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INTRODUCTION

A computer based spectral ocean wave forecasting model that purported to be capable of specifying (or hindcasting) and forecasting the directional spectra of ocean waves on a grid of points for all of the oceans of the earth was described by Pierson, Tick and Baer (1966). It was also claimed in that paper that the model was capable of using data obtained from a spacecraft. Claims made more than a decade ago have been verified by the development of methods for verifying the initial value specifications of the significant wave height for this model by means of data from GEOS-3.

If Seasat-A is launched successfully, the winds measured by it will improve the initial value specifications for this wave forecasting model and the significant wave height measurements made by the altimeter can be used to improve further the initial value specifications. In turn, the improved wind measurements over the ocean should result in improved forecasts of the winds and, thus, improved forecasts of the waves.

An early effort to develop ways to forecast waves was that of Sverdrup and Munk (1947), who derived a procedure based on graphical techniques and the careful study of the duration and speed of the winds and the distance over which they had blown. This method introduced the concept of the significant wave height and period.

Ocean wave records of the rise and fall of the sea surface as a function of time at a fixed point were at that time a mystery since only two numbers, the average of the heights of the one third highest waves and the average time interval for the passage of these waves were extracted from the data. The methods developed by Sverdrup and Munk attempted to specify and to forecast these two numbers to describe the waves, usually for only a few places of interest.

For many geophysical random processes, data obtained as a function of time at a point are highly correlated from second to second. Standard statistical techniques for the estimation of the mean and variance of a sample of independent points are, therefore, not usable. Tukey (1949) showed how to estimate the "power" spectra of such random processes and developed a theory for the sampling variability of "power" spectral estimates. Strictly speaking, the random process is resolved into a spectrum whose integral as a function of frequency is the total variance of the process. The dimensions of the spectrum are those of the square of the quantity measured times time and thus have little to do with "power."

Pierson and Marks (1952) analyzed an ocean wave record (actually the pressure fluctuations on the bottom in about

20 feet of water as the waves passed), showed that it was closely approximated by a gaussian process and computed a "power" spectrum.

Rapid progress followed. The theories of Rice (1944) were extended by Longuet-Higgins in numerous papers (Longuet-Higgins (1952), (1957), (1963)*). The concept of a spectrum was extended to that of a function of both frequency and direction and to the vector wave number spectrum. Stereographic photographs were used to estimate a vector wave number spectrum (Cote et al. (1960)). Special buoys were developed to obtain data from which certain properties of the directional wave spectrum could be estimated (Cartwright (1963)). These time series concepts were also extended to the description of the motions of ships in waves by St. Denis and Pierson (1953).

The concept of a wave spectrum led to the development of an ocean wave forecasting technique based on the idea of determining the wave spectrum at a given point on the ocean in terms of the wind field over the ocean and the growth and dispersion of the waves (Pierson, Neumann and James (1955)).

A shipborne wave recorder was developed and described by Tucker (1956). Many hundreds of wave records from this instrument were spectrally analyzed, and the spectra were

*For additional references, see Pierson (1976).

tabulated and published by Moskowitz, Pierson and Mehr (1962), (1963), (1965). Moskowitz (1964) found a subset of these records that met the requirements for fully developed seas; that is, the wind had a nearly constant speed and direction for a long enough time over a large enough area so that the spectrum of the waves was solely a function of wind speed.

Pierson and Moskowitz (1964) used this special set of data to derive a proposed spectral form for fully developed seas, and Pierson (1964) showed that three different relationships for the height of fully developed seas as a function of wind speed could be partially reconciled if the anemometer heights used in the different analyses were taken into consideration.

The six hourly variations of the spectra estimated from these wave records were used, for example, by Inoue (1967) in the development of the model described by Pierson, Tick and Baer (1966). The theories of Phillips (1957), Miles (1957, 1959, 1959, 1962), and Phillips (1966) were modified so as to describe the generation of the waves. The spectral components traveling against the wind were attenuated by a gross Austauch turbulent effect, and the various spectral components were propagated along great circle paths on a triangular grid of points arranged on the faces of an icosahedron, each face being a gnomonic projection.

This spectral ocean wave forecasting model, whose computer programs have been described by Salfi (1974), was made operational for the Northern Hemisphere at the Fleet Numerical Weather Central in mid-December, 1975, as described by Lazanoff and Stevenson (1975). Some key features of the model have been used to develop a special model for the Mediterranean, as described by Lazanoff, Stevenson and Cardone (1973), and for tropical cyclones, as described by Cardone, Pierson and Ward (1976).

VERIFICATION TECHNIQUES

Prior to the launch of GEOS-3, the usual way to study the variation of waves with the winds and to verify ocean wave hindcasts and forecasts was to measure the waves at as many points as possible as a function of time. The spectra were then estimated from the wave records. They were functions of frequency only. Case studies such as the one by Bretschnieder et al. (1962) demonstrated what has recently been called a hysterisis effect by Parsons (1978). Also, the forecasted spectra and heights were compared with the estimated spectra and heights. Examples can be found in Pierson (1976) and in Salfi and Pierson (1977).

Such verification techniques are difficult, time consuming, and limited to the few selected places where the waves are recorded. Until recently, only weather ships such as Poppa in the North Pacific and I, J and K in the North Atlantic recorded waves routinely. Within the past few years, data buoys in the North Pacific, the Western Atlantic and the Gulf of Mexico and wave recorders on offshore oil platforms have supplemented this source of data.

The measurement of waves at fixed points has many disadvantages with reference to attempts to verify and to improve ocean wave forecasting models. Data for the western sides of the oceans, for the subtropical highs and for the trade wind areas have been lacking. The forecasting model could thus be in error on a climatological basis for those oceanic areas different from the areas where data are available.

Usually associated with a wave recorder is an anemometer so that the wind directions and speeds in the areas where the waves are measured are better known than in those areas of the model where few ship reports of the winds are available. If the meteorological analyses and forecasts of the winds are systematically in error for some oceanic areas, then the specifications and forecasts will be systematically in error.

THE DATA

The first part of the data compared in this study consisted of significant wave heights as running averages of the height estimates for each frame of data for a set of GEOS-3 orbit segments as provided by NASA Wallops. For one altimeter mode, a frame lasts for three seconds and seven points were used. For another mode, a frame lasts for two seconds and nine points were used. The running averages thus correspond to about 20 seconds of data along the subsatellite track. Some portions were in the Southern Hemisphere and could not be compared to the SOWM data.

For some GEOS data for the Northern Hemisphere no SOWM data could be located. The latitudes and longitudes for each significant wave height estimate along the subsatellite altimeter track were provided for each orbit segment along with the date and starting and ending time. The reasons for the selection of the data that were provided are not known.

The second part of the data compared in this study consisted of SOWM wave hindcasts (or wave specifications) for 1975 and 1976 from two different sources. Both kinds of data were provided in the form of 50 reels of computer tape on which the specified wave spectra were stored for every six hours at 00z, 06z, 12z and 18z for each grid point of the model in the Northern Hemisphere. One of the sources was a hindcast wave climatology produced for use by naval architects and based on the analysis of archived meteorological data on the winds and sea surface pressures over the ocean. The other source was the archived initial value update data from the operational SOWM model. Both sources provide the wave spectra and significant wave height as specified by the model and as based on the best available data and analysis techniques at that time for the computation of the wind speed and direction at each of the grid points of the model.

The first problem in the analysis was to find those SOWM grid points close enough in space and time to be compared to the GEOS heights. This was accomplished by means of a massive data sort in which the co-location algorithm described by Greenwood and Pierson (1977) was used to find SOWM grid points within an assigned distance of the points along the GEOS track. The result (except for some cases where something went wrong) was a listing of the GEOS-3 heights and their latitudes and longitudes and of the SOWM heights and their latitudes and longitudes for two six hourly synoptic times, one preceding and one following the time of the GEOS data. A linear time interpolation to the nearest hour (or the nearest half hour, if needed, because of rapid changes) then gave SOWM heights to be compared to the GEOS heights.

SAMPLING VARIABILITY

There are major problems in probability theory and in statistics that have not been solved with reference to the wave heights estimated by the altimeter on GEOS-3. The wave heights calculated for the altimeter data are estimates in the statistical sense of the term. It is worthwhile to review these concepts for the simplest of possible examples and for the estimation of the significant wave height from an ocean wave time history.

The simplest example is that of the estimation of the variance of a normal distribution with zero mean, given N independent samples. It is well known that this estimate of the variance has a chi-square distribution and that the fiducial confidence intervals on the estimate of the variance yield a large confidence interval if N is small. For example, for 100 independent values the probability is 0.9 that the true value of the variance will lie between 1.26 and 0.79 times the estimate of the variance calculated from the data. The ratio of the lowest possible value to the highest is 1.59.

For ocean wave time histories, the basic difficulty is that even a 20-minute long record is the equivalent of only 100 to 200 <u>independent</u> samples from a normal population. A 20-minute long wave record is usually digitized about once per second to yield 1200 points. Spectral theory then yields the result that effectively there are much fewer independent points (see Neumann and Pierson (1966)). Had another ship, or data buoy, recorded the waves just a few kilometers away from the place where a record had been obtained, the record would have been completely different. The estimate of the square of the height would have been different, and each estimate would have been a sample point from a chi-square distribution with about the same number of degrees of freedom.

For high waves, the effective number of degrees of freedom is small, and for swell, it is small. Miles (1971) has given examples from the analysis of records obtained by the Tucker Shipborne wave recorder. Table 1, abbreviated from Miles, shows some of these results. The data from Miles are the first five columns. The process was inverted to obtain the effective number of degrees of freedom, given in the last column.

Even if the waves are measured with a perfect instrument at a fixed point, the value of the wave height that is obtained as a correct description of the waves in an area, say, 20 km on a side, is only good to ± 1.5 meters, or so, for 13 meter high waves. The situation is unavoidable, and any reported wave height is only an "estimate" in the statistical sense of the word.

Table 1 90% Fiducial Confidence Intervals and Effective Number of Degrees of Freedom for Twenty Minute Ocean Wave Records. (abbreviated data from Miles (1971))

Record N.	Date Hr.	Day	Mo.	Yr.	H (1/3) meters	Confidence Interval Upper 95%	Confidence Interval Lower 5%	Effective Degrees of Freedom
NW 204	12	29	7	64	1.600	1.744	1.468	178
201	12	5	2	64	2.189	2.400	1.997	157
205	12	30	7	64	3.804	4.222	3.427	122
193	12	20	1	64	4.739	5.173	4.342	173
183	12	28	12	61	5.331	5.756	4.938	225
186	12	29	1	62	6.968	7.765	6.252	113
197	12	29	1	64	8.047	8.990	7.203	108
185	12	22	1	62	9.229	10.285	8.282	113
190	12	11	2	62	10.084	11.107	9.156	142
198	12	30	1	64	11.327	12.772	10.046	92
189	12	10	2	62	13.657	15.170	12.294	120

THE MEASUREMENT OF WAVES
WITH A RADAR ALTIMETER ON A SPACECRAFT

The primary purpose of a radar altimeter on a spacecraft is the more accurate determination of the geoid over the ocean. The shape of the return pulse contains information on the height of the waves within the foot print of the pulse limited transmitted radar waves. Attempts to measure waves with the S193 altimeter on Skylab were not successful because of damage to the antenna for the last manned period when the waves were highest, but some theory was available as given by Pierson and Mehr (1972).

The measurement of waves by GEOS-3 has been studied intensively by numerous scientists. Research, both published and unpublished, by Roy and McMillan (1977), Walsh (1977), Godbey (1977), Gower (1977), Feldman (1977) and others have clarified some parts of the problem.

The technique for processing the return altimeter pulse wave forms used in this study is the latest one developed at NASA Wallops as a result of the collaboration of Normand A. Roy, Edward Walsh, and James McMillan. It will be described in a forthcoming publication.

The technique has been verified for waves with significant heights of up to 12 meters by comparing the estimated significant heights from GEOS-3 data with the estimated significant heights of waves measured by National Data Buoys in the North Pacific, Gulf of Mexico and the western middle latitude Atlantic Ocean.

Ocean waves can be described as a first approximation as a quasi-stationary gaussian random process. Non-linear and, hence, non-gaussian effects can be partially treated according to theories of Longuet-Higgins (1963). However, the first parameter to describe the waves is the variance of the random process as given by equation (1) where $S(\ell, m)$ and $S(\omega, \chi)$ are two ways to represent the spectrum.

$$\sigma_W^2 = m_o = \int_{-\infty}^{\infty}\int S(\ell, m)\, d\ell\, dm = \int_0^{\infty}\int_{-\pi}^{\pi} S(\omega, \chi)\, d\omega\, d\chi \qquad (1)$$

In the notation used by those who have studied the GEOS-3 altimeter wave form, σ_W^2 can be determined. Given this quantity, the significant wave height can be computed as in equation (2).

$$H_{\frac{1}{3}} = 4\,\sigma_W \qquad (2)$$

For the GEOS-3 altimeter, the altimeter wave form can be approximated (skewness effects omitted) by equation (3).

$$F(t) = \int_{-\infty}^{t} 2\pi^{-\frac{1}{2}}\,\sigma_T^{-\frac{1}{2}} \exp\left[-\tfrac{1}{2}\,(\tau/\sigma_T)^2\right] d\tau \qquad (3)$$

where a speed of 15 cm per nanosecond is used to convert σ_T to units of nanoseconds and where

$$\sigma_T^2 = \sigma_p^2 + \sigma_j^2 + \sigma_W^2 \qquad (4)$$

In equation (4), σ_p represents the effect of the transmitted pulse which would produce the classical ogive shape of the cumulative normal distribution in the complete absence of waves (except for small roughness elements) and of tracking jitter. Similarly, in (4), σ_j represents the jitter of the tracking loop. The value of σ_j is found by fitting the altimeter range values over a given time interval to a smooth curve and then computing the variance of the residuals.

The value of σ_T can be estimated from the return altimeter pulse wave form (equation (3)) at points roughly six nanoseconds apart in time centered near one of the range gates. A technique closely approximating, but not exactly equal to, a maximum likelihood method is used to find σ_T.

With σ_T and σ_j estimated and σ_p known, the significant wave height is estimated by equation (5).

$$H_{\frac{1}{3}} = 4\left(\sigma_T^2 - \sigma_p^2 - \sigma_j^2\right)^{\frac{1}{2}} \tag{5}$$

According to Forristall (1978), a more precise calculation of the average height of the one third highest waves (that is the significant wave height) from the Rayleigh distribution yields equation (6).

$$H_{\frac{1}{3}} = 4.005\,\sigma_W = 4.005(m_o)^{\frac{1}{2}} \tag{6}$$

The study by Forristall (1978) of actual wave records yielded the result that equation (7) should be used, or that the significant height should be about 94% of the value presently used.

$$H_{\frac{1}{3}} = 3.77\sigma_W = 3.77\ m_o^{\frac{1}{2}} \qquad (7)$$

This result implies the need to reexamine the entire theory of the estimation of wave heights by a radar altimeter. Some of the higher waves must be missing. The description of the sea surface as quasi-gaussian, even as improved by Longuet- Higgins (1963), probably needs revision.

It is possible that the significant wave heights given by the SOWM should be reduced in the ratio of 3.77 to 4.005. What is not clear is whether or not the value of σ_W determined by the altimeter has already been reduced by this proportion. The value of σ_W in equation (5) may either correspond to $m_o^{\frac{1}{2}}$ or to the value reduced in the above proportion. It will be difficult to decide on which of these two alternatives is correct because of the effect of sampling variability.

The wave height estimated from the GEOS-3 altimeter data have a large amount of sampling variability. The heights estimated from one altimeter frame fluctuate from frame to frame by very large amounts.

The GEOS-3 spacecraft travels over the ocean about 14 km during the time required to obtain the data for one two-second frame. For illustrative purposes, let it be assumed that the track over the ocean is perpendicular to the wave crests. If the waves have an apparent period of about ten seconds, then the wavelengths might be 100 meters $\left(2(gT^2/2\pi)/3\right)$ and there would be 140 waves along the track. The 14 km would be the equivalent of a 1400 second (23.3 minutes) long ocean wave time history at a point. For higher waves with an apparent period of 15 seconds, the corresponding results would be 234 meters, or 60 waves, and 900 seconds (15 minutes). For still higher waves, with an apparent period of 20 seconds, the corresponding results could be 416 meters, or 34 waves and 670 seconds (11 minutes).

If the radar track is not perpendicular to the wave crests, for directions up to 45°, or so, the equivalent times that result should be reduced in proportion to the cosine of the angle involved, so that the equivalent times could respectively be as short as 16 minutes, 11 minutes, and 8 minutes.

The guesstimates are crude, but in the right sense. The vector wave number spectrum (perhaps as given by the SOWM) might possibly be used to calculate the effective numbers of degrees of freedom (just as for time histories at a point) for a given altimeter wave height estimate.

If a 20 minute long ocean wave record has only about 100 effective degrees of freedom, and if the preceding guesstimates are close, the individual heights gotten by the GEOS-3 altimeter have somewhere between 80 and 40 degrees of freedom for each frame of data. As shown in Table 2, the factors that multiply the estimate of the wave height for these degrees of freedom are substantial.

Table 2 - Factors for Fiducial Confidence Intervals on Significant Wave Height

(Two second data frames and 9 point averages)

Degrees of Freedom	Upper 95%	Lower 5%
40	1.20	0.83
80	1.14	0.88
360	1.06	0.94
720	1.04	0.96

The scatter from frame to frame in the GEOS-3 wave heights seems to be even greater than that equivalent to 40 or 80 degrees of freedom. To reduce this scatter, seven or nine point overlapping averages were produced of the form given by equation (8) for the nine point averages. The last two rows of Table 2 represent nine times the first two rows for the left hand column. Additional sampling variability may be introduced by the procedure used to estimate the jitter.

$$H_{\frac{1}{3}} AVE(p) = \frac{1}{9} \sum_{q=p-4}^{p+4} H_{\frac{1}{3}}(q) \tag{8}$$

A disadvantage of running averages is that the smooth curves so produced can appear to have realistic sensible variations. They are often a consequence of the time domain average producing the effect of a filter on the white noise part of the spectrum of the fluctuations.

These considerations are suggestive but not conclusive. A much better theory for the estimation of significant wave heights from GEOS-3 data is needed. The confidence intervals for these estimates are needed. These confidence intervals will have to depend on the properties of the waves on the sea surface as well as on the data recorded by the spacecraft. For the purpose of this study, the wave heights estimated from the GEOS-3 data can be considered to have a confidence interval of about ± 15% of the given height for waves over about 3.3 meters, even for the seven and nine point running averages. This broader range does not square with the preceding material. It is based more on the nature of the smoothest height graphs, which still have considerable fluctuations.

Another problem with the GEOS-3 data arises for low waves. Too large a value for the estimate of the jitter can result in the term under the square root on the right hand side of equation (5) being negative. The confidence interval for low waves should, therefore, be considerably larger because of the effect of the variability of σ_j. For waves under 3-1/3 meters, the heights may be good to $\pm$ 0.5 meters.

FEATURES OF THE SOWM

The SOWM is highly sensitive to the input wind field that drives it. Errors in the wind field propagate into the prediction of the significant wave height, into the value of m_o and into the frequency and value of the spectral peak. The relationships are as follows for fully developed seas.

$$H_{\frac{1}{3}} \sim v^2 \qquad (9)$$

$$m_o \sim v^4 \qquad (10)$$

$$S(f\ max) \sim v^5 \qquad (11)$$

$$f\ max \sim v^{-1} \qquad (12)$$

A 5% error in wind speed produces a 10.25% error in wave height, a 21.55% error in m_o and a 27.6% error in the spectral peak. The corresponding values for a 10% error in wind speed are 21%, 46.4% and 61%.

During the period for which the SOWM data used in this study were produced, the error structure of the model was analyzed at FNWC in terms of the accuracy of the wind fields that were used. At both the theoretical and operational level, the quality of the wind fields both as specifications (that is the descriptions of the wind field every three hours based on ship reports and other observations) and forecasts of the winds from a meteorological forecasting model were found to be unsatisfactory at times. It was found that the waves were biased low, that there were problems in the tropics, and that occasional poor analyses and forecasts of the wind fields produced substantial "busts" in the wave height forecasts.

Since midsummer 1977, improved wind fields with somewhat stronger winds for high winds and better analysis techniques have eliminated many of the poor wind field analyses that may have been produced in the 1975 to 1976 time frame.

The main purpose of this study is to illustrate how the wave height data obtained by GEOS-3 could have been used to detect day to day errors in the SOWM specifications and to correct the SOWM specifications in time to produce improved forecasts. Had GEOS-3 data been routinely available, the process of improving the SOWM would have been quicker and easier. Much of what has been found from the GEOS-3 data was learned by other means during the one to two year time lag required to put the GEOS-3 wave height measurement theory on a firm foundation.

The SOWM was not operational until mid-December 1975 so that a number of comparisons of the SOWM with the GEOS data are probably for the wave climatology that used archived data to produce hindcasts. The discrepancies between what GEOS measured and the wave climatology demonstrate that actual observations are superior to attempts to hindcast waves using the presently available data base of ship reports and meteorological analyses.

For fully developed seas, it is possible to relate errors in the specification of the significant wave height to the errors in the specification of the wind speed that generated the waves. With the height in meters and the wind speed in meters per second, equation (9) can be written as equation (13) and solved for the wind speed that generated a given wave height as in equation (14).

$$H_{\frac{1}{3}} = 0.0212 \, v^2 \tag{13}$$

$$v = (47.17 \, H_{\frac{1}{3}})^{\frac{1}{2}} \tag{14}$$

As an example, a GEOS wave height of 6 meters for an ocean area where the SOWM waves were 4.5 meters suggests that the winds in the area might actually have been 16.8 m/s instead of perhaps 14.6 m/s, which would have generated the 4.5 meter waves.

Table 3 shows the relationship between the SOWM wave heights and the wind speed for fully developed seas except for a small additional increase in the height for a given wind of perhaps 0.2 m to 0.5 m for the Kitaigorodski range, where $S(f) \sim u_* f^{-4}$ may increase the value of m_o at high winds (Pierson (1976)). For ocean areas where the SOWM is consistently too low, either the swell has not been correctly specified or the winds in the area are too low. A wind at least capable of generating the measured wave height, or one even stronger with a briefer duration, must have been present.* For low waves, errors in the wind speed of 1.5 to 2 m/s produce height errors of 0.5 m. For moderate waves, errors of 1 m/s produce height errors of 0.5 m. For 10 meter waves, errors of 0.5 m/s in the wind produce 0.5 m errors in the waves.

Unfortunately, for ship reports, the higher the wind the larger the error in its measurement, and so on both a percentage basis and on a height difference basis, the errors in specifying, or forecasting, high waves will be large.

*In the absence of swell.

Table 3 - Wind Speeds Required to Generate Waves of a Given Height in the SOWM and Change in Wind Speed Equivalent to a One Half Meter Change in Wave Height

Height (M)	Wind Speed (M/S)	Change in Wind (M/S)
0.5	4.86	
1.0	6.86	2.00
1.5	8.41	1.55
2.0	9.71	1.30
2.5	10.86	1.15
3.0	11.89	1.03
3.5	12.85	0.96
4.0	13.74	0.88
4.5	14.57	0.83
5.0	15.36	0.79
5.5	16.11	0.75
6.0	16.82	0.71
6.5	17.51	0.69
7.0	18.17	0.66
7.5	18.81	0.64
8.0	19.43	0.62
8.5	20.02	0.59
9.0	20.60	0.58
9.5	21.17	0.57
10.0	21.72	0.55
10.5	22.25	0.53
11.0	22.78	0.53
11.5	23.29	0.49

RESULTS

Method of Analysis

After co-locating the SOWM and GEOS-3 data by means of the procedure described previously, a further study of the paired data sets was made. Some of the GEOS orbit segments turned out to be over land, although nearby water points provided SOWM wave heights. There were, for example, a number of cases where waves over ten meters were reported over the Siberian land mass. Careful editing of these data with a high resolution land-sea table, not available during this investigation, could reduce this source of difficulty.

Another difficulty with studying the GEOS-3 data was the effect of the proximity of land on wave height measurements. If undetected, an altimeter measurement of the wave height over land yields a very large wave height incorrectly. If running weighted averages are used and if these incorrect measurements for a particular frame are not suppressed, the result is a series of very high waves over the water close to the land along the track. Some of the points on the graphs that will follow were painted over with white paint when this was believed to be the situation.

A number of the orbit segments turned out to have just a few points in the Northern Hemisphere and to be dominantly data for the Southern Hemisphere. Since the SOWM does not produce wave specifications for the Southern Hemisphere, all of this fascinating data had to be omitted in this study. Particularly high waves were measured during the Southern Hemisphere winter of July and August.

The SOWM height fields were plotted on a polar stereographic Northern Hemisphere map as interpolated to the time of the GEOS pass. Significant wave height contours were then sketched on the chart. The significant wave heights along the subsatellite track from the GEOS-3 data were plotted as a function of latitude and longitude along the track by means of a computer program that produces graphs as the printout from a UNIVAC 1108. The interpolated significant wave heights to an accuracy of 0.1 meters from the SOWM data were then entered on these computer plots for every tenth point along the orbit.

One of the features of the GEOS-3 significant wave height measurements is that they have fluctuations over short distance scales along the orbit that are not reproduced in the SOWM specifications. By choosing every tenth point along the orbit for comparison with the SOWM wave heights, which were interpolated in both space and time, the fluctuations in the GEOS-3 data were treated as a part of the total random error in the SOWM specification. The chance that the smaller scale fluctuations along the subsatellite track would be too high or too low would be about the same at this spacing for verification.

The GEOS-3 wave heights will be compared with the wave heights specified by the SOWM. For some of these orbit segments, the SOWM wave height field will be given. For others, only the graph of the GEOS-3 wave heights and of the wave heights extracted from the SOWM analysis will be given. In all cases, the technique for analysis was the same.

A number of data sets were rejected at the last stage of the analysis because of lack of time, and because they were not considered to alter any of the major conclusions of this study. Other data sets were rejected because they were very short segments that did not seem to add any new information for this study. Still other GEOS-3 passes in the polar regions were rejected because of the high probability of sea ice, which would give erroneous results for the wave height.

Potential Impact of Remote Sensing

Those who have not been active in describing measuring, hindcasting (or specifying) and forecasting ocean waves may not appreciate the impact that the capability demonstrated by GEOS-3 to measure waves will have and the tremendous scientific advances that will be possible, once these data are used routinely in an operational way. Simply to obtain a set of data comparable to one single orbit pass that requires only 10 or 15 minutes to travel from the equator to landfall by any other means would be prohibitively difficult. Without remote sensing techniques from a spacecraft, the only other way to obtain such a data set would have been to position ships at every degree of latitude with ocean wave recorders on them along a line such as one in the subsequent figures, extending from the equator to a continent in either the Atlantic or the Pacific, and have them all make wave recordings of approximately 20-minute duration simultaneously on a particular day at an agreed upon time. The cost would be prohibitive. If it were done, however, by the time the ships got on station, it probably would be worthwhile to have them stay there for several weeks so as to obtain additional data. The advantage would be, of course, that wave spectra could be obtained from the records, whereas present remote sensing techniques provide only an estimate of the wave height. The need for spectra may be met by spacecraft of the future.

Even if an experiment of the type hypothesized above could be carried out, it would still not be possible to repeat it enough times to obtain the global coverage that will be obtained from the spacecraft, SEASAT-A, due to be launched in May 1978. The capability to study storms and storm waves in any ocean at any time with a 12-hour separation between observations will become a reality with this spacecraft.

By neglecting the time difference between successive orbits and grouping all of those that cover a particular ocean during a series of either northbound or southbound passes, it is possible to contour the wave height field for that entire ocean, relative to a time centered near the time of the middle orbit of the sequence. This has been done successfully by Parsons (1978) for a sequence of orbit segments over the North Atlantic obtained by GEOS-3, and height fields so generated can be a useful quasi-synoptic climatology for waves.

General Comments

In general, it was found that the SOWM missed the details of the short, spatial scale fluctuations in the measured GEOS-3 wave heights. These fluctuations may or may not be real. They could be caused by sampling variability effects. This is one of the reasons why a ± 15% confidence interval has been placed on the measured GEOS-3 heights as graphed. Some of these fluctuations exceed the confidence interval that has been chosen. There are a number of reasons that can be given to suggest that these fluctuations may actually be a real part of the wave environment of the Northern Hemisphere oceans. They are pronounced around islands where wave shadowing effects, venturi winds between islands, and lee of island calms could produce them.

There were a number of times when the SOWM wave heights and the GEOS-3 measured heights agreed very well for low waves over great distances in the tropics and during the summer. At these times, the shorter scale wave height fluctuations along the orbit did not occur. At other times, the SOWM wave heights in the tropics, that is from 30° N to the equator, were very low, the GEOS-3 measured wave heights were much higher, and the short spatial scale fluctuations were pronounced. These results indicate that the winds in the tropics and swell traveling through the tropics were not properly modeled at times. Somewhat higher winds in the tropics with superimposed swell from some distant anticyclone, which long ago had weakened, could have produced the measured scales of fluctuations in the significant wave height along the subsatellite track.

Pass by Pass Analyses

Forty-four GEOS-3 orbit segments with altimeter wave height data in the northern hemisphere were co-located with SOWM data for dates starting on August 24, 1975 and ending on October 16, 1976. Twenty-nine of the segments were for 1975. Fifteen were for 1976. On the following pages each orbit segment is identified by orbit number, date and time, and a statistical summary of the comparison of every tenth GEOS-3 height with an interpolated SOWM height is given, along with a discussion of that particular pass with reference to the nature and possible reasons for the differences between the GEOS measurements and the SOWM specifications.

To illustrate the procedure used for all orbit segments, seventeen of the statistical summaries are followed by a portion of a polar stereographic map projection on which are plotted the sub-satellite track and the time interpolated SOWM significant wave heights to the nearest 0.1 meter. For example, the northbound Pacific pass for orbit #3291 shows SOWM heights of 7.4 m near 45° N, 180° E. These SOWM heights were contoured so as to be able to read off the wave heights to be plotted on the GEOS-3 height graphs. The variable spacing of the SOWM points on these maps is partly caused by the fact that the SOWM grid points are on a gnomonic projection for each triangular face of an icosahedron representing the earth.

Finally, for each orbit segment, a graph of the GEOS wave heights for either seven or nine point running averages is given. Also, the bounds for a 15% or ± 0.5 m confidence interval, as a guess, are given. For every tenth point, a dot shows the wave height from the SOWM. For most of the graphs, the wave height from the SOWM is far enough away from the GEOS height, even with a 15% sampling variability, to permit the conclusion that the differences are not due to sampling variability. The values at the dots are compared to the GEOS values immediately above or below at the same latitude and longitude point to prepare the statistical summary given at the start of each orbit segment. The most striking difference between the GEOS heights and the SOWM heights is the more rapid spatial fluctuation of the GEOS heights compared to the SOWM heights.

ORBIT 1929 AUGUST 24, 1975 9:08 TO 9:33

NORTHBOUND PACIFIC

EQUATOR AT 136.7° E TO CHINA COAST NW OF TAIWAN

24 POINTS RMS 0.8 M BIAS - 0.6 M

HIGHEST SOWM; ON TRACK 0.9 M; IN FIELD 1.1 M

HIGHEST GEOS; ON GRID 2.0 M; AT ONE POINT 2.8 M

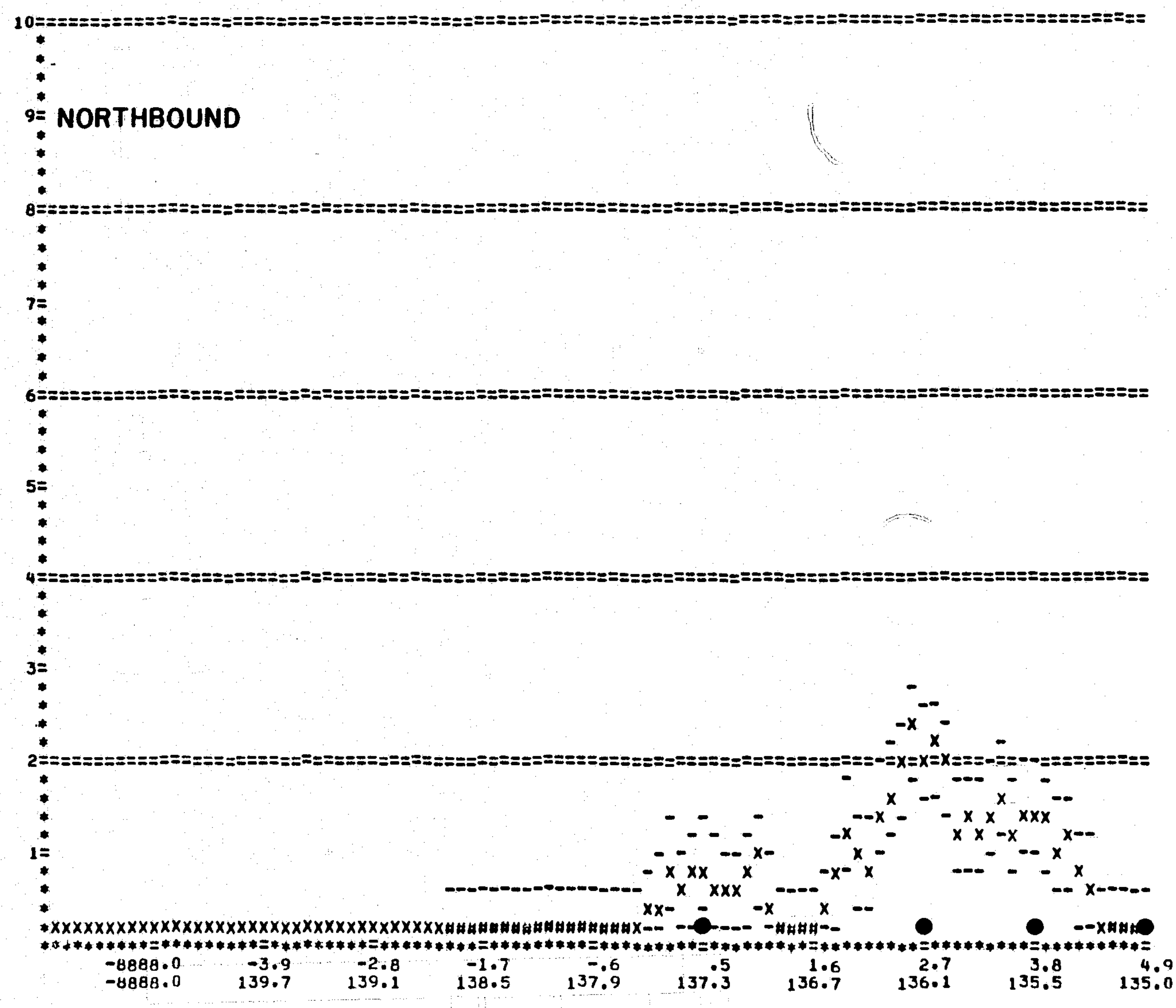
LOWEST SOWM; ON TRACK 0.2 M; IN FIELD 0.1 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

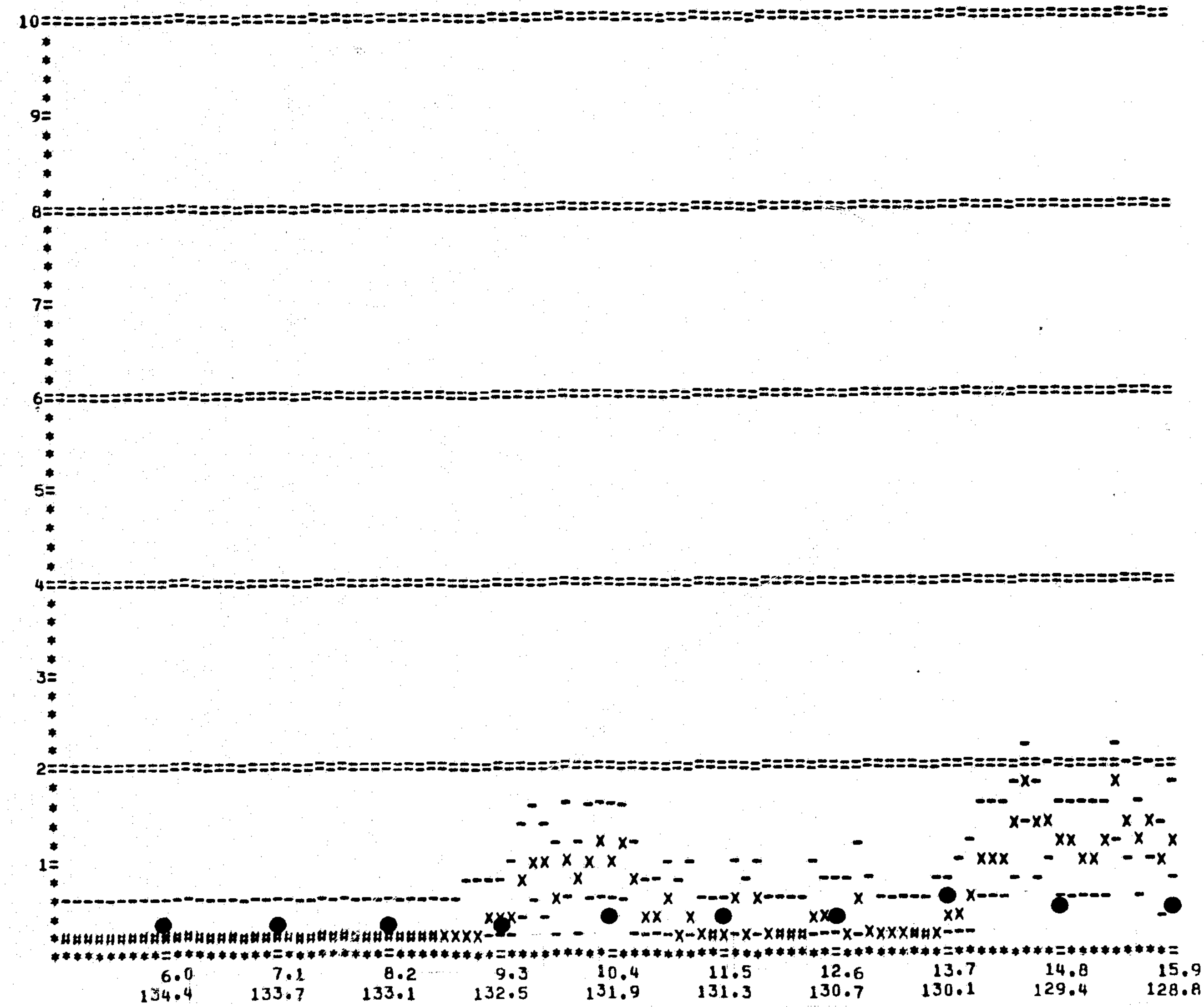
LARGEST ERROR - 1.8 M; SOWM 0.2 M, GEOS 2.0 M

Large fluctuations in GEOS heights from calm to 2.8 m. Slowly varying SOWM heights do not reproduce the fluctuations. Winds near the equator of 8 m/s could have produced the waves; could also be bands of swell.

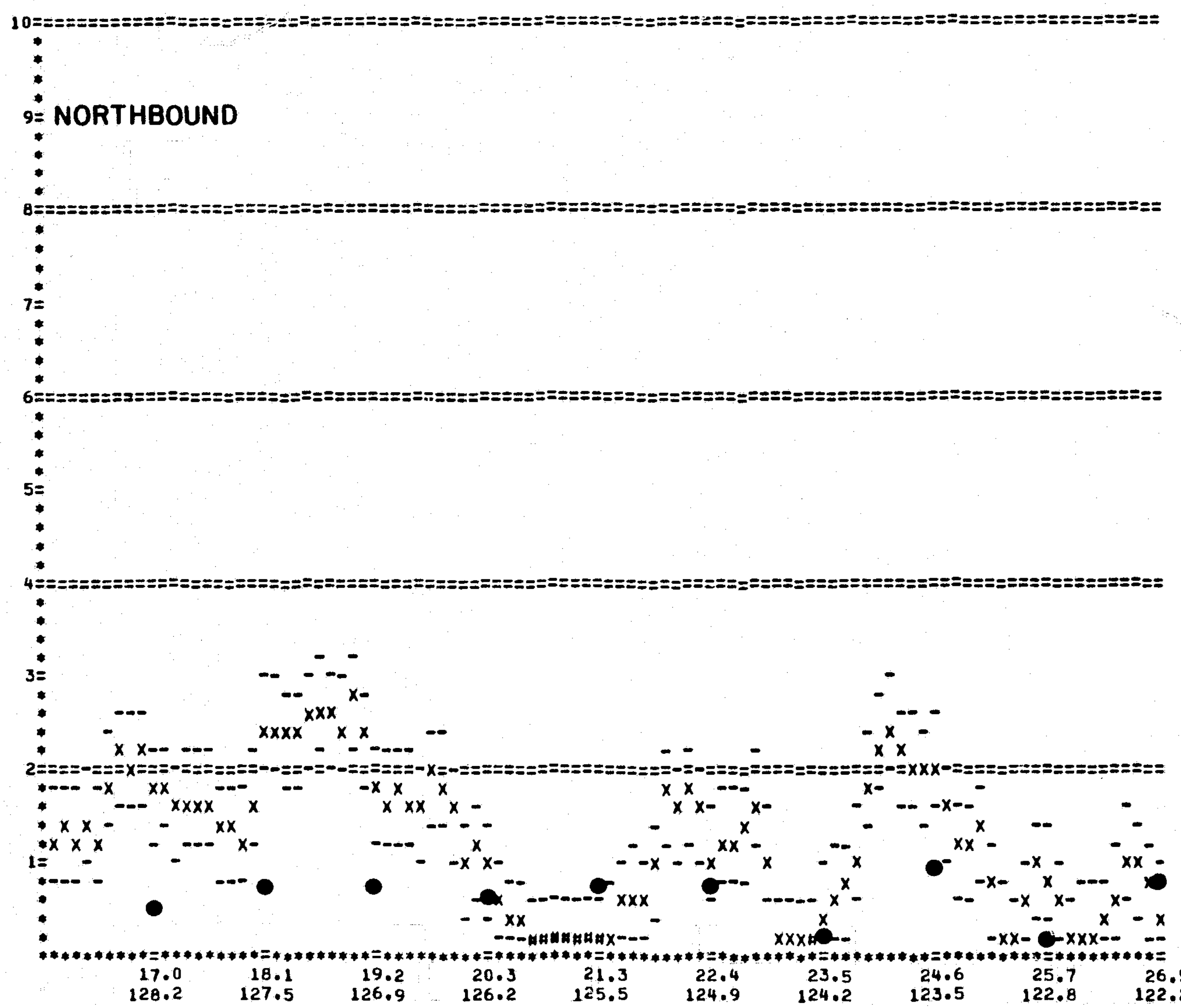
ORBIT 1929 UNIQUE # 260 DATE 8/ 24/ 75
STARTING LAT -51.190000 LON 176.97000 TIME 9: 8
ENDING LAT 26.620000 LON 26.620000 TIME 9: 33



ORBIT 1929 UNIQUE # 260 DATE 8/ 24/ 75
STARTING LAT -51.190000 LON 176.97000 TIME 9: 8
ENDING LAT 26.620000 LON 26.620000 TIME 9: 33



ORBIT 1929 UNIQUE # 260 DATE 8/ 24/ 75
STARTING LAT -51.190000 LON 176.97000 TIME 9: 8
ENDING LAT 26.620000 LON 26.620000 TIME 9: 33



ORBIT 1991 AUG. 28, 1975 17:29 TO 17:56

SOUTHBOUND PACIFIC

SEATTLE TO 9° N, 205° E

36 POINTS RMS 1.0 M BIAS - 0.2 M

HIGHEST SOWM; ON TRACK 3.6 M; IN FIELD 3.7 M

HIGHEST GEOS; ON GRID 4.0 M; AT ONE POINT 4.0 M

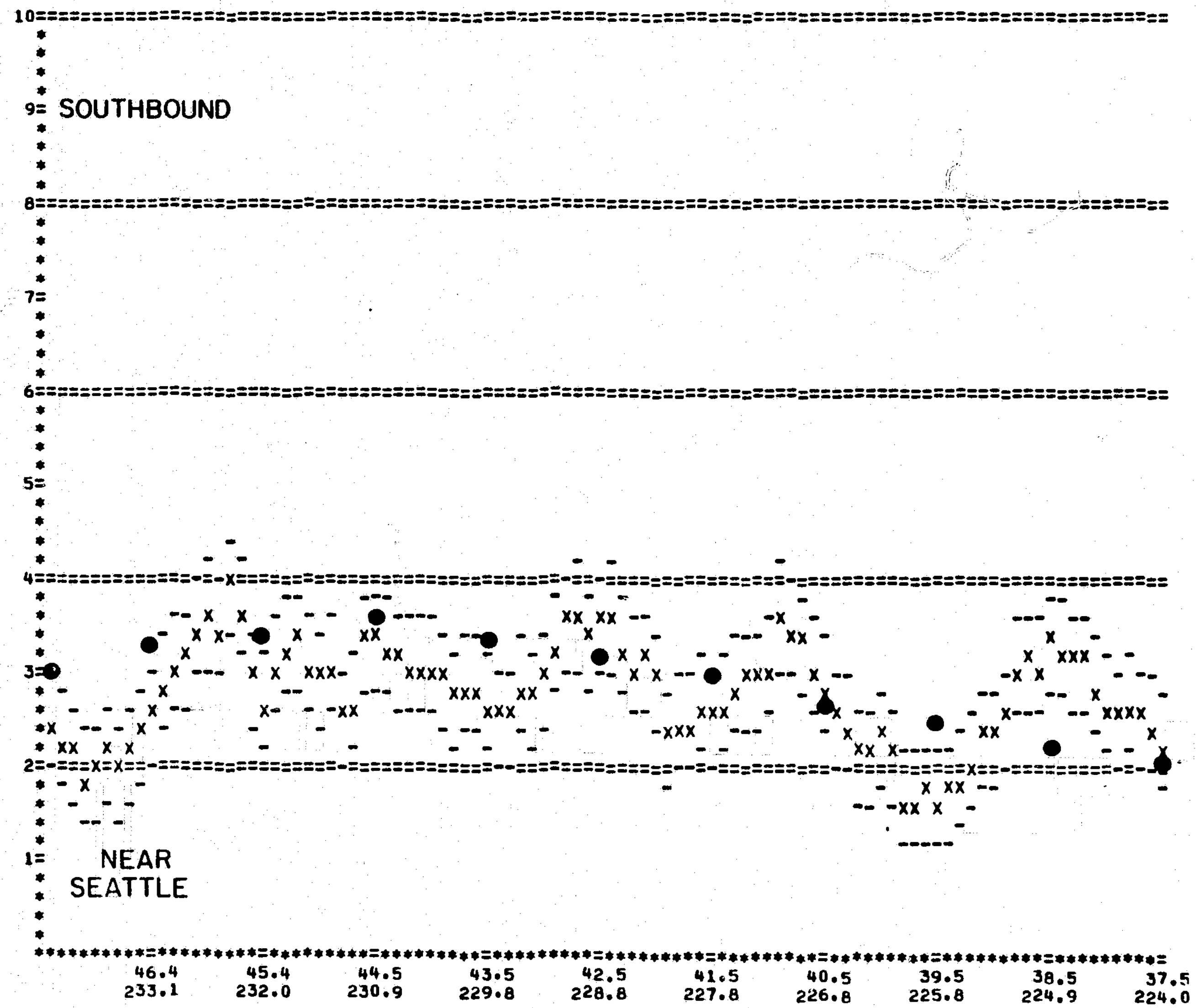
LOWEST SOWM; ON TRACK 0.8 M; IN FIELD 0.9 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

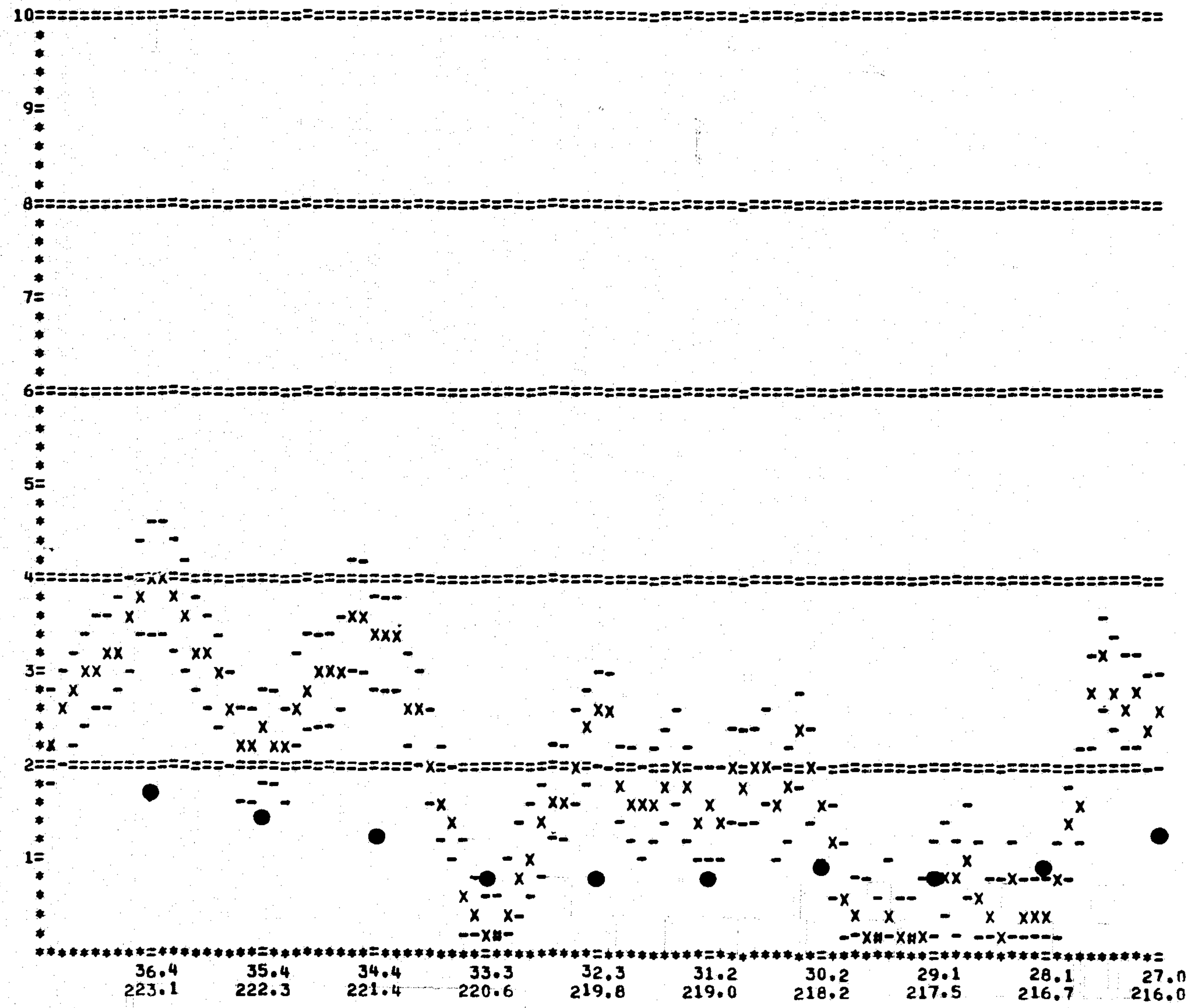
LARGEST ERROR - 2.3 M; SOWM 1.7 M, GEOS 4 M

SOWM quite good 47° N to 37° N where GEOS fluctuations are small. South of 37° N SOWM too low and GEOS fluctuations from zero to four meters. Could be groups of swell from previous storms to the north passing through area.

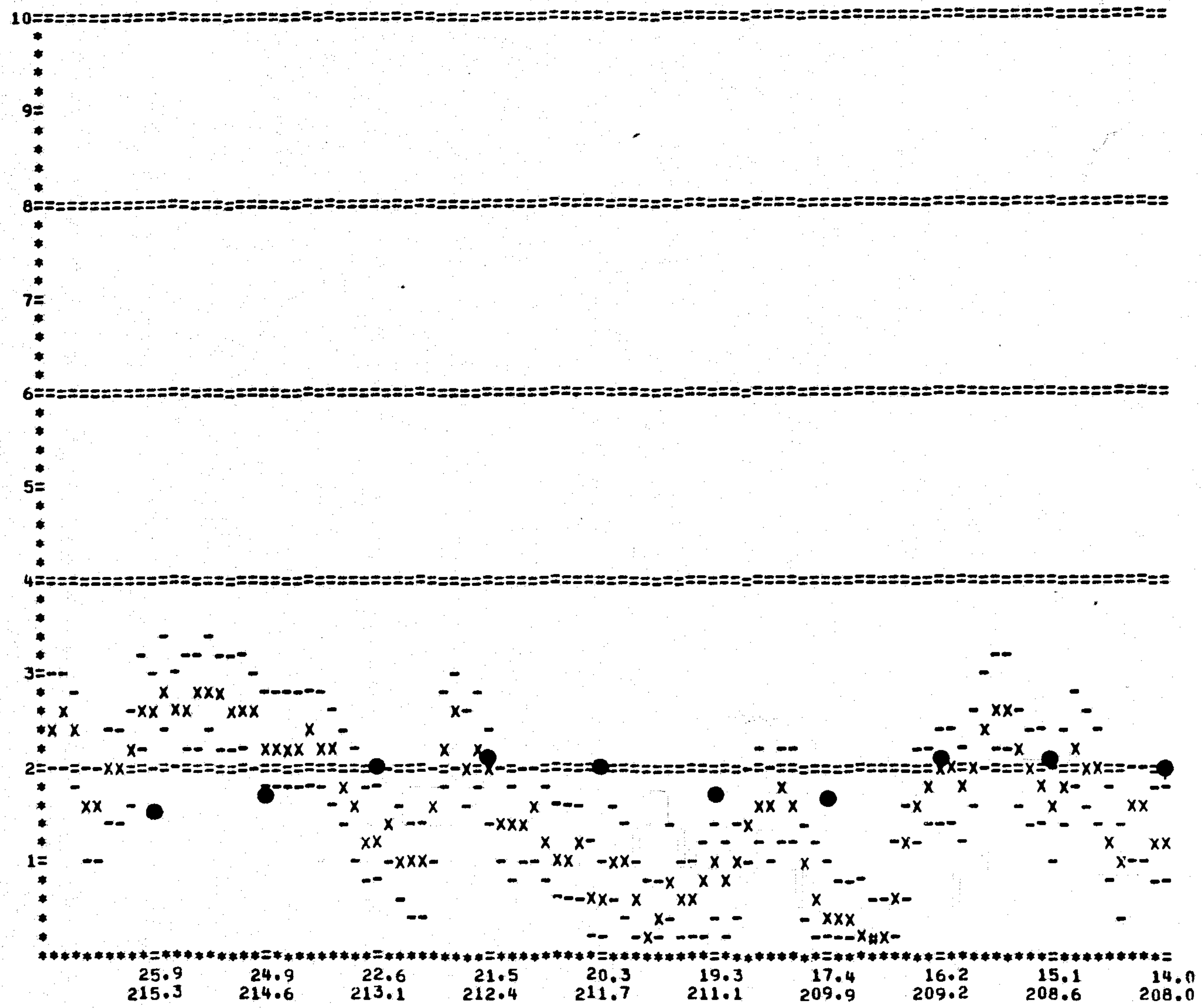
```
      ORBIT        1991  UNIQUE #        306  DATE          8/           28/          75
STARTING LAT  47.240000     LON  234.14000     TIME        17:           29
  ENDING LAT -8888.0000     LON -8888.0000     TIME        17:           56
```



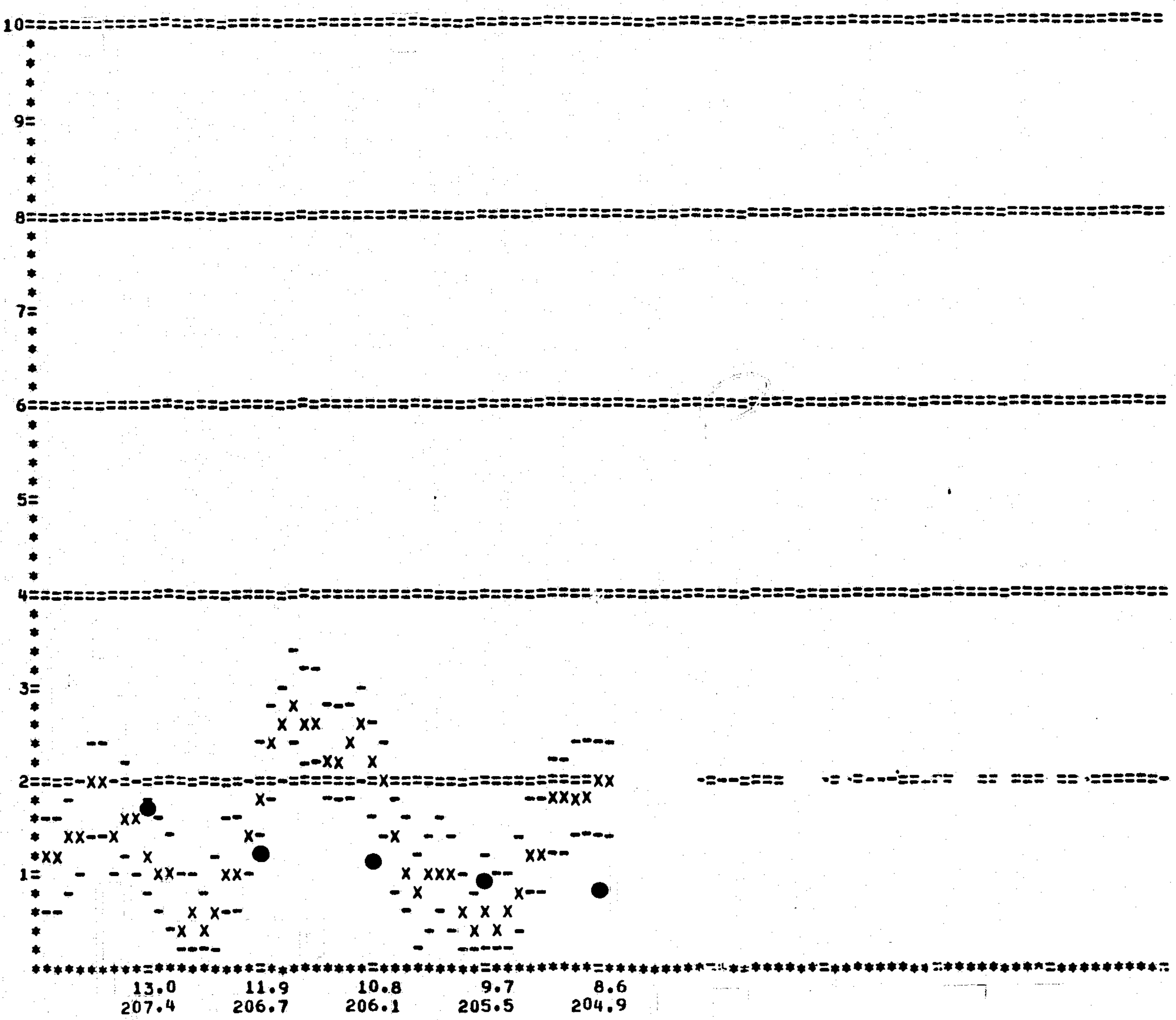
ORBIT 1991 UNIQUE # 306 DATE 8/ 28/ 75
STARTING LAT 47.240000 LON 234.14000 TIME 17: 29
ENDING LAT -8888.0000 LON -8888.0000 TIME 17: 56



ORBIT 1991 UNIQUE # 306 DATE 8/ 28/ 75
STARTING LAT 47.240000 LON 234.14000 TIME 17: 29
ENDING LAT -8888.0000 LON -8888.0000 TIME 17: 56



```
      ORBIT          1991  UNIQUE #          306  DATE            8/           28/          75
STARTING LAT  47.240000       LON  234.14000      TIME           17:           29
  ENDING LAT -8888.0000       LON -8888.0000      TIME           17:           56
```



ORBIT 2100 SEPT. 5, 1975 11:11 TO 11:35

(Partly Southern Hemisphere)

NORTHBOUND PACIFIC

CELEBES SEA, SULU ARCHIPELAGO, SULU SEA, 15.6° N, 118.7° E

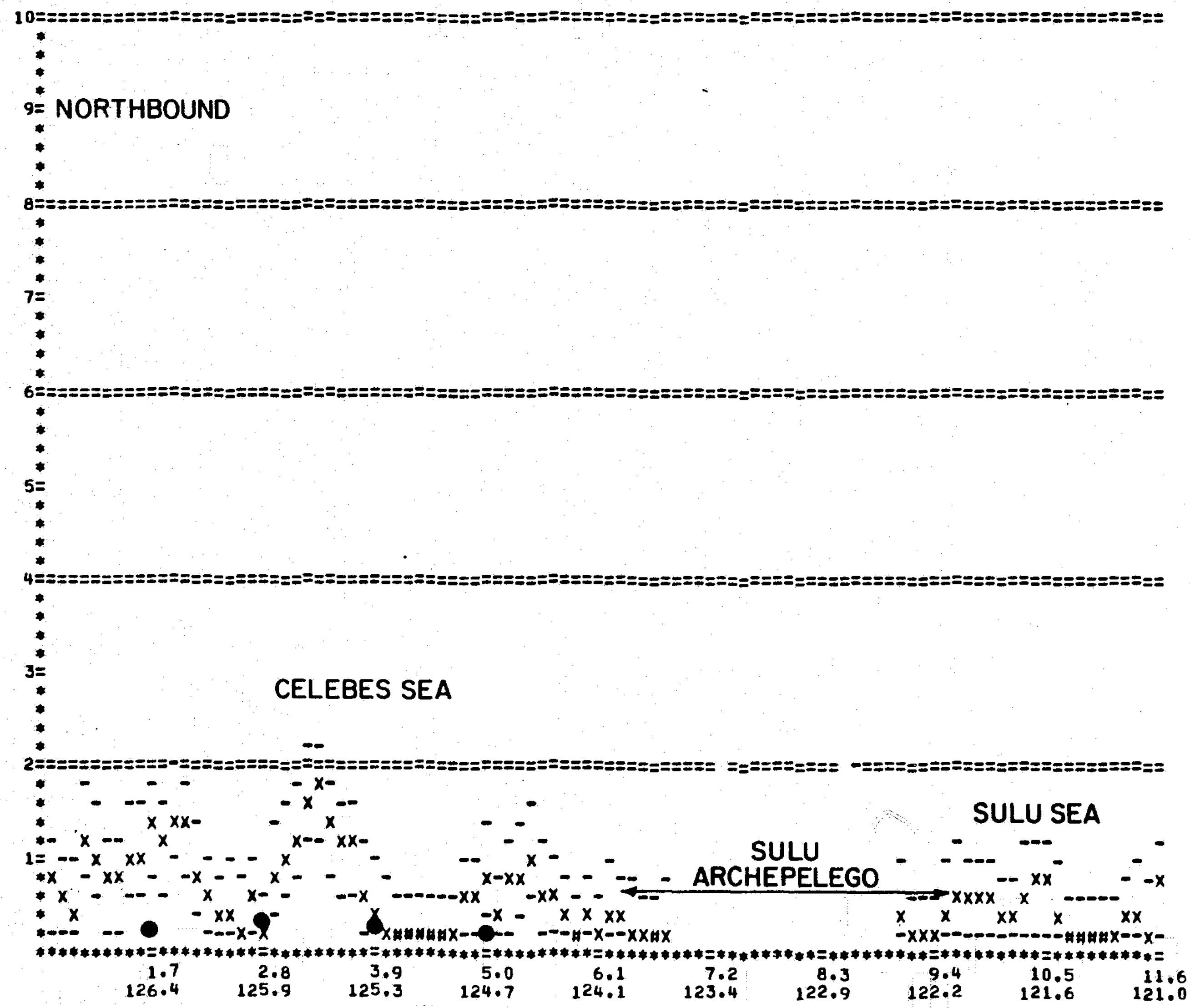
7 POINTS RMS 0.5 M BIAS - 0.3 M

LAT	SOWM	GEOS	S - G
2	0.2	1.4	- 1.2
3	0.3	0.2	+ 0.1
4	0.2	0.4	- 0.2
5	0.2	0.8	- 0.6
14	0.4	0.6	- 0.2
15	0.3	0.2	+ 0.1
16	0.3	0.2	+ 0.1

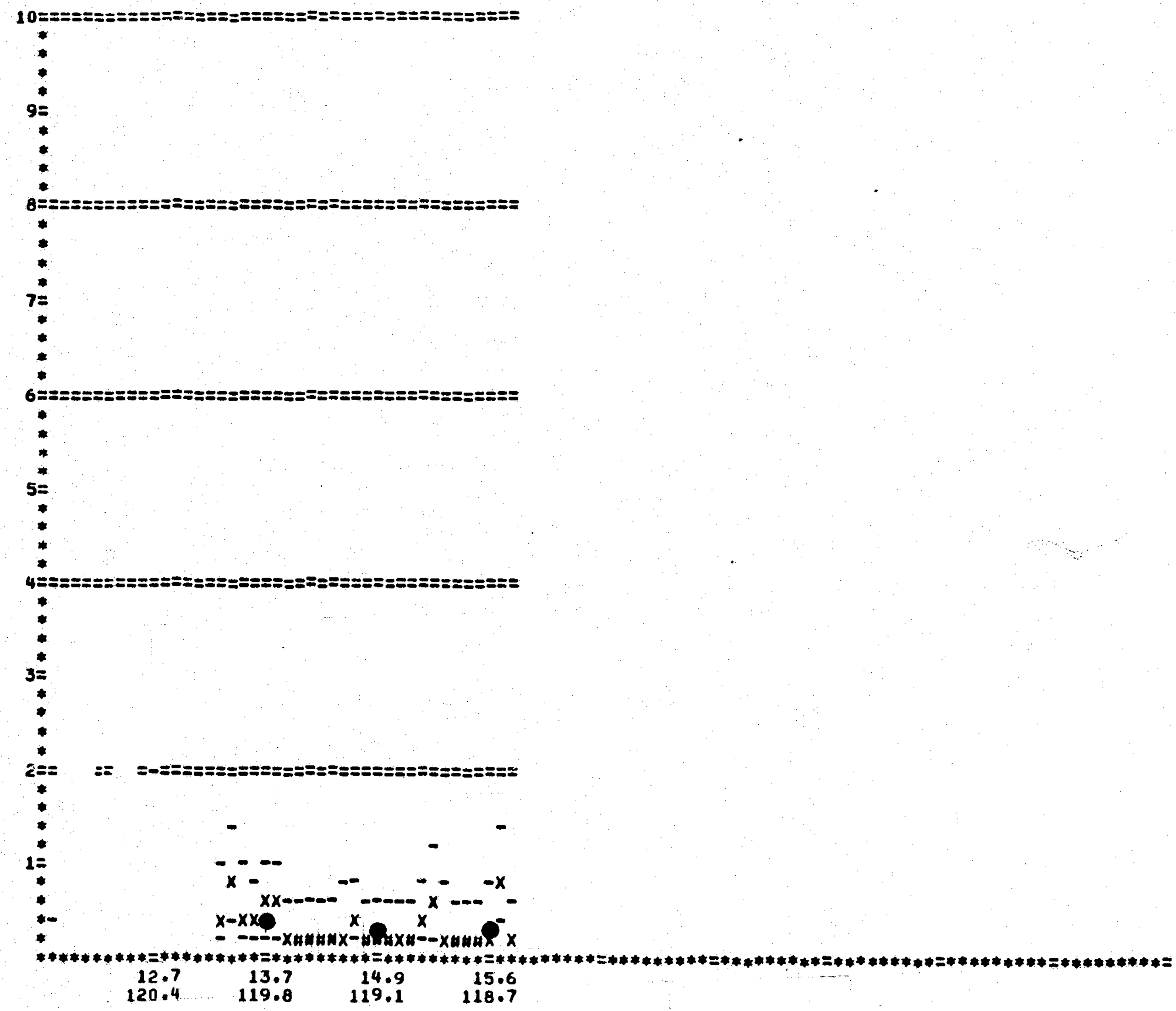
HIGHEST SOWM IN FIELD 0.9 M
HIGHEST GEOS 1.8 M

Demonstrates need for more detailed models near islands and in island shadow regions.

