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Technical Memorandum 78032

The Analysis of Geos-3 Altimeter Data in the Tasman and Coral Seas

(NASA-TM-78032) THE ANALYSIS OF GEOS-3
ALTIMETER DATA IN THE TASMAN AND CORAL SEAS
Technical Report, Apr. - Nov. 1975 (NASA)
40 p HC A03/MF A01

N78-15550

CSSL 05B

Unclas
57920

G3/43

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NOVEMBER 1977

National Aeronautics and
Space Administration

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TM 78032

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IN THE TASMAN AND CORAL SEAS

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November 1977

Presented at the GEOS-3 Principal Investigator's Final Meeting,
Fairmont Hotel, New Orleans, 18-19 November 1977

GODDARD SPACE FLIGHT CENTER
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ABSTRACT

A technique has been developed for pre-processing GEOS-3 altimetry data to establish a model of the regional sea surface. The algorithms, as presently used, develop models for a $35 \times 10^6 \text{ km}^2$ area with an internal precision of $\pm 1 \text{ m}$. This figure is substantially influenced by the data acquisition period and the sea state. There are discrepancies between the sea surface model so obtained and GEM6 based geoid profiles with wavelengths of approximately 2500 km and amplitudes of up to 5 m in this region. The amplitudes are smaller when compared with GEM10-based geoid determinations. However, the comparison of 14 pairs of overlapping passes in the region indicates altimeter resolution at the $\pm 25 \text{ cm}$ level if the wavelength corresponding to the Nyquist frequency were 30 km. In most cases, the spectral analysis of such comparisons indicates the existence of significant signal strength in the discrepancies after least squares fitting, with wavelengths in excess of 200 km. Regional studies of time varying features of the sea surface in the data analysis area are not currently possible due to inadequate tracking support and the limited time span over which a dense data coverage was available.

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THE ANALYSIS OF GEOS-3 ALTIMETER DATA IN THE TASMAN AND CORAL SEAS

1. INTRODUCTION

1.1 Experimental Objectives — 1973

The proposal submitted in early 1973, sought to determine the quasi-stationary sea surface topography off north-east Australia on a differential basis using the altimeter of the GEOS-3 spacecraft in the short pulse mode. The 1970 adjustment of the Australian levelling network indicated the existence of an apparent slope of 1.7 m in the sea surface, as sampled from geodetic levelling/tide gauge comparisons, sea level appearing to rise in relation to the level surface towards the equator (Fig. A-1).^{*} While such a rise is not unexpected from oceanographic considerations, its magnitude is about three times greater than that computed from hydrostatic considerations using temperature, pressure and salinity data.

In principle, the GEOS-3 altimeter provides an independent means of resolving this apparent anomaly. The original research plan, illustrated in Figure A-2, called for the acquisition of short pulse mode altimetry in the test area between 10°S and 25°S, extending 500 km to sea. Laser tracking support of such altimetry from a site near Townsville would provide the basis for defining the radial displacement of the sea surface above the selected reference surface as illustrated in Figure A-3.

It was assessed that the available surface gravity and astro-geodetic data in the area, on combination with satellite altimetry data in the data acquisition region bounded by the parallels (0°S; 60°S) and the meridians (140°E; 180°E) could provide a basis for computing the regional geoid on a differential bases to ±30 cm. This experiment proposal was accepted by both NASA and the Australian (Government's) Research Grants Committee in 1974.

1.2 The Data Requested

The experiment plan was modified as it was not possible to obtain funding for siting a transportable laser tracking system near the test area. In addition to extensive coverage of the test and data acquisition areas with short pulse mode GEOS-3 altimetry, the supplementary types of data sought for the investigation are shown in Figure A-4.

^{*}Note Figures A-1 to A-7 not included in GEOS-3 final report

The sea surface profiles obtained from the altimetry were to be corrected for the effects of tides, temperature and salinity variations to obtain the quasi-stationary sea surface (Fig. A-3). The surface gravity data, on combination with the astro-geodetic and altimetry data in the region, was to be used to compute a differential geoid with a precision of ± 50 cm in the test area. This, in turn, required that all surface gravity anomaly data were free from systematic error to ± 0.2 mGal through all wavelengths greater than that sought in the sea surface topography. An additional requirement was the control of differential errors in the global gravity field model used, over the test area to less than ± 0.2 mGal through wavelengths greater than 6000 km.

Such an approach assumes that the sea surface slope sought in the test area had linear gradients. This assumption was considered valid as the objective of the experiment was to establish whether or not a uniform slope existed in the sea surface as obtained in Figure A-1.

1.3 The Data Currently Available

The surface gravity data whose distribution is shown in Figure A-5, were made available by the Bureau of Mineral Resources, Geology & Geophysics, Canberra for this investigation. This data was supplemented by the latest Goddard Earth Models (GEM) from the Geodynamics Branch at Goddard Space Flight Center (Lerch, et al. 1977). A global file of $1^\circ \times 1^\circ$ free air anomalies was made available for this investigation by the Defense Mapping Agency Aerospace Center (DMAAC). The available astro-geodetic deflections of the vertical were provided by the Division of National Mapping, Canberra.

Tracking data in support of the altimeter data acquisition was provided by Wallops Flight Center (WFC). Only C-Band, S-Band and Doppler data has been provided to date. A Smithsonian Astrophysical Observatory (SAO) laser tracking system commenced operation at an Orroral Valley site near Canberra on the south east coast of Australia in mid-1976. No tracking data in support of altimeter data acquisition in the test area has been received to date.

The first passes of altimeter data in the data acquisition region were received in August 1976. The number of passes received by February 1977 was 44. This number had increased to 167 by September 1977, covering the period from launch until April 1976. The details of the altimetry data used in this study are summarized in Table 1.

1.4 Modification of Short Term Aims of Investigation

It was intended to determine the differential quasi-stationary sea surface topography ζ_s using the relation

$$\zeta_s = h - N \quad (1)$$

where h is the height of the stationary sea surface and N that of the geoid above the selected reference surface, the former being determined from the altimetry and precise regional tracking data, while the latter is obtained from a combination of the available surface gravity anomalies, astro-geodetic deflections and the altimetry data in the data acquisition region. A careful study of the problem (Mather 1975; Mather, et al. 1976) called for a revision of this procedure for the following reasons:

- (a) Altimetry data were subject to orbital errors radially. The orbits implied from the data on the altimetry data tape in the test area were subject to radial error which could be many tens of meters (e.g., Mather, et al. 1977, p. 30).
- (b) Inadequate surface gravity coverage. The surface gravity anomaly data needs to be carefully controlled by a standardization network at least as good as IGSN 71 (Morelli, et al. 1971) if it were to play a meaningful role in determinations of uniform gradients in the sea surface topography in the test area. The gravity data should also extend over the entire data analysis area in order that an adequate coverage were available for a differential geoid determination in the test area.
- (c) All data is related to the sea surface and not the geoid. Oceanographic evidence for the discrepancy between the sea surface and the geoid indicate magnitudes of up to $\pm 1 \frac{1}{2}$ m. Most of this discrepancy (over 70% of the power) appears to have the characteristics of a second degree zonal harmonic (Mather 1975, p. 67). If this were established to be the case, it may be possible to reduce the magnitude of the sea surface topography by solving for a differential model. Low degree harmonics in the quasi-stationary sea surface topography can be obtained directly from altimeter orbit analysis as described in (Mather, et al. 1976a). The techniques proposed in this paper can be implemented without making any assumptions about the nature of the sea surface topography.

All surface gravity anomaly data currently available are flawed in the context of geoid computations due to regional elevation datums not necessarily coinciding with the geoid with a precision better than ± 1 m. In a regional study of the type originally envisaged, all the land gravity anomaly data on the Australian continent are controlled by the Australian Gravity Standardization Network (ANGN) and the Australian Height Datum (AHD) (Mather, et al. 1976b). The latter is not a freely adjusted level network, being distorted to fit local sea level. The resulting gravity anomaly data bank is subject to long wave errors with wavelengths

up to 5000 km and amplitudes of up to 1/2 mGal. A new gravity anomaly data bank for sea surface topography studies (AUSGAD 76) was prepared with a view to minimize the effect of such errors, the resulting data set being related to the Jervis Bay datum level surface. Factors taken into account in the preparation of AUSGAD 76 are the following:

- the even degree harmonic effects caused by using free air anomalies in lieu of gravity anomalies;
- the effect of the atmosphere; and
- the non-geocentricity of geodetic coordinates used in computing normal gravity.

The data set AUSGAD 76 was assessed as being free from errors with wavelengths greater than 5000 km and amplitudes in excess of 0.2 mGal and therefore adequate for studying linear sea surface slopes in the test area.

The same degree of certainty does not extend to the quality of the gravity data in the ocean areas falling with the data analysis region. While documentation has still to be produced regarding its quality, it is commonly held that its precision is at least one order of magnitude inferior to that of land gravity data, with a strong possibility of the errors having significant wavelength. The use of such data in sea surface slope determinations may well produce distorting effects in excess of ± 50 cm on ocean geoid computations. Consequently, it was considered necessary to formulate the solution to this problem taking all the above factors into consideration as outlined in the appendix.

The determination of a linear sea surface slope over a 2500 km distance can be solved if refined orbits (in this case, differential radial errors over the test area of ± 50 cm) and a global gravity field model of equivalent precision through wavelengths greater than 5000 km were available. Neither of these types of data are available in the test area at the present time. Attempts are still being made to resolve this problem.

In the interim, the altimeter data provided to date is being analyzed to study the following problems:

- (i) Determination of the shape of the sea surface on a regional basis from the satellite altimeter data, using the information provided on the altimeter data tape.

- (ii) The coherence of sea surface profiles by comparing overlapping passes after integral multiples of 526 revolutions of GEOS-3, and studying the power spectrum of the discrepancies.

The study at (i) is reported in Section 2 and that at (ii) in Section 3.

2. REGIONAL SEA SURFACE MODELS FROM SATELLITE ALTIMETRY

2.1 Basic Techniques

The orbits implied from the altimetry data tapes are subject to radial errors varying from a few meters in most cases, to in excess of 700 m in one instance (Mather, et al. 1977, p. 30). This latter pass overlapped another pass 37.18 days earlier and not more than 5 km away. While the sea surface heights were discrepant at the 700 m level, the fit of one pass to the other with allowance for corrections for tilt (c) and bias (b) by least squares gave residuals which had an rms of ± 61 cm (ibid., p. 34).

The inspection of other pairs of overlapping passes showed that a basis existed for determining a regional model of the sea surface with a resolution of at least ± 1 m from the altimetry data tape using the following assumptions:

- (i) Orbital errors greater than ± 1 m can be adequately modelled by corrections b for bias and c for tilt.
- (ii) The sea surface was radially stationary during the period of data acquisition.

The maximum pass length was approximately 3500 km. The assumption at (i) would be questionable for such long groundtracks if the effect of gravity model errors with shorter wavelengths were to significantly affect the radial component of orbital position. However, computations appear to indicate that the contribution of this effect is likely to be less than ± 20 cm (Wagner 1977).

As the ocean tide amplitudes in deep oceans are not expected to exceed 30 cm, a quasi-stationary differential model of the sea surface with a precision of $\pm \ell$ cm ($\ell > 30$) can be obtained by adopting one of the techniques described below if the following assumptions were valid:

- (a) Orbital errors with wavelengths > 7000 km contributed less than $\ell/3$ cm² to the error spectrum.
- (b) Time variations in sea surface topography were less than $\pm \ell/\sqrt{3}$ cm.

- (c) Variations in the geoid height over the area adopted as a junction (cross-over) point were less than $\pm \ell / \sqrt{3}$ cm.
- (d) The ocean tide amplitudes were either eliminated by modelling or, alternately, too small to affect the adjustment (e.g., only 30 cm when the precision sought is ± 50 cm).

