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Final Report of GEOS-3 Ocean Current Investigation Using Radar Altimeter Profiling

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FINAL REPORT OF GEOS-3 OCEAN CURRENT INVESTIGATION USING

RADAR ALTIMETER PROFILING

BY

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INTRODUCTION

This investigation began with a desire to locate the Gulf Stream by detecting the geostrophically induced slope in the ocean surface across the current. The Gulf Stream was chosen because: (1) a 1 meter surface elevation change was expected across the Stream, (2) it was one of the most studied currents, (3) it was in the GEOS-3 calibration area, (4) a detailed geoid was available for the area, and (5) corroborating information defining the location of the Stream was available from the Coast Guard, NOAA-NESS, and the Naval Oceanographic Office. If the Gulf Stream could be detected, then two other western boundary currents could also be studied; i.e., the Kuroshio Current south of Japan and the Agulhas Current east of Africa. The analysis began by selecting a set of 20 northbound GEOS altimeter profiles, both global and intensive modes, which crossed the Gulf Stream. Northbound passes were chosen because they would cross the current at a more orthogonal angle in the region between Florida and Cape Hatteras and thus provide a maximum slope when crossing the Stream. Both global and intensive mode data were used to evaluate the advantages of each mode. The early analysis showed that the intensive mode data, with its inherently lower noise characteristics required less filtering and therefore shorter length filters could be used. Also, the 100 sample per second data was not used for three reasons: (1) it was felt that 10 samples per second data was dense enough to detect the elevation change, (2) much longer filters would be required to force the 100 samples per second data to provide results compatible with the 10 per second data, and (3) not much 100 sample per second data had been acquired.

A few different altimeter measurements and derived parameters were investigated to determine if they produced any anomaly in the signature when sensing the Gulf Stream. The altimeter measurements studied were sea surface heights (SSHITE), automatic gain control (AGC), and the altimeter waveform sample and hold gates. In addition, the derived parameter sea state (H 1/3) was also studied. In investigating the SSHITE capability, correlation of both the geoid and ocean bottom topography with measured altitude was evaluated. Preliminary analysis indicated that the SSHITE measurement when referenced to a detailed geoid showed the most promise in being able to detect the Gulf Stream. The other parameters, AGC, H 1/3 and the waveform data did not show much potential at that time, so that total effort was directed to the SSHITE analysis. Incidentally, this technique had been tried once before (ref. 1) using SKYLAB altimeter data referenced to a 15" x 15" geoid. The results were inconclusive.

DATA ANALYSIS PROCEDURE

A satellite radar altimeter is an instrument which measures precisely the distance from a satellite platform to the ocean surface. The geometry of the measuring system is illustrated in figure 1. The altitude measured by the altimeter can be represented as:

$$h_a = h_s - h_g - \Delta h + \epsilon_n \tag{1}$$

where h_a is the altitude measured by the altimeter, h_s is the satellite height above a reference ellipsoid as estimated from satellite tracking data, h_g is the geoid height, Δh is the height deviation from the geoid due to ocean dynamic processes such as tides and currents, and ϵ_n is the random error in the measurement. Initial analysis did not consider tide effects because of the short wavelength of the profiles being analyzed. However, later on in the analysis longer profiles were analyzed, thus requiring a consideration of tide effects. Typical ranges and uncertainties of the terms in equation (1) are shown in Table I.

The altimeter was designed to make 100 individual measurements per second and to telemeter either them, or a 10 pulse per second average, to the telemetry stations. For the reasons mentioned above and to save processing time, only the 10 samples per second average is used. These altitude measurements are then preprocessed and converted to sea surface heights (ref. 2) and are treated in this report as raw sea surface heights. The data processing procedure, using data from orbit 1710, is summarized in figure 2. The raw sea surface heights shown in figure 2a are first edited to eliminate anomalies due to internal noise and unknown data spikes. The edit criterion is based on a predicted sea surface height calculated by fitting a straight line through the last eight seconds of data (80 data points representing 60 km in physical distance). Any point differing from

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the predicted height by more than two meters (approximately three standard deviations of the noise level of 70 cm) is replaced by the predicted height value. The edited sea surface height data shown in figure 2b was then originally filtered with a 41 point, equal weight, midpoint filter. This filter did not suppress enough noise and resulted in very noisy velocity estimates. After a brief filter study, an 81 point equal weight, midpoint filter was chosen since it reduced the noise without seriously compromising the sea surface signature and resulted in more stable velocity computations. The eight second time constant was chosen so that the noise level of the data could be maintained below the 10 cm level. After the filtering process, the smooth sea surface height was referenced to the Marsh-Chang 5' x 5' geoid (see figure 2c . This geoid, however, was only defined between 16° N to 39° N and 278° E to 300° E. Yet, the Gulf Stream could very easily meander north of the latitude limit. Therefore, mean anomaly gravity data was obtained and a new 5' x 5' geoid was computed to 41.5° N thus providing more geoid definition in the Gulf Stream meandering area. Subtracting the geoid from the smooth sea surface heights results in a residual which is nearly flat in the static open ocean, as shown in figure 2d. Next, to minimize the error between the geoid and the smooth sea surface height south or east of the mean position of the Gulf Stream, a linear fit is made to the residuals over the section representing the open ocean. The straight line is then subtracted from all the residuals thereby removing any potential orbital bias or slope errors and producing an estimate of dynamic heights as shown in figure 2e. Finally, the dynamic heights are differentiated with a filter designed to match the smoothing filter in order to compute the slope of the sea surface along the profile. The computed slope is substituted in the following geostrophic equation to obtain velocity estimates as shown in figure 2f.

$$V_s = \frac{g}{2\Omega \sin \phi} \frac{\Delta h}{\Delta L} \tag{2}$$

where V_s is the surface velocity; g is the gravity acceleration at 980 cm/sec^2; Ω is the angular speed of the earth at .0000729 rad/sec; ϕ is the latitude of the location; Δh the total height anomaly and ΔL the horizontal distance over which the height anomaly occurred.

RESULTS

The first few months of this investigation were devoted to processing as many northbound passes as possible in the area of the Gulf Stream using the data processing procedure outlined above. Each region where the Gulf Stream flowed had its own problem areas. For example, in the region east of the Florida and Georgia coasts there was not enough altimeter data acquired over the open ocean to supply enough data for a reliable fit. Either the profile would intersect land in the Bahamas or the altimeter was not

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turned on until after passing over the Islands. Also, the accuracy of the Marsh-Chang geoid in this area was suspect. Most of the early analysis was performed in the area between South Carolina and Cape Hatteras. This area was chosen because the subsatellite trace crossed the Gulf Stream in an almost orthogonal angle and therefore would provide a maximum slope signature in the profile. There were two shortcomings in this area. First, the current seems to hug the break in the continental shelf. This characteristic made both the geoid and the Gulf Stream produce an anomaly along the same general area, making early separation of the two signals difficult. Also, the geoid near the Blake Spur was not defined well enough to produce the kind of results expected as can be seen in figure 3. Note the double hump in the dynamic height, this occurs directly over an ocean bottom feature associated with a steep gravity gradient. Next, the region centered around Cape Hatteras provided early difficulties also because of the sharp geoid change occurring along the line of current flow. In addition, the geoid accuracy was again uncertain. Finally, the analysis moved out to the open ocean east of Cape Hatteras where it was felt that the bottom topographic influence on the Gulf Stream would be minimal and that the geoid, especially between 285° E and 292° E would be relatively flat. The analysis in this region provided the first conclusive proof that indeed the slope of the ocean surface was located in the same vicinity where the NOAA satellite IR imagery indicated a surface temperature anomaly indicative of a thermal front. Analysis in this area progressed until it was found that profiles in the vicinity of the New England Seamount Chain tended to produce poor results. The poor distribution and lack of measurements in the area of the seamounts produced large uncertainties in the mean anomalies in this general region. Therefore, profiles were terminated early or started late when approaching the seamount area.

Ocean Truth Sources

In order to be certain that the altimeter profile actually passed over the Gulf Stream, some source of ocean truth (Gulf Stream location) was needed. The first product used was that of the "Gulf Stream," a monthly publication produced by NOAA. The information in it is good, however, usually only two western boundaries are given; one for the beginning of the month and one for the end of the month. The publication is very useful for following the path of some spawned eddies which are not followed by other data products. The next data product used was the Experimental Gulf Stream Analysis produced weekly by NOAA-NESS. The product defines current width and is based primarily on satellite VHRR-IR imagery and therefore is limited by cloud cover. The cloud cover especially in the area south of Cape Hatteras precluded some early analysis in this area. A final product, the Experimental Ocean Frontal Analysis produced bi-weekly has the advantage of supplementing the IR data with hydrographic data. This data product also was able to discern both the eastern and western boundaries of the Gulf Stream more readily

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than any of the other data products used thus far. Therefore, most analysis comparison were made using the Experimental Ocean Frontal Analysis to define Gulf Stream current positions.

Single Profiles

After the dynamic heights were computed the profiles were analyzed to determine the location of the Gulf Stream. The inferred eastern and western boundaries of the current were defined at the breaks of the sharp height changes of the dynamic height profiles. The altimeter-determined boundaries were then compared with the boundary defined by NOAA's Experimental Gulf Stream Analysis product. An example of a single pass analysis is shown in figure 4. Note the agreement of the altimeter-determined western boundary and the NOAA-determined boundary. In order to be able to compare more altimeter passes with Gulf Stream truth data, and because the Naval Oceanographic Office's analysis seemed more detailed and reliable, the Experimental Ocean Frontal Analysis (EOFA) product became the independent baseline for comparing future altimeter-inferred Gulf Stream boundary data. The mean position discrepancy in the determination of the western boundary by the altimeter and EOFA was calculated for 60 profiles acquired during August, September, and October 1975. The bias of the altimeter-determined western boundary was 23 km $\pm$ 36 km west or north of the highest surface thermal gradient as defined by the EOFA chart. This result is encouraging since Hansen and Maul (ref. 3) determined that the thermal surface boundary was 14.5 $\pm$ 11.8 km north or west of the Gulf Stream axis defined to be located at the position of the 15° C isotherm at 200 m depth. This results in the altimeter western boundary being approximately 37 km west of the core of the current, a reasonable result. In addition, an estimate of the height difference and surface velocity was made using the same 60 passes. The mean surface current velocity was 107 $\pm$ 29 cm/sec and the mean height difference was 100 $\pm$ 15 cm. Both of these means are in very much agreement with both measurements of the surface velocity and with expected height deviations across the Stream.