ORBIT 2100 UNIQUE # 386 DATE 9/ 5/ 75
STARTING LAT -55.680000 LON 174.72000 TIME 11: 11
ENDING LAT 15.720000 LON 15.720000 TIME 11: 35



ORBIT 2100 UNIQUE # 386 DATE 9/ 5/ 75
STARTING LAT -55.680000 LON 174.72000 TIME 11: 11
ENDING LAT 15.720000 LON 15.720000 TIME 11: 35



ORBIT 2114 SEPT. 6, 1975 10:54 TO 11:22

(PARTLY SOUTHERN HEMISPHERE)

NORTHBOUND PACIFIC

EQUATOR AT 133° E, EAST OF PHILIPPINES, SOUTHWEST OF TAIWAN

20 POINTS RMS 1.3 M BIAS - 1.0 M

HIGHEST SOWM; ON TRACK 1.0 M; IN FIELD 1.0 M

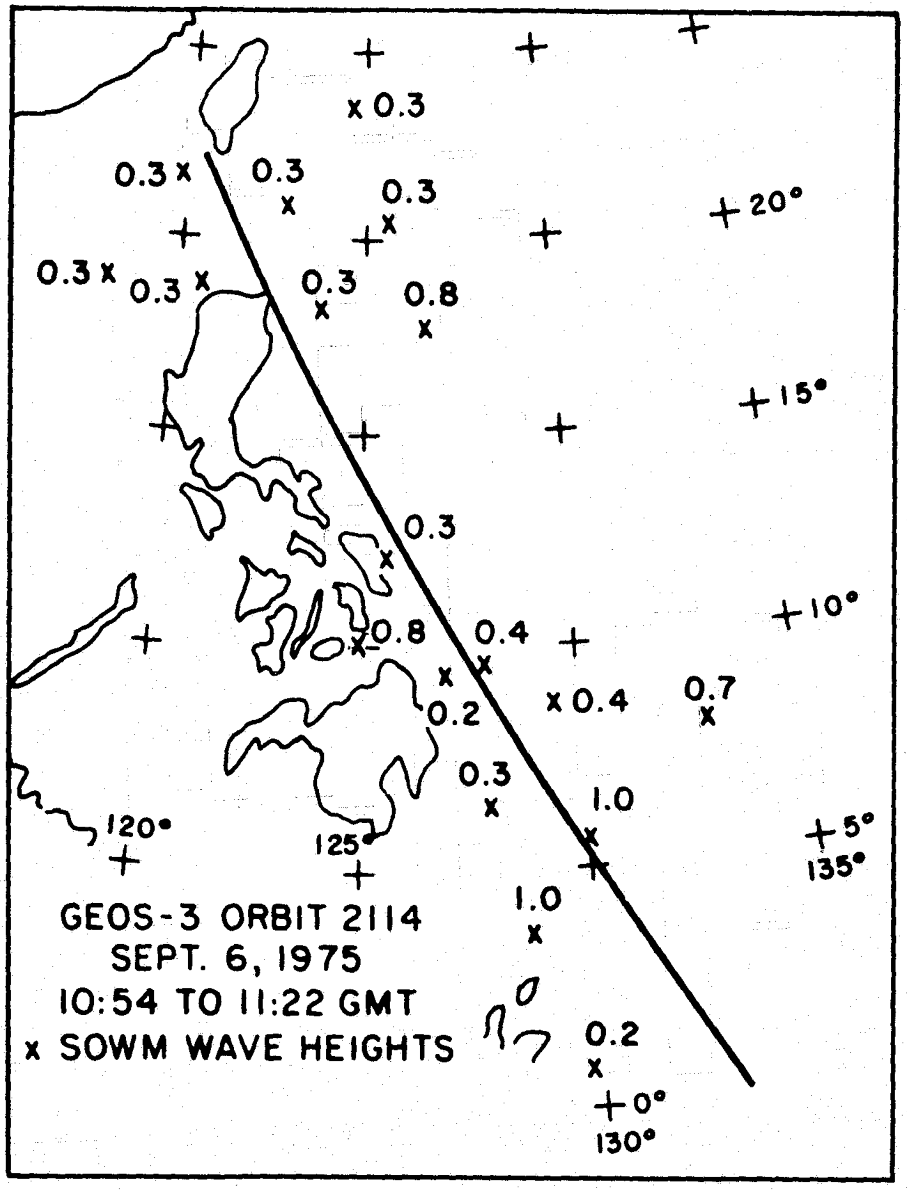
HIGHEST GEOS; ON GRID 3.6 M; AT ONE POINT 3.8 M

LOWEST SOWM; ON TRACK 0.2 M; IN FIELD 0.2 M

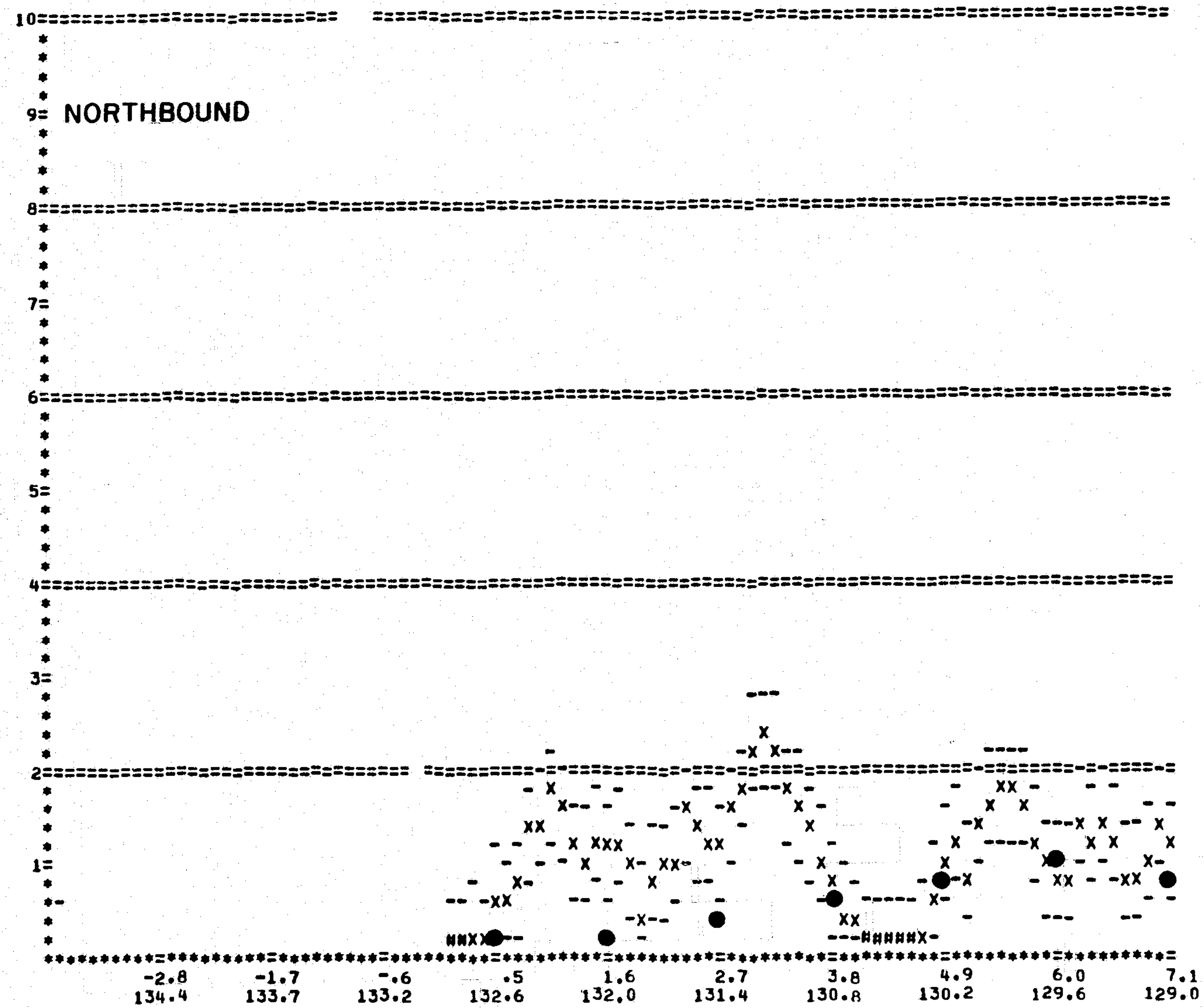
LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 3.2 M; SOWM 0.4 M, GEOS 3.6 M

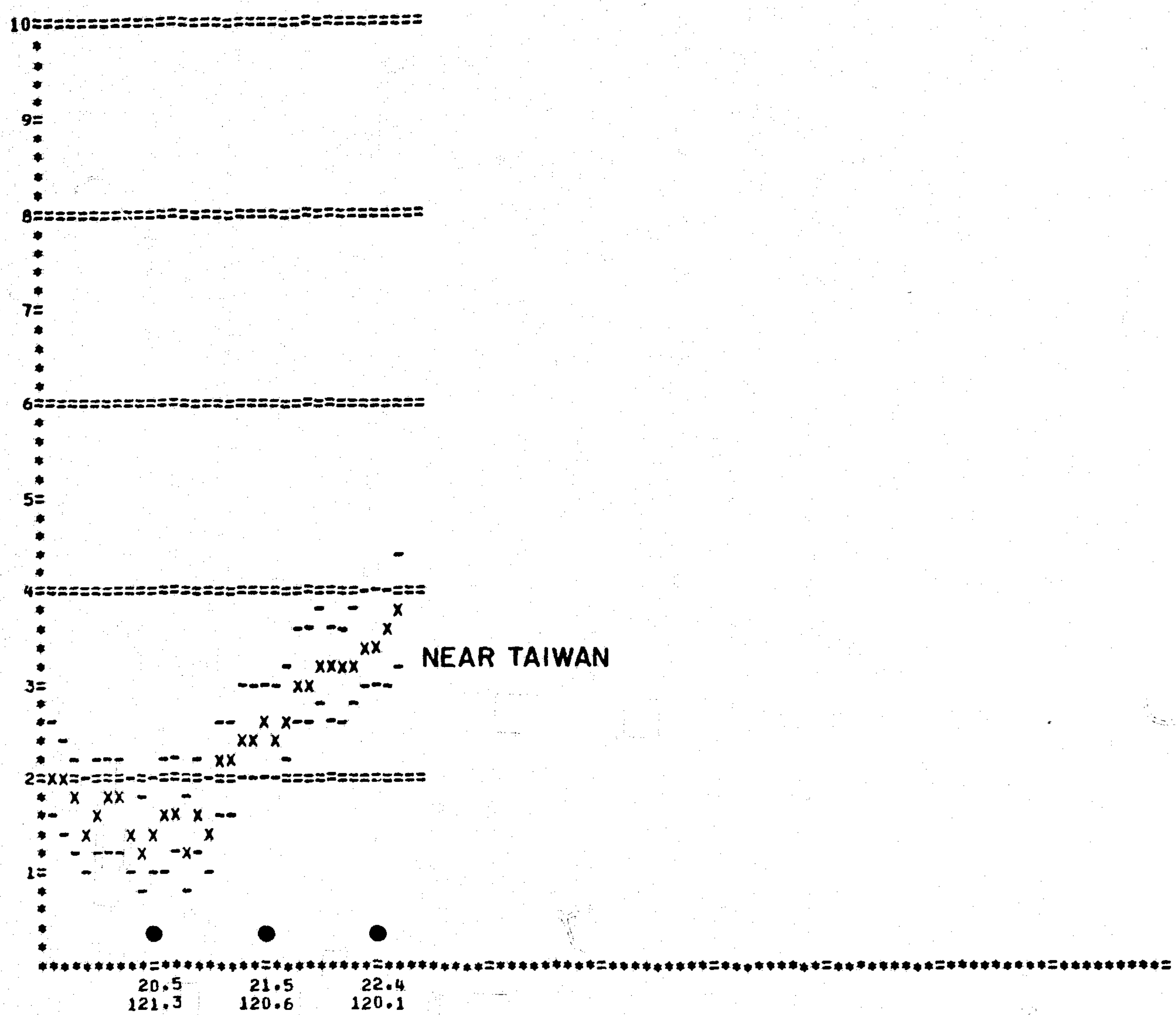
SOWM nearly everywhere too low. Consistent errors of 1, 2 and 3 meters north of 10° N. Winds of 8 to 11 m/s needed to explain waves.


x 0.3
0.3 x
0.3
0.3
20°
0.3 x
0.3
0.3
0.8
15°
0.3
10°
0.8
0.4
x 0.4
0.7
0.2
0.3
1.0
120°
125°
5°
135°
1.0
GEOS-3 ORBIT 2114
SEPT. 6, 1975
10:54 TO 11:22 GMT
x SOWM WAVE HEIGHTS
0.2
0°
130°

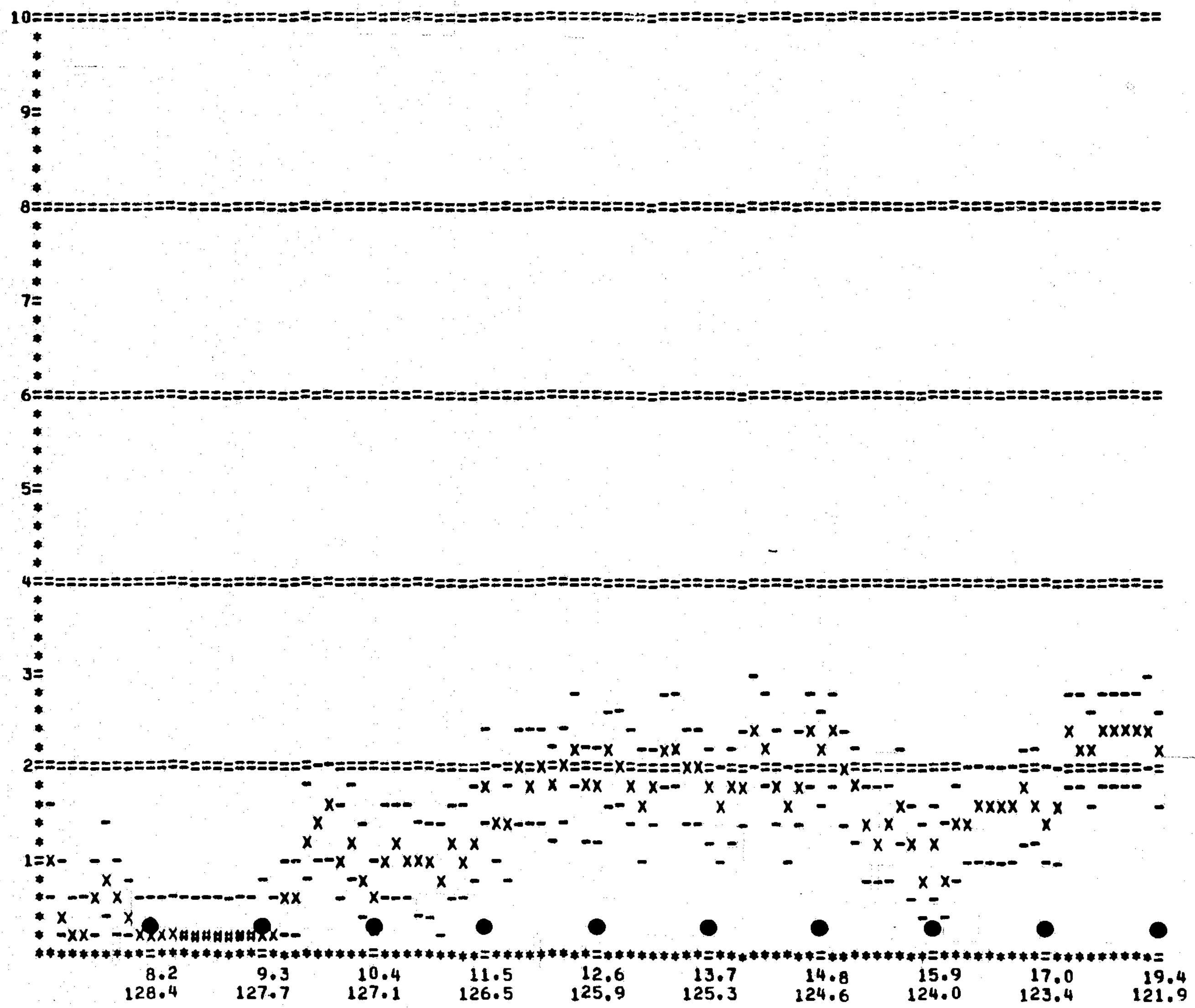
ORBIT 2114 UNIQUE # 395 DATE 9/ 6/ 75
STARTING LAT -60.730000 LON 193.83000 TIME 10: 54
ENDING LAT 22.610000 LON 22.610000 TIME 11: 22



ORBIT 2114 UNIQUE # 395 DATE 9/ 6/ 75
STARTING LAT -60.730000 LON 193.83000 TIME 10: 54
ENDING LAT 22.610000 LON 22.610000 TIME 11: 22



ORBIT 2114 UNIQUE # 395 DATE 9/ 6/ 75
STARTING LAT -60.730000 LON 193.83000 TIME 10: 54
ENDING LAT 22.610000 LON 22.610000 TIME 11: 22



ORBIT 2254 SEPT. 16, 1975 8:34 TO 9:03

NORTHBOUND PACIFIC

EQUATOR AT 187° E TO SEA OF OKHOTSK

30 POINTS RMS 1.10 M BIAS - 0.8 M

HIGHEST SOWM; ON TRACK 2.0 M; IN FIELD 2.4 M

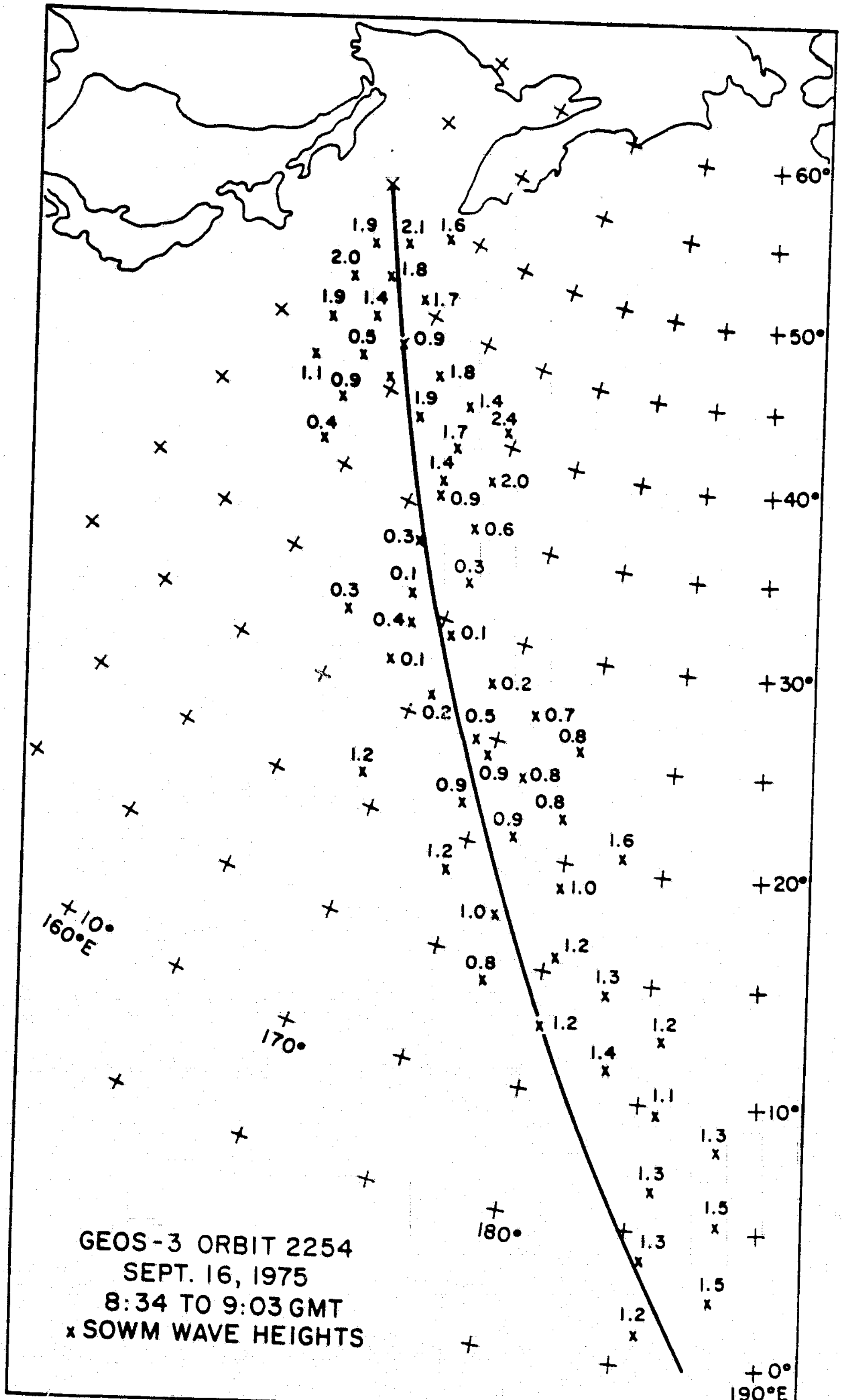
HIGHEST GEOS; ON GRID 4.2 M; AT ONE POINT 4.2 M

LOWEST SOWM; ON TRACK 0.1 M; IN FIELD 0.1 M

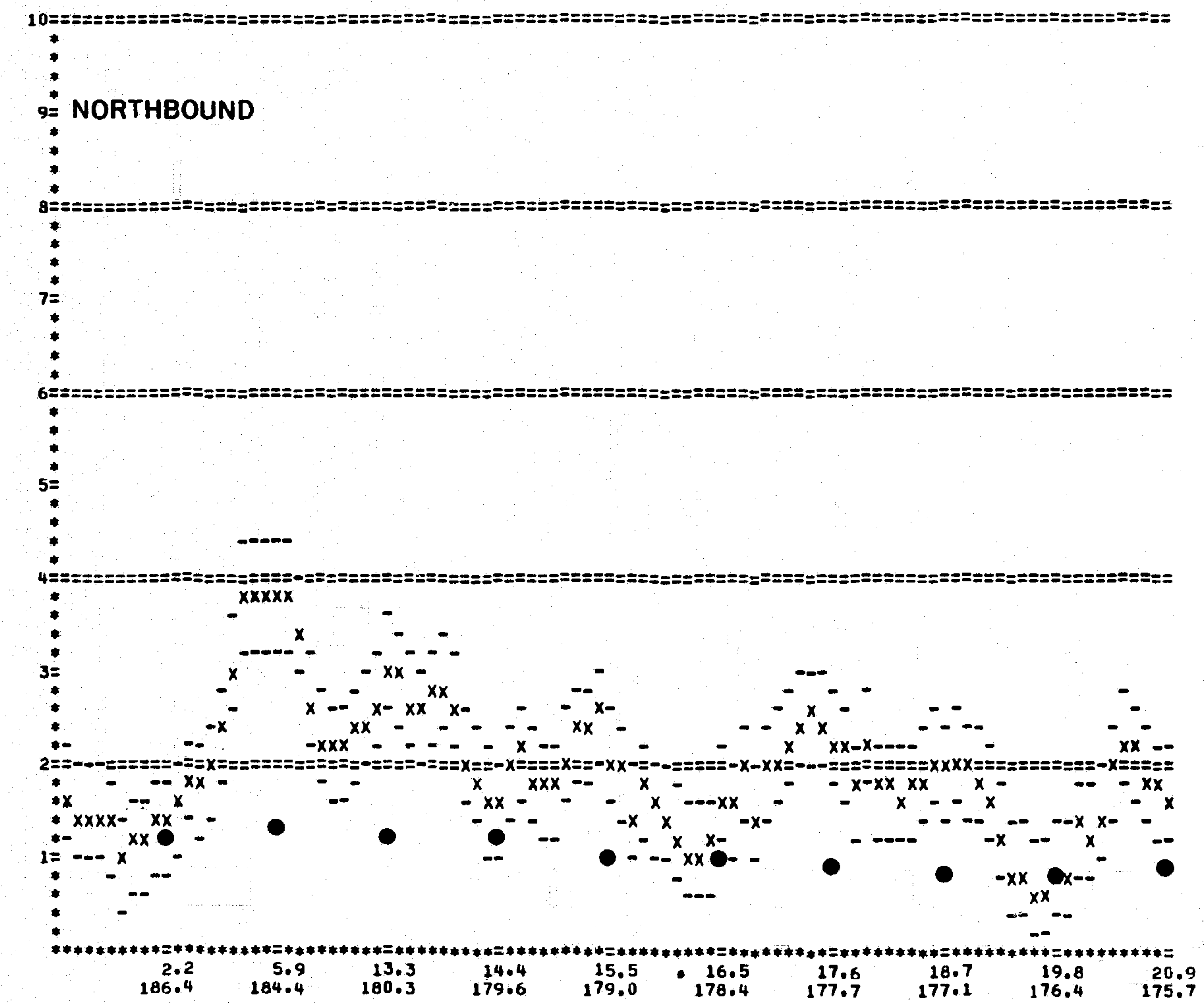
LOWEST GEOS; ON GRID 0.6 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 2.6 M; SOWM 1.6 M, GEOS 4.2 M

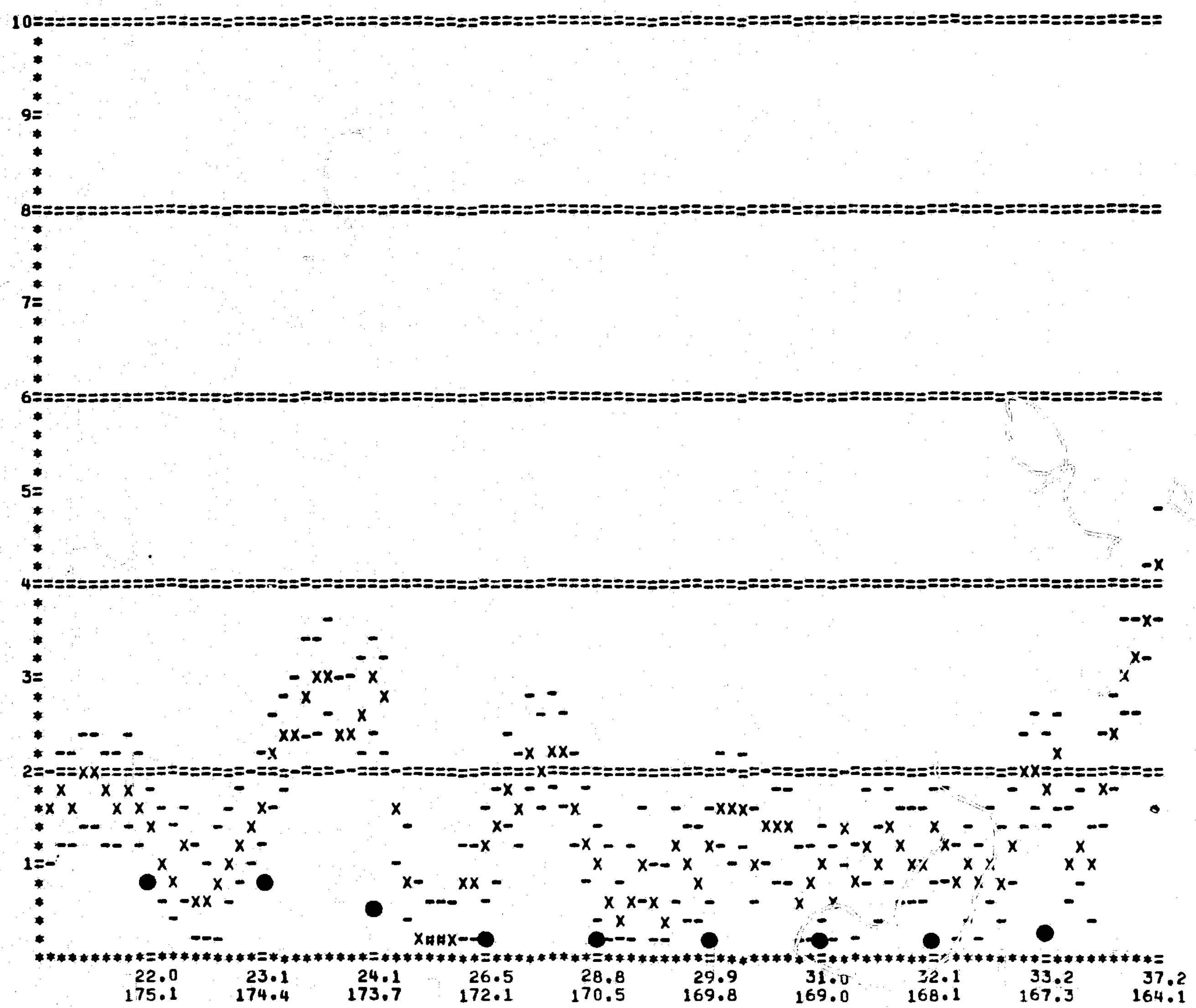
SOWM a bust, everywhere too low except at three points. Winds of 12 to 13 m/s needed instead of 8 to 10 m/s.


GEOS-3 ORBIT 2254
SEPT. 16, 1975
8:34 TO 9:03 GMT
x SOWM WAVE HEIGHTS
+60°
+50°
+40°
+30°
+20°
+10°
+0°
10°
160°E
170°
180°
190°E

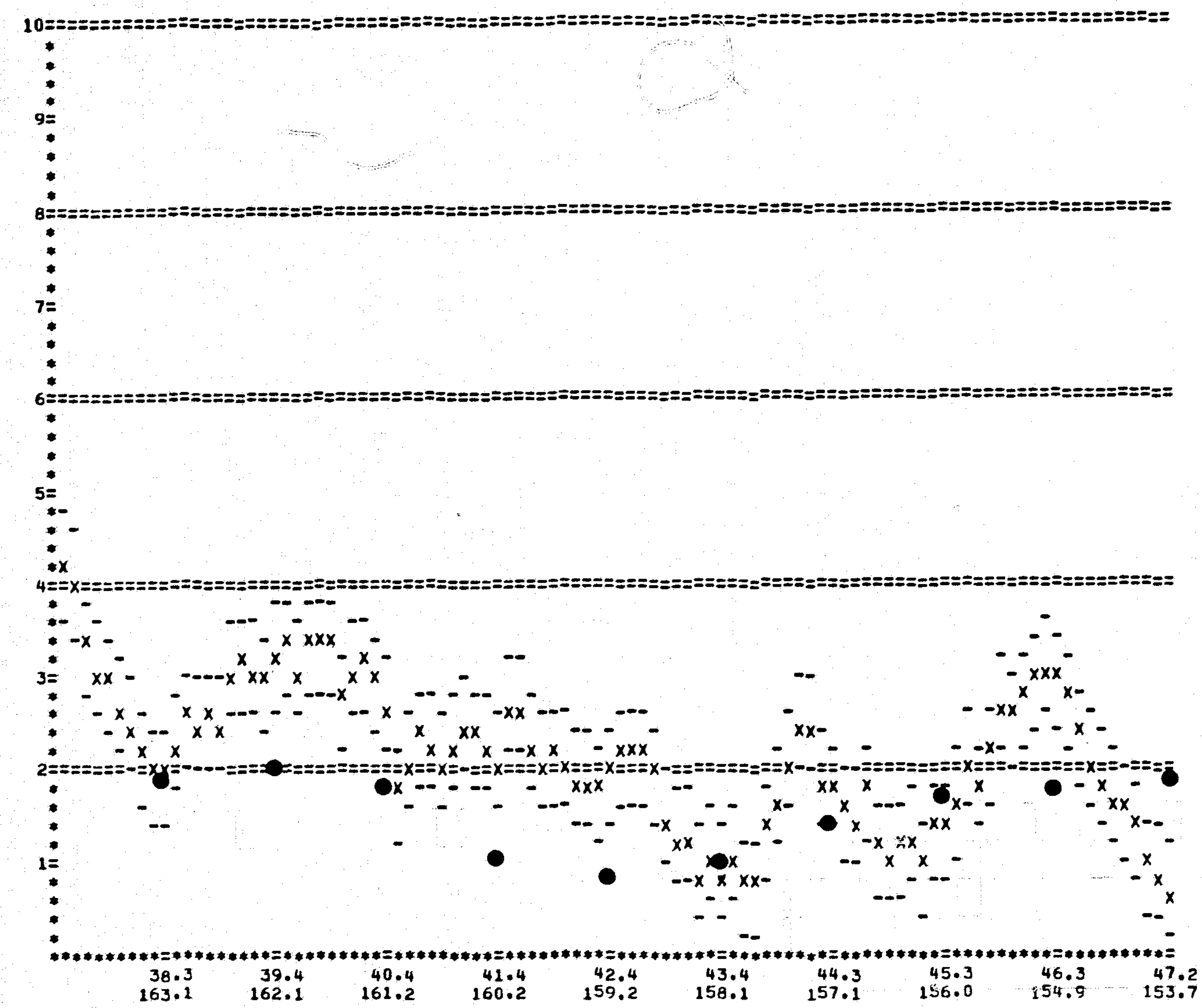
ORBIT 2254 UNIQUE # 493 DATE 9/ 16/ 75
STARTING LAT -33.080000 LON 207.73000 TIME 8: 34
ENDING LAT -8888.0000 LON -8888.0000 TIME 9: 3



ORBIT 2254 UNIQUE # 493 DATE 9/ 16/ 75
STARTING LAT -33.080000 LON 207.73000 TIME 8: 34
ENDING LAT -8888.0000 LON -8888.0000 TIME 9: 3



ORBIT 2254 UNIQUE # 493 DATE 9/ 16/ 75
STARTING LAT -33.080000 LON 207.73000 TIME 8: 34
ENDING LAT -8888.0000 LON -8888.0000 TIME 9: 3



ORBIT 2318 SEPT. 20, 1975 20:12

(Most of the data were in Southern Hemisphere)

SOUTHBOUND PACIFIC

NEAR SEATTLE TO 37.9° N, 223.6° W

10 POINTS RMS 0.6 M BIAS 0 M

HIGHEST SOWM; ON TRACK 1.0 M; IN FIELD 1.2 M

HIGHEST GEOS; ON GRID 2.2 M; AT ONE POINT 3.0 M

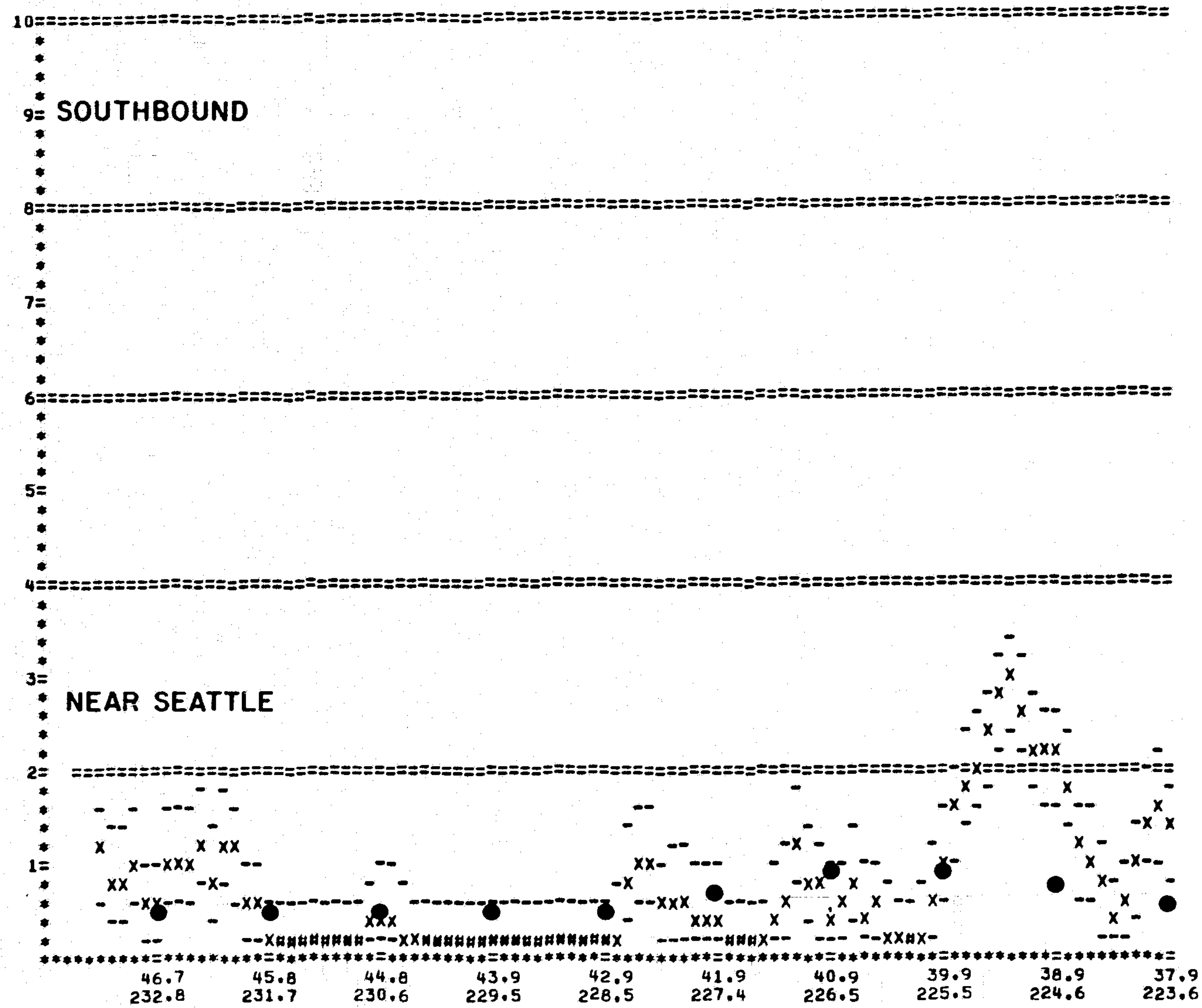
LOWEST SOWM; ON TRACK 0.5 M; IN FIELD 0.5 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M

LARGEST ERROR - 1.3 M; SOWM 0.9 M, GEOS 2.2 M

GEOS waves highly variable, stretches of low waves 0.2 m or less and a few degrees of high waves up to 3 m. Height field would be hard to describe with present resolution of the SOWM.

ORBIT 2318 UNIQUE # 549 DATE 9/ 20/ 75
STARTING LAT 47.600000 LON 233.89000 TIME 20: 12
ENDING LAT -60.250000 LON -60.250000 TIME 20: 49



56

ORBIT 2658 NOV. 14, 1975 20:41 TO 20:51

WESTBOUND ATLANTIC

SOUTHERN TIP OF NORWAY TO ICELAND TO GREENLAND

9 POINTS NORWAY TO ICELAND RMS 0.8 M BIAS - 0.5 M

6 POINTS ICELAND TO GREENLAND RMS 3.1 M BIAS - 2.8 M

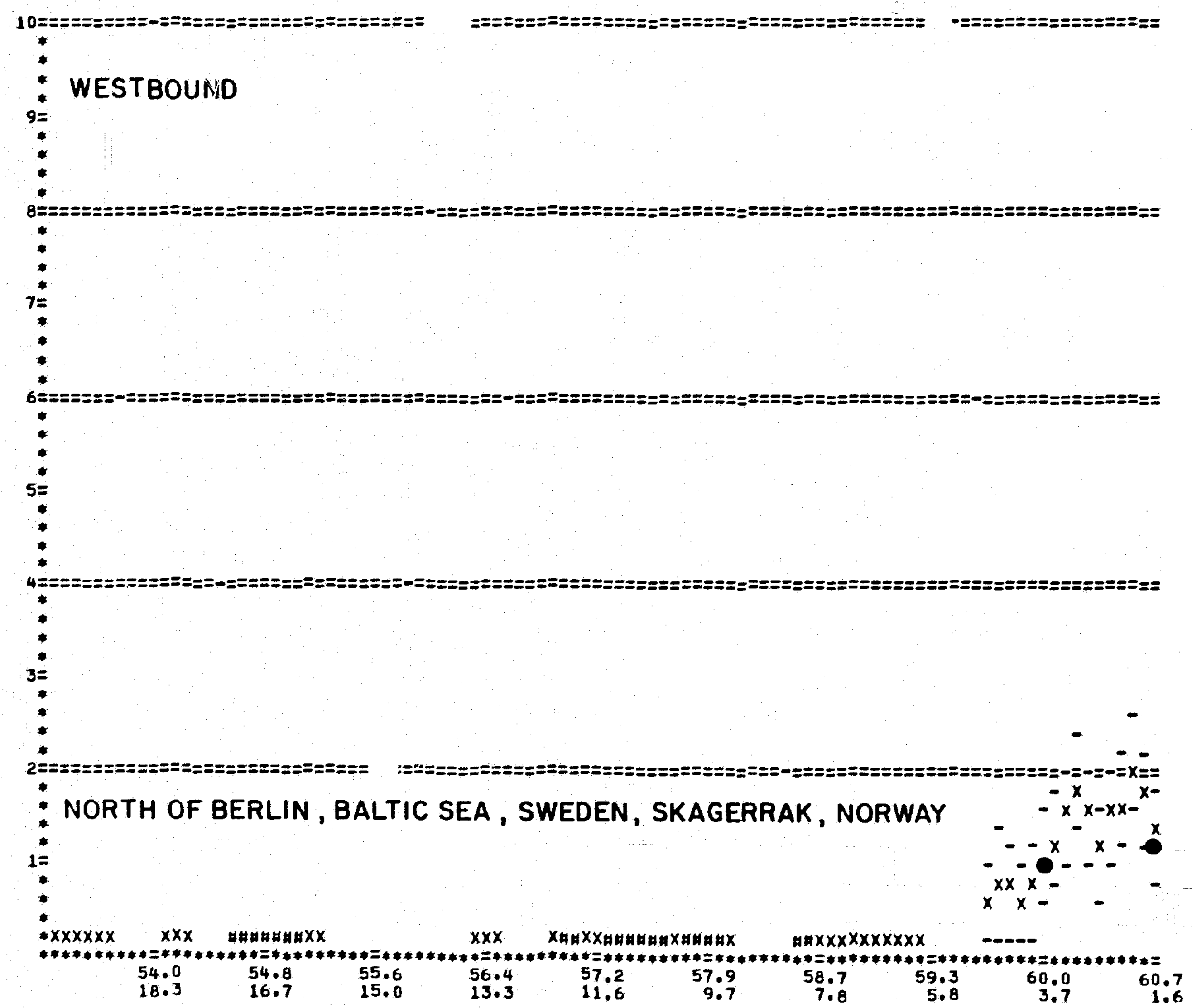
NORWAY TO ICELAND				ICELAND TO GREENLAND			
LONG	SOWM	GEOS	S - G	LONG	SOWM	GEOS	S - G
4°	1.0	1.0	0	336°	2.0	3.8	- 1.8
2°	1.2	1.4	- 0.2	333°	2.8	6.6	- 3.8
-	1.3	1.0	+ 0.3	330°	2.9	7.6	- 4.7
357°	1.7	2.4	- 0.7	327°	2.8	6.2	- 3.4
355°	1.9	2.2	- 0.3	324°	2.6	3.6	- 1.0
352°	2.5	3.0	- 0.5	321°	1.0	3.0	- 2
350°	2.5	4.2	- 1.7				
347°	2.4	3.6	- 1.2				
344°	2.4	2.2	0				

HIGHEST SOWM IN FIELD 2.9 M

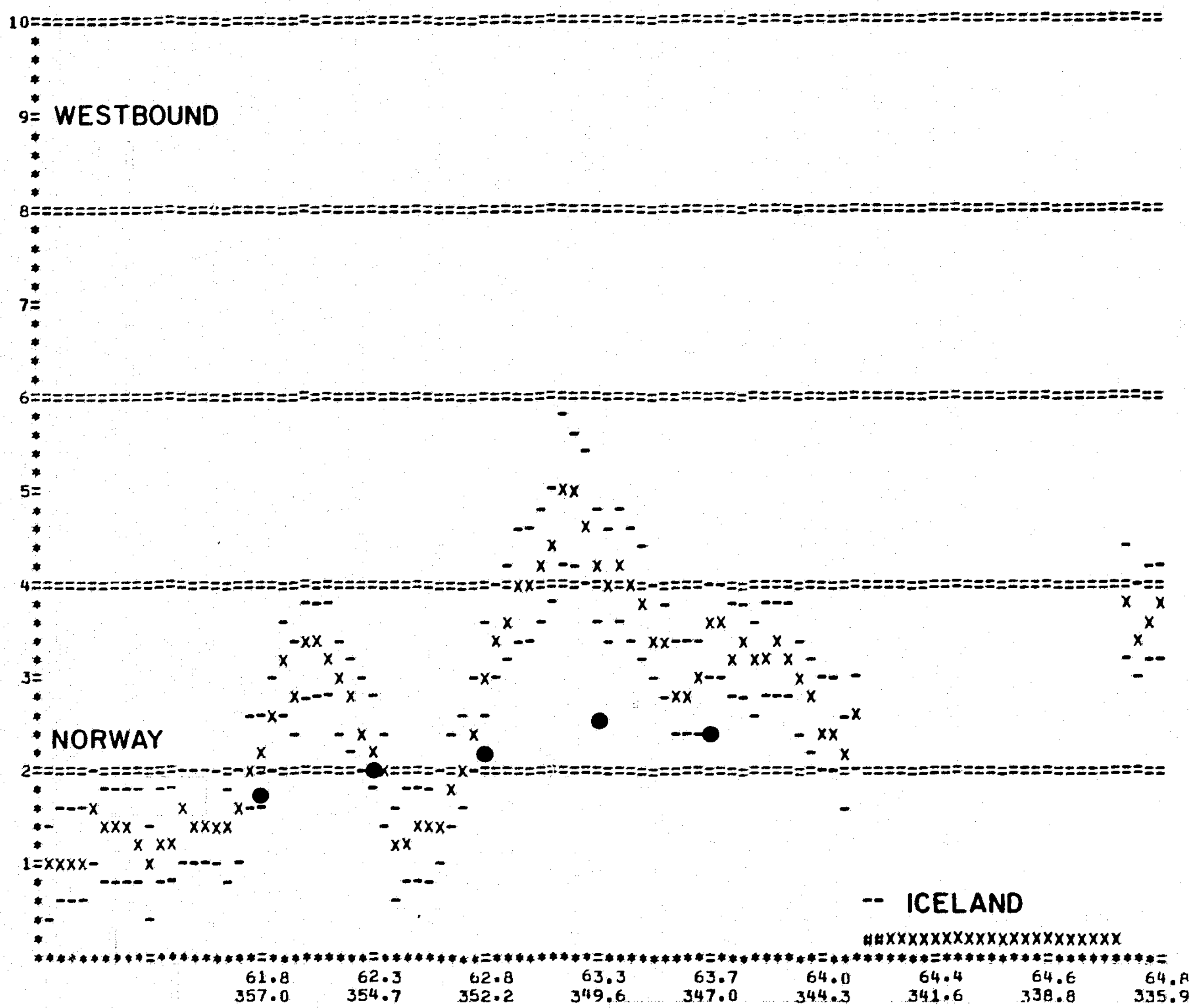
LOWEST SOWM IN FIELD 0.7 M

SOWM did not track oscillations in wave height between Norway and Iceland. General level was good. High GEOS waves between Iceland and Greenland may or may not be real because of sea ice. If they are real, wind field analysis must have been completely in error with winds of 18 m/s instead of 12 m/s in the area.

```
       ORBIT           2658  UNIQUE #          360  DATE           10/          14/          75
STARTING LAT  53.220000     LON  19.630000      TIME           20:          41
  ENDING LAT  64.440000     LON  64.440000      TIME           20:          51
```



```
      ORBIT          2658  UNIQUE #         360  DATE          10/          14/          75
STARTING LAT  53.220000     LON  19.630000     TIME          20:          41
  ENDING LAT  64.440000     LON  64.440000     TIME          20:          51
```



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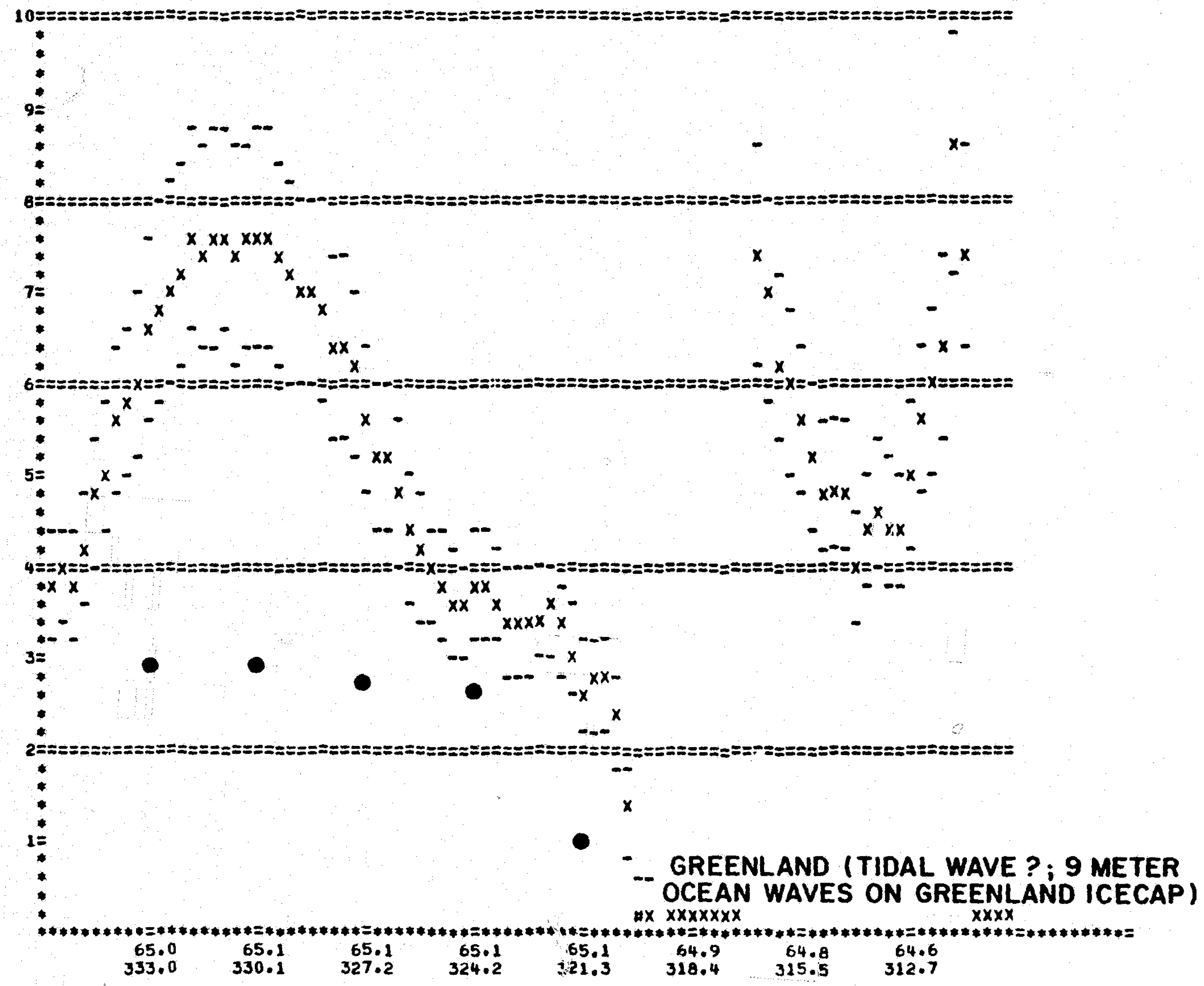
          ORBIT        2658  UNIQUE #          360  DATE          10/          14/          75
STARTING LAT  53.220000       LON  19.630000      TIME           20:          41
  ENDING LAT  64.440000       LON  64.440000      TIME           20:          51
```



ORBIT 2782 OCT. 23, 1975 15:24 TO 15:28

SOUTHBOUND ATLANTIC

SOUTHWEST CORNER OF SPAIN, APPROXIMATELY 150 KM OFF COAST OF NORTH AFRICA TO 25° N, 344° E

11 POINTS RMS 0.7 M BIAS - 0.1 M

HIGHEST SOWM; ON TRACK 2.2 M; IN FIELD 3.5 M

HIGHEST GEOS; ON GRID 3.2 M; AT ONE POINT 3.2 M

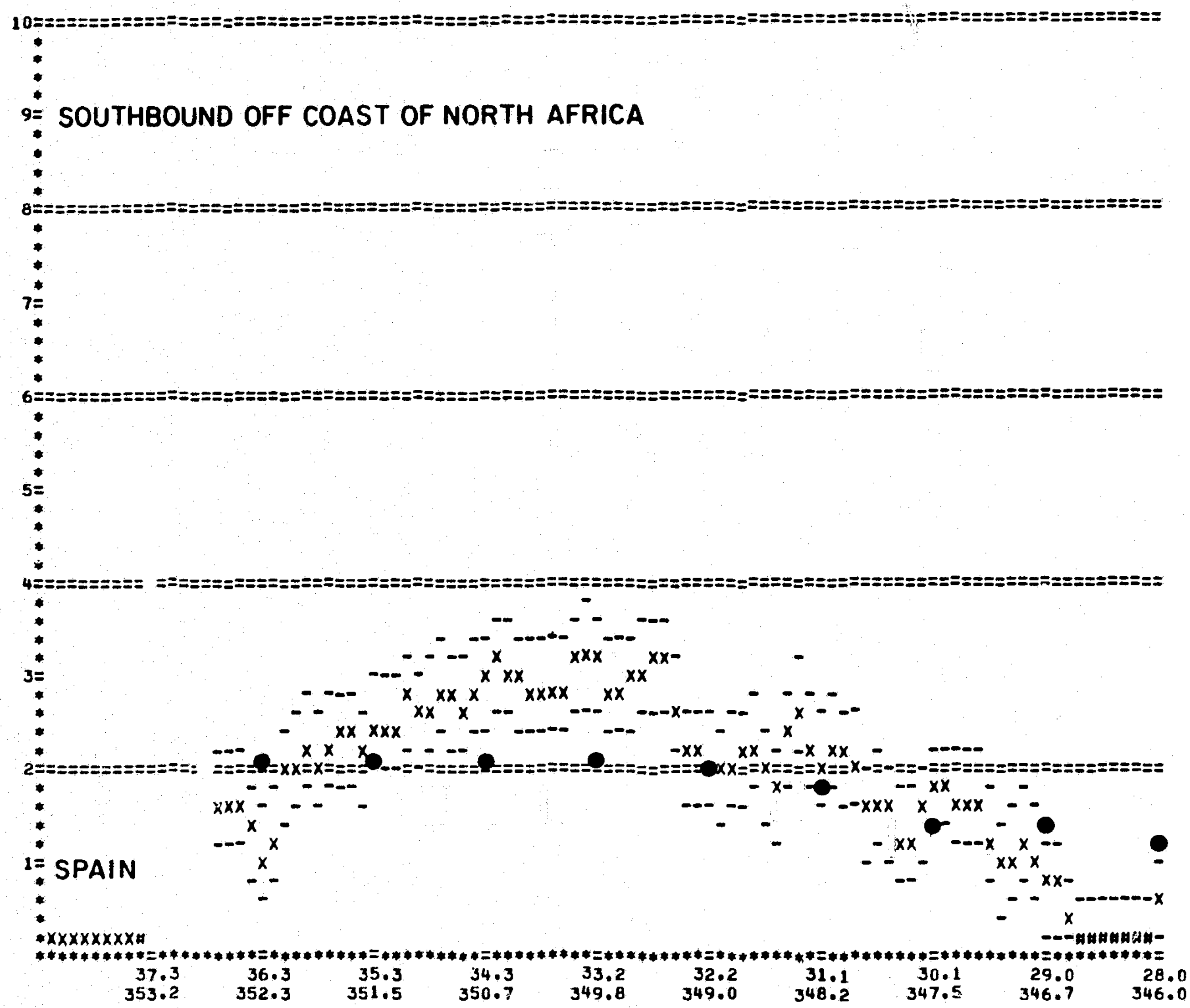
LOWEST SOWM; ON TRACK 1.3 M; IN FIELD 1.2 M

LOWEST GEOS; ON GRID 0.6 M; AT ONE POINT 0.2 M (O)

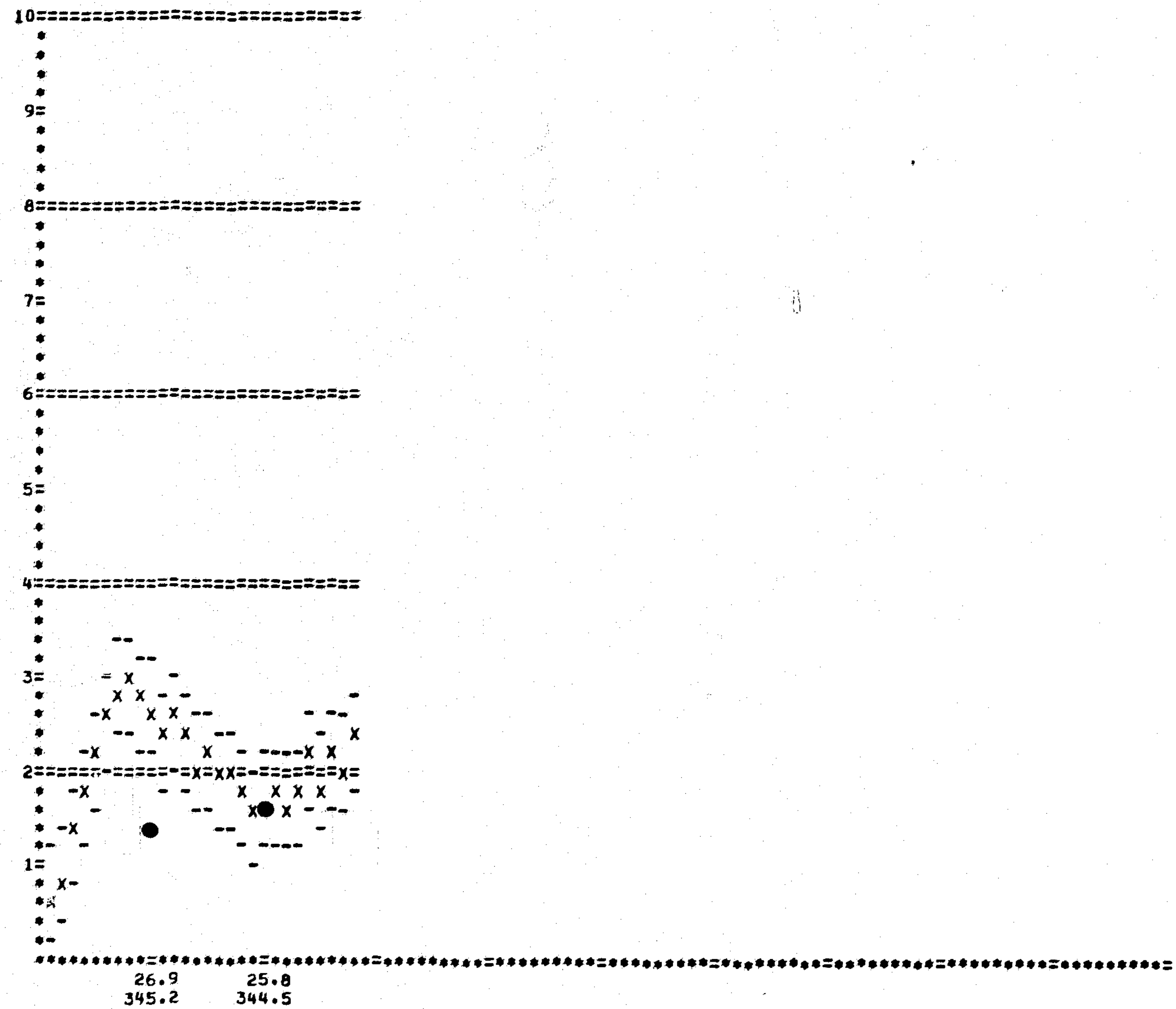
LARGEST ERROR - 1.2 M; SOWM 1.4 M, GEOS 2.6 M

SOWM waves vary less than GEOS; too low 36° N to 31° N, close 31° N to 29° N, too high 29° N to 28° N, too low 27° N. Winds of 12 m/s instead of 10 m/s would define high waves near 33° N.

```
     ORBIT          2782  UNIQUE #          455  DATE            10/          23/          75
STARTING LAT -8888.0000      LON -8888.0000      TIME            15:          24
  ENDING LAT  25.400000      LON  25.400000      TIME            15:          28
```



ORBIT 2782 UNIQUE # 455 DATE 10/ 23/ 75
STARTING LAT -8888.0000 LON -8888.0000 TIME 15: 24
ENDING LAT 25.400000 LON 25.400000 TIME 15: 28



ORBIT 2812 OCT. 25, 1975 18:05 TO 18:16

SOUTHBOUND ATLANTIC

NORWAY TO 43° N, 319° E

28 POINTS RMS 1.0 M BIAS - 0.8 M

HIGHEST SOWM; ON TRACK 4.8 M; IN FIELD 5.0 M

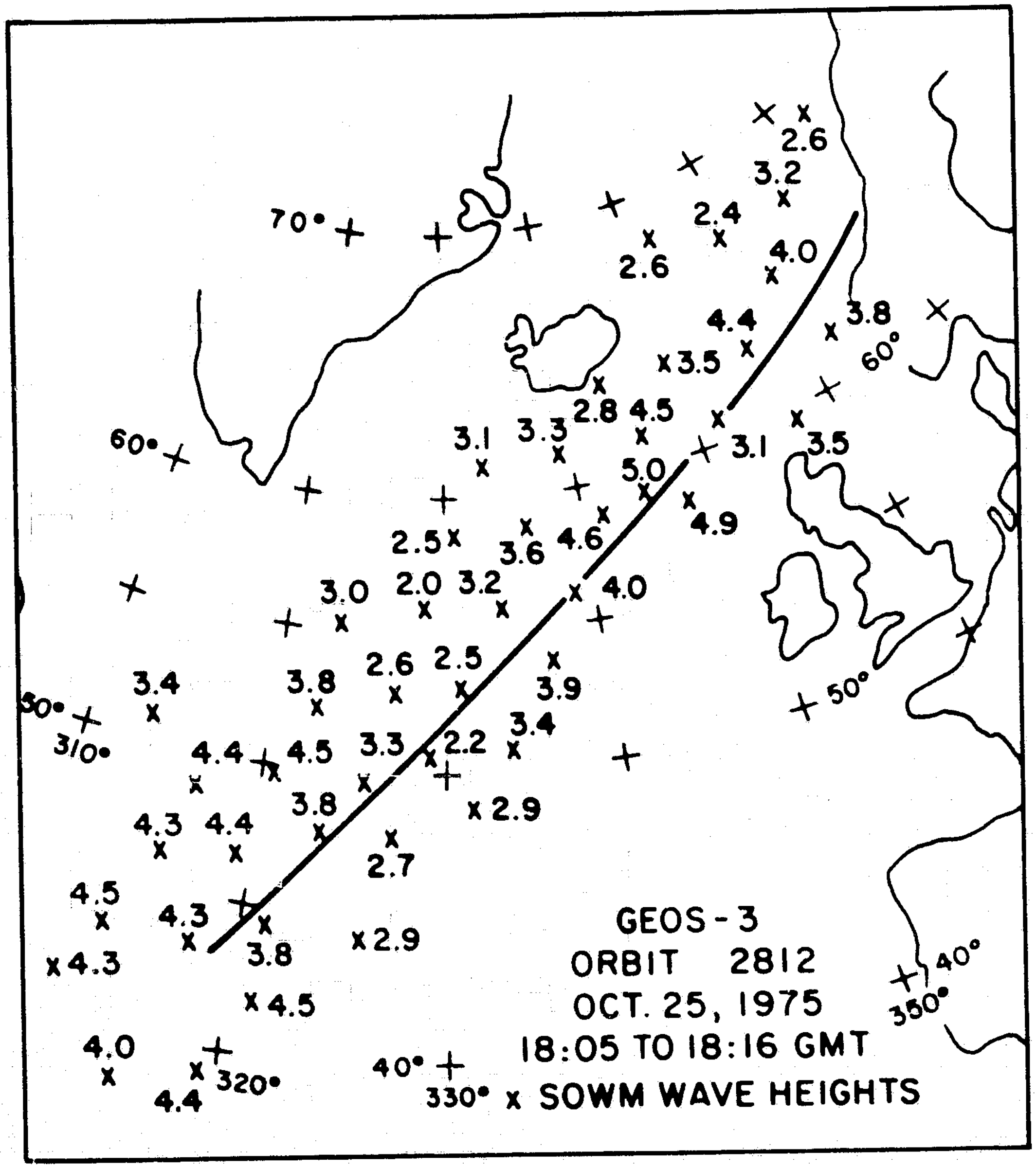
HIGHEST GEOS; ON GRID 5.8 M; AT ONE POINT 6.2 M

LOWEST SOWM; ON TRACK 2.3 M; IN FIELD 2.0 M

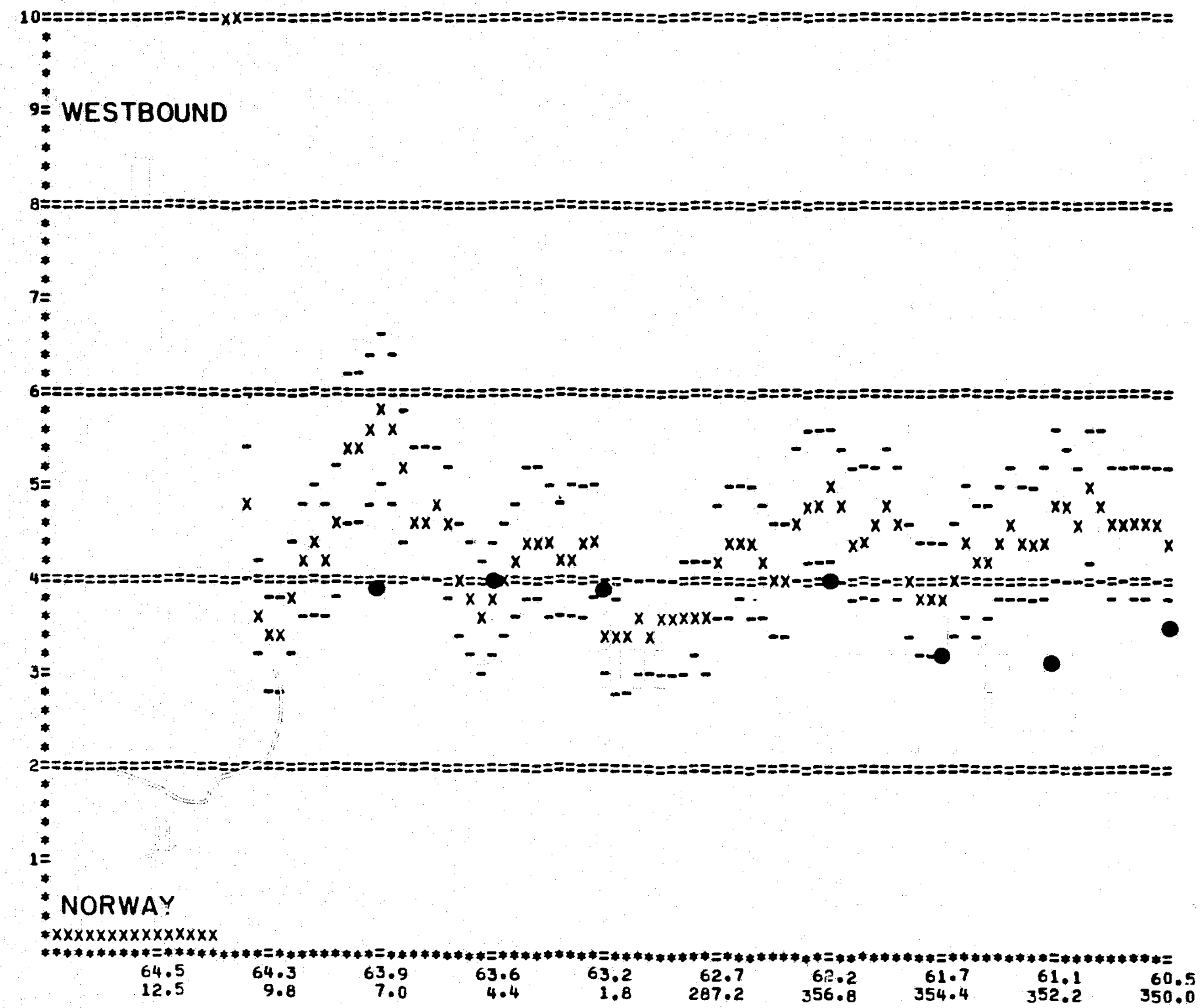
LOWEST GEOS; ON GRID 3.2 M; AT ONE POINT 2.6 M

LARGEST ERROR - 2.0 M; SOWM 3.8 M, GEOS 5.8 M

SOWM slightly low 65° N to 61° N, close 60° N to 54° N, and one to two meters too low 52° N to 44° N. Winds need to be about 17% stronger between 50° N and 44° N, increasing from 13.5 m/s to 16 m/s.


GEOS - 3
ORBIT 2812
OCT. 25, 1975
18:05 TO 18:16 GMT
x SOWM WAVE HEIGHTS

ORBIT 2812 UNIQUE # 470 DATE 10/ 25/ 75
STARTING LAT 64.730000 LON 15.100000 TIME 18: 5
ENDING LAT 42.940000 LON 42.940000 TIME 18: 16



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      ORBIT        2812  UNIQUE #          470  DATE            10/            25/            75
STARTING LAT  64.730000       LON  15.100000      TIME            18:             5
  ENDING LAT  42.940000       LON  42.940000      TIME            18:            16
```

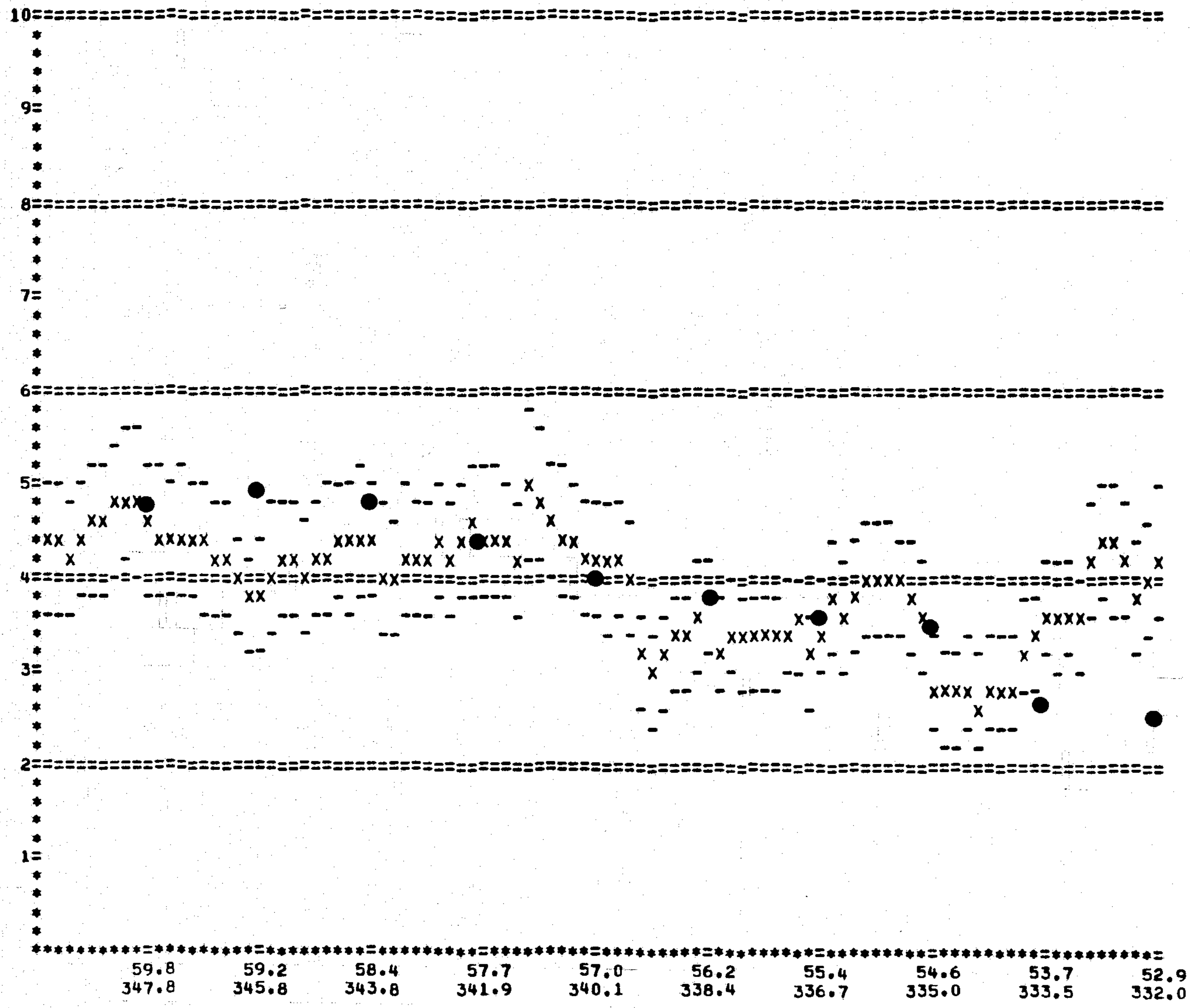

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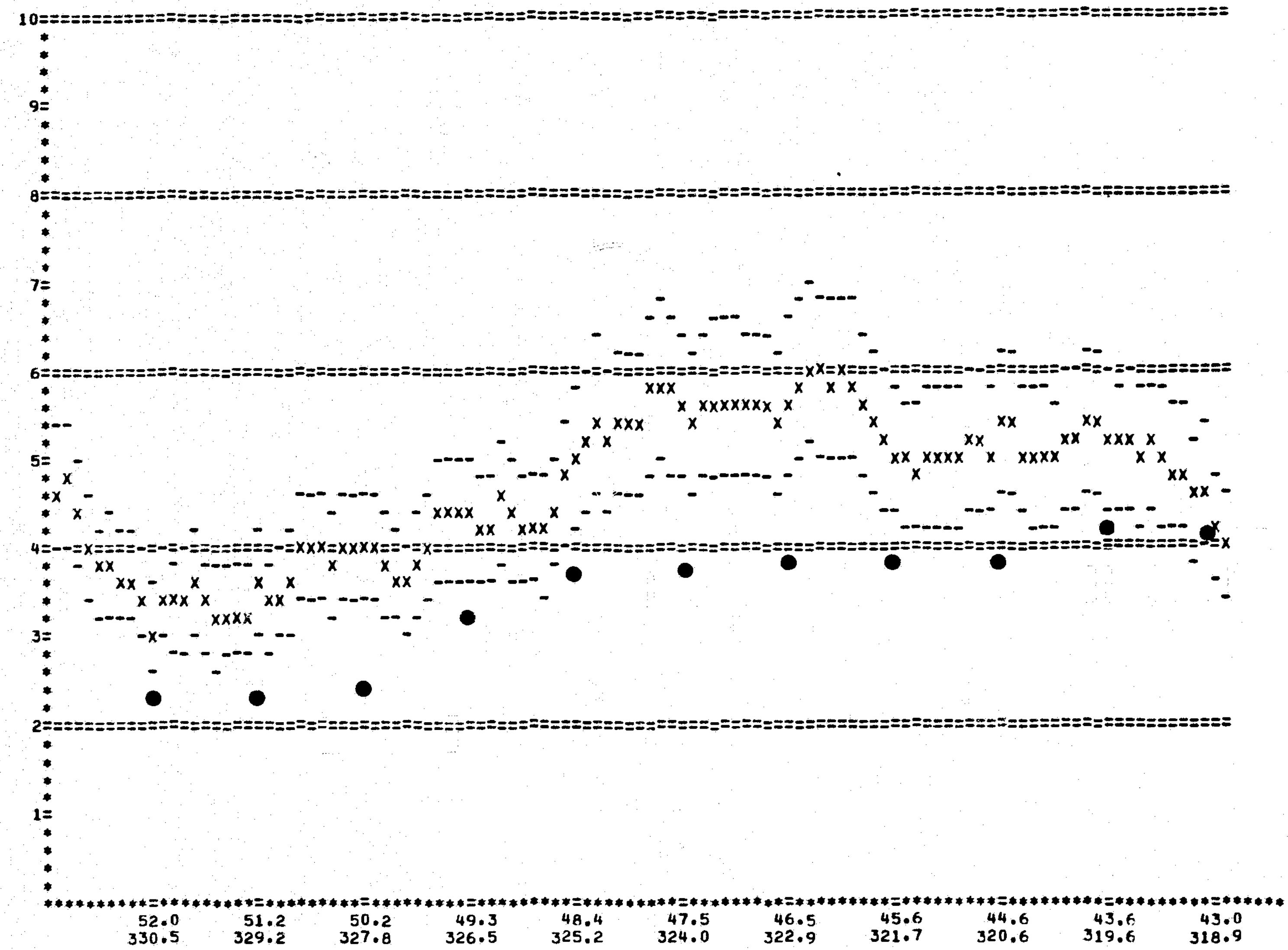
ORBIT 2812 UNIQUE # 470 DATE 10/ 25/ 75
STARTING LAT 64.730000 LON 15.100000 TIME 18: 5
ENDING LAT 42.940000 LON 42.940000 TIME 18: 16



ORBIT 2827 OCT. 26, 1975 19:30 TO 19:39

WESTBOUND ATLANTIC

NORWAY, SOUTH OF ICELAND ALMOST TO NEWFOUNDLAND AT 58° N, 324° E

26 POINTS RMS 1.1 M BIAS - 1.0 M

HIGHEST SOWM; ON TRACK 3.5 M; IN FIELD 6.9 M

HIGHEST GEOS; ON GRID 5.4 M; AT ONE POINT 5.4 M

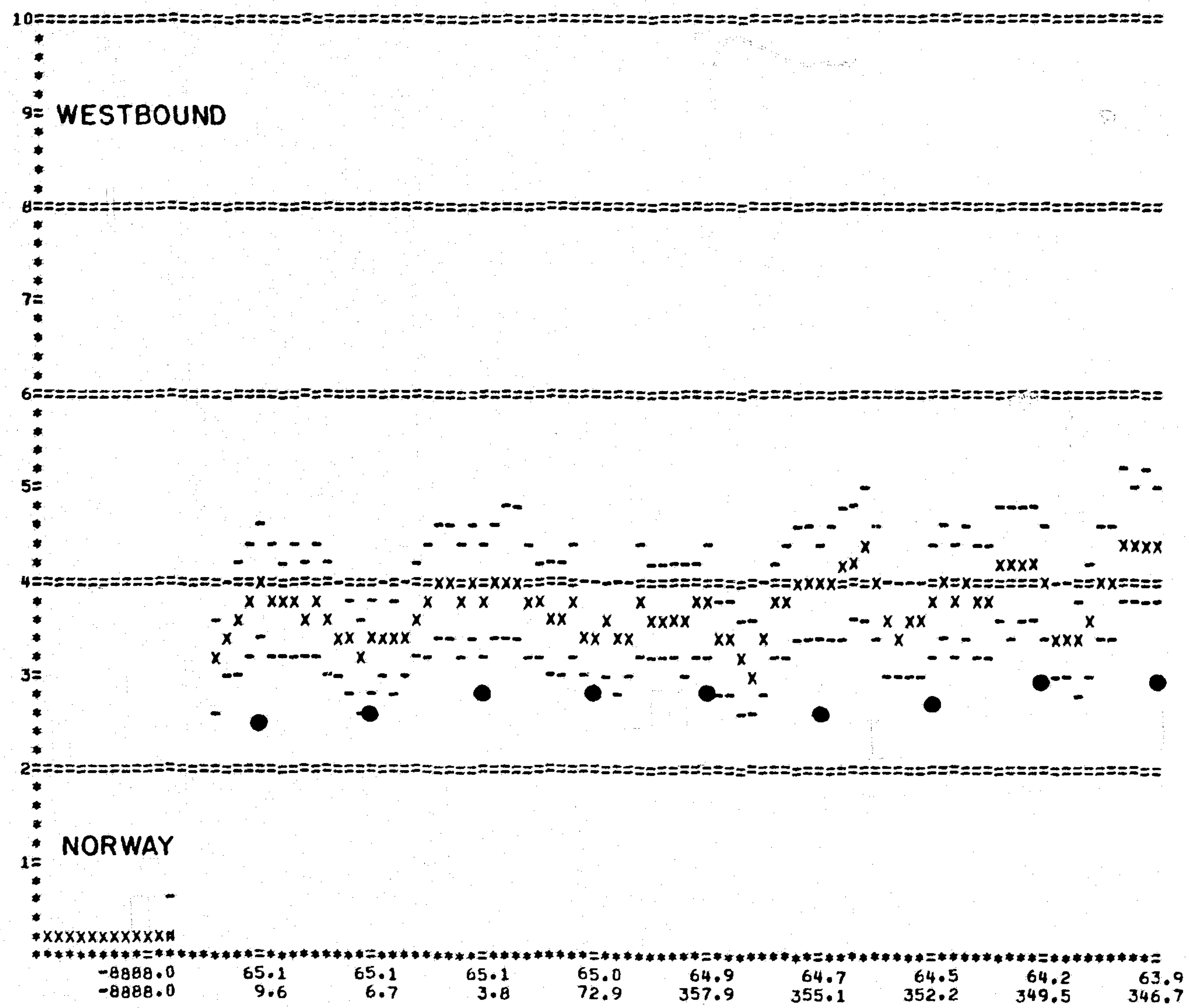
LOWEST SOWM; ON TRACK 1.2 M; IN FIELD 1.0 M

LOWEST GEOS; ON GRID 2.2 M; AT ONE POINT 1.8 M

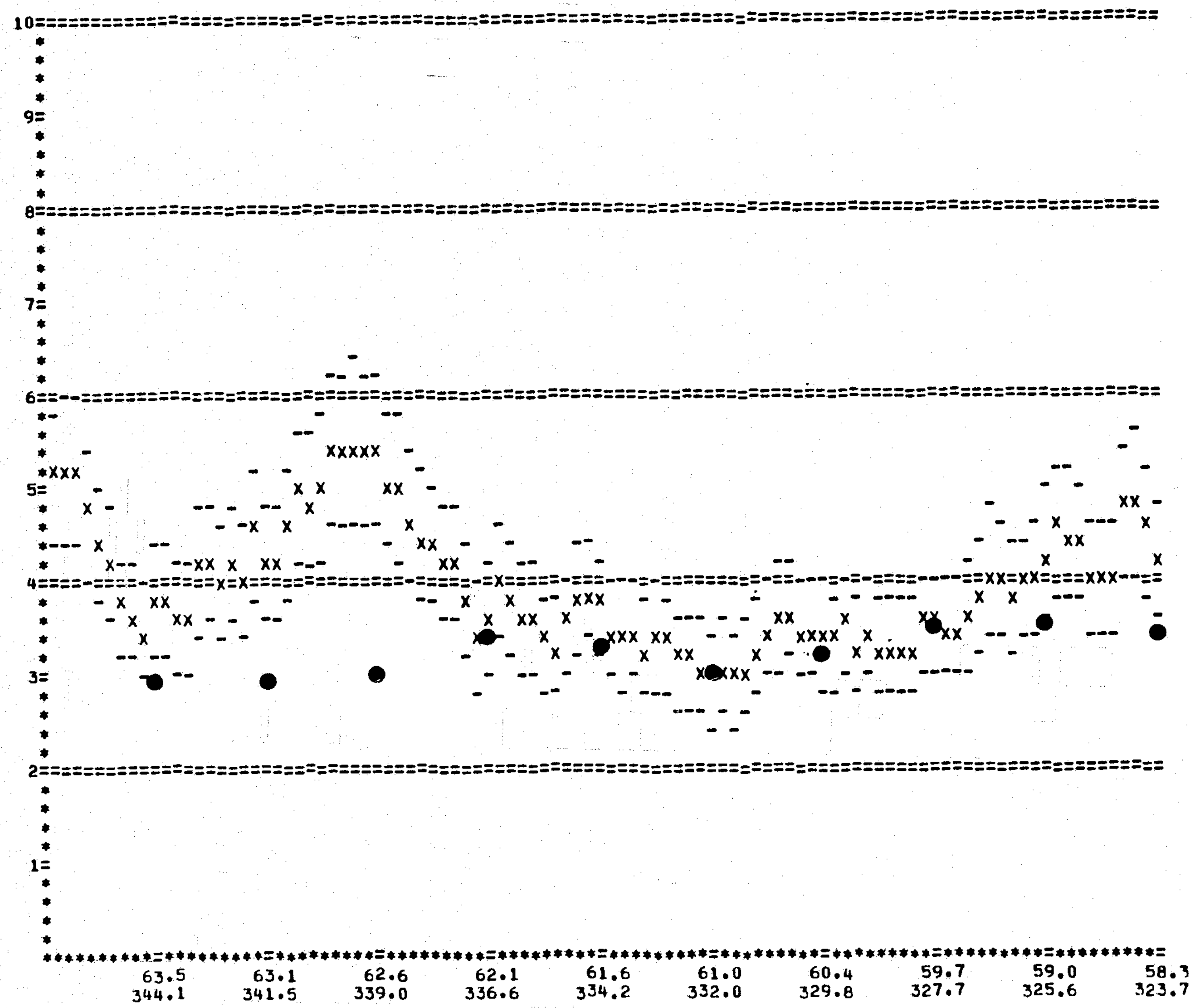
LARGEST ERROR - 2.4 M; SOWM 3.0 M, GEOS 5.4 M

SOWM too low by approximately 1 m except 336° E to 326° E. From Norway to south of Iceland winds might have been 13.8 m/s instead of 12 m/s. Note that SOWM specified high waves somewhere near the sub-satellite track so that there were high winds and high waves nearby.

```
      ORBIT         2827  UNIQUE #          478  DATE            10/          26/          75
STARTING LAT  64.890000      LON  15.180000      TIME            19:          30
  ENDING LAT  52.680000      LON  52.680000      TIME            19:          39
```



ORBIT	2827	UNIQUE #	478	DATE	10/	26/ 75
STARTING LAT	64.890000	LON	15.180000	TIME	19:	30
ENDING LAT	52.680000	LON	52.680000	TIME	19:	39



