PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The N.A.S.A. Earth and Ocean Dynamics Programme

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Phil. Trans. R. Soc. Lond. A 1977 **284**, 607-619
doi: 10.1098/rsta.1977.0037

Phil. Trans. R. Soc. Lond. A. **284**, 607–619 (1977) [607]
Printed in Great Britain

The N.A.S.A. Earth and ocean dynamics programme

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The central theme of N.A.S.A.'s applications programme in general is to provide a platform for a broad effort to develop practical tools, predictive models and observational spaceborne and ground systems to further social and economic benefits to society. This programme should serve as a tool for and as a positive impetus to (*a*) realizing the equitable and efficient use and conservation of natural resources, (*b*) expanding the educational opportunities and medical services for all people, (*c*) providing new opportunities for exchange of information and lessening of international tensions, and (*d*) providing increased business and social communications between nations.

The Earth and ocean dynamics programme is part of N.A.S.A.'s overall applications programme and consists in essence of two major parts; one dealing with the solid Earth and the other with the world's oceans.

In this paper, the main emphasis will be placed upon the first, since this part fits best into the theme of this special session. Practical uses and applications of space systems, science and technology will be discussed. What are the phenomena to be observed, their state of the art and their possible future needs? For instance, the present state of tectonic motion determination is to estimate its average motion over millions of years. Our aim is to understand and determine these motions to say 0.5 cm/year over one or two years in order to help in the development of earthquake prediction models, to quote an example. Is there a correlation between the Earth's gravity and magnetic fields and what is its implication for earth resources exploration? The Bangui anomaly in central Africa is a good example. Large mineral deposits are associated with this gravity and magnetic anomaly.

1. Introduction

In recent years N.A.S.A. has made a rather strong effort to further its programmes in space applications. These programmes are concerned with the 'use' of space science and technology to forecast weather and climate, search for and manage our Earth resources, predict and monitor the dynamic conditions of the Earth and the oceans, monitor pollution on a global scale, improve communication services and process special materials under gravity free conditions.

The central theme of N.A.S.A.'s applications programme is thus to provide a platform for a very broad effort for the development of 'practical' tools – prediction models and observational spaceborne and ground systems to further the social and economic benefit of mankind.

To provide an effective future space programme in applications it has to (94th U.S. Congress 1975) (*a*) satisfy human needs, (*b*) contribute to the economy, (*c*) contribute to the advancement of knowledge, (*d*) further international participation, and (*e*) serve our national security.

The first goal of a progressive applications programme has to be that its accomplishments provide clear and immediate benefits to society. Further, such a programme should give a positive impetus to (*a*) realizing the equitable and efficient use and conservation of our national resources, (*b*) expanding the educational opportunities and medical services for all people, (*c*) providing new opportunities for exchange of information and lessening the international tensions, and (*d*) providing increased business and social communications between nations.

The purpose of this paper is to outline one specific part of N.A.S.A.'s overall applications programme, namely that dealing with the Earth and ocean dynamics (N.A.S.A. CR-1579 1970; Vonbun 1972, 1975). This programme evolved over the years starting with the launch of N.A.S.A.'s geodetic satellites, Geos-1 and -2 in 1965 and 1968, respectively. Here for the first time extremely high precision information was required for spacecraft tracking essential for exact orbit computations in order to determine the Earth's gravity field and to perform geodynamic studies. These efforts are culminated in a N.A.S.A. sponsored study which took place in Williamstown, Massachusetts, in 1969 (N.A.S.A. CR-1579, 1970). This study identified several ways in which space and astronomic techniques could contribute to advance our know-how in the fields of solid earth and ocean physics fitting the trend outlined above.

Since this paper describes mostly a programme rather than new scientific findings it is not subject to many short-time changes. Thus, portions of this paper can be found in NASA CR-1579 (1970) and Vonbun, (1972, 1975 *b*). Modifications of the programme as they occurred during the last years are, however, taken into proper consideration. It should also be noted that most of the present and described experiments were concerned with the Earth dynamics part of the programme. Most of the ocean dynamics experimental results involving Geos-3 are still in the prepublication state. This may explain to a certain extent the lack of new ocean dynamics results to date. Papers dealing with altimetry and ocean surface topography based upon data taken during the last Skylab missions have, however, been published (McGoogan 1974; McGoogan, Miller & Brown 1974; Vonbun 1975 *a*).

2. Objectives and requirements

The solid Earth and the oceans have provided a basis for man's existence and activities on this planet since the beginning of mankind. They have provided the needed condition for his life development and have further stimulated his aspirations throughout history. At the same time both have acted as its masters, plagued him with natural disasters and influenced severely his daily existence. Earthquakes, severe storms, tidal waves, floods, hurricanes, to name a few, have wreaked havoc to mankind, taking a large toll of life and property. Today, the path of severe storms can be tracked from space, together with many other weather phenomena. No question, space science and technology play already and will do so even more in the future, a major part in helping man to observe, monitor, manage and hopefully prevent in the future some of nature's disasters.

