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HIGH PRECISION TIDAL GRAVITY

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The progress made during the second year of the programme is described. The 3 gravimeter conversions and systems construction are nearly complete. A six month tidal gravity experiment at AFGL was undertaken using E.T.10. and preliminary results from this experiment are described. Calculations of Indian Ocean tidal loading at various sites around the ocean have been made and from these results, together with a visit to India and Pakistan, initial sites for the primary observation programme have been selected.		

20. Abstract (Continued)

In addition a tidal prediction software package is described which will have a wide range of applications in geodynamics measurements which require tidal corrections accurate to ± 0.5 cm or $\pm 1 \mu\text{gal}$.

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HIGH PRECISION TIDAL GRAVITY: 2nd Interim Scientific Report
April 1981 - March 1982

INTRODUCTION

This 2nd scientific report describes the recent progress of the research programme "High precision tidal gravity measurements". The details and objectives of this programme are given in the 1st scientific report* which also described the first year's progress. The year discussed here covers the later stages of Phase 1 and the start of Phase 2 of the project. Phase 1 is principally concerned with instrumental modifications and improvements to the LaCoste-Romberg gravimeters ET10, ET13 and ET15 together with the design and construction of ancilliary systems for providing continuous, reliable, high resolution, digital data. Phase 1 also involves the complete testing and calibration of the systems and their first extended tests under control conditions in the field environment. The initial stages of Phase 2 include preparations for tidal gravity measurements close to ocean tide anti-amphidromes and involves ocean load calculations and measurement site selection. The main objectives of Phase 2 are outlined in the body of this report.

As part of phase 1, E.T.10 was operated at AFGL, Bedford, Mass. with a prototype ancilliary system. A preliminary analysis of 108 days of data from this experiment has been completed

*Baker, T.F., Edge, R.J. and Jeffries, G., 1981. High precision tidal gravity: 1st interim scientific report, April 1980 - March 1981, AFGL-TR-81-0339. 26pp.

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PHASE 1

GRAVIMETER CONVERSIONS AND SYSTEM CONSTRUCTION

During the year ET10 was returned to the manufacturer, where it was given a full service, fitted with S.G. electro-levels and re-calibrated on the Texas short range gravity baseline. The instrument was then forwarded to Maryland Instrumentation where it was converted to electrostatic feedback and then commissioned by I.O.S. and Dr. J.V. Larson at AFGL during August 1981. This conversion of ET10 brought it nominally to the same standard as ET13 and ET15 which had been similarly converted during 1980. It was observed though that the data used to provide the manufacturer's absolute calibration for ET10 are highly scattered and show calibration factors dependent upon measuring screw position. There is therefore uncertainty at this stage in the absolute calibration $\sim \pm 1\%$ and the possibility of a non-linearity in the measuring screw. No such problems were observed with ET13 and ET15 following the manufacturer's calibration. This large uncertainty confirms the requirement of calibrating ET10 on the Hannover short range gravity baseline where it is hoped that these problems and apparent inconsistencies may be resolved.

Considerable effort has been put into the construction of 3 complete ancilliary systems, and their interfaces to the gravimeters, such that each gravimeter will operate continuously and provide reliable, digitally recorded, high resolution signals over a large range and with minimum maintenance. A block diagram of a single system is shown in Figs. 1 and 2. By the end of March 1982 this work was nearing completion. Following further testing and calibration ET13 and ET15 will be run together at Bidston for an extended period. This is the I.O.S.(Bidston)Experiment. ET10 arrived at Bidston in early April 1982 following deployment at AFGL. Before it may be used in conjunction with ET13 and ET15 it requires re-cabling followed by substantial testing and calibration.

THE AFGL TIDAL GRAVITY EXPERIMENT

To determine tidal gravity at AFGL, ET10 was operated at the site between August 1981 and March 1982 together with a fully tested and calibrated prototype gravimeter system and data acquisition system. Tidal data was recorded for a period in excess of six months.