Two techniques of adjustment suggest themselves with strong analogies to conventional geodetic levelling (Mather, et al. 1977, p. 37). Both techniques incorporate assumption (fi) above. In Technique (i), it is assumed that the internal fidelity of the pass is not in question. The corrections required to fit the j -th pass of a network of N passes to the true sea surface are a bias b_j and a tilt represented by the grade c_j . If the i -th sea surface data point recorded at time t_{ij} , was ζ_{ij} at the k -th junction point whose true sea surface height was ζ_k , with quasi-stationary component ζ_{ok} and temporal variation $\Delta\zeta(t_{ij})$, it follows that the following relation holds:

$$\zeta_k = \zeta_{ok} + \Delta\zeta(t_{ij}) = \zeta_{ij} + b_j + c_j(t_{ij} - t_{lj})/\Delta t_j \quad (2)$$

t_{ij} being the time at which the first element in the pass was recorded and Δt_j the total duration of the j -th pass. In view of the uncertainties associated with current ocean tide models in the region, the entire network of passes was adjusted in the first instance using observation equations of the form

$$\zeta_k = \zeta_{ok} + v_k \quad (3)$$

instead of the first equality at (2), v_k being treated as a normally distributed quantity. Thus, if the i -th element of the j -th pass and the l -th element of the m -th pass both provided estimates of ζ_k , a network of observation equations of the form

$$v = b_j - b_m + c_j(t_{ij} - t_{lj})/\Delta t_j - c_m(t_{lm} - t_{lm})/\Delta t_m + (\zeta_{ij} - \zeta_{lm}) \quad (4)$$

where v is the residual to be minimized. The resulting set of observation equations are solved by least squares for the biases b_j and grades c_j for all passes which traverse at least one junction point. By its very nature, the resulting model for the quasi-stationary sea surface is insensitive to

- datum; and
- errors in orbit integration which are factors of position but not time.

In Technique (ii) solutions, the internal fidelity of a pass is no longer assumed. The basic assumption made is that the difference in sea surface height between

adjacent junction points on a single pass is subject only to random errors. If ξ_{ij} , ξ_{lk} were the trial sea surface heights at two adjacent junction points corresponding to the i-th and l-th points on the respectively on the m-th pass at which the input sea surface heights were ξ_{im} , ξ_{lm} , the resulting observation equation is of the form

$$v = \Delta\xi_j - \Delta\xi_k + (\xi_{ij} - \xi_{lk}) + (\xi_{im} - \xi_{lm}) \quad (5)$$

where $\Delta\xi_j$, $\Delta\xi_k$ are the desired corrections to the trial sea surface heights ξ_{ij} , ξ_{lk} at the j-th and k-th junction points respectively.

Both techniques were used to determine

- the height of the quasi-stationary sea surface at each junction point; and
- the corrections for bias and tilt (grades) per pass needed to fit the orbits the resulting sea surface model.

For a discussion of the two techniques, see (ibid., p. 39). As summarized therein, tests showed that the stability of solutions for bias and tilt corrections were not jeopardized in the case of passes longer than 300 km if the size of the junction points (i.e., crossovers) were increased to 100 km squares. In this case, all sea surface heights within such a square were treated as estimates of the height of a single point. The only effect was to increase the residual noise in the adjusted system. It is estimated that increasing the size of a junction point from a 20 km square to a 100 km square increases the system noise by ± 80 cm (ibid., p. 40).

2.2 Results

An initial analysis of the GEOS-3 altimeter data in the Tasman and Coral Seas was performed in March 1977 (ibid.) using the 44 passes available at the time (Table 1). The internal noise in the system of observations for this solution with 102 junction points was ± 0.8 m. The resulting quasi-stationary sea surface model for the epoch April - September 1975 (MAR77) was compared with the Marsh-Vincent gravimetric geoid based on GEM6 and provided with the altimeter data tape. The resulting discrepancies were highly correlated with position (ibid., p. 44), the sea surface model being systematically biased over the area of comparison in relation to the geoid model. Similar trends are obtained when comparing GEM8 to GEM10 (Marsh 1977). A major discrepancy is noted in the region of the Lord Howe Rise in the Tasman Sea.

A second solution was obtained for the shape of the sea surface from the data available in September 1977 and described in Table 1. The resulting sea surface

model - SEP77 - shown in Figure 1, covers a greater area than MAR77, the additional region in the north east corner taking in the New Hebrides Trench with depths in excess of 8000 m.

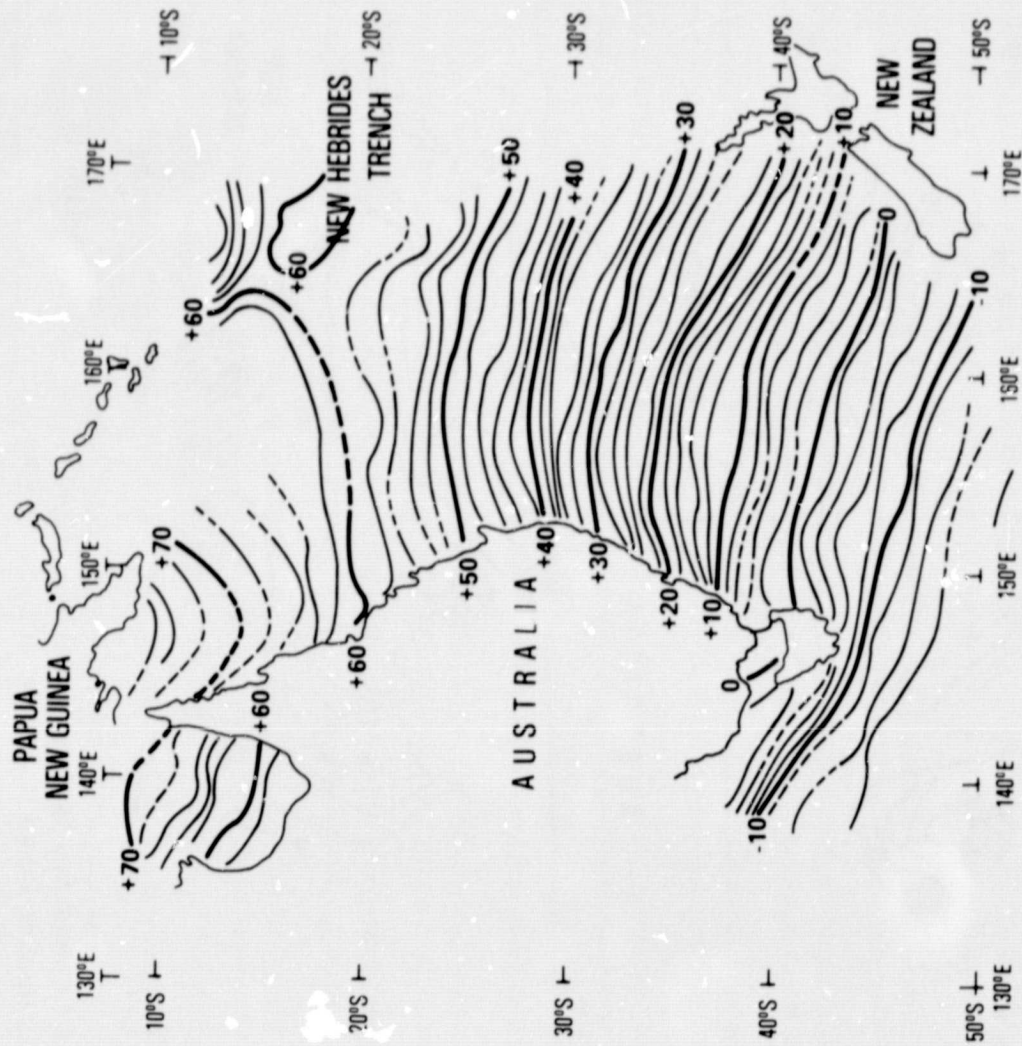
Figure 2 illustrates the resulting discrepancies on comparing the sea surface model MAR77 against a gravimetric geoid computed by Marsh and based on GEM10 (Marsh 1977). While these discrepancies have an rms of ± 3.2 m over the entire region without resorting to any selective elimination of data, as opposed to an rms of ± 1.6 m in the case of the MAR77/Marsh-GEM6 geoid comparisons (Mather, et al. 1977, p. 45), the pattern of contours in both cases is similar in common areas. Two observations of significance can be made in the case of the SEP77/Marsh-GEM10 comparisons:

- (i) The GEM10-based geoid has discrepancies with the sea surface model SEP77 with wavelengths of approximately 4000 km.
- (ii) The largest discrepancies are correlated with sea floor features:
 - the New Hebrides trench (sea surface up to 10 m lower than geoid model);
and
 - the Lord Howe rise (sea surface higher than geoid model).

In evaluating comparisons of sea surface and geoid models in this region, it should be recognized that the regional surface gravity field is represented by only a sparse data set in the Tasman and Coral seas of questionable quality. The discrepancy patterns reflect the absence of high frequency representation of the surface gravity field in a region where the gravity anomalies have a range of 300 mGal. It follows that it would be preferable to use satellite based gravity fields for such comparisons in poorly surveyed ocean areas, e.g., GEM9 (Lerch, et al. 1977) and thereby extract sea surface features with wavelengths less than 2000 km using comparisons of the type illustrated in Figure 2.

Figure 3 illustrates the discrepancies between Technique 1 solution (i.e., relative geometry of each pass maintained with corrections only for bias and tilt) and GEM9. Table 2 illustrates in summary, the statistics of comparison between Technique 1 and Technique 2 solutions comprising the SEP77 sea surface models, with both the Marsh/GEM6 and Marsh/GEM10 geoid models as well as GEM9. In general Technique 2 solutions have smaller rms residuals on comparison. This apparent index of quality needs closer examination.

An examination of Figure 3 indicates that, in addition to the two features apparent in Figure 2, significant discrepancies are also obtained along the continental shelf