This particular programme is so designed to blend geophysics, geodynamics, and ocean dynamics with techniques developed under the space programme to actually achieve practical applications of benefit to man.

Thus, the objective of this programme is to provide a forum for a broad cooperative effort for the development of practical tools – predictive models and observational systems – whose output will ultimately be used by the operating agencies responsible for the different aspects according to their charters.

The programme objectives fall more or less naturally into two major categories, namely (*a*) Earth dynamics and (*b*) ocean dynamics.

The discipline of Earth dynamics includes the study and observation of such phenomena as tectonic plate motion, fault motion, Earth rotation and polar motion, solid Earth tides, as well as the motion of the Earth in space. It further includes the exact determination of location of tracking stations on the Earth surface, the determination and improvements of the Earth gravitational and magnetic fields and in particular the study of their anomalies. The latter ones are important for practical applications in the area of mineral and energy resources, to quote an example.

The discipline of ocean dynamics encompasses studies and observations such as currents, circulation, waves, surface wind temperature fields, sea ice, polar ice and its structure, age and dynamics. It is understandable that all these phenomena are closely related and are of great interest to the shipping and fishing industries, the coastal zones as well as for the general area of weather forecasting. The vast ocean areas covering about 70% of the globe's surface play a large role in interacting with the atmosphere, thus influencing the world's weather and climate.

Table 1. Practical uses of outer space Earth dynamics requirements

phenomena	state of the art	possible future needs
fault motion	known near the fault line (±20 km)	0.5 to ±1 cm/year accuracy near and far from the fault
tectonic motion	no real geodetic measurements, average over millions of years to ±0.5 cm/year	0.5 cm/year over 300–500 days
polar motion	±80 cm over 6–12 h N–S component, laser or corner cube spacecraft, v.l.b.i.	±2 to ±5 cm total
Earth rotation	1 ms or 50 cm	less than 0.05 to 0.1 ms or ~ 2 to 5 cm
vertical motion	insufficient data over large distances (500 km)	0.5 cm/year over few hundred kilometres regions
solid Earth tide	±10 cm amplitude, phase error large (ocean loading)	±1 cm amplitude and ~ 10° in phase, globally
gravity field	25 × 25 order and degree	1–3 mGal (2° × 2°) globally
surface geology	detected linears, Skylab, Landsat	accurate linear structure identifications
geoid	accuracy 3–5 m local 1500 km, 5–25 m global	accuracy 2–10 cm, λ = 200 km, global mean ocean < 1 cm
surveys (land) mapping	±10 m using transit and other positioning system	m range
surveys (oceans)	±10 m using transit	5–10 m
magnetic field	±20 nT scalar, global	±3 nT scalar, ±6 nT in vector components global at 300 km height

The major potential Earth oriented Earth and ocean dynamics objectives are thus to develop and validate methods and models to:

(*a*) support our continuous and ever growing needs and thus search for mineral and energy resources by studying the anomalies and possible correlation of the Earth gravity and magnetic fields, the geologic composition and structure of the Earth surface;

(*b*) study plate tectonic, fault and polar motions, solid Earth tides and Earth rotation leading together with ground observations to better predict probable time, location and intensity of major earthquakes;

(*c*) refine our knowledge of the Earth's gravitational and magnetic fields, particularly its globally distributed anomalies, to support studies mentioned under (*a*) above and to refine the Earth geoid (see surface topography) to support and further our knowledge on ocean currents, circulation, storm surges, and other surface phenomena;

(*d*) synoptic monitor the world's oceans, transient phenomena including the magnitudes and geographical distribution of sea state, surface salinity, eddies, tides, surface winds, storm surges, swells with emphasis if identifying potential hazards for the shipping and fishing industries as well as the coastal zone areas to provide needed ocean surface (air/sea interaction) information for weather and climate forecasting; and

(*e*) assess the general ocean circulations, currents and their transport of mass, heat, nutrients, polar ice, ice structure, drift and age, and open water areas important for the fishing industry, weather and climate forecasting.

Tables 1 and 2 list the phenomena, the state of the art and possible future needs in the area of earth and ocean dynamics as is possible today. Obviously, the values quoted are flexible ones and are intended to give some boundaries of what is and/or may be needed. They will be modified to a certain extent as time and our accumulated knowledge progresses.