(a) Gravimeter installation

The gravimeter installation was assembled over a period of 5/6 days and a further 5 days were spent ensuring that the system was optimally operated for the recording of Earth Tides. When installed the gravimeter had been levelled to better than ± 3 arc secs, made linear to better than 0.1%, and internally calibrated (measuring screw turns/Volt) to better than 0.2%. Prior to removal in March 1982 the linearity was confirmed and the uncertainty in internal calibration reduced to better than 0.1% following the procedures described in ref.1. The calibrations indicate that within the confidence limits there was no change in the internal calibration over the six month period.

(b) Instrument behaviour during the experiment

Both the gravimeter and the ancilliary electronics were found to be reliable and no major failures of instrumental origin were observed during the six month experiment. The main source of data loss from the prototype installation was through interruption of the mains power supply. In future, systems will be fully independent of mains failures. In spite of this, the data recovery during the 108 days examined so far has been $\sim 98\%$.

A major concern with ET10 is its observed instability with the outer heater cycling. At Maryland large 2-3 μ gal oscillations in the tidal output, at the cycling frequency (~ 2 mins) were observed by J.V. Larson. This meant that in order to record a tide at AFGL it was necessary to keep the outer heater on continuously. The cause of this oscillation is as yet unknown but could be due to the instrument being

highly sensitive to small direct temperature changes or to the instrument being particularly sensitive to changes in the magnetic field caused by the currents in the heater blanket. This will need to be investigated in more detail at Bidston before ET10 may be used fully in the tidal measurement programme. However, the lack of outer heater temperature control could contribute to a higher noise level, particularly in the diurnal band at some field stations. For the AFGL experiment these problems are not believed to be serious.

In addition ET10 experienced a large number of discontinuities (tares) triggered by earthquakes. Some of these exceeded 50 μ gals and are clearly instrumental. This type of behaviour has not been previously observed with ET13 and ET15. Processing data with a large number of discontinuities, particularly those which occur with earthquakes, is likely to lead to a somewhat larger uncertainty in the observed tidal constituents.

(c) Preliminary tidal results

108 days of chart data have been digitised at hourly values, filtered using a Doodson-Lennon Xo tidal filter and analysed for tides using the standard analysis procedures of HYCON. The results of the principal tidal harmonics M_2 , N_2 , S_2 , O_1 and K_1 are shown in Table 1. It is important to note that only part of the total data set obtained at AFGL has been used and that the absolute calibration has an uncertainty $\sim \pm 1\%$. The results given therefore, particularly for the observed tidal loads, must be regarded as preliminary.

(d) long term drift

Preliminary analysis of the non tidal long period signal indicates that during the first 108 days of this experiment the long term drift rate was substantially constant and was about 5.5 μ gals per day, typical of LaCoste-Romberg ET meters.

From the limited analysis performed to date, together with the calibration uncertainty of ET10 it is not yet possible to

draw any conclusions about absolute values of tidal loading at AFGL. This must await further work in the coming year. However, much experience and confidence in the new gravimeter system has been obtained, confirming the likelihood of making meaningful measurements in remote field locations during Phase 2.

TABLE 1

PRELIMINARY TIDAL RESULTS

Observed gravimetric factors (δ) and phases (κ) in degrees

M_2	δ	κ	N_2	δ	κ	S_2	δ	κ	O_1	δ	κ	K_1	δ	κ
	1.198	(-2.80°)		1.219	(-2.81°)		1.183	(-1.39°)		1.168	(+1.19°)		1.157	(+1.15°)
	+0.0023	(+0.12°)		-0.012	(-0.56°)		-0.005	(-0.23°)		-0.008	(+0.37°)		0.006	(±0.29°)