REFERENCE ELLIPSOID
 $a = 6,378,145\text{m}$
 $f = 1/298.255$

EPOCH - APRIL TO NOVEMBER 1975
 NO. OF GEOS-3 ALTIMETRY
 PASSES USED = 167
 WAVELENGTHS > 200 km
 CONTOUR INTERVAL - 2m

Figure 1. Model of Quasi-Stationary Sea Surface - Tasman and Coral Seas SEP77

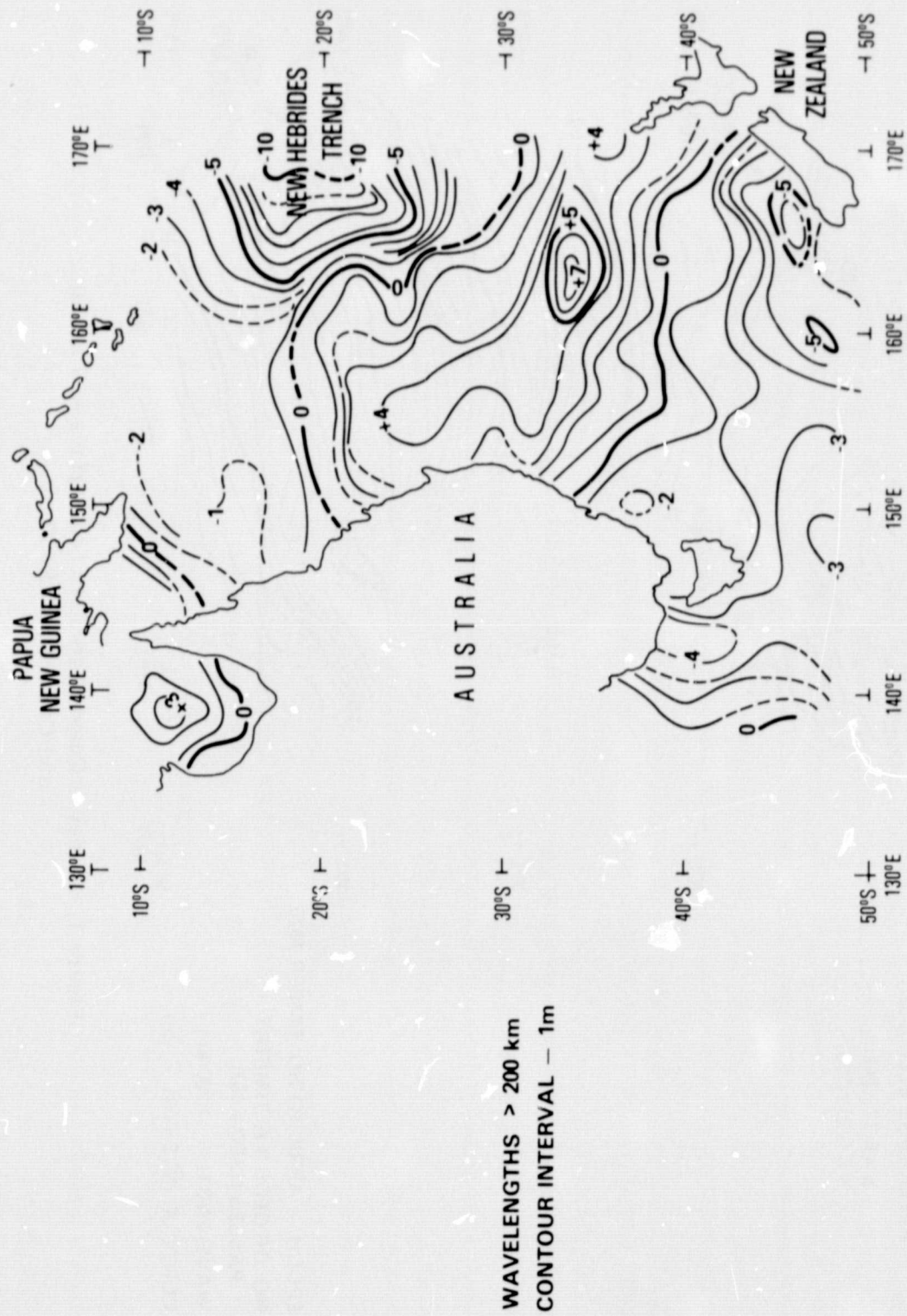


Figure 2. Discrepancies Between Sea Surface Model SEP77 and Marsh GEM10 Detailed Gravimetric Geoid in Tasman and Coral Seas

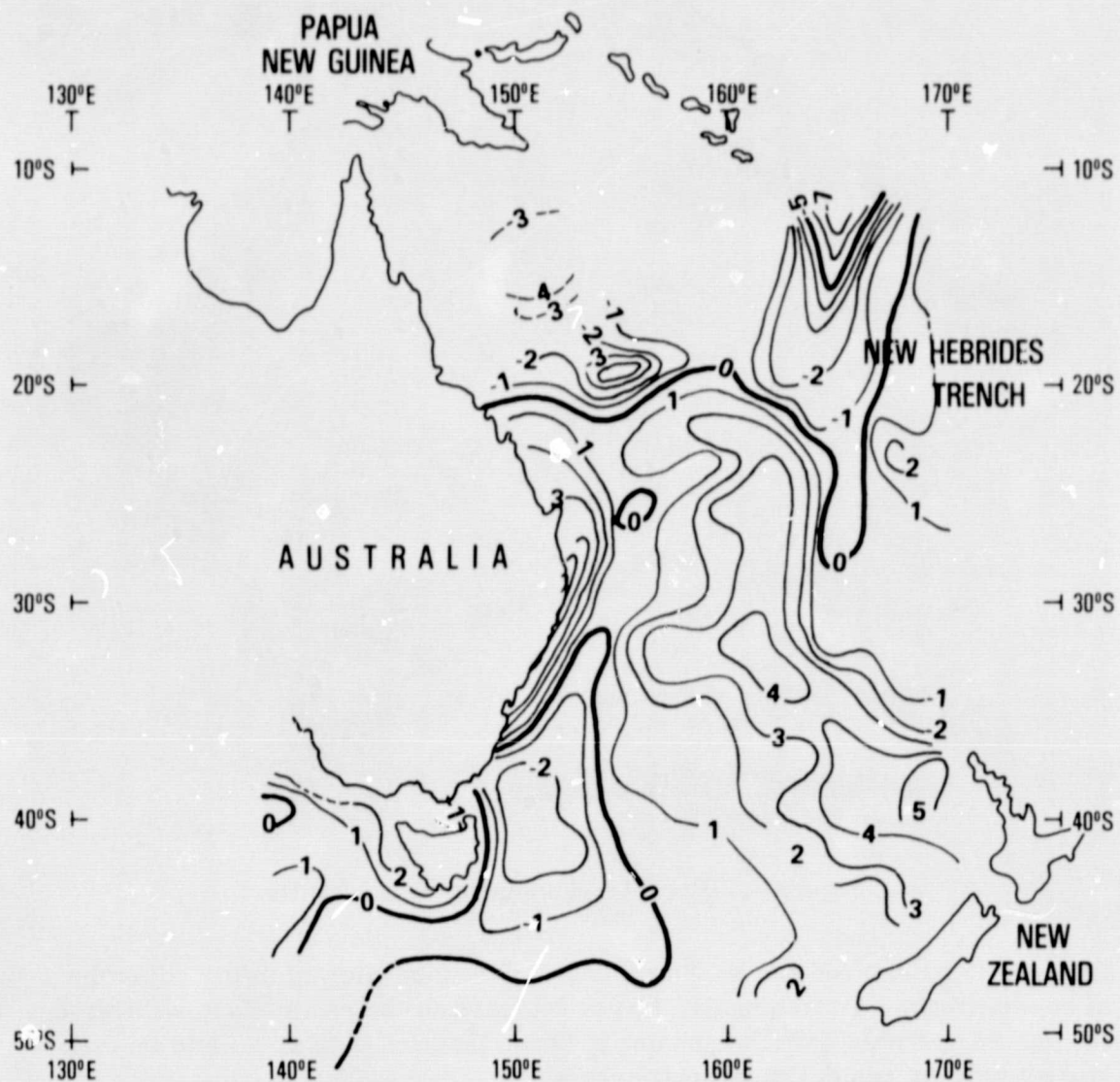


Figure 3. Discrepancies Between Sea Surface Model SEP77
(Technique 1 Solution) and the GEM9 Geoid Model
(Contour Interval - 1 m)

margin east of New South Wales. The gravity anomaly field in this region is abnormal with a north-south belt of large negative gravity anomalies lying immediately to the west of a similarly oriented belt of large positive anomalies along the margin of the narrow continental shelf (Fig. 4). A similar study in the case of a Technique 2 solution (Fig. 5) (each pass adjusted in sections between junction points and not as entities) shows a tendency of the shapes of such dominant

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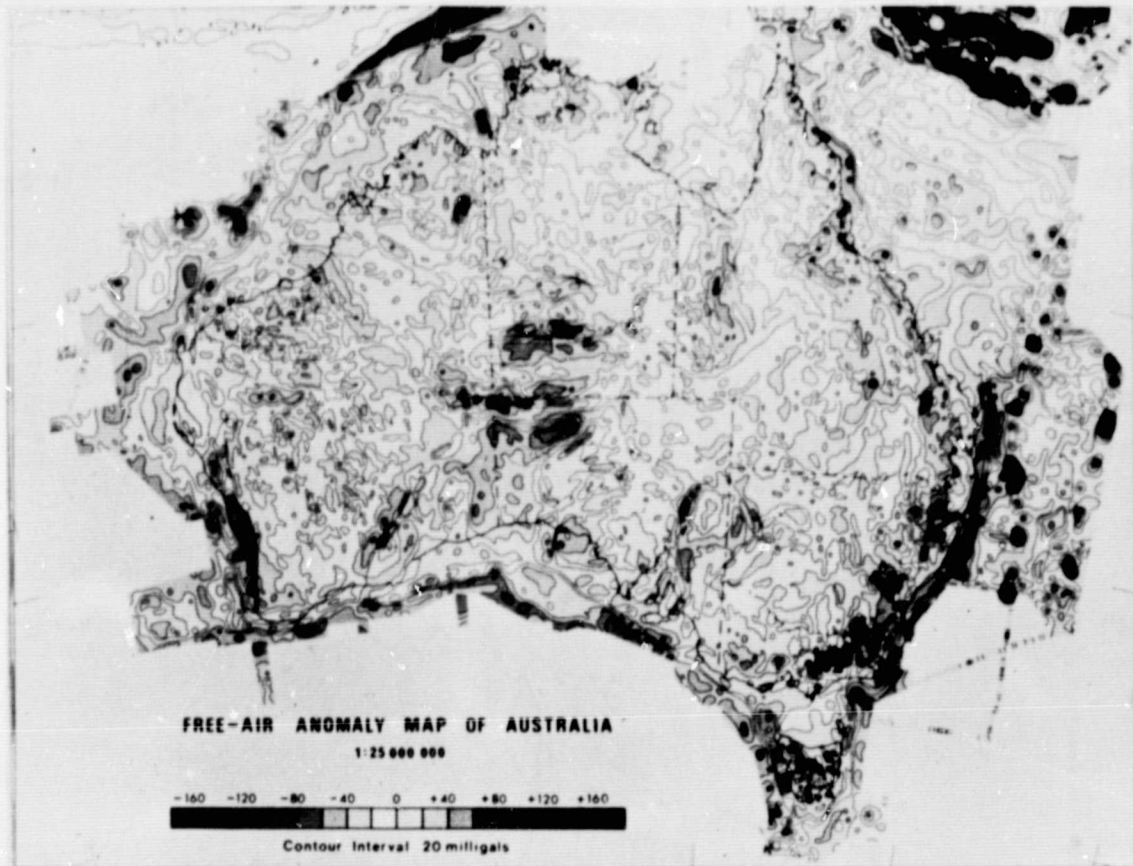


Figure 4. Free Air Anomalies — Australia

features to be blurred due to the excessive freedom allowed in the adjustment of observations. Consequently, larger features in the sea surface with wavelengths comparable with the spacing between junction points, tend to be absorbed into the residuals as orbit errors.

2.3 Conclusions

It appears that a basis exists for obtaining models of the sea surface with a precision equivalent to that underlying the assumption of stationarity of the sea surface, over extents of 6000 km^2 . The correctness of such models in a global context depend on the precision with which harmonics of the gravity field with longer wavelengths are known.

It is important that the internal geometry of altimeter passes be maintained over the test area in order that the geometry of intermediate features in the