Table 2. Practical uses of outer space ocean dynamics requirements

phenomena	state of the art	possible future needs
wave height	± 30% accuracy, limited ocean coverage	0.5 m or ± 10% global
wave directional spectrum	limited in very localized areas	direction + 5°, 10% magnitude λ = 50–1000 m
surface temperature field	± 1 to 2 °C, 5 km resolution ir radiometer, 0 to 35 °C	+ 0.3 °C globally, resolution 10 km, 2–40 °C
surface winds	speeds determined 3 to 15 m/s from microwave radiance (Nimbus)	determine speed to ± 10% and direction to ± 15°
currents, circulation	boundaries determined by temperature mapping (Skylab, Nimbus)	velocity determination to ± 1 to 3 cm/s (geostrophy)
tides	tidal model predictions: 1.5 m amplitude in open ocean, 5–15° in phase (many metres near shore)	global to 2–10 cm in amplitude and 0.3° in phase
ice, polynyas	ice areas mapped, age determined, open areas grossly mapped resolution ~ 30 km (Nimbus)	ice structure, and drifts, polar ice caps variation, cm/year, depth, age, open water with high resolution 10–20 m
surface salinity	sparse data, L-band, Skylab, 12% accuracy at 30 °C only	worldwide, 1% accuracy over larger temperature range
oceanic eddies	only sparse information available from temperature maps	scale 100–300 km 2–10 cm topography, position to ~ 10 km

3. Major goals and experiments

The major goals of the Earth and ocean dynamics programme are shown in table 3 for Earth dynamics and table 4 for ocean dynamics (Vonbun 1972).

It is obvious that for a programme of this size and complexity a rather large supplemental experimental effort has to be undertaken. Strongly empirical numerical computer models have to be developed to obtain the answers needed. These, in turn, and because of insufficient theoretical support, need a rather large number of measurements with accuracies never thought of before. Tables 5 and 6 list experiments planned, some of them are already active, for both disciplines.

Further, the nceessary theories, mathematical models and data handling problems are being developed at present to assure that these goals are available as soon as the missions are flown or the experiments performed.

Table 3. Major goals – Earth dynamics

earthquake hazard assessment and alleviation
- *utilize* space capability to provide important information for earthquake hazard assessment and alleviation (fault motion, polar motion, Earth rotation variations, tectonic motion)
- *develop* mathematical models to predict probable time, location and intensity of earthquakes

global surveying and mapping
- *utilize* space capability to extend geodetic control to remote areas and the ocean floor (0.5 m vert., 10 m horiz.)
- *provide* reference fields (gravimetric, magnetic) of the Earth for use in surveying geophysical studies, and possible assistance in search for mineral resources

Table 4. Major goals – ocean dynamics

ocean currents and circulation
- *utilize* space capability to determine sea surface topography and the separation between the sea surface and the geoid to improve models of ocean circulation and currents
- *apply* models for circulation and current to problems associated with pollution, food resources, shipping and climate

ocean surface condition monitoring
- *utilize* space capability for synoptic measurements of sea state, surface wind and its direction, storm surges...
- *apply* the above to help shipping, fishing, weather forecasting

Table 5. Experiments – Earth dynamics

earthquake hazard assessment and alleviation
- San Andreas fault experiment (SAFE) (laser; poss. v.l.b.i.)
- plate motion experiment (v.l.b.i., laser) east–west coast, U.S.–Japan, U.S.–Germany and others
- solid Earth tides (laser, ATS-G)
- Earth motion determination: polar motion; U.T. 1, motion in space (laser, v.l.b.i., radio)

global surveying and mapping
- gravity field determination (laser, satellite-to-satellite track (s.s.t.) ATS-Nimbus Geos..., gradiometer) N.G.S.P.
- geoid and gravity fine structure (altimeter, laser, radar)
- station location determination (laser, U.S.B., radar, optical, Doppler)
- magnetic field determination (magnetometer, scalar, vector)
- international geod. exp., Isagex, Epsoc, ...

Table 6. Experiments – ocean dynamics

ocean current and circulation
- ocean surface topography; geoid, trenches; slope, (altimeter, s.s.t., laser)
- general circulation (lagrang. tracers, altimeter, s.s.t.)
- open ocean tides, tsunamies (altimeter, s.s.t.)

ocean surface condition monitoring
- sea state, wave direction (altimeter, spec. mode)
- surface winds (altimeter, scatterometer)
- storm surges (altimeter, s.s.t)

4. Spacecraft and ground systems

Both spaceborne as well as ground systems are needed to accomplish, or better help to accomplish, the programme goals as listed in tables 3 and 4. It should be emphasized, however, that space science and technology alone can, of course, not provide all the answers needed to attain the necessary results. Other branches of science must help to 'build' the mathematical models, for instance, for earthquake prediction or ocean currents determination, to quote only two examples. Nevertheless, space techniques are needed to provide the necessary data to be used as input to the prediction models together with ground based and/or *in situ* measurements. At the end, only a real combined effort will succeed.