Initial results were further substantiated by comparing the results of consecutive passes occurring over the same profile. Results of three profiles acquired over the same track over a three month period are shown in figure 5. Note the agreement of the signatures of both the dynamic topography and the derived surface velocity. The relative agreement of these passes was very encouraging since the decreasing surface velocity trend was in agreement with reported mean values (ref. 4).

Another short study was performed with data off the coast of Onslow Bay, North Carolina, acquired during the first week of May 1975. Detailed ocean truth data was available from R. Perchal of the Naval Oceanographic Office and it was decided to compare the two data sources. The results of this analysis are shown in figures 6 and 7. Note the signature of the altimeter data compared to the special EOFA chart. It can be seen

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from the chart that water is moving north at "C"; however, at "B" a south component of the loop current or meander is seen which then flows back in a north direction at "A". Looking at figure 6 it can be seen that points A, B, and C on the map correspond quite well with the changes in slope in figure 7. The total meander is shown to be about 150 km wide with surface velocities on the order of 150 cm/sec.

Throughout all the analysis thus far, the only valuable "truth" data used to corroborate the altimeter results were the EOFA products based primarily on VHRR-IR satellite data and random ship reports and oceanographic data. It was decided that in-situ oceanographic data would be necessary to further justify the capability of altimetric techniques. Therefore, an experiment designed by N. E. Huang was implemented during May and June of 1976 to compare hydrographic data with remote sensing measurements from instrumentation such as satellite radar altimeters and aircraft laser profilometers and a radar scatterometer. A result obtained over the four day period 19 May to 22 May 1976 is shown in figure 8. The darkened contour is the boundary of the Gulf Stream as determined from the EOFA charts. Two tongues of water are discerned; one east of South Carolina and the other east of Cape Hatteras. Passing through each of these tongues and the Gulf Stream is a GEOS altimeter pass. A plot depicting the estimated surface velocity across the subsatellite track is shown for two profiles. In addition, another profile crosses the Stream in the southbound direction. A ship crossing the Gulf Stream from Cape Charles, Virginia, was acquiring hydrographic data from which surface velocity could be estimated. This velocity is also plotted in figure 8. Note the relative agreement of the surface velocity estimates which intersect the current perpendicular to the flow. The agreement of the hydrographic and altimetric profiles provides the most dramatic support to the altimeter data. In addition, the velocity estimates across the tongues of water being shed from or coalesced with the Gulf Stream are indicative of the movement of these waters. Figure 8 was obtained from a detailed hydrographic analysis on this two-week experiment prepared by T. B. Curtin of North Carolina State University.

Dynamic Topographic Maps

All results so far have shown only instantaneous estimates of ocean surface dynamics. Maps attempting to delineate the position of the Gulf Stream were prepared using only northbound data acquired during August, September, and October 1975. It must be pointed out that these maps are not monthly means, but rather a mosaic consisting of instantaneous measurements obtained at different times during the month similar to a scanning time exposure along the subsatellite trace. The direction, number and both time and spatial distribution of the satellite passes influence the validity of the maps to a large degree. The contour maps were based on dynamic topographies contoured at the 20 cm level using data located east of Cape Hatteras and avoiding the New England Seamount Chain. A

typical result is shown in figure 9 computed for the month of September. The crowding of the contour lines running northeast from Cape Hatteras agree quite well with the general direction of flow of the Gulf Stream as shown in reference 5. Some shortcomings of the above method are that it did not use any southbound data passes, it did not use any passes intersecting land south of Cape Hatteras and that the final product was not truly a mean map. These problems were overcome by enlarging the data base to include southbound tracks and tracks intersecting land south of Cape Hatteras. The southbound data was used to constrain the northbound passes by using a minimum variance technique to minimize the differences of the profiles at the intersecting points. This technique is documented in reference 6 which describes the theory and operation of the computer program, SEAHT. Results obtained from employing the technique are shown in figure 10. In general, the maps were obtained by processing the data acquired over one month through the SEAHT program. The adjusted values obtained at the intersecting points were the points used to be contoured. Note the absence of valid contour lines southeast of orbit 3097. The absence of intersecting points in the southeast area caused this void to occur.

In a further extension of processing the data acquired during the latter six months of 1975, it was decided to calculate a mean surface dynamic topography over the entire six months of data. The mean surface was computed in the following manner. First, all six months of dynamic height profiles were analyzed through the SEAHT program. Next, in places where many profiles crossed one another, a cluster was defined (see figure 11). A mean and standard deviation of the values in the cluster were calculated using the adjusted values from the SEAHT program. The cluster means over the six-month period were contoured as shown in figure 12. The pass coverage used to produce the map is in the bottom right of the figure. This map shows a well defined Gulf Stream initially flowing north from Florida and then changing direction about 32° N and then flowing in a north-easterly direction. Also note the depression of 40 cm at location 34° N, 71° W. This low was caused by an eddy maintaining a static position over the span of three consecutive months during the six-month data span. Also, the high elevation in the northeast corner of the map is indicative of the New England Seamount Chain influencing the results since the geoid is poorly defined in that area. In addition to the mean topography over the six month period, the standard deviation is shown in figure 13. This map essentially depicts the regions where high energy cells exist in the area of computation. For example, in the region north of 35° N, large anomalies exist where the Gulf Stream meanders quite freely. Smaller isolated depressions exist in the central portion of the map. These depressions tend to occur where the cold eddies, having spawned from the current, are migrating in a southwesterly direction. Finally, near the coast of Long Bay, North Carolina, another dynamic region is apparent. This coincides with the meandering at the coast which has been mentioned (ref. 7 and 8). Next, the map for the monthly means was calculated using only the values for that particular month which were available within

the cluster. A typical plot is shown for November in figure 14. Again note the definition of the Gulf Stream and the meander north of 35° N between 70° W and 65° W. Finally, a sea surface dynamic height anomaly is calculated by differencing the mean values for each month with the overall six-month mean. A representative plot is shown in figure 15 for the month of November. The meander above 35° N is easily seen in this type presentation as are the eddies just south at 35° N.

A dramatic application of using the sea surface dynamic height anomaly maps can be seen in figure 16. The tracking of a Gulf Stream ring using the depressions found in the sea surface with altimetry is shown compared to the inferred position determined from satellite IR imagery. The observed six-month sequence shows that the agreement is very good in months when both techniques detect a ring. Two interesting points are apparent in this figure; first, the eddy seems to be stationary during August through October (both sensors agree with this conclusion) and second, during November the satellite IR does not detect the ring probably because of cloud cover or a weak surface thermal gradient. However the altimeter, which is an all-weather system, continues to track the ring.

All maps generated to date have been contoured manually. A simple technique to contour November data using a computer method is shown in figure 17. The technique divides the scanned area into 5' x 5' cells. All adjusted observations occurring within a cell are averaged. Any cells with no observations are filled by using a linear interpolation along a constant band of latitude. Some strange signatures exist using this method such as the anomalies at 30° N and 291° E and at 35° N and 296° E. These few anomalies are due to the type of interpolation being employed. A new three-point planar method is being programmed at present and it is hoped that it will resolve some of the strange signatures.

Even though most work done during the execution of this investigation was done with the Gulf Stream data, another area has been studied. As defined earlier, in order to employ this current detection technique, one must have access to a well-defined, high resolution geoid. Such a geoid was not available either off the east coast of Africa to study the Agulhas and Somali Current, or off the south coast of Japan to study the Kuroshio Current. Gravity data was available in the Japan area and these point anomalies were averaged to produce 5' x 5' mean anomalies. The mean anomaly data was then used by Detailed Geoid Computation Program (DGC) to compute a 5' x 5' resolution geoid for the Japan area. Early results in this area are very poor primarily because: (1) The area of definition is centered on three trenches south of Japan and the steep gravity gradients are difficult to map with available spatial resolution, and (2) in some areas there existed almost no data and therefore bathymetric data was used to interpolate and infer gravity data so that a geoid could be computed. It is hoped that more dense gravity data

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will become available in the Japan area so that a better geoid can be computed and therefore work can continue on the Kuroshio Current.

CONCLUSIONS

It has been demonstrated that the larger geostrophic ocean currents, their meanders and spawned eddies can be detected and measured utilizing the techniques employed in this study. Many applications are apparent in the areas of weather forecasting, climate changes, submarine warfare, ocean fishing, and shipping industries. Radar altimetry is only a surface remote sensor; however, it can provide the field of dynamic oceanography with sea surface parameters which up to the present were not directly measurable. Since no measurements can be made below the surface with altimetry, it should complement more traditional hydrographic methods.

ACKNOWLEDGEMENTS

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TABLE I. - STATISTICS OF TERMS IN EQUATION (1)

	Range	Uncertainty
h_s	800 - 900 km	5 m
h_g *	-25 to -70 m	2 - 5 m
Δh	< 3 m	20 cm
ϵ_n	0	70 cm