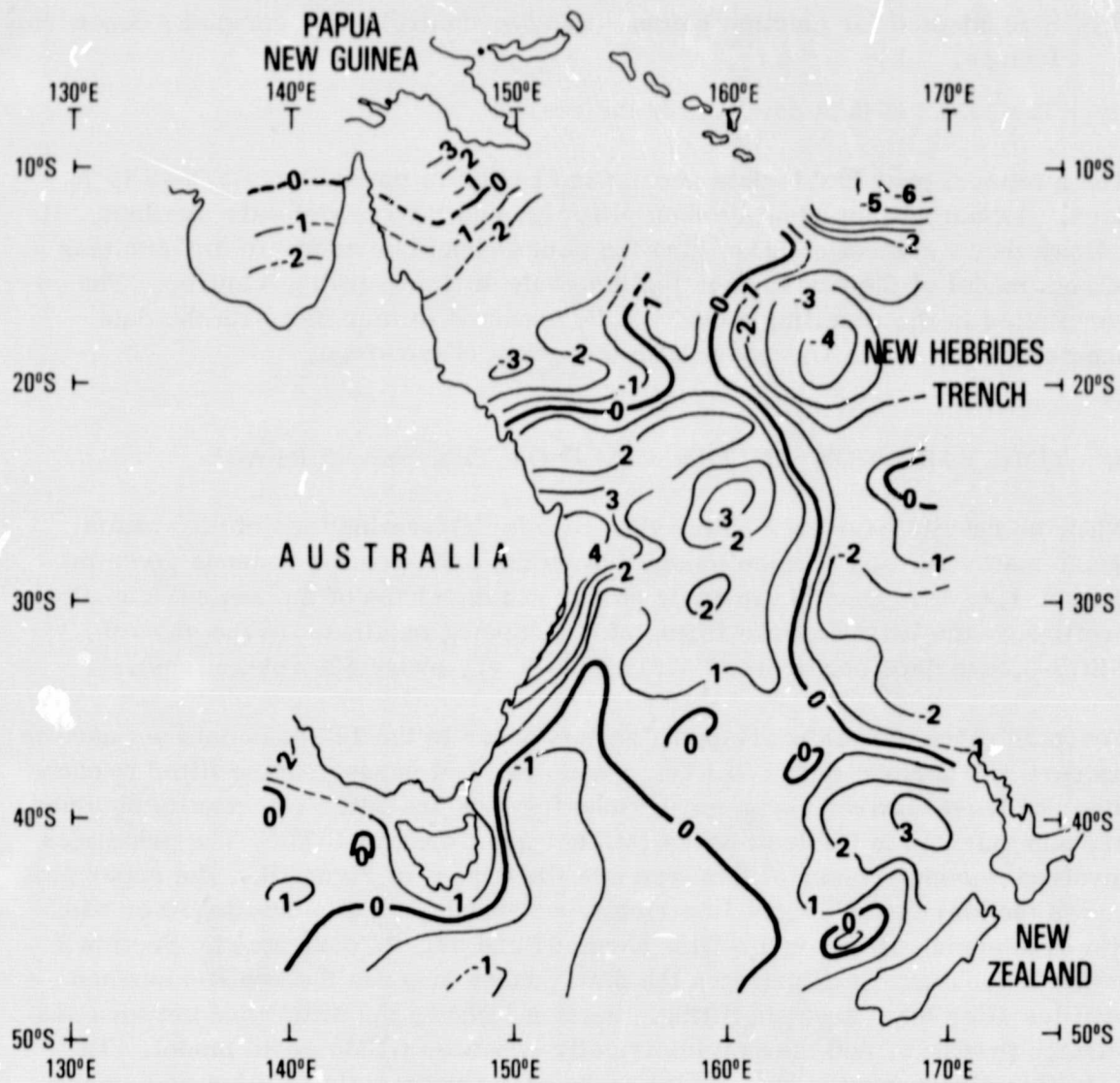


Figure 5. Discrepancies Between Sea Surface Model SEP77
(Technique 2 Solution) and the GEM9 Geoid Model
(Contour Interval - 1 m)

sea surface are not blurred by absorption into the system errors. The precision achievable by from the techniques suggested are limited by the following factors:

- (i) Tidal uncertainties, not expected to exceed ± 30 cm.
- (ii) Mesoscale variations in the sea surface topography of up to ± 50 cm with decay times of 10^2 days.

- (iii) Size adopted for junction points - a factor controlled by computer dependent factors.
- (iv) The extent of data coverage in the region.

The minimum practicable data acquisition period in the case of GEOS-3 is 25 days. Assuming that adequate data coverage and tidal models are available, it follows that a system of 50 km junction points should be adequate for obtaining a ± 25 cm model of the sea surface for the study of time varying features. The uncertainties in the resulting model can be expected to increase with the data acquisition period and decrease with the extent of coverage.

3. TIME VARIATIONS IN THE SHAPE OF THE SEA SURFACE

While no results have been obtained to date for determinations of differential quasi-stationary sea surface topography in the test area for reasons given in Section 1.4, it is possible to study changes in the shape of the sea surface along profiles by the least squares fitting of overlapping profiles. In the case of GEOS-3, overlaps occur every 37.13 days (i. e., every 526 revolutions).

Fourteen pairs of such overlapping passes occur in the 167 pass data set used to prepare sea surface model SEP77. These pairs of passes can be fitted to each other by least squares using corrections for bias and tilt. The results obtained are summarized in Tables 3 and 4 (Mather and Coleman 1977). The principles involved in comparisons of this type are illustrated in Figure 6. The upper plot shows the Marsh/GEM6 gravimetrically enhanced geoidal model together with two overlapping altimetry profiles (Nos. 67 and 97), 72 days apart. Section 2 in the lower diagram illustrates the discrepancy between the two sea surface profiles after least squares fitting. Section 1 shows the difference between sea surface profile 97 and the gravimetrically enhanced GEM6 geoid model. The resulting discrepancies have wavelengths of approximately 2500 km and amplitudes of about 5 m. The discrepancies between the two overlapping sea surface profiles have an rms residual of ± 44 cm (Table 3, Row 13), the discrepancies exceeding the spectrum of white noise only in respect of the "bin" labelled ($\ell = 200$ km) in Table 4.

Figure 7 illustrates the same information in the case of 3 overlapping passes in the test area (Nos. 57, 62, 109). Passes 62 (37.2 days later) and 109 (148.7 days later) were fitted by least squares to pass 57 and the residuals and plotted in Figure 12 with summaries in Tables 3 and 4 (Rows 7 and 8). The rms residual in each case is approximately ± 30 cm.

BEFORE CORRECTION FOR TILT AND BIAS

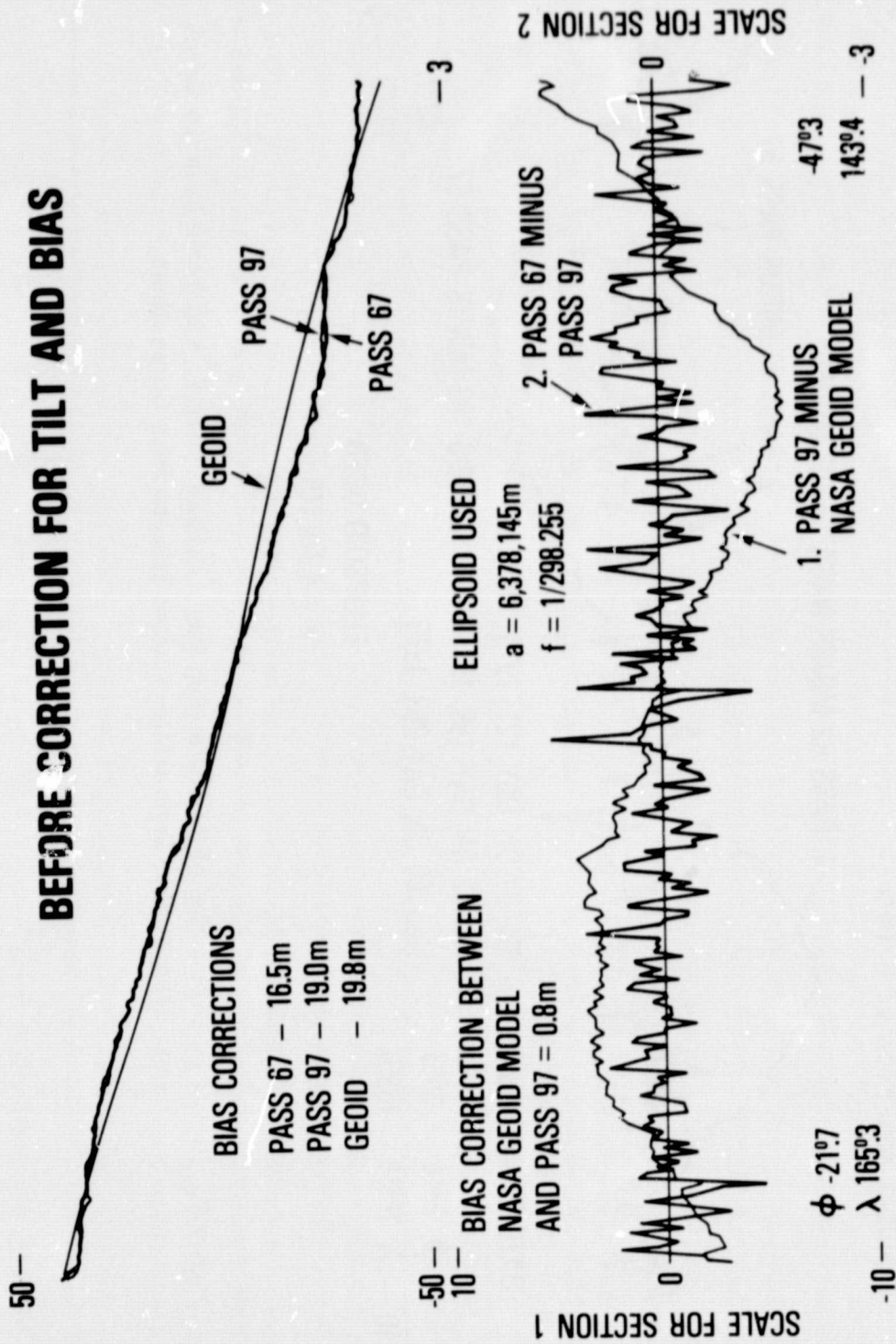


Figure 6. Differential Plots of Overlapping Sea Surface and NASA Geoid Models Illustrating the Effect of Errors in the Gravity Field Model — Passes 67 and 97 (Tables 3 and 4: Row 13), Date of Acquisition — No. 67 on Day 185, 1975, No. 97 on Day 259, 1975

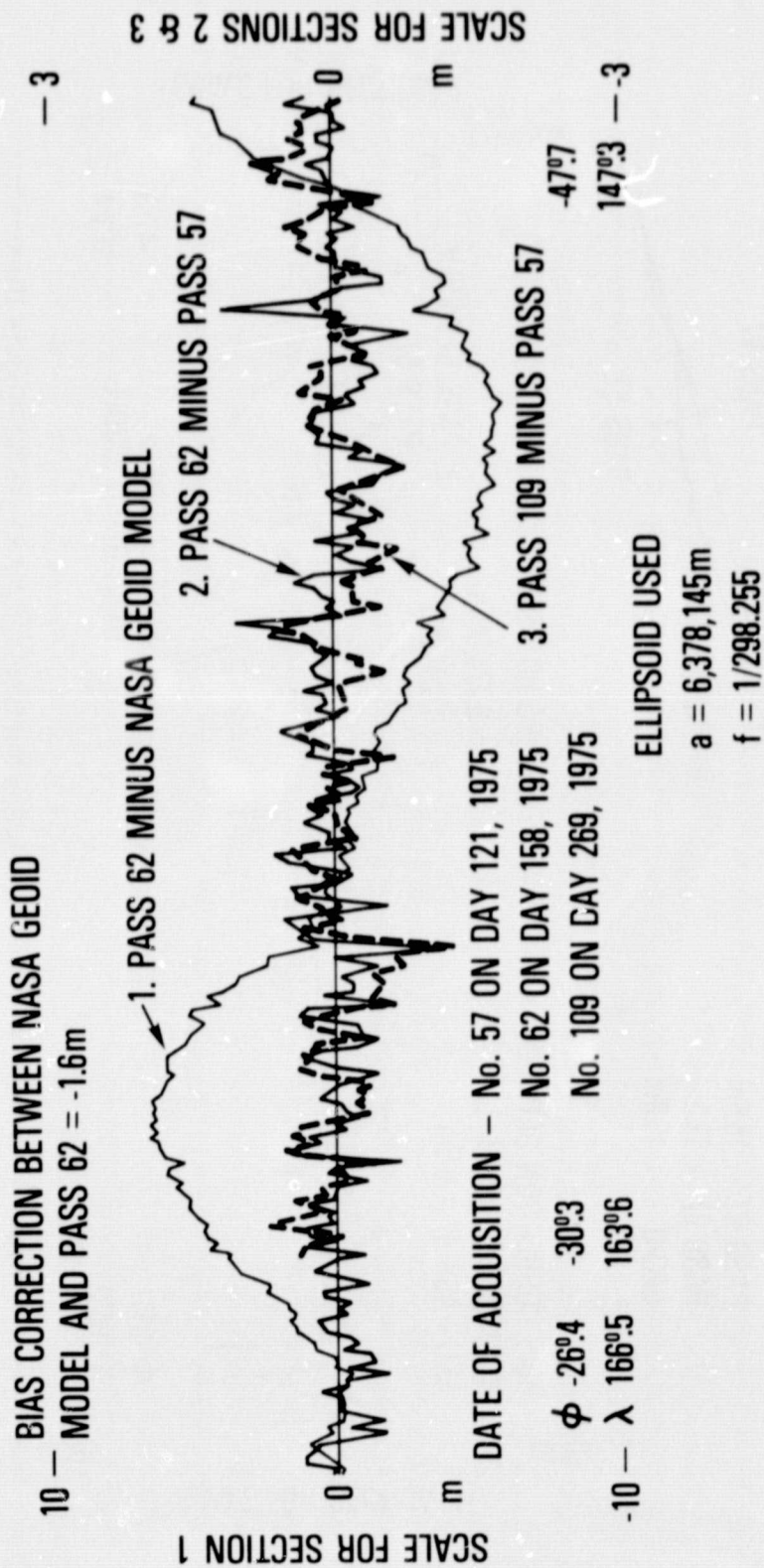


Figure 7. Plot of Discrepancies of 3 Overlapping Passes (Pass Pairs 7, 8 in Table 3) in the Coral and Tasman Seas from GEOS-3 After Tilt and Bias Corrections

The further analysis of profile discrepancies of the type illustrated in Figures 6 and 7 for non-trivial signals in the discrepancies calls for the definition of a model for the expected spectrum of errors (Fig. 8).