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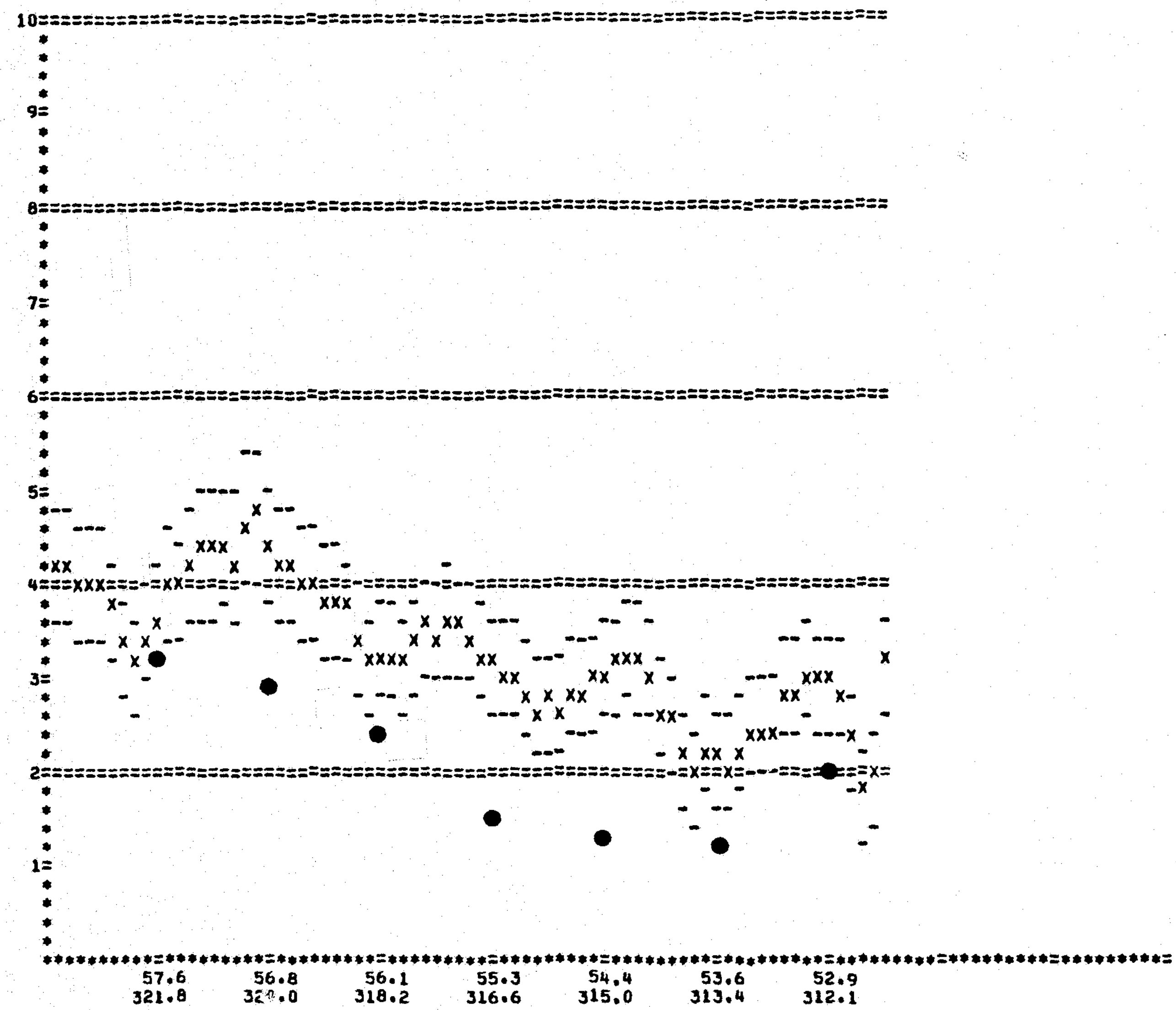
ORIGINAL PAGE IS OF POOR QUALITY

ORBIT 2827 UNIQUE # 478 DATE 10/ 26/ 75
STARTING LAT 64.890000 LON 15.180000 TIME 19: 30
ENDING LAT 52.680000 LON 52.680000 TIME 19: 39



ORBIT 2829 OCT. 26, 1975 22:40 TO 22:55

WESTBOUND ATLANTIC

GERMANY NEAR HAMBURG, JUST SOUTH OF ICELAND TO GREENLAND

19 POINTS RMS 0.9 M BIAS - 0.5 M

HIGHEST SOWM; ON TRACK 4.6 M; IN FIELD 4.5 M

HIGHEST GEOS; ON GRID 5.0 M; AT ONE POINT 5.0 M

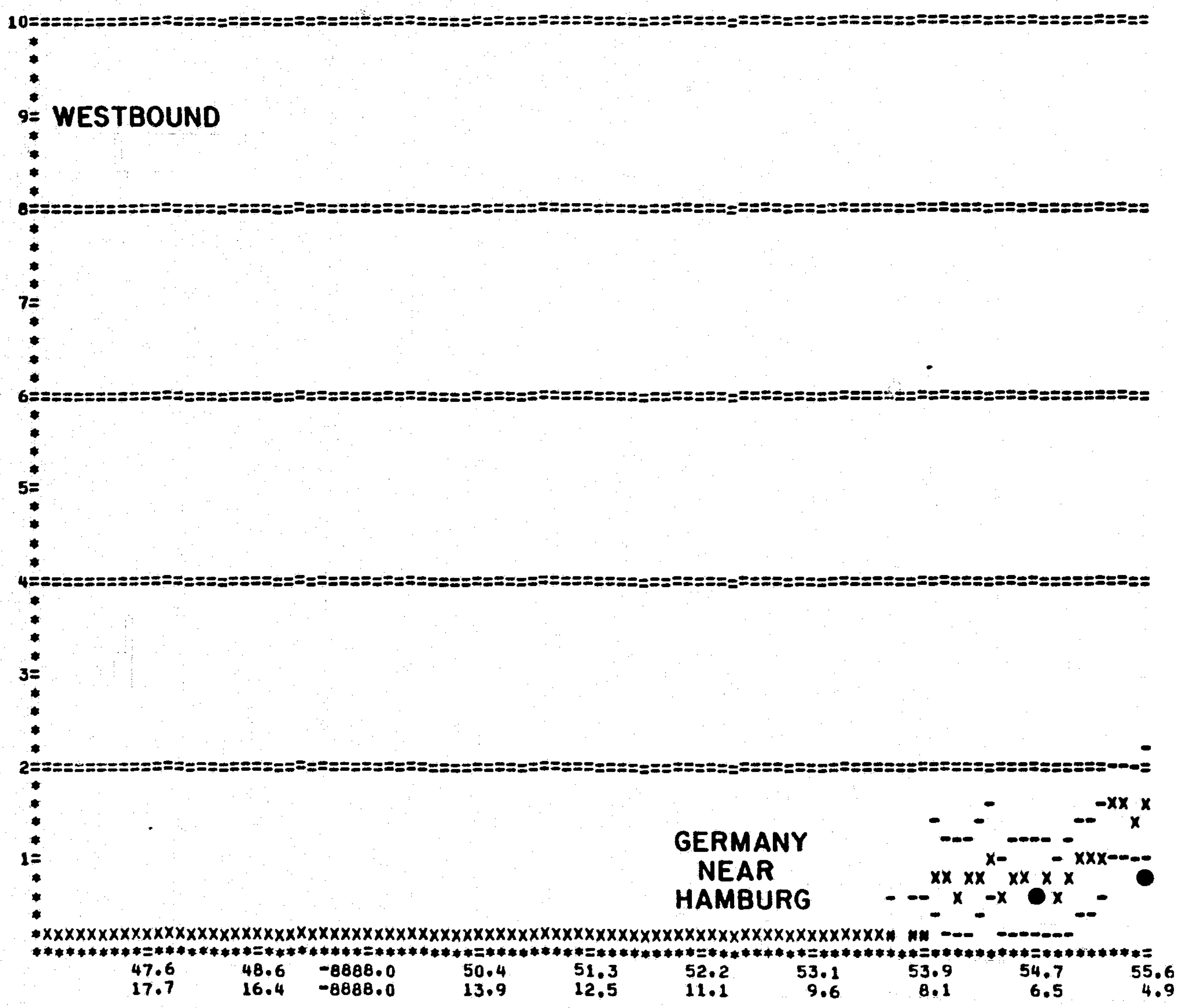
LOWEST SOWM; ON TRACK 0.6 M; IN FIELD 0.7 M

LOWEST GEOS; ON GRID 0.6 M; AT ONE POINT 0.6 M

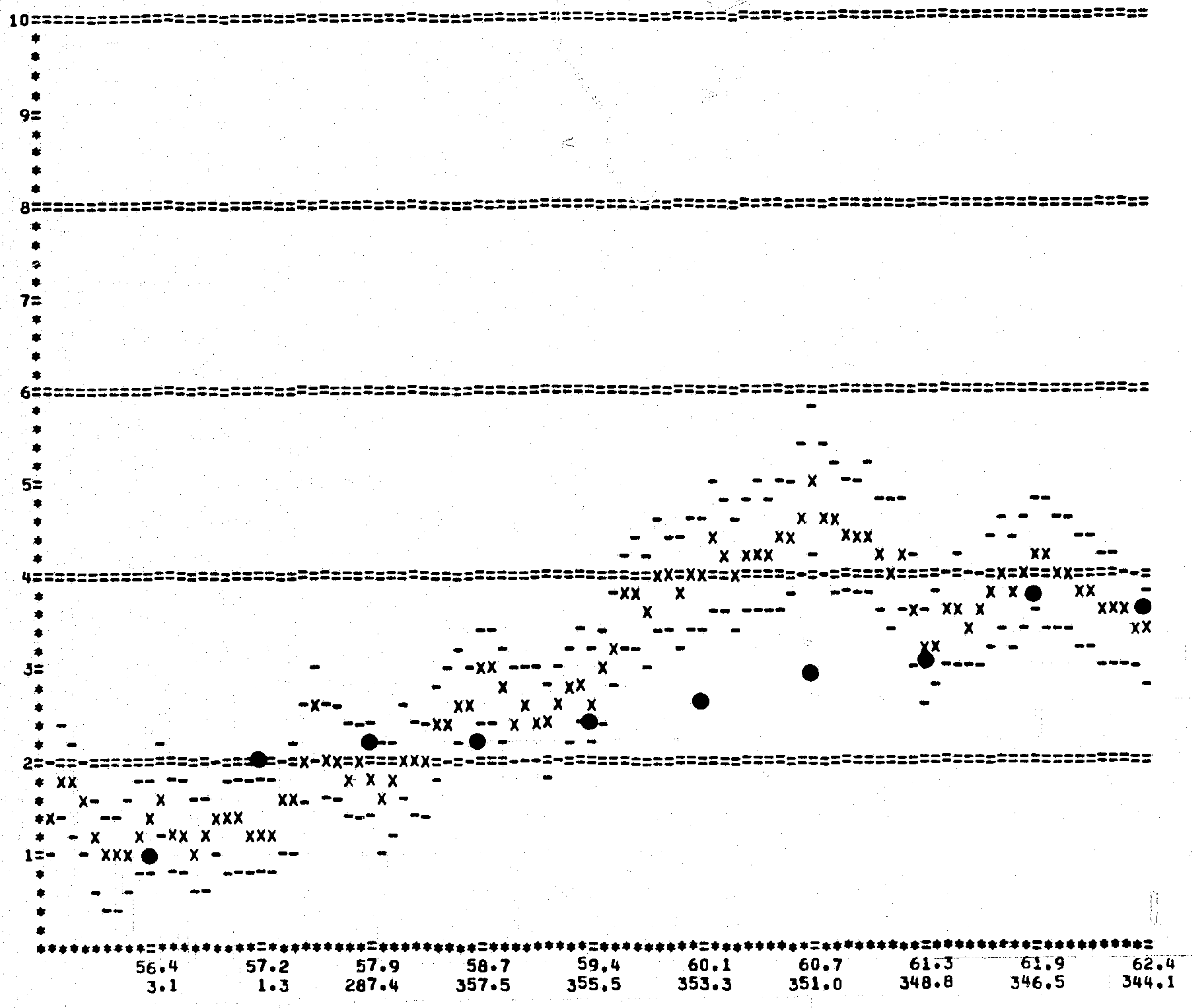
LARGEST ERROR - 2.1 M; SOWM 2.9 M, GEOS 5.0 M

SOWM missed highest waves between Europe and Iceland by 2 meters but did well from 8° E to 355° E. Fairly good Iceland tc Greenland except GEOS heights may be incorrect close to Greenland because of sea ice. Winds of 12 m/s may have been in the SOWM wind field, whereas 15 m/s could have generated the measured waves.

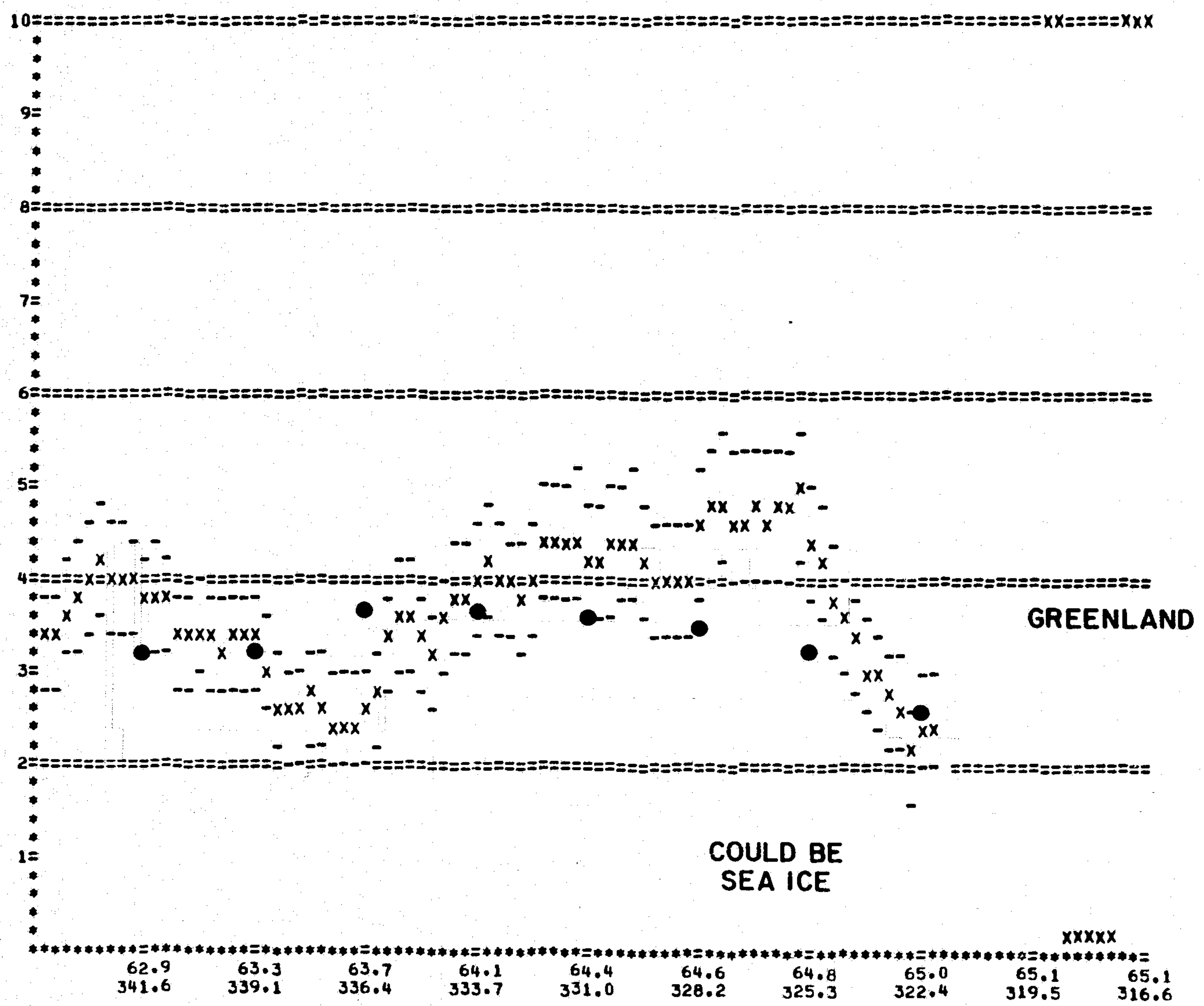
```
    ORBIT          2829  UNIQUE #          479  DATE          10/          26/          75
STARTING LAT  35.510000      LON  29.930000      TIME          22:          40
  ENDING LAT  65.070000      LON  65.070000      TIME          22:          55
```



ORBIT 2829 UNIQUE # 479 DATE 10/ 26/ 75
STARTING LAT 35.510000 LON 29.930000 TIME 22: 40
ENDING LAT 65.070000 LON 65.070000 TIME 22: 55



ORBIT 2829 UNIQUE # 479 DATE 10/ 26/ 75
STARTING LAT 35.510000 LON 29.930000 TIME 22: 40
ENDING LAT 65.070000 LON 65.070000 TIME 22: 55



ORBIT 2904 NOV. 1, 1975 5:47 TO 5:57

NORTHBOUND ATLANTIC

15.8° N, 304° E TO COAST OF NEW JERSEY

24 POINTS RMS 1.2 M BIAS - 0.8 M

HIGHEST SOWM; ON TRACK 4.0 M; IN FIELD 4.1 M

HIGHEST GEOS; ON GRID 5.4 M; AT ONE POINT 6.0 M

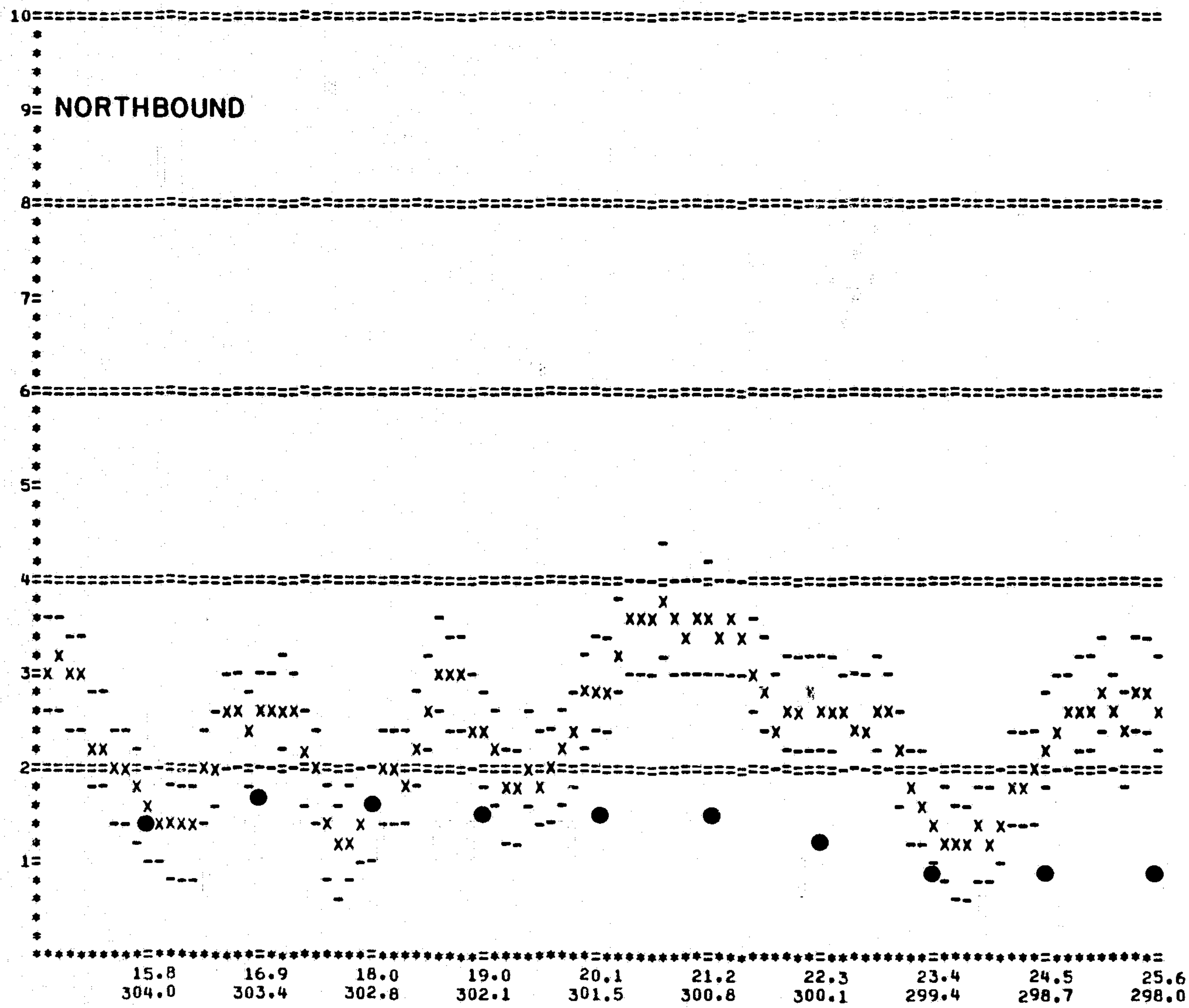
LOWEST SOWM; ON TRACK 0.8 M; IN FIELD 0.9 M

LOWEST GEOS; ON GRID 1.0 M; AT ONE POINT 0.6 M

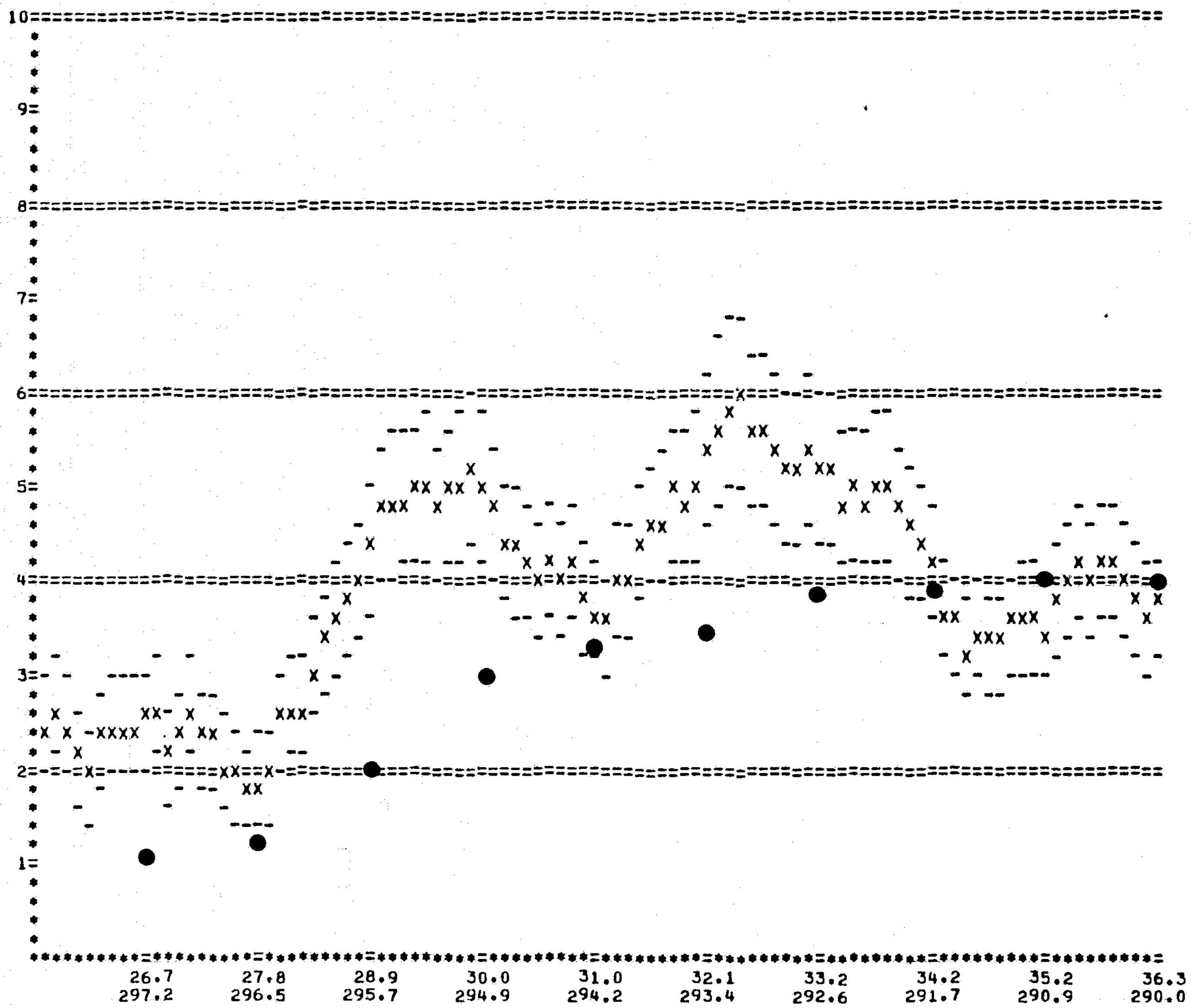
LARGEST ERROR - 2.0 M; SOWM 3.4 M, GEOS 5.4 M

SOWM missed 3 m waves 20° N to 22° N and 5 and 6 m waves 29° N to 33° N. SOWM gave good fetch effect from 35° N to New Jersey coast. Winds near 33° N may have been 16 m/s instead of 13 m/s.

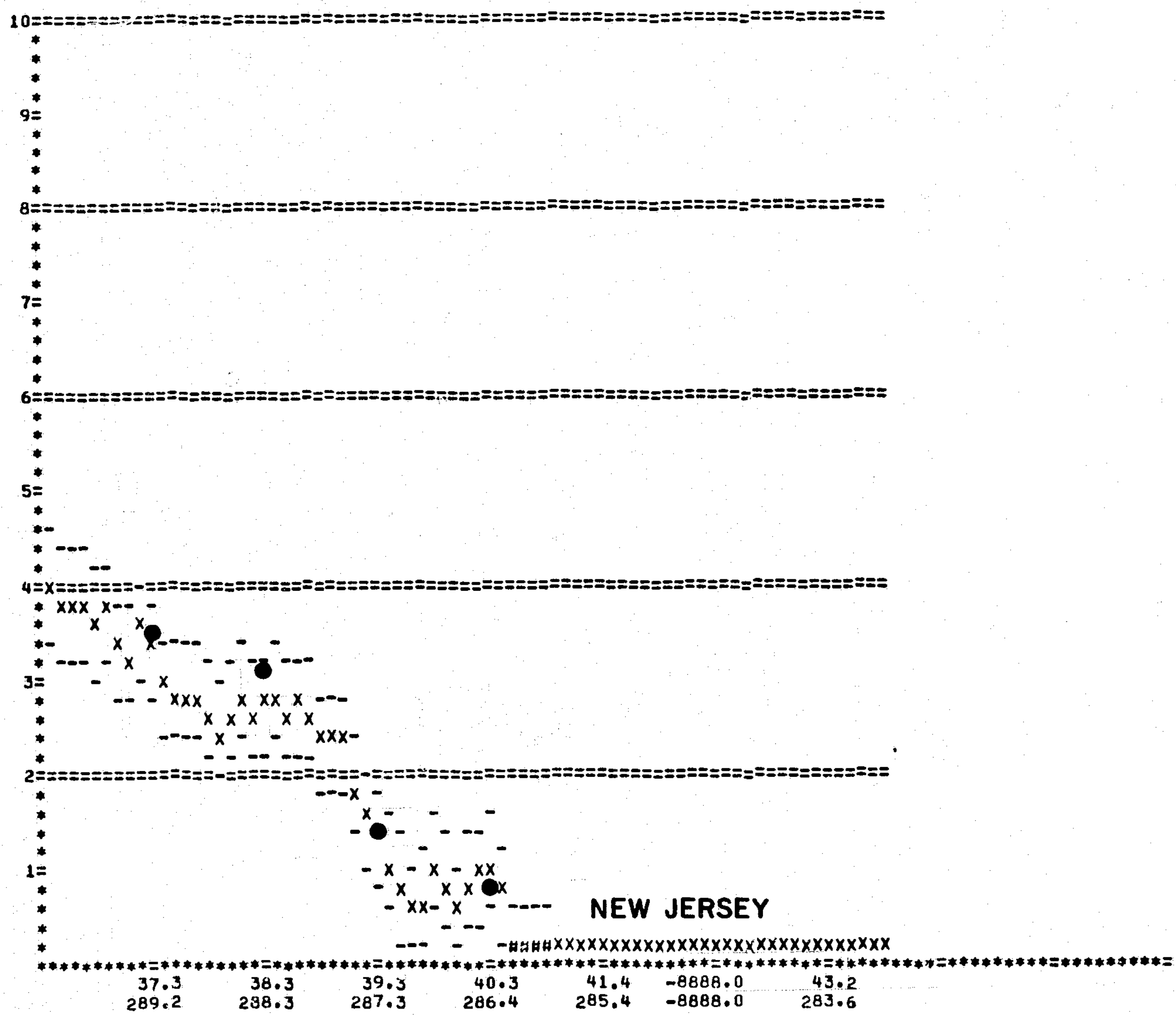
ORBIT 2904 UNIQUE # 519 DATE 11/ 1/ 75
STARTING LAT 14.780000 LON 304.62000 TIME 5: 47
ENDING LAT 43.440000 LON 43.440000 TIME 5: 57



ORBIT	2904	UNIQUE #	519	DATE	11/	1/	75
STARTING LAT	14.780000	LON	304.62000	TIME	5:	47	
ENDING LAT	43.440000	LON	43.440000	TIME	5:	57	



ORBIT	2904	UNIQUE #	519	DATE	11/	1/	75
STARTING LAT	14.780000	LON	304.62000	TIME	5:	47	
ENDING LAT	43.440000	LON	43.440000	TIME	5:	57	



ORBIT 2919 NOV. 2, 1975 7:13 TO 7:20

NORTHBOUND ATLANTIC

VENEZUELA, OVER JAMAICA, OVER CUBA, OVER FLORIDA KEYS TO FLORIDA PANHANDLE

12 POINTS RMS 0.8 M BIAS - 0.5 M

HIGHEST SOWM; ON TRACK 2.4 M; IN FIELD 3.2 M

HIGHEST GEOS; ON GRID 2.8 M; AT ONE POINT 3 M

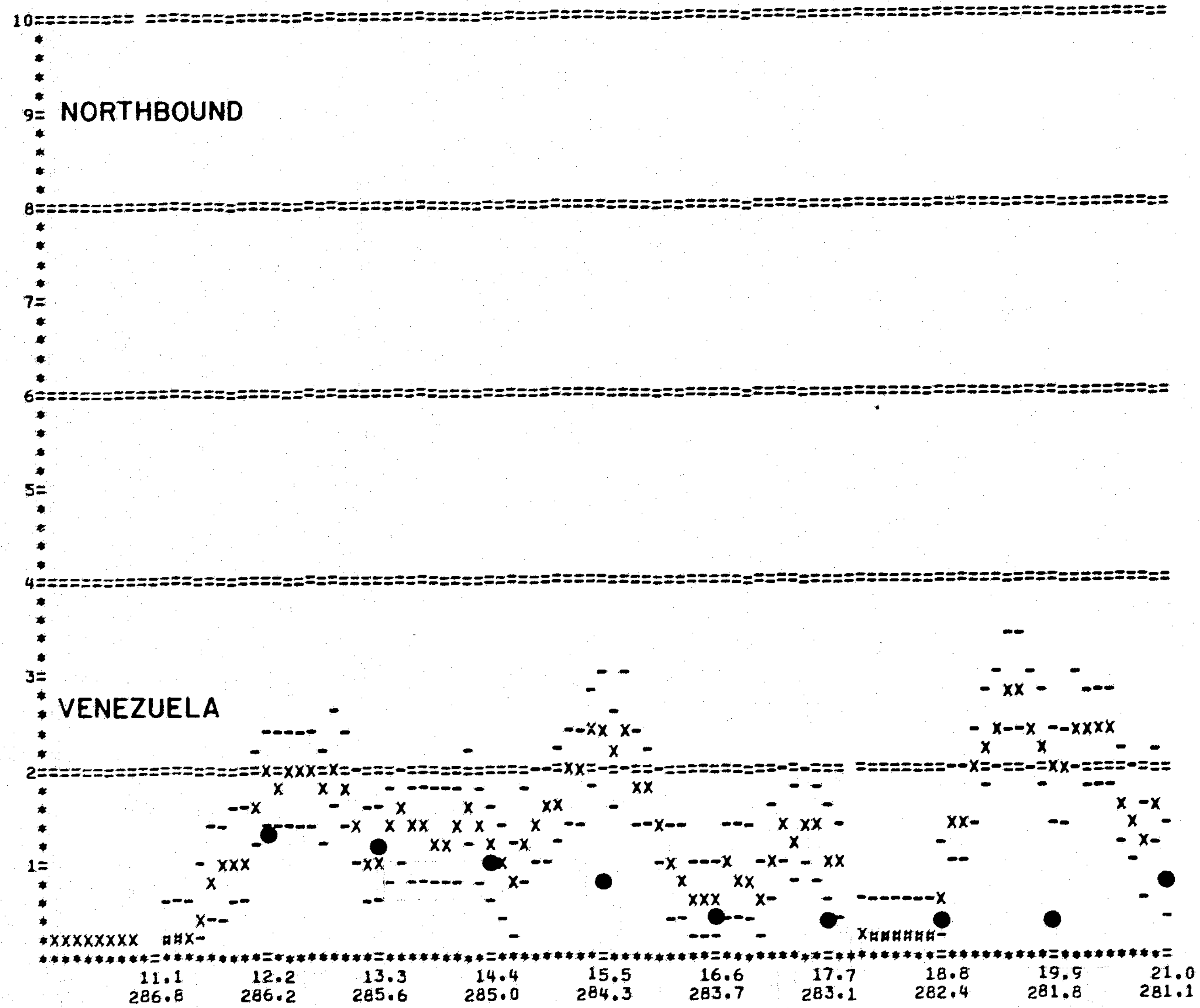
LOWEST SOWM; ON TRACK 0.3 M; IN FIELD 0.3 M

LOWEST GEOS; ON GRID 0.6 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 1.7 M; SOWM 0.3 M, GEOS 2.0 M

SOWM low Venezuela to Jamaica, much too low Jamaica to Cuba, good between Cuba and Key West and good between Key West and Florida panhandle. The variations along the track illustrate the need for higher resolution models in the Caribbean Sea, the Gulf of Mexico and the West Indies.

ORBIT 2919 UNIQUE # 527 DATE 11/ 2/ 75
STARTING LAT 10.140000 LON 287.40000 TIME 7: 13
ENDING LAT -8888.0000 LON -8888.0000 TIME 7: 20



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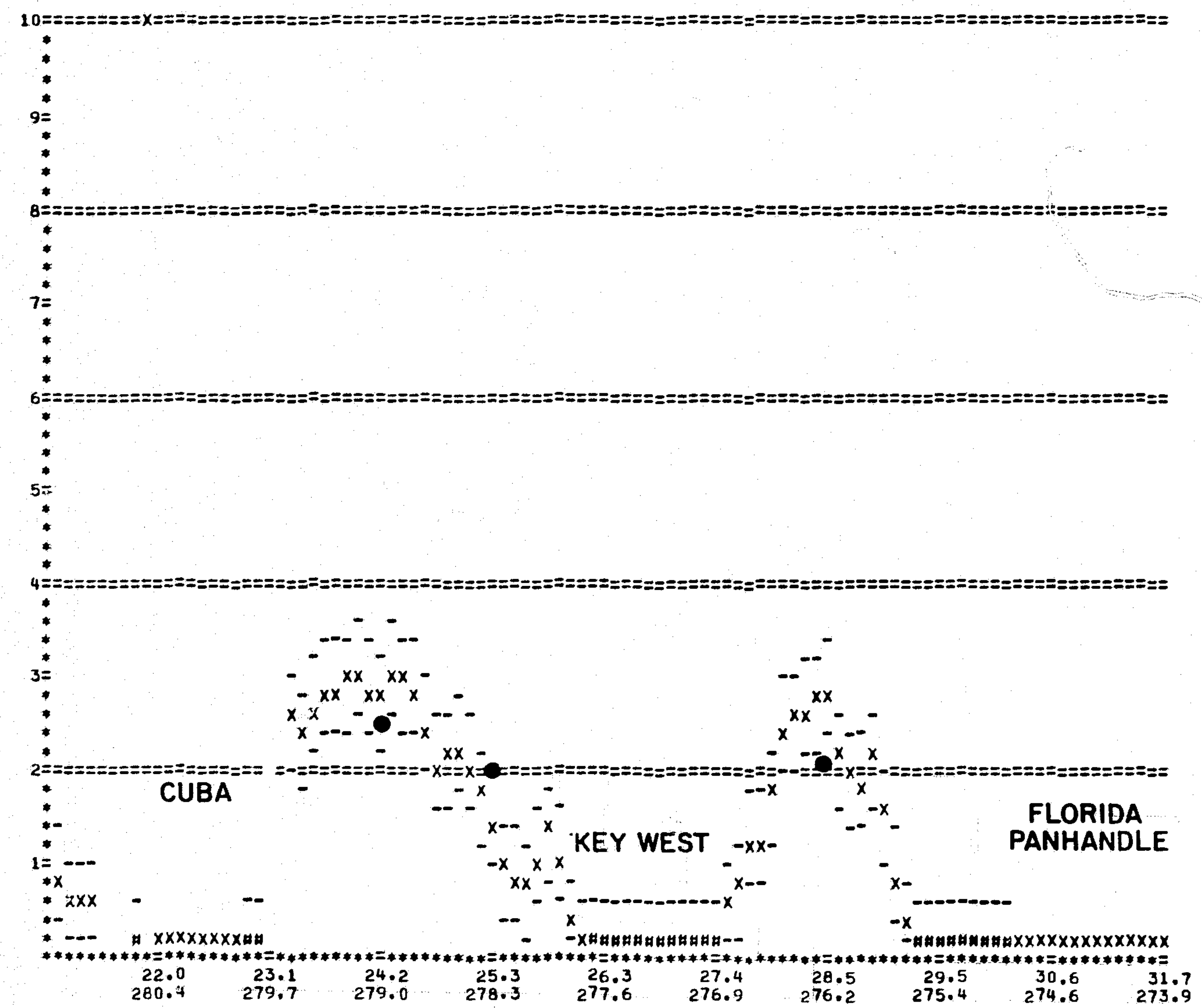
ORBIT 2919 UNIQUE # 527 DATE 11/ 2/ 75
STARTING LAT 10.140000 LON 287.40000 TIME 7: 13
ENDING LAT -8888.0000 LON -8888.0000 TIME 7: 20



ORBIT 2936 NOV. 3, 1975 12:01 TO 12:22

NORTHBOUND PACIFIC

39.8° N, 196.6° E TO KAMCHATKA PENINSULA

21 POINTS RMS 0.7 M BIAS - 0.3 M

HIGHEST SOWM; ON TRACK 3.9 M; IN FIELD 3.9 M

HIGHEST GEOS; ON GRID 6.2 M; AT ONE POINT 6.4 M

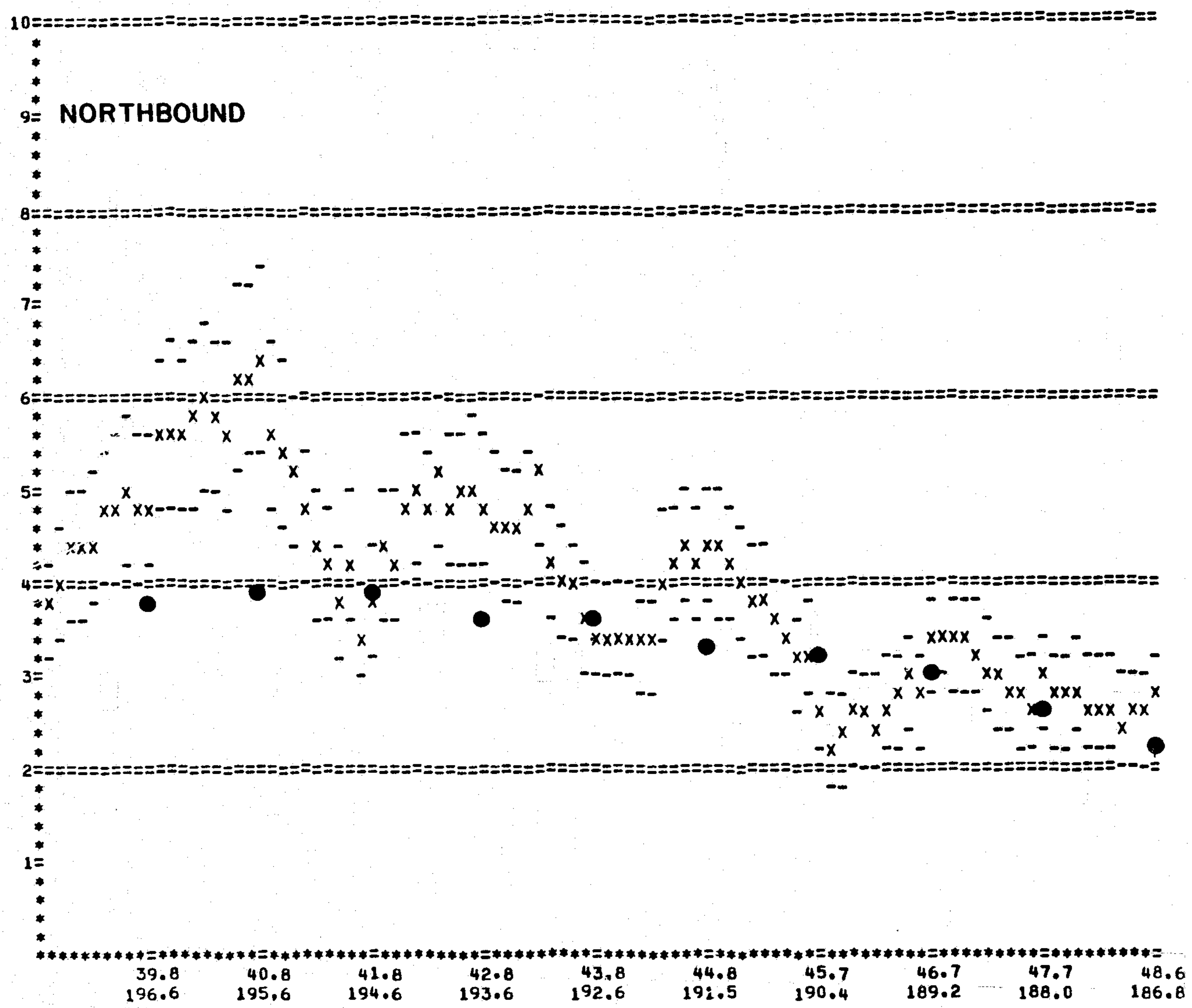
LOWEST SOWM; ON TRACK 0.5 M; IN FIELD 0.3 M

LOWEST GEOS; ON GRID 0.6 M; AT ONE POINT 0.2 M

LARGEST ERROR - 2.3 M; SOWM 3.9 M, GEOS 6.2 M

Winds of 16.5 m/s near 40° N instead of 14 m/s and decreasing to the values actually used at 45° would have eliminated the larger errors. The dip near 50.4° N may be an effect of the Aleutian Islands. Close agreement over most of the track reduces effect of the large errors at the first few points.

ORBIT 2936 UNIQUE # 537 DATE 11/ 3/ 75
STARTING LAT 5.1900000 LON 219.64000 TIME 12: 1
ENDING LAT -8888.0000 LON -8888.0000 TIME 12: 22



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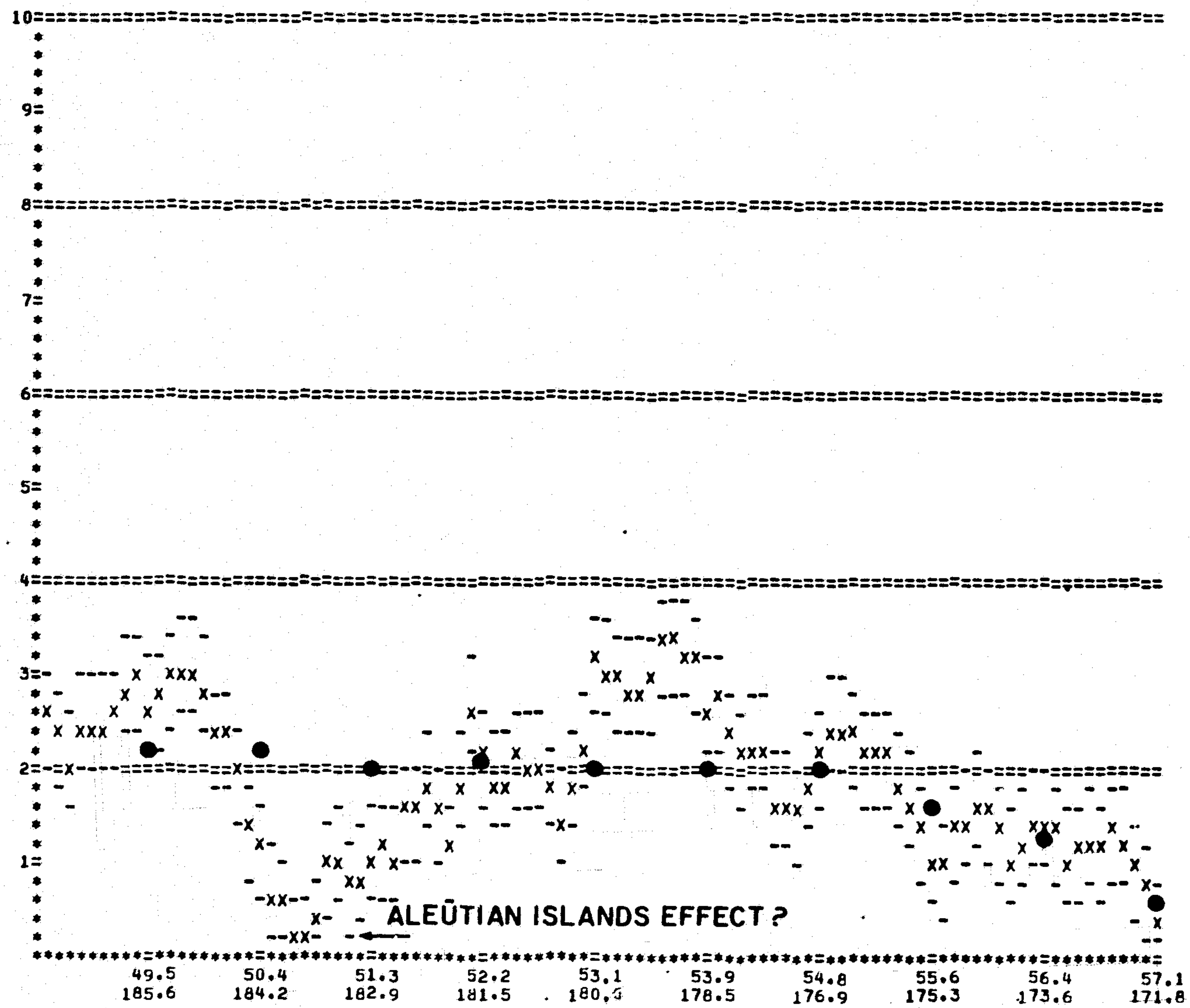
ORBIT 2936 UNIQUE # 537 DATE 11/ 3/ 75
STARTING LAT 5.1900000 LON 219.64000 TIME 12: 1
ENDING LAT -8888.0000 LON -8888.0000 TIME 12: 22



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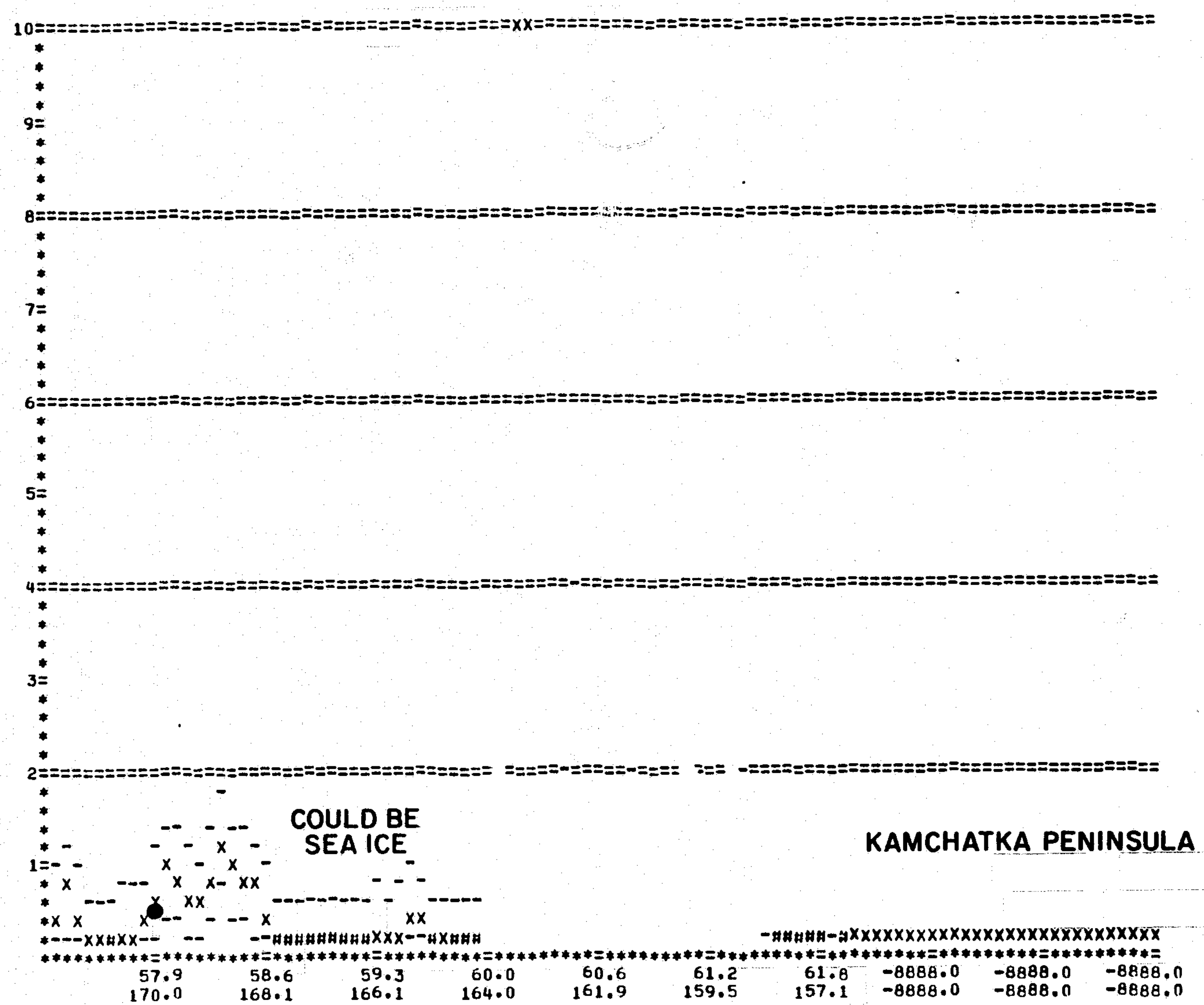
   ORBIT         2936  UNIQUE #        537  DATE          11/         3/        75
STARTING LAT  5.1900000     LON  219.64000     TIME          12:         1
  ENDING LAT -8888.0000     LON -8888.0000     TIME          12:        22
```



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ORBIT 2998 NOV. 7, 1975 21:34 TO 21:42

WESTBOUND ATLANTIC

NORWAY, OVER ICELAND, JUST SOUTH OF GREENLAND

17 POINTS RMS 0.9 M BIAS + 0.2 M

HIGHEST SOWM; ON TRACK 5.3 M; IN FIELD 5.6 M

HIGHEST GEOS; ON GRID 5.4 M; AT ONE POINT 5.4 M

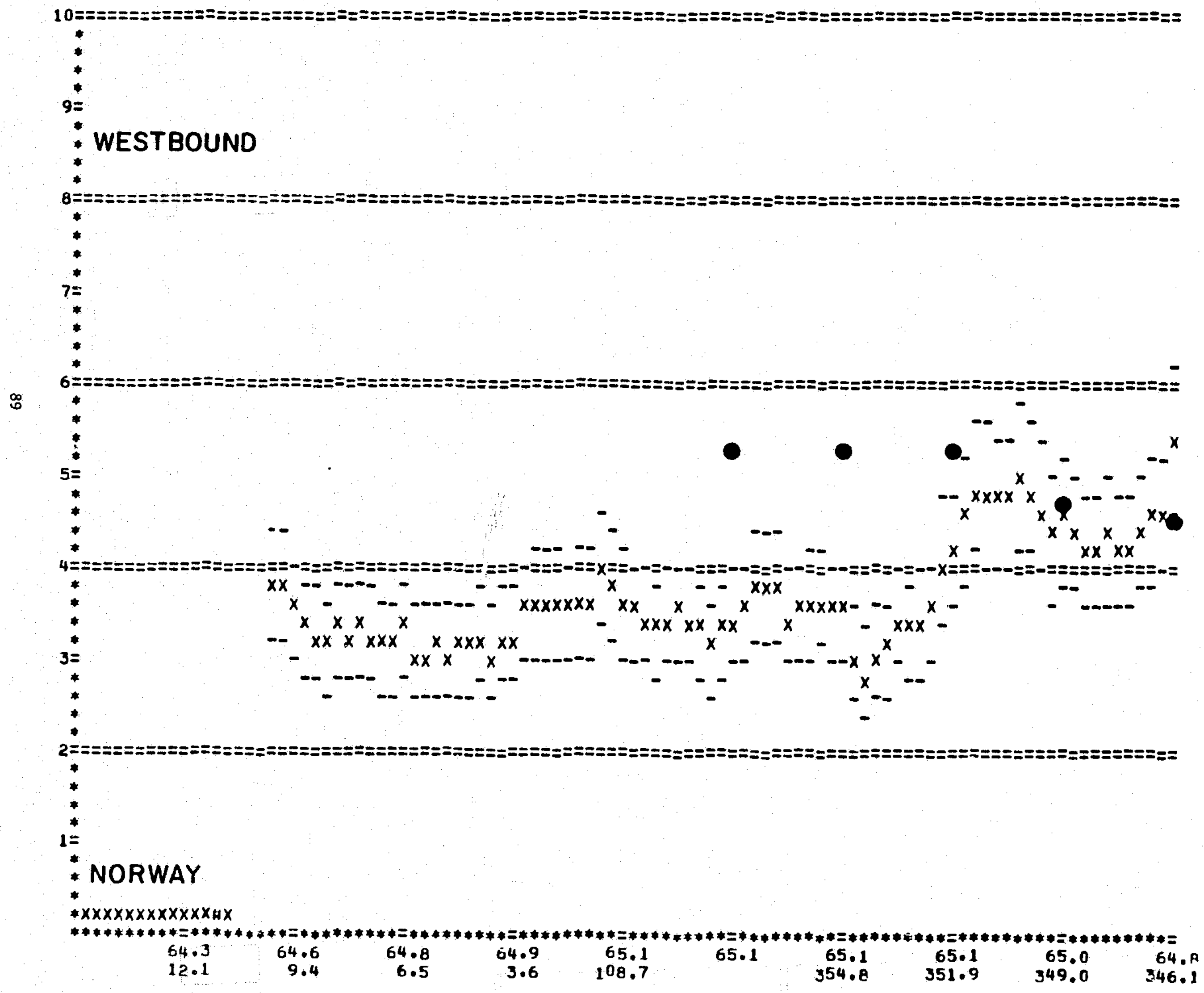
LOWEST SOWM; ON TRACK 2.7 M; IN FIELD 2.7 M

LOWEST GEOS; ON GRID 3.4 M; AT ONE POINT 2.8 M

LARGEST ERROR 1.9 M; SOWM 5.3 M, GEOS 3.4 M

Good agreement for such high waves, slightly weaker winds close to Norway and slightly stronger winds near Greenland would have produced excellent agreement. West of Iceland errors are all one meter or less. Winds of 13 m/s instead of 15.5 m/s would correct largest error.

ORBIT 2998 UNIQUE # 571 DATE 11/ 7/ 75
STARTING LAT 64.020000 LON 14.620000 TIME 21: 34
ENDING LAT 57.500000 LON 57.500000 TIME 21: 42



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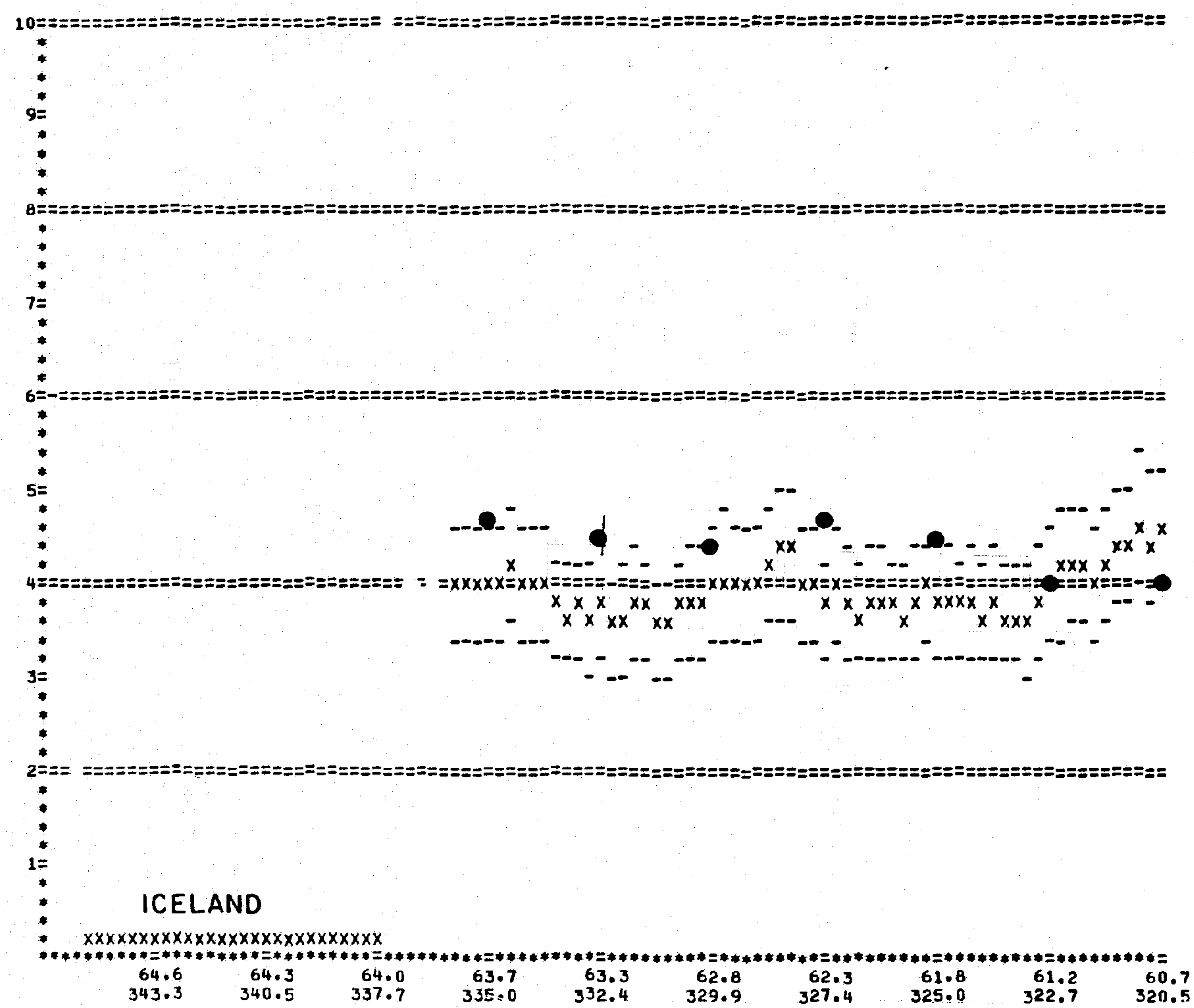
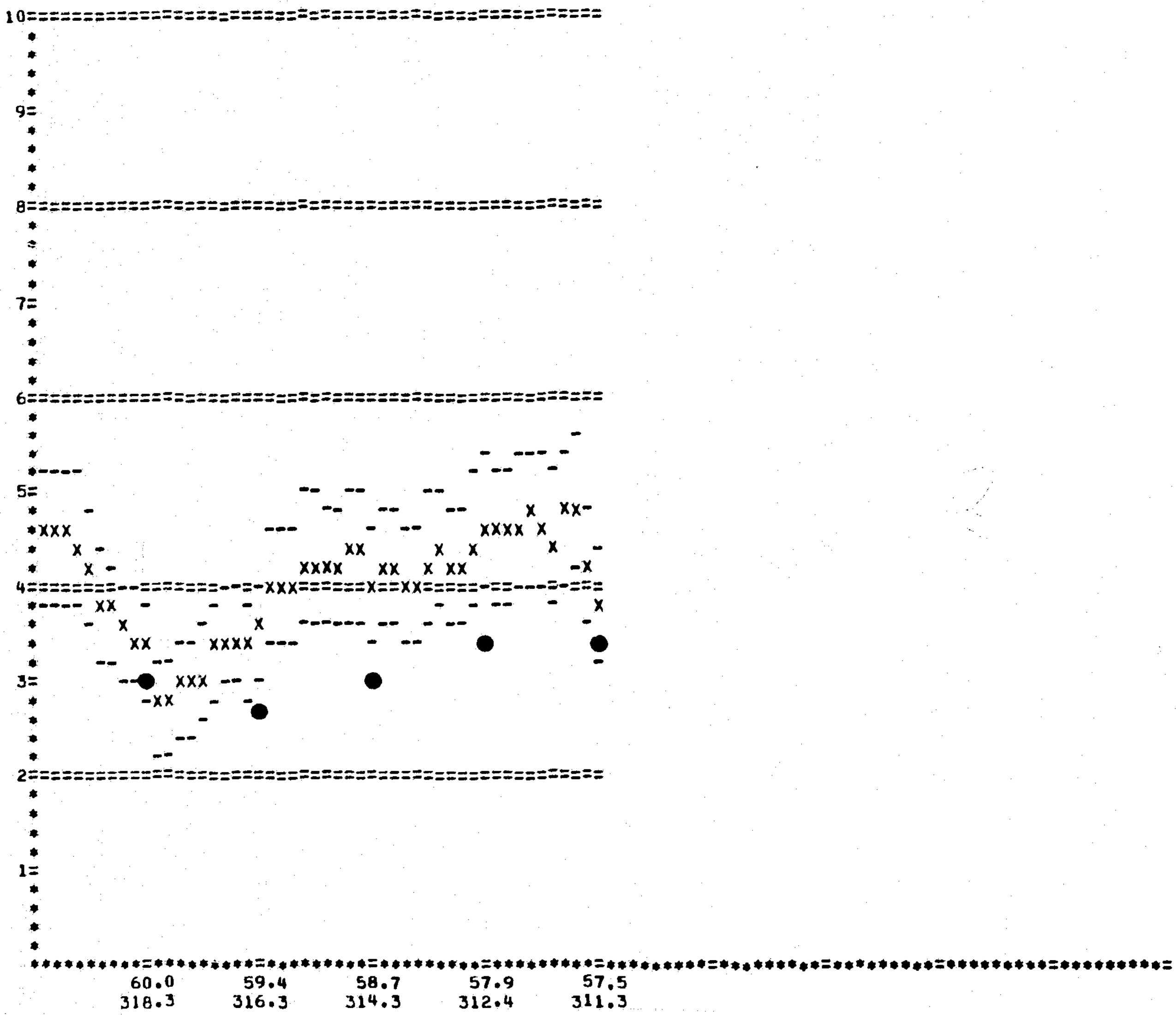
ORBIT 2998 UNIQUE # 571 DATE 11/ 7/ 75
STARTING LAT 64.020000 LON 14.620000 TIME 21: 34
ENDING LAT 57.500000 LON 57.500000 TIME 21: 42



ORBIT	2998	UNIQUE #	571	DATE	11/	7/	75
STARTING LAT	64.020000	LON	14.620000	TIME	21:	34	
ENDING LAT	57.500000	LON	57.500000	TIME	21:	42	



ORBIT 3030 NOV. 10, 1975 3:35 TO 3:46

NORTHBOUND ATLANTIC

NORTH AFRICA TO LABRADOR SEA

28 POINTS RMS 2.0 M BIAS - 1.5 M

HIGHEST SOWM; ON TRACK 2.4 M; IN FIELD 3.4 M

HIGHEST GEOS; ON GRID 6.2 M; AT ONE POINT 7.0 M

LOWEST SOWM; ON TRACK 0.3 M; IN FIELD 0.3 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 4.2 M; SOWM 1.6 M, GEOS 5.8 M

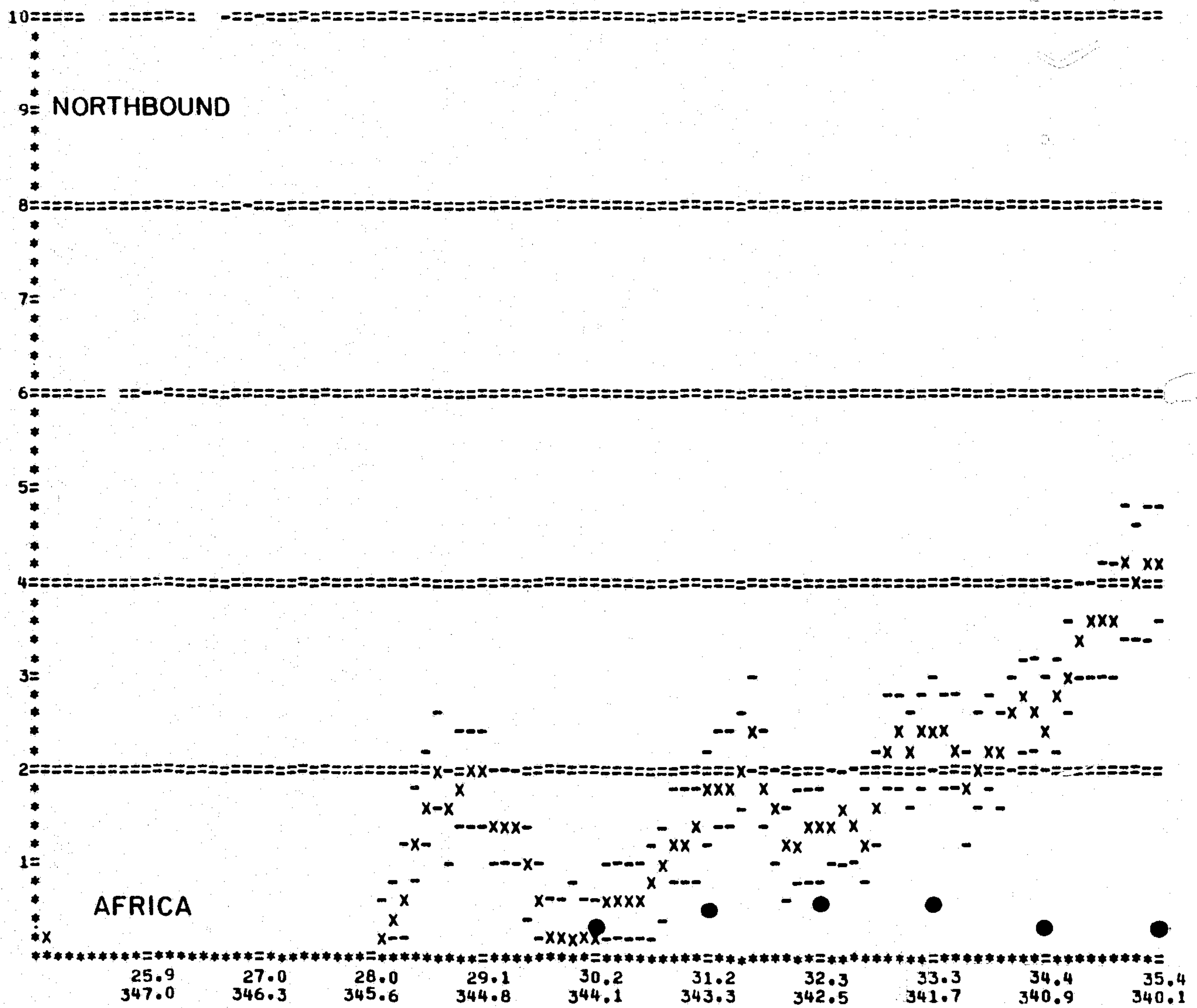
One of the poorest verifications of the SOWM in the entire data set. High waves from 33° N to 47° N were missed completely. If GEOS heights were correct, winds near 17 m/s would be needed near 43° N instead of 10 m/s.

SEE TABLE NEXT PAGE.

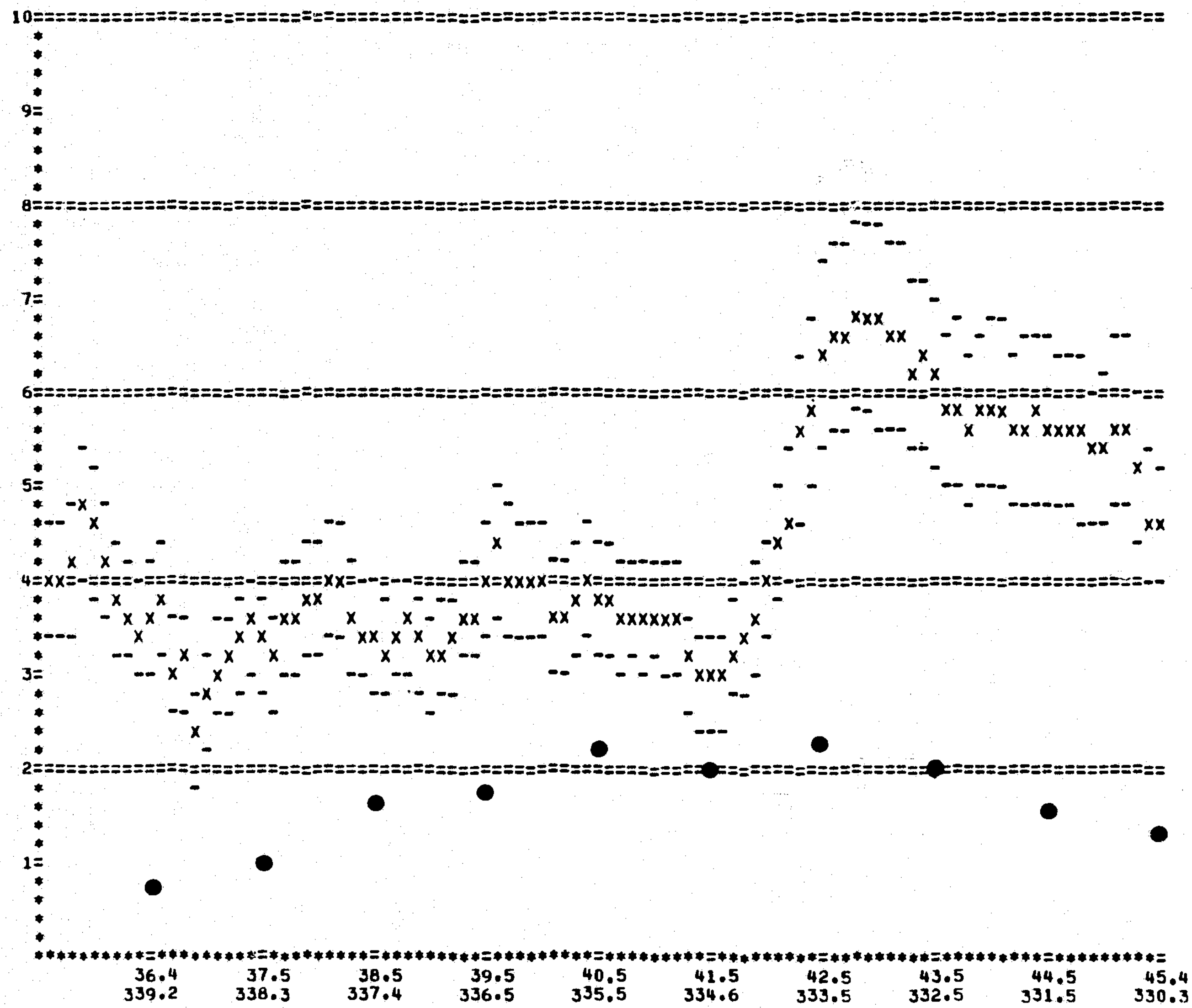
ORBIT 3030 CONTINUED

LAT	SOWM	GEOS	S - G	LAT	SOWM	GEOS	S - G
30.2	0.4	0.2	+ 0.2	45	1.6	5.8	- 4.2
31	0.6	1.8	- 1.2	45	1.3	4.6	- 3.3
32	0.6	1.4	- 0.8	46	1.6	3.6	- 2.0
33	0.6	2.4	- 1.8	47	0.7	1.4	- 0.7
34	0.3	2.4	- 2.1	48	1.0	0.8	+ 0.2
35	0.4	4.2	- 3.8	49	1.1	1.6	- 0.5
36	0.6	3.4	- 2.8	50	2.0	2.6	- 0.6
38	1.0	3.6	- 2.6	51	2.1	2.4	- 0.3
39	1.6	3.4	- 1.8	52	2.4	2.8	- 0.4
40	1.7	3.6	- 1.9	53	1.9	1.8	+ 0.1
41	2.2	3.8	- 1.6	54	2.2	2.6	- 0.4
42	2.0	3.0	- 1.0	55	1.9	1.6	+ 0.3
43	2.2	5.8	- 3.6	55	1.3	2.6	- 1.3
44	2.0	6.2	- 4.2	56	1.3	2.4	- 1.1

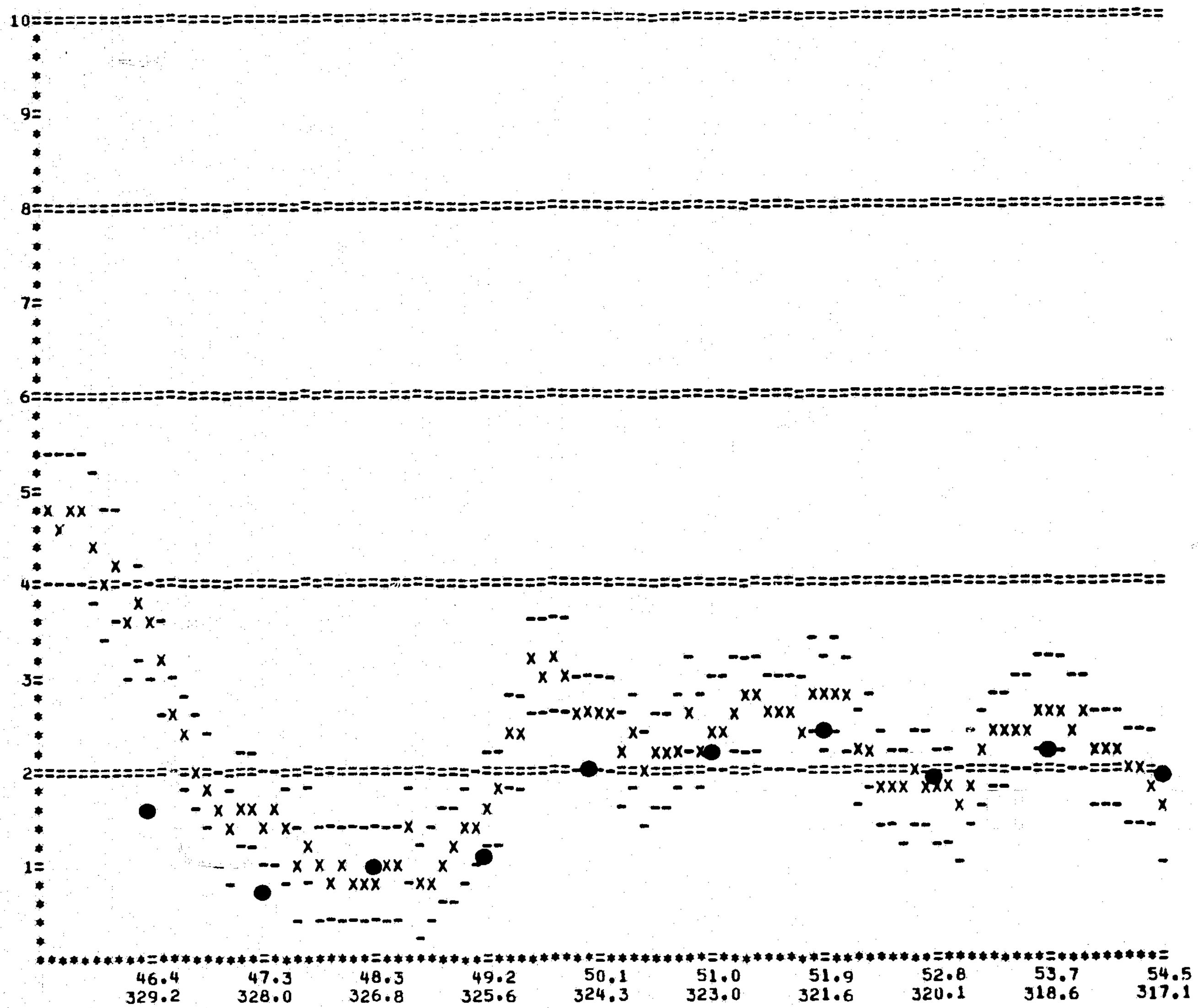
ORBIT 3030 UNIQUE # 590 DATE 11/ 10/ 75
STARTING LAT 24.930000 LON 347.69000 TIME 3: 35
ENDING LAT 55.800000 LON 55.800000 TIME 3: 46



ORBIT 3030 UNIQUE # 590 DATE 11/ 10/ 75
STARTING LAT 24.930000 LON 347.69000 TIME 3: 35
ENDING LAT 55.800000 LON 55.800000 TIME 3: 46



ORBIT	3030	UNIQUE #	590	DATE	11/	10/ 75
STARTING LAT	24.930000	LON	347.69000	TIME	3:	35
ENDING LAT	55.800000	LON	55.800000	TIME	3:	46



```
     ORBIT          3030  UNIQUE #            590  DATE              11/             10/            75
STARTING LAT  24.930000      LON  347.69000      TIME              3:              35
  ENDING LAT  55.800000      LON  55.800000      TIME              3:              46
      10====================
       *
       *
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       *
       9=
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       *
       8====================
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       7=
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       6====================
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       *
       5=
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       *
       *
       *
       4====================
       *
       *
       *
       *
       3=          ---- -    -
       *   -  ---    - - --
       *    --    XXX    -
       * --   XXX   X XX X X
       *   XXX      X  X X
       2=-X=======---=-====-
       *  X-  ---    - - --
       *X   --         -
       * --     ●        ●
       *
       1=-
       *
       *
       *
       *
       **********=*********=********=*********=**********=*********=*********=*********=*********=**********=*********=
             55.3      55.8
            315.5     314.5
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ORBIT 3075 NOV. 13, 1975 7:51 TO 7:59

NORTHBOUND ATLANTIC

VENEZUELA, NEAR TRINIDAD, THROUGH MONO PASSAGE TO NORTH CAROLINA

21 POINTS RMS 0.6 M BIAS - 0.4 M

HIGHEST SOWM; ON TRACK 1.7 M; IN FIELD 1.6 M

HIGHEST GEOS; ON GRID 2.2 M; AT ONE POINT 2.8 M

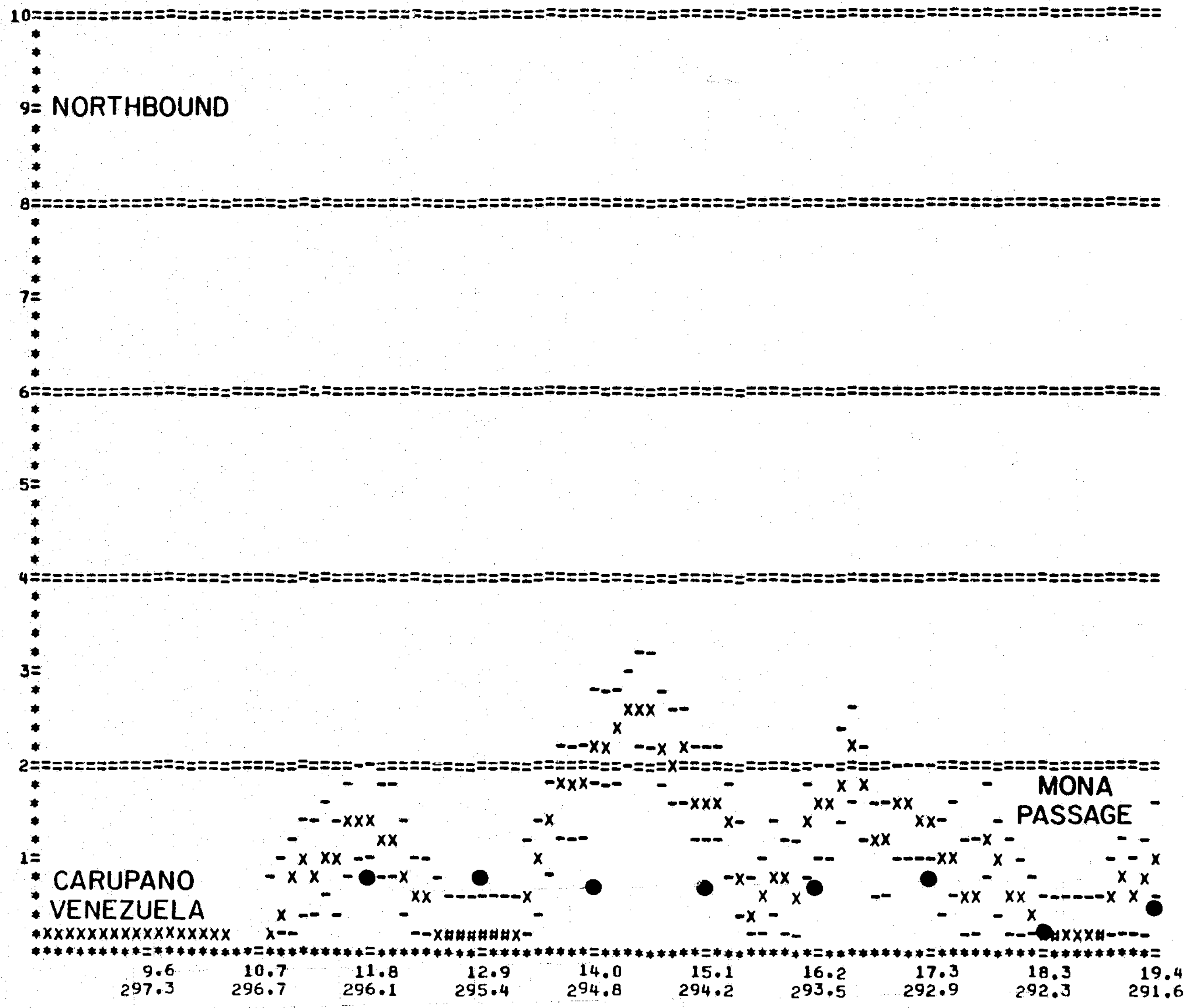
LOWEST SOWM; ON TRACK 0.2 M; IN FIELD 0.5 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

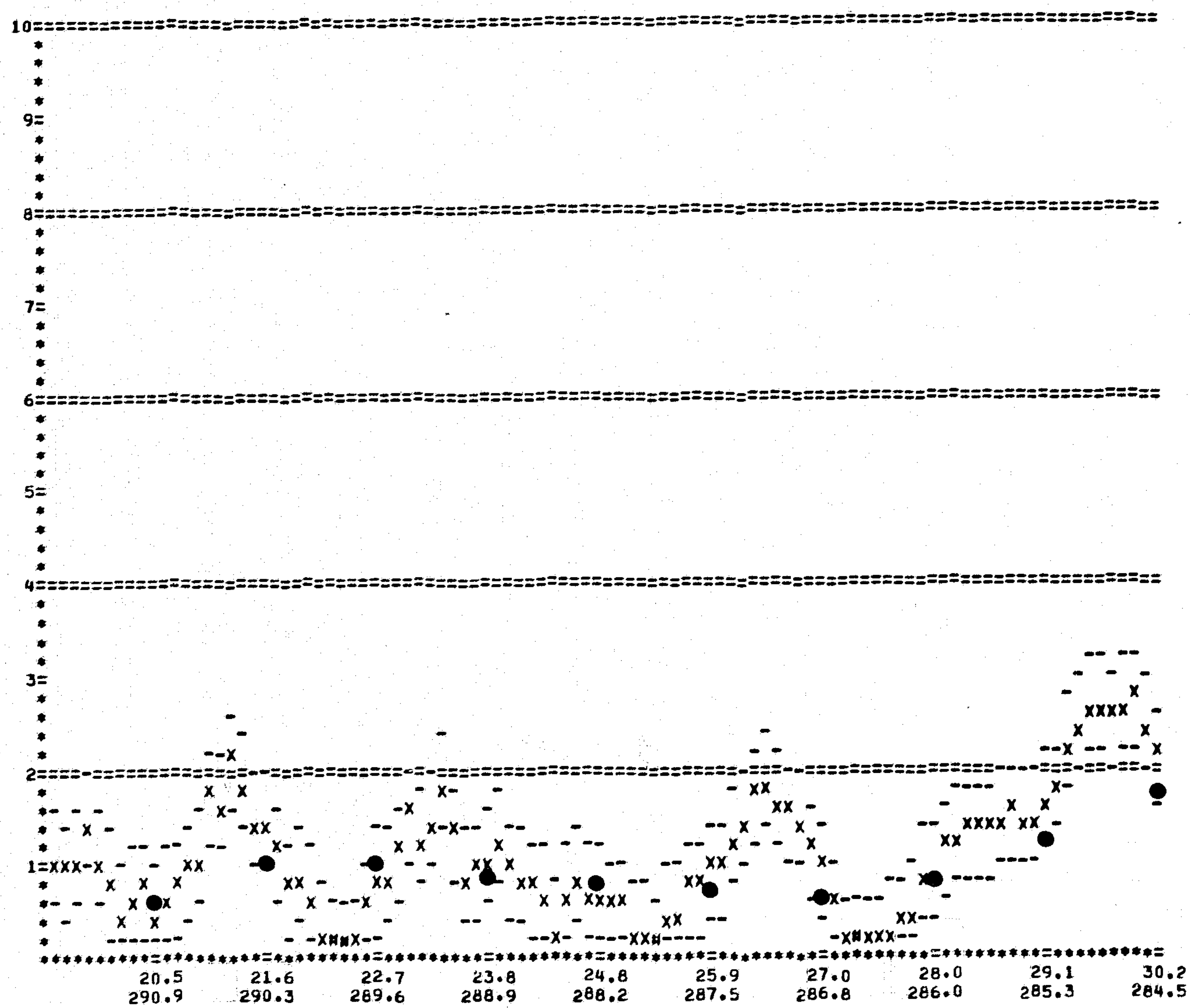
LARGEST ERROR - 1.3 M; SOWM 0.7 M, GEOS 2.2 M

SOWM heights varied gradually along GEOS track with increase at northernmost part from 0.7 m to 1.6 m. GEOS heights very oscillatory to the lee of the Antilles and Puerto Rico. Part of the good agreement is because the SOWM hits the GEOS fluctuations at just the right points.