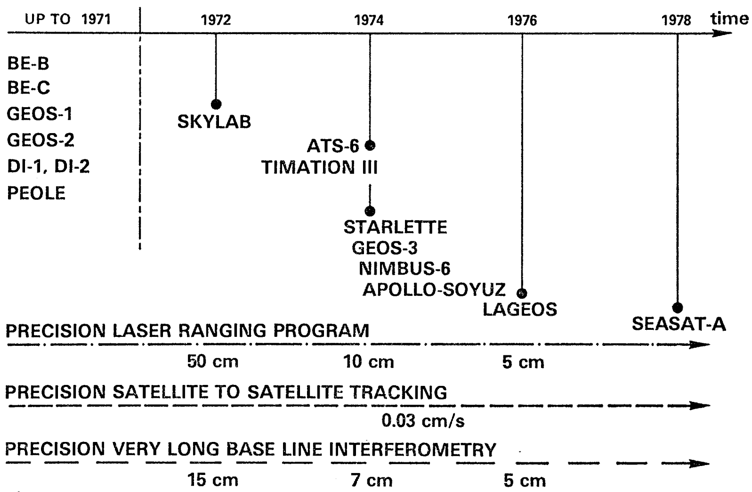

Figure 1. Spacecraft and tracking systems used (to be used) for the Earth and ocean dynamics applications programme.

CAL. YEAR	73	74	75	76	77	78	79	80	81	82
LAGEOS		S ——	——	L						
SEASAT-A			S ——	——	——	——	L			
MAGSAT				- - -	- - -	- - -	- - -			
EVAL				- - -	- - -	- - -	- - -		CONTINUED	
SEASAT-B				UNDER	CONSIDERATION					
GRAVSAT				UNDER	CONSIDERATION					
GEOPAUSE										

S, START L, LAUNCH

Figure 2. Planned flight mission schedule.

Figure 1 shows a time sequence of spacecraft in orbit or under development together with ground and spaceborne (satellite-to-satellite tracking, S.S.T.) systems and their capabilities. It is interesting to note that all spacecraft, except Skylab and ATS-6 are equipped (or will be) with laser corner cube reflectors for high precision laser tracking essential for both disciplines as will be outlined in the next chapter.

Figure 2 depicts a planned flight mission schedule in somewhat modified and thus more up to date form as presented to COSPAR in 1971 (Vonbun 1972).

Lageos (laser geodynamic satellite) is a completely passive spacecraft of high mass-to-area ratio (411 kg, 60 cm diameter) covered with about 426 laser corner cubes. This satellite, to be launched in May 1976, will be in a near polar circular orbit, about 6000 km above the Earth surface. The main objective of this spacecraft is to act for decades to come as a high precision space reference to help to solve problems in the area of Earth dynamics (geodetic control, plate and fault motion, orbit parameters, laser calibration, etc.).

Seasat-A (sea satellite)

This spacecraft is the first ocean dynamic satellite within the programme. It constitutes a major step in the progression from the initial experiments of Skylab and Geos-3 in the evaluation of an ocean dynamics measuring satellite leading towards the capability to monitor and predict ocean conditions on a global scale. The Seasat spacecraft will weigh 1000 kg with an average power of 500 W. Its orbit will be an 108° inclined circular with a height of 800 km. The spacecraft will carry a microwave altimeter (10–20 cm accuracy), a microwave imaging radar, a microwave scatterometer, an i.r. imager, a visible and i.r. radiometer, and an array of laser corner cubes for high precision laser tracking. It may also carry a satellite-to-satellite tracking transponder.

Magsat (magnetic satellite)

This is a spacecraft with a weight of 170 kg and power of approximately 175 W to be launched in 1980 into an almost circular near polar orbit with a perigee height of about 250 km. It will carry a vector magnetometer having a measuring accuracy of 3 nT and an angular accuracy of about 20″ in the determination of the direction of the magnetic field vector. The objectives are: (*a*) to contribute to the study of the structure of the Earth's crust, mantle and core, and (*b*) to obtain an accurate, up-to-date description of the Earth's main magnetic field.

Eval (Earth viewing applications laboratory)

This is a N.A.S.A. applications programme which utilizes the Shuttle Sortie mode for accomplishing remote sensing objectives necessary for the total N.A.S.A. applications programme. In general those payloads will require a major portion of the Spacelab capacity and resources. They will be designed for maximum cost effectiveness by using as much as possible common instruments and integrated facilities for multiple objectives, multiple disciplines and multiple missions. A series of Spacelab payloads will be devoted to the Earth applications programme using pallets and/or pressurized modules having a mission duration from 7 to 30 days. Payload specialists, if needed, may accompany some of the experiments in orbit.

Gravsat/Geopause

The Gravsat/Geopause combination is a system of satellites; one in low orbit (250 km) and one in high orbit (30000 km) whose main purposes are to probe the Earth's gravitational field and help improve its precise description, and to provide precise, satellite-to-satellite tracking to Seasat needed for the programme. It should, however, be mentioned that those spacecraft are only in an advanced planning state at the present time.

Figure 3 depicts major ground systems and/or experiments for the Earth and ocean dynamics programme. At present, SAFE s.s.t. and the mobile net for altimeter calibration for Geos-3 are active. The others are in the planning (almost ready) stage as of this time.

The San Andreas fault experiment (SAFE) has as its main goals to learn more about the motions along the fault line and strain build up in the earth crust, which when too large, causes earthquakes (Smith & Vonbun 1973). More specific it is intended to measure the motion between two points 100–300 km away from the fault line and separated by about 1000 km (San Diego and Quincy, California) over several years to within 0.5 cm/year.