If the rms residual of comparisons were $\pm\sigma$, and the number of frequencies used in the spectral analysis were N , it follows that the contribution per frequency, to a white noise spectrum is $\pm\sigma/\sqrt{N}$, assuming the spectrum of white noise to be flat.

The contribution E_{oi} per "bin" in Table 4 is

$$E_{oi} = \pm \sqrt{\frac{n}{N}} \sigma \quad (6)$$

where n is the number of frequencies included in the bin. Table 4 sets out the expected noise levels per bin assuming a banded white noise spectrum, together with the observed contributions to the discrepancies for the five dominant wavelength ranges. The latter are expressed as the percentage strength of signal S obtained according to the relation

$$S = \sum_i \frac{A_{1i}^2 + B_{1i}^2}{2\sigma^2} \times 100 \quad (7)$$

the index i being taken over the frequencies included per bin, A_1 , B_1 being given by (Mather and Coleman 1977, p. 10)

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \frac{2}{l_0} \int_0^{l_0} v_s \begin{bmatrix} \sin \\ \cos \end{bmatrix} \left(\frac{2\pi s}{l_0} \right) j ds \quad (8)$$

i being the integral number of complete wavelengths in the length l_0 over which the comparisons are made, ds being the sampling interval, the residual v_s occurring at a distance s from the commencement of comparisons.

Non-trivial amplitudes above the expected level of white noise are obtained in certain wavelengths (values boxed in Table 4). The significance of these results needs to be assessed with caution. Possible contributing factors are the following:

- (i) Tidal effects. Conventional tidal models in the test area (e.g., Hendershott 1973, p. 81) show distance between amphidromes of up to 5000 km. If this were the case, tidal effects should be completely absorbed in tilt and bias

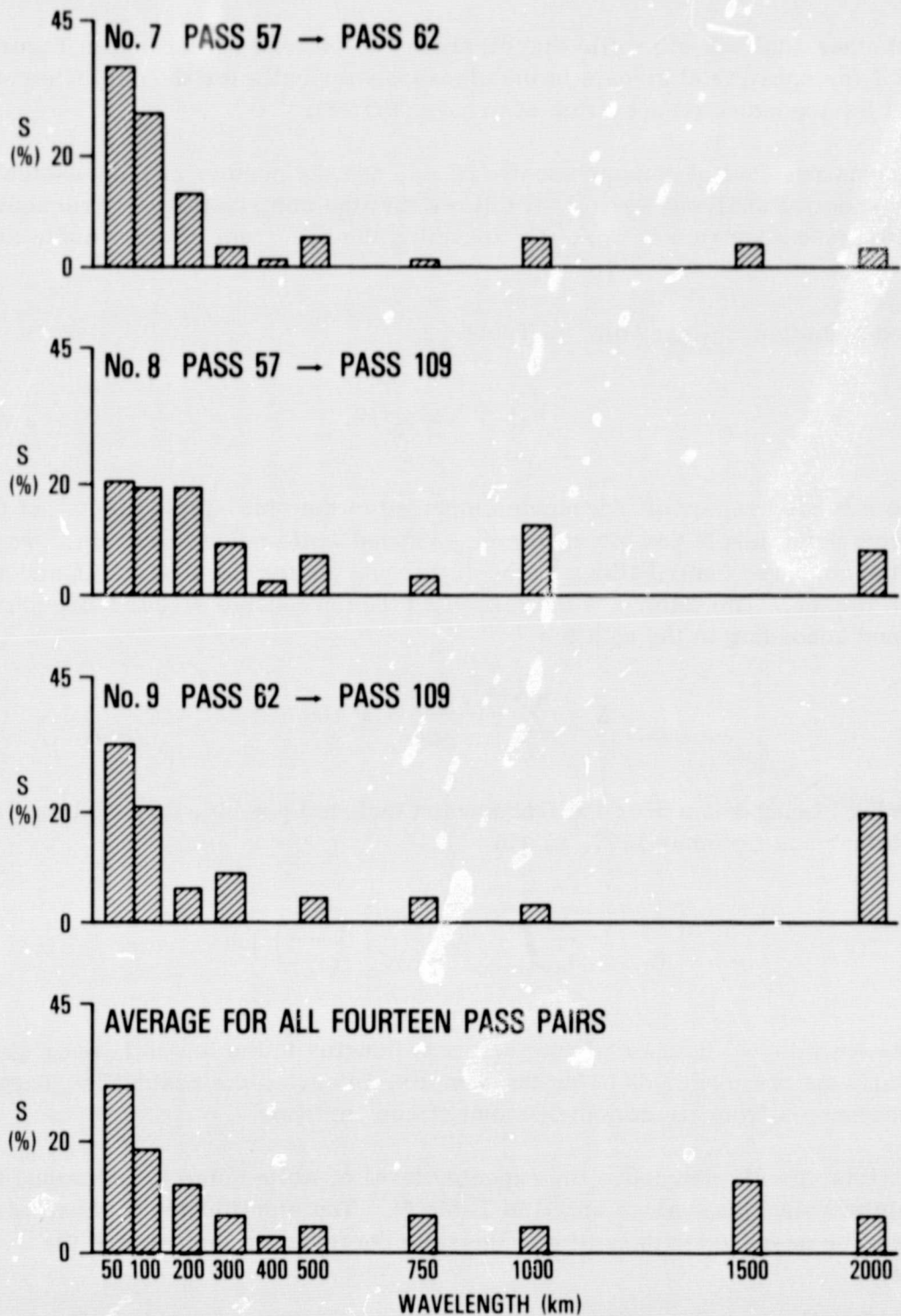


Figure 8. Power Spectra, Expressed as % Strength of Signal(s) — Equation 7 — for 3 Overlapping Passes Plus Average Values for 14 Pass Pairs Listed in Tables 3 and 4

corrections. However, these models are not considered error-free and their ability to represent fine structure of the ocean tide, if any, has not been established. Table 4 sets out the phase difference between the two passes for the M_2 tide. Current ocean tide models can represent about two-thirds the ocean loading of Earth gravity tides (Bretreger and Mather 1977) in this region.

(ii) Short period orbital errors with wavelengths less than 5000 km. Such errors can be expected to be of two types:

- Errors which are a function of position alone.
- Errors which are a function of both position and time.

The first type of error occurs when integrating orbits with an erroneous gravity field model using a fixed complement of tracking stations. The second type of error occurs due to a change in the configuration of the tracking stations used in integrating the orbits. It is estimated that errors in the gravity field model affect radial orbital position through wavelengths which cannot be absorbed in tilt and bias corrections, with amplitudes of less than ± 20 cm (Wagner 1977). In a gross case (Table 4, Row 1), where the bias correction was over 700 m (Table 3, Row 1), significant discrepancies occur with wavelength equal to the length of comparisons, the amplitude being approximately 50 cm. In most other cases, the bias corrections are less than 10 m, lending credence to the above figure. It can therefore be concluded that radial orbital position errors with wavelengths less than 3500 km using present day gravity models are unlikely to exceed ± 20 cm.

(iii) Errors in the radar altimeter. At the level of precision being considered, this is largely an unknown quantity. Systematic errors in the altimeter with periods in excess of 6-7 minutes are absorbed in tilt and bias corrections. A study of the results in Table 4 indicate a level of white noise of around ± 25 cm, due to a combination of the altimeter errors and the sea state. Noisier rms discrepancies may be attributed to disturbed sea state. Attempts to correlate noisy altimetry groundtracks in the Tasman Sea with ships logs made available by the Australian Bureau of Meteorology were not conclusive. While there is a tendency for noisy groundtracks to occur during periods of disturbed ground meteorological conditions, the correlations are subject to offsets.

(iv) Mesoscale variations in the sea surface topography with time. Significant non-trivial strengths of signal are obtained more frequently in the case of south-to-north passes than for north-to-south passes (Table 4). The bias corrections in the case of rows 1 and 3 are large and may result in large discrepancies (at the ± 25 cm level) due to tracking station configuration changes as discussed at (ii) above. This may also be a contributory factor

in the case of comparison 6 in Table 4. No such argument is obvious in the case of non-trivial discrepancies obtained in the case of comparisons 2, 4 and 5.

The use of the non-trivial strength of signal obtained by using Equations (6) to (8) does not provide a basis for studying all contributions to the spectrum of meso-scale variations in sea surface topography. Ocean eddies are features of importance in ocean dynamics and have finite structure with variations in both position and time. Signatures of such features will appear in the distribution of residuals of the form

$$v = v_s - \sum_i A_{1i} \sin\left(\frac{2\pi s}{\ell_0} i\right) + B_{1i} \cos\left(\frac{2\pi s}{\ell_0} i\right) \quad (9)$$

4. CONCLUDING REMARKS

The following conclusions can be drawn from the analysis of the GEOS-3 altimeter data in the Tasman and Coral Seas:

- Short pulse mode altimetry data appears to have adequate resolution to delineate variable features in the sea surface with amplitudes greater than 20 cm and wavelengths between 10^2 and 10^3 km, provided the tracking station configuration remains fixed and rough seas are not encountered.
- Such resolution can be obtained without the benefit of high precision tracking data if the orbit integration were performed from a fixed complement of tracking stations. The adoption of such a procedure may enable fast-varying features such as ocean eddies, to be tracked without the benefit of either an accurate global gravity field model or a global high precision tracking network.
- The determination of ocean tides can only be obtained from the global consideration of GEOS-3 altimetry data if the dominant characteristics of such models are of long wavelength, as implied by the occurrence of amphidromes about 5000 km apart in present day representations. Such a tidal analysis will have to be preceded by gravity model improvement to ± 1 m with determinations restricted to areas with dense enough coverage of overlapping altimetry (Bretreger 1976, p. 90).
- The non-trivial sea surface height variations implied in Table 4 require further study in relation to the available ground truth.

- A basis exists for determining regional models of the sea surface with an internal precision of $\pm 1\text{ m}$, where 1 is the estimated departure from the assumption that the sea surface is stationary over the period of data analysis. Such models generated in the Tasman and Coral Seas correlate well with both gross features in the bathymetry and the surface gravity anomalies.

5. ACKNOWLEDGMENTS

Research in the development of techniques to determine sea surface topography from satellite altimetry is financially supported by the Australian Research Grants Committee.

Systems programming support was provided by Bernd Hirsch. This program of research is carried out in collaboration with Richard Coleman, Chris Rizos and Oscar Colombo.

Helpful and stimulating discussions with Carl Wagner are acknowledged with pleasure. Useful discussions were also had with David Smith and Jim Marsh.

This paper was written while the author was a Senior Resident Research Associate of the National Academy of Sciences at Goddard Space Flight Center.