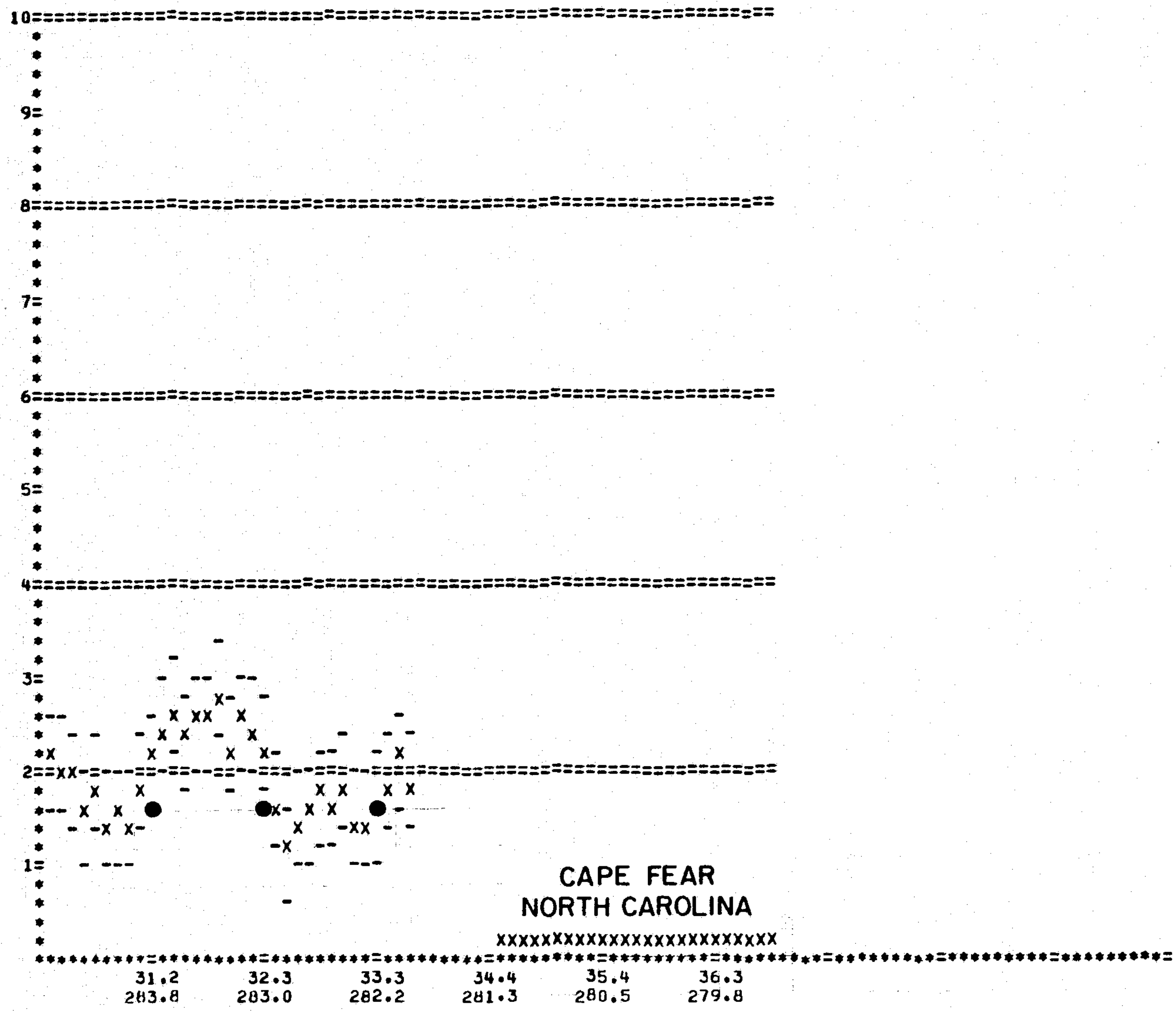
ORBIT 3075 UNIQUE # 620 DATE 11/ 13/ 75
STARTING LAT 8.6000000 LON 297.84000 TIME 7: 51
ENDING LAT -8888.0000 LON -8888.0000 TIME 7: 59



ORBIT 3075 UNIQUE # 620 DATE 11/ 13/ 75
STARTING LAT 8.6000000 LON 297.84000 TIME 7: 51
ENDING LAT -8888.0000 LON -8888.0000 TIME 7: 59



ORBIT 3075 UNIQUE # 620 DATE 11/ 13/ 75
STARTING LAT 8.6000000 LON 297.84000 TIME 7: 51
ENDING LAT -8888.0000 LON -8888.0000 TIME 7: 59



ORBIT 3152　　　NOV. 18, 1975　　　18:57 TO 19:09

SOUTHBOUND　　ATLANTIC

DENMARK, NORTH SEA, OVER ENGLAND, EAST OF NORMANDY, MISSES NW CORNER OF SPAIN, TO 27.3° N, 336.0° E

26 POINTS　　　RMS 1.0 M　　　BIAS - 0.6 M

HIGHEST SOWM; ON TRACK 3.2 M; IN FIELD 3.6 M

HIGHEST GEOS; ON GRID 4.0 M; AT ONE POINT 4.4 M

LOWEST SOWM; ON TRACK 0.2 M; IN FIELD 0.2 M

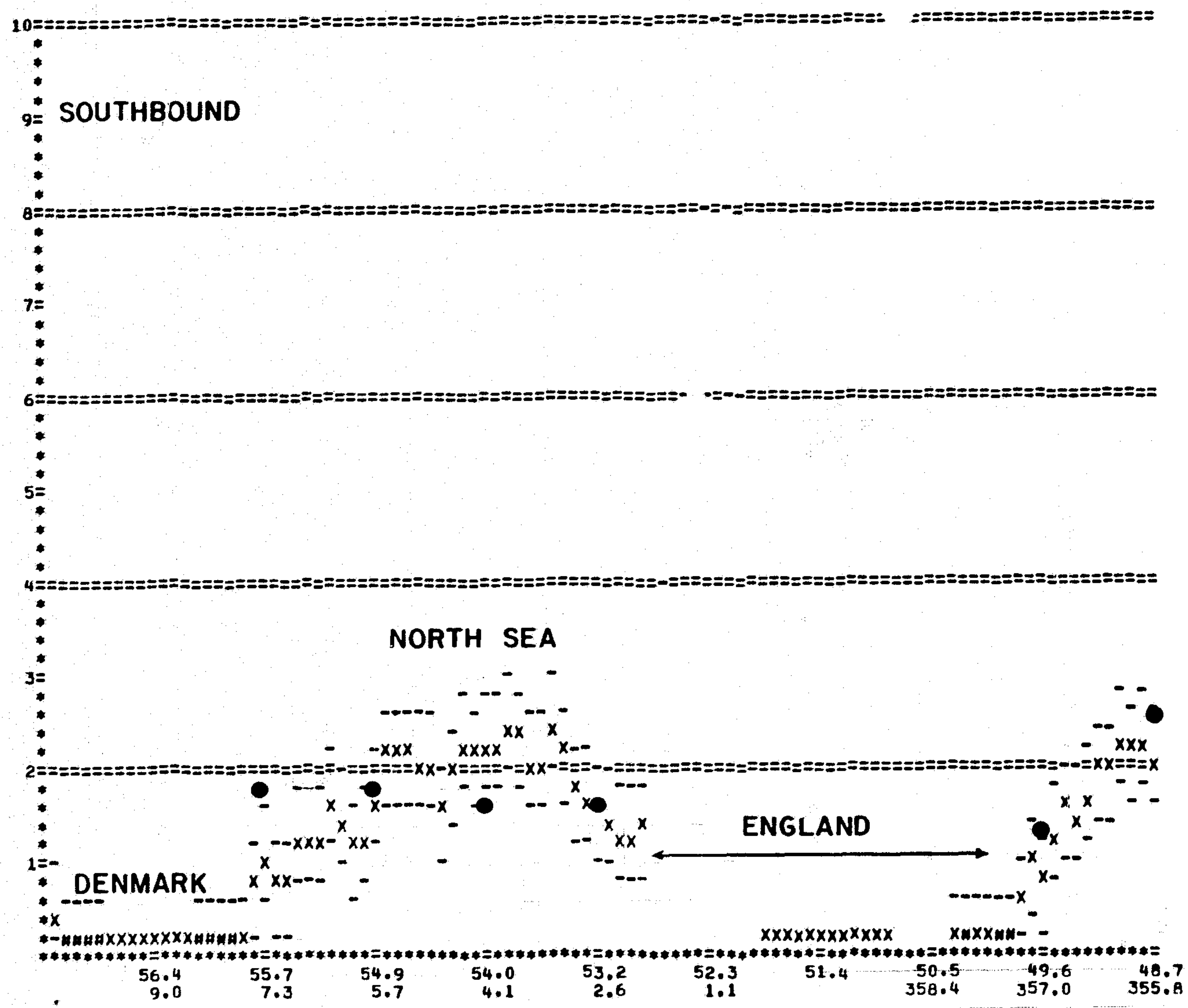
LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 1.9 M; SOWM 2.1 M, GEOS 4.0 M

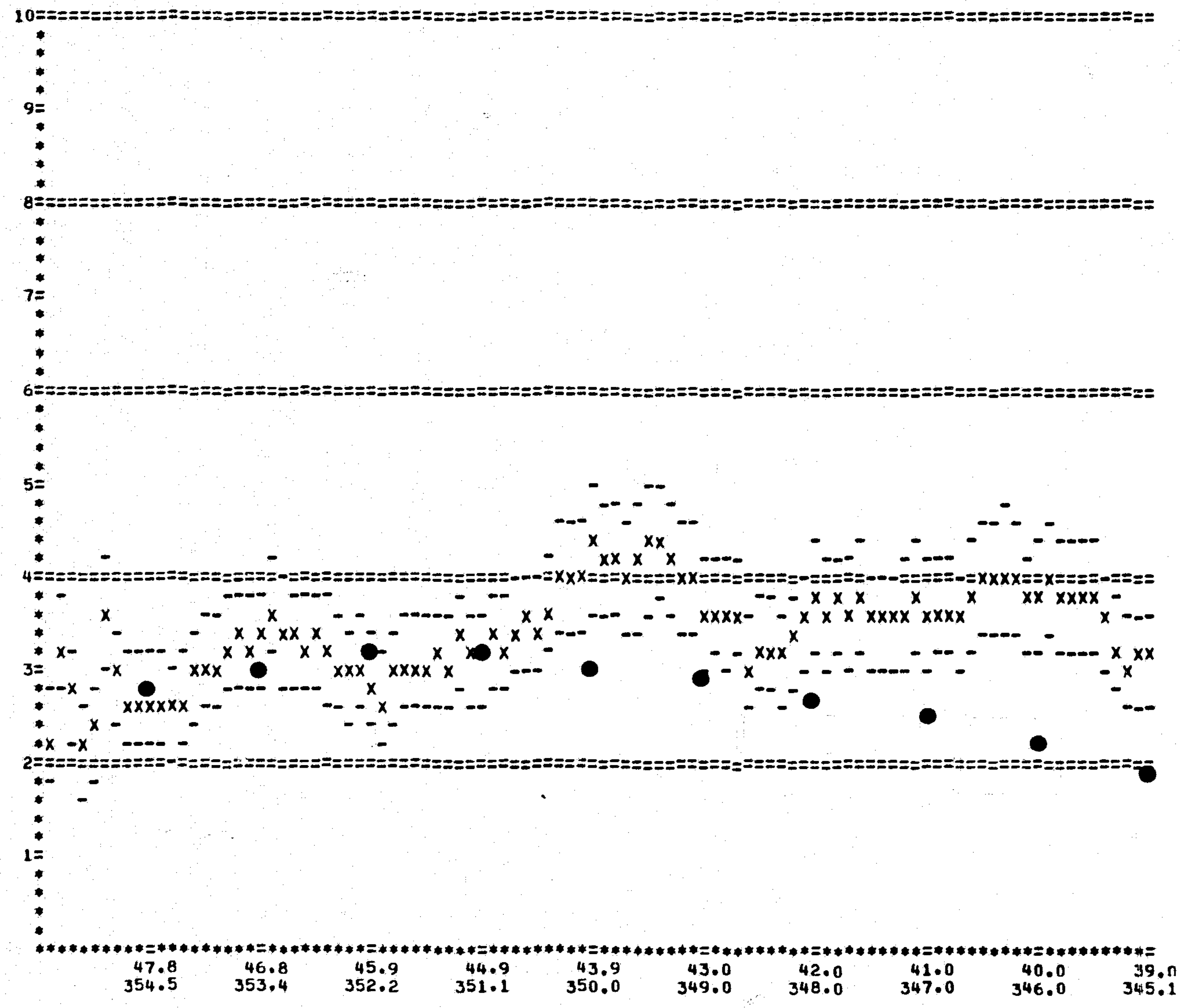
(ALSO) SOWM 0.7 M, GEOS 2.6 M

Excellent agreement North Sea and south of England to 45° N. SOWM too low south of 45° N. Winds near 11.5 m/s instead of 9.2 m/s could explain the difference.

ORBIT 3152 UNIQUE # 660 DATE 11/ 18/ 75
STARTING LAT 57.150000 LON 10.630000 TIME 18: 57
ENDING LAT 21.750000 LON 21.750000 TIME 19: 9



ORBIT 3152 UNIQUE # 660 DATE 11/ 18/ 75
STARTING LAT 57.150000 LON 10.630000 TIME 18: 57
ENDING LAT 21.750000 LON 21.750000 TIME 19: 9



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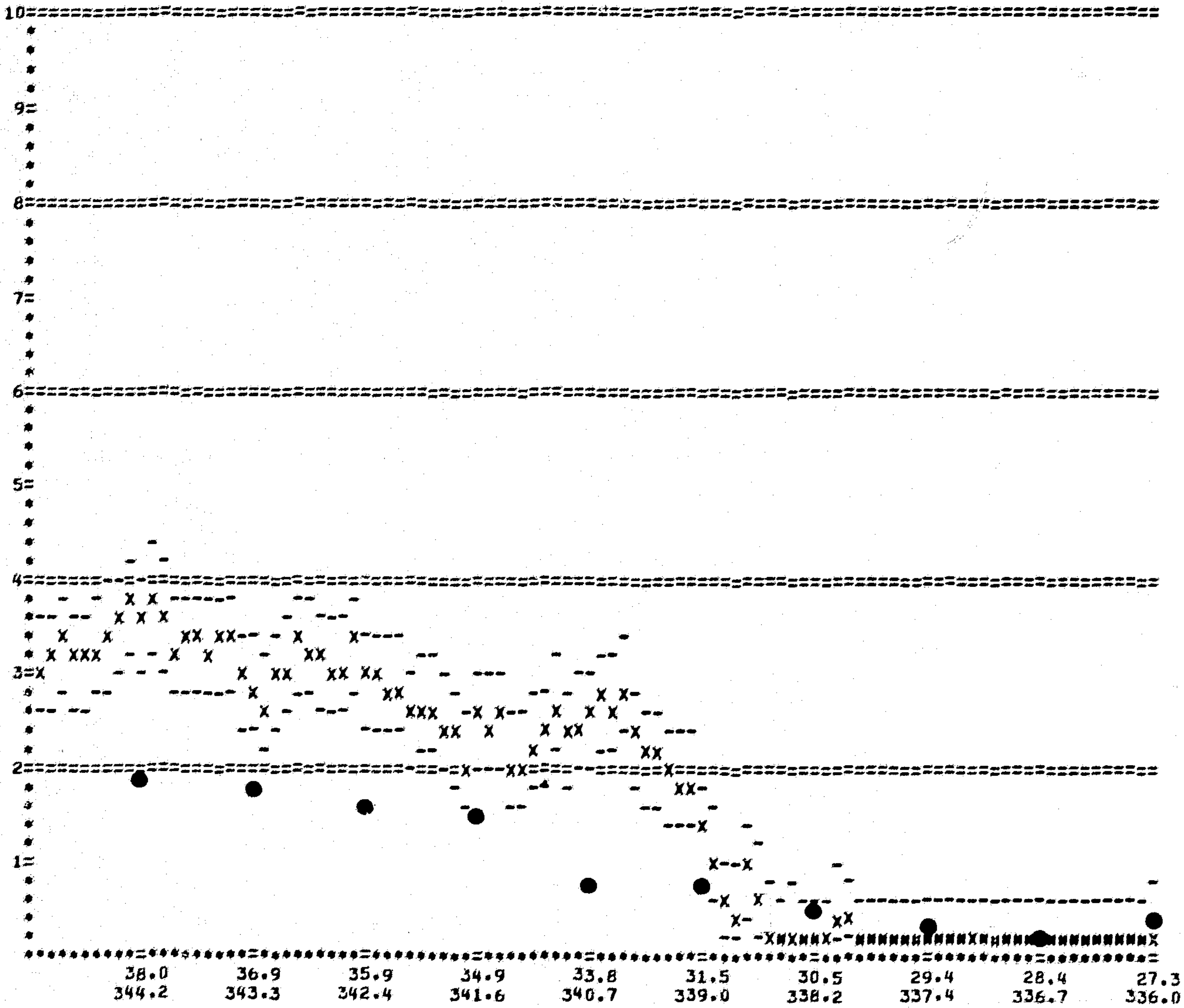
        ORBIT        3152  UNIQUE #          660  DATE            11/              18/            75
STARTING LAT  57.150000      LON  10.630000      TIME            18:              57
  ENDING LAT  21.750000      LON  21.750000      TIME            19:               9
```



ORBIT 3167 NOV. 19, 1975 20:21 TO 20:31

SOUTHBOUND ATLANTIC

NORWAY, NORTH OF SCOTLAND AND IRELAND TO 38° N, 324° E

29 POINTS RMS 1.1 M BIAS + 0.5 M

HIGHEST SOWM; ON TRACK 5.2 M; IN FIELD 5.3 M

HIGHEST GEOS; ON GRID 4.0 M; AT ONE POINT 4.0 M

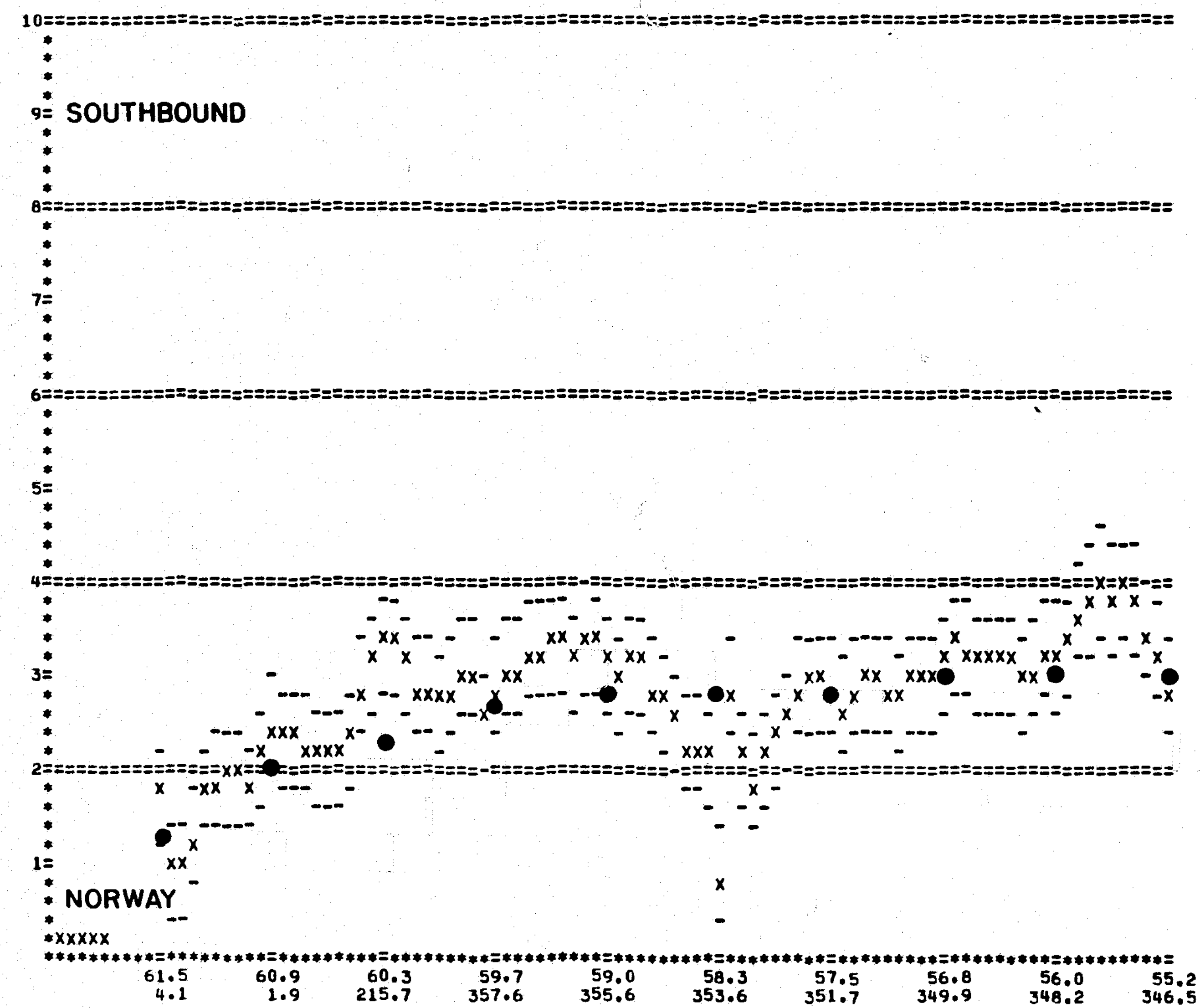
LOWEST SOWM; ON TRACK 1.3 M; IN FIELD 1.3 M

LOWEST GEOS; ON GRID 1.0 M; AT ONE POINT 0.2 M

LARGEST ERROR + 2.6 M; SOWM 4.4 M, GEOS 1.8 M

Largest error is caused by brief dip in GEOS heights near 42° N. Only one error over two meters. Waves of 3.8 m and 4 m measured by GEOS are specified to be 5 to 5.2 m by SOWM. Actual winds may have been closer to 14 m/s instead of 15.5 m/s at 44° to 39° N.

ORBIT 3167 UNIQUE # 668 DATE 11/ 19/ 75
STARTING LAT 62.010000 LON 6.2500000 TIME 20: 21
ENDING LAT 37.680000 LON 37.680000 TIME 20: 31



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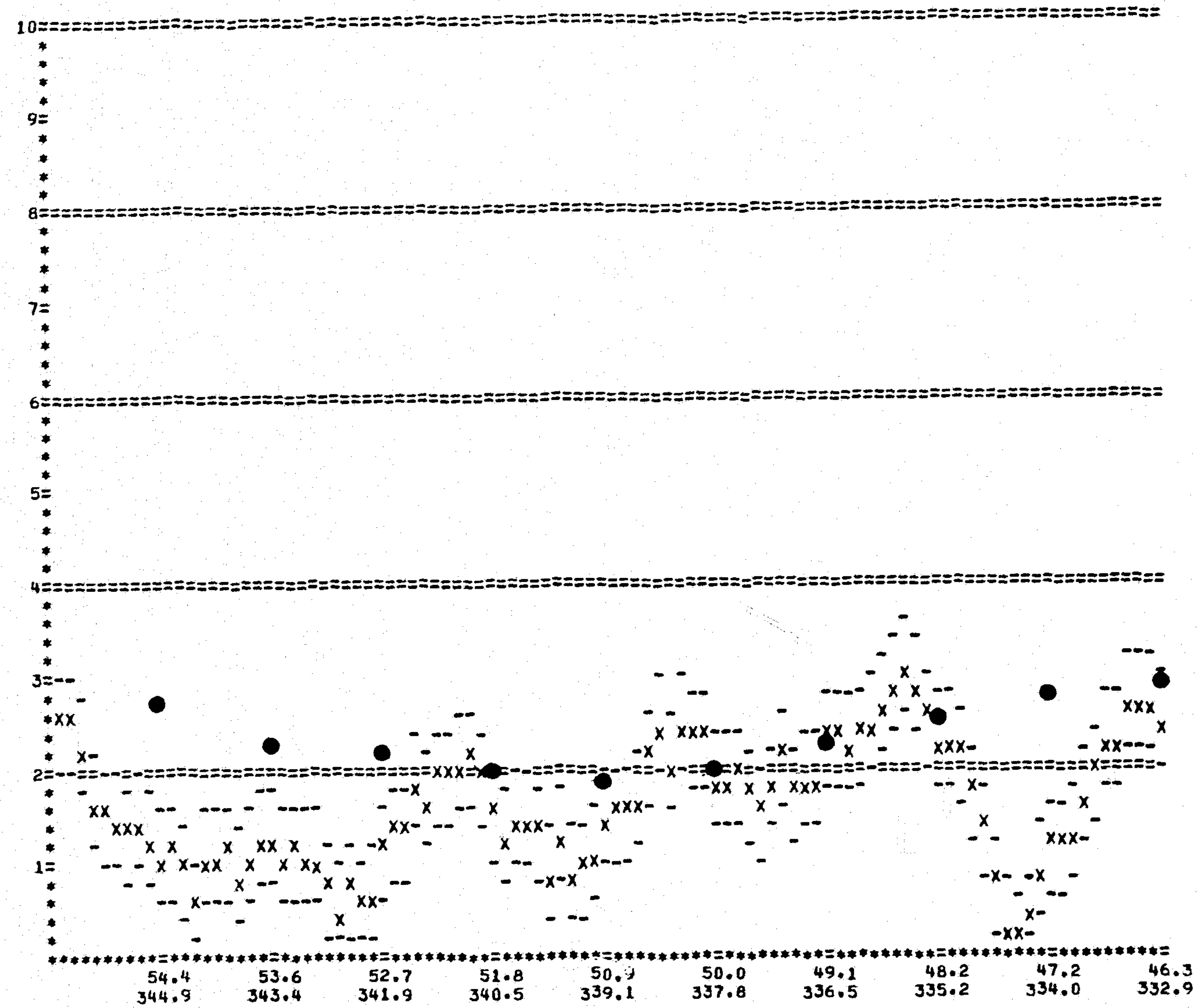
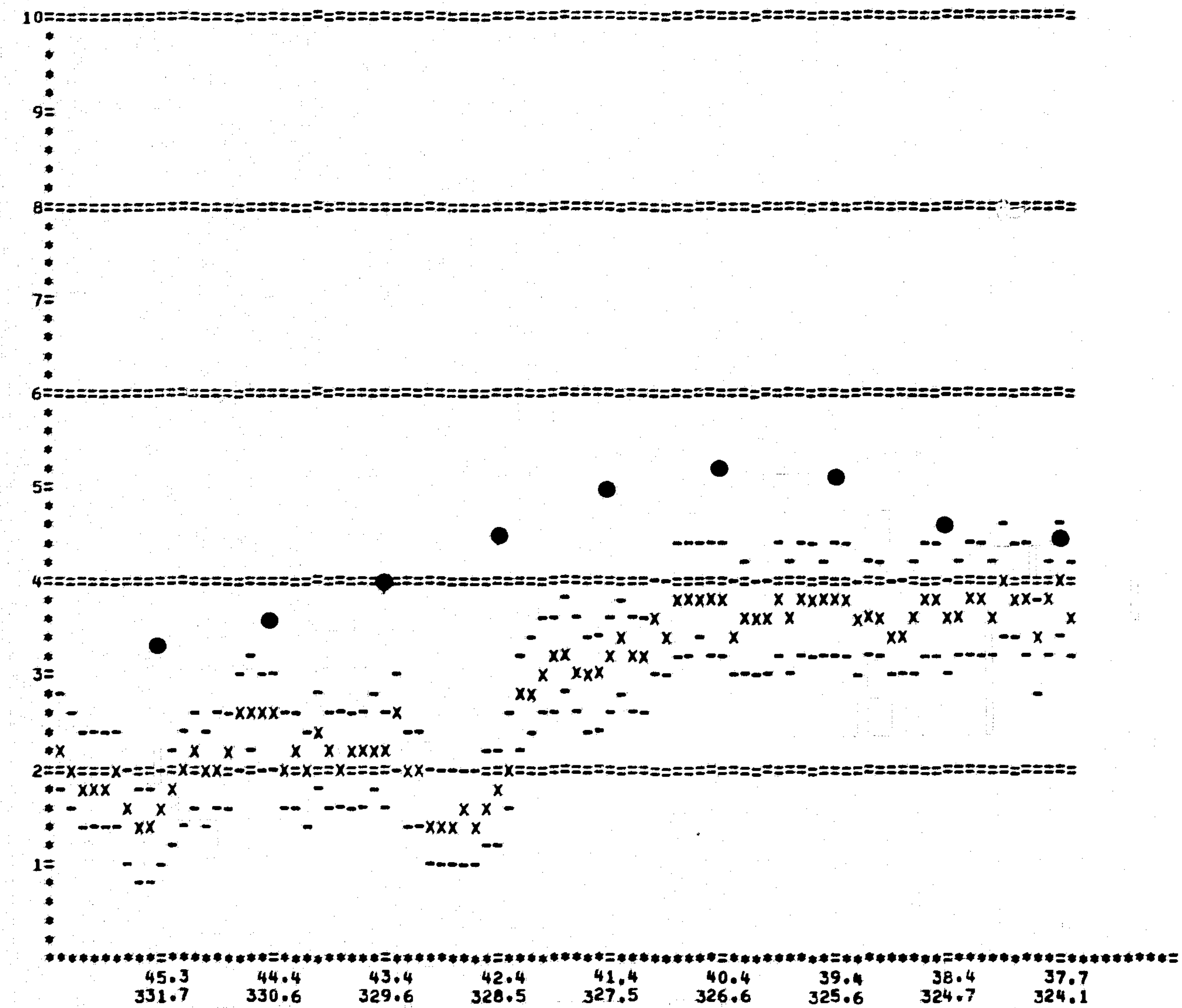
ORIGINAL PAGE IS OF POOR QUALITY

ORBIT 3167 UNIQUE # 668 DATE 11/ 19/ 75
STARTING LAT 62.010000 LON 6.2500000 TIME 20: 21
ENDING LAT 37.680000 LON 37.680000 TIME 20: 31



ORBIT 3167 UNIQUE # 668 DATE 11/ 19/ 75
STARTING LAT 62.010000 LON 6.2500000 TIME 20: 21
ENDING LAT 37.680000 LON 37.680000 TIME 20: 31



ORBIT 3214 NOV. 23, 1975 4:25

SOUTHBOUND PACIFIC

SMALL SOUTHBOUND SEGMENT NEAR EQUATOR; 5.6° N, 193.0° E TO 0° N, 190.0° E

6 POINTS RMS 1.2 M BIAS - 1.1 M

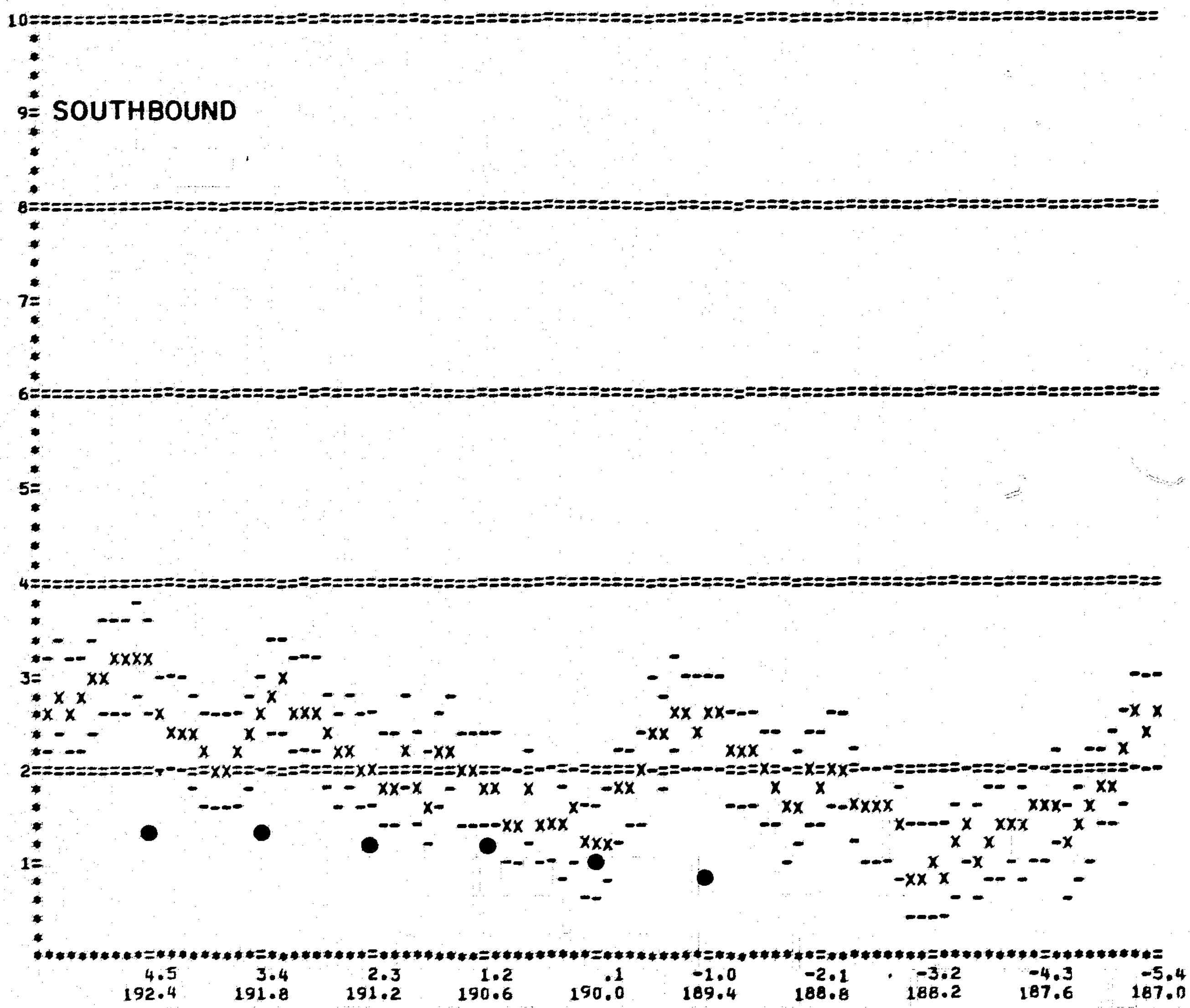
LAT	SOWM	GEOS	S - G
6	1.3	2.6	- 1.3
5	1.2	3.2	- 2.0
3	1.2	2.6	- 1.4
2	1.1	2.0	- 0.9
1	1.0	1.8	- 0.8
0	0.8	1.2	- 0.4

HIGHEST SOWM IN FIELD 1.3 M

HIGHEST GEOS 3.2 M

Either the winds were about 12.2 m/s in the area instead of 7.5 m/s or a high 3 m swell was running that was not forecast.

ORBIT 3214 UNIQUE # 698 DATE 11/ 23/ 75
STARTING LAT 5.5100000 LON 192.93000 TIME 4: 25
ENDING LAT -21.170000 LON -21.170000 TIME 4: 34



ORBIT 3229 NOV. 24, 1975 5:34 TO 5:44

SOUTHBOUND PACIFIC

GULF OF ALASKA NEAR SKAGWAY TO 36° N, 192° E

21 POINTS RMS 0.8 M BIAS - 0.5 M

HIGHEST SOWM; ON TRACK 6.3 M; IN FIELD 6.6 M

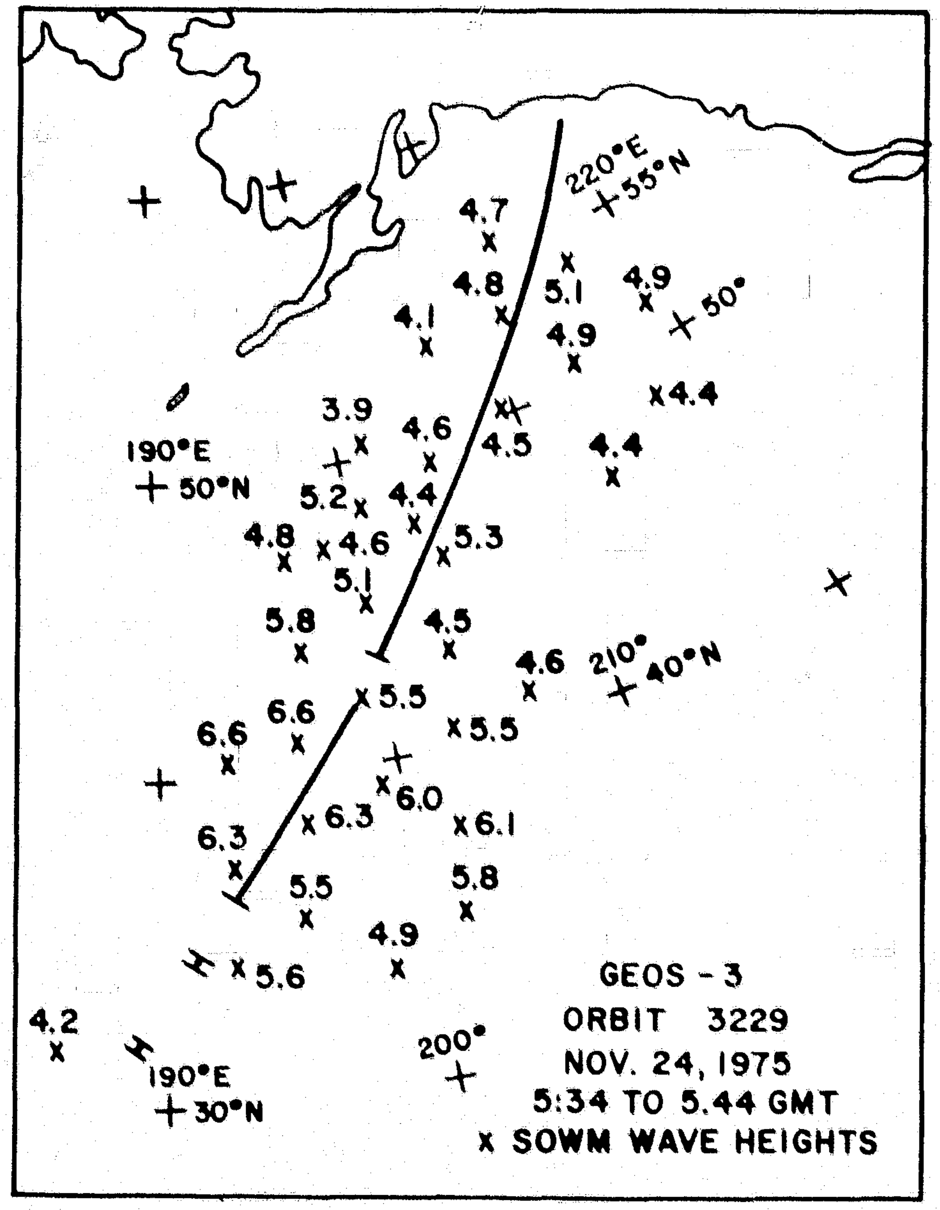
HIGHEST GEOS; ON GRID 6.8 M; AT ONE POINT 7.8 M

LOWEST SOWM; ON TRACK 4.4 M; IN FIELD 3.9 M

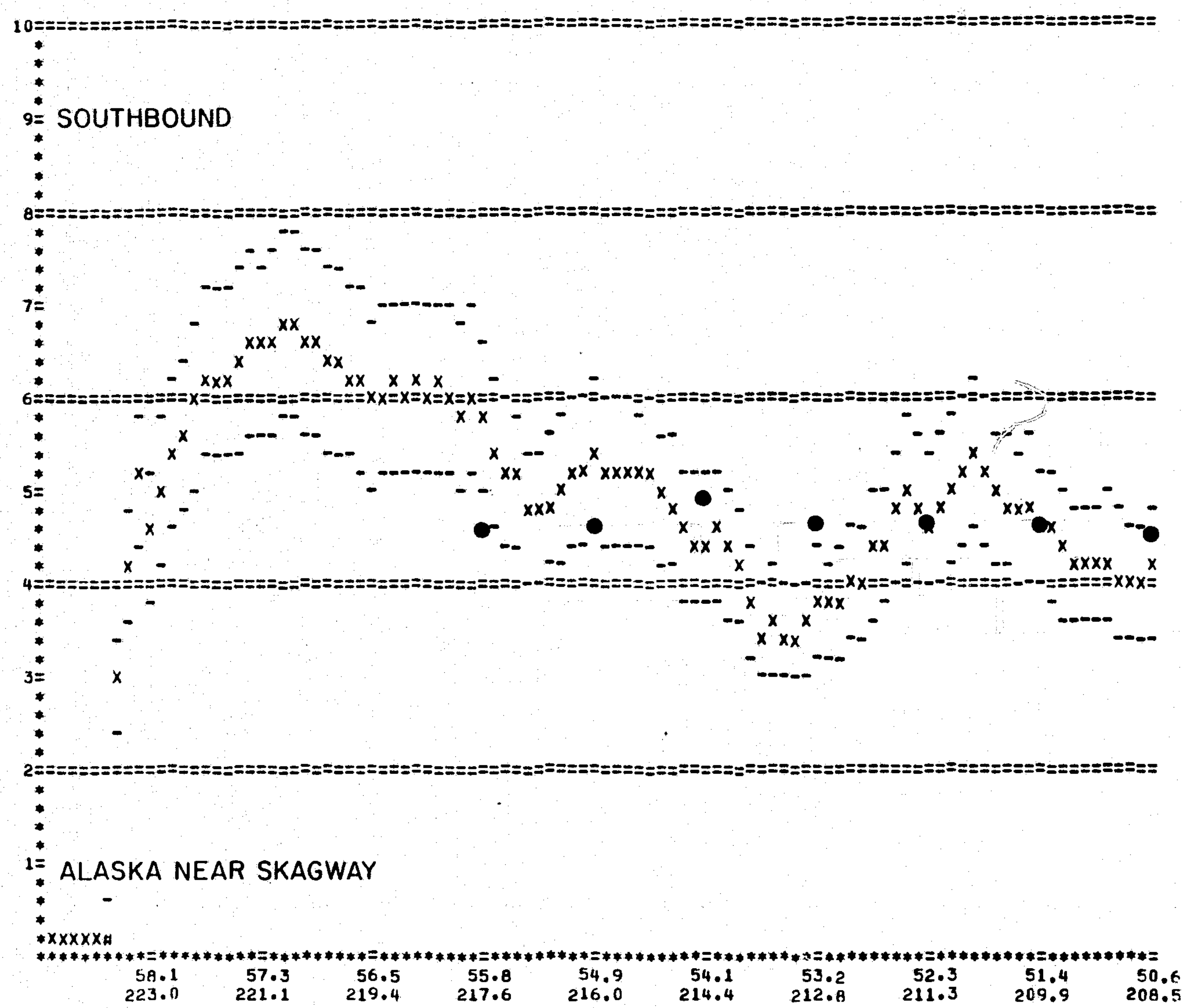
LOWEST GEOS; ON GRID 3.8 M; AT ONE POINT 3.4 M

LARGEST ERROR - 1.6 M; SOWM 4.6 M, GEOS 6.2 M, AND
SOWM 5.0 M, GEOS 6.6 M

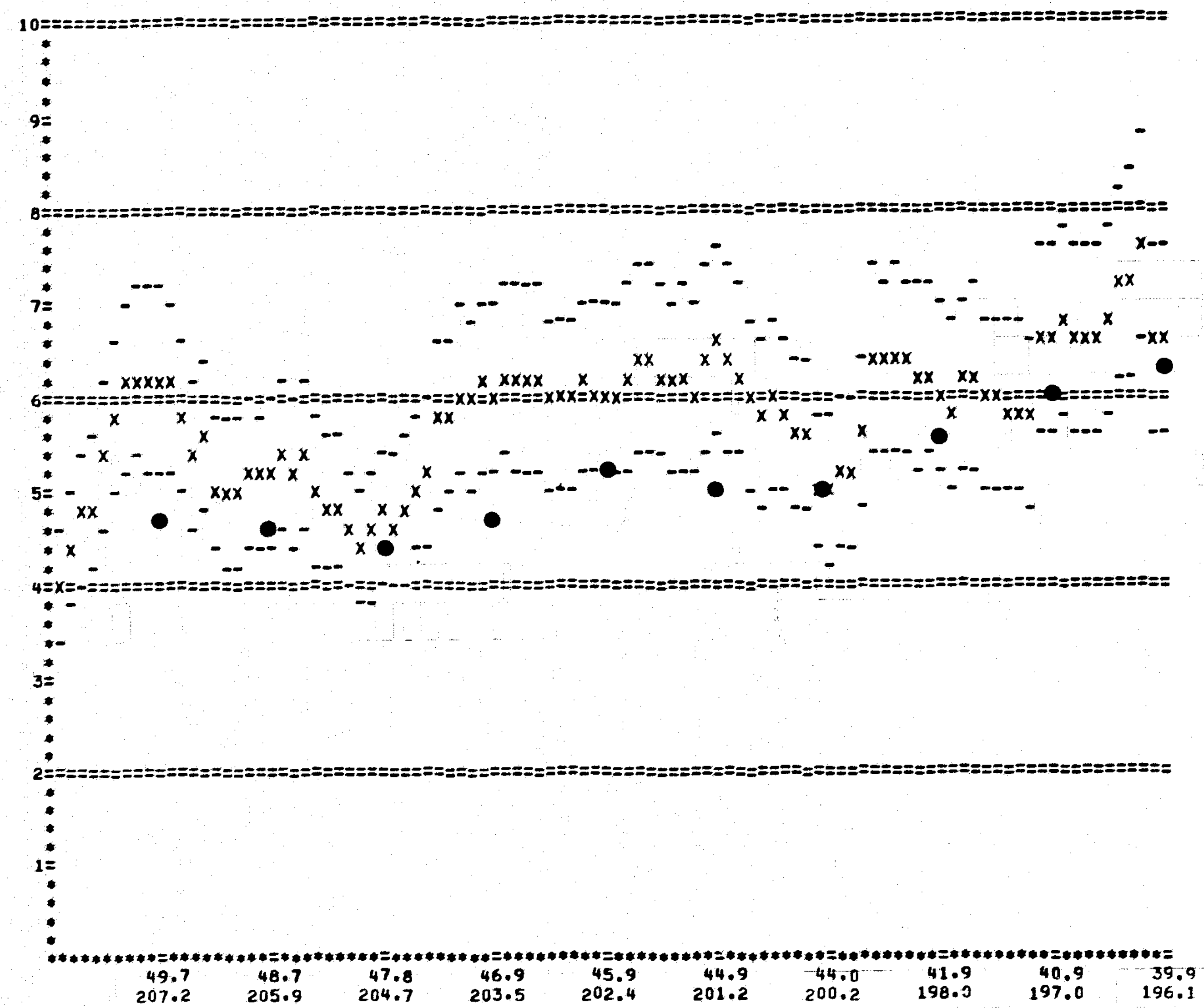
SOWM slightly too low and does not track 2 meter oscillations in measured waves. A slightly stronger wind of 17 m/s instead of 16 m/s would produce better agreement.


220°E
55°N
50°
190°E
50°N
210°
40°N
190°E
30°N
200°
4.7
4.8
5.1
4.9
4.1
4.9
4.4
3.9
4.6
4.5
4.4
5.2
4.4
4.8
4.6
5.3
5.1
5.8
4.5
4.6
5.5
6.6
6.6
5.5
6.0
6.3
6.1
6.3
5.5
5.8
4.9
5.6
4.2
GEOS - 3
ORBIT 3229
NOV. 24, 1975
5:34 TO 5.44 GMT
x SOWM WAVE HEIGHTS

ORBIT	3229	UNIQUE #		708	DATE	11/	24/	75
STARTING LAT	58.690000	LON	224.72000		TIME	5:	34	
ENDING LAT	-8888.0000	LON	-8888.0000		TIME	5:	44	



ORBIT 3229 UNIQUE # 708 DATE 11/ 24/ 75
STARTING LAT 58.690000 LON 224.72000 TIME 5: 34
ENDING LAT -8888.0000 LON -8888.0000 TIME 5: 44



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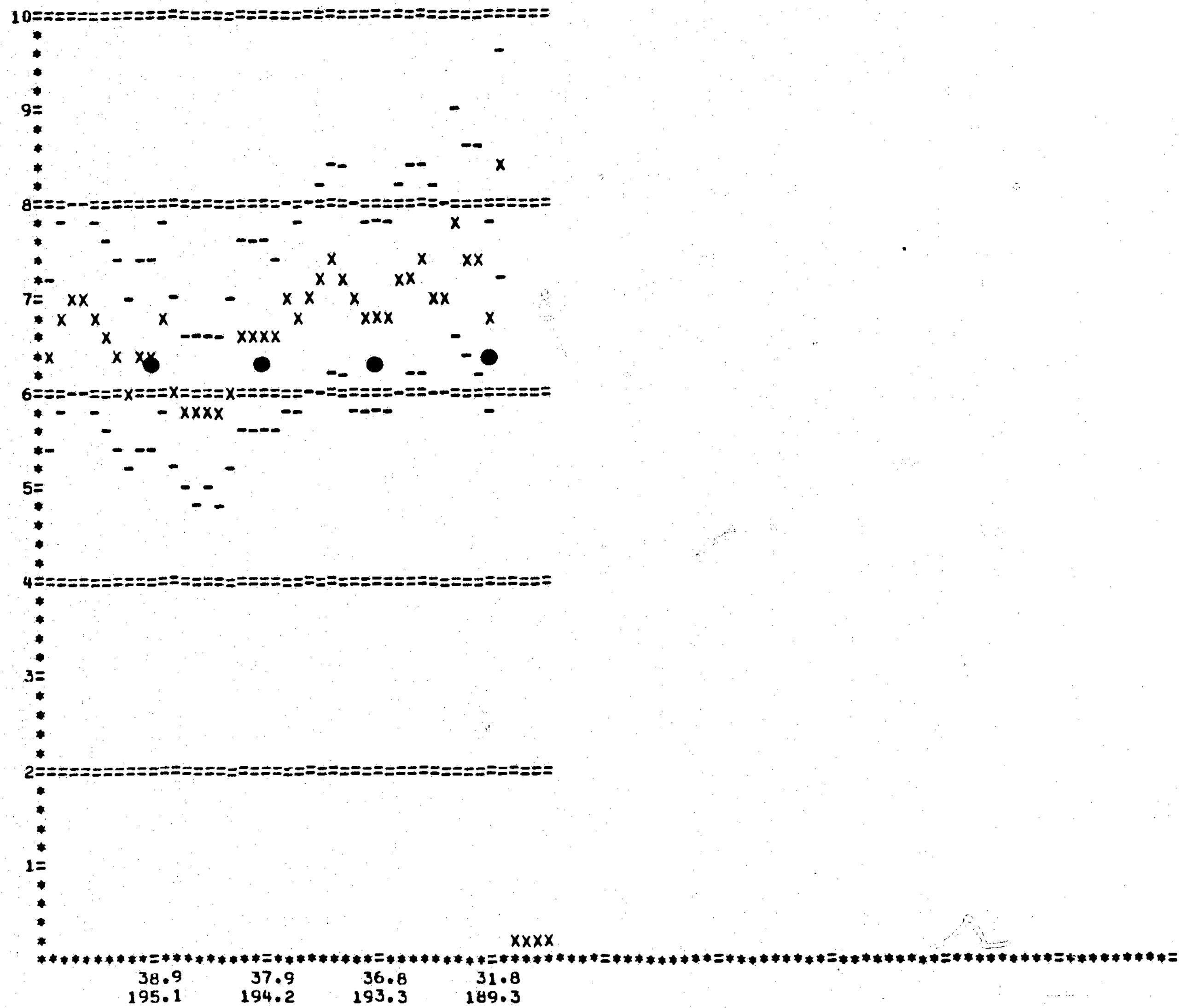
ORBIT 3229 UNIQUE # 708 DATE 11/ 24/ 75
STARTING LAT 58.690000 LON 224.72000 TIME 5: 34
ENDING LAT -8888.0000 LON -8888.0000 TIME 5: 44



ORBIT 3231 NOV. 24, 1975 8:31 TO 8:35

NORTHBOUND ATLANTIC

15° N, 304° E TO COAST OF NEW JERSEY

23 POINTS RMS 1.1 M BIAS - 0.7 M

HIGHEST SOWM; ON TRACK 4.0 M; IN FIELD 4.3 M

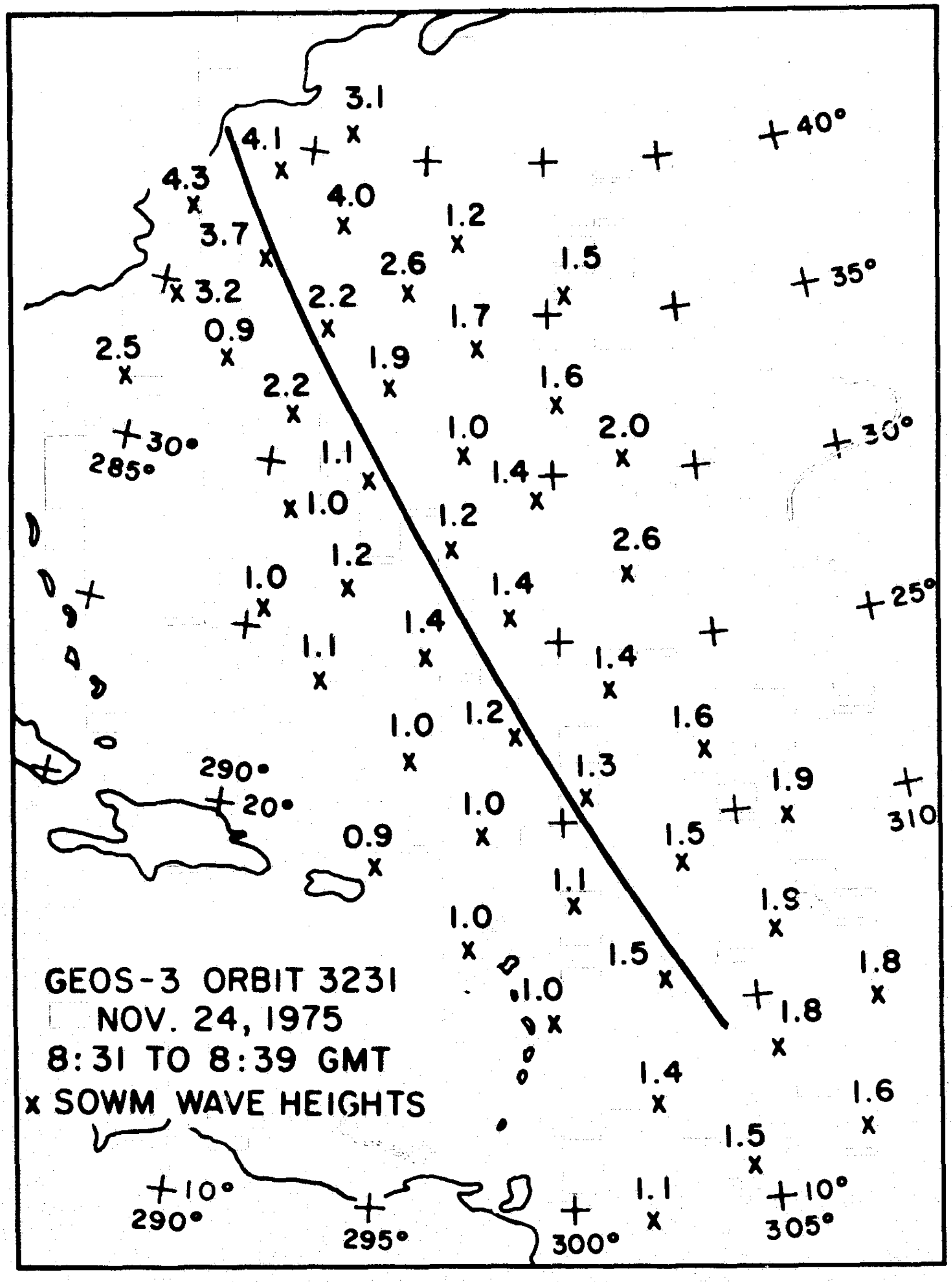
HIGHEST GEOS; ON GRID 4.0 M; AT ONE POINT 4.8 M

LOWEST SOWM; ON TRACK 0.9 M; IN FIELD 0.9 M

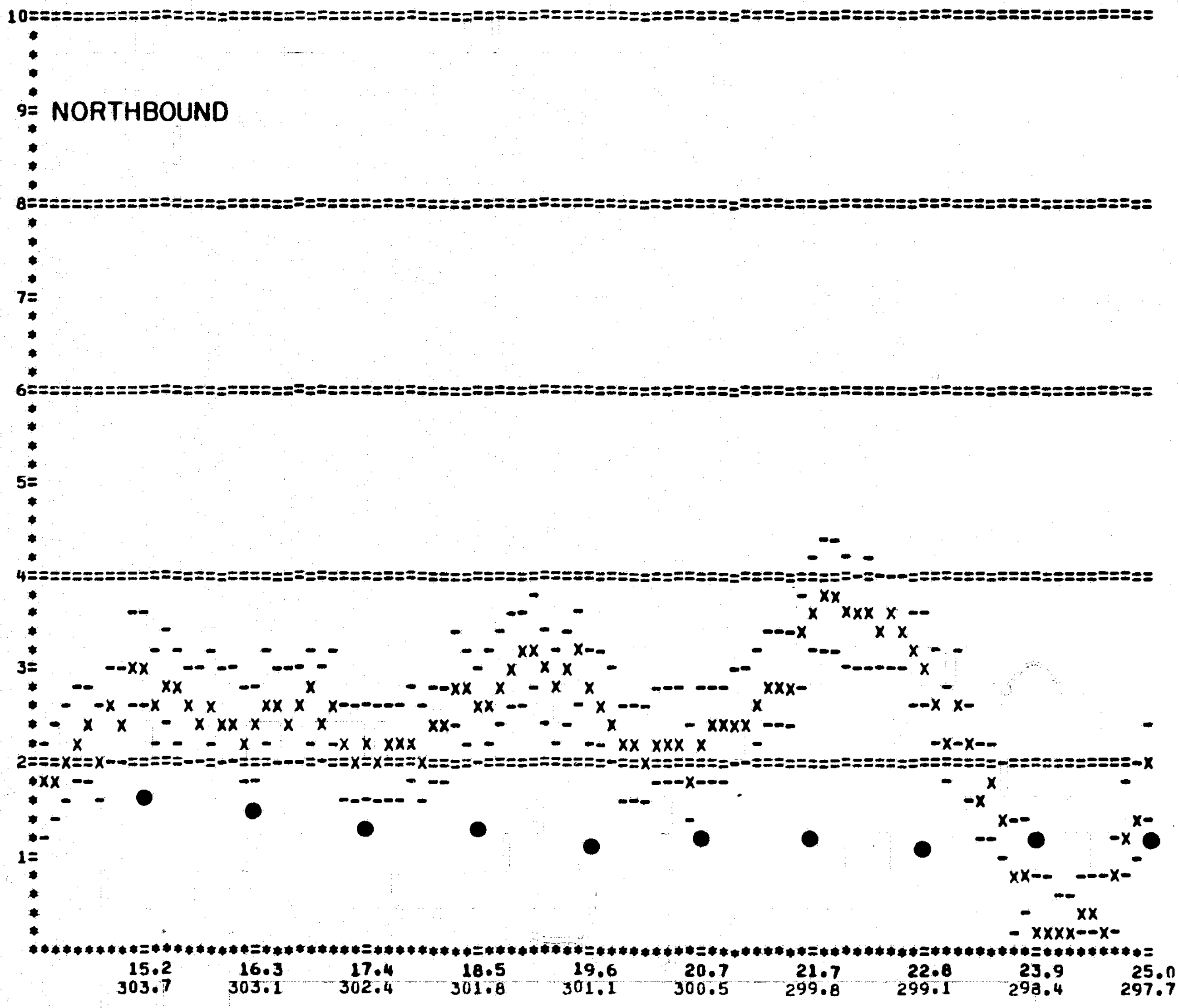
LOWEST GEOS; ON GRID 0.4 M; AT ONE POINT 0.2 M

LARGEST ERROR - 1.9 M; SOWM 1.1 M, GEOS 3.0 M

SOWM too low by one to two meters southern portion of pass. Winds from 15° N to 28° N may have been 12 to 13 m/s instead of 8 m/s. Missed 4 m waves at 35° N. Good agreement near New Jersey coast.


GEOS-3 ORBIT 3231
NOV. 24, 1975
8:31 TO 8:39 GMT
x SOWM WAVE HEIGHTS
40°
35°
30°
25°
20°
10°
285°
290°
295°
300°
305°
310

ORBIT 3231 UNIQUE # 712 DATE 11/ 24/ 75
STARTING LAT 14.230000 LON 304.26000 TIME 8: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 8: 39



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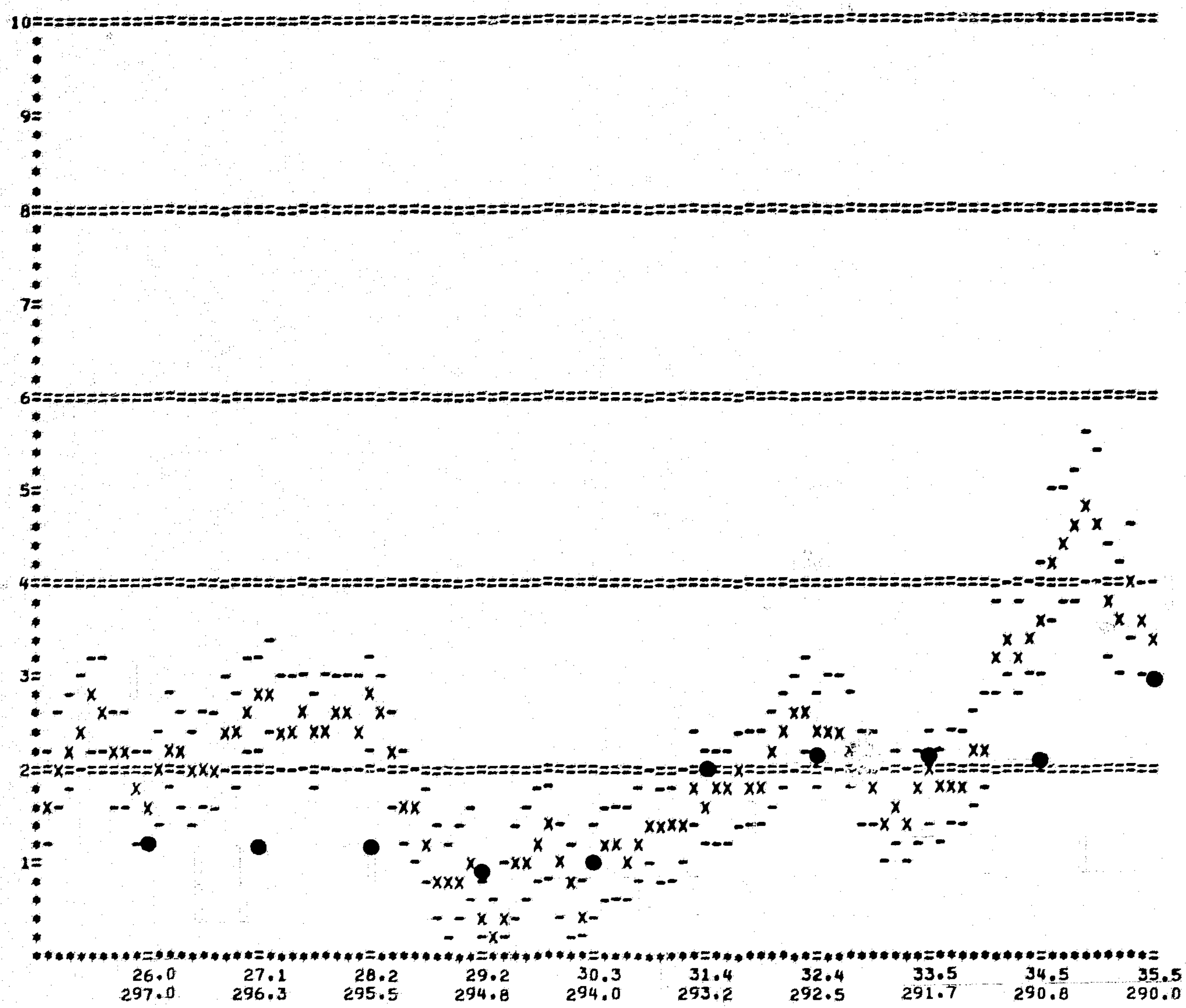
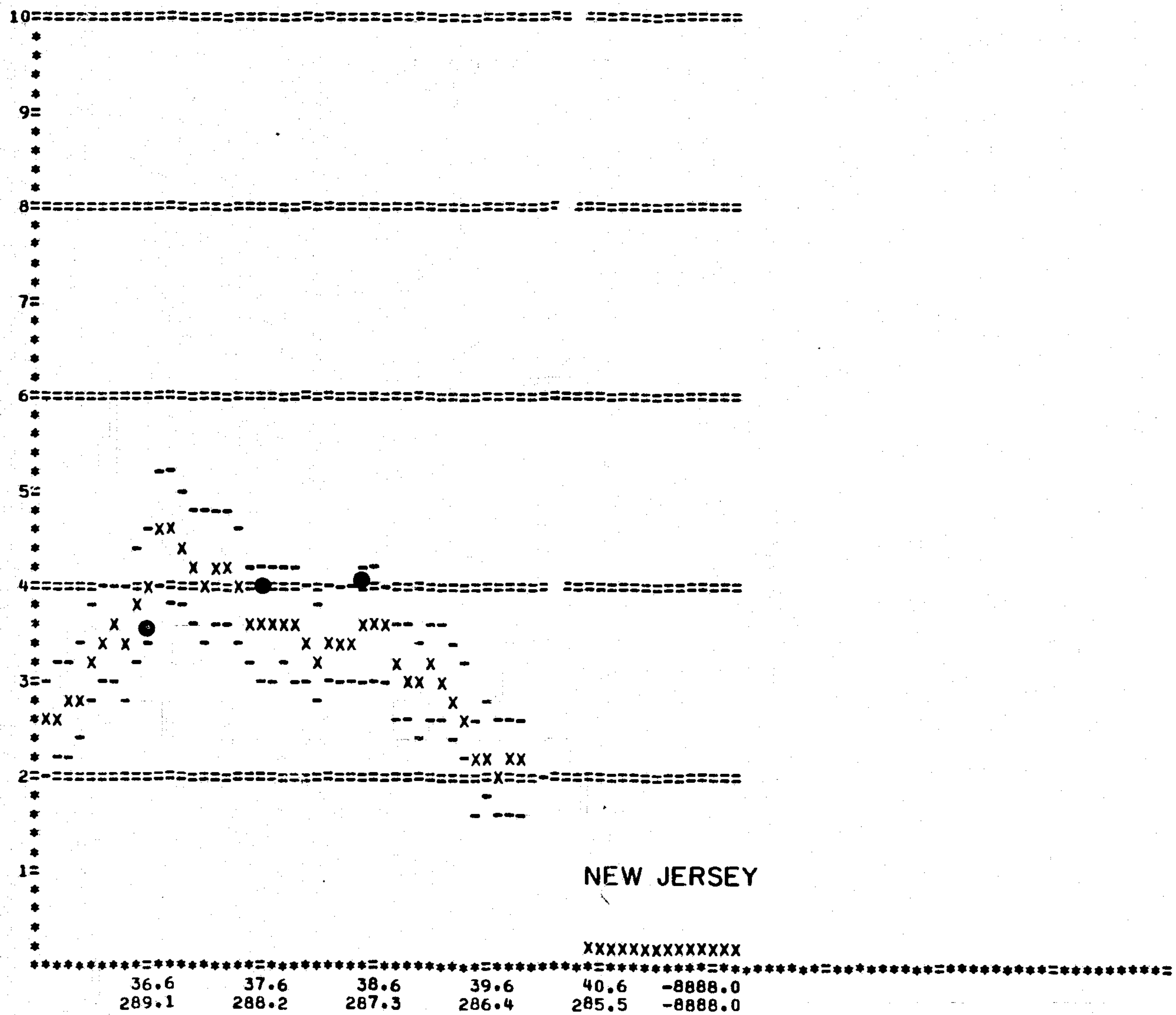
ORBIT 3231 UNIQUE # 712 DATE 11/ 24/ 75
STARTING LAT 14.230000 LON 304.26000 TIME 8: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 8: 39



ORBIT 3231 UNIQUE # 712 DATE 11/ 24/ 75
STARTING LAT 14.230000 LON 304.26000 TIME 8: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 8: 39



ORBIT 3291 NOV. 28, 1975 15:40 TO 16:15

NORTHBOUND PACIFIC

EQUATOR NEAR 206° E, WEST OF HAWAIIAN ISLANDS, TO KAMCHATKA PENINSULA

38 POINTS RMS 1.4 M BIAS - 1.0 M

HIGHEST SOWM; ON TRACK 7.2 M; IN FIELD 7.4 M

HIGHEST GEOS; ON GRID 8.4 M; AT ONE POINT 8.8 M

LOWEST SOWM; ON TRACK 0.3 M; IN FIELD 0.3 M

LOWEST GEOS; ON GRID 1.8 M; AT ONE POINT 0.2 M (0)

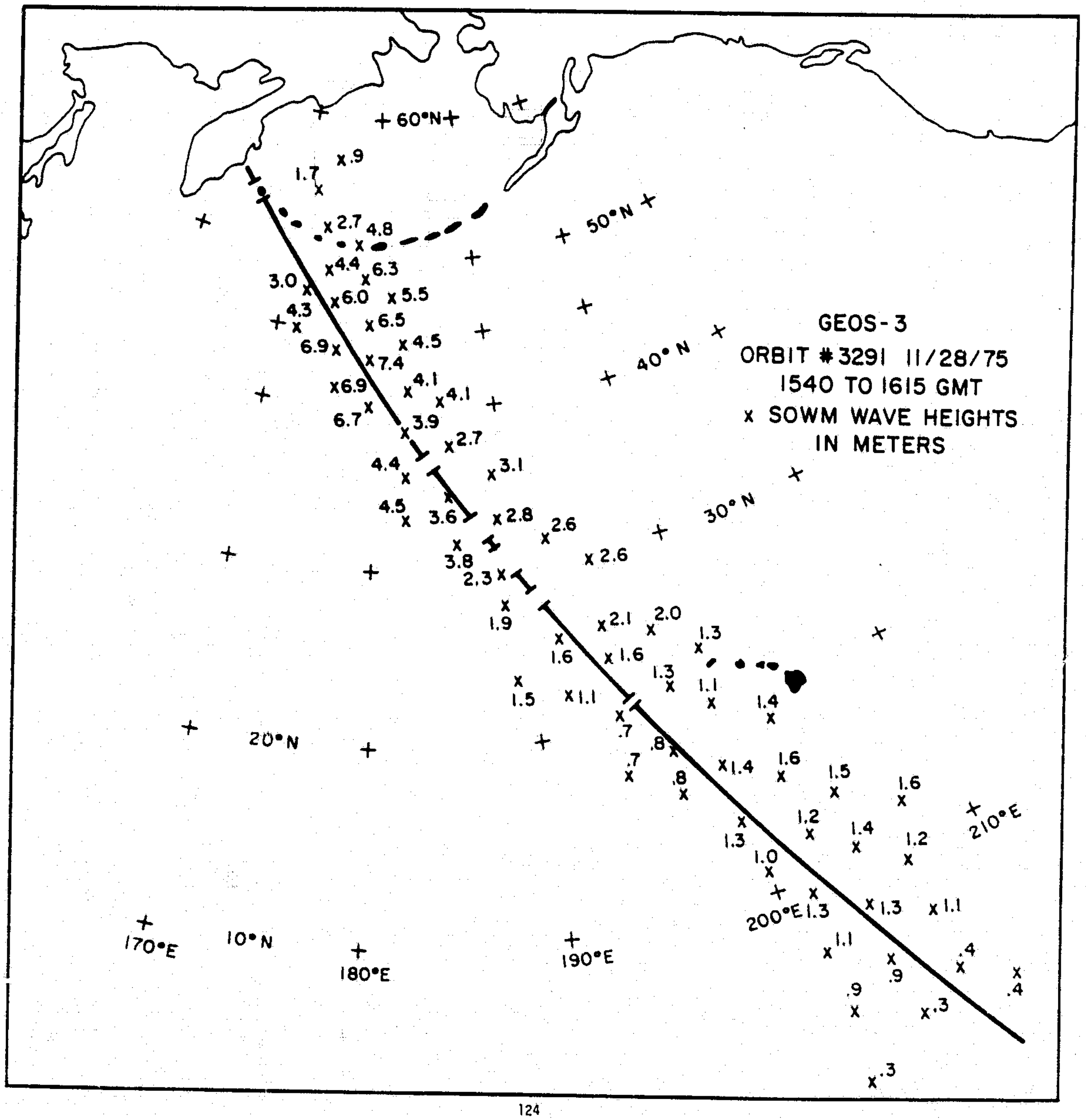
LARGEST ERROR - 2.3 M; SOWM 1.3 M, GEOS 3.6 M

SOWM too low to 35° N. Sudden increase in GEOS heights just north of 35° N missed by SOWM. Sudden increase in wave height may have been a dispersion effect in which waves generated to the north earlier in time have propagated with a high group velocity to the point defining the jump, but not past it. Excellent agreement 40° N to 50° N, missed peak 8.8 m waves in SOWM. Winds of 20 m/s instead of 19 m/s could have produced agreement near 44° N.

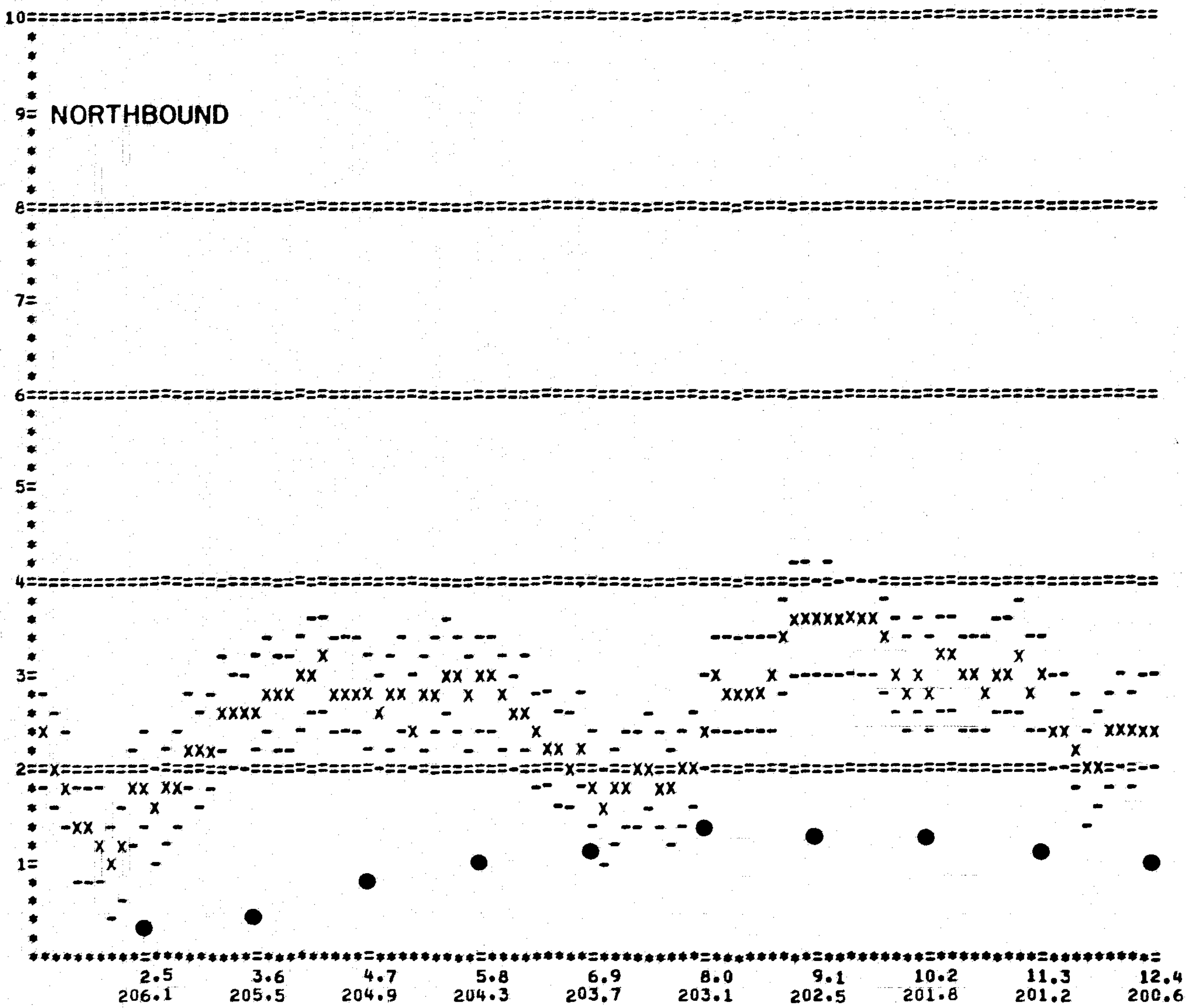
SEE TABLE NEXT PAGE.

ORBIT 3291 CONTINUED

LAT	SOWM	GEOS	S - G	LAT	SOWM	GEOS	S - G
3	0.3	1.8	- 1.5	23	1.6	1.2	+ 0.4
4	0.4	2.6	- 2.2	24	1.6	3.6	- 2.0
5	0.8	2.8	- 2.0	25	1.8	3.4	- 1.6
6	1.0	3.0	- 2.0	27	1.9	3.8	- 1.9
7	1.1	1.8	- 0.7	29	2.2	3.2	- 1.0
8	1.4	2.3	- 1.0	31	2.8	3.6	- 1.8
9	1.3	3.6	- 2.3	38	4.0	6.2	- 2.2
10	1.3	2.8	- 1.5	39	4.4	6.4	- 2.0
11	1.1	3.0	- 1.9	40	6.2	7.4	- 1.2
12	1.0	2.4	- 1.4	41	6.6	7.0	- 0.4
14	1.2	3.2	- 2.0	42	7.2	7.4	- 0.2
15	1.4	2.6	- 1.2	43	7.2	7.6	- 0.4
16	1.3	2.6	- 1.3	44	7.2	8.4	- 1.2
17	0.8	1.0	- 0.2	45	7.0	7.8	- 0.8
18	0.8	2.2	- 1.4	46	6.0	6.0	0
19	0.7	2.6	- 1.9	47	4.6	4.6	0
20	0.7	2.4	- 1.7	48	3.0	4.4	- 1.4
21	0.9	0.2	+ 0.7	49	2.6	2.8	- 0.2
22	1.4	2.0	- 0.6	50	2.2	2.2	0


GEOS-3
ORBIT #3291 11/28/75
1540 TO 1615 GMT
x SOWM WAVE HEIGHTS
IN METERS
60°N
50°N
40°N
30°N
20°N
10°N
170°E
180°E
190°E
200°E
210°E

ORBIT 3291 UNIQUE # 751 DATE 11/ 28/ 75
STARTING LAT -48.230000 LON 242.55000 TIME 15: 40
ENDING LAT 58.620000 LON 58.620000 TIME 16: 15



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ORBIT            3291  UNIQUE #          751  DATE           11/            28/          75
STARTING LAT -48.230000     LON  242.55000      TIME          15:            40
  ENDING LAT  58.620000     LON  58.620000      TIME          16:            15
```
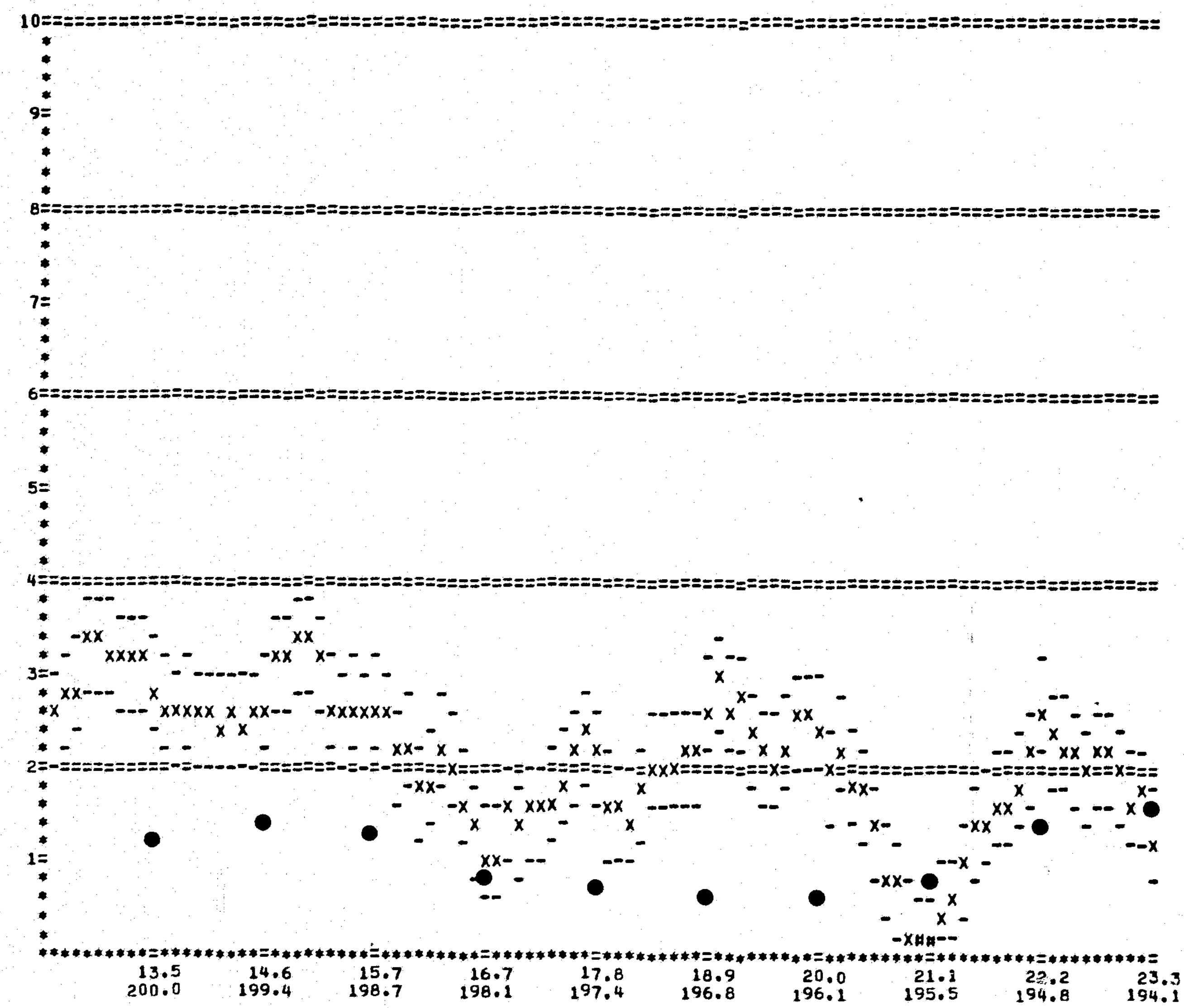
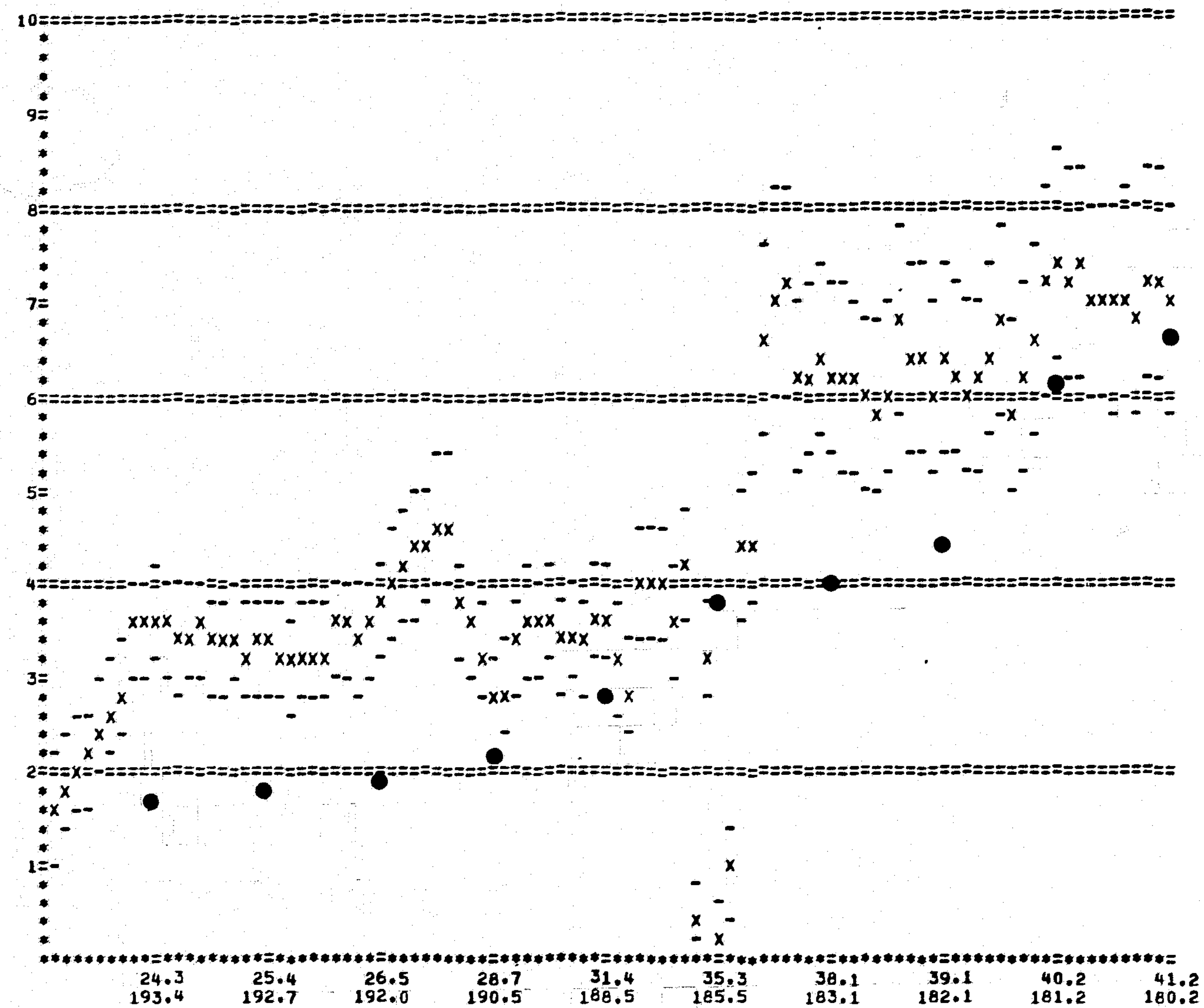
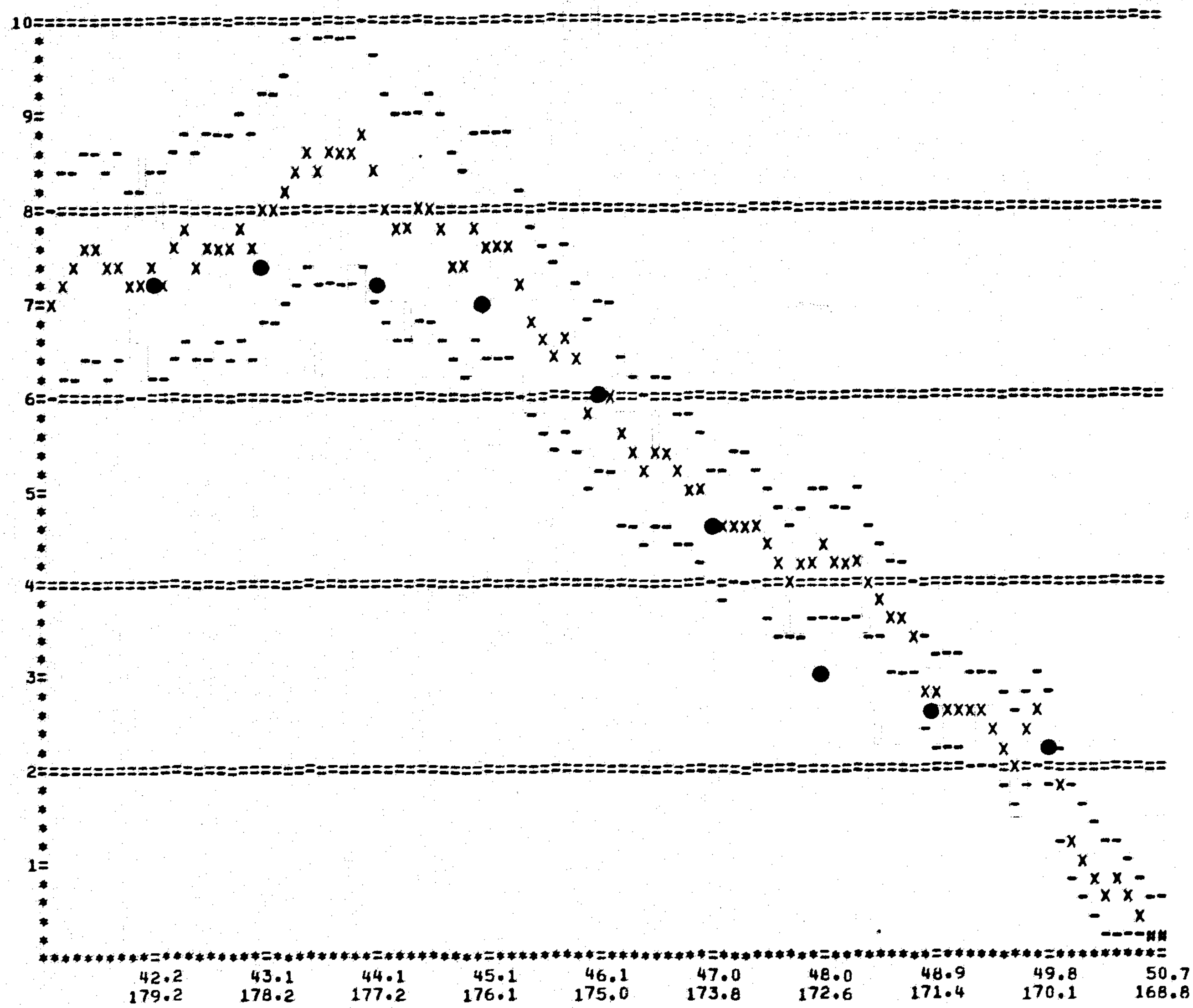