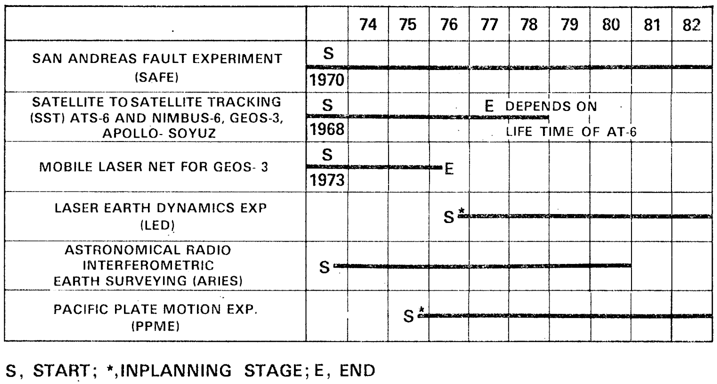

FIGURE 3. EODAP – ground systems (experiments)

Satellite-to-satellite tracking (s.s.t.)

The tracking and data relay experiment started out originally to be an experiment to track and communicate between a low orbiting spacecraft, namely, Nimbus-6 and a synchronous spacecraft, ATS-6 (Vonbun 1972). The objectives of this experiment were threefold:

(1) To test the capability of this technique for orbit determination of the low flying spacecraft. If this can be done with this new type of tracking data then the number of ground stations, particularly those overseas, can be reduced and in addition the coverage will be increased considerably. Both of these facts, of course, are of importance and of practical interest.

(2) To test the capability of relaying on-board data from the Nimbus-6 via ATS-6 back to a N.S.A. ground station. If this can be done successfully, it will solve some of our problems with both tape recorders as well as problems we had in the past with real time data transmission.

(3) To help us discover whether this satellite-to-satellite tracking technique can be used to help to improve our knowledge of the Earth's gravity fields? In the meantime, two other spacecraft have been added as low orbiting spacecraft to this experiment, namely, the Geos-3 and lately the Apollo–Soyuz. Data from the Apollo–Soyuz look very encouraging and may help us to determine short wavelength gravity anomalies of the Earth's gravity field with extreme precision (0.03 cm/s for 10 s integration). Doppler trackings were obtained from the Apollo–Soyuz/ATS-6 combination. Satellite-to-satellite tracking is not really a ground based experiment but rather one which includes a ground station and at least two spacecraft at the same time, such as ATS-6 and Nimbus-6, Geos-3 or the Apollo–Soyuz (Vonbun 1972; Schmid & Vonbun 1974). It is, however, listed here under ground systems more or less arbitrarily.

The mobile Geos-3 laser net is a system of four precision lasers at Goddard, Bermuda, Cape Kennedy and Grand Turk. Its main purpose is to determine very accurately (*ca.* 50 cm) the height of Geos-3 above the ocean surface (Vonbun 1975 *a*). Together, with an effort at Goddard to 'compute' the sea surface enclosed by these stations to the same accuracy the Geos-3 project

(Wallops) will then be able to calibrate the radar altimeter. This is the first time that an active orbiting radar system will be calibrated to a possible accuracy to be approximately in the submeter range.

Laser Earth dynamics project (LED)

This project is part of the approved Lageos project. Its purpose is to undertake highly accurate (1–2 cm) range measurements to the Lageos and other spacecraft on a global scale using U.S. and possibly foreign laser tracking stations. More specific, the LED project objectives are to develop techniques to determine a broad range of parameters of importance to geodynamic experiments with improved precision and apply them to the analyses of the Earth internal structure, the geometry and motion of tectonic plates, internal deformation, measurements for generation of earthquakes, irregularities in the Earth rotation, variations of the Earth's poles and strains induced by tidal stresses in the solid earth. The precision of the laser systems globally distributed will enable us to determine plate motions with an accuracy of 1 cm/year and pole position to say 1 cm, tidal amplitudes to 2–5 cm and variations in the Earth rotation to less than a millisecond.

Astronomical radio interferometric Earth survey (ARIES)

This proposed project (executed by the Jet Propulsion Laboratory) employs v.l.b.i. techniques to determine parameters of geophysical interest. The primary objective of this project is to demonstrate the utility of v.l.b.i. and related techniques in a system for measurement of far field tectonic plate movements and the three-dimensional motions in and adjacent to fault zones. A series of tests have been performed at Goldstone, California, showing that these kind of techniques give compatibility results with laser techniques, that is, distance determination can be made with errors in the subdecimetre range.