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Table 1
The Analysis of GEOS-3 Altimeter Data in the Tasman and Coral Seas

Solution	Date Prepared	Total No. of Passes	No. of South-North Passes	No. of North-South Passes	RMS Residual $\pm m$	Reference
MAR77	March 1977	44	22	22	0.8	Figs. A-6 & A-7
SEP77	October 1977	167	78	89	1.2	Figs. 1, 2, 3, 5

Table 2
Residuals on Comparison of Various Geoid Models with Stationary Sea Surface Model SEP77 in the Tasman and Coral Seas

No. of Passes: 167; No. of Junction Points: 626;
Junction Point Size: $1^\circ \times 1^\circ$ sq.; Internal rms Residual: $\pm 1.2 m$

Technique Used	Root Mean Square Residual ($\pm m$) on Comparison Against		
	Marsh/GEM6	Marsh/GEM10	GEM9
1	Gravimetric	Gravimetric	Satellite
	3.4	3.8	2.3
2	Gravimetric	Gravimetric	Altimetry
	2.4	3.6	1.9
			Altimetry
			1.5
			1.5

Table 3

Parameters Defining the Relative Fit of Fourteen Pairs of Overlapping Passes of GEOS-3 Altimetry in the Tasman and Coral Seas from April to November 1975

	Pass Pair	Length of Pass (km)	Time Lapse Between Passes (days)	M ₂ Tide Phase Diff. (°)	Corrections for		RMS Residual (± cm)	Type**
					Bias (m)	Tilt (arcsec)		
1	2-10	1462	38	154	-724.9	-1.75	61	SN
2	4-21	799	75	-29	-6.0	0.74	32	SN
3	26-52	811	223	-37	67.5	-0.57	35	SN
4	18-34	1493	37	-182	-3.1	-0.24	132	SN
5	8-51	1588	112	149	-1.7	0.43	27	SN
6	22-36	3227	37	178	-17.4	0.35	170	SN
7	57-62	2882	37	-182	3.0	-0.09	30	NS
8	57-109	2449	149	-8	4.8	-0.15	33	NS
9	62-109	2388	111	174	2.1	-0.07	32	NS
10	72-121	2704	223	-37	-0.9	0.05	28	NS
11	86-102	2828	37	178	0.5	0.05	35	NS
12	82-93	3221	37	-182	1.9	-0.05	56	NS
13	67-97	3354	74	-4	-2.2	-0.04	44	NS
14	69-89	804	37	178	1.5	-0.11	59	NS
4	18-34*	1493	37	-182	-3.2	-0.19	95	SN
6	22-36*	3227	37	178	-18.1	0.48	85	SN

*Each data point in pass treated as the average of two contiguous values

**NS = North South Passes; SN = South North Passes

Table 4
Significance of Percentage Contributions to the Mean Square Residual [Equation (6)] for the Five Dominant Wavelengths* After the Least Squares Relative Fit of 14 Pairs of Overlapping Passes

Type	Pass Pair	Length of Pass (km)	Time Lapse Between Passes (days)	RMS Residual (\pm cm)	Phase Difference M_2 Tide ($^\circ$)	Percentage Contribution of Five Dominant Wavelength Ranges (l)* in km											
						l = 50		l = 100		l = 200		l = 750		l = 1500			
						E**	O**	E	O	E	O	E	O	E	O		
1	S-N	1462	37	61	154	66	12	18	3	9	7	4	7	2	66		
2	S-N	799	75	32	-29	68	29	16	2	10	5	3	6	-	-		
3	S-N	811	223	35	-37	68	37	16	10	10	4	3	39	-	-		
4	S-N	1493	37	132	-182	65	38	18	13	7	15	4	7	2	14		
5	S-N	1588	112	27	149	67	31	18	26	8	17	3	3	2	14		
6	S-N	3227	37	170	178	65	8	18	13	6	10	2	14	1	12		
7	N-S	2882	37	30	-182	65	36	17	28	7	13	3	1	2	4		
8	N-S	2449	149	33	-8	65	20	18	19	6	19	2	3	2	0		
9	N-S	2388	112	32	174	65	33	17	21	7	6	2	4	2	0		
10	N-S	2704	223	28	-37	65	47	17	24	7	9	2	1	1	2		
11	N-S	2828	37	35	178	65	59	17	17	7	9	3	0	1	1		
12	N-S	3221	37	56	-182	65	52	18	18	6	11	2	2	2	1		
13	N-S	3354	74	44	-4	65	46	18	21	7	14	2	2	2	3		
14	N-S	804	37	59	178	68	14	19	38	10	18	3	7	-	-		

*The wavelength ranges used in computing percentages were the following: l = 50 (26 \leq l < 75); l = 100 (75 \leq l < 150); l = 200 (150 \leq l < 250); l = 750 (625 \leq l < 875); l = 1500 (1250 \leq l < 1750)

**E = Expected value from a flat white noise spectrum using Equation (6)

O = Value obtained by using Equations (7) and (8)

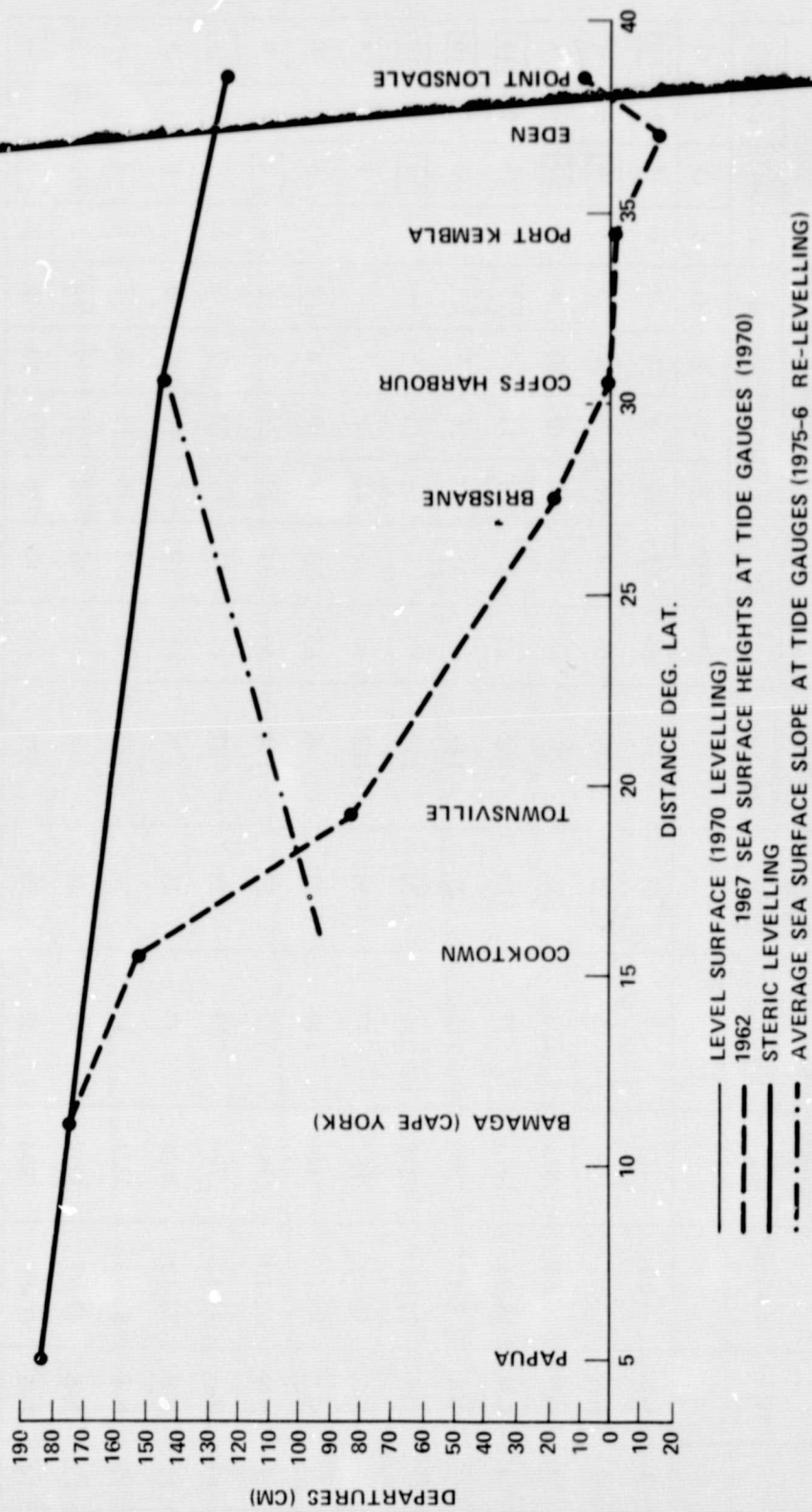
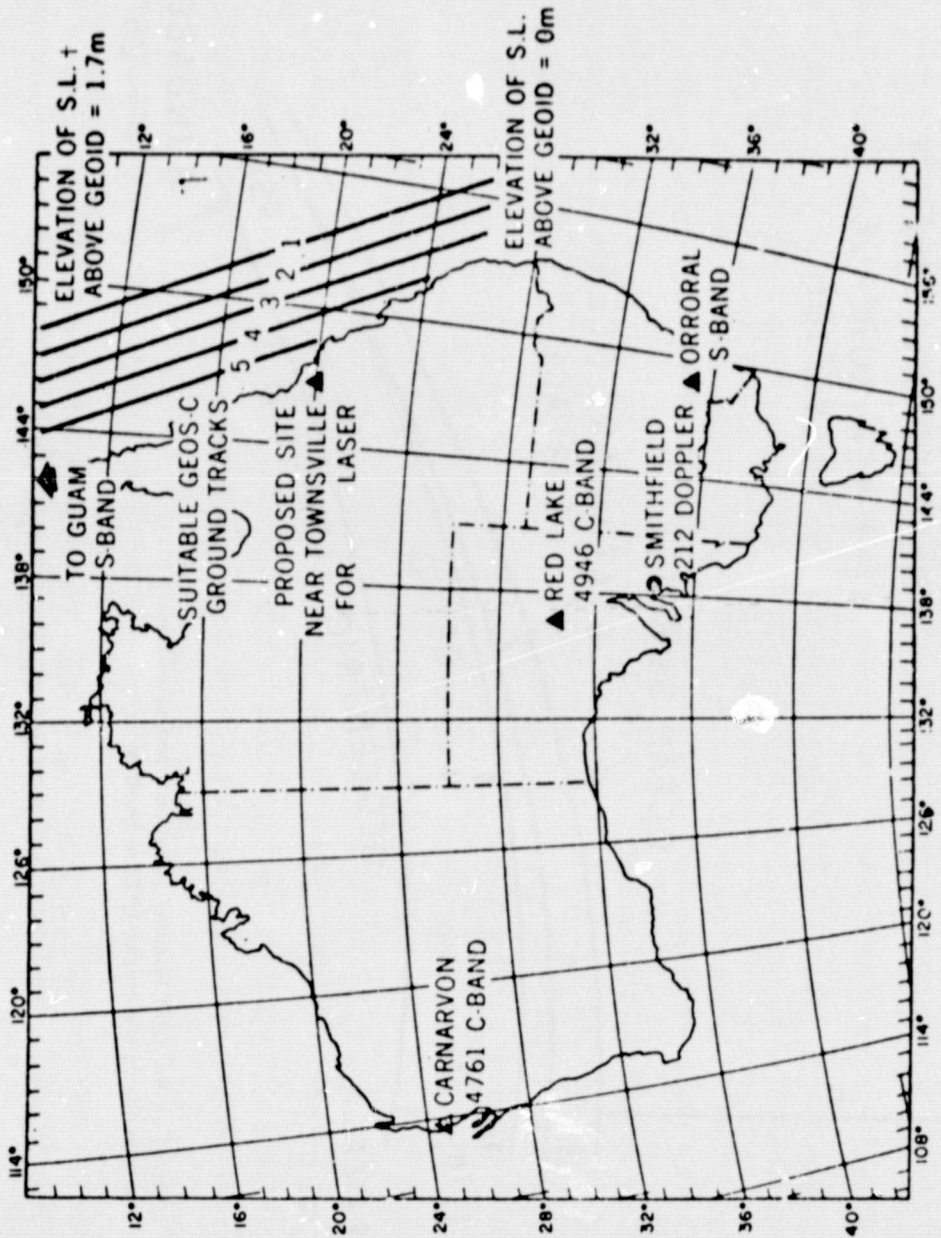
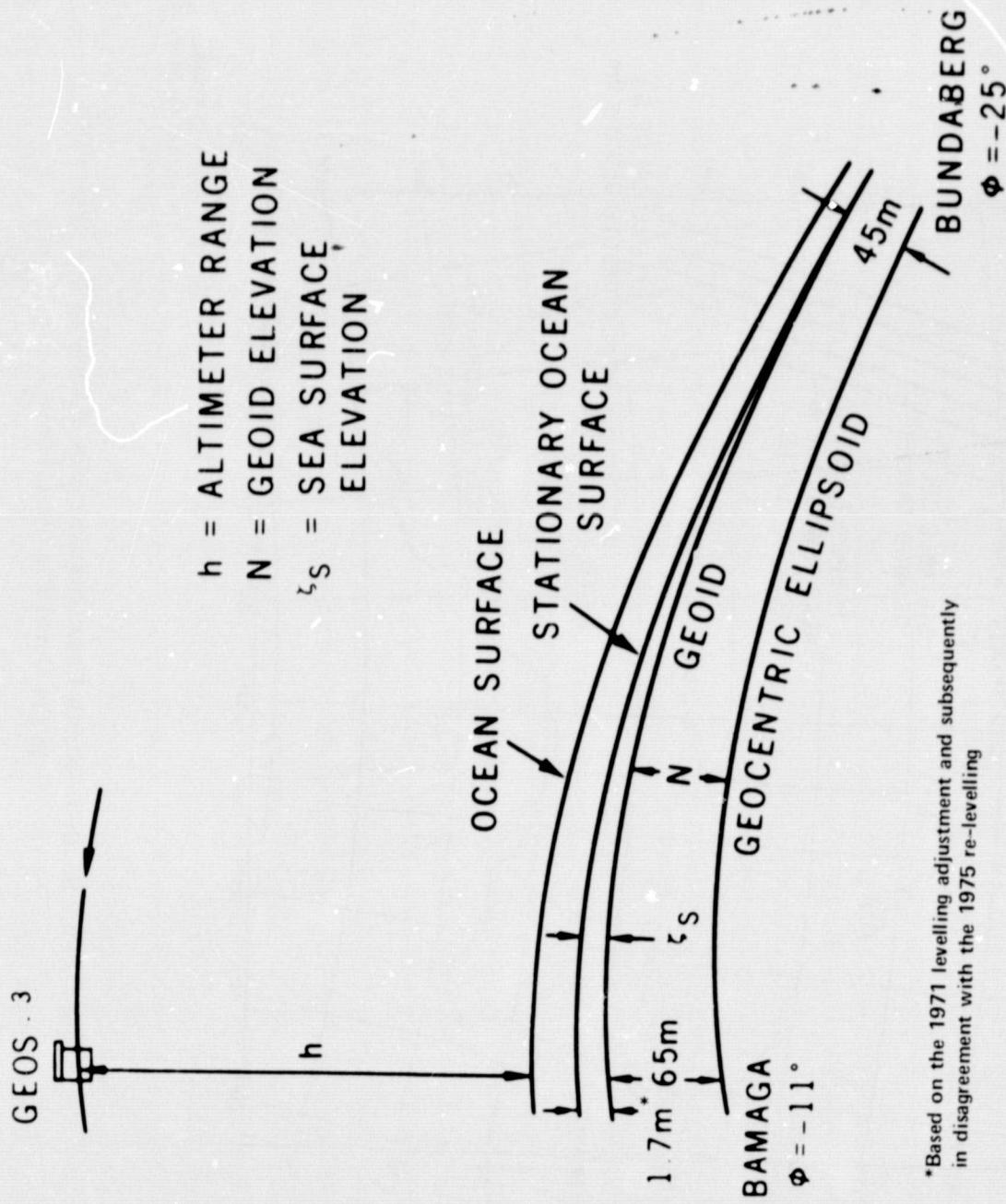


