniscule cost. Informal estimates of the annual costs for maintaining the JHU/APL groundstation for command and data acquisition are roughly the order of \$1 million or less. This must be compared with the total price tag for development of a new altimetric satellite which can cost several \$100 M over its mission lifetime. Thus, the extended, repeat orbit mission for GEOSAT represents by several orders of magnitude the most cost effective way to obtain global information on the oceanic mesoscale.

Through the initial planning for the NORDA Special Focus Program (SFP) in altimetry, it has become clear that the GEOSAT-ERM is of crucial importance for future progress in Navy oceanography and remote sensing. In order to insure that this extended mission becomes an officially recognized Navy objective, I conclude with a number of specific recommendations on which immediate action should be taken.

¹¹An extra benefit of solar minimum is the low concentration of free ionospheric electrons, hence the anticipation that ionospheric pathlength interference will be minimal for GEOSAT (<5 cm pathlength correction at 100 km spatial scales). This should allow for the very effective use of the single frequency altimeter onboard GEOSAT.

5. Recommended Responses

The following immediate actions are recommended:

The U.S. Navy should formally recognize an Oceanographic Steering Group to immediately address the following issues:

- (a) the appropriate repeat orbit strategies for optimized recovery of mesoscale topography,
- (b) the specification of tracking plans for removal of orbit error and,
- (c) the mounting of sufficient and appropriate in-water programs to be carried out concurrently with GEOSAT.

Towards this immediate end, NORDA/ONR is hosting a workshop on 20-22 July 1983 with invited participants. It is expected that the Oceanographic Steering Group will be distilled from representatives of several scientific communities in attendance at this workshop.

Finally, it is imperative for the full interests of the U.S. Navy that these recommended responses be made rather immediately. The time scales for mounting major in-water programs are typically several years. With a planned launch of GEOSAT in fall, 1984, time is of the essence for realization of the full potential of GEOSAT.

APPENDIX 1: ESTIMATES OF GEOSAT SURVIVABILITY AND MANEUVERABILITY

In this appendix we estimate the survivability of the GEOSAT system (satellite + altimeter) and its maneuverability based upon nominal Freon-14 gas useage during the initial geodetic mission. I greatly appreciate the help of Drs. Chuck Kilgus, Bruce Holland, and John McArthur of JHU/APL.

Survival Probability

(1) According to John McArthur (GEOSAT Program Scientist, JHU/APL), best engineering estimates of survival probability (P_s) to the end of an initial 7 months are:

P_s for altimeter subsystem ~ 0.941

P_s for spacecraft (excluding altimeter) ~ 0.950

Thus, the total survival probability at 7 months is 0.894.

(2) Survival probabilities are estimated as exponentially decaying functions with time, hence the above estimate may be used to express total GEOSAT survival probability in the following functional form:

$$P_s = e^{-0.016t}$$

for t expressed in months.

Figure 9 illustrates this simple functional form. Note that through the end of the nominal 18-month mission (+ one initial month for calibration) the survival probability remains at above 0.75. It is not until two additional years have passed that this probability drops to the 50% level.

It is important to note that these estimates of P_s include relatively high infant mortality rates (in order to model the relatively high failure rates associated with the initial several months after orbital insertion). Thus, estimates based upon Figure 9 are apt to be overly pessimistic. On the other

hand, these estimates do not include the risk factor associated with the launch and orbit insertion.

At any present time the "survivability" of GEOSAT is apt to be either 1.0 or 0.0. Thus, during the mission estimates of P_s will undergo continuous update. The natural tendency is for P_s at some time $t_0 + \Delta t$ to increase if the total satellite system survives intact to time $t = t_0$.

To a great extent the longer lifetime estimates for the GEOSAT altimeter subsystem are based upon the lower power traveling wave tube amplifier (TWTA) used in GEOSAT (to be operated in continuous mode) as contrasted with much higher power tubes used on SEASAT and GEOS-3. It is also important to note that the failure of SEASAT is believed to be due to a major electrical short circuit, having nothing to do with the SEASAT altimeter subsystem. Thus, SEASAT died with a functioning altimeter, while the GEOS-3 altimeter survived for over 3.5 years (with a limited duty cycle), finally succumbing to what may well have been a tube related failure (a failure of the 10 watt "preamp" tube rather than the main 2 kilowatt tube). John McArthur estimates a lifetime for the GEOSAT TWTA in excess of 4 years.

GEOSAT Maneuverability

Two factors which potentially limit the maneuverability of GEOSAT are:

(1) The allowable operating altitude window in which the altimeter can maintain lock; based on a GEOSAT pulse return frequency (PRF) of 1020 Hz this allowable altitude window is 745 km to 867 km (i.e., an allowable window in nodal period of 155 secs width). Centered on the nominal nodal period of 6043.6 secs the corresponding window is approximately 5966.1 secs to 6121.1 secs.

(2) The amount of Freon-14 gas available for changing the nodal period of the orbit. The initial amount of cold gas aboard GEOSAT is 81 lbs. According to a worst case scenario developed by Bruce Holland (JHU/APL), approximately 65 lbs of cold gas would be expended during the nominal 18-month mission. The most likely scenario is one which would expend approximately 45 lbs during the nominal mission. Thus, approximately 36 lbs of Freon-14 should remain onboard at the

completion of the geodetic mission (while even in a worst case scenario 16 lbs should remain onboard). Based upon estimates similar to those in the next section, approximately 30 lbs of Freon-14 allows a maneuverability of 6043.6 ± 27 secs (expressed in nodal period).

Thus, the bottleneck on allowable orbital periods is that imposed by the residual gas budget at the end of the nominal 18-month mission. There are many exact repeat orbits within reach of the estimated residual gas budget. An example follows.