Pacific plate motion experiment (PPME)

PPME is a project to develop wide-band v.l.b.i. for geodynamic applications on a global scale· The objective of PPME is to measure directly the three-dimensional movement of the central part of the Pacific plate relative to the North American plate. Movement of the plate is estimated from current modes to be about 8 cm/year toward the northwest from the east Pacific rise. There have been, however, no direct measurements of this movement except from local geodetic surveys along bounding faults such as the San Andreas; in addition, it is not known how this motion varies over relatively short time of say 3 years. In the 1977–80 time frame it is expected that the equatorial baseline components by two v.l.b.i. stations can be determined to 5 cm or less and the polar baseline component to 8 cm or less. The second objective is to determine polar motion and Earth rotation variations and compare that with the results obtained from laser tracking techniques. It should be mentioned here that intercomparison is of utmost importance since the measurements accuracy required are so extreme and have never been done before. In essence, one has no way of checking the results with one system alone. A third objective is to study the modelling errors of the v.l.b.i. systems limited mostly by the atmosphere.

Other experiments contributing to the programme were performed in the past or are under way are present in ocean dynamics, particularly in the area of radar altimetry and sea surface topography (McGoogan 1974; Vonbun 1975*a*).

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5. Accomplishments

(a) *Earth dynamics*

Satellites have in the past contributed essential information for the determination of the Earth's gravity field (O'Keefe, Eckels & Squires 1959). The latest Goddard Earth models, GEM 5 and 6 were developed by using 400000 optical and electronic space tracking data from 27 spacecraft (Lerch *et al.* 1974). In addition, *ca.* 1600 ground gravity data (5° × 5° average) from the Air Force Chart Information Service in St Louis have been used in the construction of this 25° order model. The estimated accuracy of the model is about ± 8 mGal averaged over 4° × 4° segment of the Earth's surface. In the past polar motion and Earth tides have been determined by using precision laser tracking of the Beacon Explorer C (BE-C) satellite (Smith *et al.* 1972, Kolenkiewicz, Smith & Dunn 1973). Further baselines have been determined between laser stations separated about 900 km with an accuracy to the decimetre range shown in figure 4 for the San Andreas fault experiment (SAFE) (Smith & Vonbun 1973). During the last few years new tracking and sensing methods, namely, satellite-to-satellite tracking has been developed to specifically detect and determine gravity anomalies of the Earth field (Vonbun 1975 *b*). Spacecraft such as Geos-3, Nimbus-6 and, recently, the U.S./U.S.S.R. Apollo–Soyuz has been tracked via the ATS-F communications satellite. Gravity anomalies on Earth have been detected for the first time during this experiment.

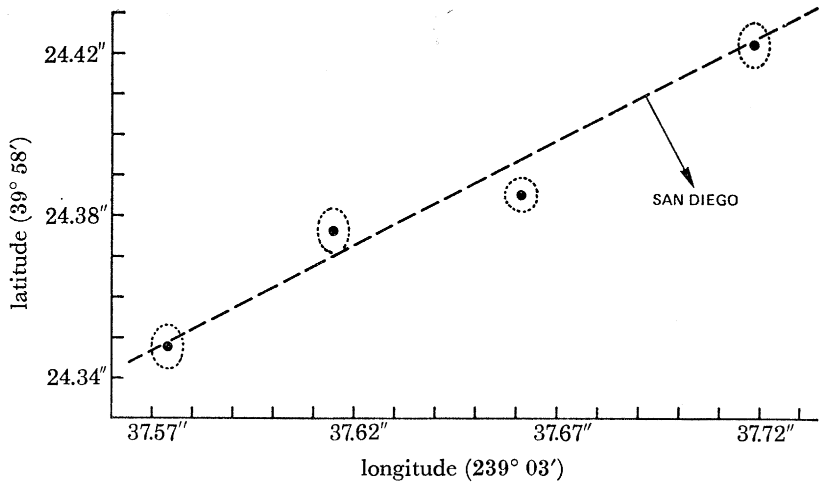

Figure 4. SAFE 1972, Quincy location – GEM 1 gravity model.

Figure 5 shows the ground tracking together with the detected anomalies, namely the Himalayan and the Indian Ocean anomaly. The Indian Ocean anomaly results in a range rate variation (between Apollo and ATS-6) in the order of 3 cm/s as shown on the left side of figure 5. This is in good agreement with the expected variation computed with the assumed value of the Indian Ocean anomaly. These 'range rate' signatures have been detected repeatedly giving us confidence that they are real. We have further in the past developed a new geoid at Goddard as shown in figure 6 together with the Skylab 4 ground track (Marsh & Vincent 1974) based upon the Lerch field. During the last Skylab mission we had our first opportunity to test to a certain extent the accuracy of this geoid (Vonbun 1975 *a*). The Skylab on-board radar altimeter was turned on over the portion of the ocean as shown in figures 6 and 7 depicts the 'measured' and 'computed' geoid based on the latest Goddard model. As can be seen, fairly good agreement was achieved during this first test of this kind ever made.

The latter investigation brings us already into the area of ocean dynamics and demonstrates clearly that Earth observation disciplines are interconnected. The study of the deviation of the real ocean surface from the geoid reveals such information as geostrophic currents, wind pile-ups, eddies, storm surges, etc. providing, of course, that the sea surface is accurately known.