ORBIT 3291 UNIQUE # 751 DATE 11/ 28/ 75
STARTING LAT -48.230000 LON 242.55000 TIME 15: 40
ENDING LAT 58.620000 LON 58.620000 TIME 16: 15



ORBIT 3291 UNIQUE # 751 DATE 11/ 28/ 75
STARTING LAT -48.230000 LON 242.55000 TIME 15: 40
ENDING LAT 58.620000 LON 58.620000 TIME 16: 15



ORBIT 3430 DEC. 8, 1975 10:08 TO 10:15

NORTHBOUND ATLANTIC

20° N, 301° E TO NEW JERSEY

17 POINTS RMS 1.4 M BIAS + 0.3 M

HIGHEST SOWM; ON TRACK 5.8 M; IN FIELD 6.0 M

HIGHEST GEOS; ON GRID 3.8 M; AT ONE POINT 4.8 M

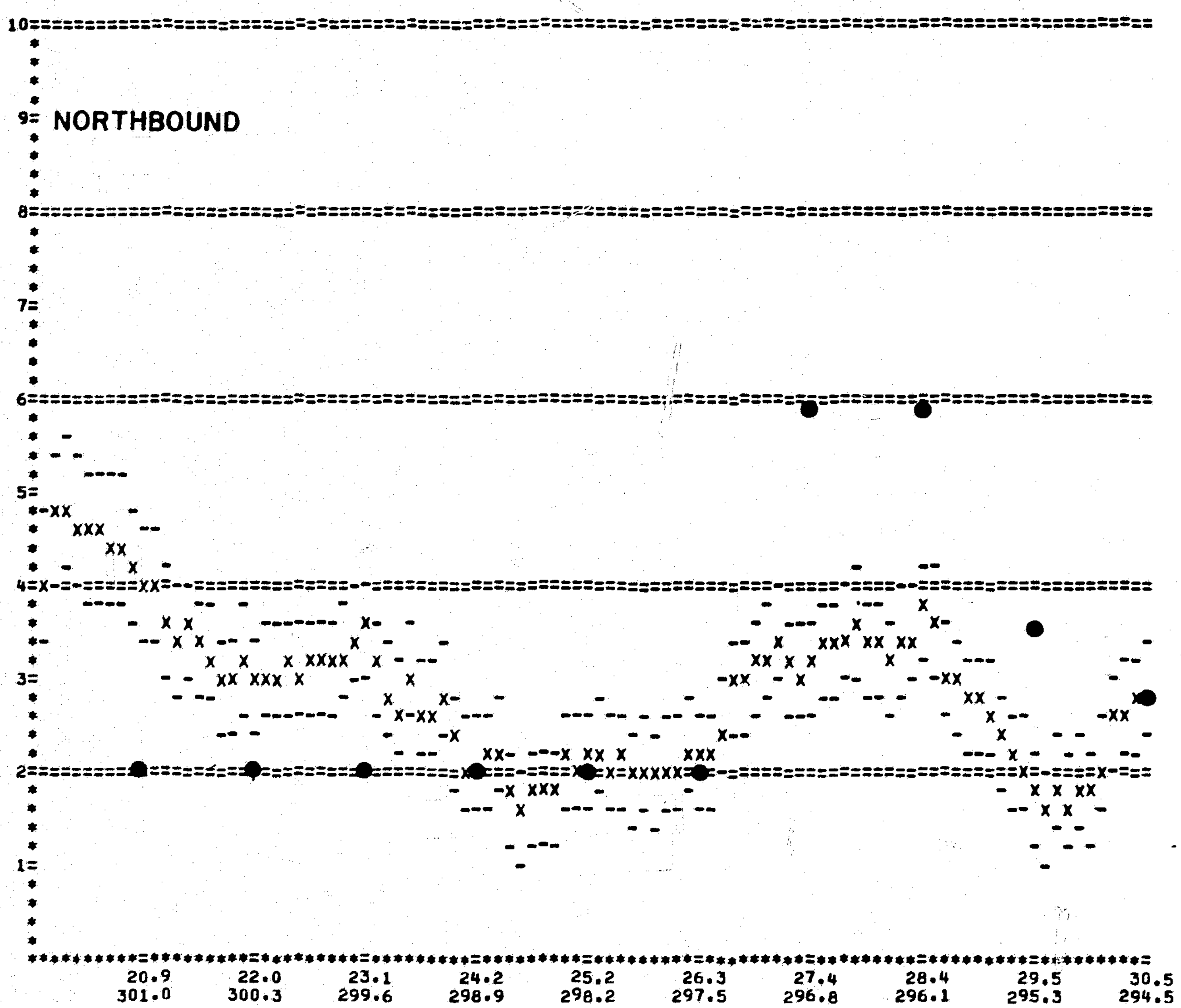
LOWEST SOWM; ON TRACK 1.0 M; IN FIELD 0.9 M

LOWEST GEOS; ON GRID 0.6 M; AT ONE POINT 0.6 M

LARGEST ERROR + 2.6 M; SOWM 5.8 M, GEOS 3.2 M

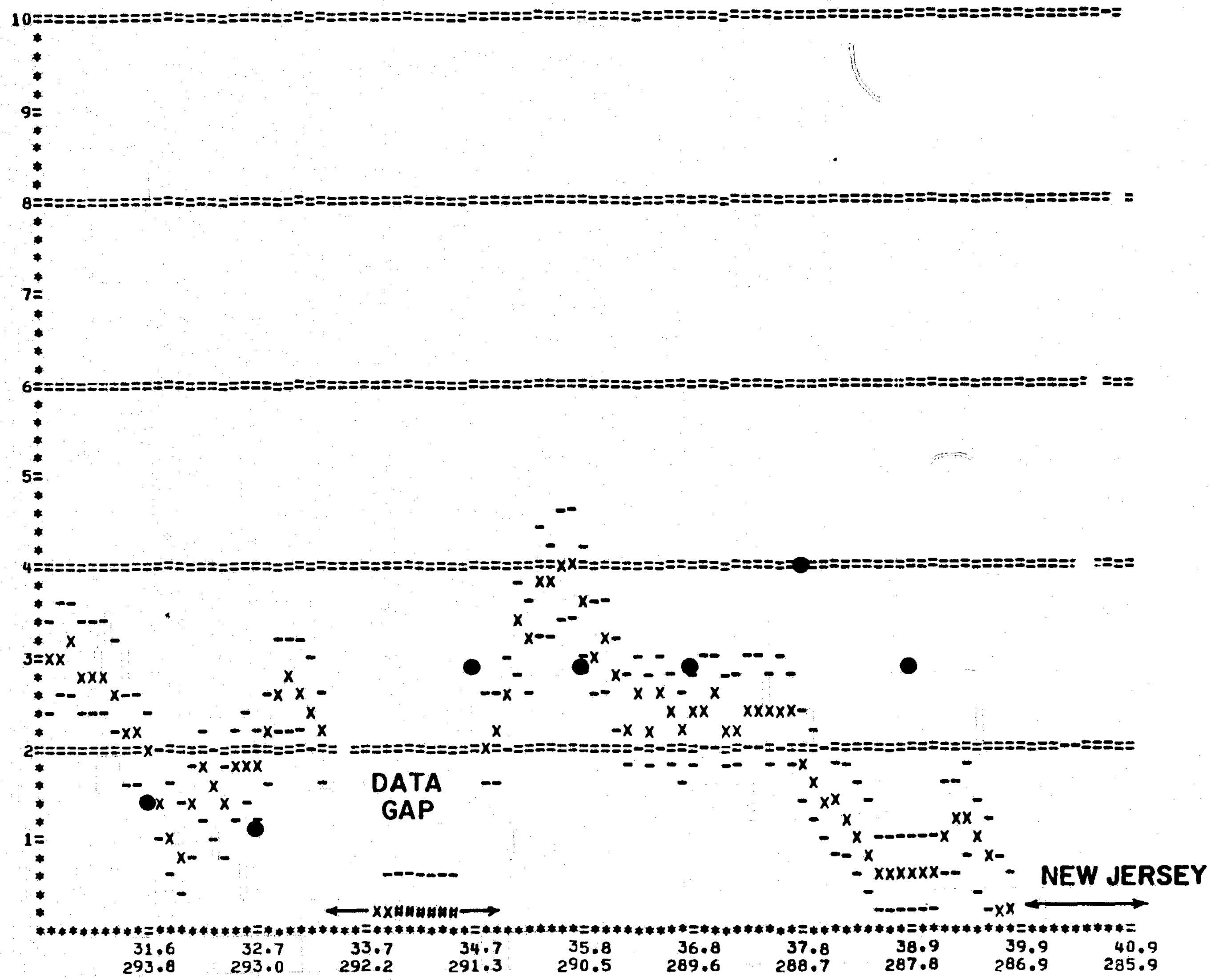
Error structure hard to explain; SOWM either much too high or much too low over half the track. Could imply large errors in wind field analysis.

ORBIT 3430 UNIQUE # 816 DATE 12/ 8/ 75
STARTING LAT 19.930000 LON 301.59000 TIME 10: 8
ENDING LAT -8888.0000 LON -8888.0000 TIME 10: 15



130

ORBIT 3430 UNIQUE # 816 DATE 12/ 8/ 75
STARTING LAT 19.930000 LON 301.59000 TIME 10: 8
ENDING LAT -8888.0000 LON -8888.0000 TIME 10: 15



ORBIT 3524 DEC. 15, 1975 2:11 TO 2:35

(PART IN SOUTHERN HEMISPHERE)

SOUTHBOUND GULF OF MEXICO AND PACIFIC

FLORIDA, YUCATAN PENINSULA, SOUTH PACIFIC TO 5° N, 262.5° E

12 POINTS RMS 0.6 M BIAS - 0.2 M

HIGHEST SOWM; ON TRACK 2.6 M; IN FIELD 2.7 M

HIGHEST GEOS; ON GRID 3.6 M; AT ONE POINT 3.8 M

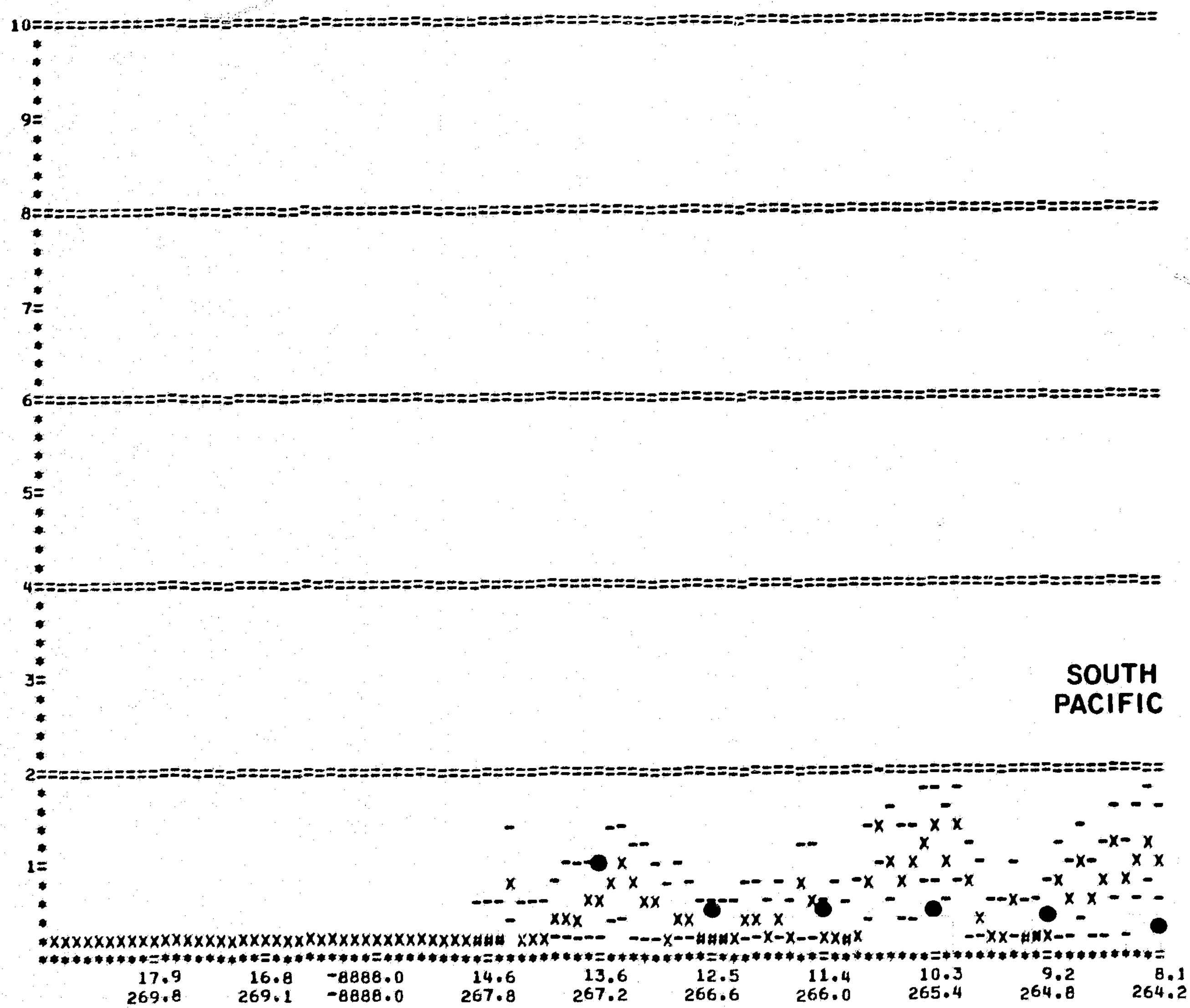
LOWEST SOWM; ON TRACK 0.4 M; IN FIELD 0.2 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 1 M; SOWM 2.6 M, GEOS 3.6 M

Slightly too low in Gulf of Mexico. Waves fluctuate 0.2 m to 1.4 m in Pacific; SOWM close. Probably swell in Pacific.

ORBIT 3524 UNIQUE # 863 DATE 12/ 15/ 75
STARTING LAT 29.590000 LON 277.34000 TIME 2: 11
ENDING LAT -47.460000 LON -47.460000 TIME 2: 35



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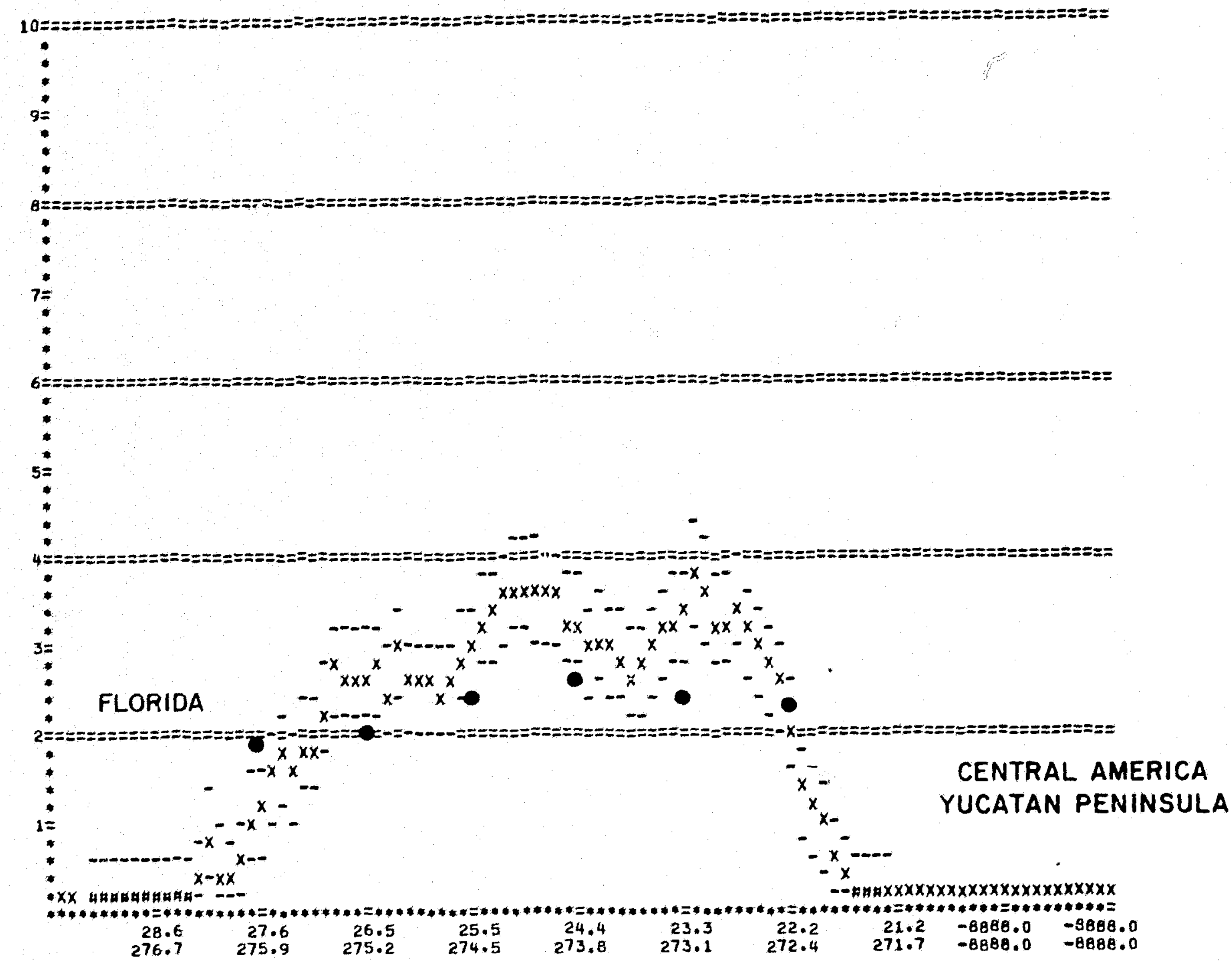
ORBIT 3524 UNIQUE # 863 DATE 12/ 15/ 75
STARTING LAT 29.590000 LON 277.34000 TIME 2: 11
ENDING LAT -47.460000 LON -47.460000 TIME 2: 35



ORBIT 3539 DEC. 16, 1975 3:39 TO 3:58

SOUTHBOUND PACIFIC

MEXICO NEAR MAZATLAN, 2.5° N, 241.3° E

19 POINTS RMS 0.9 M BIAS - 0.2 M

HIGHEST SOWM; ON TRACK 0.9 M; IN FIELD 1.8 M

HIGHEST GEOS; ON GRID 2.0 M; AT ONE POINT 2.4 M

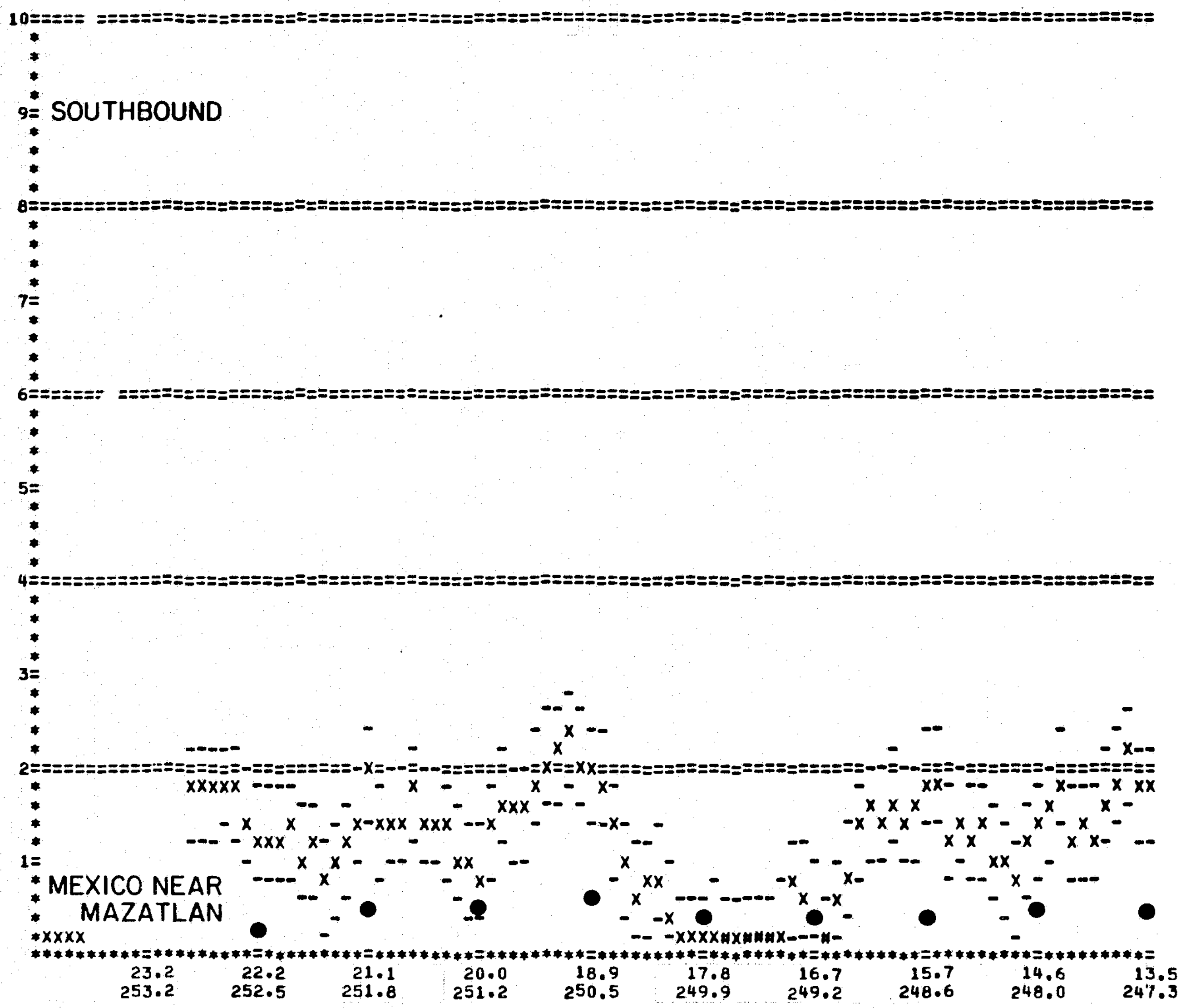
LOWEST SOWM; ON TRACK 0.3 M; IN FIELD 0.2 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0 M

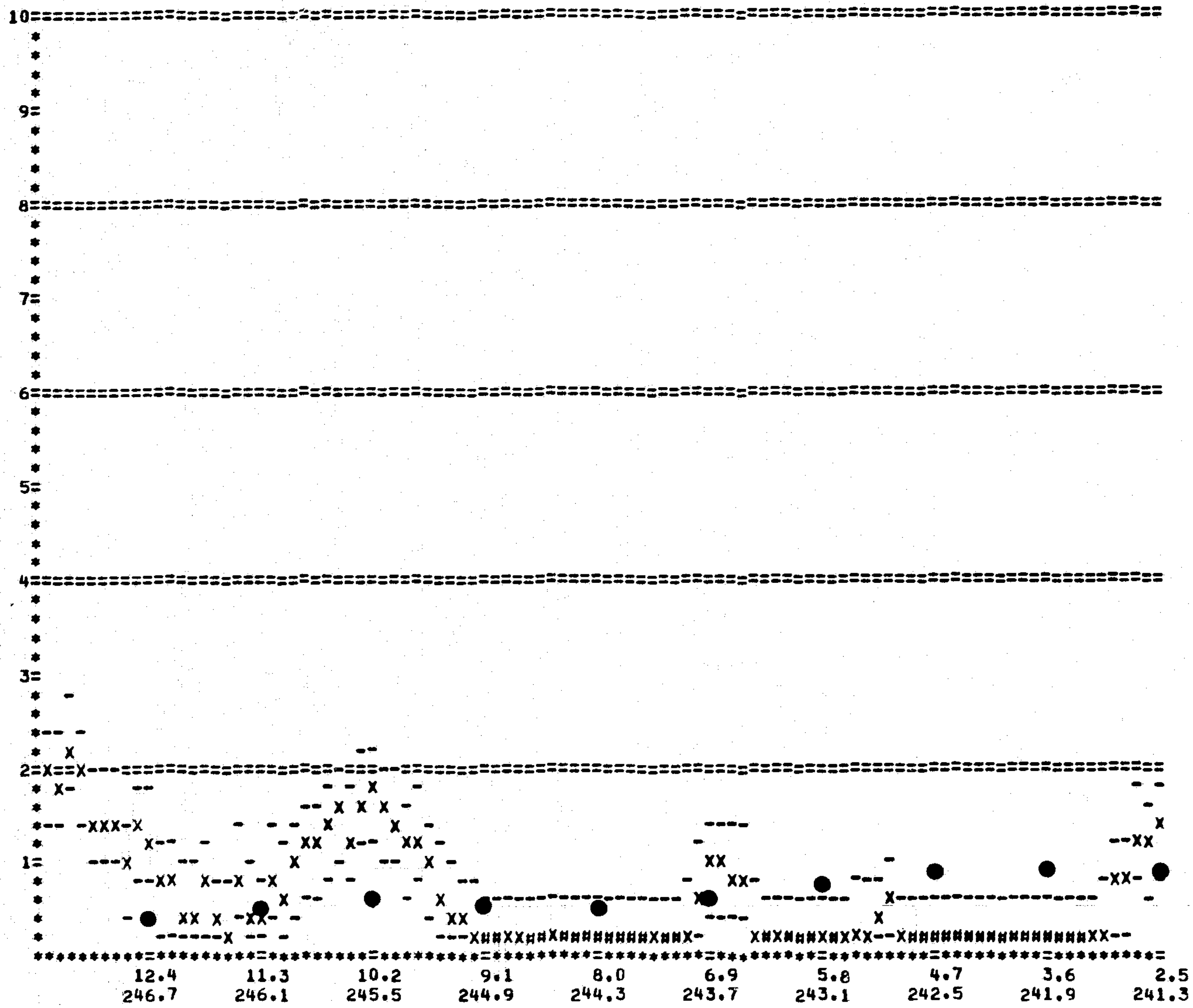
LARGEST ERROR - 1.5 M; SOWM 0.5 M, GEOS 2.0 M

SOWM consistently too low over large portions of swath. GEOS heights fluctuate from essentially zero to over 2 M. Measured waves four to five times higher than SOWM at places. Either a stronger wind or some swell is required.

```
      ORBIT         3539  UNIQUE #          873  DATE            12/           16/          75
STARTING LAT -8888.0000      LON -8888.0000      TIME            3:            39
  ENDING LAT -34.880000      LON -34.880000      TIME            3:            58
```



ORBIT 3539 UNIQUE # 873 DATE 12/ 16/ 75
STARTING LAT -8888.0000 LON -8888.0000 TIME 3: 39
ENDING LAT -34.880000 LON -34.880000 TIME 3: 58



ORBIT 3554 DEC. 17, 1975 5:03 TO 5:11

SOUTHBOUND PACIFIC

SOUTHERN CALIFORNIA, SANTA BARBARA CHANNEL, SANTA CRUZ,

11.2° N, 226.2° E

18 POINTS RMS 0.6 M BIAS + 0.1 M

HIGHEST SOWM; ON TRACK 2.0 M; IN FIELD 2.4 M

HIGHEST GEOS; ON GRID 2.6 M; AT ONE POINT 2.6 M

LOWEST SOWM; ON TRACK 1.3 M; IN FIELD 1.3 M

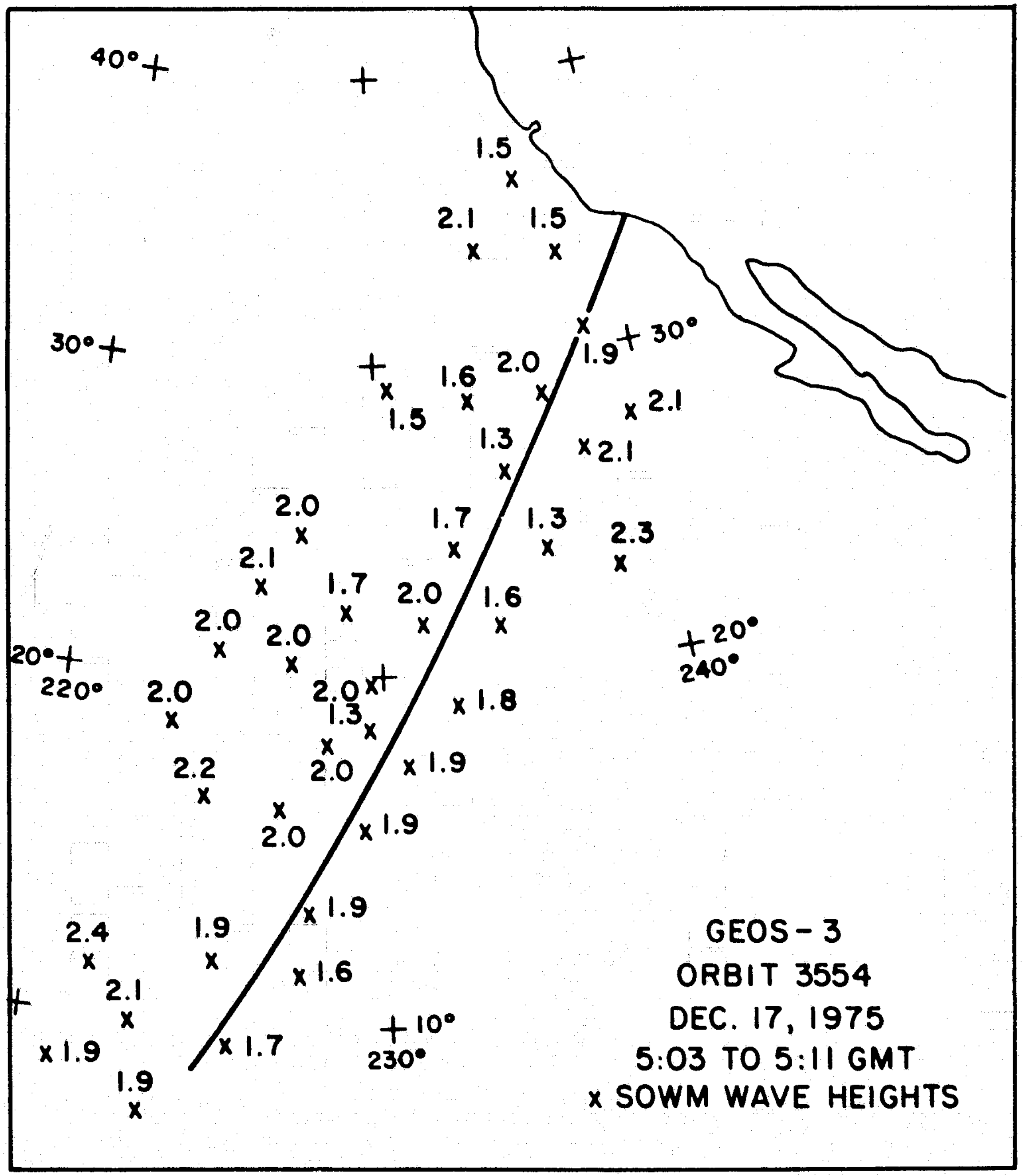
LOWEST GEOS; ON GRID 0.6 M; AT ONE POINT 0.2 M

LARGEST ERROR + 1.3 M; SOWM 1.9 M, GEOS 0.6 M

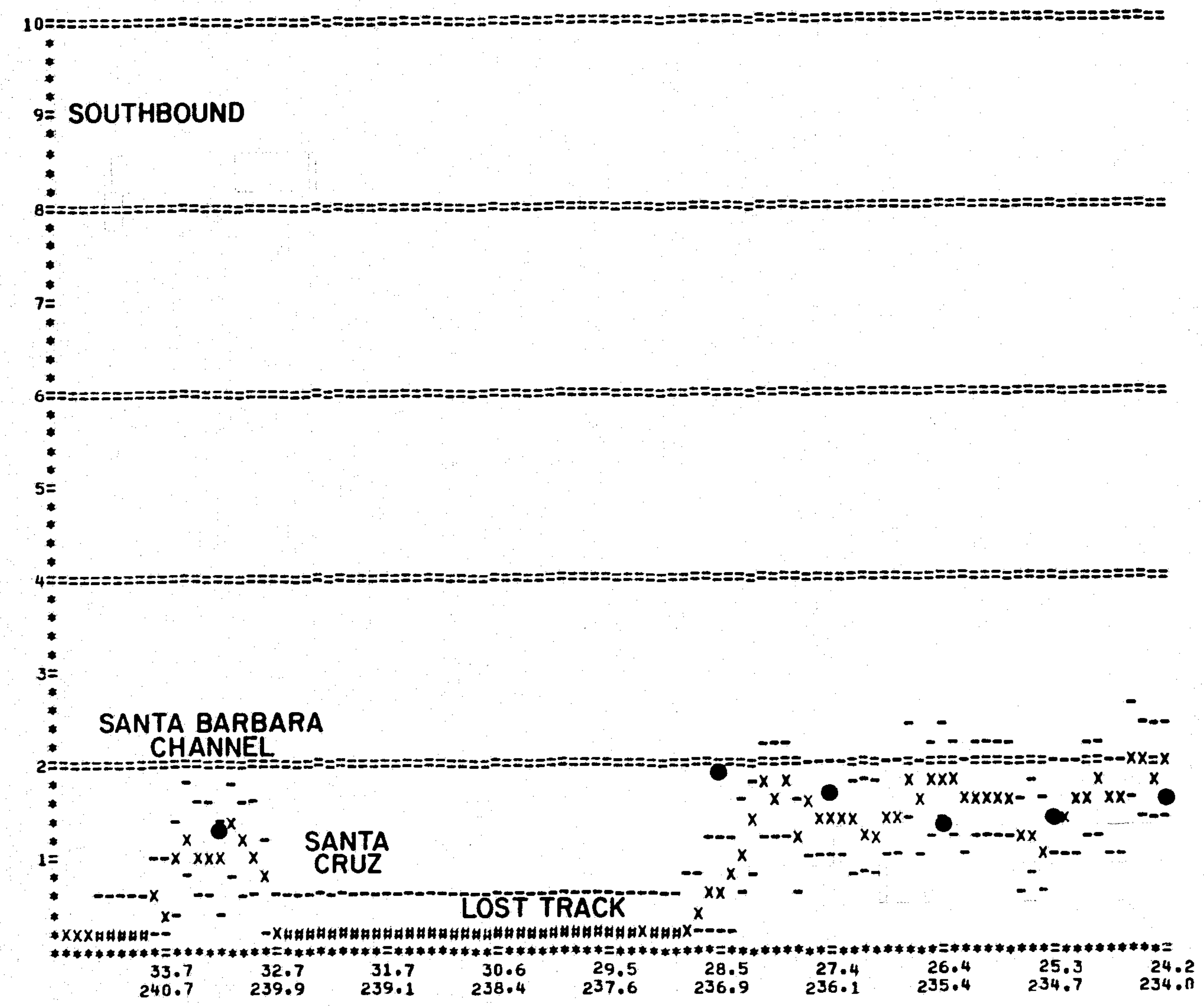
(in Santa Barbara Channel near Santa Cruz)

LARGEST ERROR PAST ISLAND + 1.1 M; SOWM 1.7 M, GEOS 0.6 M

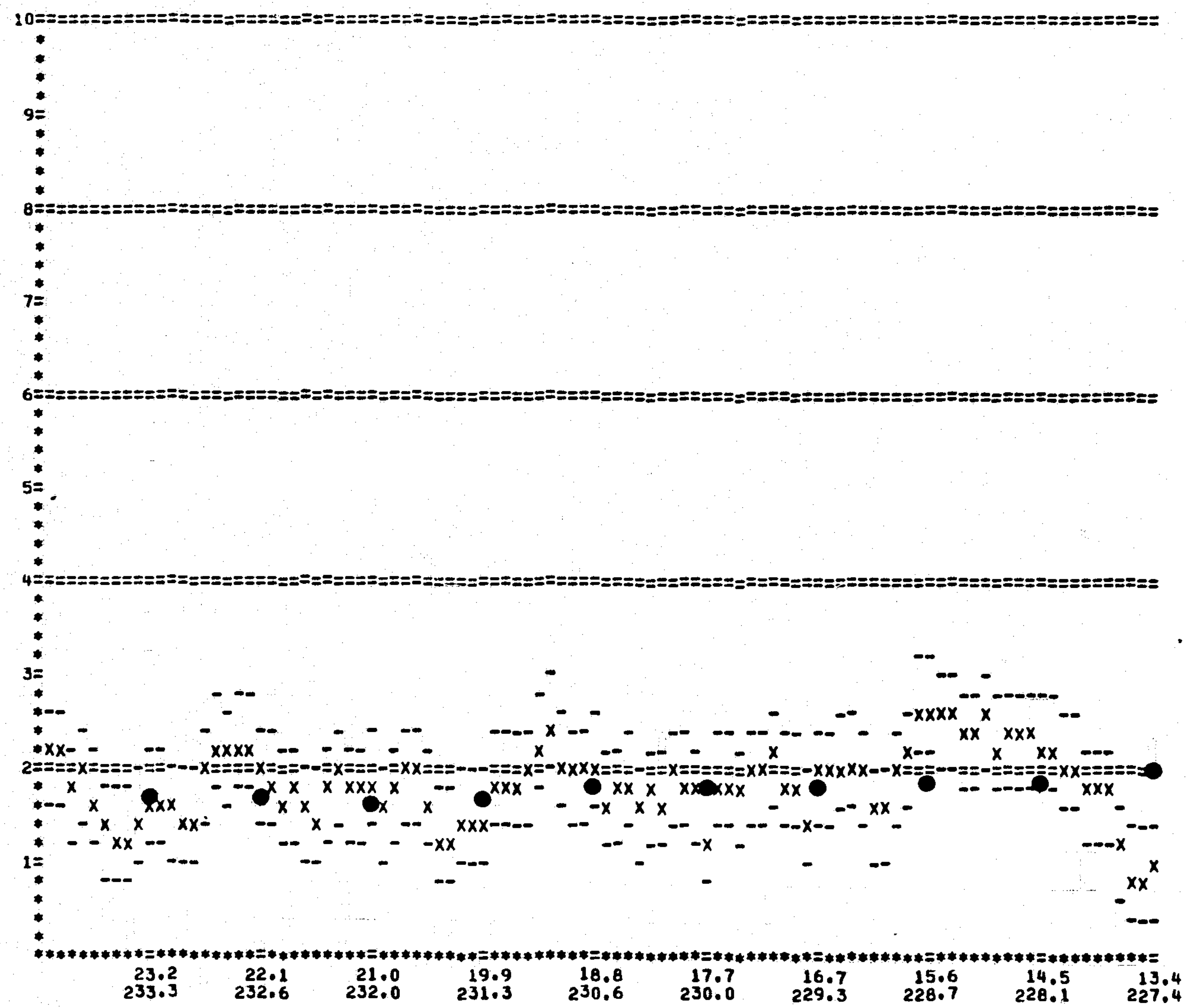
Excellent overall agreement, GEOS fluctuations are small.


40°
30°
30°
20°
220°
20°
240°
10°
230°
GEOS-3
ORBIT 3554
DEC. 17, 1975
5:03 TO 5:11 GMT
x SOWM WAVE HEIGHTS

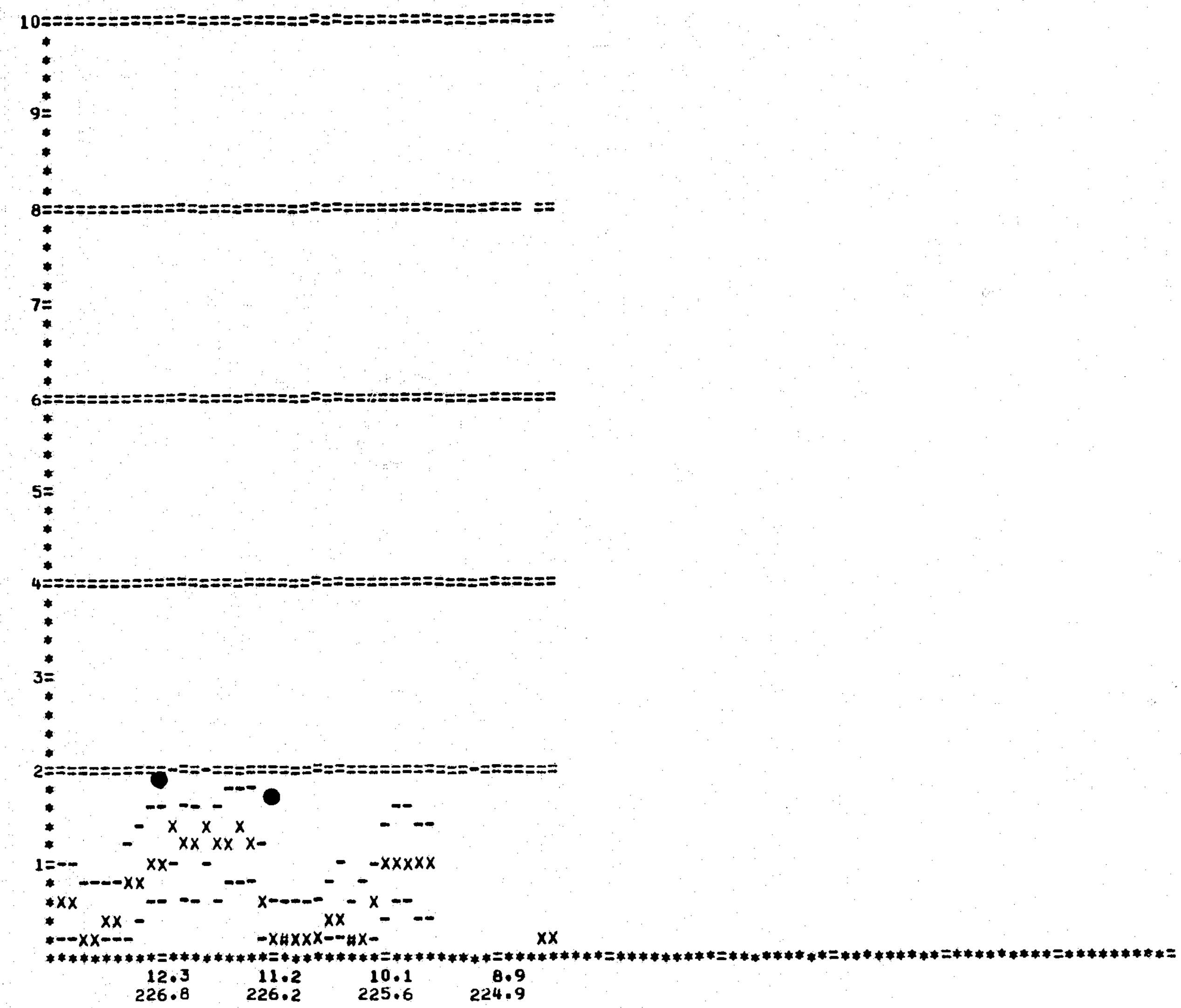
ORBIT 3554 UNIQUE # 881 DATE 12/ 17/ 75
STARTING LAT 34.670000 LON 241.49000 TIME 5: 3
ENDING LAT -8888.0000 LON -8888.0000 TIME 5: 11



ORBIT 3554 UNIQUE # 881 DATE 12/ 17/ 75
STARTING LAT 34.670000 LON 241.49000 TIME 5: 3
ENDING LAT -8888.0000 LON -8888.0000 TIME 5: 11



ORBIT 3554 UNIQUE # 881 DATE 12/ 17/ 75
STARTING LAT 34.670000 LON 241.49000 TIME 5: 3
ENDING LAT -8888.0000 LON -8888.0000 TIME 5: 11



ORBIT 3586 DEC. 19, 1975 10:50 TO 10:54

NORTHBOUND ATLANTIC

33° N, 300° E TO COAST OF MAINE

12 POINTS RMS 2.5 M BIAS - 2 M

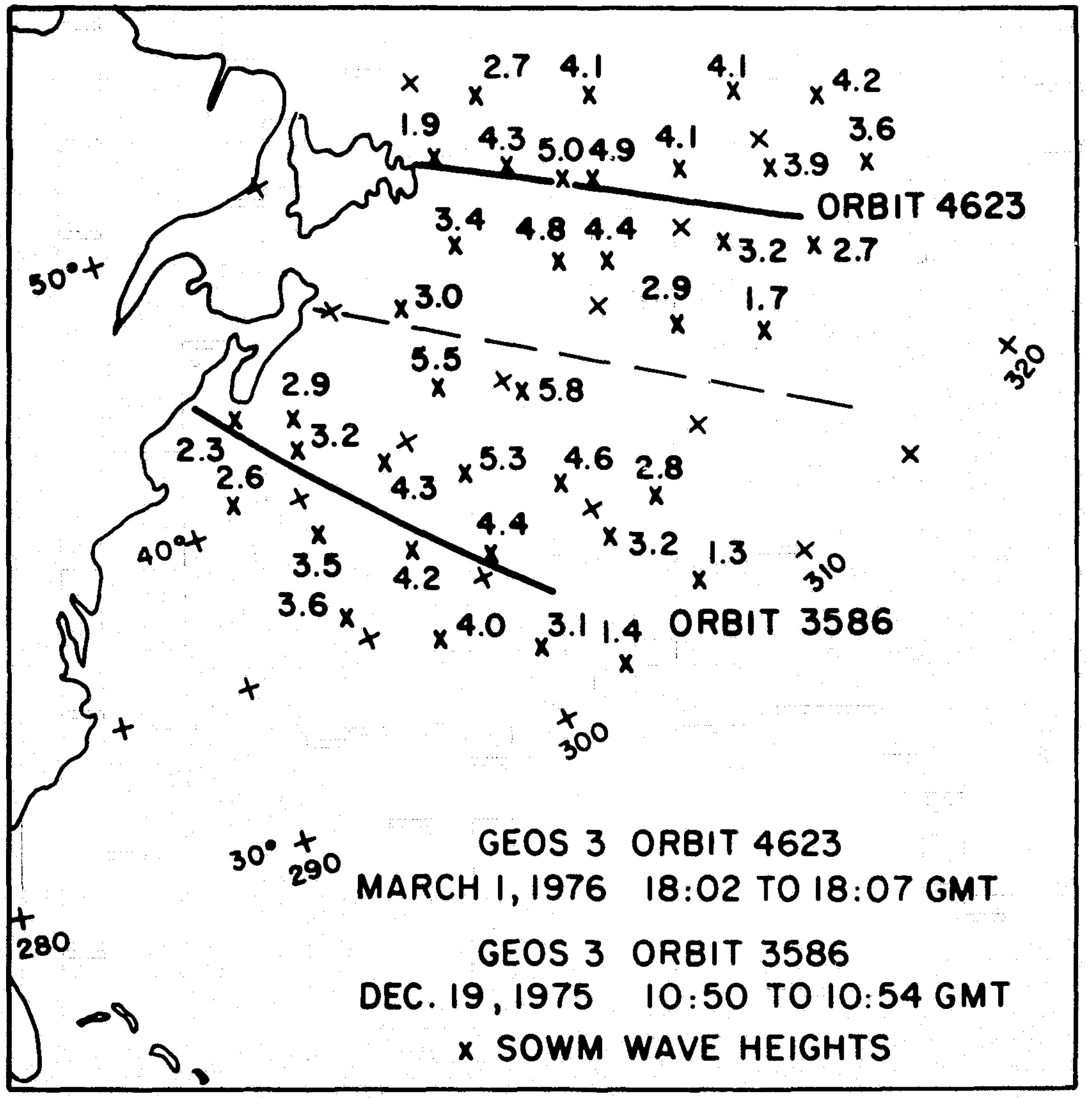
LAT	SOWM	GEOS	S - G
33	3.5	3.4	+ 0.1
34	4.3	5.2	- 0.9
35	4.4	5.2	- 0.8
37	4.6	5.6	- 1.0
38	4.0	5.8	- 1.8
39	3.9	5.8	- 1.9
40	3.8	5.6	- 1.8
41	3.4	7.4	- 4.0
42	2.9	6.6	- 3.7
43	2.7	6.8	- 4.1
44	1.8	4.4	- 2.6

HIGHEST SOWM IN FIELD 5.3 M

HIGHEST GEOS AT ONE POINT 7.6 M

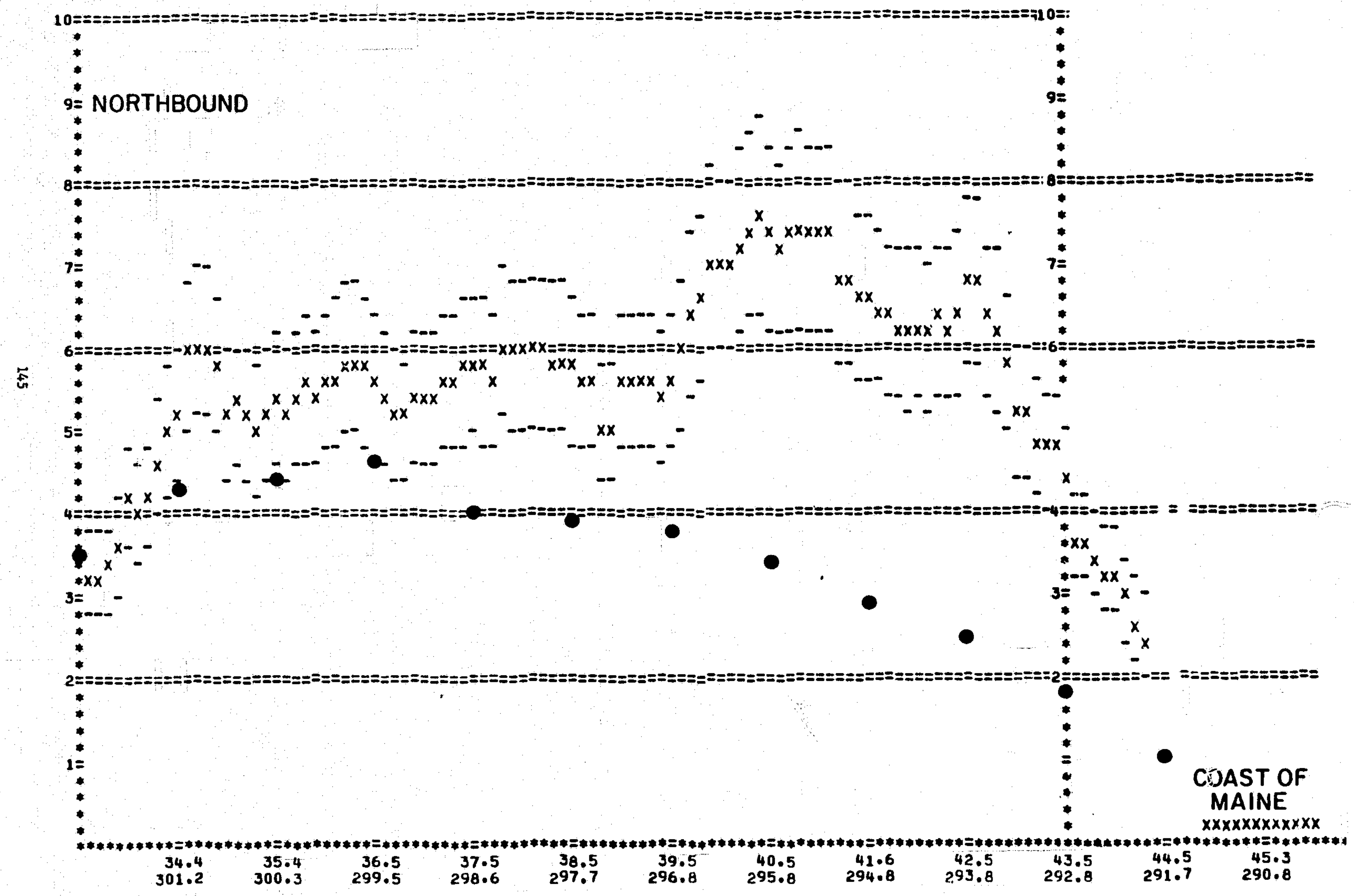
LOWEST GEOS AT ONE POINT 2.4 M

Very large errors in SOWM. One might guess that off-shore winds to 41° N were much too weak in the wind field analysis that generated the waves. SOWM waves could have been generated by 14 m/s winds, whereas GEOS waves require 18 m/s winds.