*These values are for calibration area geoid only.
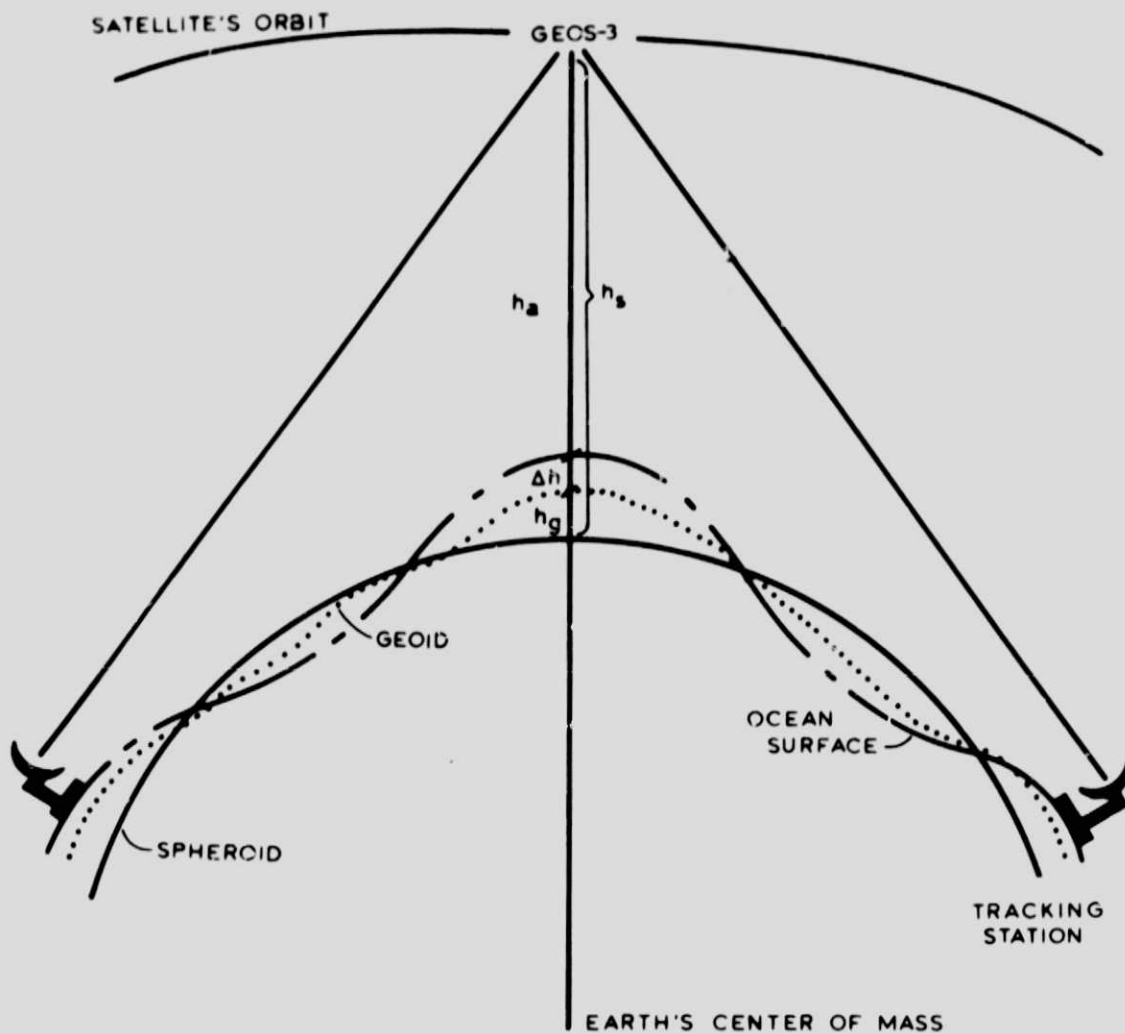
Figure 1. GEOS-3 satellite altimeter geometry. The dynamic effects Δh are obtained by subtracting h_g from the sea surface height $(h_s - h_a)$.
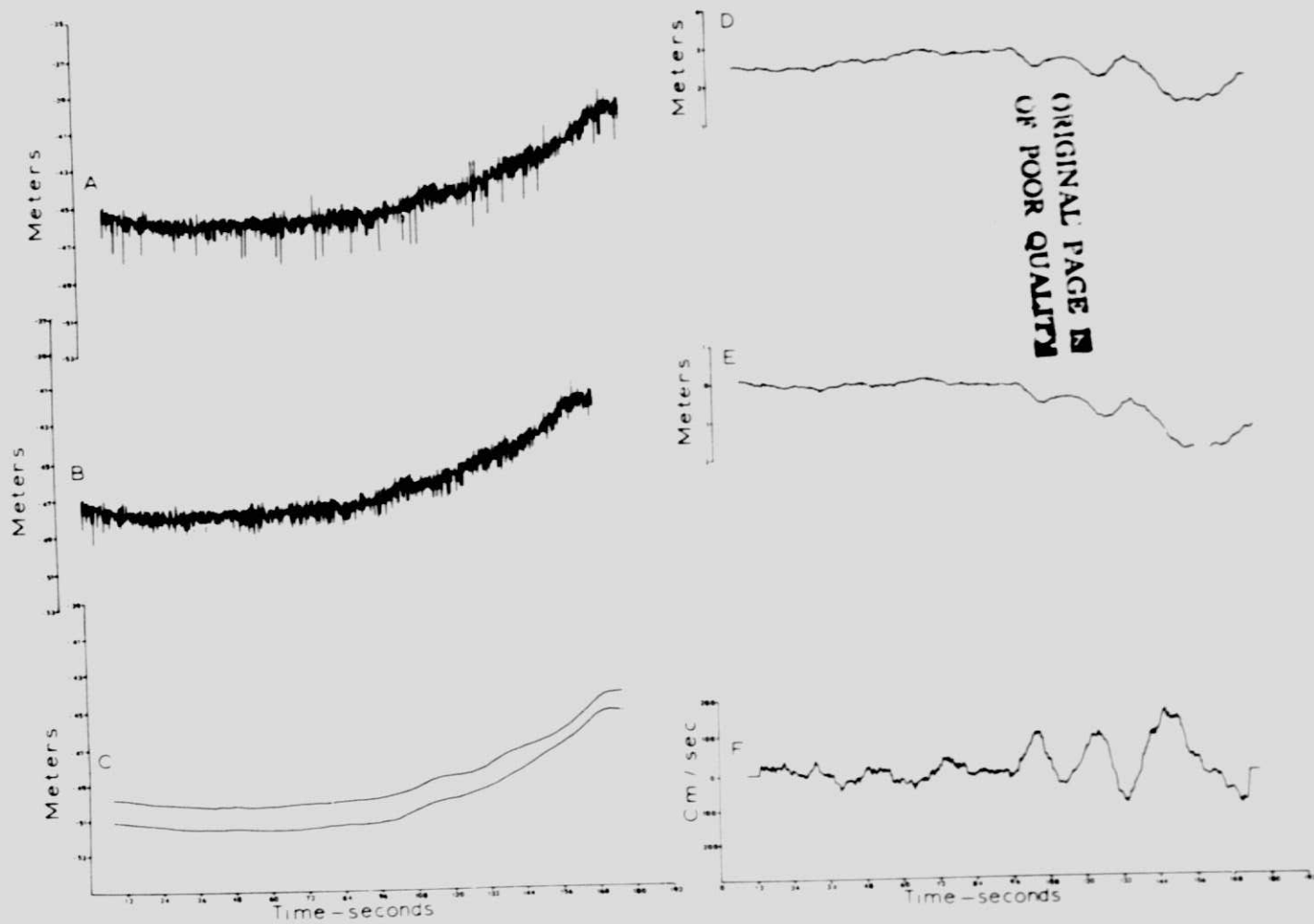
Figure 2. Data processing diagram. The raw sea surface heights (A) are edited (B) and filtered. When compared with the geoid (C) they yield residual values (D) which can be corrected to produce dynamic heights (E). These in turn produce the velocity measurements (F).