Observations:- amplitudes in μ gals and Greenwich phases (G) in degrees

M_2	N_2	S_2	O_1	K_1
48.70 (+139.80°)	9.49 (139.79°)	22.38 (+141.21°)	36.14 (+72.49°)	50.36 (+72.45°)
±0.10 (±0.12°)	±0.09 (±0.56°)	±0.09 (±0.23°)	±0.23 (±0.37°)	±0.26 (±0.29°)

Theoretical body tides assuming ($\delta = 1.160$; $\kappa = 0.00$) amplitudes in μ gals and Greenwich phases (G) in degrees

M_2	N_2	S_2	O_1	K_1
47.12	9.03	21.94	35.91	50.50
+142.60°	+142.60°	+142.60°	+71.30°	+71.30°

Observed load tide = Observed - Theoretical body tide amplitudes in μ gals and Greenwich phases (G) in degrees

M_2	N_2	S_2	O_1	K_1
2.8	0.6	0.7	0.8	1.0
85.2°	96.6°	91.2°	144.8°	169.7°

At this stage the observed load tides can only be regarded as nominal due to the large uncertainty in the absolute calibration.

NOTES FOR TABLE 1

PRELIMINARY TIDAL RESULTS

1. Manufacturer's absolute calibration correct to $\pm 1\%$ only.
2. Phases (K) have been corrected for instrumental phase lags.
Negative values of K are phase lags.
3. The corrections due to inertial forces on the observed tidal amplitudes have been applied.
4. Errors are internal 95% confidence limits.
5. Upward accelerations are positive.
6. Latitude 42.633° & longitude 71.300° West have been used to determine the gravimetric factors the theoretical body tides and the Greenwich phases (G) in degrees, (Positive G are phase lags).

PHASE 2

SITE SELECTION FOR FUTURE TIDAL GRAVITY STATIONS

Following the completion and further testing of the gravimeter systems, which includes the IOS (Bidston) experiment, and further calibrations at Hannover, the gravimeter systems will be used for the primary observation programme - the investigation of the spatial variation of ocean tide loading. In this section the main criteria that are being used for site selection are described.

Initially, it is intended to concentrate on a single ocean area. The measurements of the spatial variation of ocean tide loading will (a) allow an assessment of the accuracy of the various models of the ocean tide in the area and (b) enable calculations to be made of Earth and ocean tide loading corrections, accurate to ± 0.5 cm and ± 1 μ gal, for various measurement techniques used in Geodynamics e.g. Laser ranging, VLBI and measurements of absolute and relative gravity.

The Indian Ocean/Arabian Sea area has been selected for these initial measurements. The published ocean tide models in this area differ by typically 20-40%. This is largely due to the absence of ocean bottom tide gauge measurements which would constrain the models. From the ocean loading maps of Parke and Hendershott*, there are local maxima in the semi-diurnal ocean tide loading in the central Indian Ocean, the western Indian Ocean and the Northern Indian Ocean (Arabian Sea) and the diurnal loading is a maximum in the Arabian Sea. For testing of ocean tide models, the spatial gradient of the tidal loading is important and, in particular, measurements are required at pairs of stations so that the differential signal can be used to focus onto the adjacent ocean tide. (Baker, 1980)**

*Parke, M.E. and Hendershott, M.C., 1980. M2, S2, K1 models of the global ocean tide on an elastic Earth. Marine Geodesy 3(1-4), 379-408.

**Baker, T.F. 1980. Tidal gravity in Britain: tidal loading and the spatial distribution of the marine tide, Geophys. J.R. Astro.Soc. 62, 249-267.