ORBIT 4623
ORBIT 3586
50°
40°
30°
280
290
300
310
320
GEOS 3 ORBIT 4623
MARCH 1, 1976 18:02 TO 18:07 GMT
GEOS 3 ORBIT 3586
DEC. 19, 1975 10:50 TO 10:54 GMT
x SOWM WAVE HEIGHTS

```
   ORBIT         3586  UNIQUE #          897  DATE          12/          19/          75
STARTING LAT  33.460000        LON  301.94000        TIME          10:          50
  ENDING LAT -8888.0000        LON -8888.0000        TIME          10:          54
```



ORBIT 3645 DEC. 23, 1975 16:15 TO 16:45

NORTHBOUND PACIFIC

EQUATOR AT 243° E TO ALASKA PENINSULA

42 POINTS RMS 1.3 M BIAS - 0.8 M

HIGHEST SOWM; ON TRACK 6.2 M; IN FIELD 8.7 M

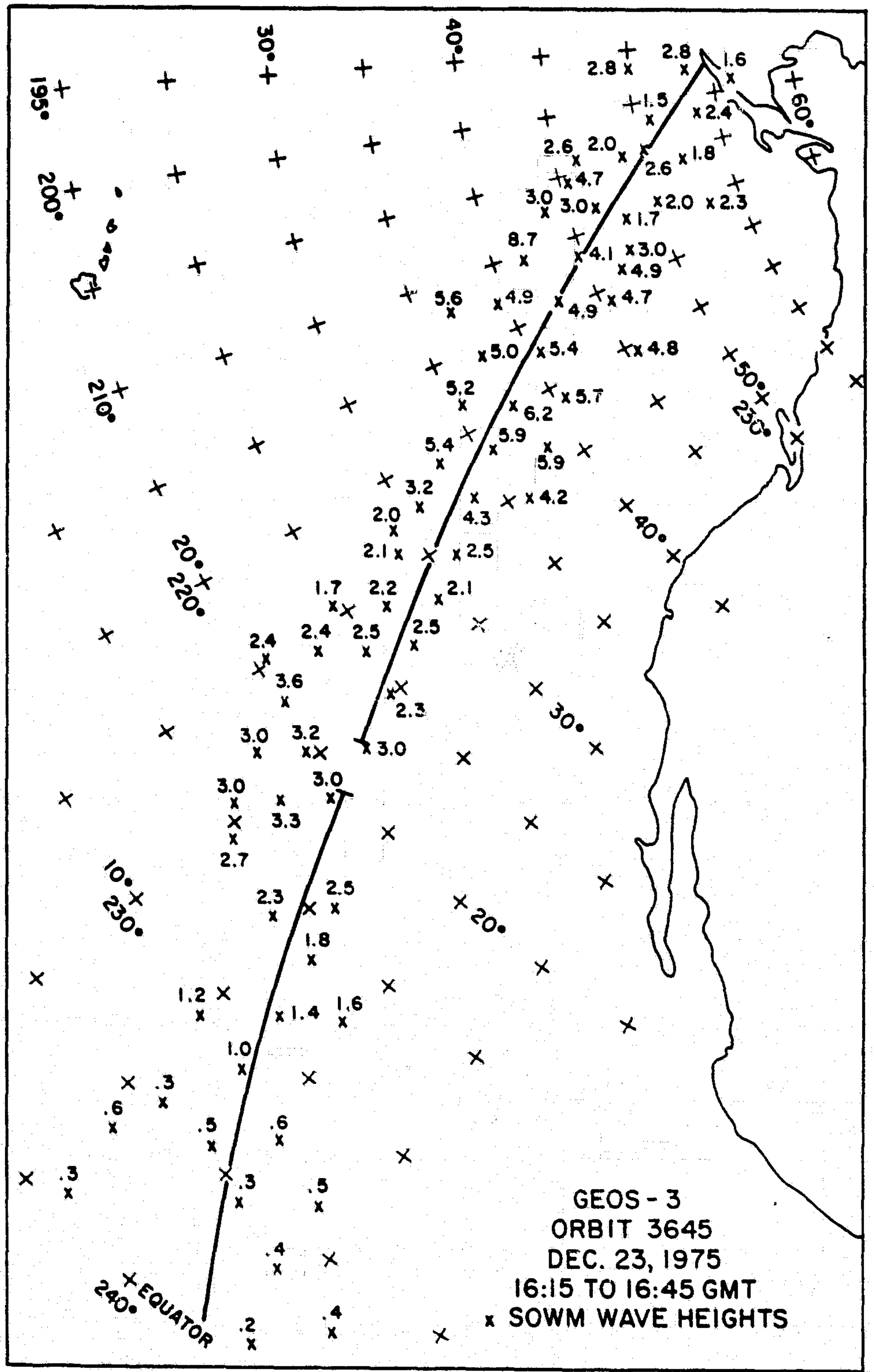
HIGHEST GEOS; ON GRID 7.8 M; AT ONE POINT 8.0 M

LOWEST SOWM; ON TRACK 0.3 M; IN FIELD 0.2 M

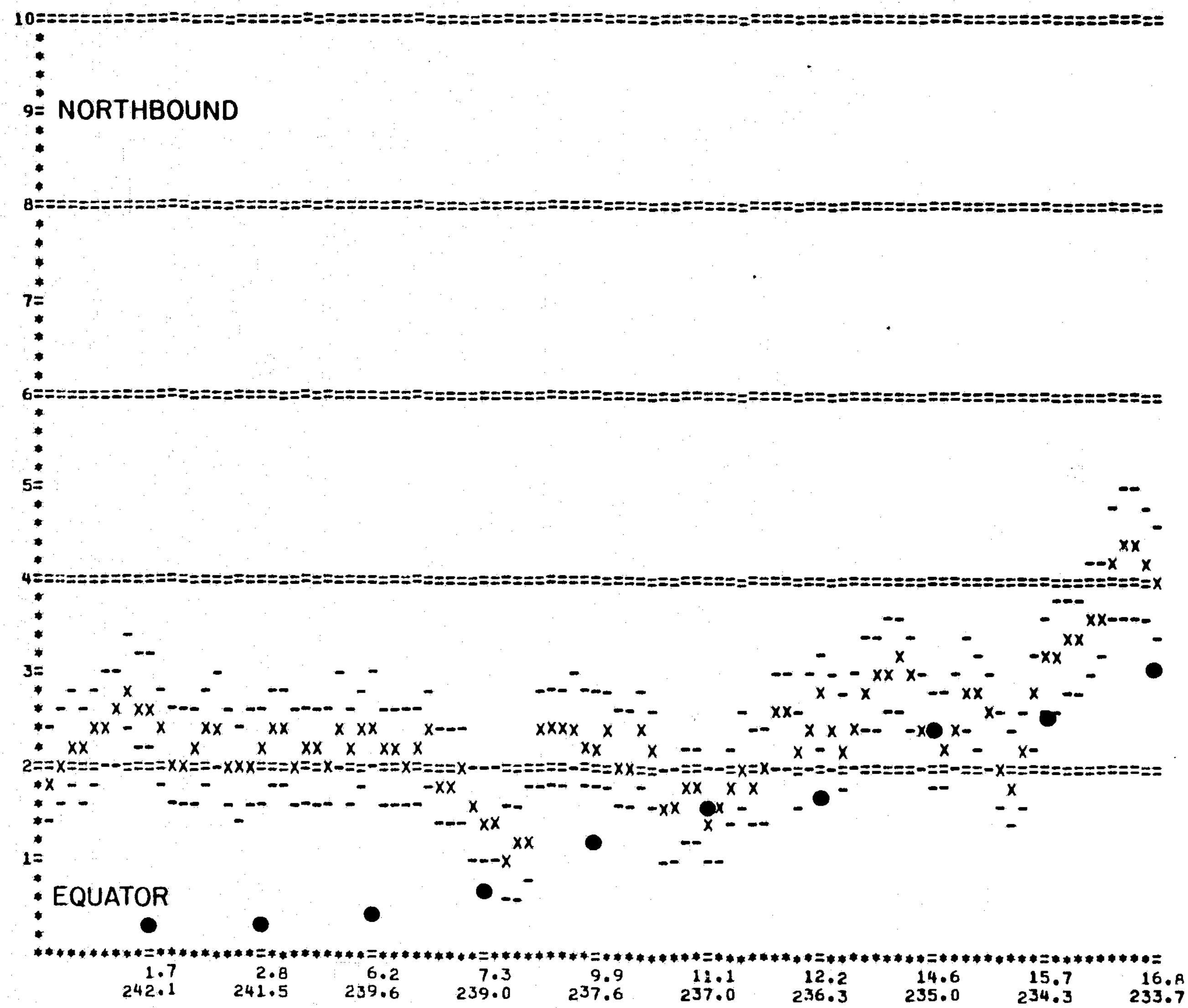
LOWEST GEOS; ON GRID 1.4 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 3.8 M; SOWM 4.0 M, GEOS 7.8 M

Swell, or local winds, missed near equator. Fairly good agreement north of 7° N to 42° N. Eight meter waves missed at 45° N. Axis of high winds in Gulf of Alaska low must have been farther north than analyzed and close to 19.5 m/s instead of about 15 m/s. Waves close to Alaskan Peninsula specified correctly.

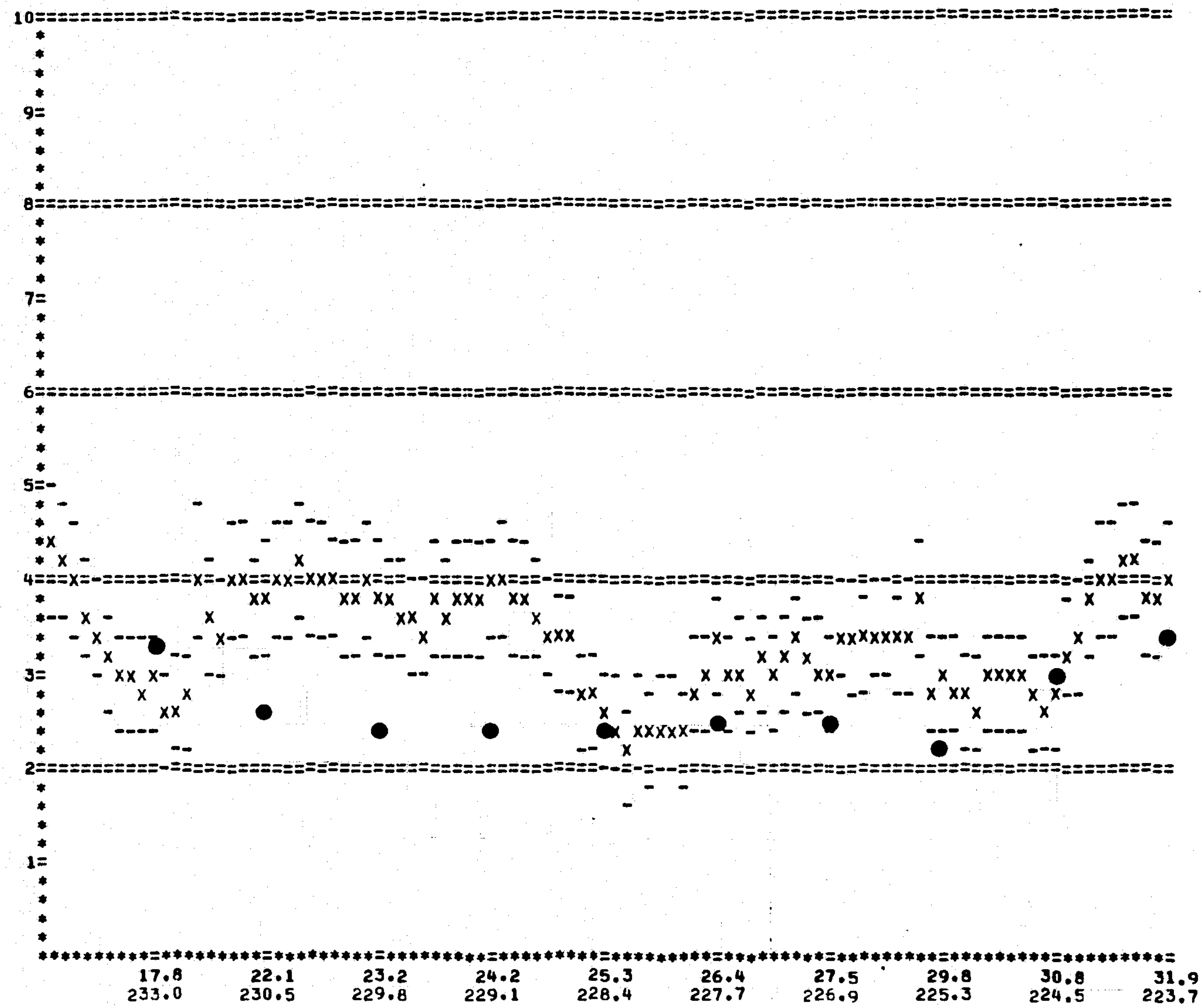

GEOS - 3
ORBIT 3645
DEC. 23, 1975
16:15 TO 16:45 GMT
x SOWM WAVE HEIGHTS
EQUATOR

ORBIT 3645 UNIQUE # 17 DATE 12/ 23/ 75
STARTING LAT -38.800000 LON 267.95000 TIME 16: 15
ENDING LAT 55.750000 LON 55.750000 TIME 16: 45



148

ORBIT 3645 UNIQUE # 17 DATE 12/ 23/ 75
STARTING LAT -38.800000 LON 267.95000 TIME 16: 15
ENDING LAT 55.750000 LON 55.750000 TIME 16: 45



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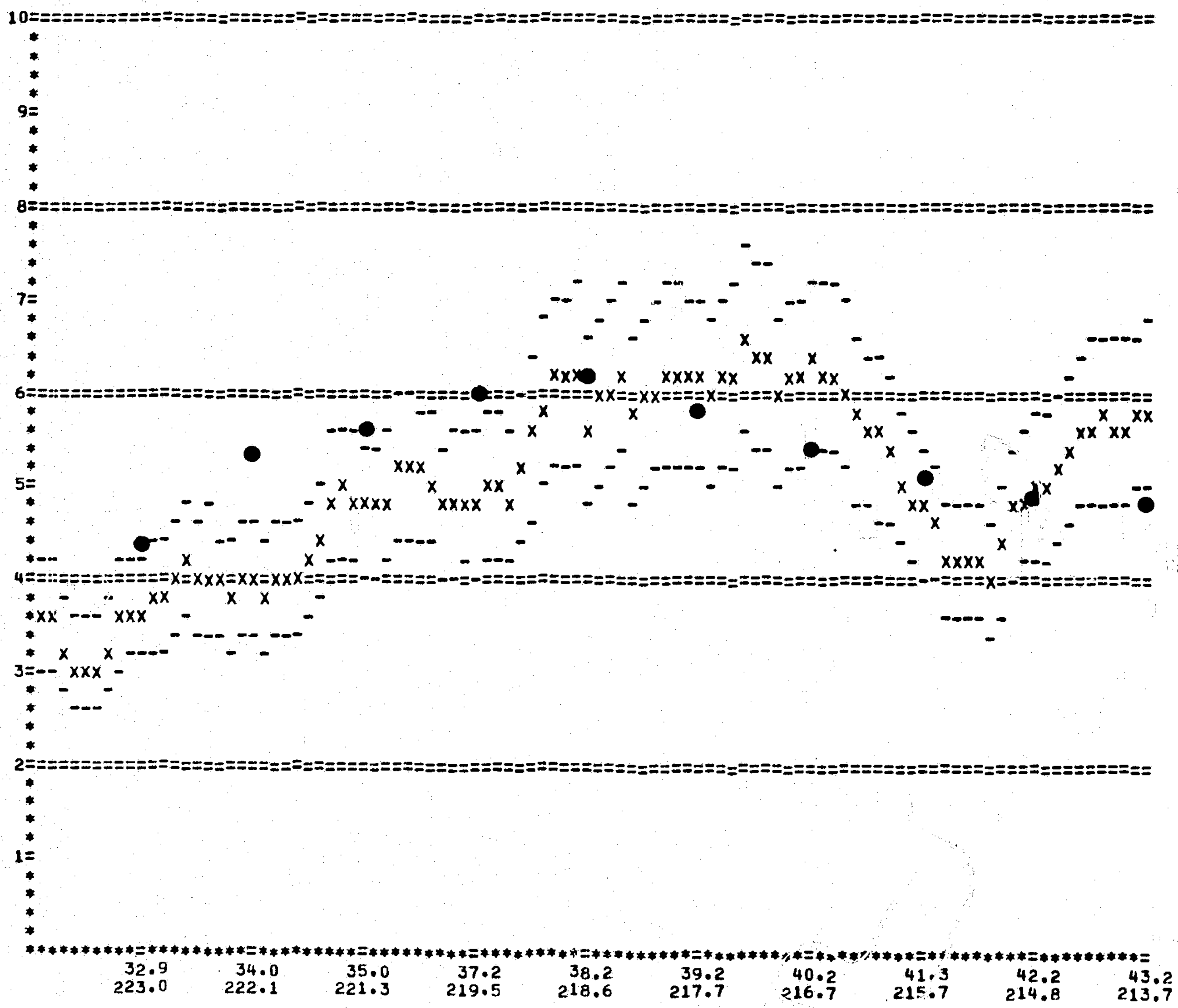
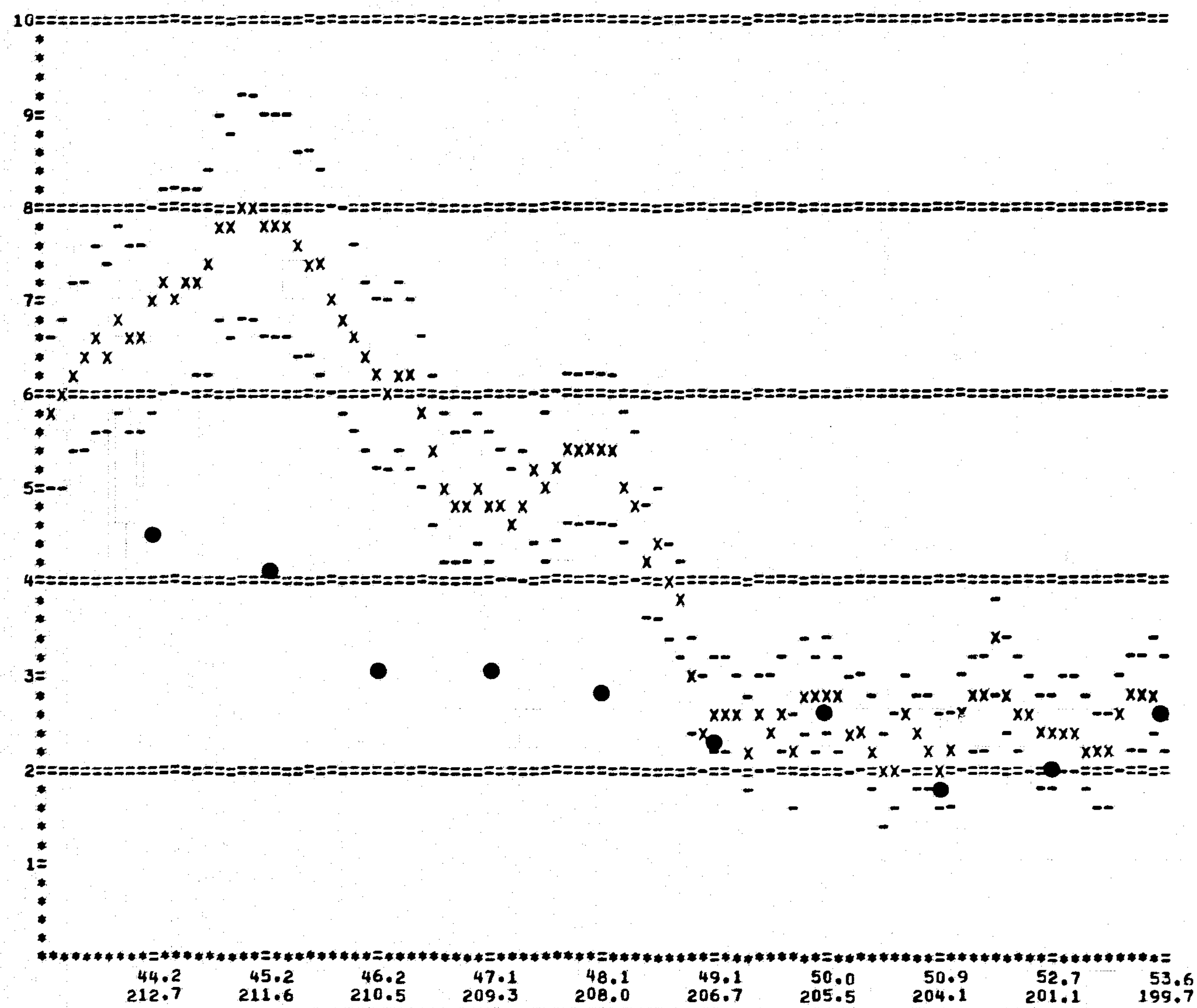
ORBIT 3645 UNIQUE # 17 DATE 12/ 23/ 75
STARTING LAT -38.800000 LON 267.95000 TIME 16: 15
ENDING LAT 55.750000 LON 55.750000 TIME 16: 45



ORBIT 3645 UNIQUE # 17 DATE 12/ 23/ 75
STARTING LAT -38.800000 LON 267.95000 TIME 16: 15
ENDING LAT 55.750000 LON 55.750000 TIME 16: 45



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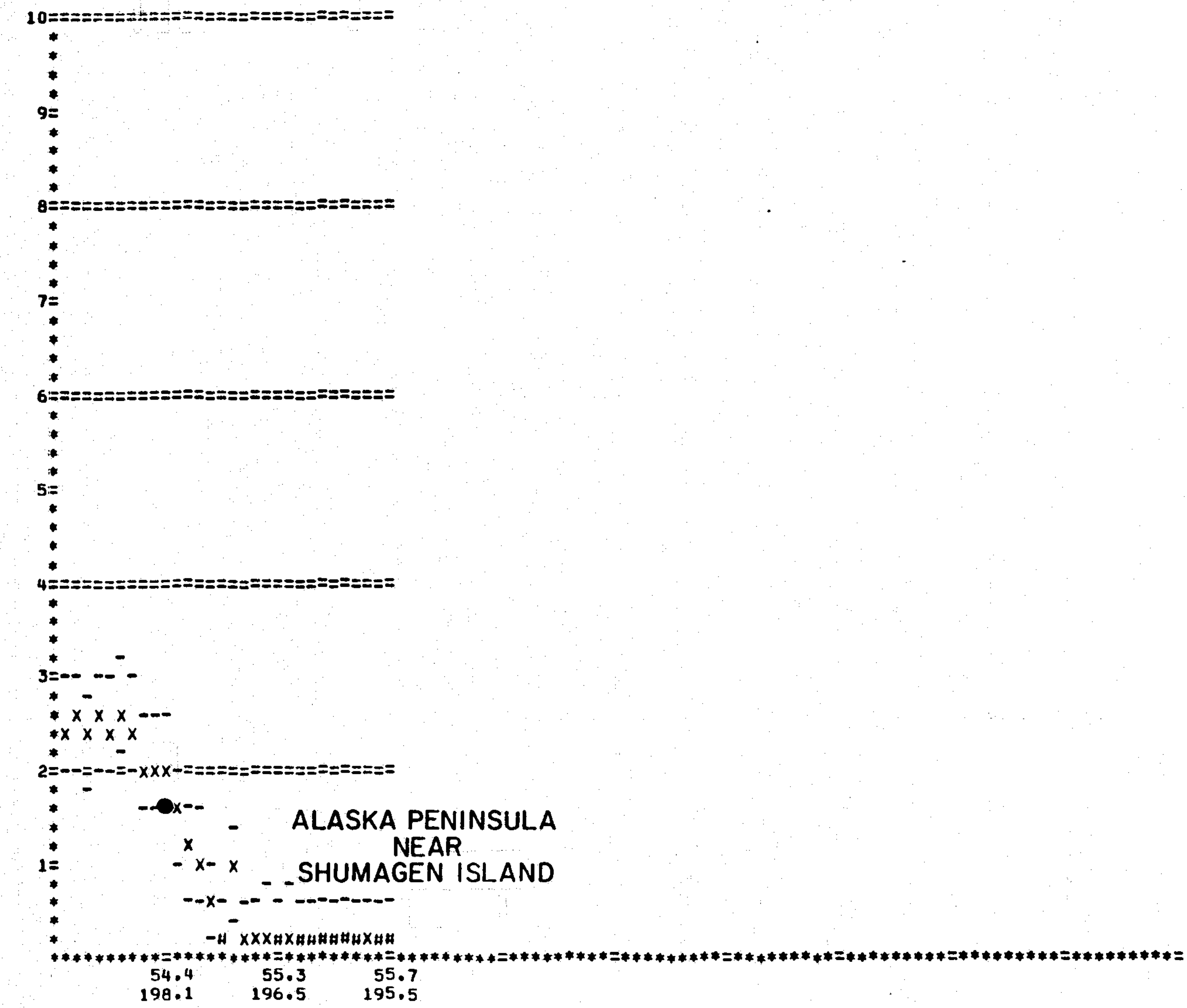
ORBIT 3645 UNIQUE # 17 DATE 12/ 23/ 75
STARTING LAT -38.800000 LON 267.95000 TIME 16: 15
ENDING LAT 55.750000 LON 55.750000 TIME 16: 45



ORBIT 4576 FEB. 27, 1976 10:30 TO 10:40

WESTBOUND ATLANTIC

NORWAY, OVER ICELAND TO LABRADOR SEA

12 POINTS RMS 1.1 M BIAS - 0.4 M

HIGHEST SOWM; ON TRACK 5 M; IN FIELD 5.1 M

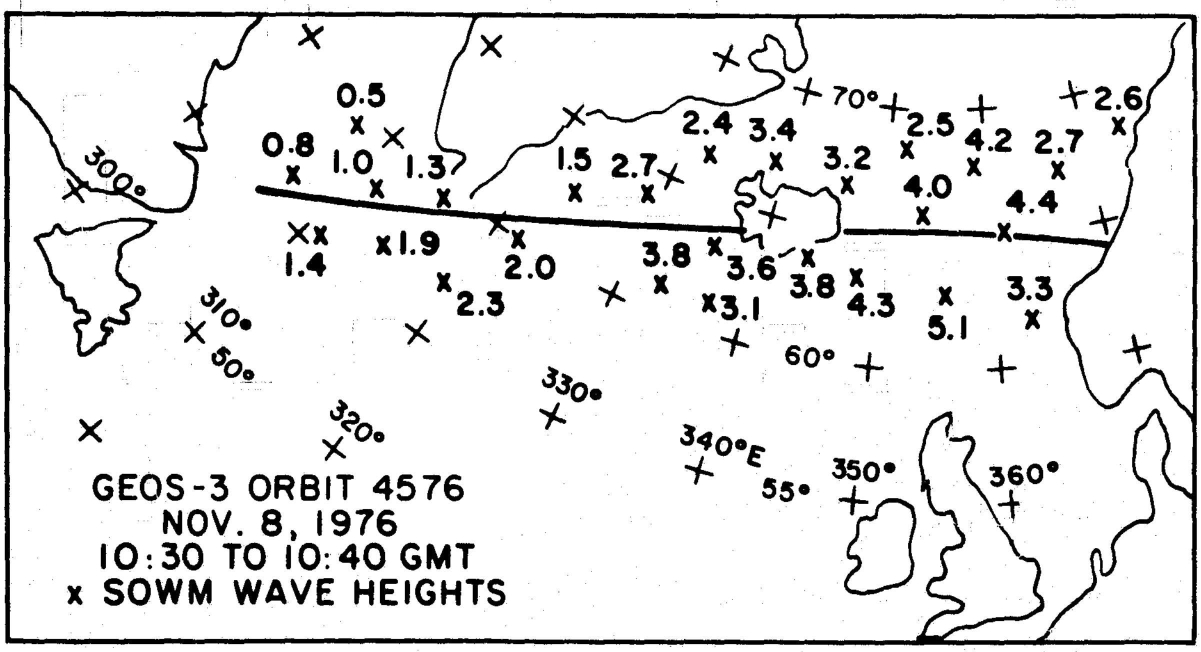
HIGHEST GEOS; ON GRID 4.8 M; AT ONE POINT 6.2 M

LOWEST SOWM; ON TRACK 1.1 M; IN FIELD 0.5 M

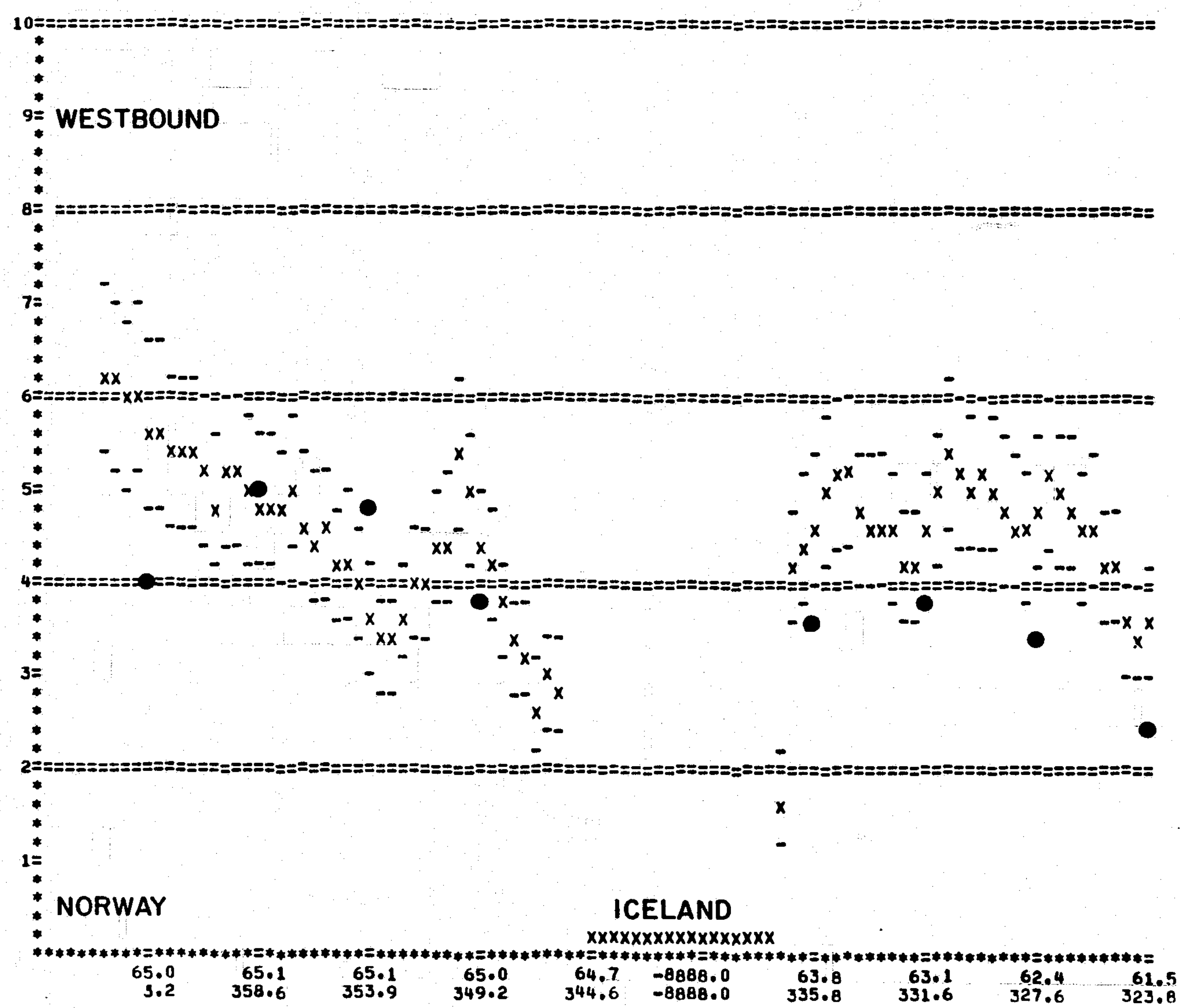
LOWEST GEOS; ON GRID 1.0 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 2 M; SOWM 4 M, GEOS 6 M

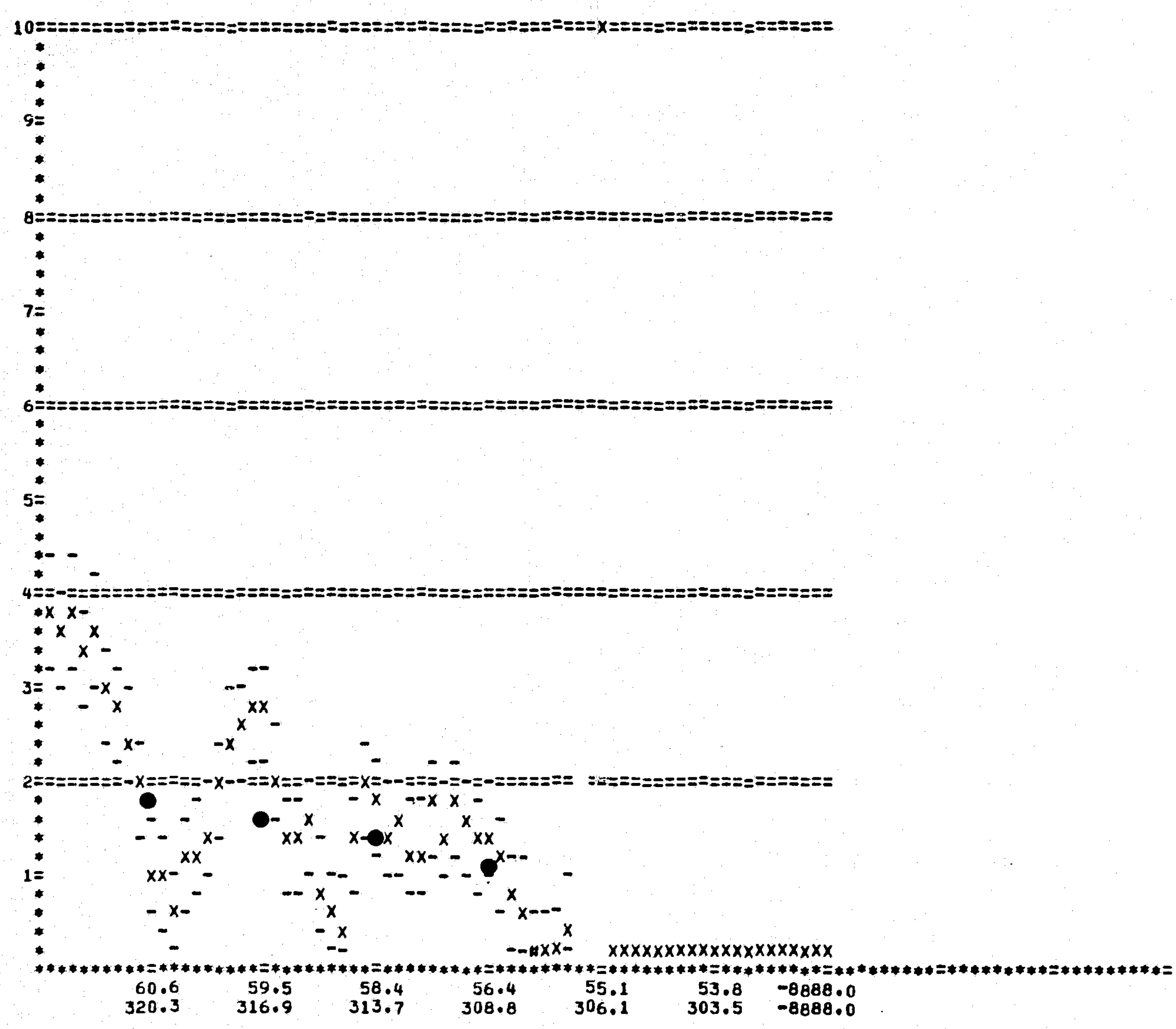
First third of pass, close but SOWM low near Norway; slightly low Iceland to south of Greenland; close to Labrador Sea.


GEOS-3 ORBIT 4576
NOV. 8, 1976
10:30 TO 10:40 GMT
x SOWM WAVE HEIGHTS
300°
310°
320°
330°
340°E
350°
360°
50°
55°
60°
70°

ORBIT 4576 UNIQUE # 231 DATE 2/ 27/ 76
STARTING LAT 64.730000 LON 7.3700000 TIME 10: 30
ENDING LAT -8888.0000 LON -8888.0000 TIME 10: 40



```
      ORBIT          4576  UNIQUE #          231  DATE              2/            27/            76
STARTING LAT  64.730000      LON  7.3700000      TIME            10:             30
  ENDING LAT -8888.0000      LON -8888.0000      TIME            10:             40
```



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ORBIT 4593 FEB. 28, 1976 15:11 TO 15:18

NORTHBOUND ATLANTIC

NORTHWEST CORNER OF SPAIN TO SOUTHERN GREENLAND

12 POINTS RMS 0.9 M BIAS - 0.7 M

HIGHEST SOWM; ON TRACK 2.4 M; IN FIELD 2.5 M

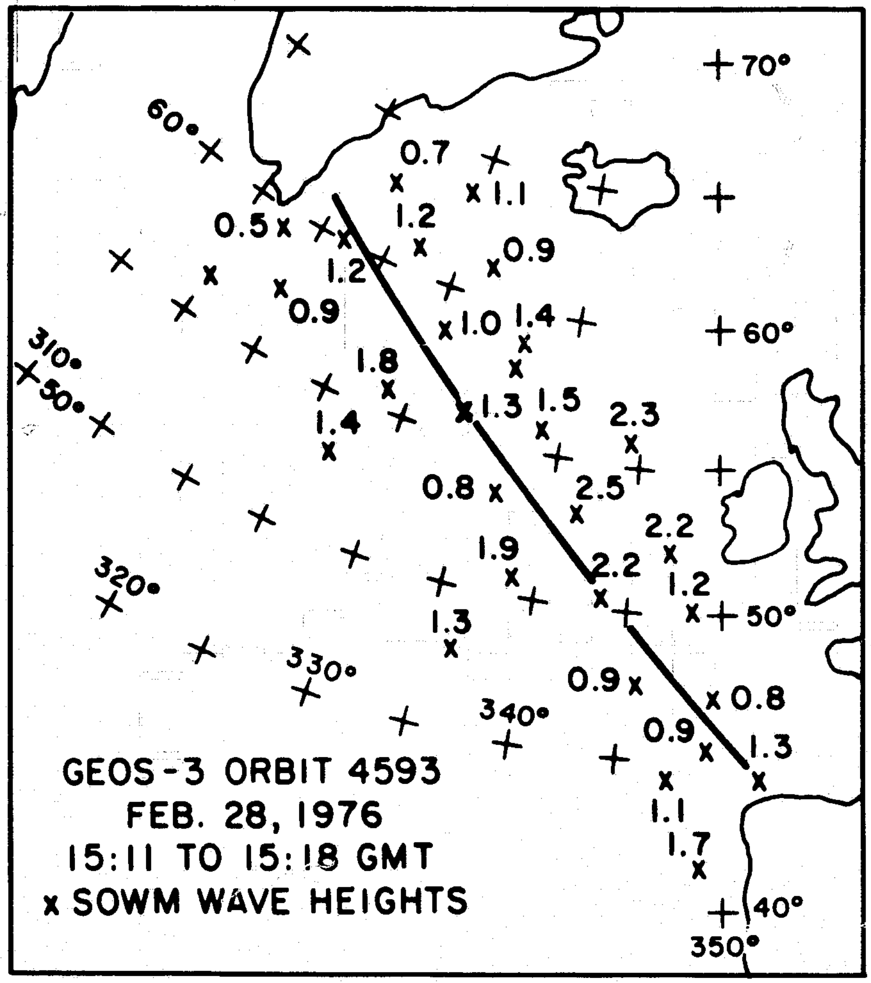
HIGHEST GEOS; ON GRID 3.6 M; AT ONE POINT 4.4 M

LOWEST SOWM; ON TRACK 0.8 M; IN FIELD 0.5 M

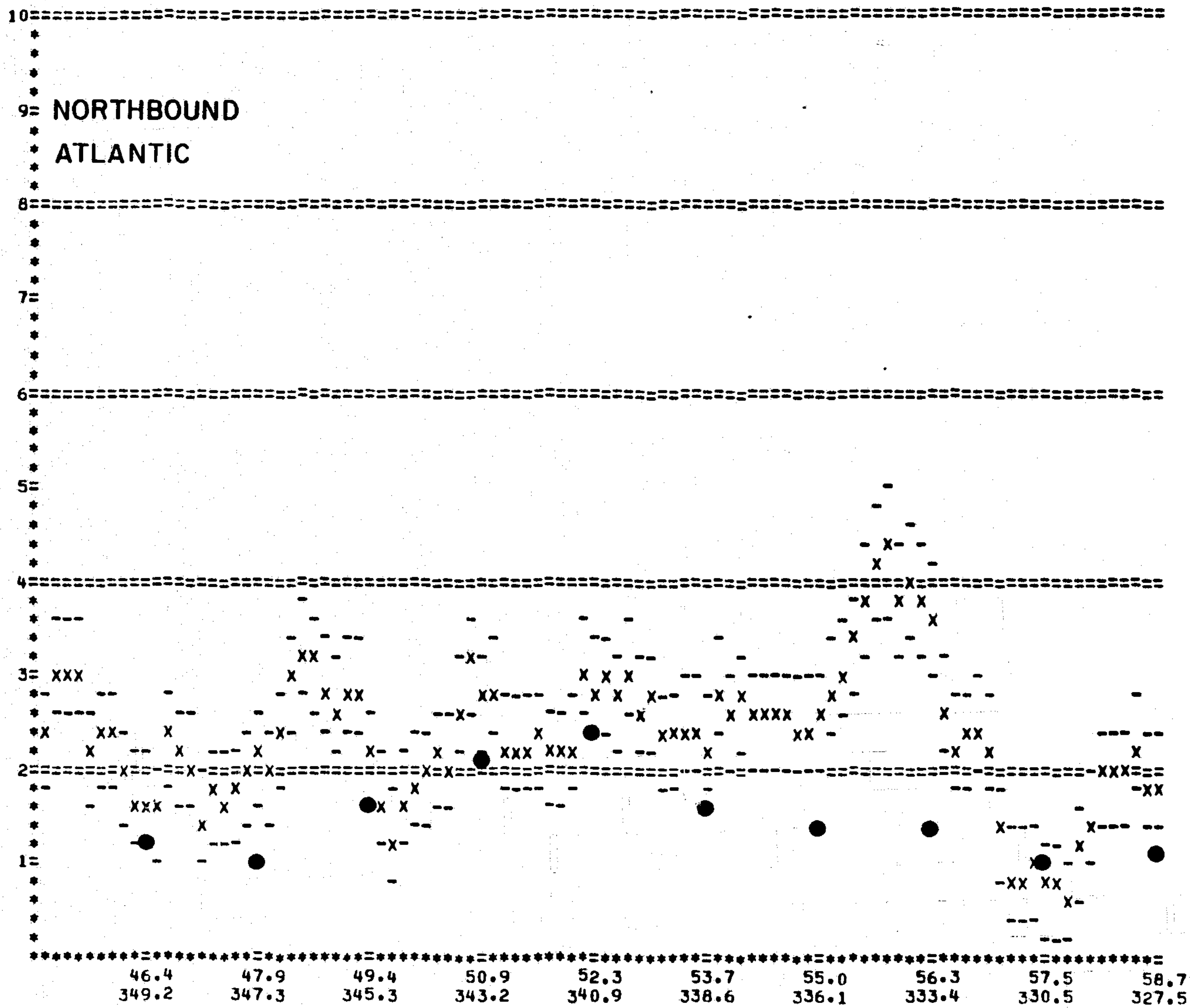
LOWEST GEOS; ON GRID 0.6 M; AT ONE POINT 0.2 M

LARGEST ERROR - 2.2 M; SOWM 1.4 M, GEOS 3.6 M

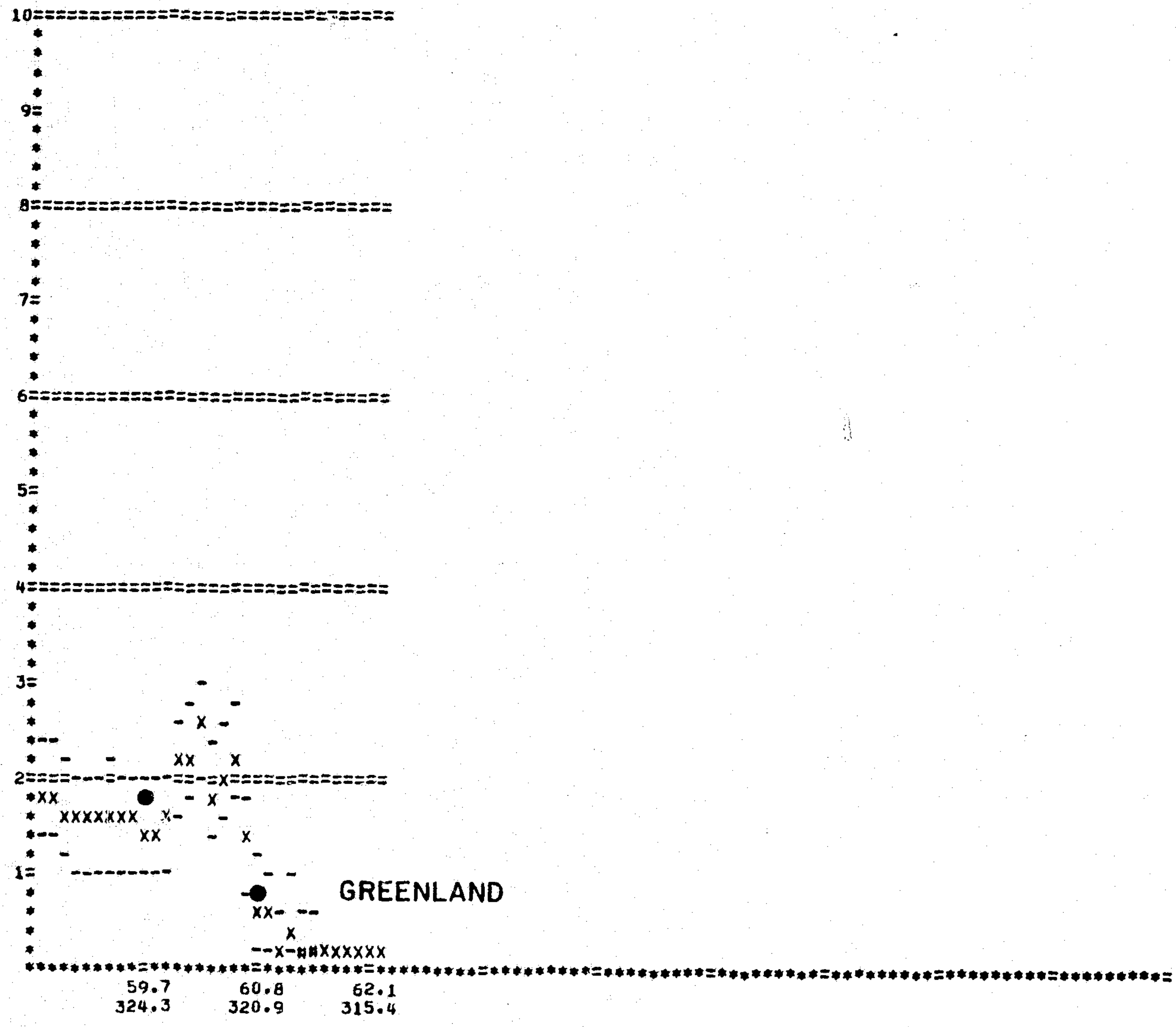
Oscillations in GEOS heights not tracked by SOWM, especially 4.4 m waves between 55^{o} and 56^{o} N. SOWM generally too low.


70°
60°
0.7
1.1
0.5
1.2
0.9
1.2
0.9
1.0
1.4
60°
310°
50°
1.8
1.3
1.5
2.3
1.4
0.8
2.5
2.2
1.9
2.2
320°
1.2
50°
1.3
330°
0.9
0.8
340°
0.9
1.3
1.1
1.7
40°
350°
GEOS-3 ORBIT 4593
FEB. 28, 1976
15:11 TO 15:18 GMT
x SOWM WAVE HEIGHTS

ORBIT 4593 UNIQUE # 243 DATE 2/ 28/ 76
STARTING LAT 45.030000 LON 350.79000 TIME 15: 11
ENDING LAT 62.170000 LON 62.170000 TIME 15: 18



ORBIT	4593	UNIQUE #		243	DATE	2/	28/	76
STARTING LAT	45.030000	LON	350.79000		TIME	15:	11	
ENDING LAT	62.170000	LON	62.170000		TIME	15:	18	



ORBIT 4608 FEB. 29, 1976 16:32 TO 16:42

NORTHBOUND ATLANTIC

OFF NORTH AFRICA TO LABRADOR SEA

19 POINTS RMS 1.0 M BIAS - 0.2 M

HIGHEST SOWM; ON TRACK 5.6 M; IN FIELD 5.9 M

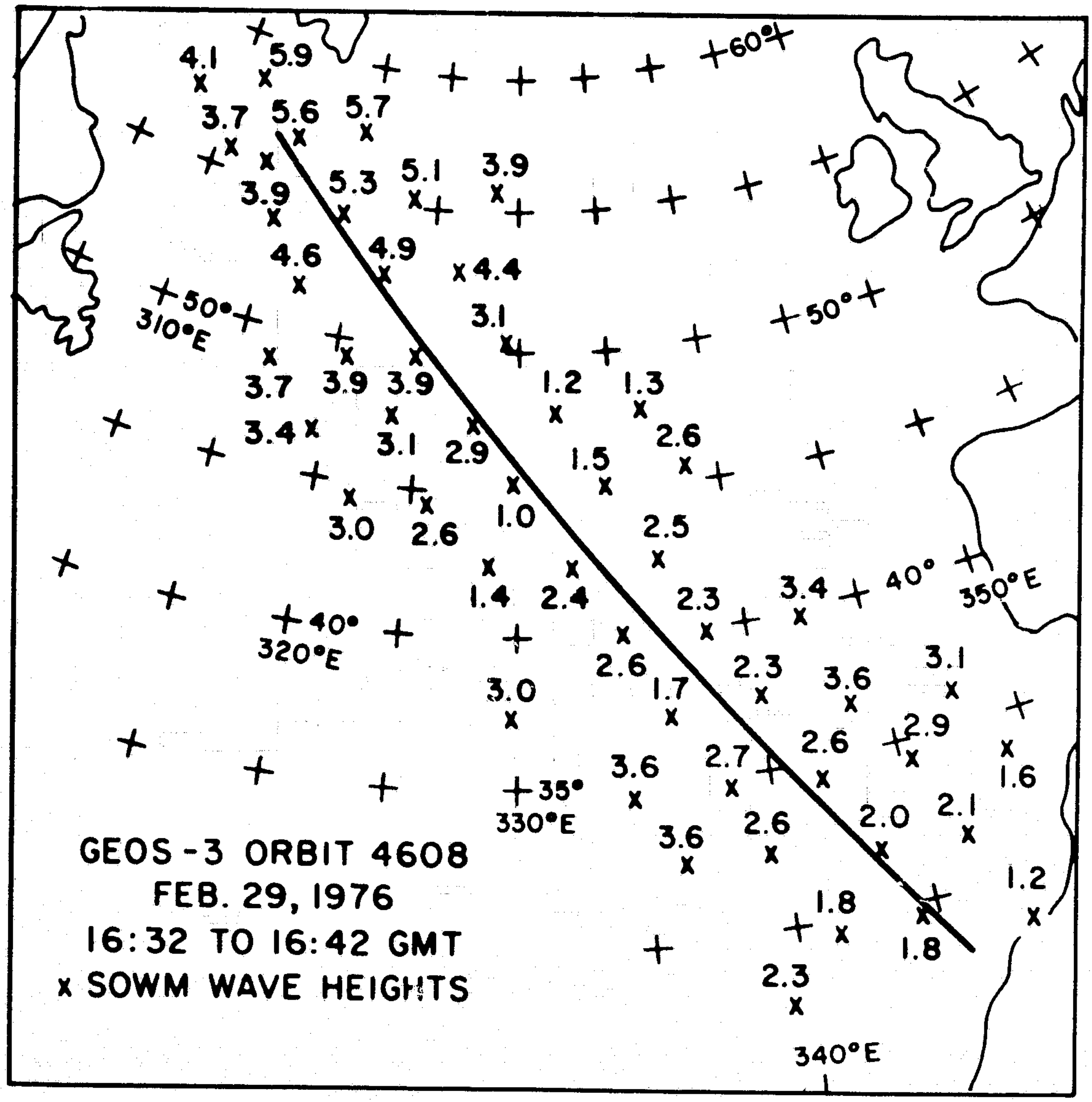
HIGHEST GEOS; ON GRID 6.6 M; AT ONE POINT 7 M

LOWEST SOWM; ON TRACK 1.2 M; IN FIELD 1.2 M

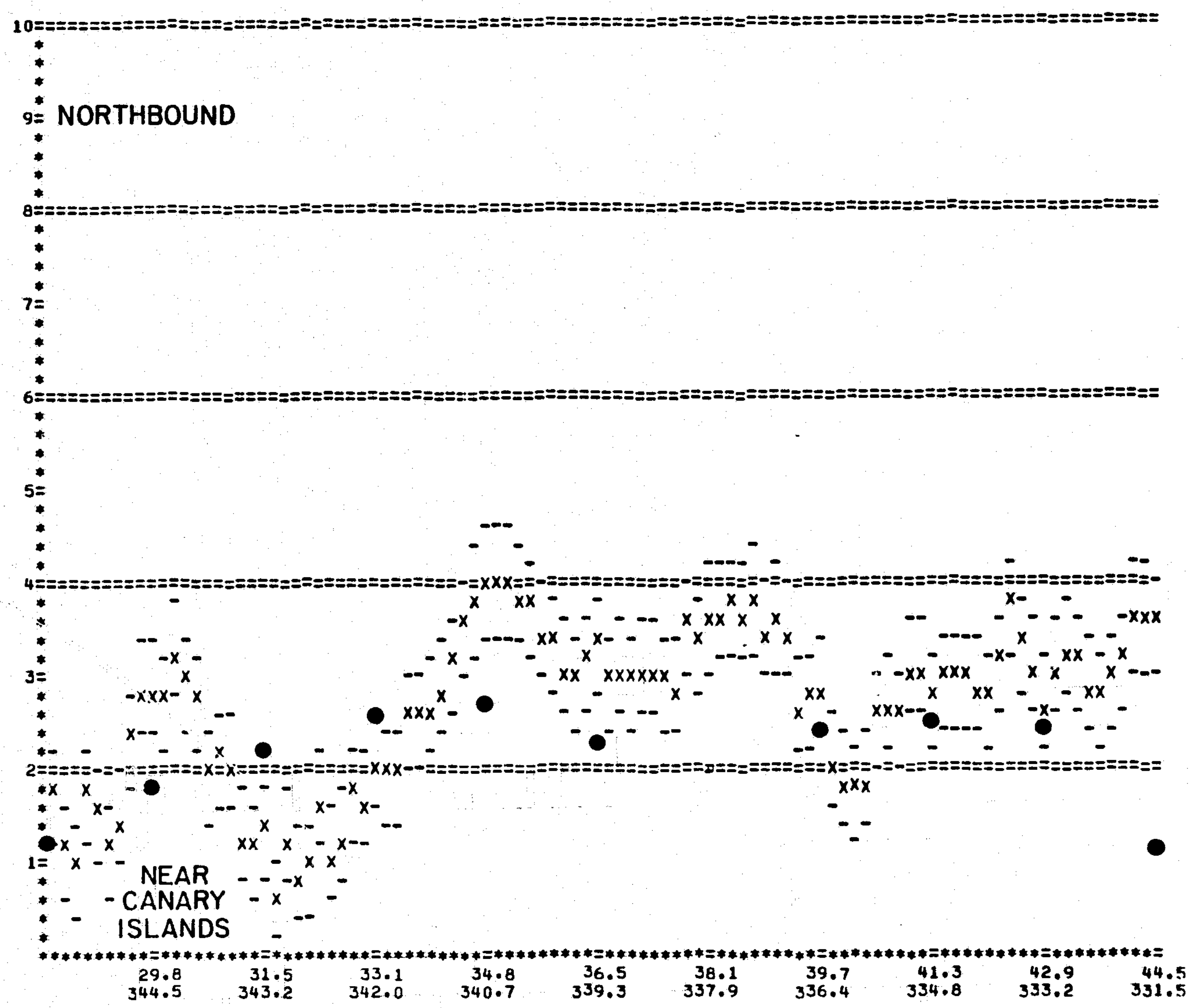
LOWEST GEOS; ON GRID 1.4 M; AT ONE POINT 0.6 M

LARGEST ERROR - 2.4 M; SOWM 1.2 M, GEOS 3.6 M

From 28° N to 46° N, rapid fluctuations in GEOS not tracked by SOWM. Could be partially swell. Excellent agreement 46° N to 56° N.


60°
50°
310°E
50°
40°
350°E
40°
320°E
35°
330°E
340°E
GEOS-3 ORBIT 4608
FEB. 29, 1976
16:32 TO 16:42 GMT
x SOWM WAVE HEIGHTS

```
          ORBIT         4608  UNIQUE #        253  DATE        2/        29/        76
STARTING LAT  28.250000     LON  345.56000      TIME        16:        32
  ENDING LAT  56.400000     LON  56.400000      TIME        16:        42
```



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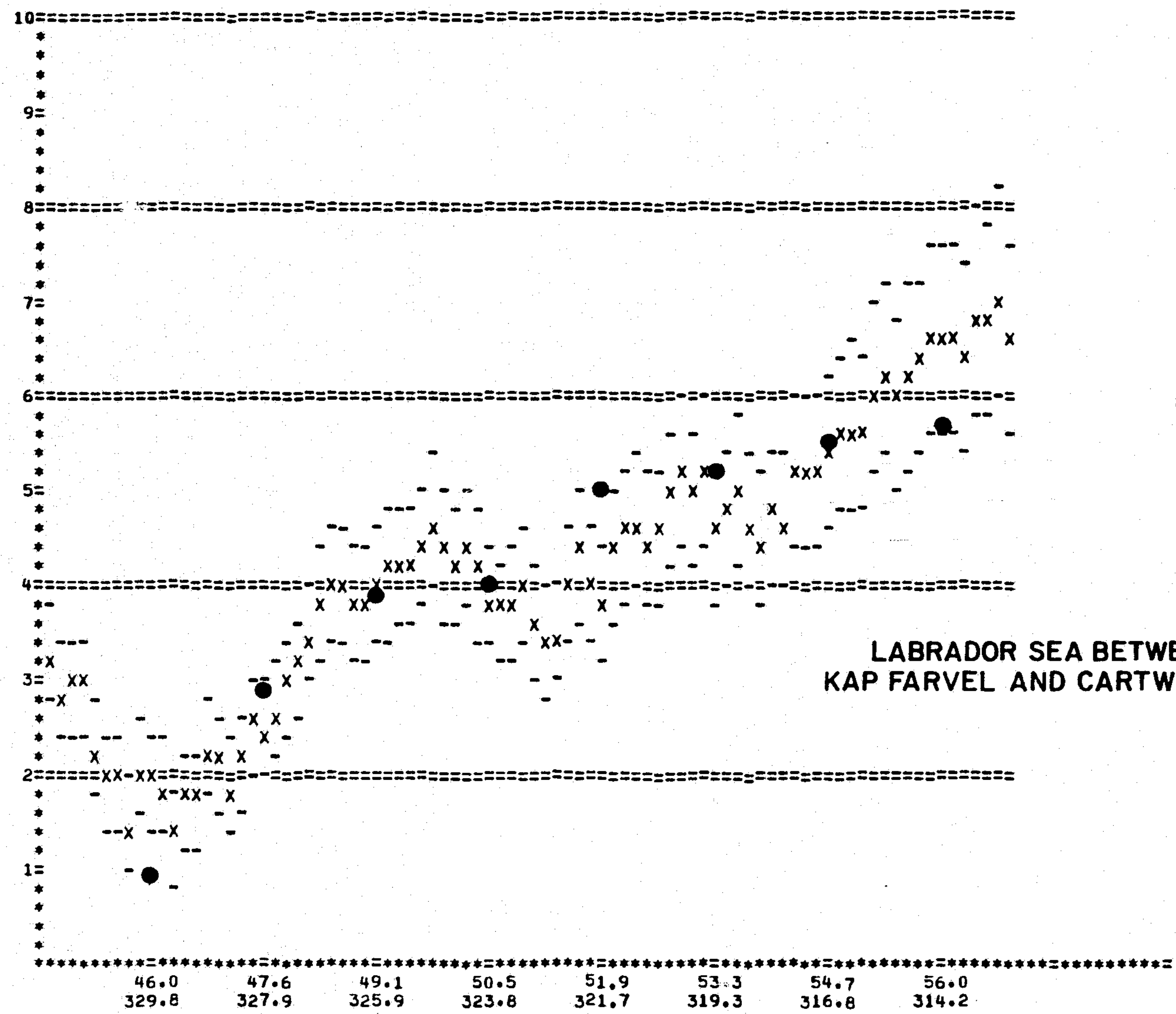
ORBIT 4608 UNIQUE # 253 DATE 2/ 29/ 76
STARTING LAT 28.250000 LON 345.56000 TIME 16: 32
ENDING LAT 56.400000 LON 56.400000 TIME 16: 42



LABRADOR SEA BETWEEN
KAP FARVEL AND CARTWRIGHT

ORBIT 4623 MAR. 1, 1976 18:02 TO 18:07

NORTHBOUND ATLANTIC

37^{o} N, 319^{o} E TO BONAVISTA BAY, NEWFOUNDLAND

7 POINTS RMS 0.5 M BIAS + 0.1 M

LAT	SOWM	GEOS	S - G
39	3.5	3.0	+ 0.5
41	4.2	4.2	0
42	4.6	4.2	+ 0.4
44	4.9	5.2	- 0.3
45	4.3	3.6	+ 0.7
47	2.4	3.2	- 0.8
48	0.2	0.2	0

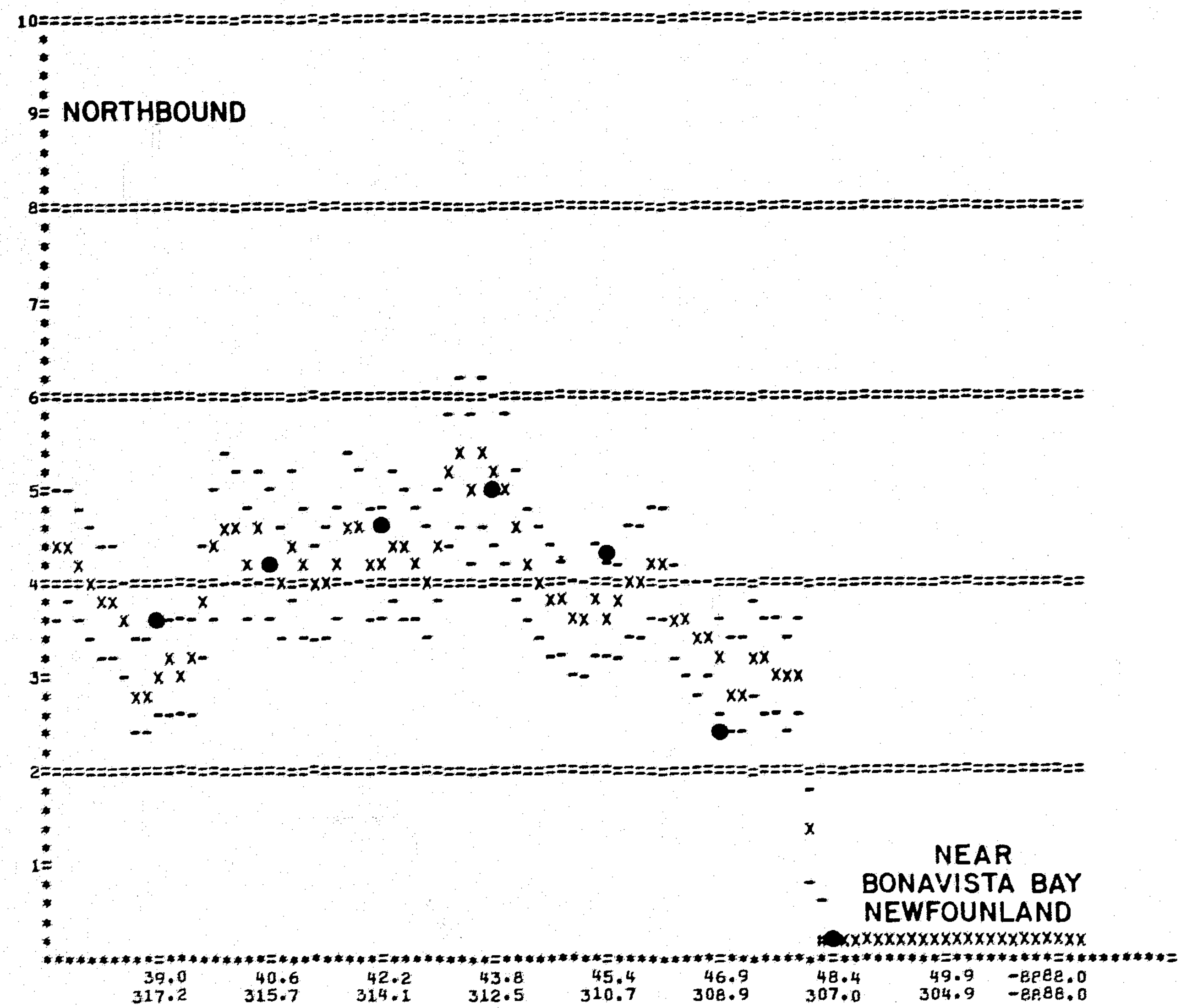
HIGHEST SOWM IN FIELD 4.9 M

HIGHEST GEOS AT ONE POINT 5.4 M

If the SOWM could do this well all of the time, there would be no need for this study.

See Orbit 3586 for SOWM height field.

```
        ORBIT         4623  UNIQUE #          275  DATE           3/          1/          76
STARTING LAT  37.540000       LON  318.51000      TIME          18:          2
  ENDING LAT -8888.0000       LON -8888.0000      TIME          18:          7
```



ORBIT 4978 MARCH 26, 1976 20:34 TO 20:40

SOUTHBOUND PACIFIC

GULF OF ALASKA NEAR YAKUTAT TO 45° N, 191° E

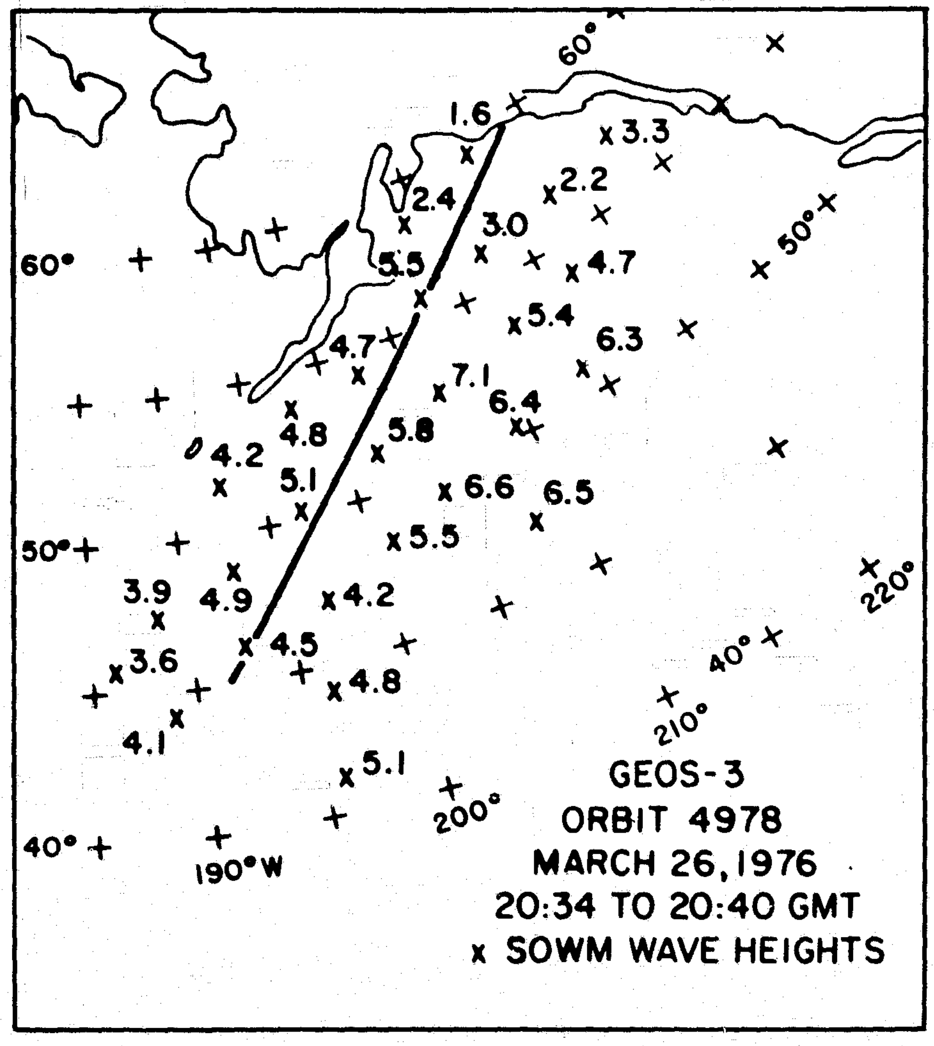
11 POINTS RMS 1.2 M BIAS + 0.5 M

LAT	SOWM	GEOS	S - G
59	2	2.2	- 0.2
58	2.5	1.4	+ 1.1
57	3.0	3.0	0
55	5.6	2.6	+ 3.0
54	5.1	4.2	+ 0.9
53	5.3	3.8	+ 1.5
51	5.5	5.0	+ 0.5
50	5.1	4.0	+ 1.1
48	4.8	5.0	- 0.2
47	4.6	5.8	- 1.2
45	4.4	5.0	- 0.6

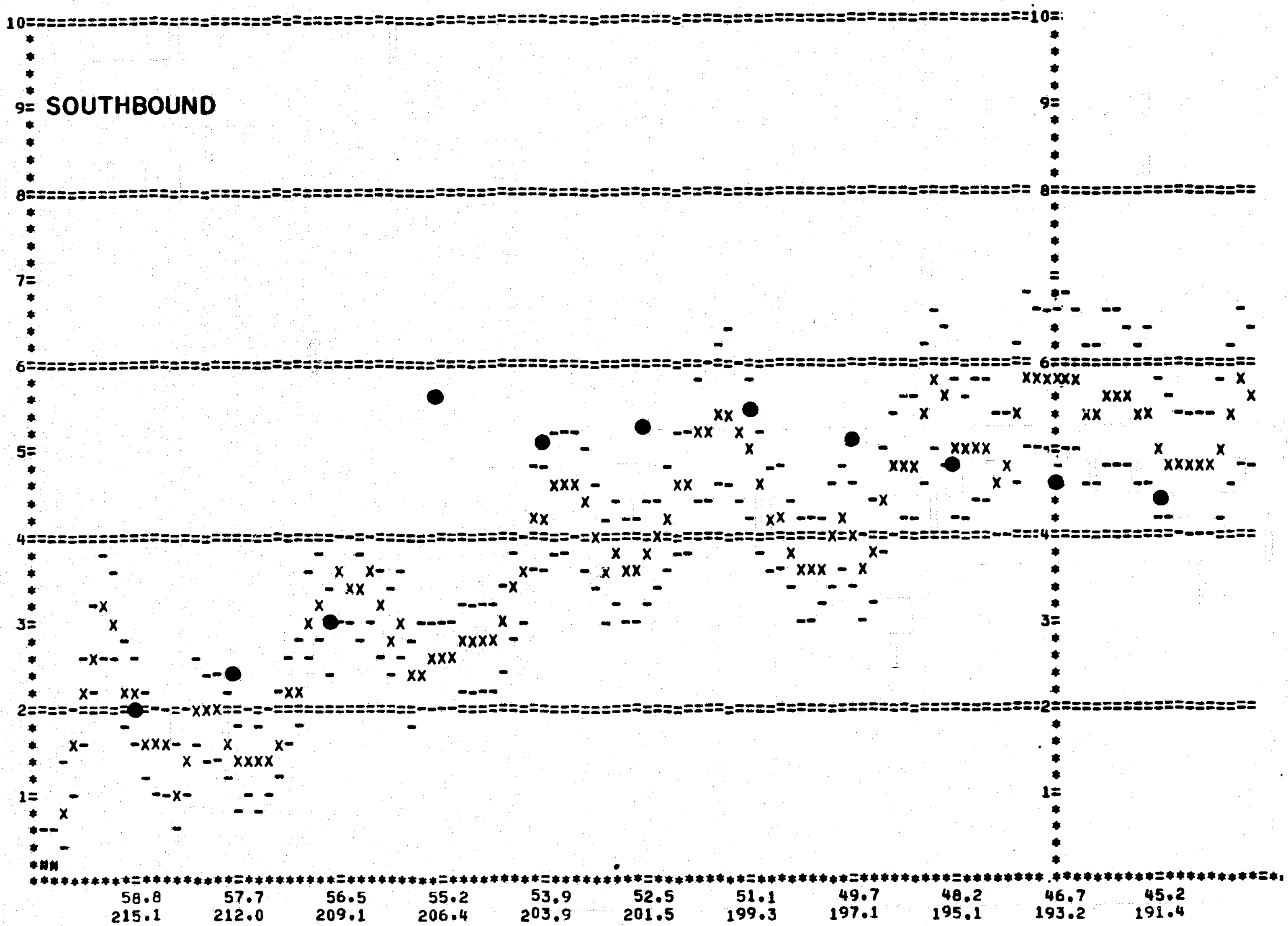
HIGHEST SOWM IN FIELD 7.1 M

HIGHEST GEOS AT ONE POINT 5.8 M

SOWM tracks peaks of GEOS fluctuations over most of track. Mislocation of highest winds in wind field could account for differences. SOWM misses general shape of GEOS heights.


GEOS-3
ORBIT 4978
MARCH 26, 1976
20:34 TO 20:40 GMT
x SOWM WAVE HEIGHTS
60°
50°
40°
190°W
200°
210°
220°

ORBIT 4978 UNIQUE # 207 DATE 3/ 26/ 76
STARTING LAT 59.820000 LON 217.97000 TIME 20: 34
ENDING LAT -8888.0000 LON -8888.0000 TIME 20: 40



ORBIT 5025 MARCH 30, 1976 5:29 TO 5:50

NORTHBOUND PACIFIC

EQUATOR AT 217° E, EAST OF HAWAIIAN ISLANDS, TO KAMCHATKA PENINSULA

46 POINTS	RMS 1.3 M	BIAS - 0.2 M
SOUTH OF 40° N	RMS 0.7 M	BIAS + 0.4 M
NORTH OF 40° N	RMS 2.5 M	BIAS + 2.4 M

HIGHEST SOWM; ON TRACK 9.5 M; IN FIELD 9.4 M

HIGHEST GEOS; ON GRID 6.8 M; AT ONE POINT 7.4 M

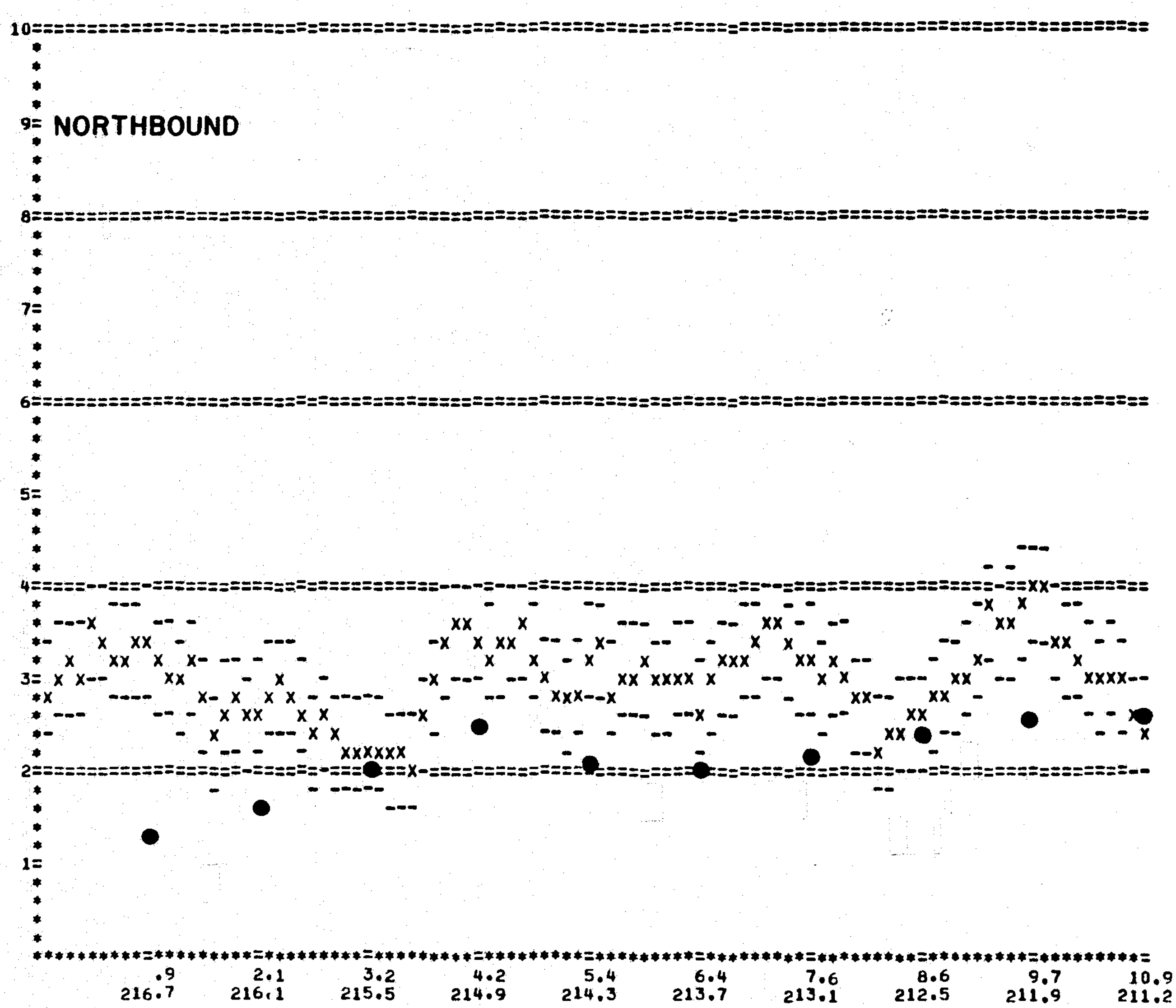
LOWEST SOWM; ON TRACK 1.3 M; IN FIELD 1.6 M

LOWEST GEOS; ON GRID 1.4 M; AT ONE POINT 1.4 M

LARGEST ERROR + 3.0 M; SOWM 9.2 M, GEOS 6.2 M

SOWM slightly too low by about 1 m from equator to 10° N. Excellent agreement 11° N to 39° N. SOWM specified higher waves 40° N to 50° N than were observed. Winds of 17 m/s instead of 20.8 m/s could explain the difference. Co-location method missed SOWM waves west of 180° E, but GEOS data are given. Waves 9 m high were measured.