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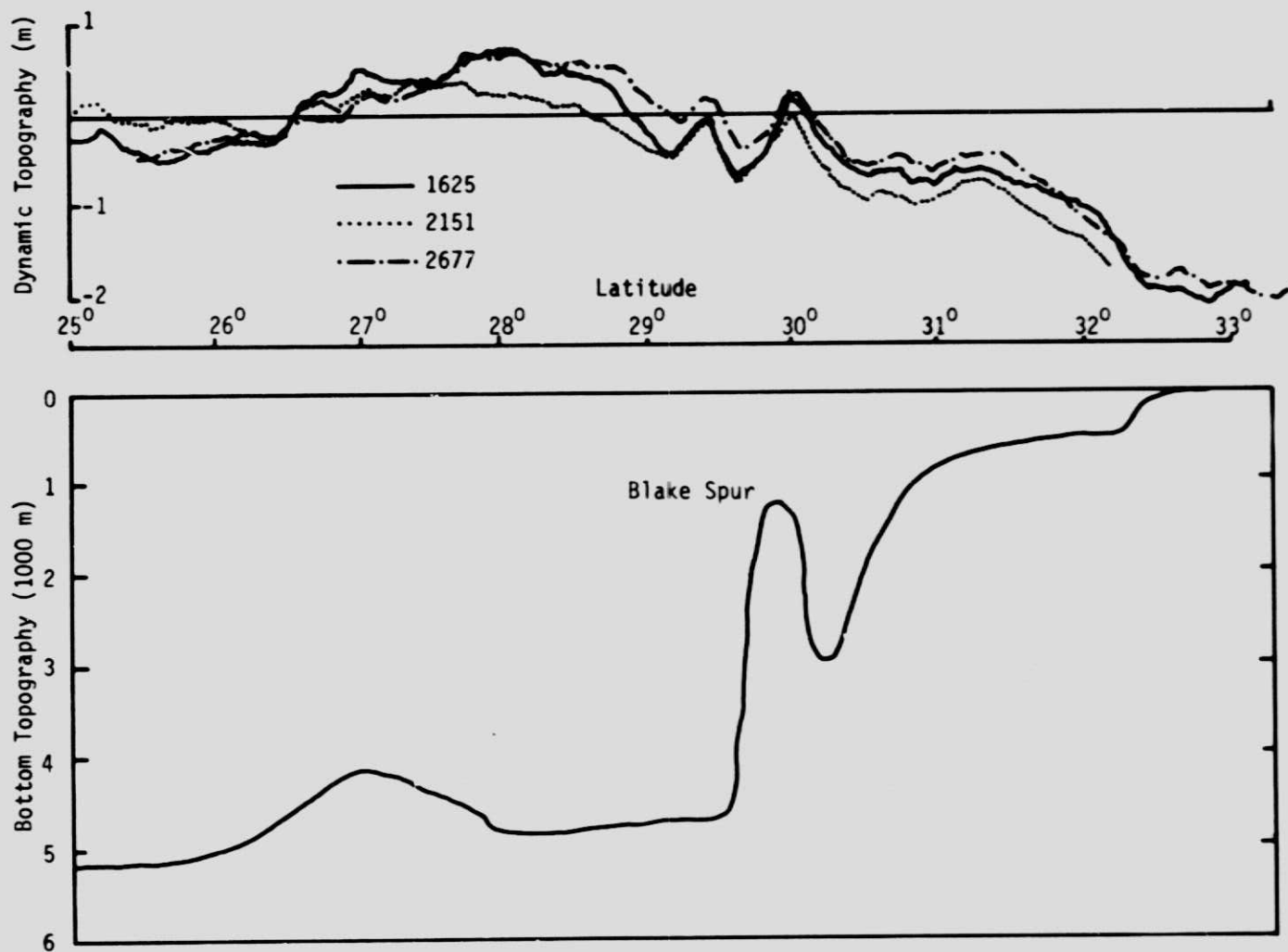
Figure 3. Dynamic heights profile and bottom topography for repeated orbits 1625, 2151, and 2677 depicting geoidal error near the Blake Spur.
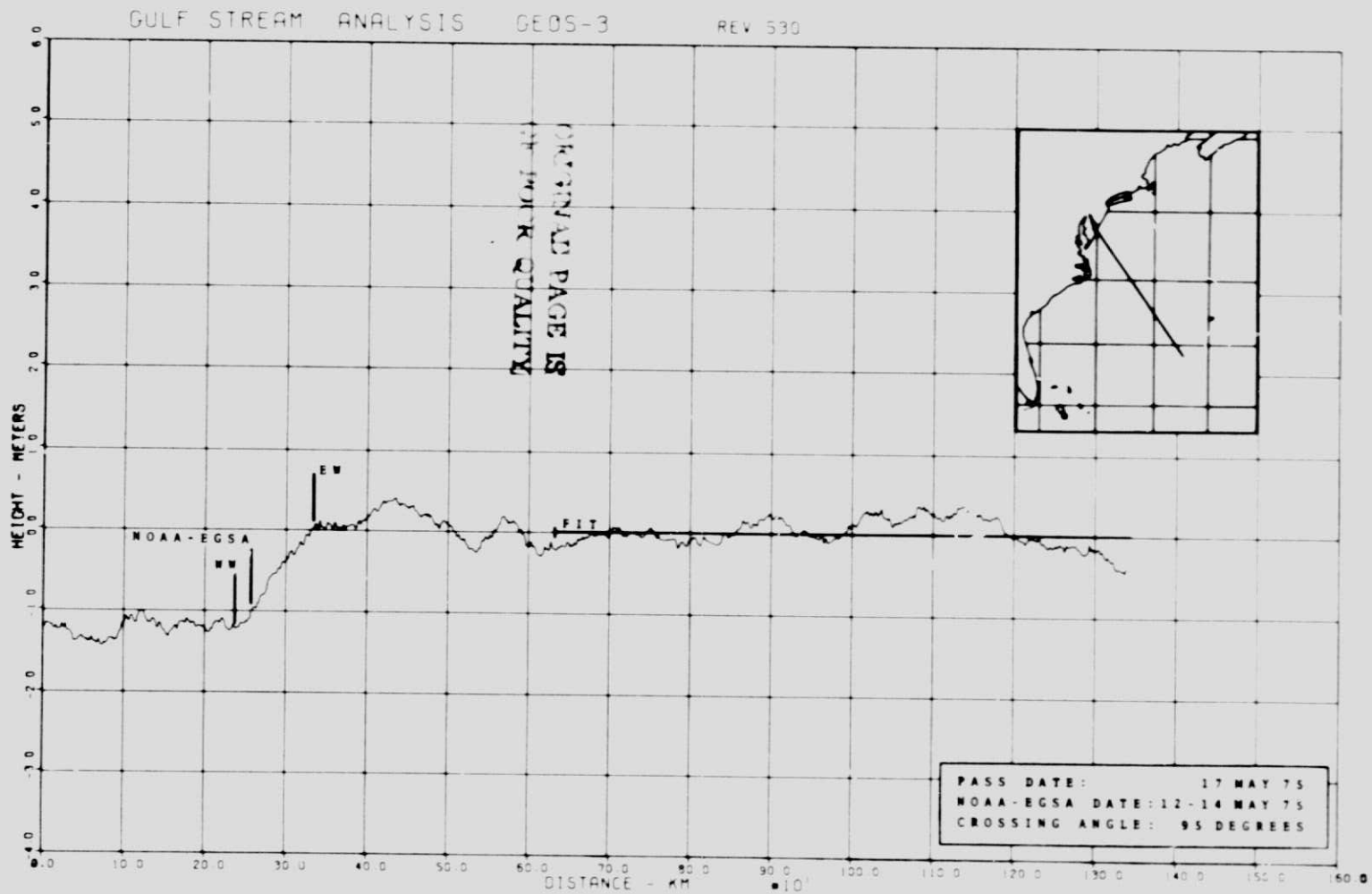
Figure 7. Single pass profile for orbit 530 indicating the Gulf Stream's eastern (EW) and western (WW) boundaries as estimated from this study and the western boundary as estimated by NOAA-EGSA.
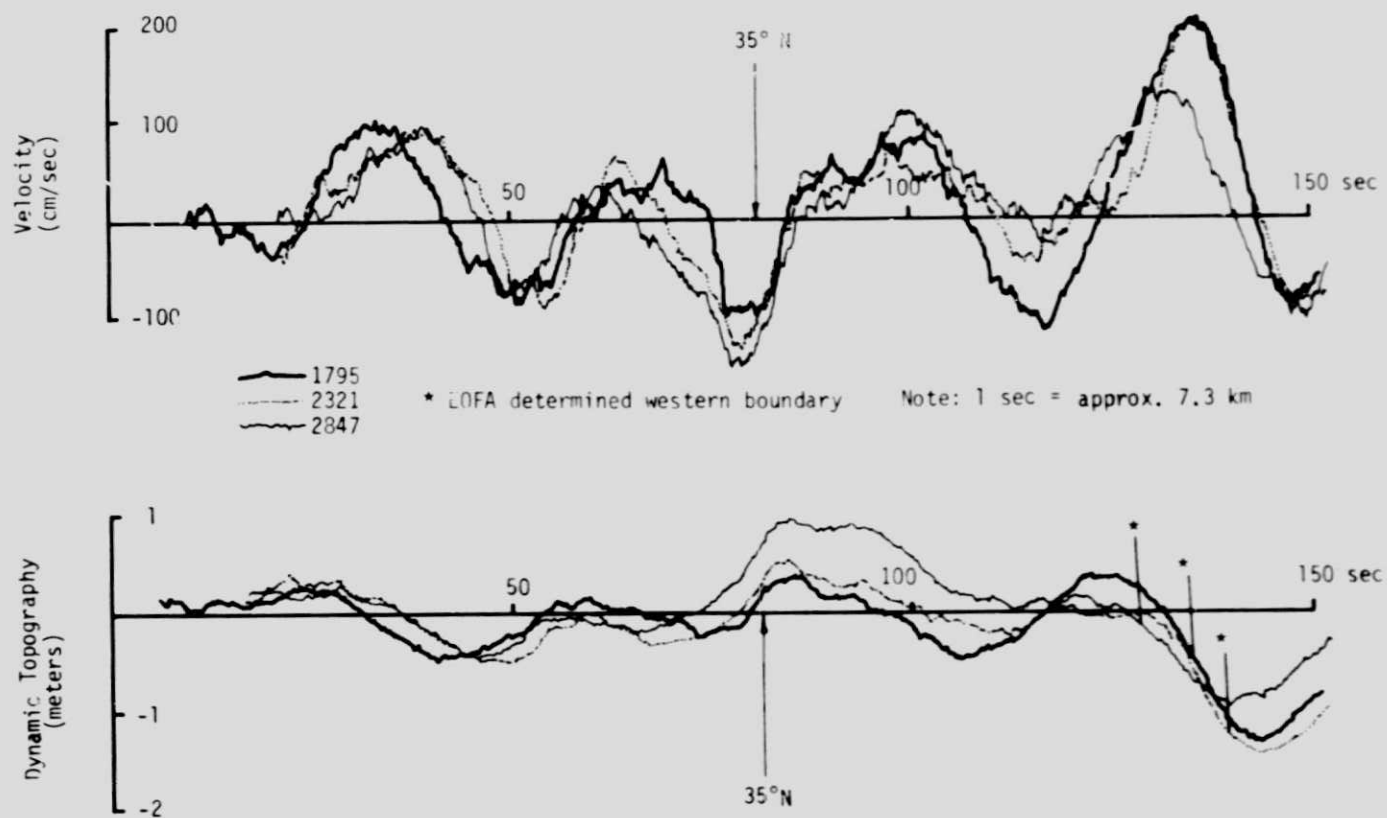
Figure 5. Comparison of Dynamic Topography and Derived Velocity for three
repeated altimeter profiles acquired over the same ground track
during three successive months.
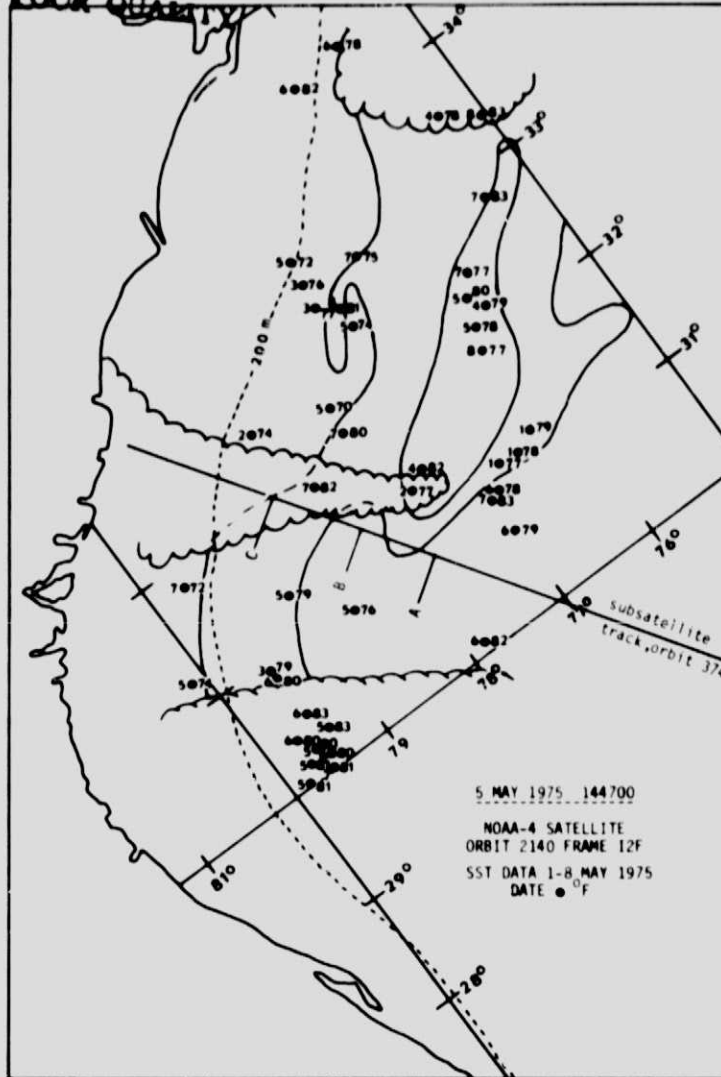
Figure 6. Composite drawing of IR data from NOAA-4 satellite and sea surface temperatures (SST) data from passing ships with Gulf Stream boundaries delineated. Subsatellite track for orbit 374 is superimposed showing the location of points AB&C (see figure 7).