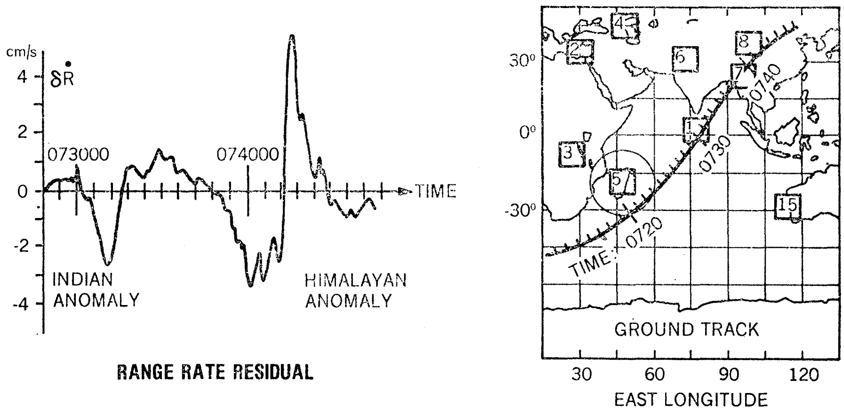

FIGURE 5. ATS-6 Apollo–Soyuz, Indian and Himalayan gravity anomalies.

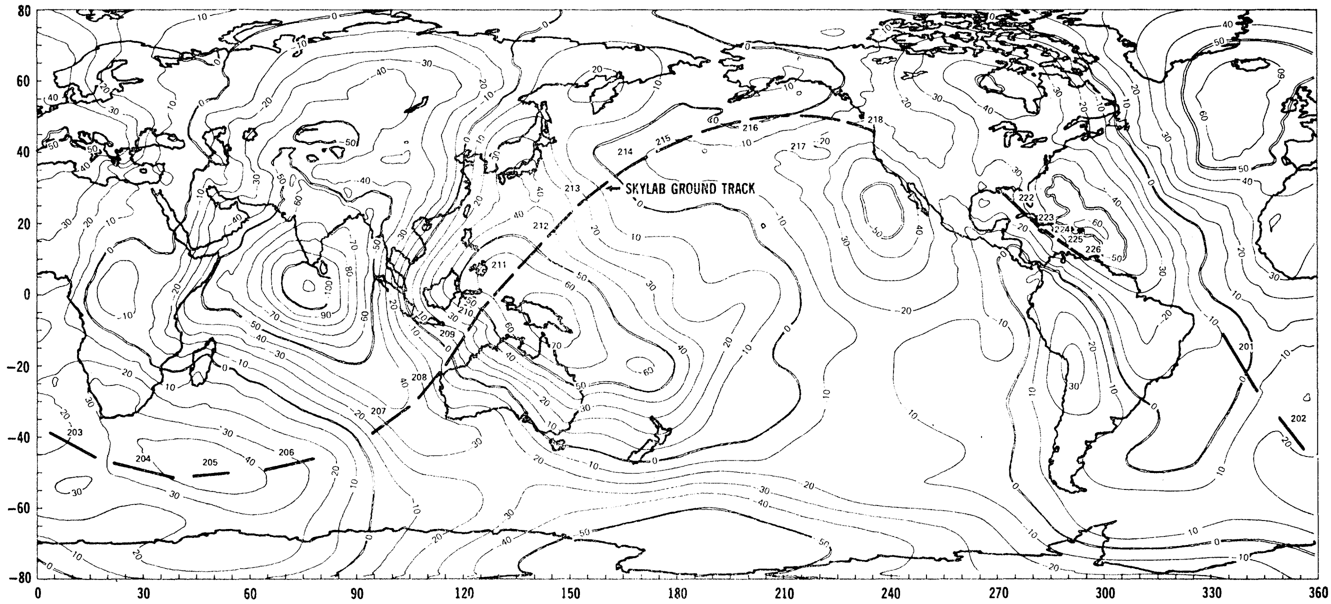

FIGURE 6. N.A.S.A. Goddard Space Flight Center, detailed gravimetric geoid. $a_E = 6378.142$ km, $G_m = 398600.9$ km^3/s^2, $1/f = 298.255$.