The 20-Day Exact Repeat Orbit

In this final section we consider one candidate orbit for synoptic survey of the oceanic mesoscale: an exact 20-day repeat orbit. We select this orbit as only one of many such possibilities. Considerations such as undesirable tidal aliasing will need to play a role in final orbit selection. Provided our reader understands that this is just an example, we proceed:

(1) We assume that during the geodetic mission GEOSAT is in the proposed near 3-day repeat orbit which has a nodal period (P_n) of 6043.6 sec (an anomalistic period of 6041.5 sec).

(2) The nearest exact 20-day repeat orbit has a nodal period of $14 \frac{7}{20}$ revs/day (14.35 revs/day) or $P_n = 6038.39$ sec.

(3) This dictates a change in nodal period during the initial firing of $\Delta P_n = -5.21$ sec.

(4) Nodal period as a function of semi-major axis (a) is given by the equation $P_n = A a^{3/2} + B a^{-1/2}$

$$\text{where, } A = \frac{2\pi}{\sqrt{GM}}$$

$$\text{and, } B = \frac{-3\pi}{\sqrt{GM}} J_2 R^2 (4 \cos^2 i - 1)$$

with $GM = 398601.3 \text{ km}^3 \text{ sec}^{-2}$

$$J_2 = 0.00108$$

$R = 6378 \text{ km}$ (radius of earth)

i = orbital inclination.

Taking the derivative within respect to semi-major axis (a) yields the expression for Δa (the change in semi-major axis) in terms of ΔP_n for an orbit of approximate semi-major axis of 7178 km and inclination $i = 108^\circ$,

$$\Delta a = 0.791 \Delta P_n \text{ (for } \Delta P_n \text{ in secs \& } \Delta a \text{ in km).}$$

Thus, $\Delta P_n = -5.21 \text{ secs}$ requires that,

$$\Delta a = -4.21 \text{ km.}$$

(5) The orbital velocity (v) for a circular orbit is given by,

$$v^2 = \frac{GM}{a}.$$

Thus,

$$\Delta v = \frac{-\frac{1}{2} \sqrt{GM}}{a^{3/2}} \Delta a.$$

Hence, for maneuvering out of the initial, geodetic GEOSAT orbit the required velocity change (Δv) can be related to Δa according to,

$$\Delta v = -0.525 \Delta a.$$

Thus, $\Delta a = -4.12$ km requires that,

$$\Delta v = +2.16 \text{ m sec}^{-1}.$$

(6) We assume that all orbital maneuvers are carried out via optimal firings within $\pm 20^\circ$ of apogee producing an incremental change in orbital velocity of $\Delta v = 0.055 \text{ m sec}^{-1}$. Each incremental firing expends 0.15 lbs of Freon-14. The relation between the total expended weight (W_p) of Freon-14 and the resulting Δv is then given approximately by,

$$W_p = 2.727 \Delta v$$

for Δv in m sec^{-1} and W_p in pounds.

Thus, $\Delta v = + 2.16 \text{ m sec}^{-1}$ requiring the expenditure of,

$$W_p = 5.9 \text{ lbs.}$$

(7) Estimates of atmospheric drag indicate that anticipated drag rates should be as low as 1 m/day (becoming lower throughout the GEOSAT mission and extended mission with a solar minimum being approached in 1987-88). A drag rate of 1 m/day necessitates a correction of $\Delta v = 5.25 \times 10^{-4} \text{ m sec}^{-1}$ or 9.55×10^{-3} firing day^{-1} (i.e., one optimal firing each 105 days). These rough estimates indicate that a cold gas expenditure of only 1.05 lbs would be needed during a 2-year extended mission over which 7 optimal firings would be performed.

I conclude that the amount of gas necessary to maneuver into the exact 20-day repeat orbit and to maintain this orbit for several years is much less (by more than a factor of 2) than the residual in the cold gas system after even the worst case nominal geodetic mission.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NORDA Technical Note 226	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Position Paper: Mesoscale Oceanography From GEOSAT		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Jim L. Mitchell		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Ocean Research and Development Activity NSTL, Mississippi 39529		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS P.E. 61153N
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Ocean Research and Development Activity NSTL, Mississippi 39529		12. REPORT DATE August 1983
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for Public Release Distribution Unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Altimetry Mesoscale Oceanography Navy GEOSAT		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The secondary mission of GEOSAT is oceanography. Several Navy elements, (OP-952, OP-02, and ONR) have a direct interest in seeing that every possible attempt is made to maximize the return of information on the oceanic mesoscale from GEOSAT derived sea surface topography. During the nominal, essentially geodetic, GEOSAT mission attempts to obtain meaningful mesoscale information will be severely hampered due to two critical considerations: (continued)		

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(1) The non-repeating nature of the satellite groundtracks during its nominal mission will allow for recovery of geoid uncontamination mesoscale topography in only a very few isolated regions with little mesoscale information in over 99% of the global oceans and;

(2) The severe temporal undersampling of the oceanic mesoscale will not allow for the desired synoptic realization of non-stationary mesoscale fields.

The best way of meeting requirements for GEOSAT's secondary mission is to remaneuver the satellite into an appropriate orbit with exactly repeating groundtracks at the completion of its nominal, geodetic mission. It is likely (at above the 50% level of probability) that GEOSAT will survive an additional two years beyond completion of its nominal mission. Studies have already been performed to assess the technical feasibility of such an extended, exact repeat mission (the GEOSAT-ERM), and no major technical difficulties are foreseeable. At a cost of roughly \$2M annually the GEOSAT-ERM represents the Navy's most cost effective possibility for obtaining critical global mesoscale information.

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