Rev 374

Velocity
(cm/sec)

—300

—150

—0

—-150

c   b   a

—3

—1.5

—0

—-1.5

Dynamic hts
(m)

180   144   108   72   36   0

Time — seconds
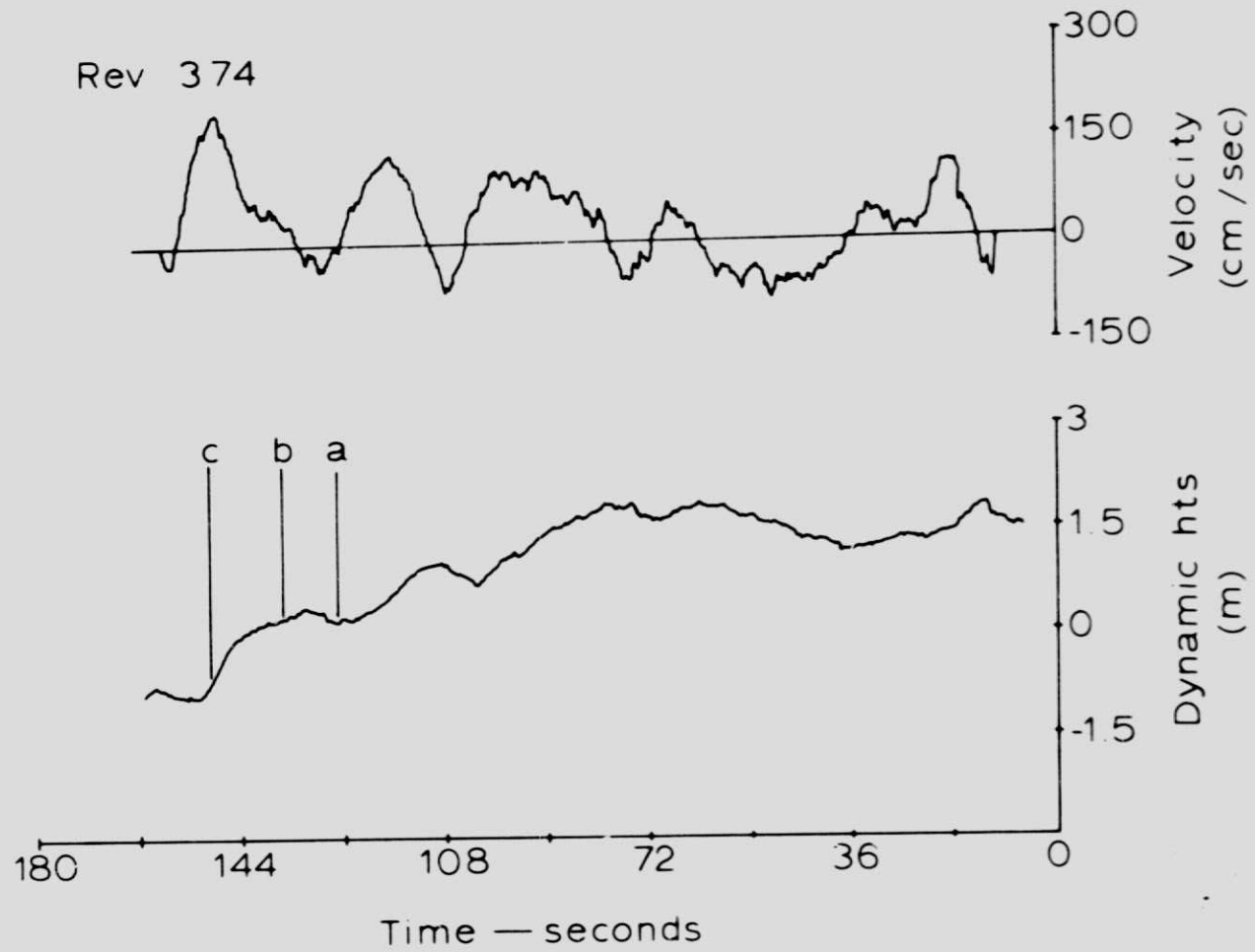
Figure 7.   Single pass profile for orbit 374 showing dynamic heights
(lower profile) and geostrophic velocities (upper profile).
Notice points AB&C located on map in figure 6.
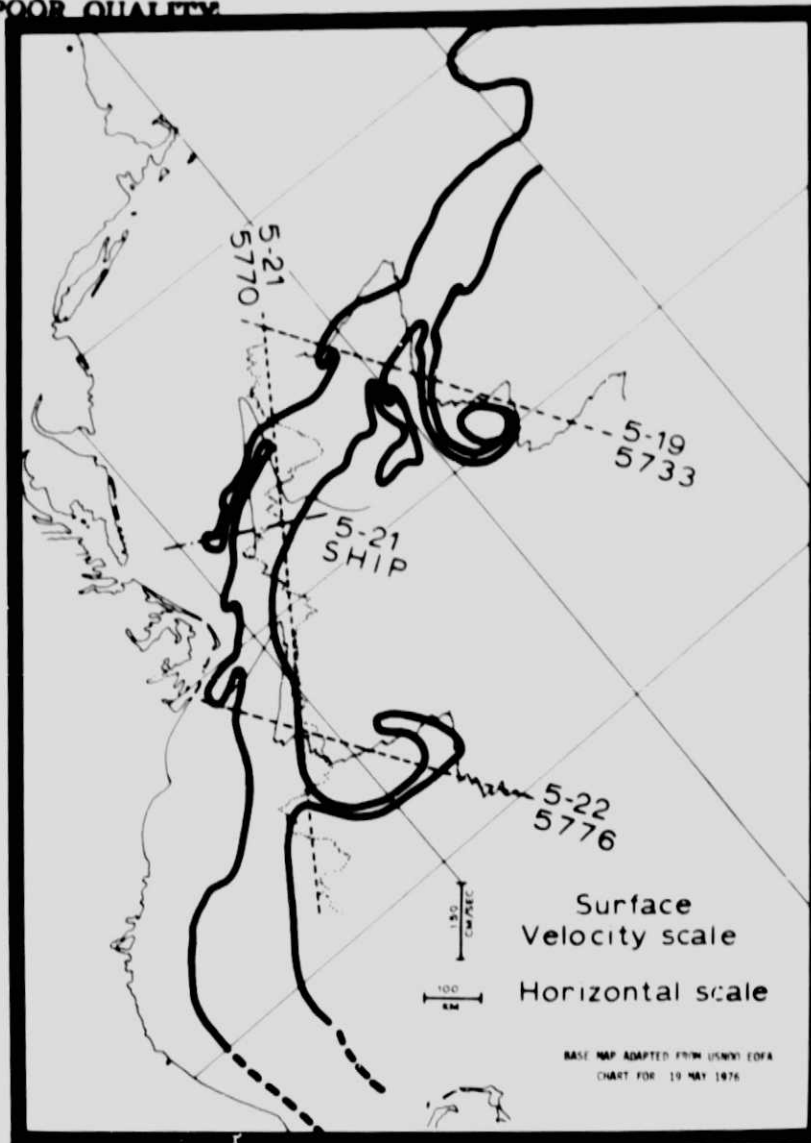
Figure 8. Composite map showing IR derived Gulf Stream boundaries with ship and GEOS-3 tracks superimposed. (Map courtesy of T. Curtin).
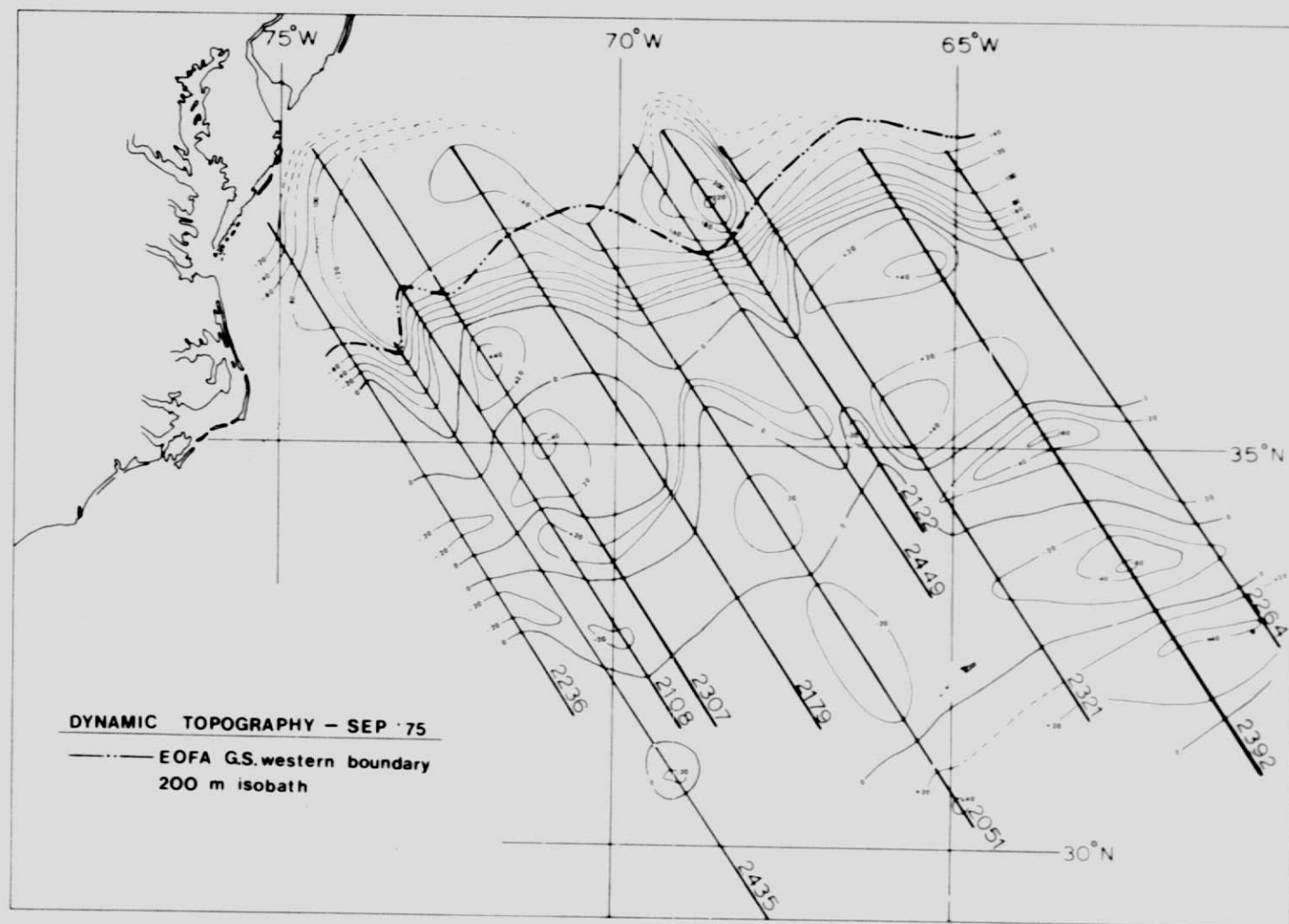
Figure 9. Dynamic Topographic map for September 1975 prepared by contouring only northbound individual profiles with no constraints.
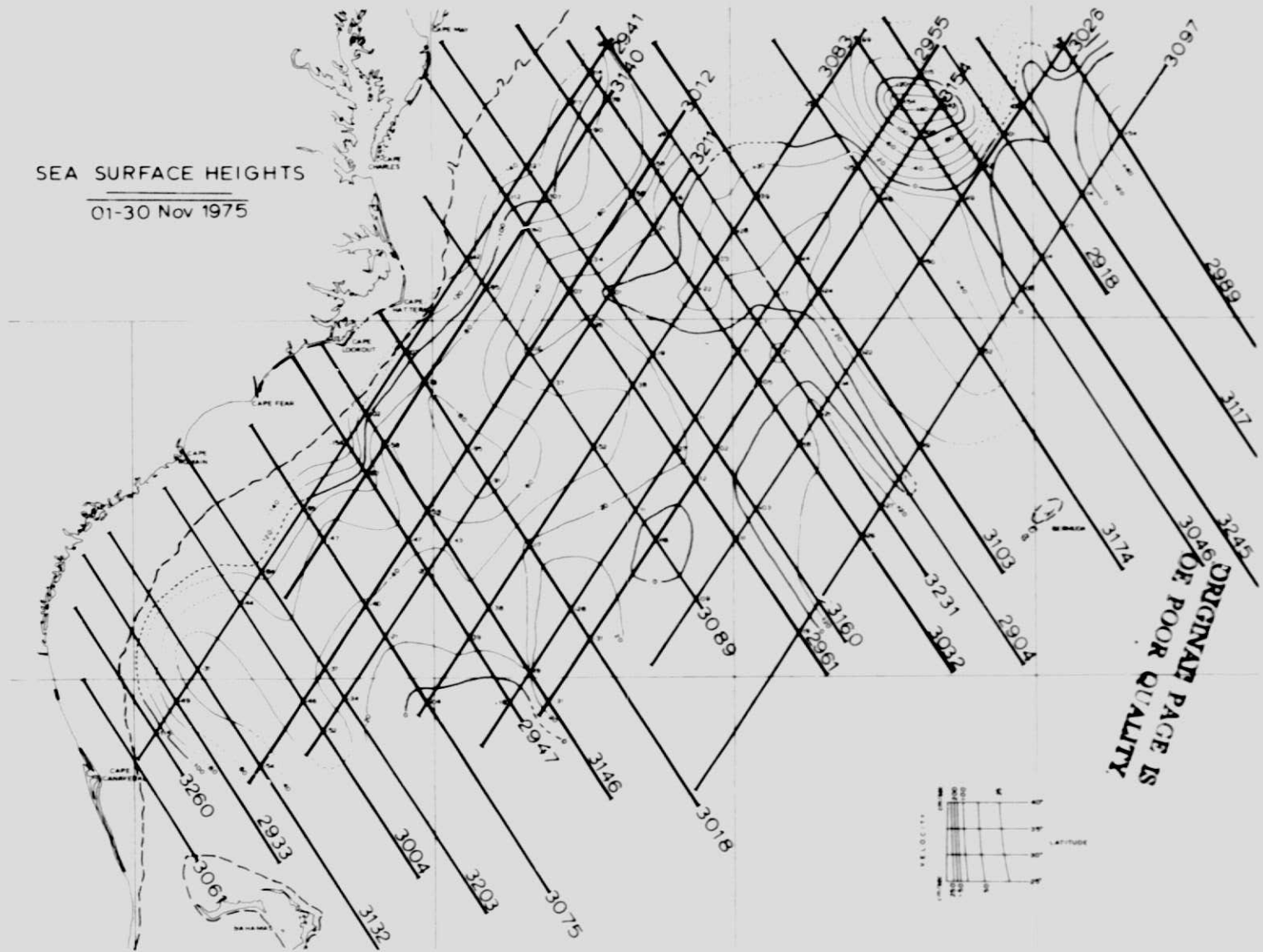
Figure 10. Sea surface heights for November 1975 from analysis adjusting data for crossings from only those orbits shown by numerals.