For selection of suitable sites for tide gravity measurements calculations are required with a higher resolution than the loading maps produced by Parke and Hendershott. The M_2 , K_1 , and O_1 Indian Ocean tide maps of McCammon and Wunsch,* were digitized and the tidal gravity loading at possible sites was calculated using the Gutenberg-Bullen Green's functions (Farrell 1972).** The results are given in Table 2. It should be noted that the McCammon and Wunsch maps only extend to 15°S . and that the resolution is still not sufficient for accurate calculation of the tidal loading at near ($<10\text{km}$) coastal sites. Nevertheless, the calculations allow the sites to be chosen so as to give the maximum information on the ocean tide distribution. On the

TABLE 2

INDIAN OCEAN TIDAL LOADING (Calculated from McCammon and Wunsch tidal maps)

	M_2	K_1	O_1
DELHI	1.08(297 $^\circ$)	0.73(151 $^\circ$)	0.46(164 $^\circ$)
BOMBAY	4.00(324 $^\circ$)	2.95(156 $^\circ$)	1.69(162 $^\circ$)
POONA	2.77(318 $^\circ$)	2.11(155 $^\circ$)	1.23(163 $^\circ$)
HYDERABAD (IND)	1.83(296 $^\circ$)	1.15(144 $^\circ$)	0.67(160 $^\circ$)
CALCUTTA	3.00(279 $^\circ$)	0.71(111 $^\circ$)	0.32(134 $^\circ$)
KARACHI	3.66(323 $^\circ$)	2.34(159 $^\circ$)	1.51(164 $^\circ$)
QUETTA	1.23(304 $^\circ$)	0.96(158 $^\circ$)	0.61(166 $^\circ$)
PESHAWAR	0.84(296 $^\circ$)	0.64(156 $^\circ$)	0.41(166 $^\circ$)
COLUMBO	1.00(30 $^\circ$)	1.22(136 $^\circ$)	0.72(163 $^\circ$)
DIEGO GARCIA	3.40(98 $^\circ$)	0.94(165 $^\circ$)	0.90(189 $^\circ$)
SEYCHELLES	3.85(198 $^\circ$)	2.64(177 $^\circ$)	1.88(181 $^\circ$)
MOBASSA	5.23(207 $^\circ$)	1.59(178 $^\circ$)	1.03(179 $^\circ$)
NAIROBI	2.19(211 $^\circ$)	0.94(174 $^\circ$)	0.63(178 $^\circ$)

Amplitudes in μgals and Greenwich phase lags (G) in degrees
Positive phase angles are lags.

*McCammon, C. and Wunsch, C., 1977. Tidal charts of the Indian Ocean north of 15°S . J. Geophys. Res. 82, (37), 5993-5998.

**Farrell, W.E. 1972, Global calculations of tidal loading. Nature, Physical Science, 238, 43-44.

basis of the calculations presented in Table 2, in February 1982 a visit was made to various Institutes and Universities in India and Pakistan in order to select suitable gravimeter sites and to make preliminary arrangements for the first experiments. Measurements will be made at pairs of stations, the near coastal site being within a distance of 10-100 Km from the ocean and the more distant 'continental' site being at a distance greater than 500 Km from the ocean. The differential signal between the near coastal and the continental station will be used to test the ocean tide models. In addition, the measurements at the continental station, after loading corrections, will be compared with the Wahr theoretical body tide model. It is hoped that the detailed calibration work on our tidal gravimeters on the Hannover baseline will then provide independent evidence to resolve the apparent discrepancies (of order 1.5%) between present tidal gravity observations and the Wahr body tide model. (Melchior 1981, Merriam 1981, Wahr 1981)*.

TIDAL PREDICTION SOFTWARE

A computer program is under development (Baker and Schüller 1982)** which will make a prediction of the total tide for any past or future time from a set of harmonic amplitudes and phases. The program calculates the vertical and horizontal displacements (for laser ranging and VLBI) and tidal gravity and uses the full Cartwright-Tayler-Edden harmonic tidal development (505 waves). In the absence of any other inform-

*Melchior, P. 1981. An effect of the earth ellipticity and Coriolis force is visible from M_2 tidal gravity measurements in the Trans World profiles. Proceedings of the 9th. Int. Symp. on Earth Tides, New York. (to be published 1982).

*Merriam, J.B. 1981. Inertial and ellipsoidal Earth effects on gravity tide observations. Proceedings of the 9th. Int. Symp. on Earth Tides, New York (to be published 1982).