Figure A-1. Heights of Local Mean Sea Levels — Western Pacific Coast (Australia)



† From the 1970
Australian Levelling
Survey

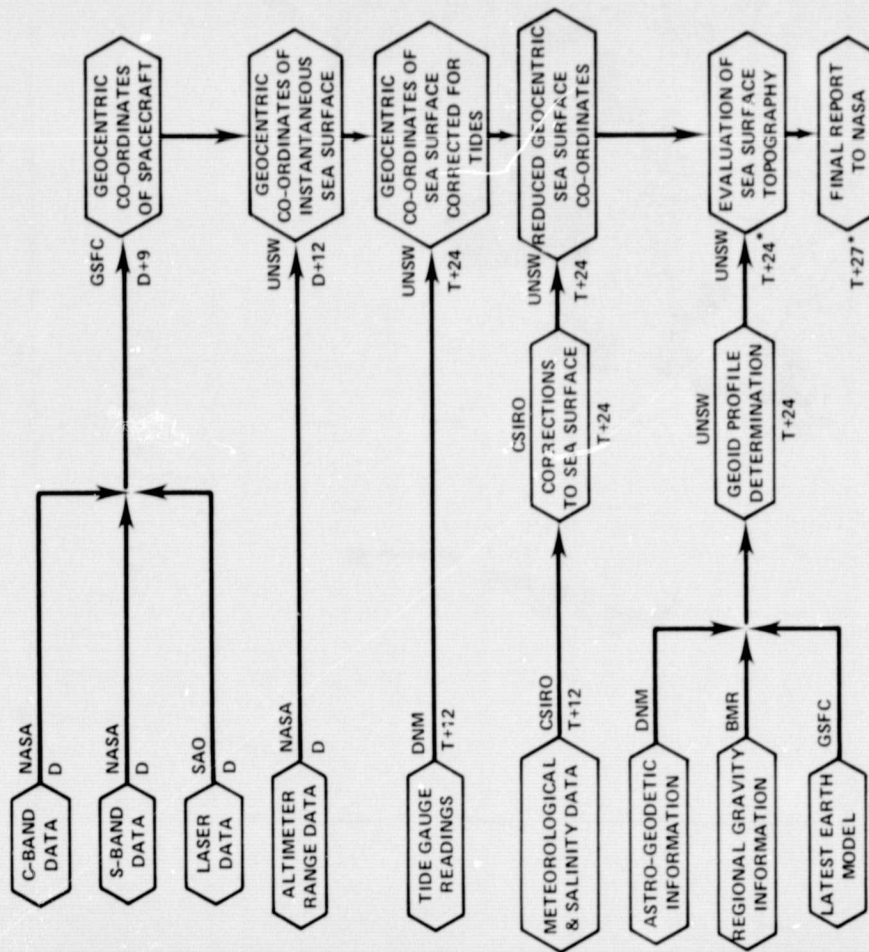
Figure A-2. South-to-North Pass Groundtracks of the GEOS-3 Spacecraft
in the Coral Sea Test Area



*Based on the 1971 levelling adjustment and subsequently in disagreement with the 1975 re-levelling

Figure A-3. Sea Surface Topography in the Orbital Plane
Northeastern Australia

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KEY:

- BMR = BUREAU OF MINERAL RESOURCES, DEPT. OF MINERALS & ENERGY, CANBERRA
- DNM = DIVISION OF NATIONAL MAPPING, DEPT. OF MINERALS & ENERGY, CANBERRA
- CSIRO = DIVISION OF FISHERIES & OCEANOGRAPHY, CSIRO, CRONULLA, NSW
- GSFC = GODDARD SPACE FLIGHT CENTER, UNIVERSITY OF NEW SOUTH WALES, KENSINGTON, NSW
- UNSW = UNIVERSITY OF NEW SOUTH WALES, WEAPONS RESEARCH ESTABLISHMENT, DEPT. OF SUPPLY, SALISBURY, SOUTH AUSTRALIA
- D = DATE OF RECEIPT OF FINAL DATA
- T = DATE OF GEOS-C LAUNCH
- SAO = SMITHSONIAN ASTROPHYSICAL OBSERVATORY

*These dates deferred by 6 months due to adoption of a revised solution procedure requiring an additional iterative sequence in close collaboration with GSFC group

Figure A-4. Flow Chart Work Schedule for Proposed Sea Surface Topography Determination Off Australia

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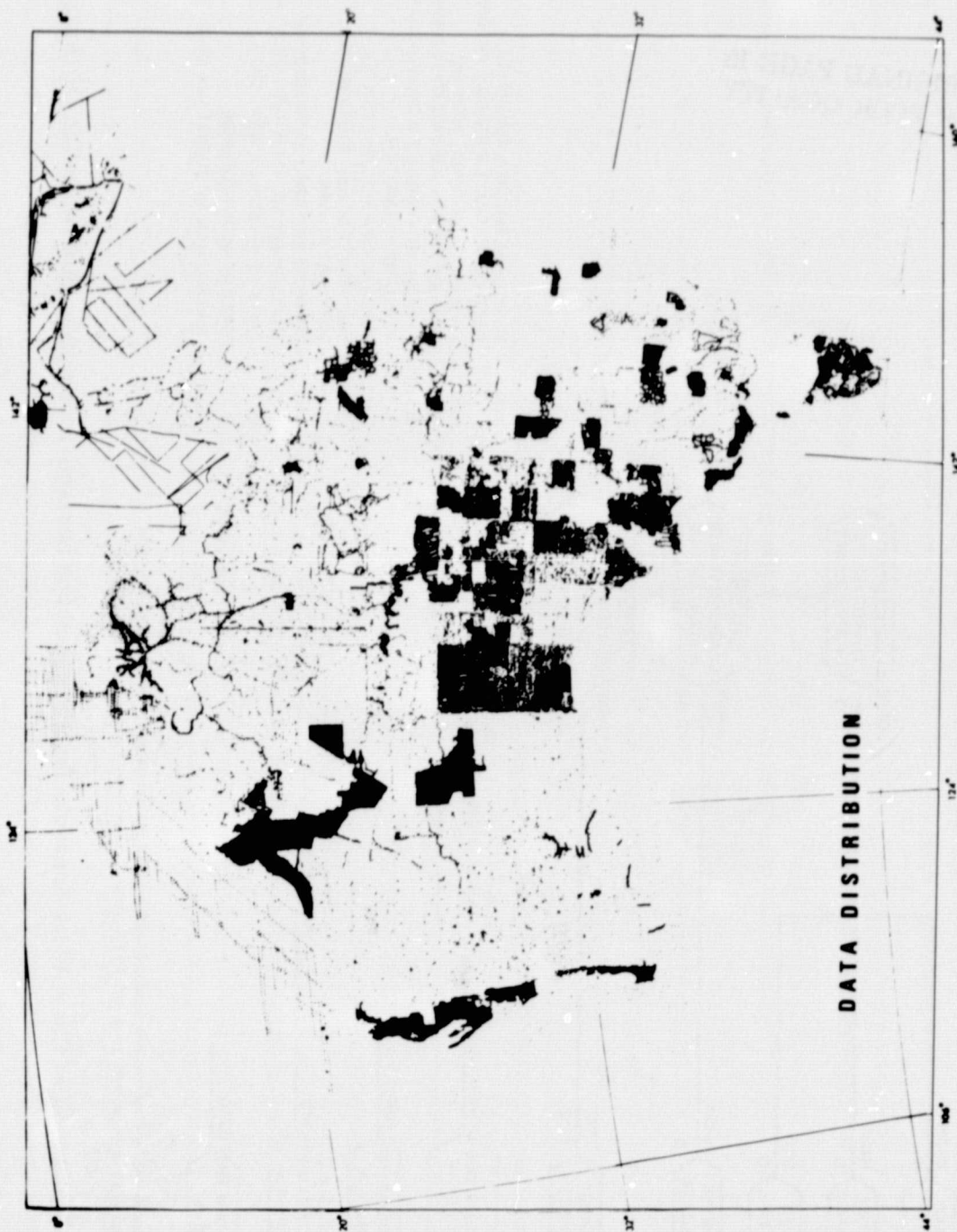