DATA CLUSTER
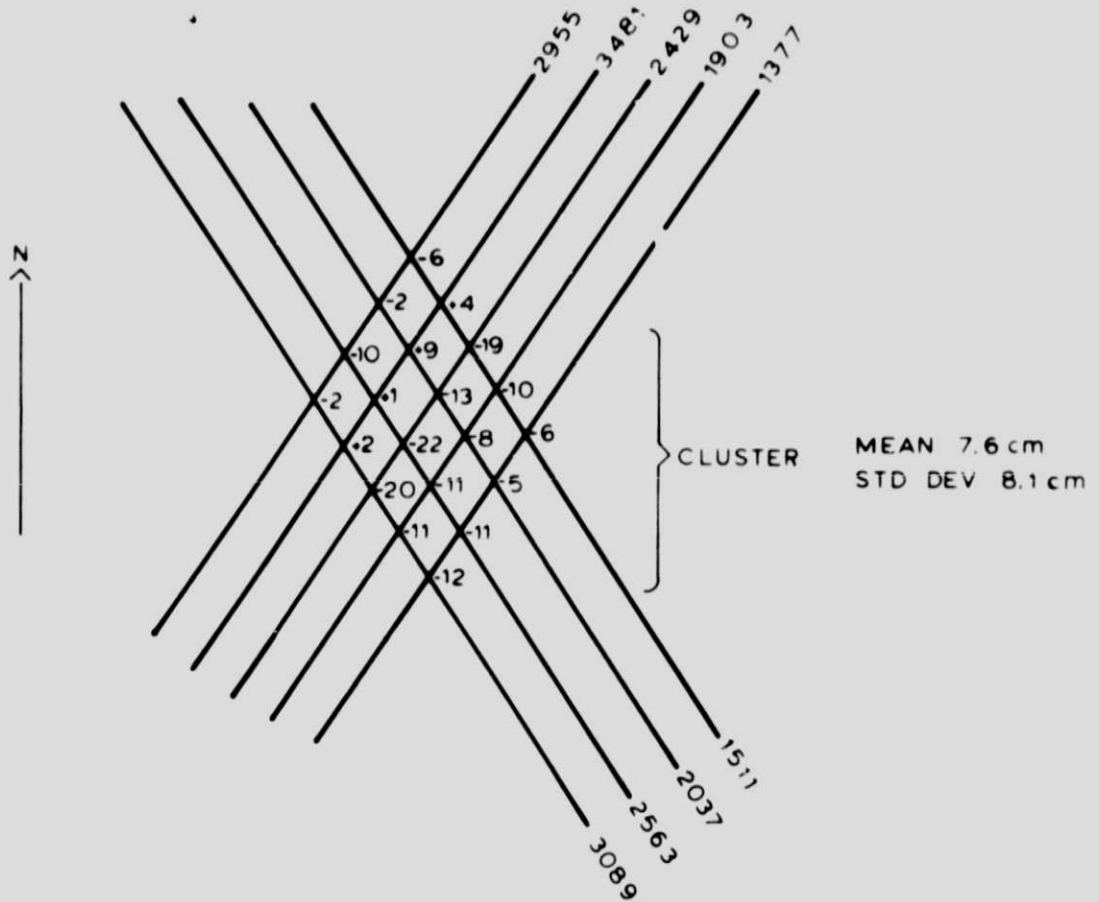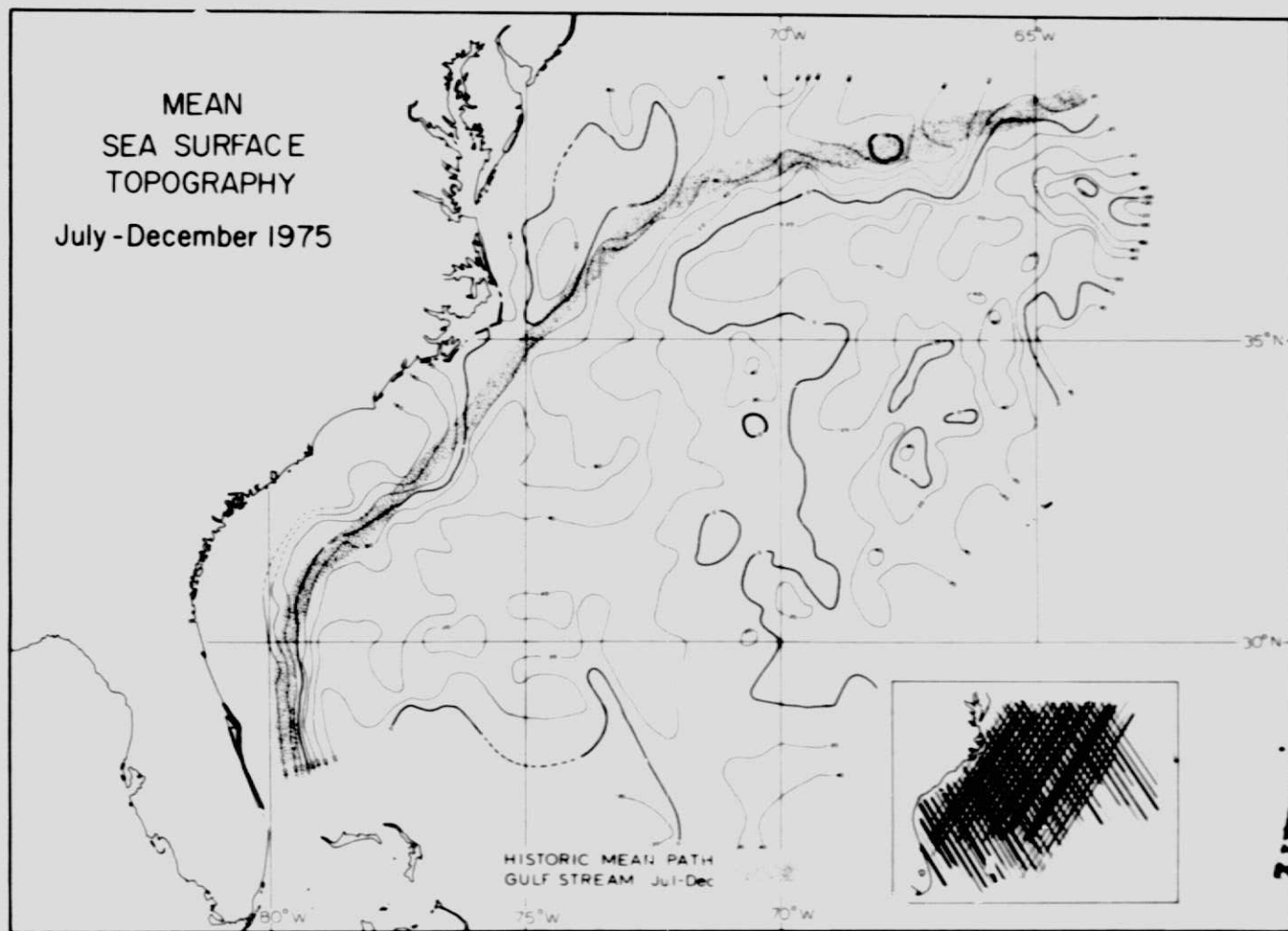

Figure 11. Example of a data cluster used in analysis for 6 months data.