*Wahr, J.M. 1981. Body tides on an elliptical, rotating, elastic and oceanless earth. Geophys. J. R. Astro. Soc. 64(3), 677-703.

tion, the program makes a prediction of the body tide, including the long period tides and the core resonance from the Wahr model. For tidal gravity, additional information for any wave or group of waves can be incorporated by using either observed gravimetric factors and phases or amplitudes and phases from Ocean loading model calculations. As options, the body and load tide predictions and the contributions from individual wave groups can be printed out separately so that, at any given time, the various contributions to the total signal can be readily assessed.

The program will have a wide range of applications in geodynamics measurements which require tidal corrections accurate to ± 0.5 cm or ± 1 μ gal. In the context of the present report the prediction software allows the maximum utilisation of the results from the tidal gravity measurement project.

CONCLUSION

Considerable progress, both experimental and theoretical, has been made during the year. The gravimeter systems comprising gravimeters, ancilliary electronics and data acquisition systems are nearly complete and preliminary results from a prototype system installed and operated for 6 months at AFGL were obtained. Further tests on the ET13 and ET15 systems are presently being carried out prior to the start of the I.O.S.(Bidston) experiment.

Preparations are well in hand for the installation of the gravimeter systems at sites adjacent to the Indian ocean/Arabian Sea anti-amphidromes. Calculations have been carried

**Reference

Baker, T.F. and Schüller, K. Earth Tide and Ocean Load Tide Corrections in Geodynamics. Symposium on Geodesy for Global Geodynamics, General Meeting of International Association of Geodesy, Tokyo, Japan May 7-20 1982. (See appendix A for Abstract).

out to select the optimum sites of the gravimeters and site visits have been made. At the current rate of progress and following a further set of absolute calibrations at Hannover, it is expected that the first instrument will be installed in India or Pakistan during the third year of the project.

Finally, a tidal prediction package for vertical and horizontal displacements and gravity which includes loading, is being developed which will allow the data obtained from this measurement programme to be used to its full extent in geodynamic applications.

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9. Baker, T.F. and Schüller, K. Earth tide and ocean load tide corrections in geodynamics. Symposium on Geodesy for Global Geodynamics. General meeting of International Association of Geodesy, Tokyo, Japan, May 7-20 1982 - to be published (Abstract A contains abstract).

APPENDIX A

EARTH TIDE AND OCEAN LOAD TIDE CORRECTIONS IN GEODYNAMICS

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Various measurement techniques used in Geodynamics (e.g. laser ranging, Very Long Baseline Interferometry, absolute and relative gravity) are now approaching accuracies of a few centimetres and a few microgals. At this level of accuracy, it is important to carefully model the systematic perturbations due to the tidal displacements and tidal gravity changes at the observing stations. Corrections are required that are accurate to ± 0.5 cm in vertical and horizontal tidal displacements and to ± 1 microgal in tidal gravity. In order to provide corrections to this accuracy, it is convenient to work in the frequency domain so that, for each harmonic, the theoretical body tide can be combined with any available tidal loading information. A synthesis can then be made to provide a prediction of the total tide for the required times.

A software package has been developed using the full Cartwright-Tayler-Edden harmonic tidal development. The theoretical body tide, including the effects of ellipticity and core resonance, is calculated and combined with the theoretical load tide. For gravity, as an alternative, observed tidal gravimetric factors and phases can be used for those wave groups with experimental information, together with theoretical calculations for other wave groups. As examples, predictions of tidal gravity and the three components of tidal displacement have been made for a site with a large loading signal (Redruth, SW England) and for a continental site (Effelsberg Radio Telescope, Federal Republic of Germany). The agreement between the gravity predictions and observations gives an indication of the expected accuracy for the displacement predictions.

