clearly observable with the new long-baseline interferometry (LBI) and laser-ranging techniques. For example, the 1960 Chilean earthquake (magnitude 8.3) has been calculated (Smith, 1977) to give a change in polar motion corresponding to a 65-cm offset in the axis about which the pole moves, if the coseismic fault plane motion derived by Kanamori and Cipar (1974) is used, and a possible additional 87-cm offset due to the preseismic motion for which they have presented evidence.

Seismologists generally believe that the "seismic moment" corresponding to the coseismic motion can be derived accurately from observed long-period seismic-wave amplitudes. However, motions occurring over periods of minutes, days, or even several months before and after the quake are difficult to determine in other ways. Thus changes in polar motion over a period of several months around the time of the quake can give a check on the total fault displacement, which complements the information available from resurveys of the surface area surrounding the fault. Nearly continuous excitation of polar motion variations also may be present because of small but frequent aseismic motions on faults or meteorological excitation. Studies of the damping rate for polar motion and of where the damping occurs are important to geophysics because no other information is available on dissipation in the earth at long periods.

The new techniques of LBI, laser ranging to artificial satellites, and laser ranging to the moon appear capable of achieving about 3-cm accuracy for determining UT and polar motion with a one-day averaging time. However, it is not yet known whether real fluctuations will be observed at this accuracy level and averaging time. The first tasks undertaken with the space techniques should include the following: determining the amplitudes of short-period variations and their causes; detecting changes in pole position after large earthquakes; correlating rotation rate changes with variations in the atmospheric circulation; and studying the excitation and damping of the Chandler wobble. Since systematic errors that are different for the various techniques are likely to be among the main limitations, a mixed international network including stations using both the laser-ranging and LBI techniques seems desirable for at least the next decade, as discussed in Section 4.2.

The same stations that determine UT and polar motion will also serve as the reference points for measurements made by mobile stations of plate tectonic motions, deformations in plate interiors, and crustal movements in areas surrounding fault zones. In view of the importance of such crustal movement measurements for understanding geodynamic processes, as well as because of the inherent scientific value of improved UT and polar motion information, we believe that the United States should support the construction and operation of stations designed for making the necessary high-accuracy measurements on a daily basis.

We recommend that the United States support three long-baseline-radio-interferometry stations and approximately six laser ranging stations at fixed locations as part of a new international service for determining UT and polar motion on a continuing basis with sufficient accuracy to meet current geodynamics needs.

The reasons for recommending support for these particular numbers of stations are discussed in Section 4.2. It should be noted that most of these stations also will fulfill other important scientific or applied objectives and that a number of them are already available or will be soon.

3.3 OCEAN DYNAMICS

The geoid is considered to be the equipotential surface that would enclose the ocean waters if all external forces were removed and the waters were to become still. The surface of the real ocean departs from this geoid because of wind-driven currents, tides and tidal currents, storm surges, tsunamis, large-scale oceanic turbulence, turbulent flows in the surface-mixed layer, and various other oceanic and atmospheric phenomena. There is little direct information about these departures at the present time, yet a clearer understanding of dynamics phenomena could be attained with such information.

There are two types of geodetic observation that are currently available to physical oceanographers along this line. The first type consists of observations of the variations of time-averaged sea level from one place to another. This gives information about steady ocean currents. The second type consists of intercomparisons of time-varying sea-level measurements at fixed stations. This gives information about inherently time-dependent and therefore usually wavelike flows, as, for example, tides, storm surges, and tsunamis.

3.3.1 Mean Sea Surface

Variation of the mean sea surface with respect to the equipotential geoid has only been directly measured in association with geodetic surveys between stations. Nevertheless, it is believed that deep-sea variations of the sea surface with respect to the geoid almost certainly exist. The time-independent variations of the sea surface are due to currents that have a large mean component such as the Gulf Stream, the Antarctic circumpolar current, and the Kuroshio current. If the surface were measured accurately, the absolute magnitudes of these large ocean currents could be estimated to a higher degree of accuracy than the present-day estimates. This would enable physical oceanographers to make a much more precise census of the movement of water masses by such large currents and to estimate fluxes of various solutes in the water such as silicates and oxygen more accurately. Such measurements would also allow physical oceanographers to observe long-time variations in these currents and to compare them with measured variations in the global wind and temperature field. The studies could lead to a better understanding of the coupling between oceans and atmosphere.

Measurements of sea-level variations have almost exclusively been confined to ground stations located upon one contiguous land mass or between islands spaced closely together. The measurements have been taken both along the shore of one body of water and across land areas that connect different bodies, such as the Isthmus of Panama (Roden, 1963). For measurements along one body of water, disagreement exists between the geodetic data and predictions by physical oceanographers as to the expected variation in sea level between the same stations due to ocean currents (Sturges, 1967; Montgomery, 1969). Moreover, new considerations of the dynamics of circulation of continental shelf waters have raised several new questions about sea-level variation along and across the shelf (Stommel and Leetmaa, 1972; Csanady, 1976). It is not known whether the errors exist principally in the geodetic data, in present understanding of ocean dynamics, or in both. At present, no direct sea-level measurements have been made from the shore across the shelf and into the deep sea, and it is not known whether the deep-sea surface couples closely to coastal-sea surface. A reconciliation of the geodetic information with the proper oceanographic measurements should lead to insight into both fields.