MEAN
SEA SURFACE
TOPOGRAPHY
July-December 1975

HISTORIC MEAN PATH
GULF STREAM Jul-Dec

Figure 12. Overall mean sea surface topography estimated at each cluster of inter-
sections as shown in inset, July-December 1975.
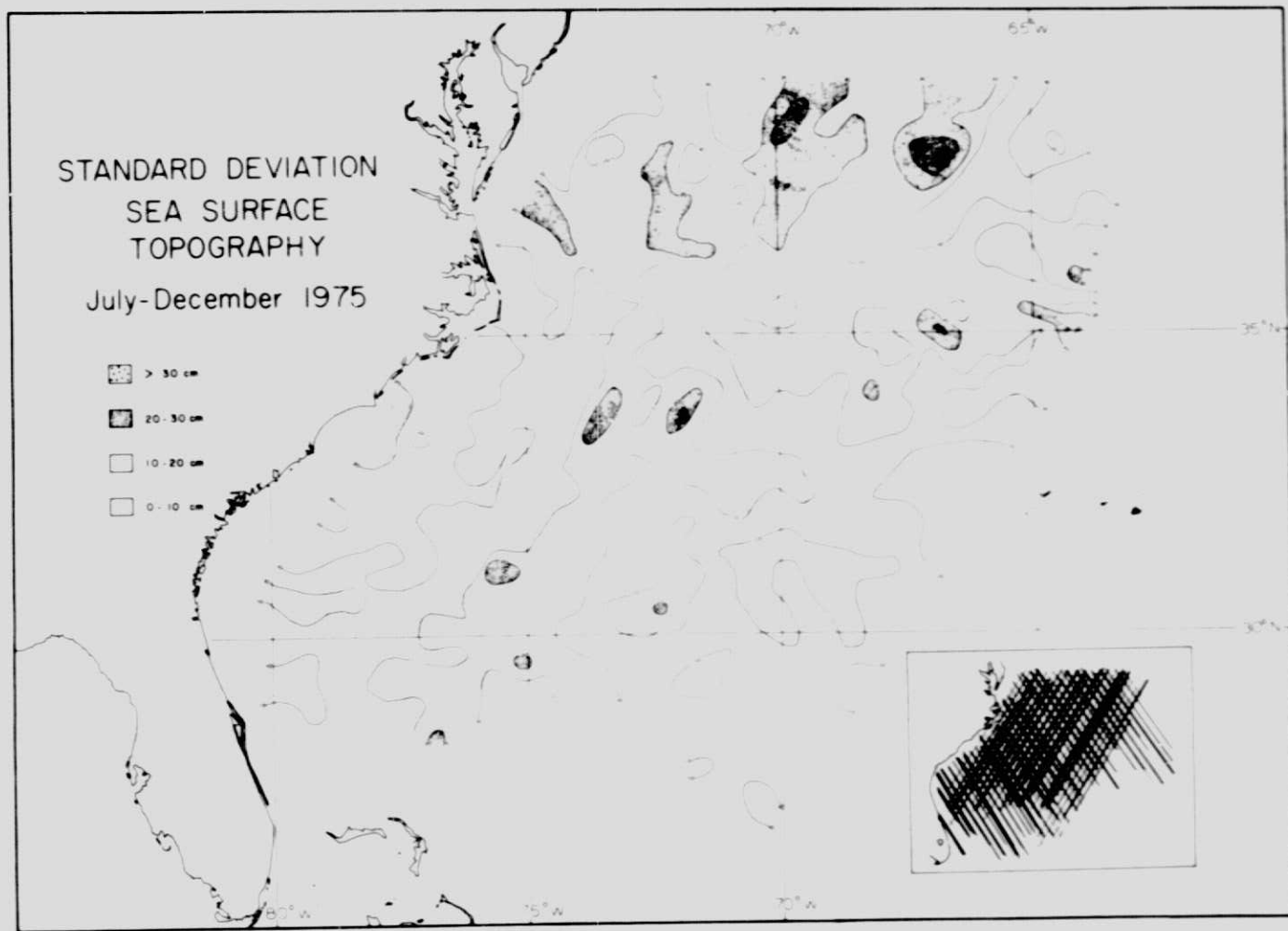
Figure 13. Standard deviation of sea surface topography estimated at each cluster of intersections as shown in inset, July-December 1975.
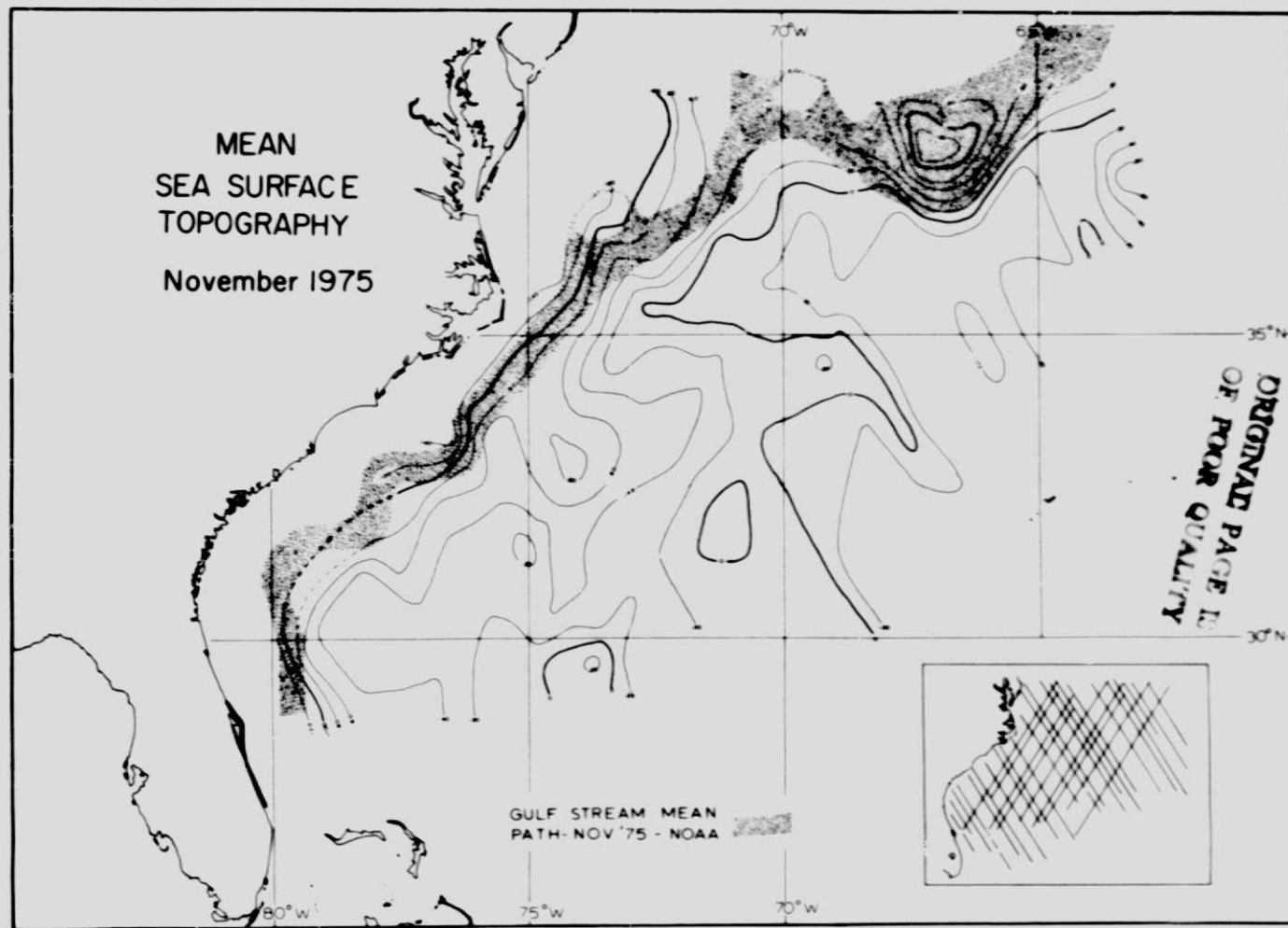
Figure 14. Mean sea surface topography using elevations obtained at each crossing shown in inset, November 1975.
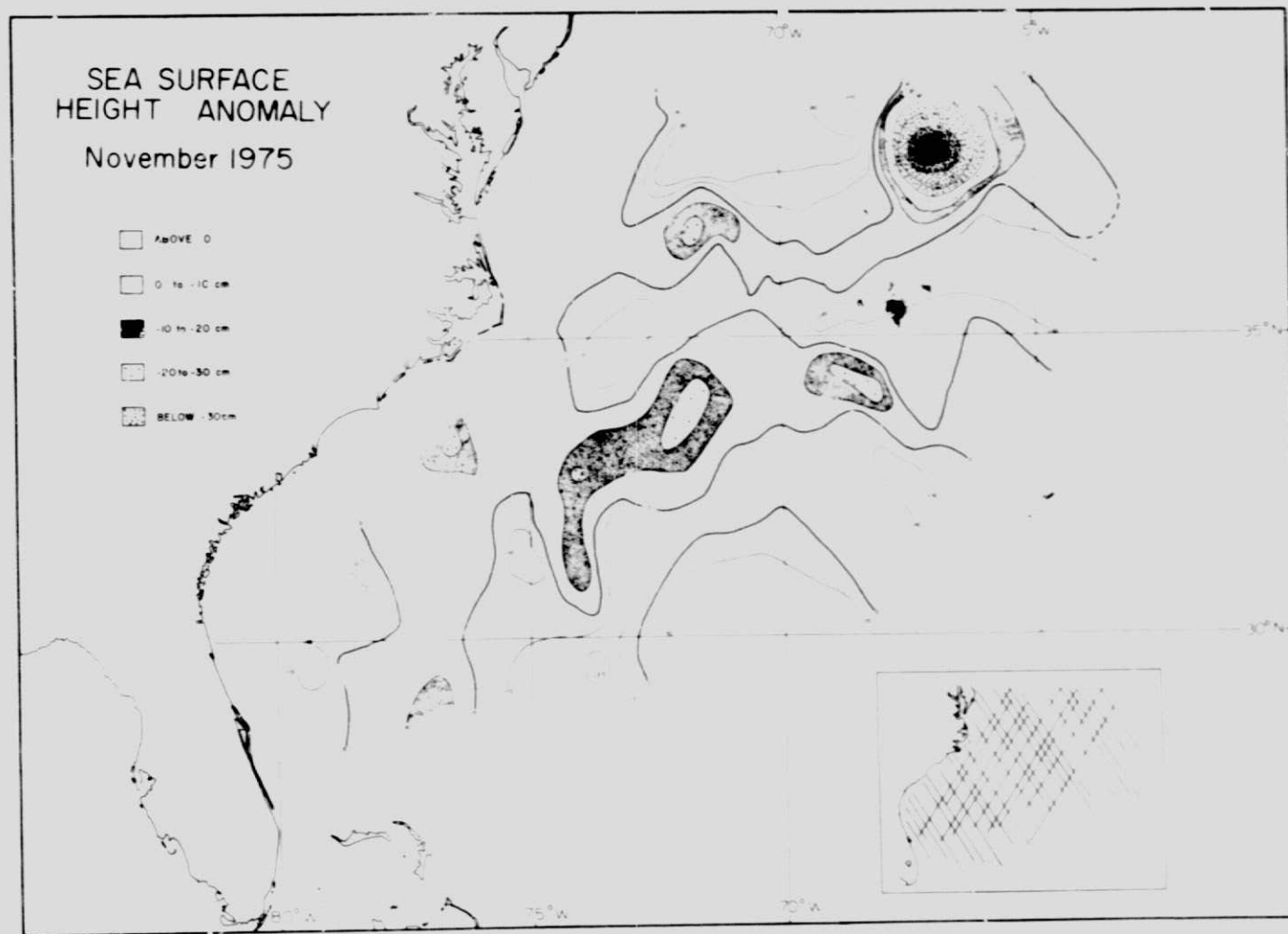
Figure 15. Differences between overall and November 1975 mean surfaces.
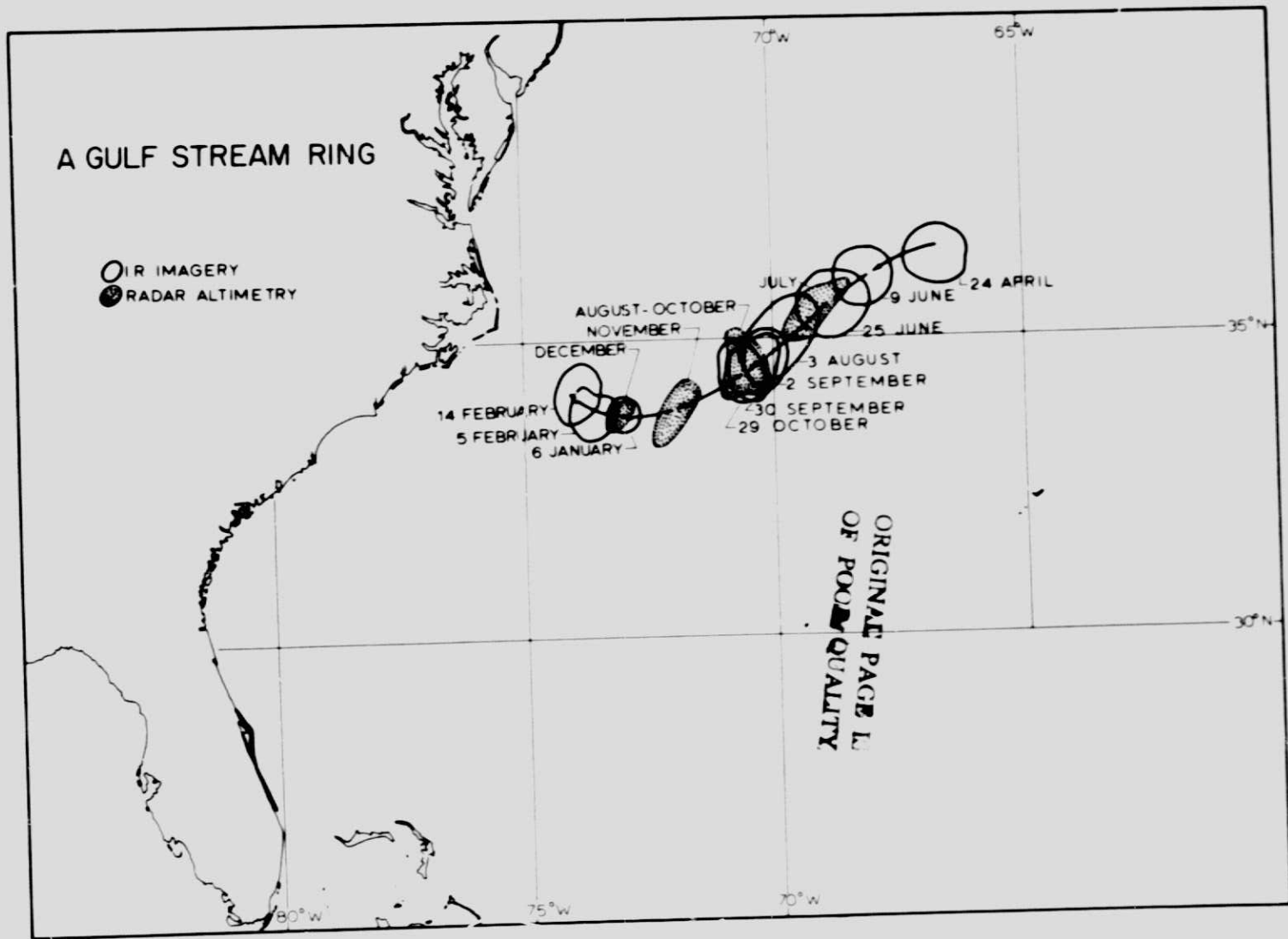
Figure 16. Gulf Stream ring movement sequence as defined by surface IR and satellite altimetry, April 1975 to February 1976.