BLOCK DIAGRAM OF ELECTROSTATIC FEEDBACK GRAVIMETER AND ASSOCIATED ELECTRONICS

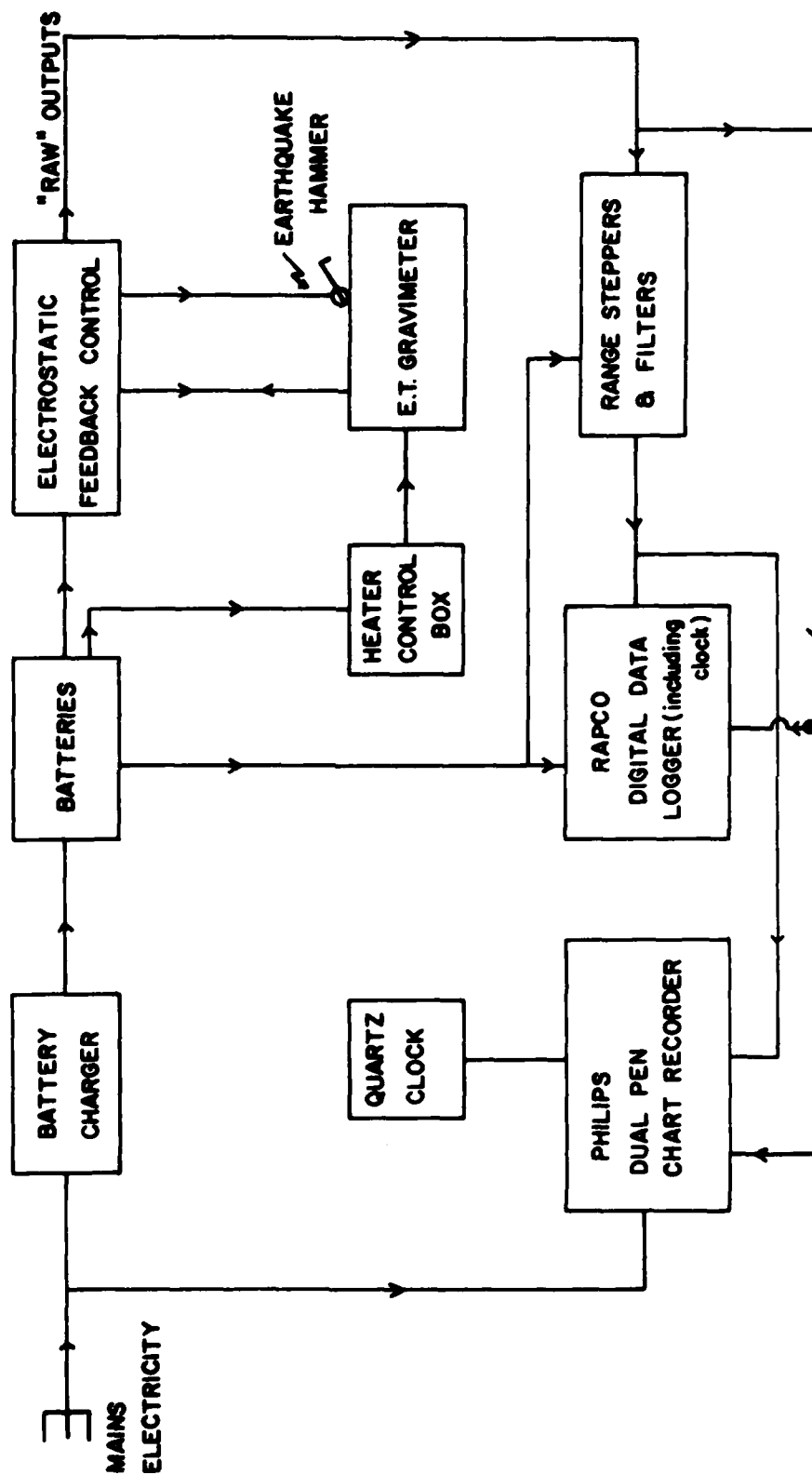