Figure A-5. Distribution of Surface Gravity Data in Australia and its Environs

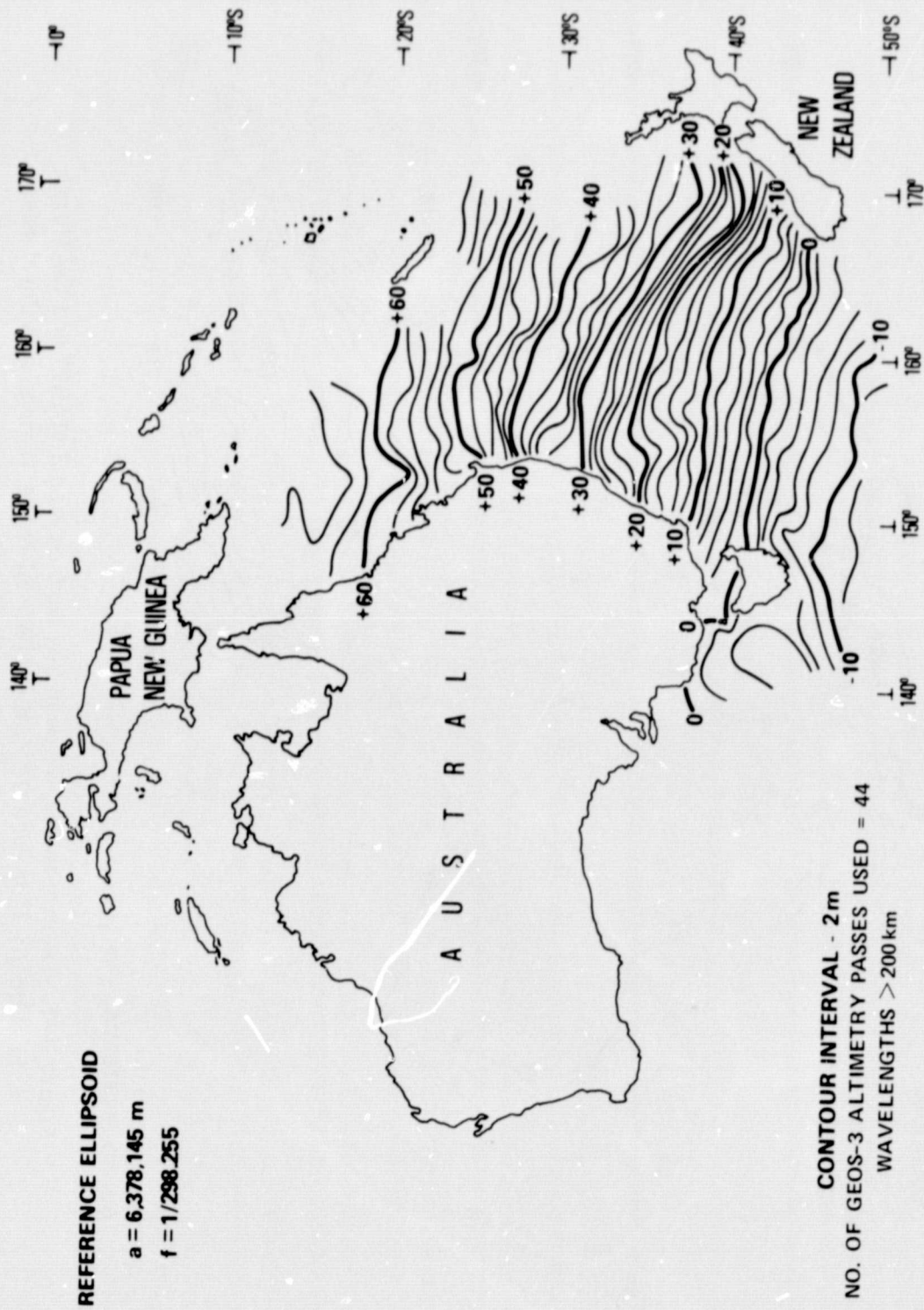


Figure A-6. Model of the Quasi-Stationary Sea Surface for the Epoch (April-September 1975) in the Coral and Tasman Seas — MAR77

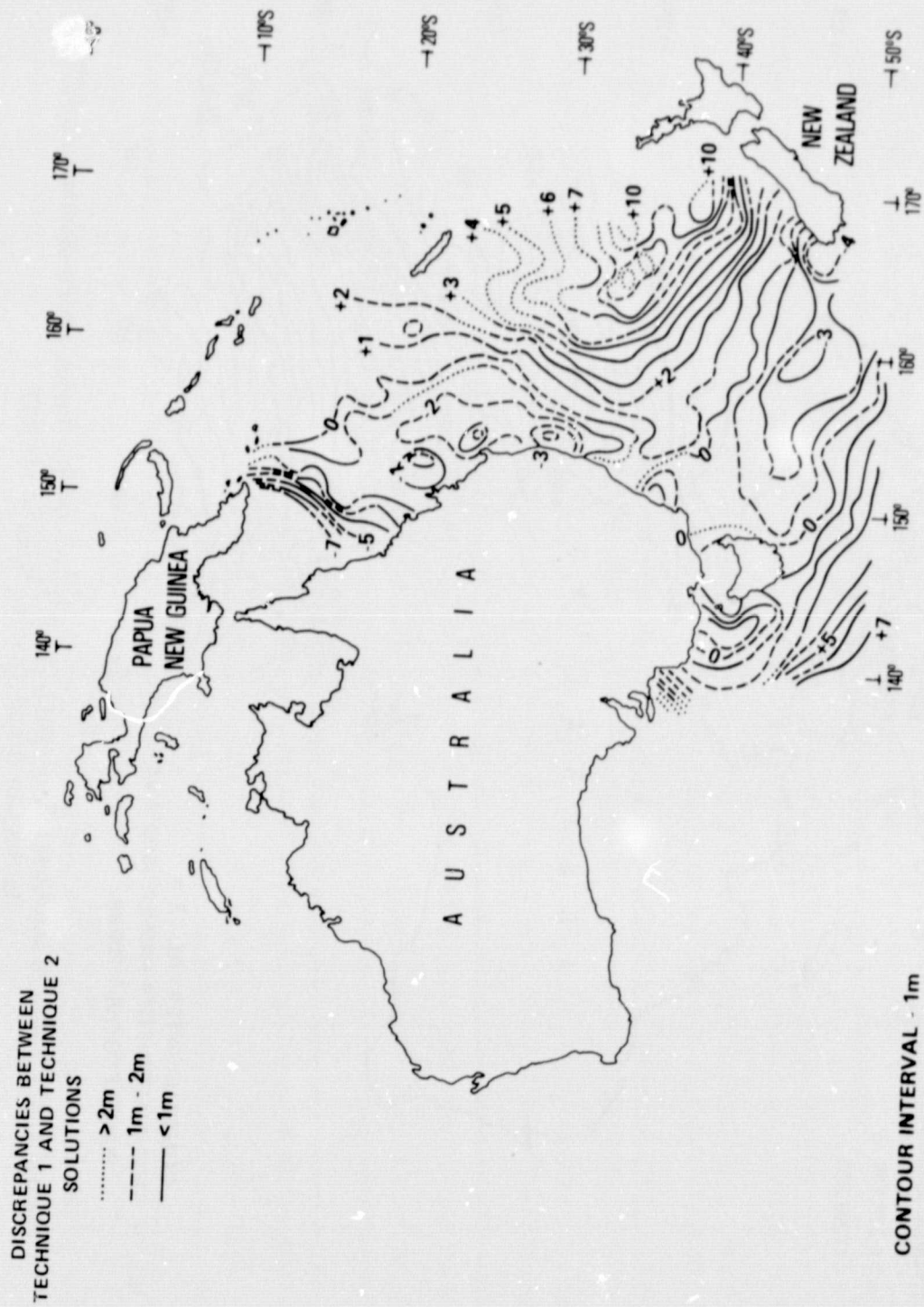


Figure A-7. Discrepancies Between Sea Surface Model MAR77 and the Marsh Gravimetrically Enhanced GEM6 Geoid Model in the Tasman and Coral Seas

FIGURE CAPTIONS

- Figure 1. Model of Quasi-Stationary Sea Surface — Tasman and Coral Seas SEP77
- Figure 2. Discrepancies Between Sea Surface Model SEP77 and Marsh GEM10 Detailed Gravimetric Geoid in Tasman and Coral Seas
- Figure 3. Discrepancies Between Sea Surface Model SEP77 (Technique 1 Solution) and the GEM9 Geoid Model (Contour Interval - 1 m)
- Figure 4. Free Air Anomalies — Australia
- Figure 5. Discrepancies Between Sea Surface Model SEP77 (Technique 2 Solution) and the GEM9 Geoid Model (Contour Interval - 1 m)
- Figure 6. Differential Plots of Overlapping Sea Surface and NASA Geoid Models Illustrating the Effect of Errors in the Gravity Field Model — Passes 67 and 97 (Tables 3 and 4: Row 13), Date of Acquisition — No. 67 on Day 185, 1975, No. 97 on Day 259, 1975
- Figure 7. Plot of Discrepancies of 3 Overlapping Passes (Pass Pairs 7, 8 in Table 3) in the Coral and Tasman Seas From GEOS-3 After Tilt and Bias Corrections
- Figure 8. Power Spectra, Expressed as % Strength of Signal(s) — Equation 7 — for 3 Overlapping Passes Plus Average Values for 14 Pass Pairs Listed in Tables 3 and 4
- Figure A-1. Heights of Local Mean Sea Levels — Western Pacific Coast (Australia)
- Figure A-2. South-to-North Pass Groundtracks of the GEOS-3 Spacecraft in the Coral Sea Test Area
- Figure A-3. Sea Surface Topography in the Orbital Plane, Northeastern Australia
- Figure A-4. Flow Chart Work Schedule for Proposed Sea Surface Topography Determination Off Australia
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FIGURE CAPTIONS (Continued)

Figure A-6. Model of the Quasi-Stationary Sea Surface for the Epoch (April-September 1975) in the Coral and Tasman Seas - MAR77

Figure A-7. Discrepancies Between Sea Surface Model MAR77 and the Marsh Gravimetrically Enhanced GEM6 Geoid Model in the Tasman and Coral Seas

BIBLIOGRAPHIC DATA SHEET

1. Report No. <i>TM 78032</i>	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle <i>The Analysis of GEOS-3 Altimeter Data in the Tasman & Coral Seas</i>		5. Report Date <i>November 1977</i>	
		6. Performing Organization Code <i>921</i>	
7. Author(s) <i>R. S. Mather</i>		8. Performing Organization Report No.	
9. Performing Organization Name and Address <i>Goddard Space Flight Center Geodynamics Branch, Code 921 Greenbelt, MD 20771</i>		10. Work Unit No.	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address <i>Goddard Space Flight Center Geodynamics Branch, Code 921 Greenbelt, MD 20771</i>		13. Type of Report and Period Covered <i>Technical Memorandum April - November 1975</i>	
		14. Sponsoring Agency Code	
15. Supplementary Notes <i>Presented at GEOS-3 Principal Investigators' Final Meeting, Fairmont Hotel, New Orleans, LA, November 18-19, 1977.</i>			
16. Abstract <i>A technique has been developed for pre-processing GEOS-3 altimetry data to establish a model of the regional sea surface. The algorithms, as presently used, develop models for a $35 \times 10^6 \text{ km}^2$ area with an internal precision of $\pm 1 \text{ m}$. This figure is substantially influenced by the data acquisition period and the sea state. There are discrepancies between the sea surface model so obtained and GEM 6-based geoid profiles with wavelengths of approximately 2500 km and amplitudes of up to 5 m in this region. The amplitudes are smaller when compared with GEM 10-based geoid determinations. However, the comparison of 14 pairs of overlapping passes in the region indicates altimeter resolution at the $\pm 25 \text{ cm}$ level if the wavelength corresponding to the Nyquist frequency were 30 km. In most cases, the spectral analysis of such comparisons indicates the existence of significant signal strength in the discrepancies after least squares fitting, with wavelengths in excess of 200 km. Regional studies of time varying features of the sea surface in the data analysis area are not currently possible due to inadequate tracking support and the limited time span over which a dense data coverage was available.</i>			
17. Key Words (Selected by Author(s)) <i>GEOS-3 Altimeter Tasman Coral Seas</i>		18. Distribution Statement	
19. Security Classif. (of this report) <i>Unclassified</i>	20. Security Classif. (of this page) <i>Unclassified</i>	21. No. of Pages <i>32</i>	22. Price*