MEAN SEA SURFACE
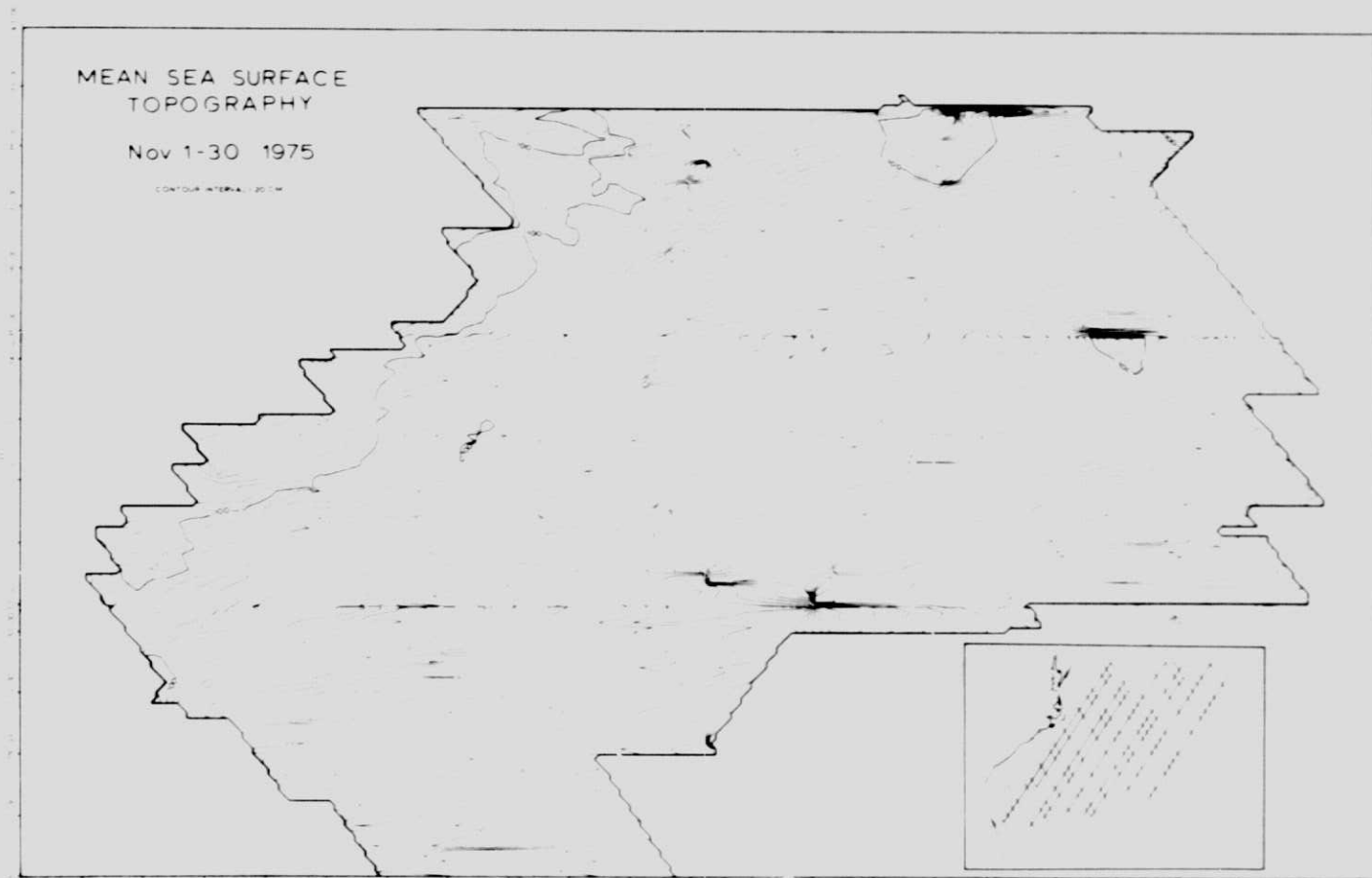TOPOGRAPHY

Nov 1-30 1975

CONTOUR INTERVAL 20 CM

Figure 17.   Example of computer plot of November 1975 data processed
using all points from those orbits shown in figure 10.