FIGURE 1

BLOCK DIAGRAM OF SIGNAL PROCESSING AND DATA ACQUISITION SYSTEM

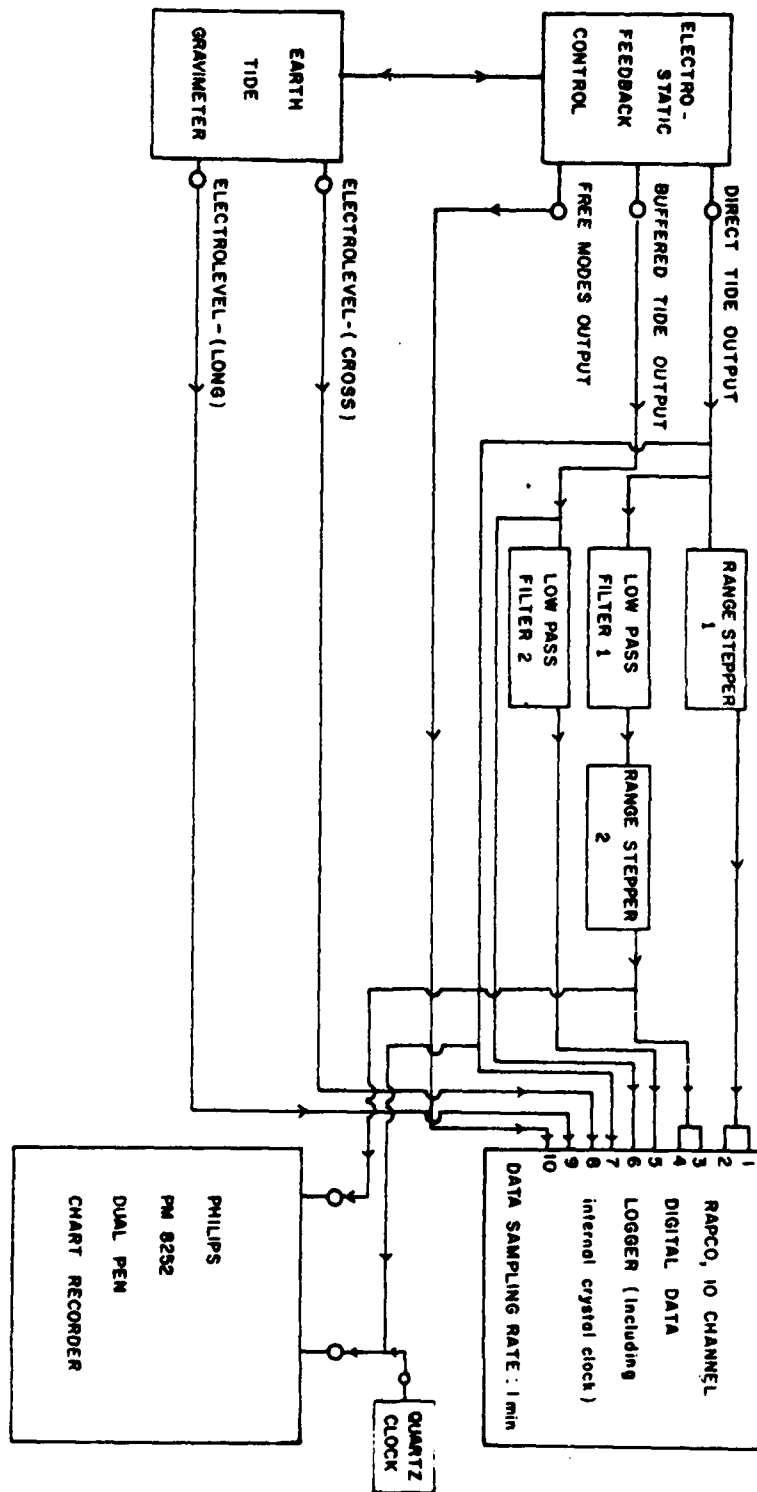


FIGURE 2