ORBIT 5025 UNIQUE # 272 DATE 3/ 30/ 76
STARTING LAT -.50000000-001 LON 217.20000 TIME 5: 29
ENDING LAT 60.510000 LON 60.510000 TIME 5: 50



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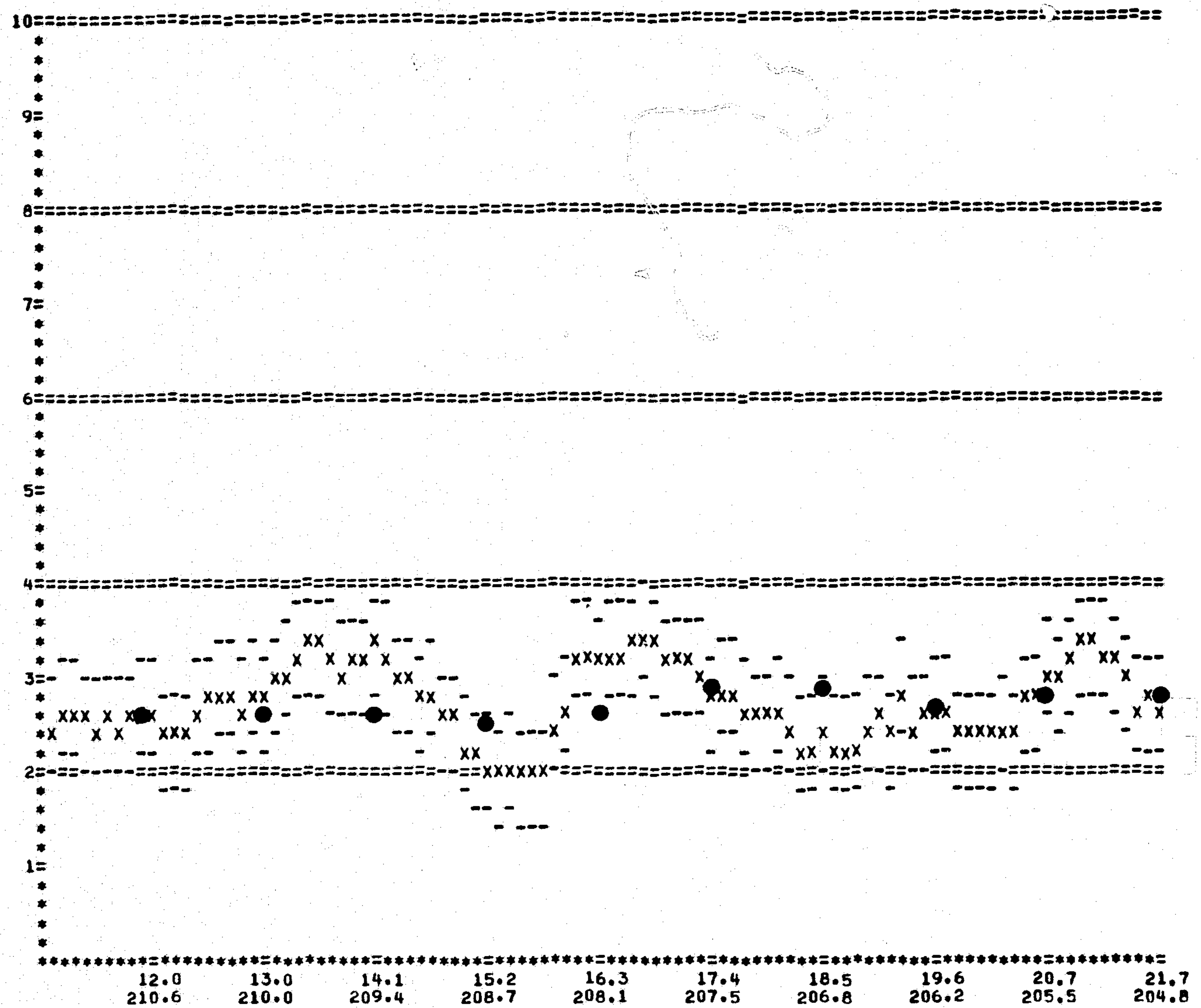
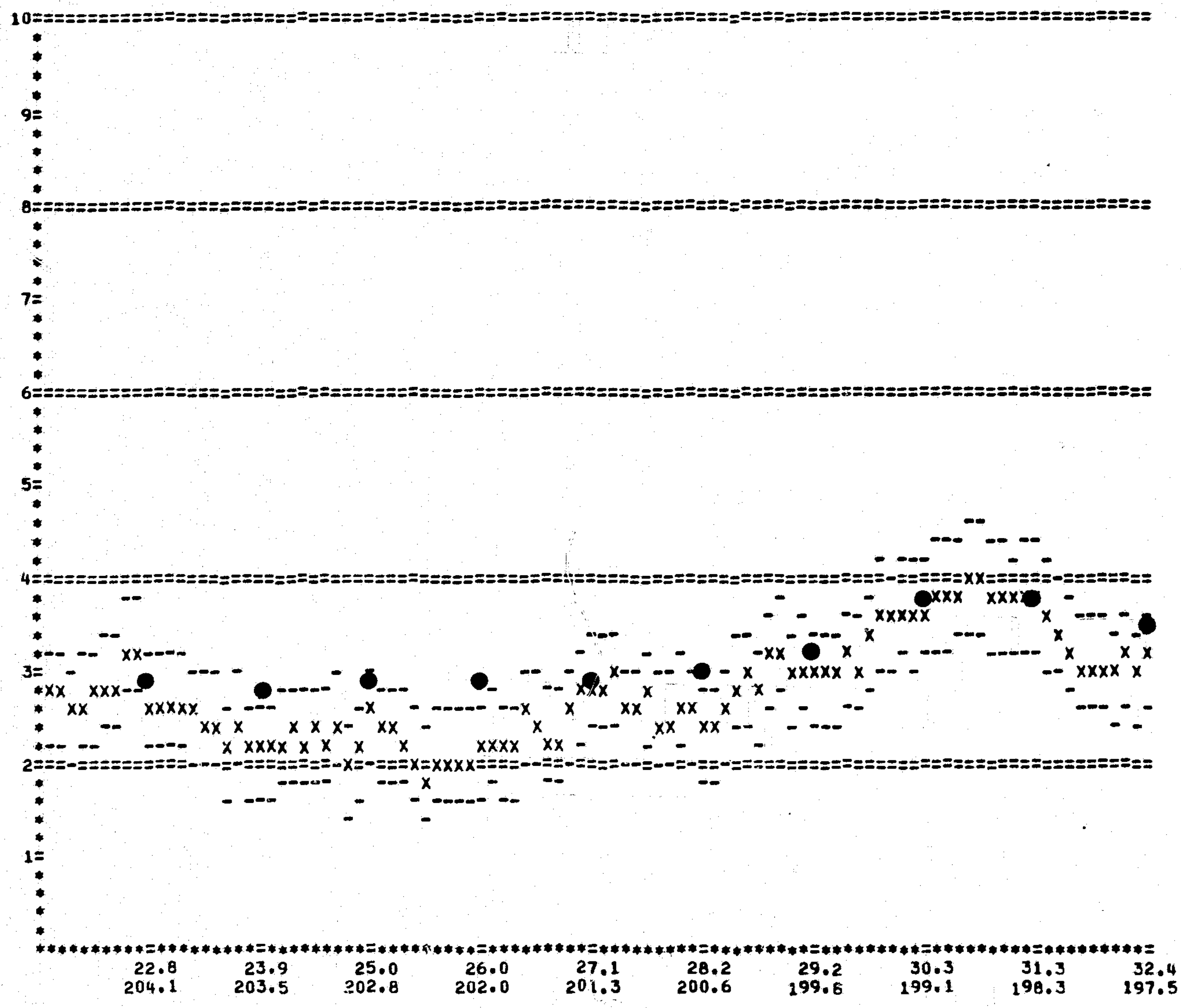
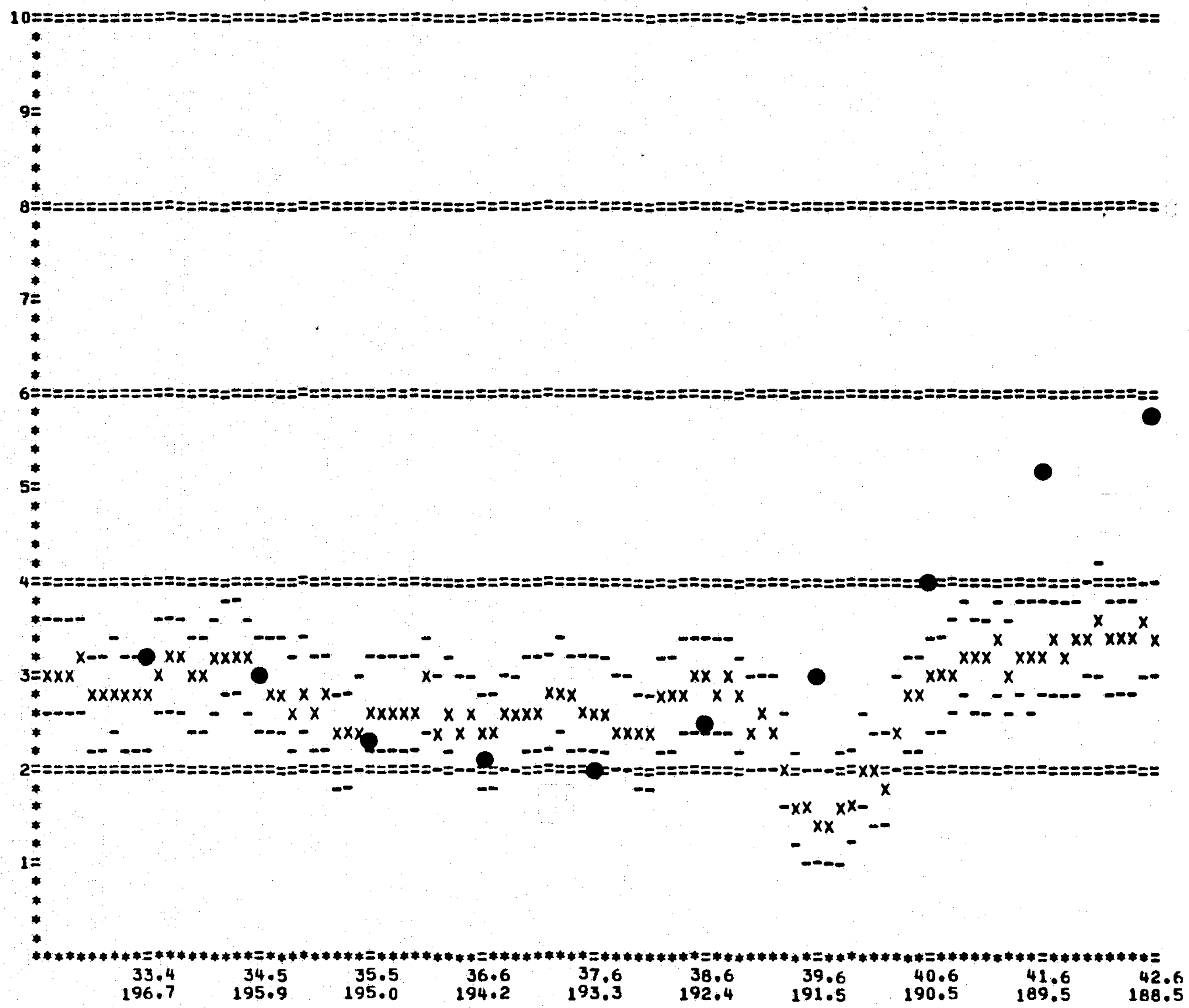
ORBIT 5025 UNIQUE # 272 DATE 3/ 30/ 76
STARTING LAT -.50000000-001 LON 217.20000 TIME 5: 29
ENDING LAT 60.510000 LON 60.510000 TIME 5: 50



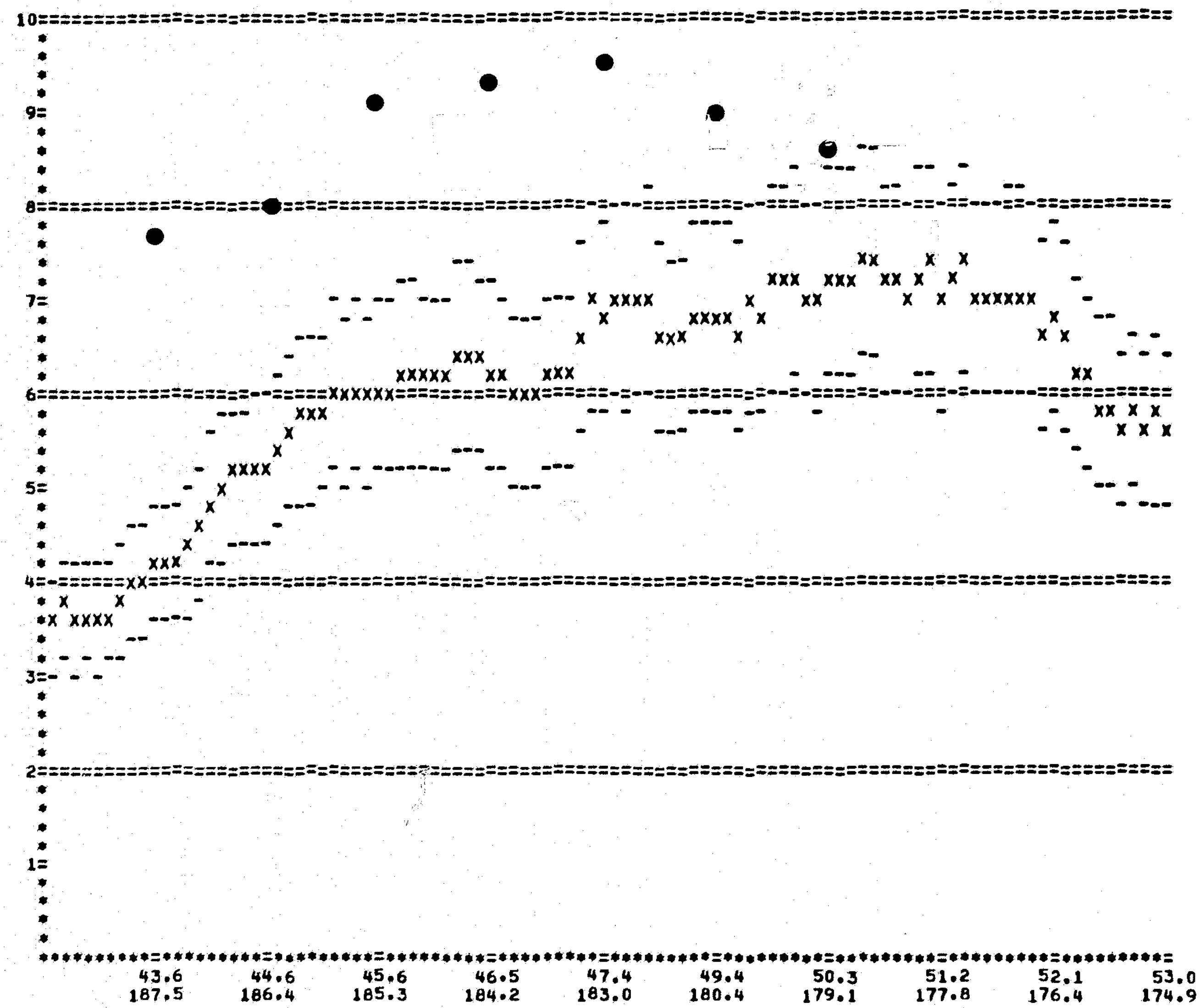
ORBIT 5025 UNIQUE # 272 DATE 3/ 30/ 76
STARTING LAT -.50009000-001 LON 217.20000 TIME 5: 29
ENDING LAT 60.510000 LON 60.510000 TIME 5: 50



ORBIT 5025 UNIQUE # 272 DATE 3/ 30/ 76
STARTING LAT -.50000000-001 LON 217.20000 TIME 5: 29
ENDING LAT 60.510000 LON 60.510000 TIME 5: 50



```
ORBIT          5025  UNIQUE #          272  DATE          3/          30/          76
STARTING LAT -.50000000-001 LON  217.20000    TIME          5:          29
  ENDING LAT  60.510000     LON  60.510000    TIME          5:          50
```



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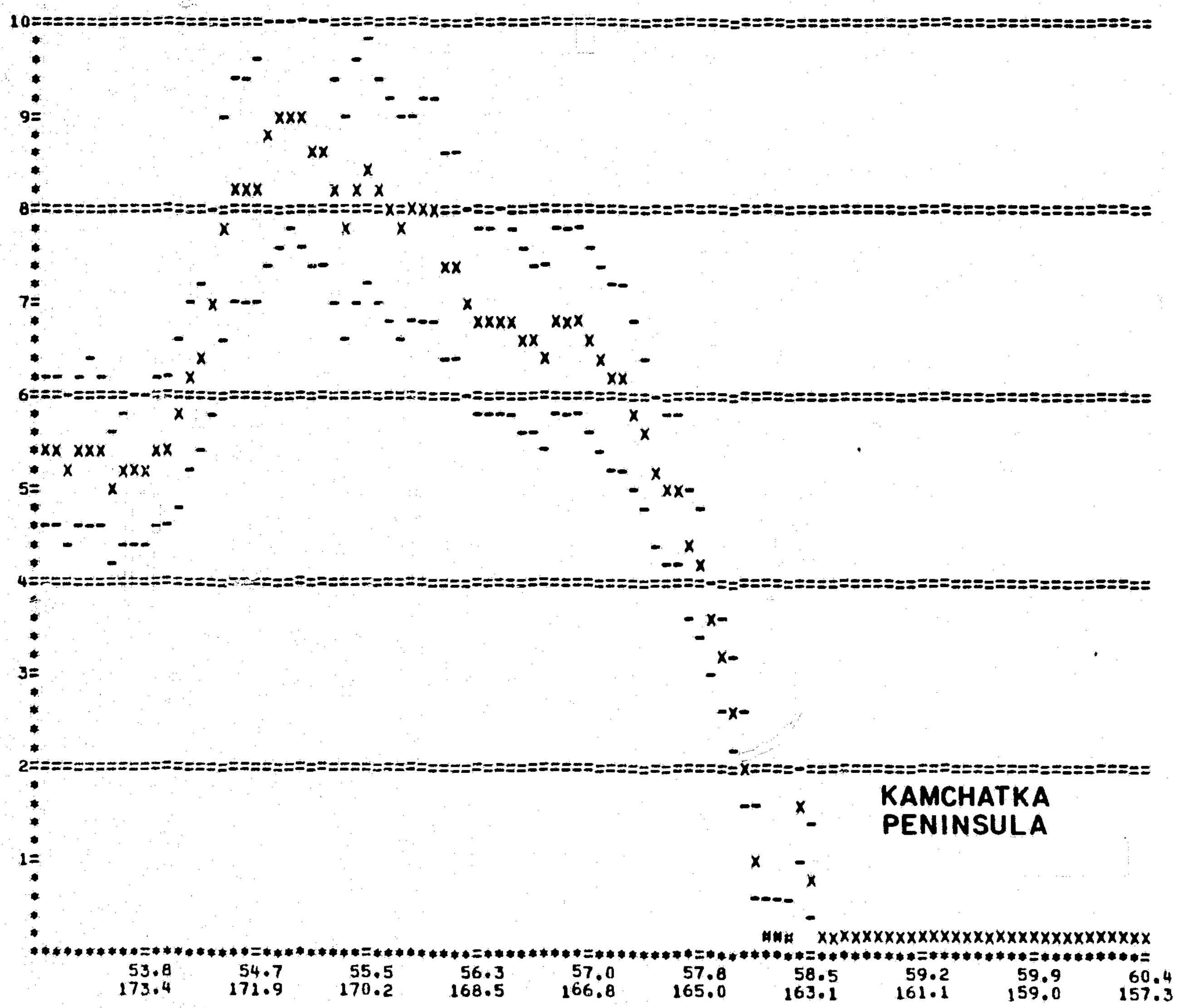
ORIGINAL PAGE IS OF POOR QUALITY

ORBIT 5025 UNIQUE # 272 DATE 3/ 30/ 76
STARTING LAT -.50000000-001 LON 217.20000 TIME 5: 29
ENDING LAT 60.510000 LON 60.510000 TIME 5: 50



ORBIT 5149 APRIL 7, 1976 22:40 TO 22:45

SOUTHBOUND PACIFIC

BRISTOL BAY, ALASKA PENINSULA, UNIMAK, AND FOX ISLANDS

TO 44.7° N, 180.6° E

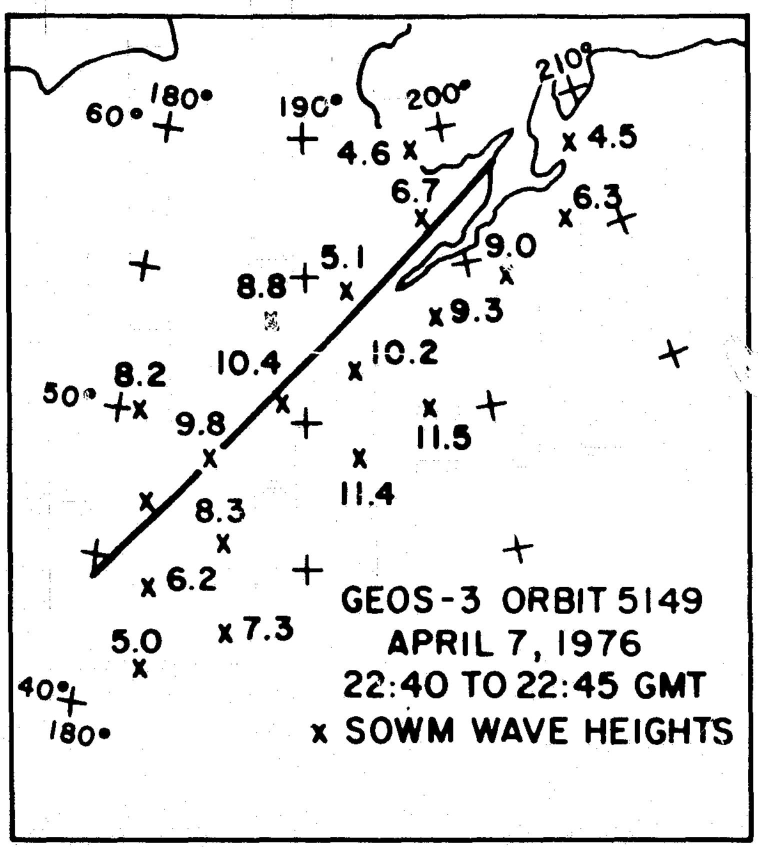
10 POINTS RMS 3.2 M BIAS + 2.6 M

LAT	SOWM	GEOS	S - G
53	9.0	6.2	+ 2.8
52	10.0	8.8	+ 1.2
51	10.4	7.6	+ 2.8
50	10.2	7.2	+ 3.0
49	10.0	6.6	+ 3.4
48	9.8	5.6	+ 4.2
47	9.0	5.8	+ 3.2
46	8.0	5.2	+ 3.8
46	6.0	5.2	+ 0.8
45	5.4	4.6	+ 0.8

HIGHEST SOWM IN FIELD 11.5 M

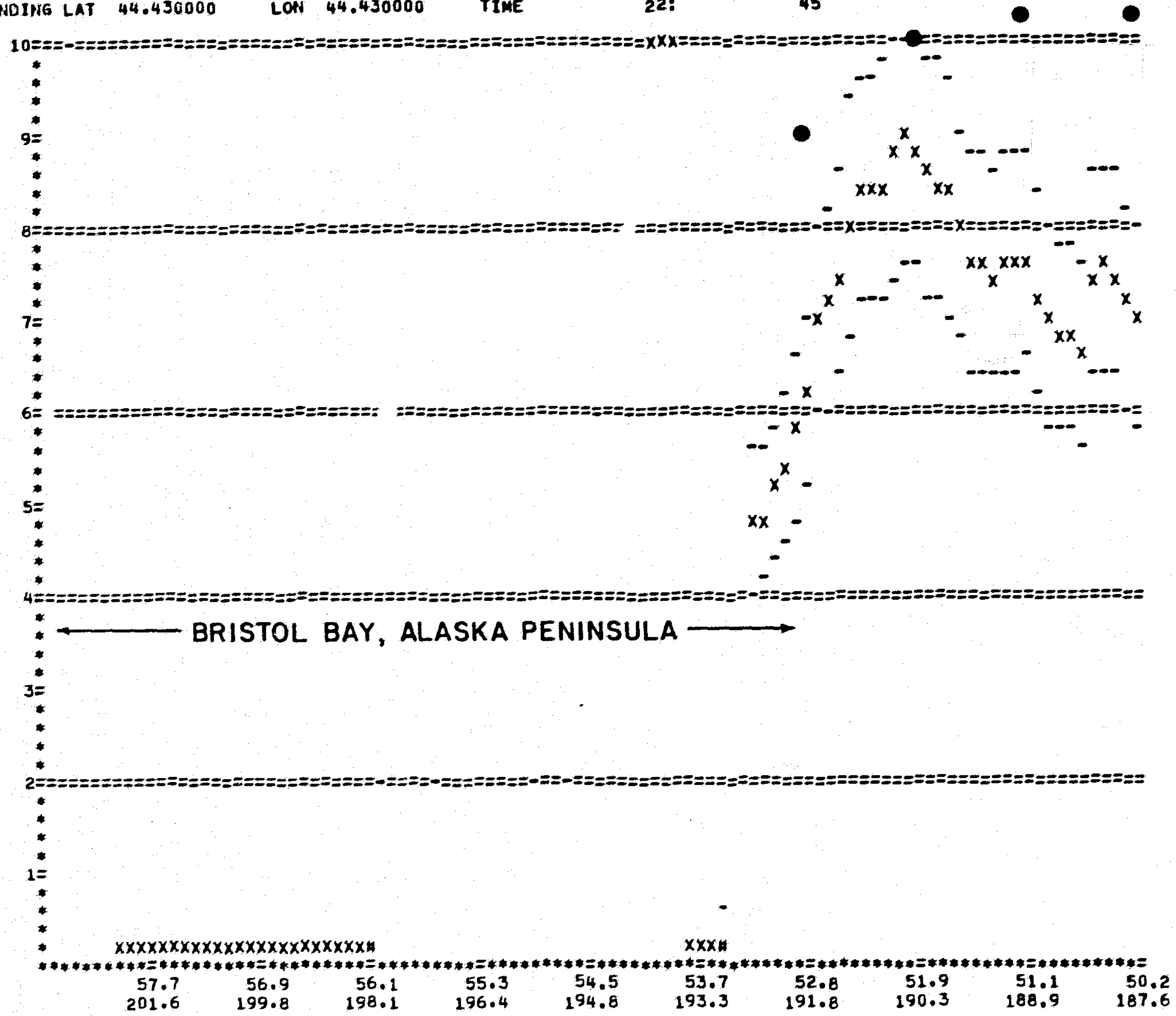
HIGHEST GEOS AT ONE POINT 9.0 M

Winds probably too high over a large area. Winds in SOWM of 22 m/s may have been only 18 m/s.



60°
180°
190°
200°
210°
4.6
4.5
6.7
6.3
9.0
5.1
8.8
9.3
10.4
10.2
8.2
50°
9.8
11.5
11.4
8.3
6.2
5.0
7.3
40°
180°
GEOS-3 ORBIT 5149
APRIL 7, 1976
22:40 TO 22:45 GMT
x SOWM WAVE HEIGHTS

ORBIT	5149	UNIQUE #	433	DATE	4/	7/	76	
STARTING LAT	58.310000	LON	203.34000	TIME	22:	40		
ENDING LAT	44.430000	LON	44.430000	TIME	22:	45		



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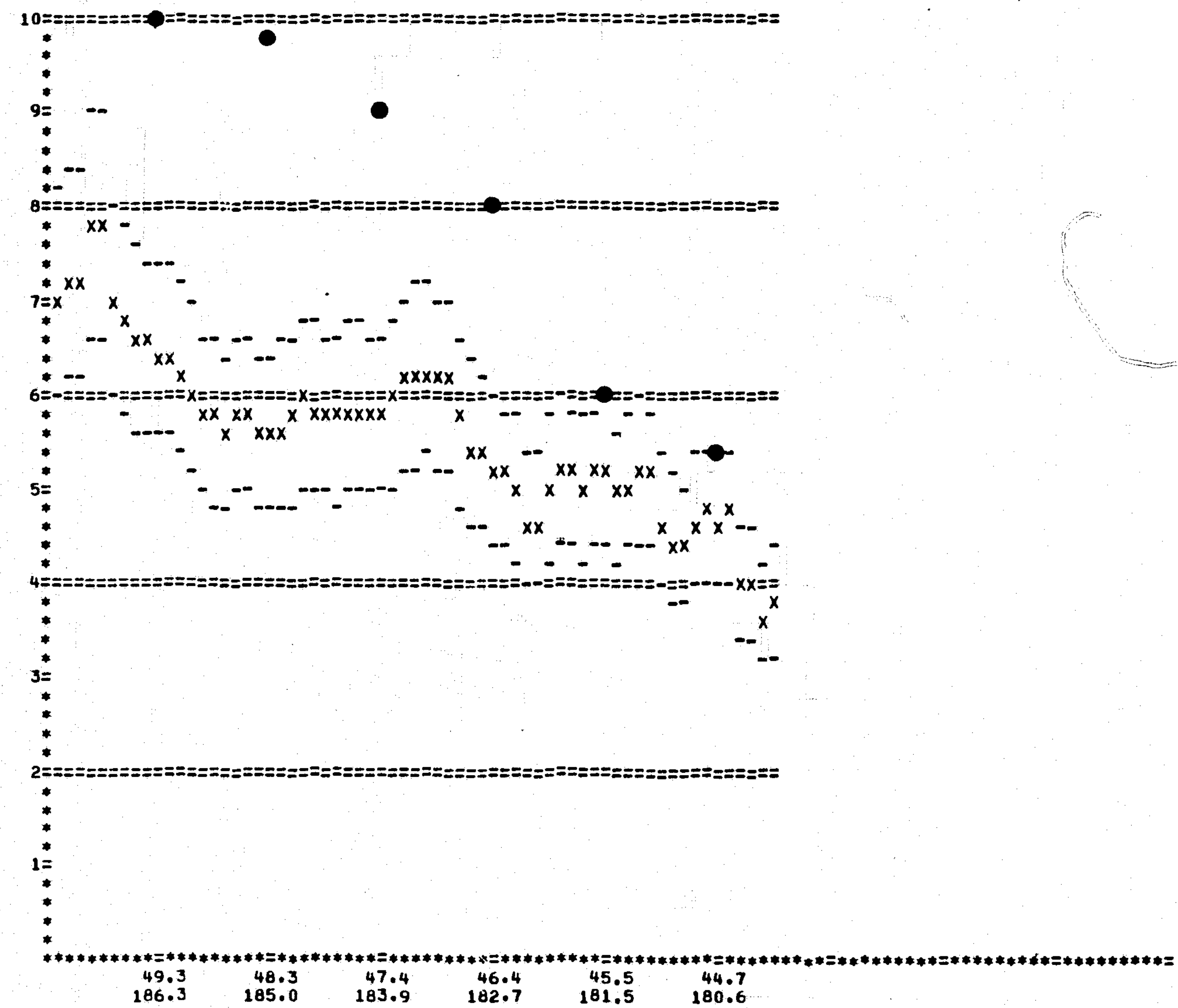
ORBIT 5149 UNIQUE # 433 DATE 4/ 7/ 76
STARTING LAT 58.310000 LON 203.34000 TIME 22: 40
ENDING LAT 44.430000 LON 44.430000 TIME 22: 45



ORBIT 5164 APRIL 9, 1976 0:4 TO 0:10

SOUTHBOUND PACIFIC

ALASKA NEAR CAPE ROMANZOF, BERING SEA TO 51° N, 169° E

9 POINTS RMS 1.8 M BIAS + 1.6 M

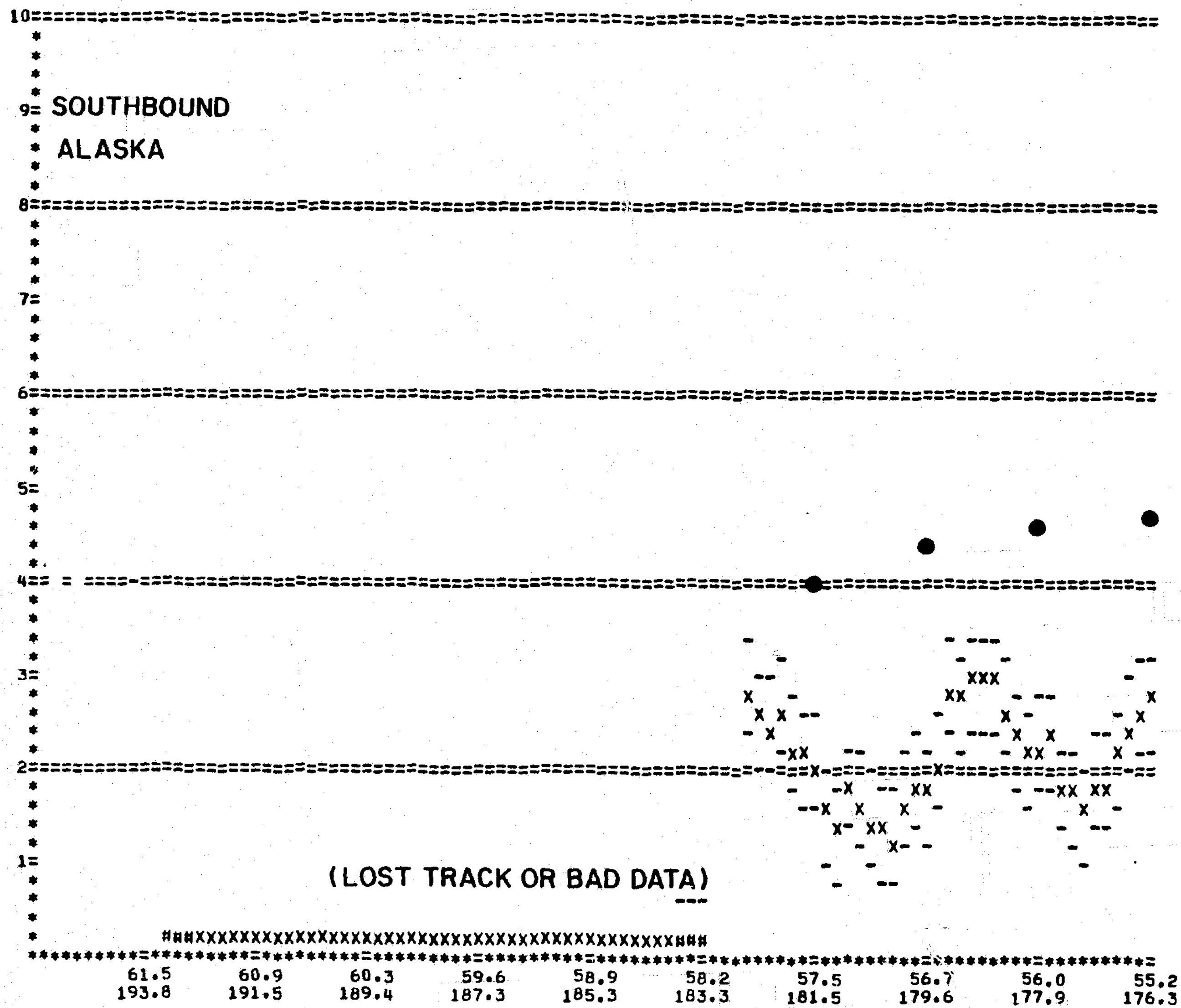
LAT	SOWM	GEOS	S - G
58	4	2	+ 2
57	4.5	1.8	+ 2.7
55	4.7	2.8	+ 1.9
54	4.6	2.8	+ 1.8
54	4.8	3.2	+ 1.6
53	6.0	5.0	+ 1
52	7.5	7.0	+ 0.5
51	8.0	7.8	+ 0.2

HIGHEST SOWM IN FIELD 9.6 M

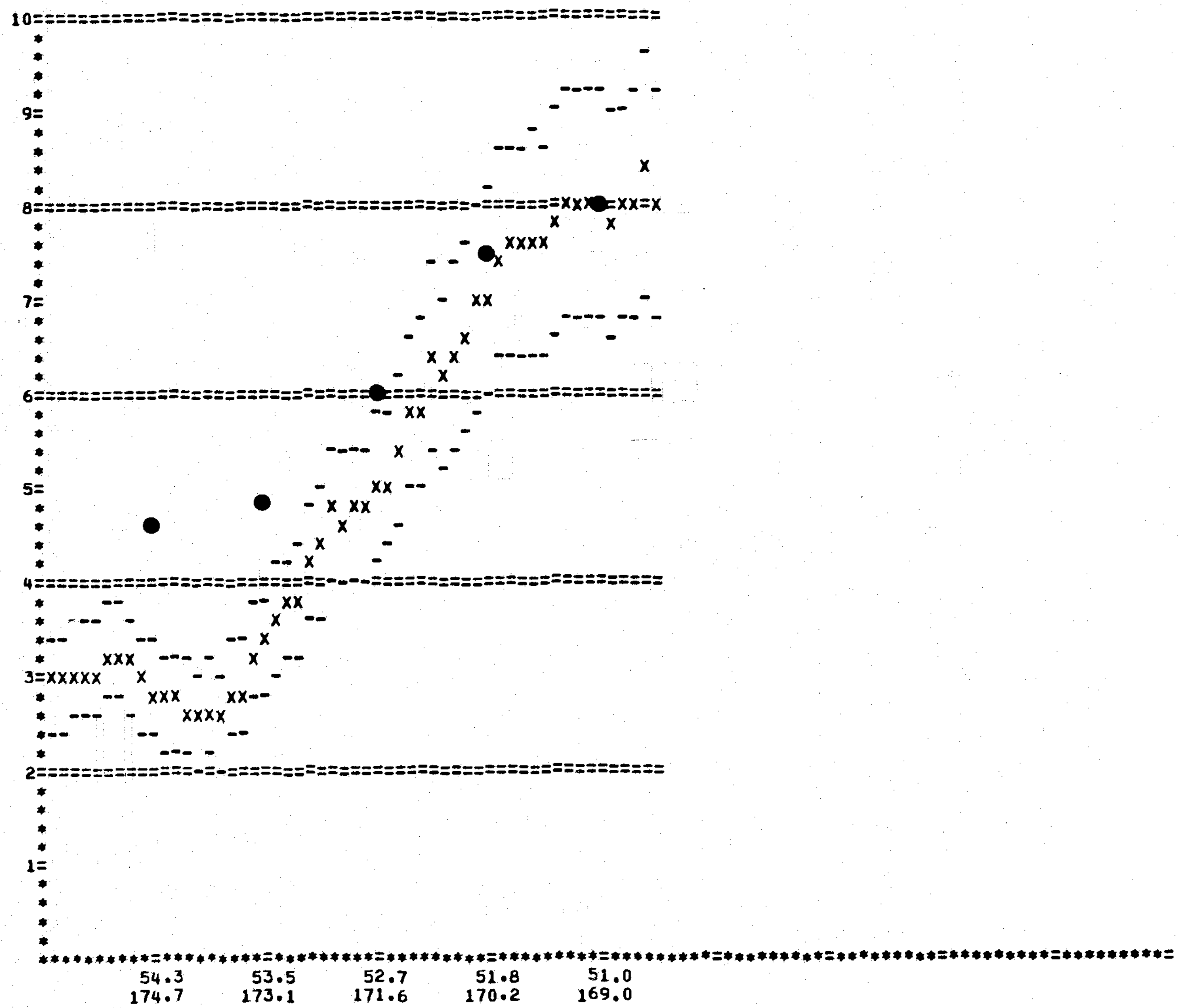
LOWEST SOWM IN FIELD 2.4 M

Peak winds for SOWM model were probably specified correctly. Winds in analysis probably did not decrease to the north rapidly enough to specify low waves 58° N to 54° N.

ORBIT	5164	UNIQUE #	452	DATE	4/	9/	76
STARTING LAT	61.980000	LON	195.89000	TIME	0:	4	
ENDING LAT	50.810000	LON	50.810000	TIME	0:	10	



ORBIT 5164 UNIQUE # 452 DATE 4/ 9/ 76
STARTING LAT 61.980000 LON 195.89000 TIME 0: 4
ENDING LAT 50.810000 LON 50.810000 TIME 0: 10



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ORBIT 5258 APRIL 15, 1976 15:38 TO 15:49

SOUTHBOUND ATLANTIC

NEWFOUNDLAND, OVER CENTER OF CUBA TO NICARAGUA

19 POINTS RMS 1.0 M BIAS + 0.2 M

HIGHEST SOWM; ON TRACK 2.4 M; IN FIELD 2.6 M

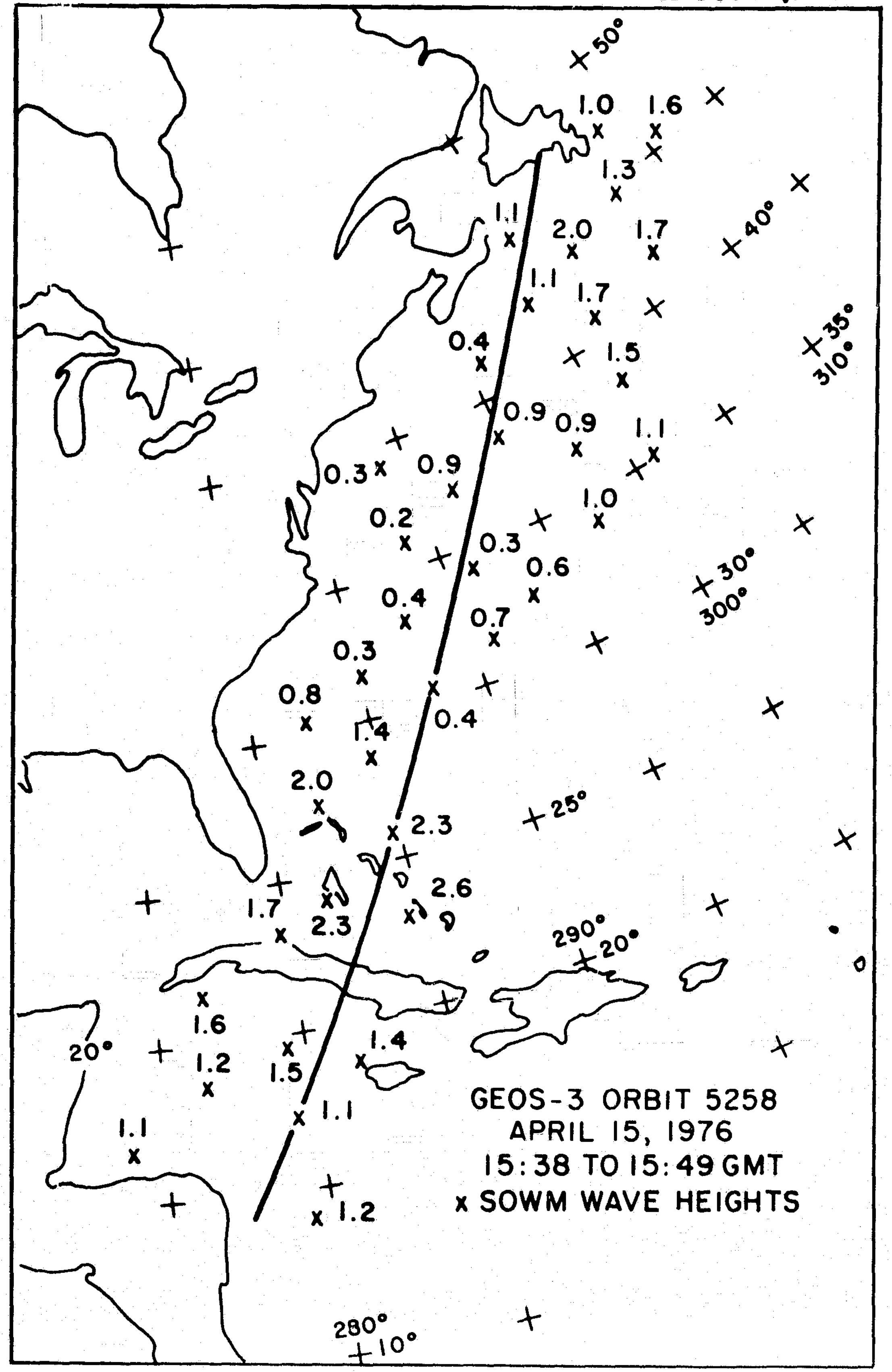
HIGHEST GEOS; ON GRID 3.2 M; AT ONE POINT 3.2 M

LOWEST SOWM; ON TRACK 0.3 M; IN FIELD 0.3 M

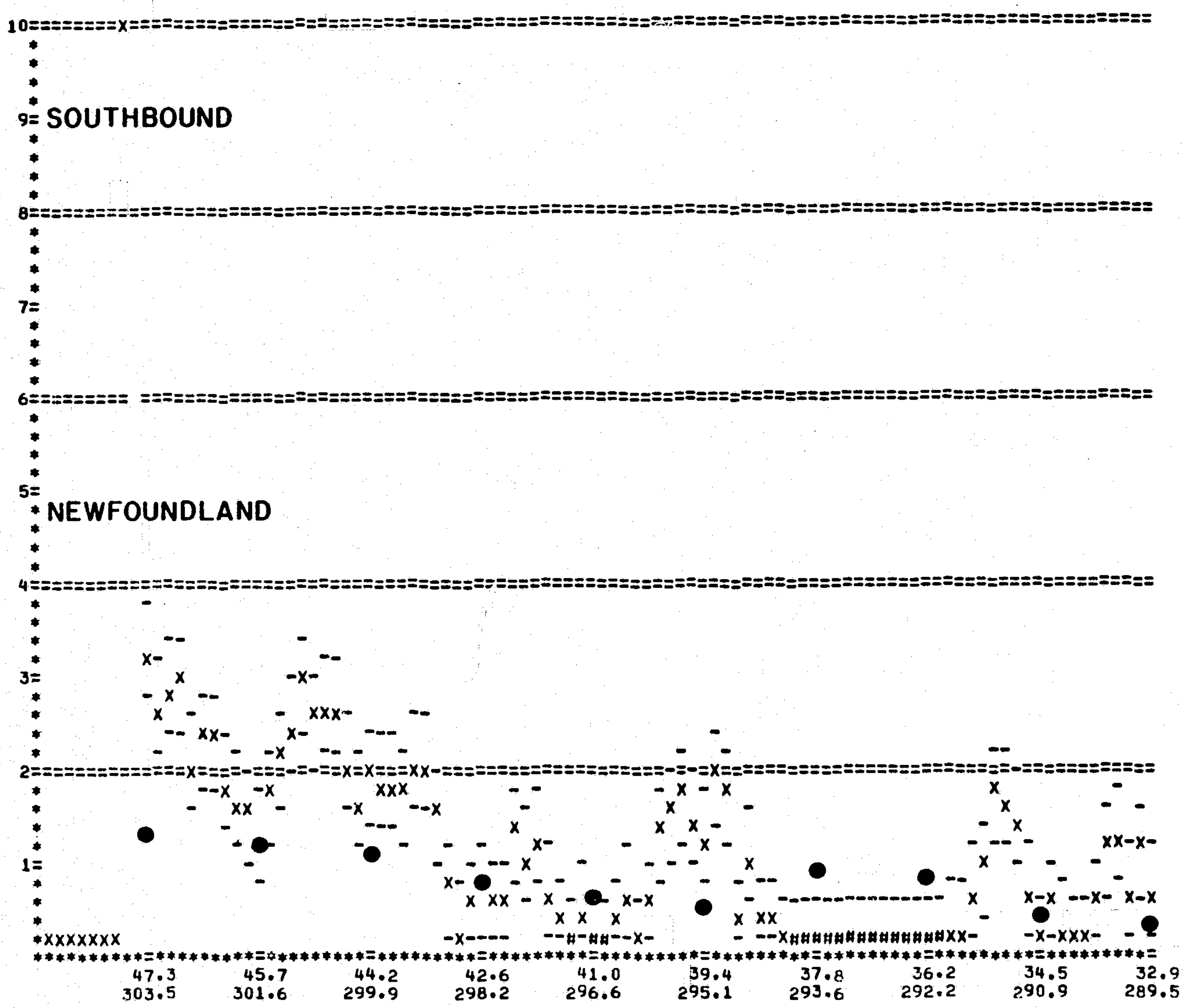
LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR + 2.2 M; SOWM 2.4 M, GEOS 0.2 M

Widely fluctuating GEOS heights scatter above and below SOWM heights. High SOWM heights near Bahamas are not verified by GEOS heights.


GEOS-3 ORBIT 5258
APRIL 15, 1976
15:38 TO 15:49 GMT
x SOWM WAVE HEIGHTS
50°
40°
35°
310°
30°
300°
25°
290°
20°
20°
280°
10°

```
    ORBIT         5258  UNIQUE #          574  DATE          4/          15/          76
STARTING LAT  48.610000      LON  305.20000      TIME         15:          38
  ENDING LAT  14.100000      LON  14.100000      TIME         15:          49
```



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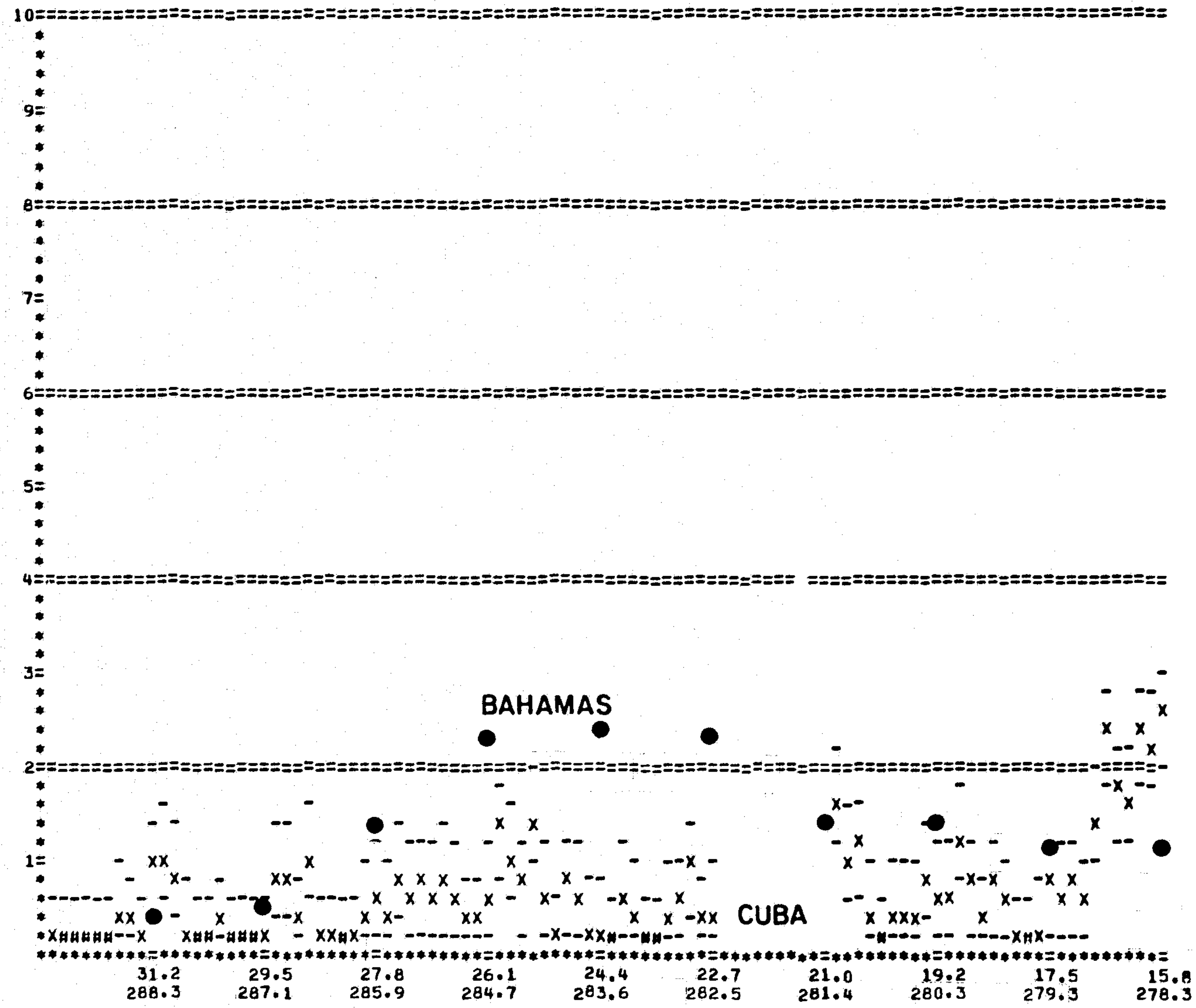
```
      ORBIT          5258  UNIQUE #          574  DATE           4/          15/          76
STARTING LAT  48.610000      LON  305.20000      TIME          15:          38
  ENDING LAT  14.100000      LON  14.100000      TIME          15:          49
```



ORBIT 6295 JUNE 27, 1976 22:45 TO 22:50

SOUTHBOUND ATLANTIC

37^{o} N, 340^{o} W TO 43.6^{o} N, 319^{o} W

14 POINTS RMS 0.9 M BIAS - 0.7 M

HIGHEST SOWM; ON TRACK 3.0 M; IN FIELD 4.1 M

HIGHEST GEOS; ON GRID 4.8 M; AT ONE POINT 4.6 M

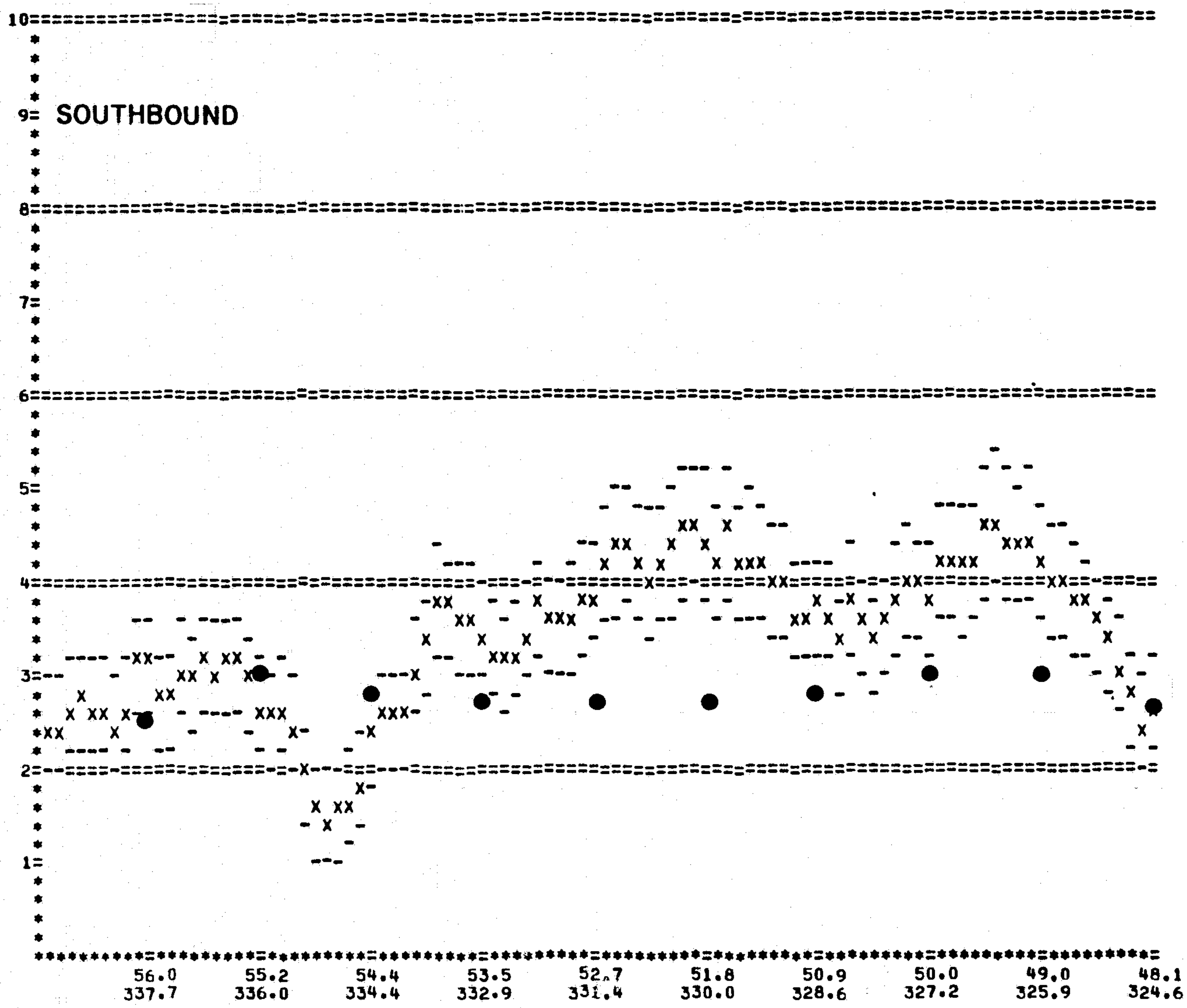
LOWEST SOWM; ON TRACK 1.6 M; IN FIELD 0.9 M

LOWEST GEOS; ON GRID 1.8 M; AT ONE POINT 1.2 M

LARGEST ERROR - 1.6 M; SOWM 2.8 M, GEOS 4.4 M

SOWM close but consistently low. A wind of 13.4 m/s instead of 11.9 m/s could have produced better agreement over center of track.

```
         ORBIT          6295  UNIQUE #          174  DATE          6/          27/          76
  STARTING LAT  56.680000      LON  339.23000     TIME          22:          45
    ENDING LAT  43.280000      LON  43.280000     TIME          22:          50
```



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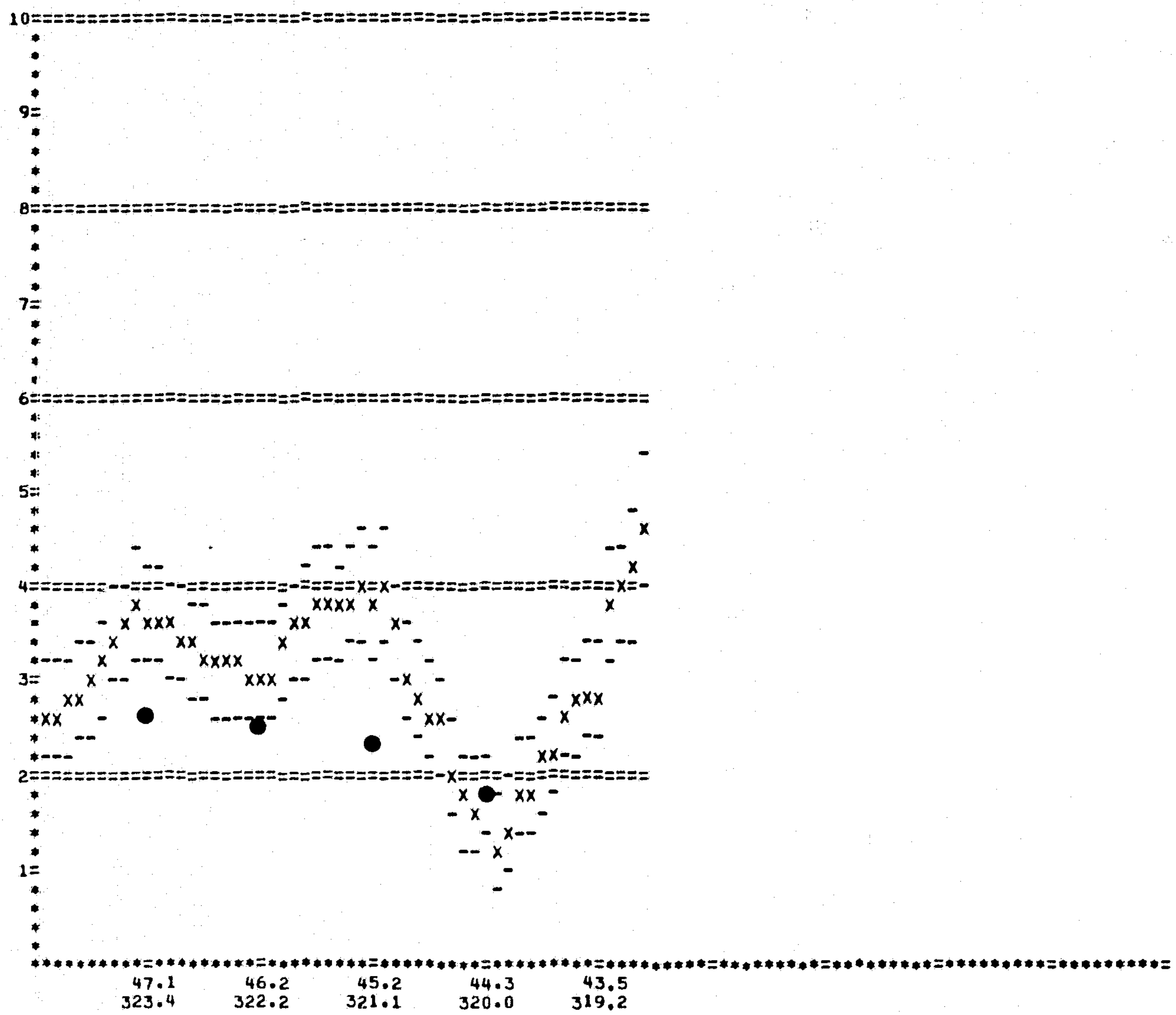
ORBIT 6295 UNIQUE # 174 DATE 6/ 27/ 76
STARTING LAT 56.680000 LON 339.23000 TIME 22: 45
ENDING LAT 43.280000 LON 43.280000 TIME 22: 50



ORBIT 6479 JULY [illegible], 1976 22:55 TO 23:08

SOUTHBOUND ATLANTIC

IRELAND to 12.9° N, 317.3° E

37 POINTS RMS 0.7 M BIAS + 0.4 M

HIGHEST SOWM; ON TRACK 4.0 M; IN FIELD 5.3 M

HIGHEST GEOS; ON GRID 3.6 M; AT ONE POINT 3.8 M

LOWEST SOWM; ON TRACK 0.2 M; IN FIELD 0.2 M

HIGHEST SOWM IN TRADES 2.0 M

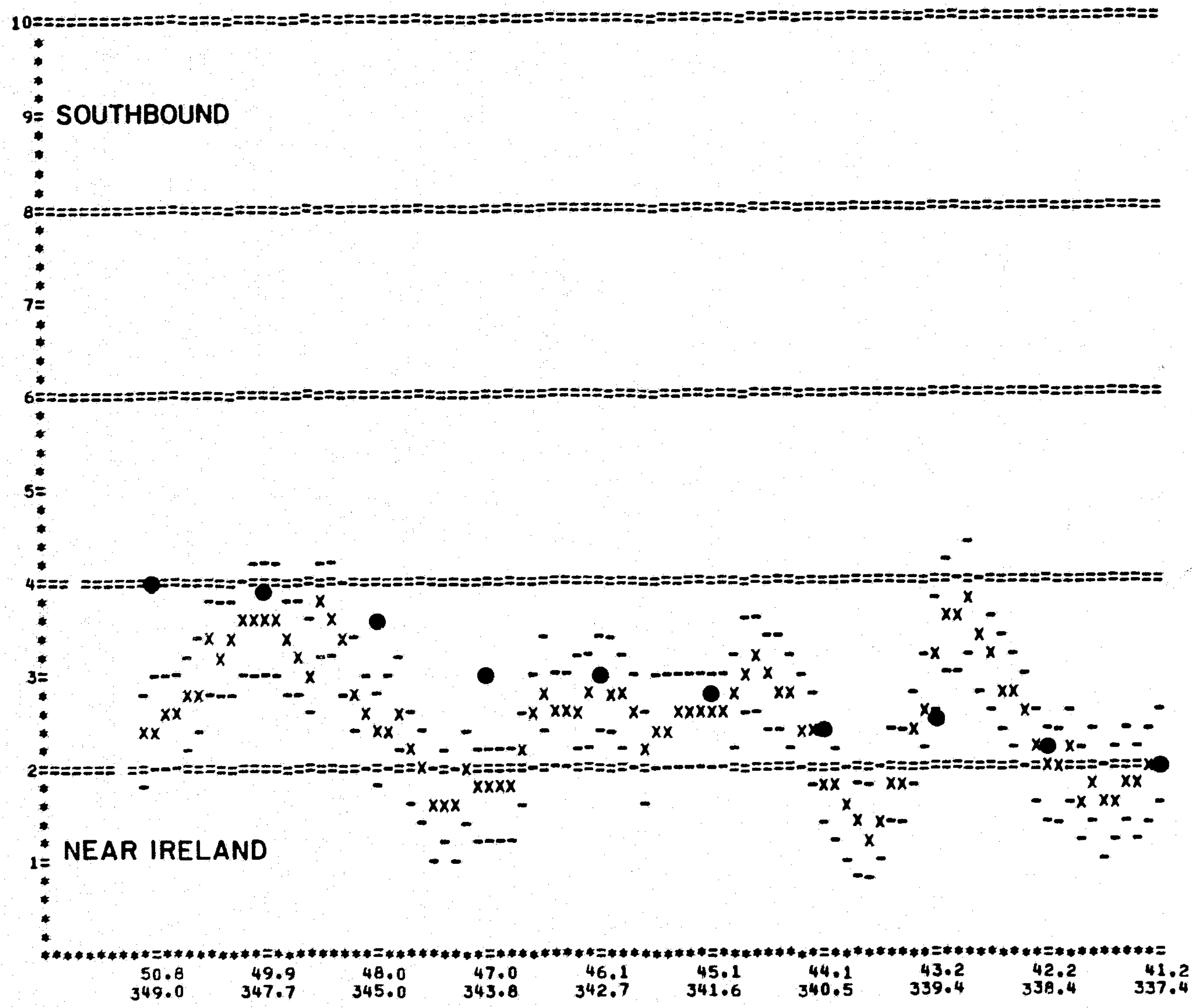
LARGEST ERROR + 1.6 M; SOWM 4.0 M, GEOS 2.4 M

Nine errors exceed 1 m, seven are from 0.6 m to 0.9 m, the remaining 21 are 0.5 m and under (see Table next page). SOWM did remarkably well for such an oscillatory GEOS height variation. SOWM specified low waves in the subtropical high center which verified except for patches of high waves. High waves in trade winds specified by the SOWM verified well except at 17° N.

ORBIT 6479 CONTINUED

LAT	SOWM	GEOS	S - G	LAT	SOWM	GEOS	S - G
51	4.0	2.4	+ 1.6	32	0.5	0.2	+ 0.3
50	3.9	3.6	+ 0.3	31	0.4	0.2	+ 0.2
48	3.6	2.4	+ 1.2	30	0.3	0.2	+ 0.1
47	3.0	1.8	+ 1.2	29	0.3	0.6	- 0.3
46	3.0	3.0	0	28	0.3	0.2	+ 0.1
45	2.8	2.6	+ 0.2	27	0.3	0.2	+ 0.1
44	2.6	1.8	+ 0.8	26	0.3	1.6	- 1.3
43	2.5	3.2	- 0.7	25	0.3	0.2	+ 0.1
42	2.2	2.0	+ 0.2	24	1.0	0.2	+ 0.8
41	2.0	2.0	0	22	1.2	0.2	+ 1.0
40	1.6	1.2	+ 0.4	21	1.7	0.8	+ 0.9
39	1.4	2.4	- 1.0	20	1.7	1.4	+ 0.3
38	1.4	0.8	+ 016	19	1.8	1.6	+ 0.2
37	1.3	1.0	+ 0.3	18	1.7	2.2	- 0.5
36	1.3	0.2	+ 1.1	17	1.8	.02	+ 1.6
35	1.3	0.2	+ 1.1	16	1.8	1.2	+ 0.6
34	0.6	0.4	+ 0.2	15	1.6	1.0	+ 0.6
33	0.5	0.2	+ 0.3	14	1.9	1.4	+ 0.5
				13	1.7	1.4	+ 0.3

ORBIT 6479 UNIQUE # 174 DATE 76/ 7/ 10
STARTING LAT 51.600000 LON 350.23000 TIME 22: 55
ENDING LAT 12.830000 LON 12.830000 TIME 23: 8



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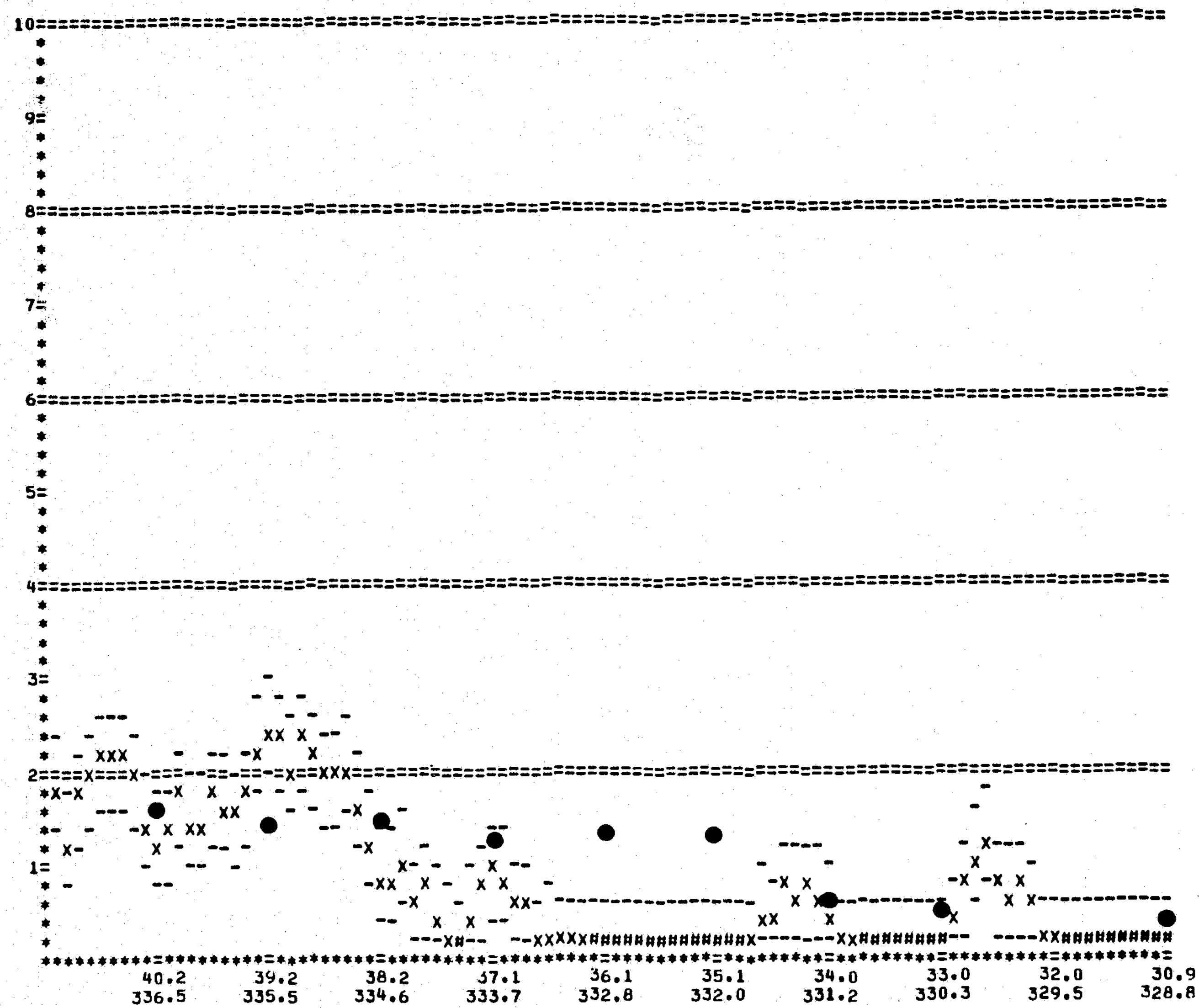
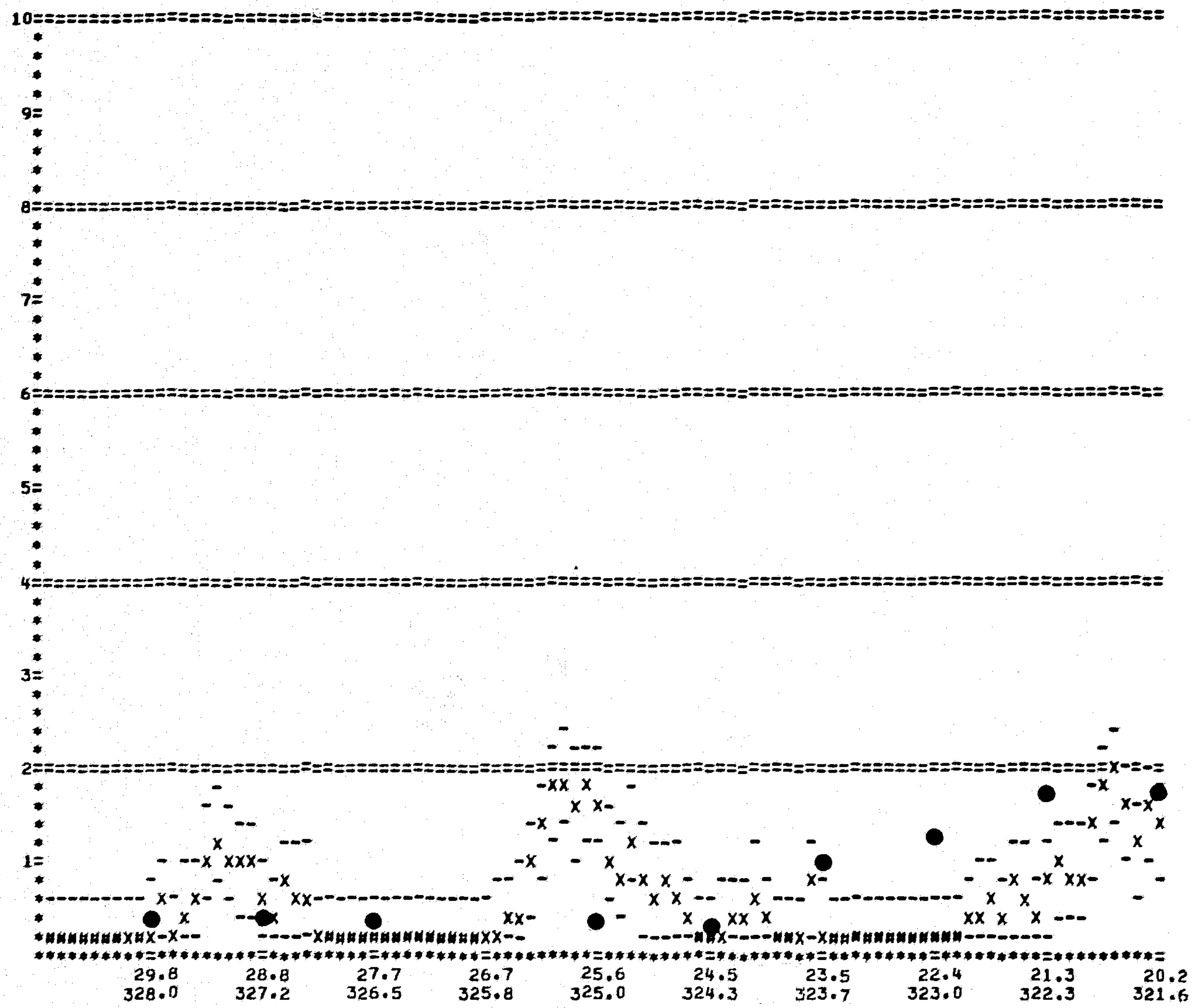
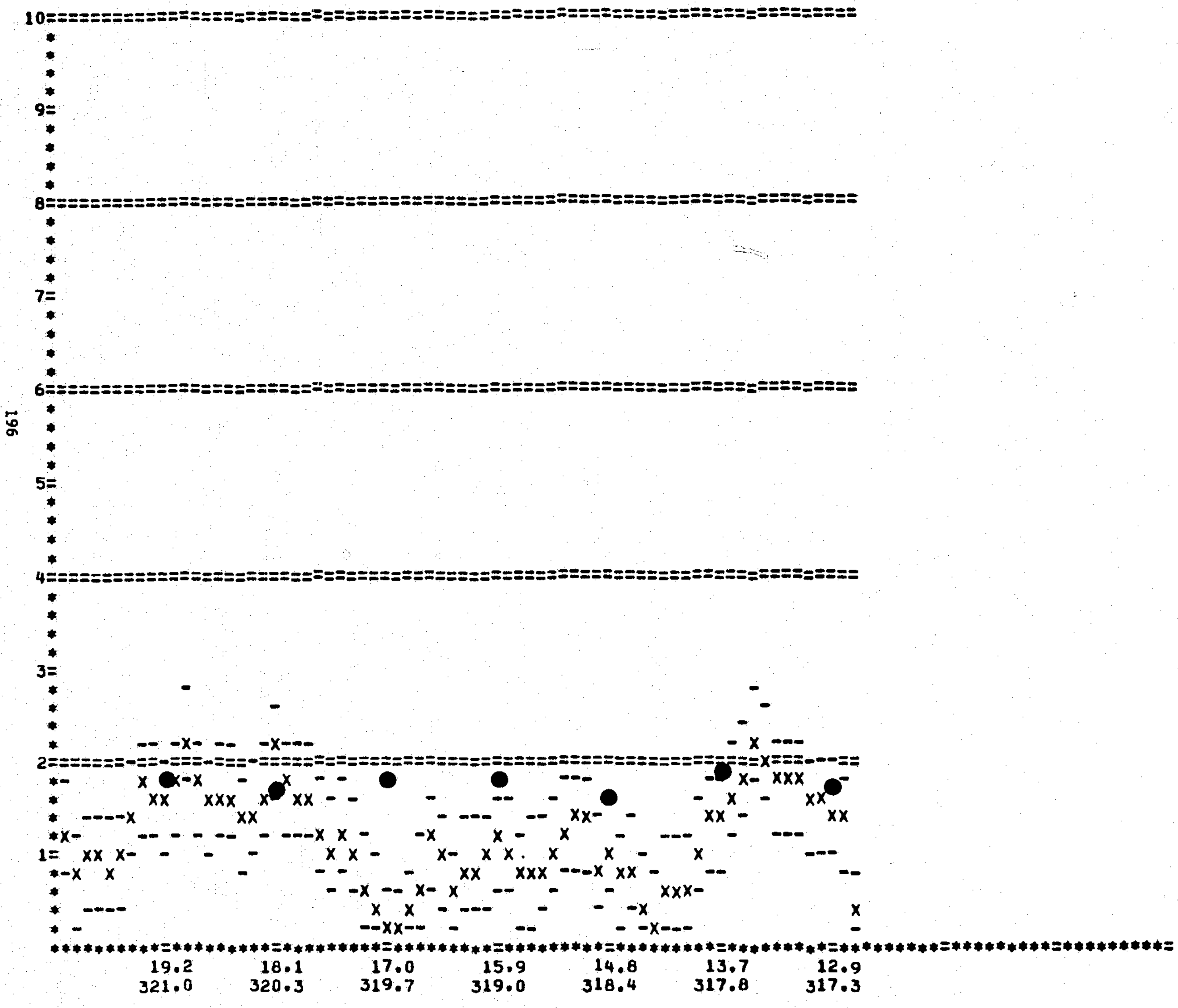
ORBIT 6479 UNIQUE # 174 DATE 76/ 7/ 10
STARTING LAT 51.600000 LON 350.23000 TIME 22: 55
ENDING LAT 12.830000 LON 12.830000 TIME 23: 8