(*b*) *Ocean dynamics*

As mentioned already, the Skylab radar altimeter data are bridging the disciplines of Earth and ocean dynamics. These data show, among other phenomena, that detailed features of the ocean topography are detectable from space. Figure 8 depicts, for instance, the Puerto Rican Trench very clearly (McGoogan 1975; Vonbun 1975*a*). Other phenomena such as water 'grabens' and 'mountains' (10 m high, 200 km baseline) have further been detected with this

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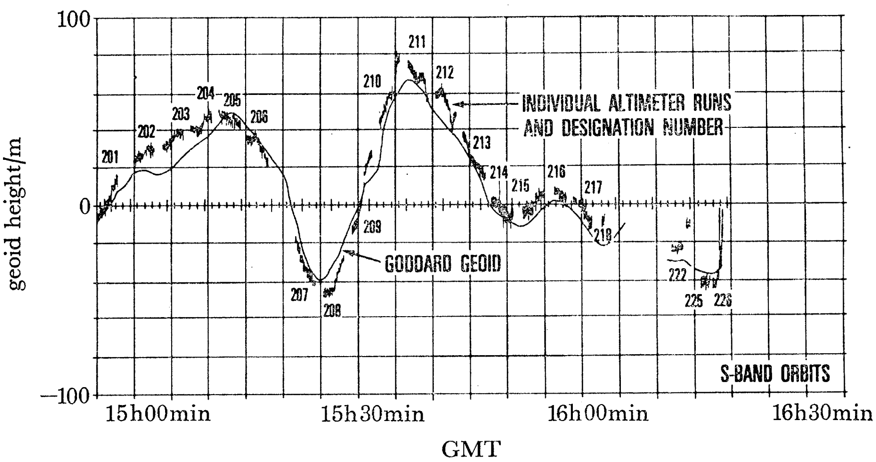

FIGURE 7. Skylab 4 altimeter geoid.

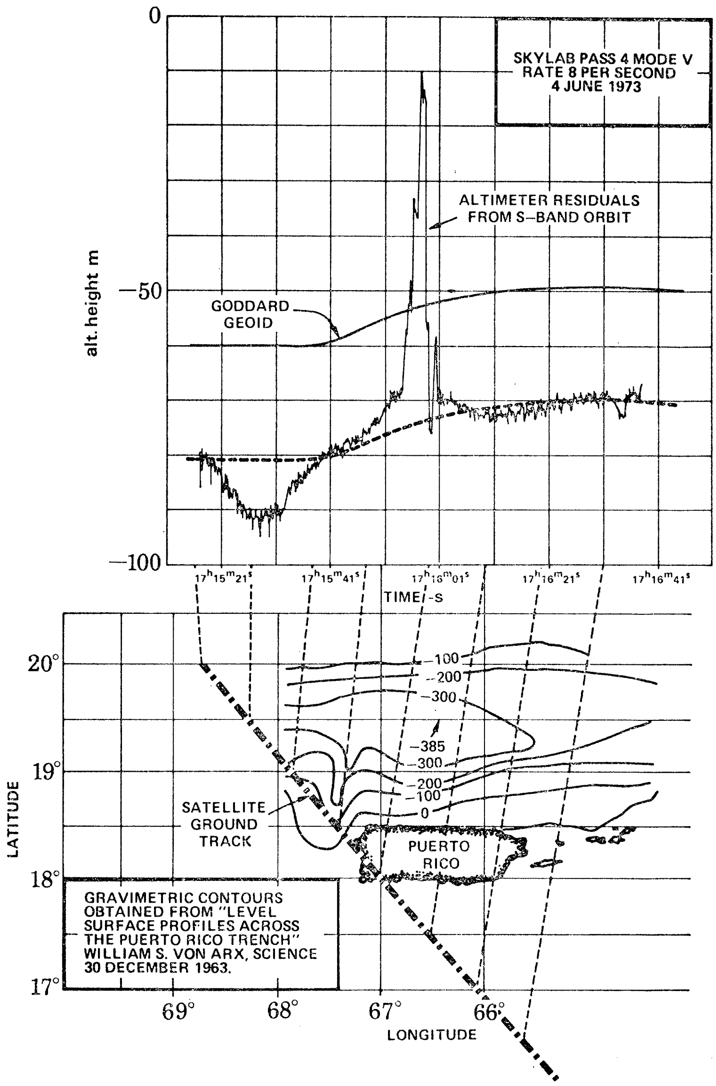

FIGURE 8. Seasurface Skylab altimeter measurements. Puerto Rican Trench, SL–2 mission.

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system clearly indicating the extreme usefulness of radar altimetry for extremely detailed topographic studies of the ocean surface. In addition, the radar altimeter was able to detect rain cells (return signal attenuated) and surface winds. Further, heights on ocean waves could be determined which manifest themselves by modifying the leading edge of the radar return pulse. To be more specific, the more the leading edge of the radar return pulse is tilted, the higher the waves (Miller & Hammond, 1972; McGoogan 1974).

Real progress is being made utilizing the altimeter flown on Geos-3 which is the first unmanned spacecraft to carry a high precision radar altimeter. Results are expected to be published by autumn 1976.

6. Conclusion

In conclusion, it can be stated that this programme has had a very successful start. Geos-3 has been orbited; the s.s.t. experiments with ATS-6 and Nimbus-6, Geos-3 and Apollo/Soyuz show promising results; the SAFE experiment is underway; Lageos was launched in May 1976; and Seasat is well under way.

Certainly new and exciting results can be expected in both the Earth and ocean dynamics disciplines.

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