ORBIT 6479 UNIQUE # 174 DATE 76/ 7/ 10
STARTING LAT 51.600000 LON 350.23000 TIME 22: 55
ENDING LAT 12.830000 LON 12.830000 TIME 23: 8



ORBIT 6479 UNIQUE # 174 DATE 76/ 7/ 10
STARTING LAT 51.600000 LON 350.23000 TIME 22: 55
ENDING LAT 12.830000 LON 12.830000 TIME 23: 8



ORBIT 6481 JULY 11, 1967 2:08 TO 2:16

WESTBOUND ATLANTIC

NORWAY, OVER ICELAND SOUTH OF GREENLAND TO LABRADOR SEA

19 POINTS RMS 0.7 M BIAS - 0.3 M

HIGHEST SOWM; ON TRACK 2.0 M; IN FIELD 2.7 M

HIGHEST GEOS; ON GRID 2.6 M; AT ONE POINT 2.8 M

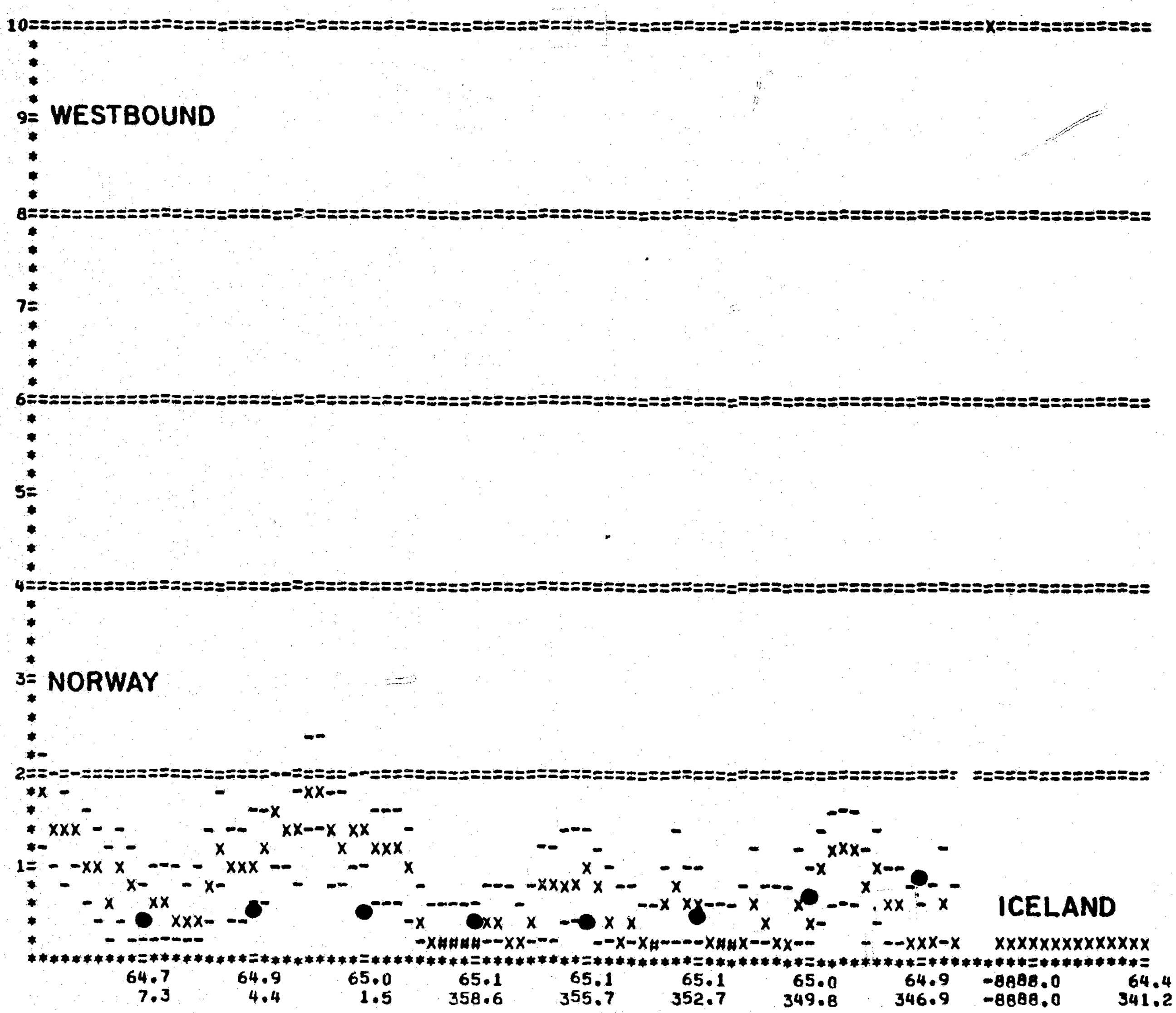
LOWEST SOWM; ON TRACK 0.4 M; IN FIELD 0.3 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (O)

LARGEST ERROR - 1.8 M; SOWM 0.8 M, GEOS 2.6 M

SOWM good Norway to Iceland except 4.4° E to 1.5° E. Also good Iceland to southern tip of Greenland. Wind field may have been too low in Labrador Sea.

```
     ORBIT          6481  UNIQUE #          179  DATE            7/             11/            76
STARTING LAT  64.510000      LON  9.8000000      TIME            2:              8
  ENDING LAT  57.850000      LON  57.850000      TIME            2:             16
```



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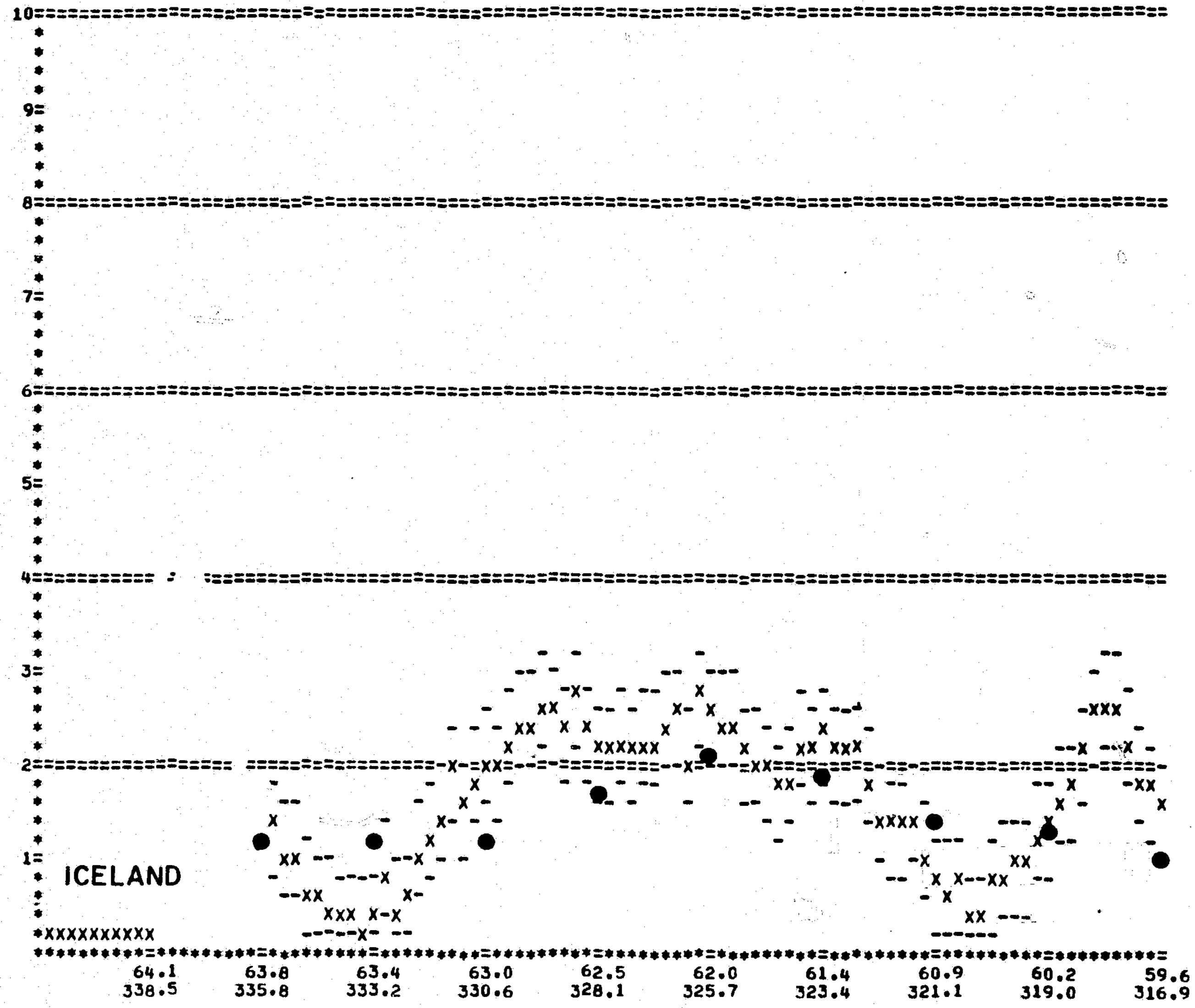
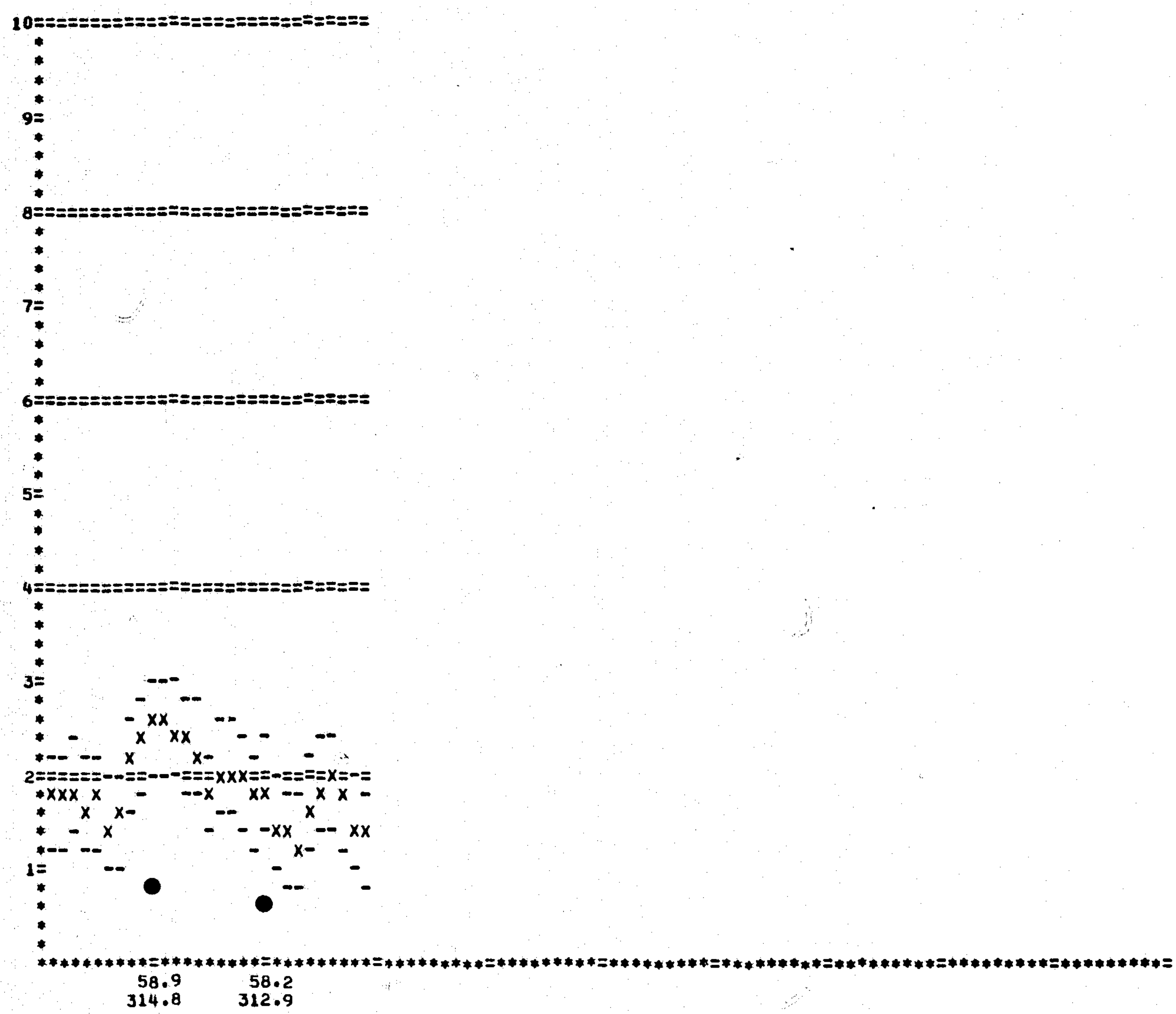
ORBIT 6481 UNIQUE # 179 DATE 7/ 11/ 76
STARTING LAT 64.510000 LON 9.8000000 TIME 2: 8
ENDING LAT 57.850000 LON 57.850000 TIME 2: 16



ORBIT 6481 UNIQUE # 179 DATE 7/ 11/ 76
STARTING LAT 64.510000 LON 9.8000000 TIME 2: 8
ENDING LAT 57.850000 LON 57.850000 TIME 2: 16



ORBIT 6635 JULY 21, 1976 23:31 TO 23:51

SOUTHBOUND ATLANTIC

DENMARK, NORTH SEA, OVER ENGLAND, NORMANDY PENINSULA TO EQUATOR AT 320° E

45 POINTS RMS 1.0 M BIAS - 0.6 M

HIGHEST SOWM; ON TRACK 2.7 M; IN FIELD 2.6 M

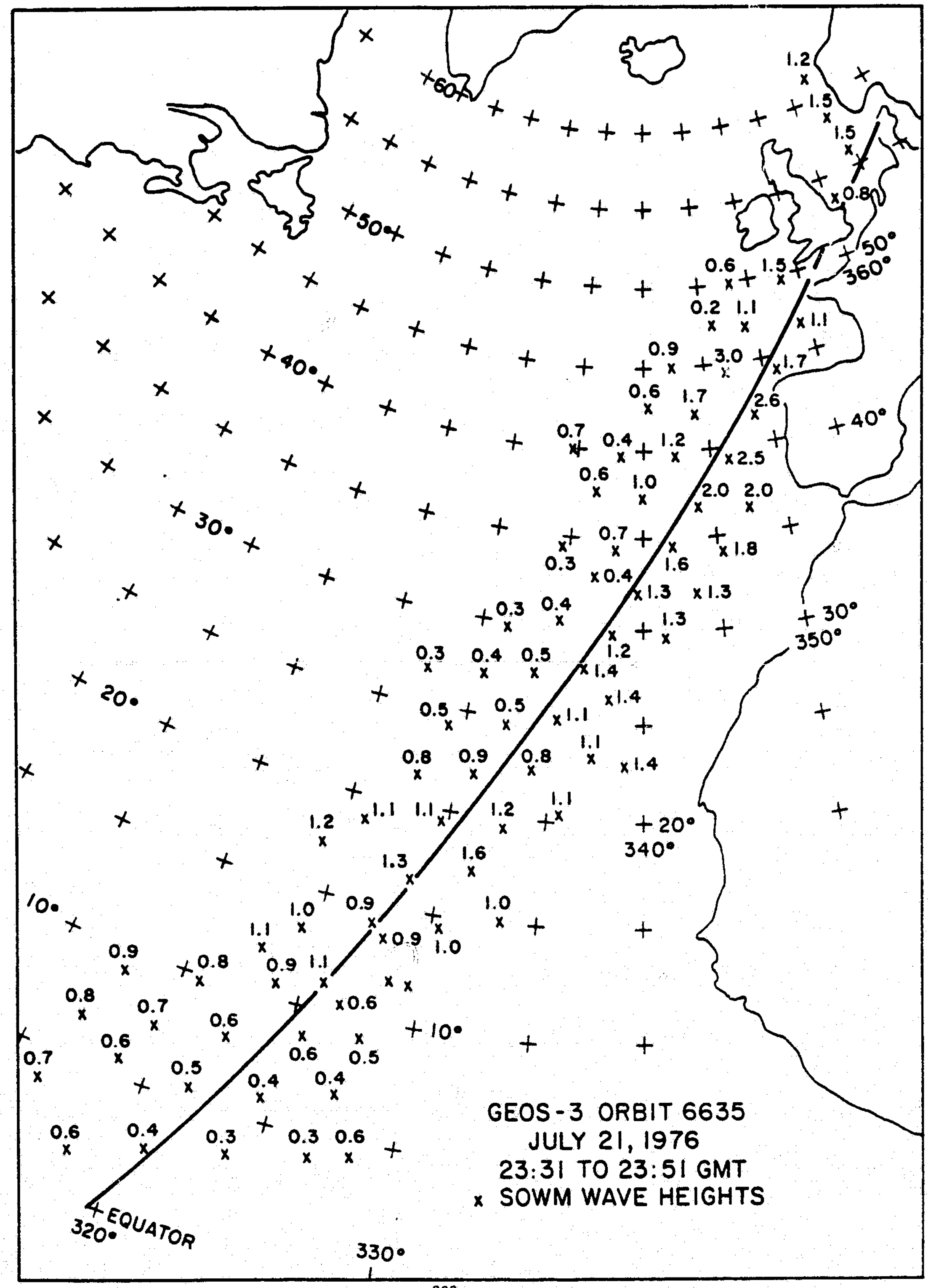
HIGHEST GEOS; ON GRID 4.0 M; AT ONE POINT 4.2 M

LOWEST SOWM; ON TRACK 0.4 M; IN FIELD 0.3 M

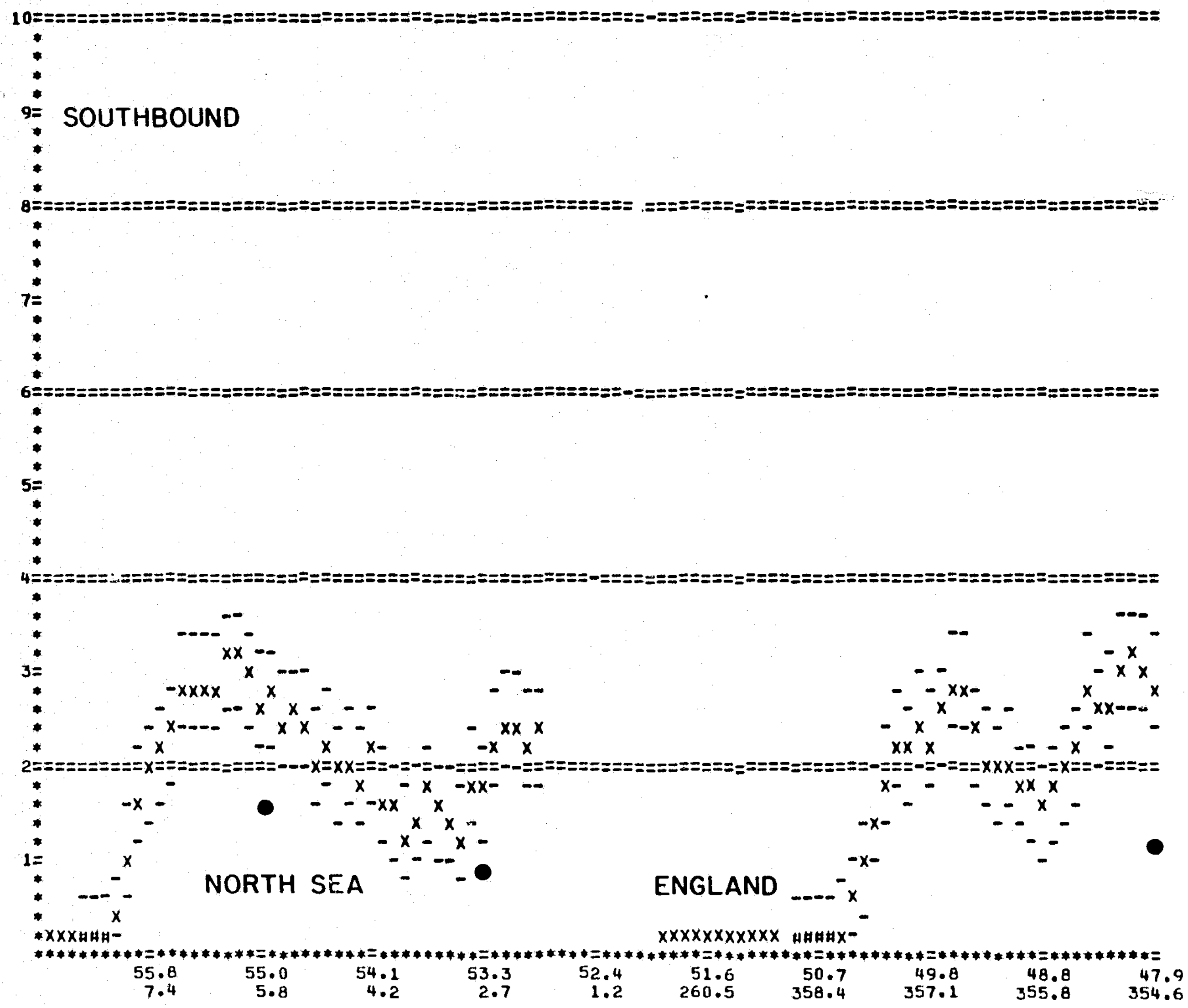
LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR - 2.5 M; SOWM 0.5 M, GEOS 3.0 M

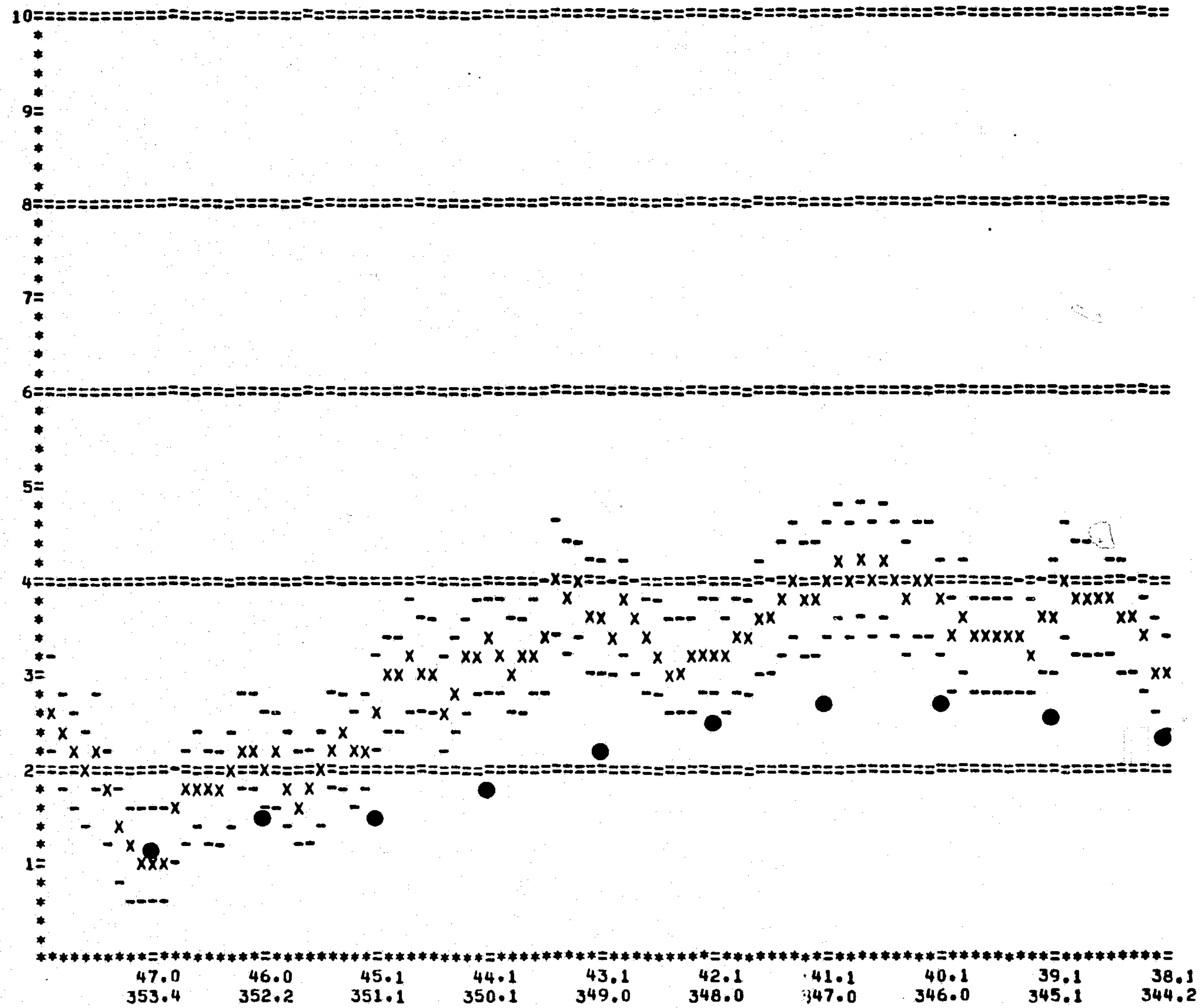
SOWM consistently too low, especially 48° N to 38° N. Follows minima of GEOS oscillations over rest of track. Fluctuations in GEOS may be swell from past storms to the north. Winds near 42° N could have been more nearly 13.5 m/s instead of 11 m/s.


GEOS-3 ORBIT 6635
JULY 21, 1976
23:31 TO 23:51 GMT
x SOWM WAVE HEIGHTS
EQUATOR
320°
330°
340°
350°
360°
10°
20°
30°
40°
50°
60°

ORBIT 6635 UNIQUE # 141 DATE 7/ 21/ 76
STARTING LAT 56.470000 LON 8.9700000 TIME 23: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 23: 51



ORBIT 6635 UNIQUE # 141 DATE 7/ 21/ 76
STARTING LAT 56.470000 LON 8.9700000 TIME 23: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 23: 51



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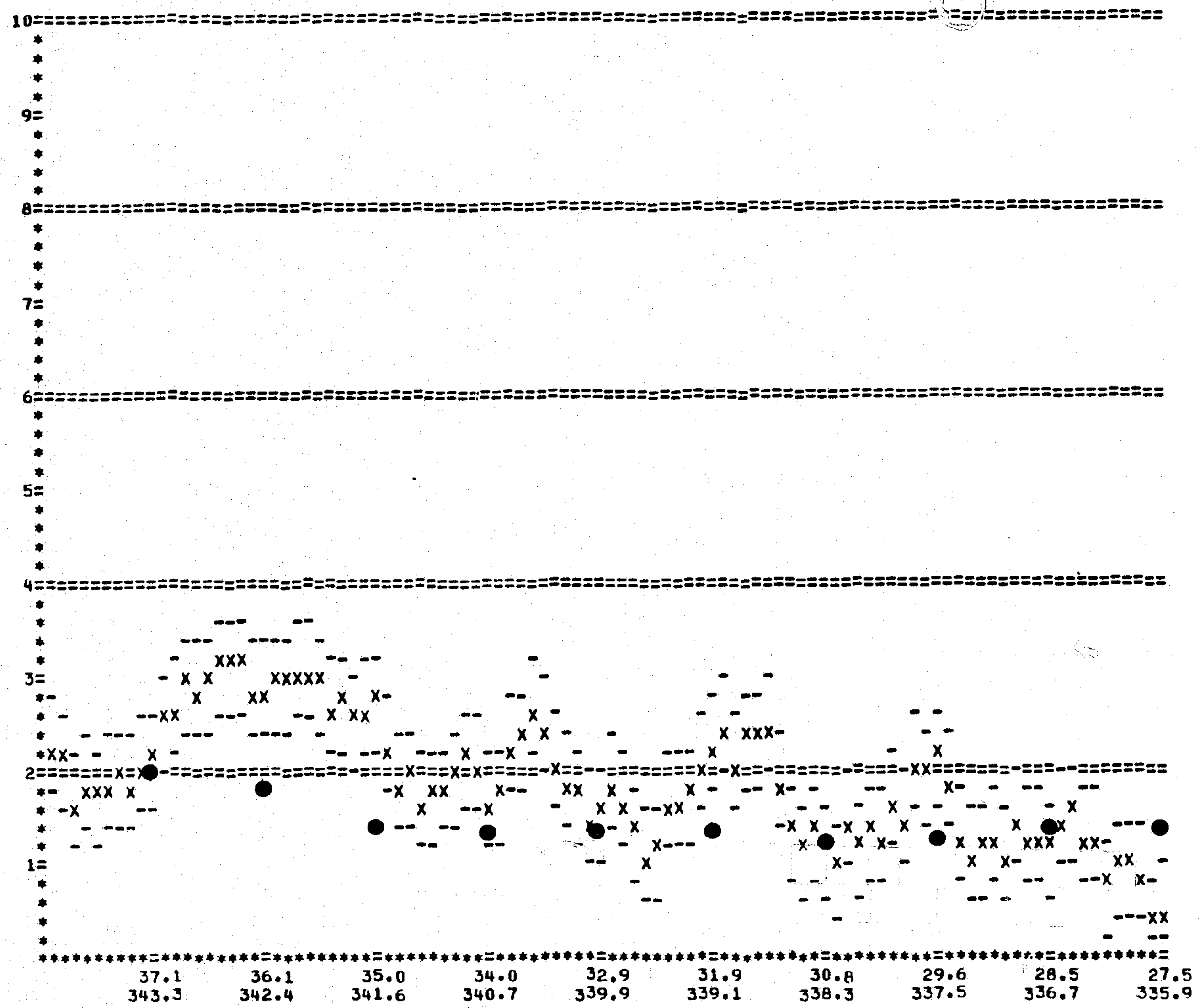
ORBIT 6635 UNIQUE # 141 DATE 7/ 21/ 76
STARTING LAT 56.470000 LON 8.9700000 TIME 23: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 23: 51



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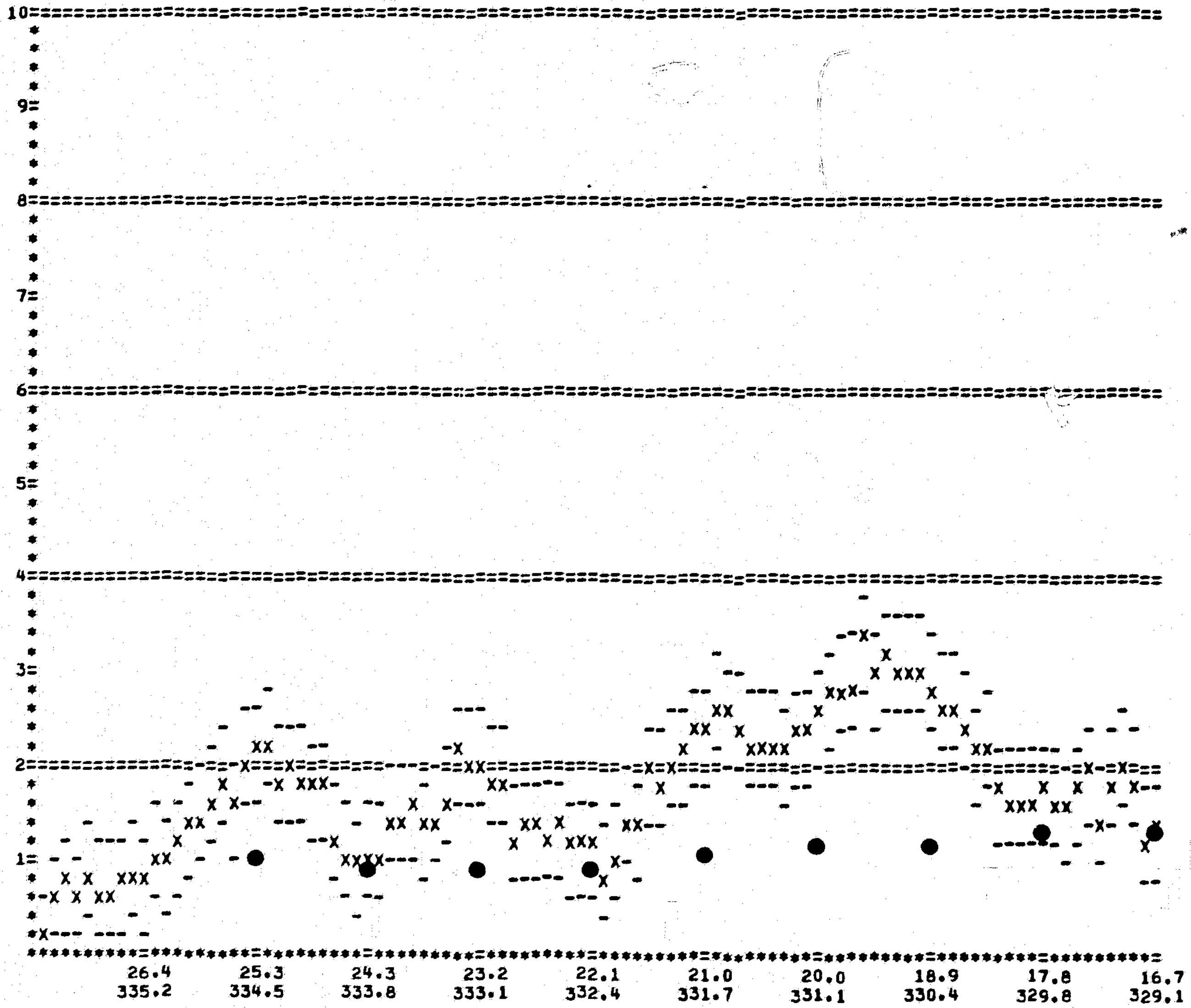
ORIGINAL PAGE IS
OF POOR QUALITY

ORBIT 6635 UNIQUE # 141 DATE 7/ 21/ 76
STARTING LAT 56.470000 LON 8.9700000 TIME 23: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 23: 51



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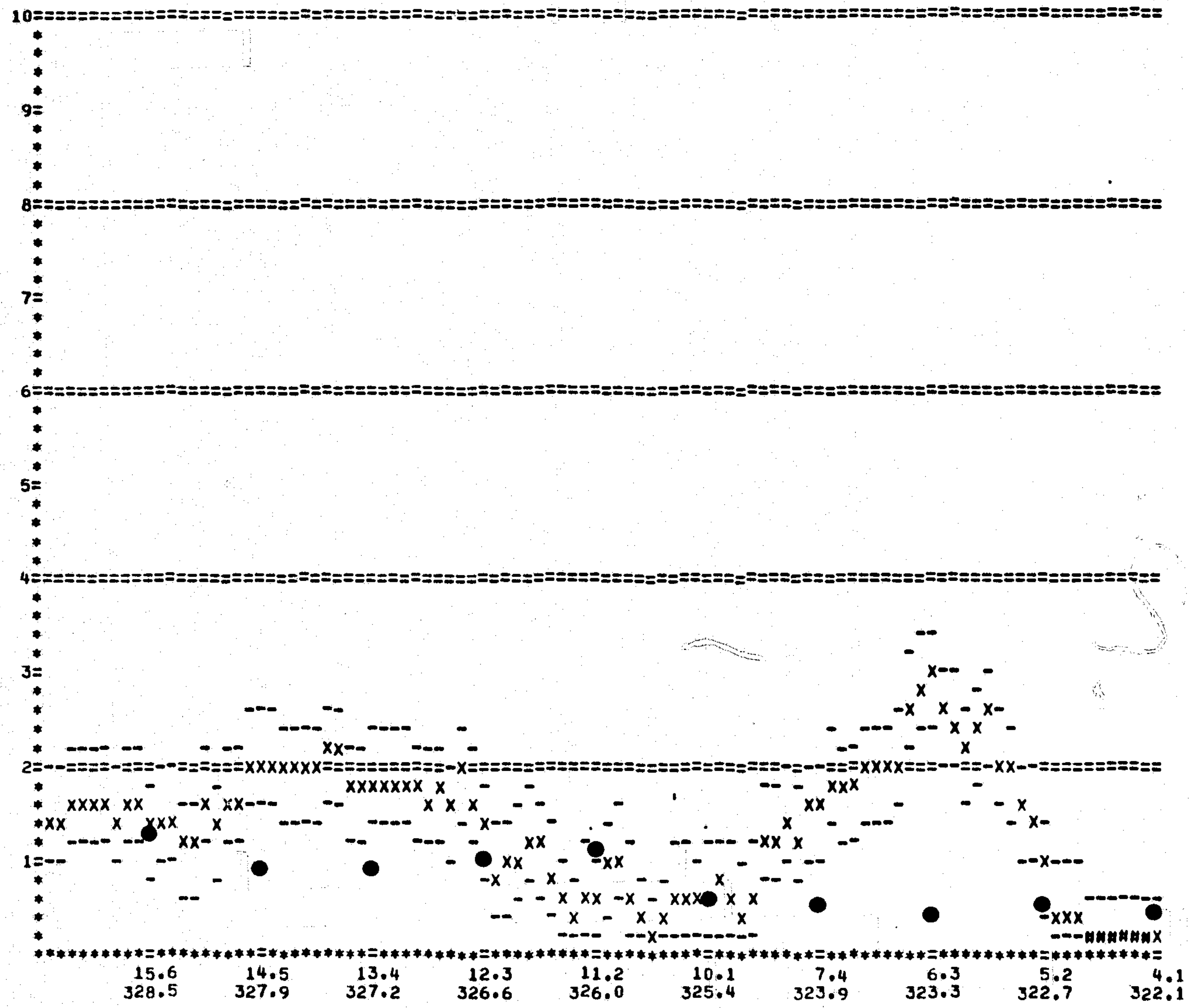
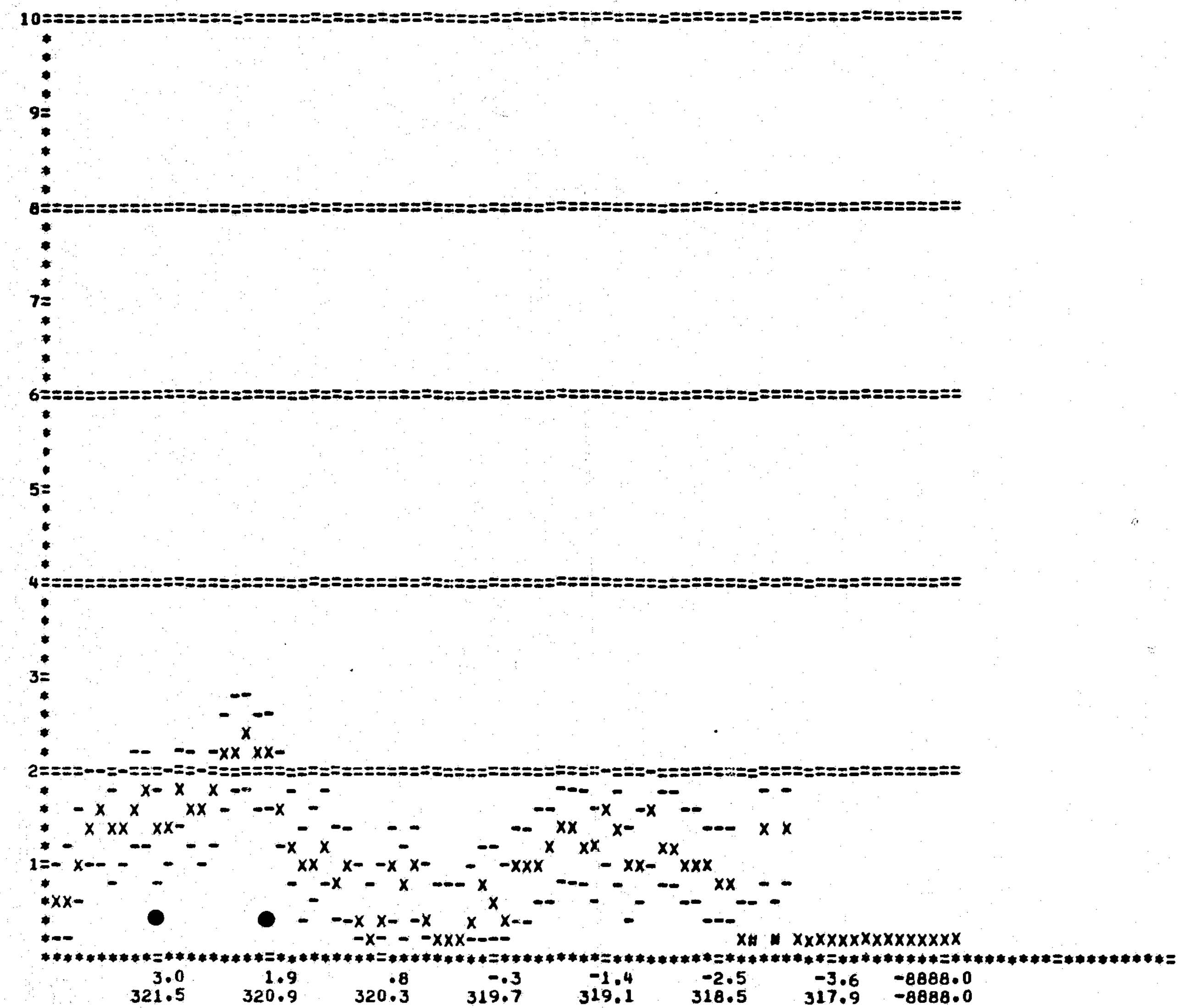
ORBIT 6635 UNIQUE # 141 DATE 7/ 21/ 76
STARTING LAT 56.470000 LON 8.9700000 TIME 23: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 23: 51



ORBIT 6635 UNIQUE # 141 DATE 7/ 21/ 76
STARTING LAT 56.470000 LON 8.9700000 TIME 23: 31
ENDING LAT -8888.0000 LON -8888.0000 TIME 23: 51



ORBIT 6883 AUG. 8, 1976 13:13 TO 13:30

(Part in Southern Hemisphere)

NORTHBOUND ATLANTIC

EQUATOR AT 327° E TO 12.2° N, 320.4° E

12 POINTS RMS 0.8 M BIAS - 0.6 M

HIGHEST SOWM; ON TRACK 1.1 M; IN FIELD 1.3 M

HIGHEST GEOS; ON GRID 1.8 M; AT ONE POINT 2.2 M

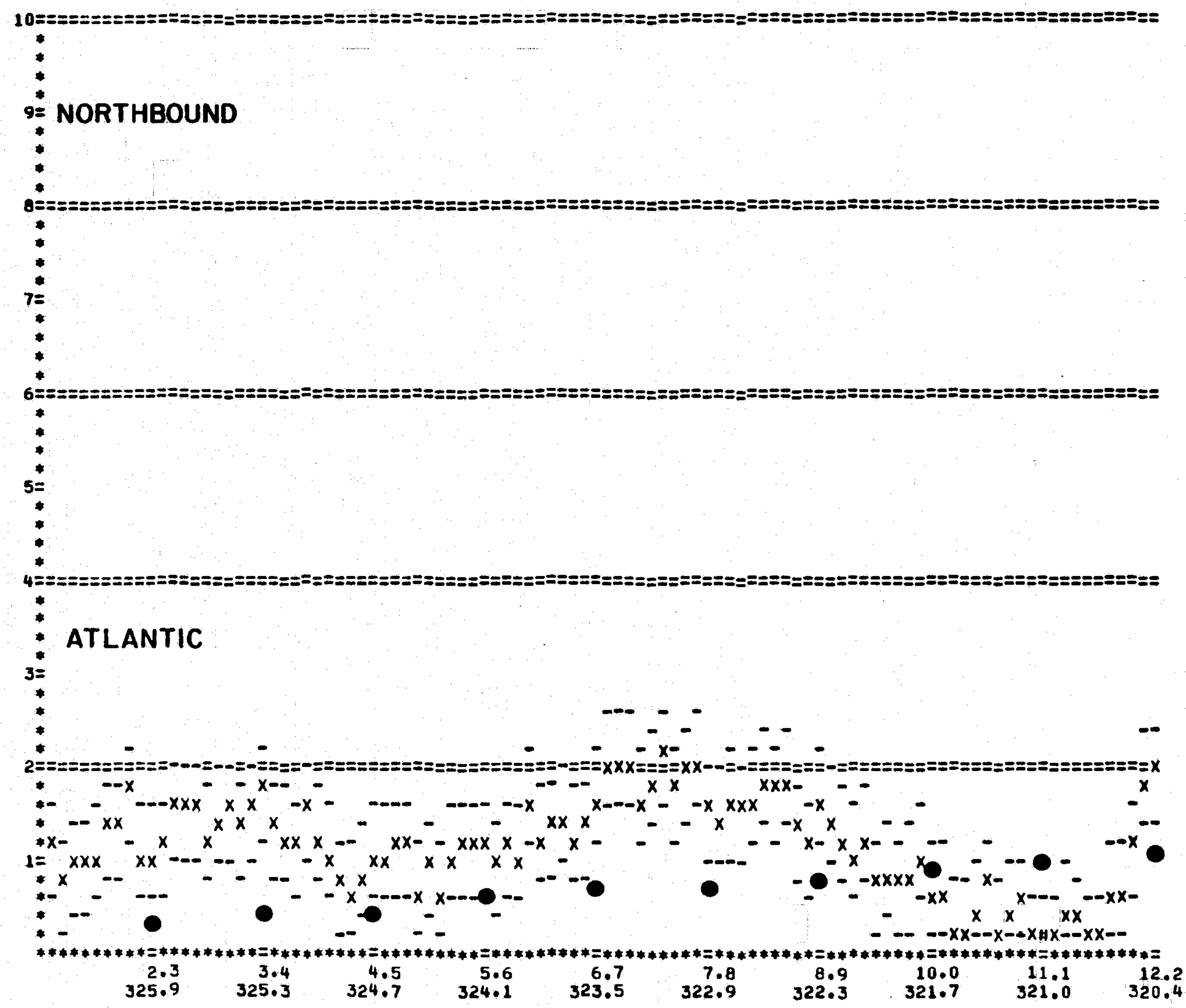
LOWEST SOWM; ON TRACK 0.3 M; IN FIELD 0.2 M

LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (Q)

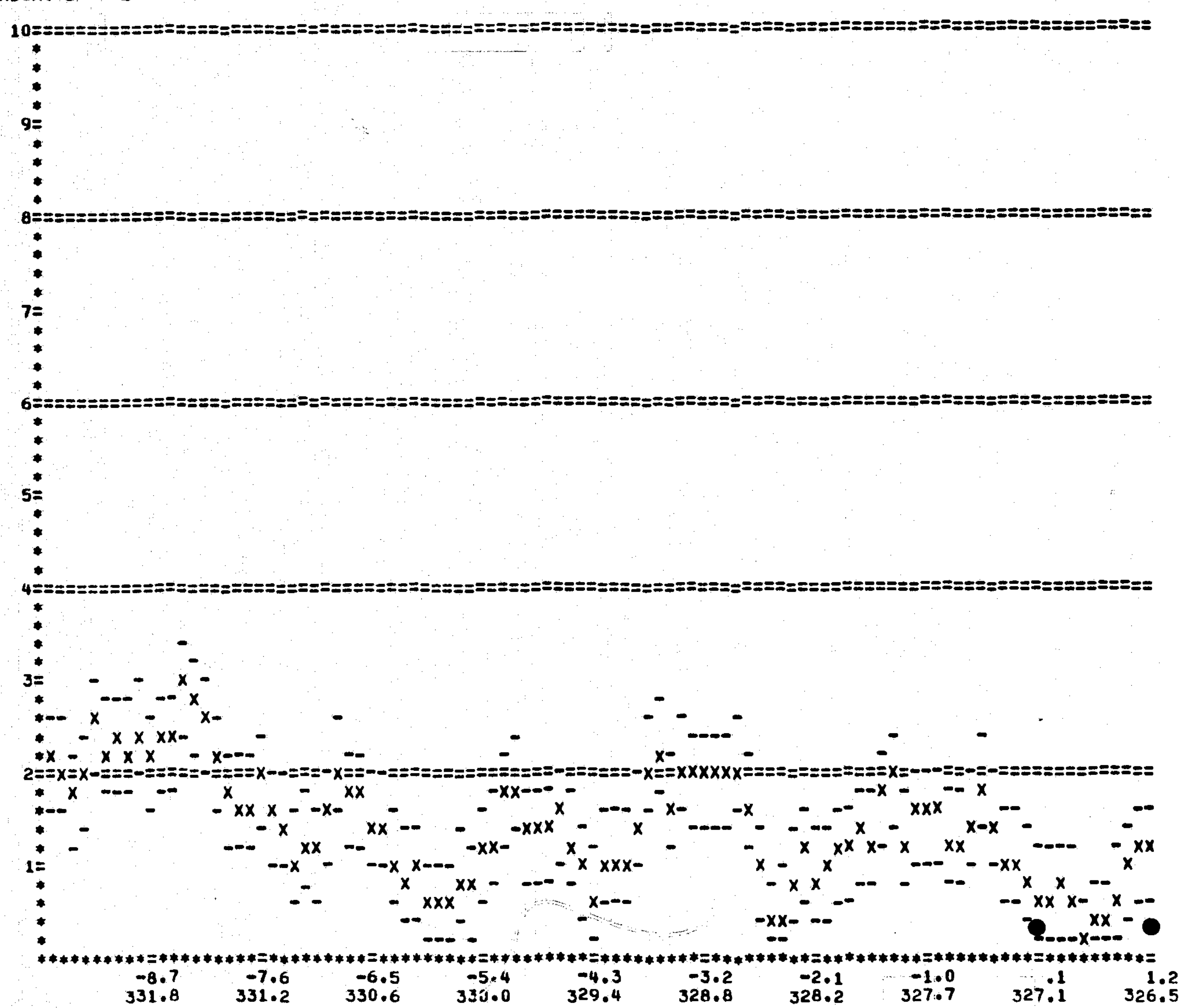
LARGEST ERROR - 1.4 M; SOWM 0.4 M, GEOS 1.8 M

Winds 2° N to 10° N may have been 2 m/s to 3 m/s too low. Superimposed swell may have come from Southern Hemisphere.

```
      ORBIT          6883  UNIQUE #          190  DATE              8/            8/           76
STARTING LAT -32.330000      LON  346.73000      TIME             13:            13
  ENDING LAT  20.600000      LON  20.600000      TIME             13:            30
```



ORBIT 6883 UNIQUE # 190 DATE 8/ 8/ 76
STARTING LAT -32.330000 LON 346.73000 TIME 13: 13
ENDING LAT 20.600000 LON 20.600000 TIME 13: 30



ORBIT 7858 OCT. 16, 1976

SOUTHBOUND ATLANTIC

16.9° N, 319.4° E TO SOUTH AMERICA NEAR MOUTH OF AMAZON

14 POINTS RMS 0.4 M BIAS + 0.2 M

HIGHEST SOWM; ON TRACK 1.0 M; IN FIELD 1.0 M

HIGHEST GEOS; ON GRID 1.4 M; AT ONE POINT 2 M

LOWEST SOWM; ON TRACK 0.4 M; IN FIELD 0.3 M

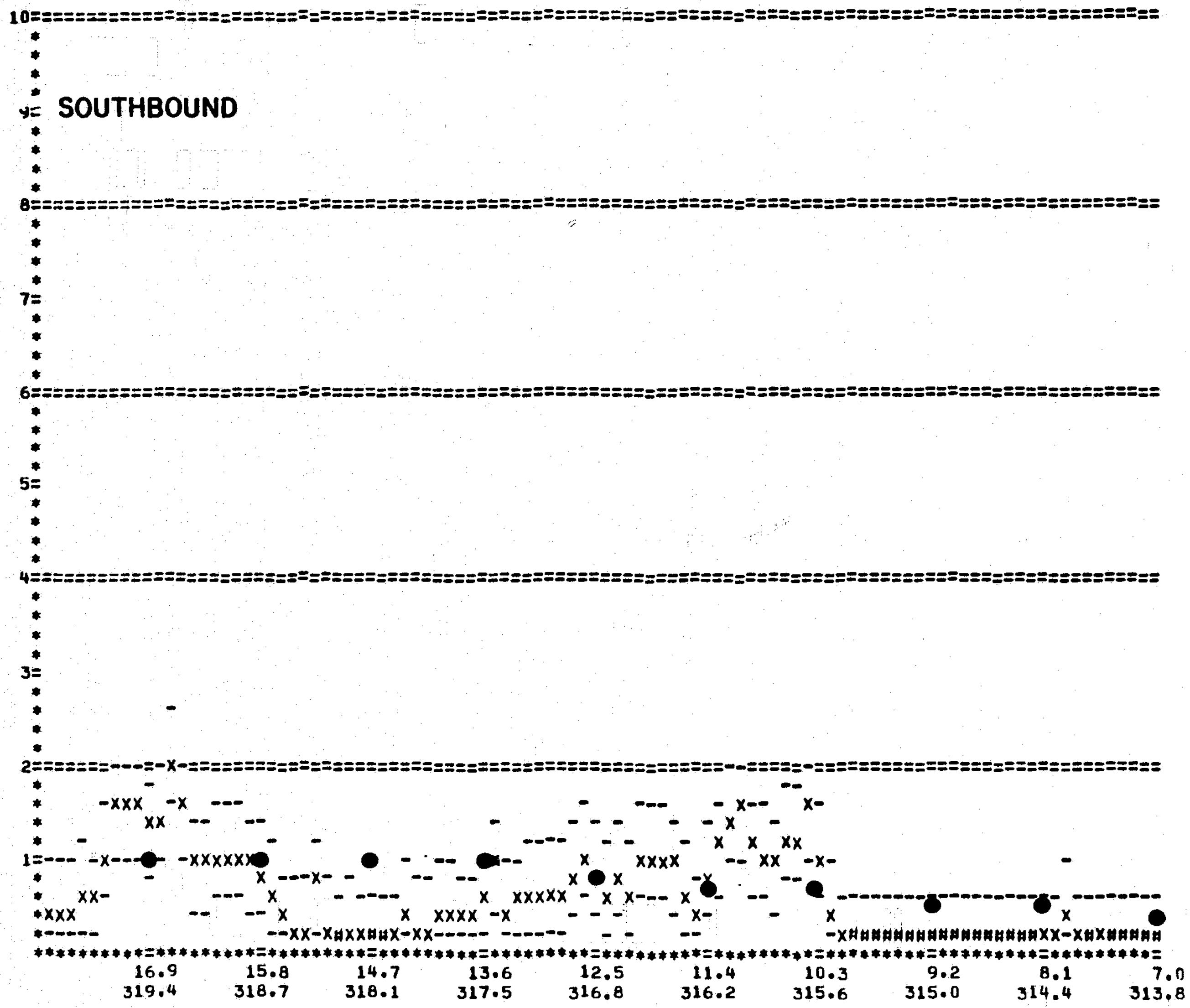
LOWEST GEOS; ON GRID 0.2 M; AT ONE POINT 0.2 M (0)

LARGEST ERROR + 0.8 M; SOWM 1.0 M, GEOS 0.2 M

(All but two errors under 0.5 m)

This orbit demonstrates that low waves can be specified by the SOWM and verified by the GEOS measurements. The two meter waves near 1.5° N are not counted in the statistics. They may have been a sea-breeze effect.

```
ORBIT          7858  UNIQUE #          165  DATE        10/         16/         76
STARTING LAT  17.860000      LON  319.95000      TIME        10:         26
  ENDING LAT -8888.0000      LON -8888.0000      TIME        10:         32
```



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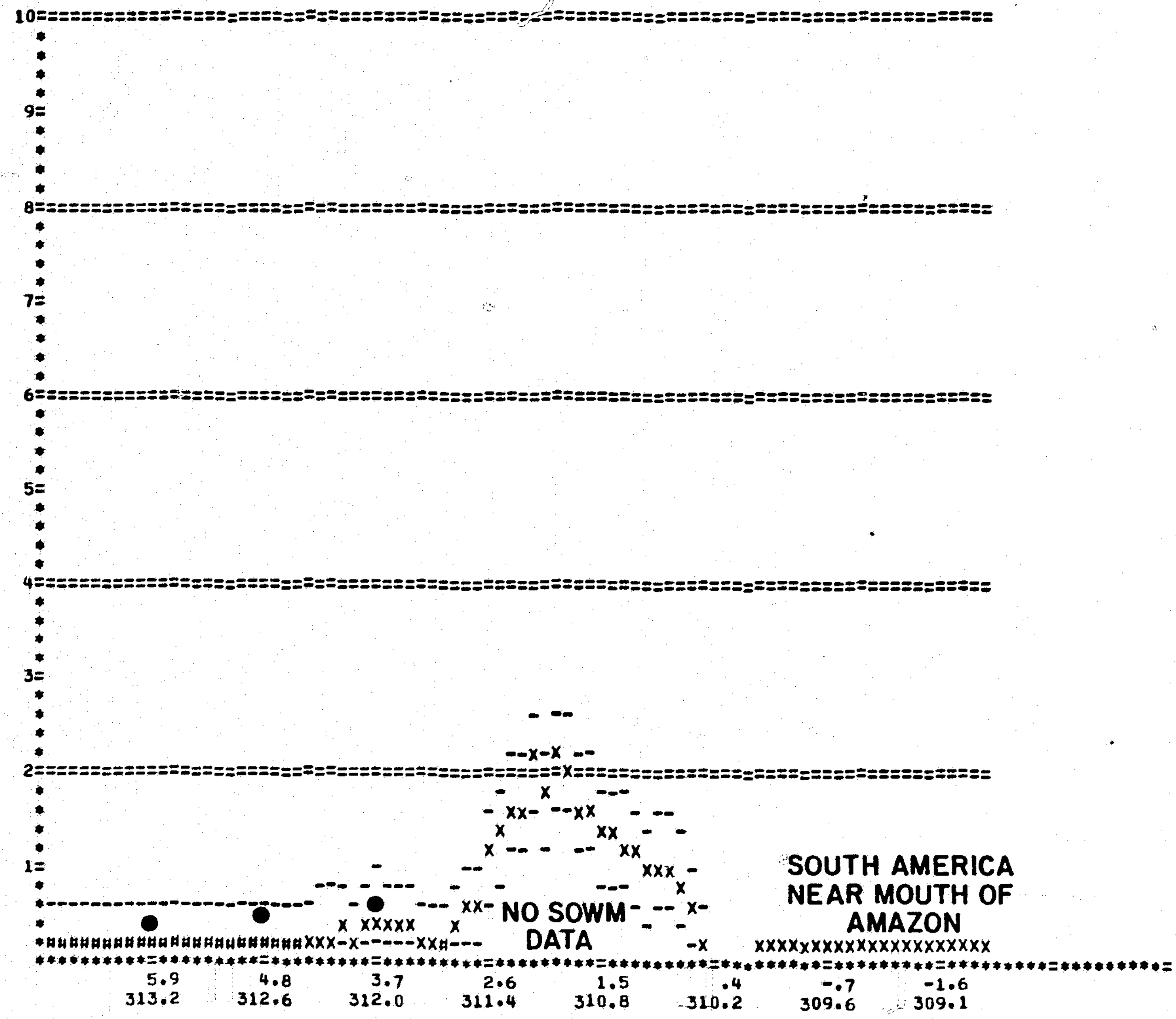
ORBIT 7858 UNIQUE # 165 DATE 10/ 16/ 76
STARTING LAT 17.860000 LON 319.95000 TIME 10: 26
ENDING LAT -8888.0000 LON -8888.0000 TIME 10: 32



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Statistical Summaries

Tables 4A and 4B provide statistical summaries of the preceding segment by segment analyses. The GEOS measured wave heights ranged from zero to 9 m and the SOWM specifications ranged from zero to 11.5 m. The column headed "Error" represents the largest difference at a point between the GEOS and the SOWM, and a positive value indicates that the SOWM specification was higher than the GEOS measurement. The statistical analysis is based upon 825 pairs of values from the SOWM and the GEOS data.

Table 5 gives the number of times the RMS error had a certain value. The average RMS errors have been computed without weighting the values by the number of points in the orbit segment, so that orbit 3214 with six points has as much weight as orbit 3645 with 42 points. If a SOWM specification were interpreted to be accurate to ± 1.4 m, it would be useful for many operational purposes for all but six of the 44 segments studied. This value of ± 1.4 m would account for much of the shorter scale point to point fluctuations in the GEOS data for resolutions not presently possible for numerical wave forecasting purposes. There would still be the possibility of a larger error for a particular part of the ocean that could be as much as ± 2 or 3 m either because of poor information on the winds or because of

Table 4A - Statistical Summary of Orbits Obtained in 1975
(Heights in meters, winds in meters per second)
The "Error" is the largest of the indicated
number of points.

ORBIT	1975	# PTS	RMS	BIAS	ERROR	GEOS RANGE	SOWM RANGE	WIND (GEOS)	WIND (SOWM)
1929	8/24	24	0.8	- 0.6	- 1.8	0 to 2.8	0.1 to 1.1		
1991	8/28	36	1.0	- 0.2	- 2.3	0 to 4.0	0.8 to 3.7		
2100	9/5	7	0.5	- 0.3	- 1.2	0 to 1.8	0.2 to 0.9		
2114	9/6	20	1.3	- 1.0	- 3.2	0 to 3.8	0.2 to 1.0	8 to 11	0 to 5
2254	9/16	30	1.1	- 0.8	- 2.6	0 to 4.2	0.1 to 2.4	12 to 13	8 to 10
2318	9/20	10	0.6	0	- 1.3	0.2 to 3.0	0.5 to 1.2		
2658	10/14	9	0.8	- 0.5	- 1.7	1.0 to 4.2	1.0 to 2.5		
TWO PARTS		6	3.1	- 2.8	- 4.7	3.0 to 7.6	1.0 to 2.9	18	12
2782	10/23	11	0.7	- 0.1	- 1.2	0.2 to 3.2	1.2 to 3.5	12	10
2812	10/25	28	1.0	- 0.8	- 2.0	2.6 to 6.2	2.0 to 5.0	16	13.5
2827	10/26	26	1.1	- 1.0	- 2.4	1.8 to 5.4	1.0 to 6.9	14	12
2829	10/26	19	0.9	- 0.5	- 2.1	0.6 to 5.0	0.6 to 4.6	15	12
2904	11/1	24	1.2	- 0.8	- 2.0	0.6 to 6.0	0.8 to 4.1	16	13
2919	11/2	12	0.8	- 0.5	- 1.7	0.2 to 3.0	0.3 to 3.2		
2936	11/3	21	0.7	- 0.3	- 2.3	0.2 to 6.4	0.3 to 3.9		
2998	11/7	17	0.9	+ 0.2	+ 1.9	2.8 to 5.4	2.7 to 5.6	13	15.5
3030	11/10	28	2.0	- 1.5	- 4.2	0 to 7.0	0.3 to 3.4	17	10
3075	11/13	21	0.6	- 0.4	- 1.3	0 to 2.8	0.5 to 1.6		
3152	11/18	26	1.0	- 0.6	- 1.9	0 to 4.4	0.2 to 3.6	11.5	9
3167	11/19	29	1.1	+ 0.5	+ 2.6	0.2 to 4.0	1.3 to 5.3	14	15.5
3214	11/23	6	1.2	- 1.1	- 2.0	0.8 to 3.2	0.8 to 1.3	12	7.5
3229	11/24	21	0.8	- 0.5	- 1.6	3.4 to 7.8	3.9 to 6.6	17	16
3231	11/24	23	1.1	- 0.7	- 1.9	0.2 to 4.8	0.9 to 4.3	12 to 13	8
3291	11/28	38	1.4	- 1.0	- 2.3	0 to 8.8	0.3 to 7.4	20	19
3430	12/8	17	1.4	+ 0.3	+ 2.6	0.6 to 4.8	0.9 to 6.0		
3524	12/15	12	0.6	- 0.2	- 1.0	0 to 3.8	0.2 to 2.7		
3539	12/16	19	0.9	- 0.2	- 1.5	0 to 2.4	0.2 to 1.8		
3554	12/17	18	0.6	+ 0.1	+ 1.3	0.2 to 2.6	1.3 to 2.4		
3586	12/19	12	2.5	- 2.0	- 4.0	2.4 to 7.6	1.3 to 5.3		
3645	12/23	42	1.3	- 0.8	- 3.8	0 to 8	0 to 8.7	19.5	15

Table 4B - Statistical Summary of Orbits Obtained in 1976
(Heights in meters, winds in meters per second)
The "Error" is the largest of the indicated number of points.

ORBIT	1976	# PTS	RMS	BIAS	ERROR	GEOS RANGE	SOWM RANGE	WIND (GEOS)	WIND (SOWM)
4576	2/27	12	1.1	- 0.4	- 2.0	0 to 6.2	0.5 to 5.1		
4593	2/28	12	0.9	- 0.7	- 2.2	0.2 to 4.4	0.5 to 2.5		
4608	2/29	19	1.0	- 0.2	- 2.4	0.6 to 7.0	1.2 to 5.9		
4623	3/1	7	0.5	+ 0.1	- 0.8	0.2 to 5.4	0.2 to 4.9		
4978	3/26	11	1.2	+ 0.5	+ 3.0	0 to 5.8	1.6 to 7.1		
5025	3/30	46	0.9	- 0.2		1.4 to 7.4	1.3 to 9.5		
TWO PARTS			2.5	+ 2.4	+ 3.0			17	21
5149	4/7	10	3.2	+ 2.6	+ 4.2	3.6 to 9.0	5.0 to 11.5	18	22
5164	4/9	9	1.8	+ 1.6	+ 2.7	1.2 to 8.4	2.4 to 9.6		
5258	4/15	19	1.0	+ 0.2	+ 2.2	0 to 3.2	0.3 to 2.6		
6295	6/27	14	0.9	- 0.7	- 1.6	1.2 to 4.6	0.9 to 4.1		
6479	7/10	37	0.7	+ 0.4	+ 1.6	0 to 3.8	0.2 to 5.3		
6481	7/11	19	0.7	- 0.3	- 1.8	0 to 2.8	0.3 to 2.7		
6635	7/21	45	1.0	- 0.6	- 2.5	0 to 4.2	0.3 to 2.7	13.5	11
6883	8/8	12	0.8	- 0.6	- 1.4	0 to 2.2	0.2 to 1.3		
7858	10/16	14	0.4	+ 0.2	+ 0.8	0 to 2.0	0.3 to 1.0		

Table 5 - Distribution of RMS Errors (Meters)

RMS ERROR	# 1975	# 1976
0.4		1
0.5	1	1
0.6	4	
0.7	2	2
0.8	4	1
0.9	3	3
1.0	3	3
1.1	4	1
1.2	2	1
1.3	2	
1.4	2	
1.8		1
2.0	1	
2.5	1	1
3.1	1	
3.2		1

AVERAGE OF RMS ERRORS

	1975	1976
Excluding "busts"	0.9 m	0.9 m
With "busts"	1.1 m	1.2 m

inadequacies in the model. These larger errors appear to occur for 13 to 15% of the orbit segments.

Table 6 gives the distribution of the bias. Except for "busts," the SOWM during 1975 was biased too low by - 0.5 to - 1.0 m. For 1975, there were two situations, of those analyzed, for which large biases of - 2.8 and - 1.5 m occurred. For 1976, except for three large positive biases, the remainder of the 15 orbit segments may be biased only slightly negative. For three segments, the SOWM overpredicted the waves by 1.6, 2.4 and 2.6 m.

The largest errors in a specification, or a forecast, are the ones that cause the most concern. Errors of 4 to 5 m are enough to cause concern, and they do occur as shown in Table 7. A ship captain would surely rather have an incorrect forecast that was 4 to 5 m too high than one that was 4 to 5 m too low.

Fortunately, these large errors are not likely to occur near most ships. They are large because no ships were in the area to report the winds, which lead to a poor analysis of the wind field, which lead to a poor specification of the waves. In turn, a poor specification of the waves and the winds will lead to a poor forecast of the waves. Present day ship routing techniques make it possible for ships to avoid high seas, but the penalty is the lack of an adequate description of the wind field

Table 6 - Distribution of Bias (Meters)

BIAS	1975	1976
- 2.8	1	
- 1.5	1	
- 1.1	1	0
- 1.0	3	0
- 0.9	0	0
- 0.8	4	0
- 0.7	1	2
- 0.6	2	2
- 0.5	4	0
- 0.4	1	1
- 0.3	2	1
- 0.2	4	2
- 0.1	1	0
0	0	0
+ 0.1	1	1
+ 0.2	1	2
+ 0.3	1	0
+ 0.4	0	1
+ 0.5	1	1
+ 1.6		1
+ 2.4		1
+ 2.6		1

Table 7 - Distribution of Largest Error for Each Orbit Segment (M). A positive value means that the SOWM specification was higher than the GEOS-3 measurement by the amount shown.

	1975	1976
- 4.9 to - 4.5	1	
- 4.4 to - 4.0	2	
- 3.9 to - 3.5	1	
- 3.4 to - 3.0	1	
- 2.9 to - 2.5	1	1
- 2.4 to - 2.0	8	3
- 1.9 to - 1.5	7	2
- 1.4 to - 1.0	5	1
- 0.9 to - 0.5		1
- 0.4 to 0		
+ 0.1 to + 0.5		
+ 0.6 to + 1.0		1
+ 1.1 to + 1.5	1	
+ 1.6 to + 2.0	1	1
+ 2.1 to + 2.5		1
+ 2.6 to + 3.0	2	1
+ 3.1 to + 3.5		2
+ 3.6 to + 4.0		
+ 4.1 to + 4.5		1

over the oceans.

Wind Specification Errors as the Cause of Errors in the Wave Height Specifications

In some of the comments for the orbit segments, two wind speeds have been mentioned. These speeds have been given in Tables 4A and 4B. They represent the wind that would have had to have been present to generate the fully developed sea with a height given either by the GEOS measurement or the SOWM specification as the heading indicates. These values are repeated in Table 8, and the differences between them are tabulated.

Of the twenty orbit segments so identified, a change in wind speed over a portion of the orbit segment by ± 3 m/s could have produced agreement between the SOWM and the GEOS heights for eleven segments. Errors in the specification of the wind of the order of ± 3 m/s are not uncommon for moderate and high winds, given the present procedures for measuring winds over the ocean. Six more of the height differences could be explained by differences of ± 3.5 to 4.5 m/s, and the last three require 6 or 7 m/s differences.

For all but four cases, the wind used in the SOWM analysis should have been stronger. Most wind field analysis techniques tend to smooth out the high wind

Table 8 - Wind Field Statistics for Orbit Segments Where Errors in Wind Speed (m/s) Are the Possible Explanation for the Difference between the SOWM Specification and the GEOS Measurement

WIND (GEOS)	WIND (SOWM)	DIFFERENCE
9.5	2.5	+ 7.0
12.5	9	+ 3.5
18	12	+ 6.0
12	10	+ 2.0
16	13.5	+ 2.5
14	12	+ 2.0
15	12	+ 3.0
16	13	+ 3.0
13	15.5	- 2.5
17	10	+ 7.0
11.5	9	+ 2.5
14	15.5	- 1.5
12	7.5	+ 4.5
17	16	+ 1.0
12.5	8	+ 4.5
20	19	+ 1.0
19.5	15	+ 4.5
17	21	- 4.0
18	22	- 4.0
13.5	11	+ 2.5

reports by ships.

As mentioned previously, these features of the SOWM, as obtained for data for 1975 and 1976, were recognized at FNWC by means of conventional analysis techniques and whatever tendency these data show to be biased too low and to miss high waves have been calibrated out by an improved wind field analysis technique that produces higher winds than those obtained by the wind field analyses in use during the time when these specifications were produced. This analysis confirms what was already known.

CONCLUSIONS

This investigation has demonstrated the feasibility of using remotely sensed wave height data to determine the accuracy of an ocean wave specification (hindcasting) and forecasting model. Data from the GEOS-3 radar altimeter were used to determine the accuracy during 1975 and 1976 of the spectral ocean wave model (SOWM) presently operational at the Fleet Numerical Weather Central. Most of the features of the SOWM found in this investigation are already known and were discovered using more conventional means. The present version of the SOWM has been corrected to account for these effects, mainly by improving the specification of the winds that generate the waves in the model.

Except for a few orbit segments with large errors, the bias in the SOWM specifications clustered around - 1.0 to - 0.5 meters and the RMS errors were 1.0 to 1.4 meters. The removal of the bias would reduce the RMS errors by a substantial amount since it was computed from the sums of squares of the differences between the SOWM and the GEOS values.

The larger errors were shown to occur for ocean areas with few ship reports of the winds and to be associated with errors in the specification of the wind fields for these areas. Given more accurate and more plentiful wind data, it can be expected that the SOWM specifications will improve dramatically.

There were numerous orbit segments in the trade wind and equatorial areas where the GEOS heights were much higher than the SOWM heights. In other segments, the two agreed quite well, even for very low waves. Improved wind fields for these areas would correct this deficiency.

In areas bounded by island arcs and where refraction and diffraction around islands and island shadowing effects can be important, the SOWM does not verify well. If these areas are important from a commercial point of view, such as near Alaska and the Aleutian Islands, special smaller scale models would be needed.

One feature of the GEOS-3 wave height data requires special comment. This is the short spatial scale variability in these heights. These fluctuations in wave height along the subsatellite track may not be entirely due to sampling variability effects. If they are not due to sampling variability effects, then they represent a spatial scale of variation that cannot be resolved by the present grid spacing, wind field resolution and time steps of the SOWM model. Halving the grid spacing and going to one hour time steps for the wind would be prohibitively expensive. It would then be necessary to study this variability by means of much more data and to provide the users of the wave forecasting product with an estimate of the effects of these superimposed height fluctuations on the forecast. These effects may well be seasonably variable and location dependent.

Similar fluctuations from hour to hour were found by Salfi and Pierson (1977) in a study of wave heights and wave spectra estimated from twenty-minute wave recordings every hour for ten successive hours at Weather Ship J. The hour to hour variations in wave height exceeded the amount that could be explained by sampling variability effects and indicated time and space scales below the resolution of the model. These results, as a function of time at a point, tend to corroborate the short scale variations in GEOS-3 heights along a line at nearly an instant of time.

RECOMMENDATIONS

Since the SOWM as an operational model is different now from what it was in 1975 and 1976, and since GEOS-3 is still obtaining wave height data, a study similar to this one should be carried out for the 1977-1978 winter period for the Northern Hemisphere. It would then be possible to document any improvement in the SOWM that may have occurred. Also, the trade wind and equatorial fluctuations can be studied in greater detail.

When SEASAT-A data become available, the amount of wave height data will increase dramatically. It would not be at all difficult to interpolate the SOWM output in space and time to the subsatellite track and prepare graphs such as those in this report routinely based on the SOWM specifications and SEASAT height measurements. Problem areas for the SOWM would rapidly become evident if such graphs were available.

SEASAT-A will also provide vastly improved wind data to such an extent that many of the kinds of "busts" seen in this report will be eliminated. With the major reason for errors in the present SOWM eliminated, any remaining differences between what the SOWM specified and what SEASAT-A will measure will more and more be due to the inadequate treatment of the physics of the problem in the wave generation, wave dissipation and wave propagation portions of the SOWM. There are many things that can be tried to attempt to improve this part of the model, but they will require improvement in both the theoretical and operational parts of the model.

There is, however, one clear and obvious way, independent of any longer term improvement in the theory, to use the SEASAT data to provide improved wave forecasts with the SOWM in its present operational condition. This would be to correct the wave spectra in areas of wave generation and dead seas to values that would yield the significant wave heights estimated by SEASAT. The corrections would be made at the low frequency end of the spectrum and in terms of the change in the saturation values at the middle and high frequencies. These corrections would eliminate any of the errors in the specification of the spectra caused by errors in modeling fetch and duration effects.

Such corrections can be applied in a way to influence the whole Northern Hemisphere, twice each day. The new initial value specification would then agree perfectly with the wave observations. It could then be used in the forecast mode with forecast winds. Since the initial value specification would then have correct wave heights (within twelve hours of the starting time), it would be expected to produce more accurate forecasts of both wind seas and swells.

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15. Supplementary Notes

16. Abstract

Significant wave heights estimated from the shape of the return pulse wave form of the altimeter on GEOS-3 for forty-four orbit segments obtained during 1975 and 1976 are compared with the significant wave heights specified by the spectral ocean wave model (SOWM), which is the presently operational numerical wave forecasting model at the Fleet Numerical Weather Central. Except for a number of orbit segments with poor agreement and larger errors, the SOWM specifications tended to be biased from 0.5 to 1.0 meters too low and to have RMS errors of 1.0 to 1.4 meters. The much fewer larger errors can be attributed to poor wind data for some parts of the Northern Hemisphere oceans. The bias can be attributed to the somewhat too light winds used to generate the waves in the model. Other sources of error are identified in the equatorial and trade wind areas.

Many of these sources of error in the model were identified by other means, and corrective measures have already been applied so that comparisons of GEOS-3 heights with more recent SOWM specifications will not give the same results that were obtained in this study.

The short spatial scale fluctuations in the GEOS-3 wave heights are pointed out. If they are real and are not caused by sampling variability, they represent wave properties that cannot either be specified or forecasted with present wave forecasting models because of resolution requirements.

Ways to use more recent GEOS-3 data and the forthcoming SEASAT-A data to identify areas where wave specifications are poor and to produce improved wave forecasts are described.

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