3.3.2 Time-Varying Sea Surface

Large current systems in the ocean have been observed to exhibit variations in their strength with time. The amplitude of these changes are often of the same strength as the errors in the standard oceanographic measurements that are used to determine the mass flux and strength of these large currents so that the character of the variations is not well documented. In some cases these variations are caused by instabilities of the currents such as the breakup of the main Gulf Stream into eddies after the Gulf Stream leaves Cape Hatteras. If time-dependent sea-surface measurements could be made of the surface of the ocean over these eddies, important new information could be gained about the dynamics of these eddies. In the open ocean, away from the large time-averaged currents, other turbulence-like eddies appear to exist. The mechanism by which such background oceanic turbulence is generated is poorly understood. The statistics of the background oceanic turbulence likewise is poorly understood, and a large view of sea-surface topography over time would give valuable new information about oceanic turbulence.

The second class of time-varying variations of the sea surface that exist are associated with tides. Deep oceanic tides have now been measured in a few places by deep pressure gauges (Snodgrass and Wimbush, 1974; Snodgrass *et al.*, 1975). With the advent of the modern computer, solutions of Laplace's tidal equations in a realistic ocean have been advanced (Pekeris and Accad, 1969), but the few checks that have been done to date indicate that there is agreement in some regions of the ocean and disagreement in others. As observations progress, solid-earth tides will also be part of the signal (Hendershott, 1972). It will not be possible to advance these calculations to a status of accurately representing the world's tides until extensive deep-sea tides have been measured and careful intercomparisons between tidal prediction and field data indicate that a predictive scheme is satisfactory to a given degree of accuracy.

Other waves are also excited on the deep ocean. For example, internal waves and shorter surface waves may be excited by various atmospheric and climatological forcings that are not yet suspected. A class of waves that is well understood theoretically propagates around the edges of the oceans. These waves are generally exemplified by storm surges, tsunamis, and other shelflike waves. The large waves are of practical importance to the safety of harbors and cities and the safety of navigation as well as of importance scientifically. The bulk of the information about such waves is now derived from tidal land stations operated by the National Ocean Survey. Measurements along the full breadth of the continental shelves as well as the deep seas would give valuable new information about the structure and behavior of such waves. At present, tide gauges and shelf pressure gauges yield information about such waves. In all cases, instrumental output represents contributions from many time-dependent sources superimposed, along with various sources of noise and bias in the instrument itself. The problem of inverting signals from one or more of these instruments to get a particular piece of information is considerable.

Time variations that are observed on tide gauges in tectonically active regions may be due to vertical tectonic movements. If time-varying sea-surface characteristics are not known, we cannot extract the tectonic signal, and vice versa; hence, we must know tectonic movements to extract oceanographic effects. In such a case the pressure signal would need to be combined with a knowledge of sea-surface height and calculated pressure due to density variations in the water column.

3.3.3 New Developments

It can be expected that new data are going to augment the traditional sea-surface information in the next few years. One new source of data will be satellite altimeters, which may give indications of time-dependent sea-level variations and in association with gravimetric surveys will give information about the change in the mean sea levels from station to station. SEASAT-A is expected to measure the satellite-to-sea surface distance with 10-cm accuracy. However, long-wavelength variations in the orbit will not be known to comparable accuracy, because of gravity modeling errors and insufficient tracking. Reduction of the ocean dynamics data from the SEASAT altimeter will be a major task because the signal will record the contributions of many processes simultaneously. Since SEASAT repeats its pattern of coverage every 180 days during the first year, a close interaction of data processing with *in situ* observations and theoretical calculations appears to be vital to unscramble the contributions of various oceanic flows. The full exploitation of the data will require adjustment of the orbits, including the measured altitudes as a data type thereafter, with special weight on cross-track intercomparisons.

Some unique data-analysis constraints will arise in the SEASAT data. For example, a Gulf Stream ring will move approximately its own radius before it is sampled again, and sophisticated techniques may be necessary to track such features properly. Deconvolution of the contributions of tides to signal, of up to 1 m, will be necessary before other long-wavelength features can be identified, yet the procedure to do this is by no means trivial or clearly understood at present. Lastly, the sea-surface height arising from time-averaged flows will not be known until the gravity field, and hence the local geoid, is determined over the same area by other methods to the resolution accuracy of the altimeter. Such a task may involve extensive ship surveys, if wavelengths of less than 1000 km are needed.

Many details of the oceanic flows require resolution better than 10 cm, and an improvement of the altimeter to 1-cm resolution would increase the potential uses of this instrument. Likewise, knowledge of the position of the satellite to the same accuracy would greatly ease the data-reduction problems.

Another set of instruments that have just recently been developed and that will reach more potential in the coming years will be the deep-sea pressure gauges (Snodgrass and Wimbush, 1974), which give some indication of the overburdened water over each station. These devices have already given new information about deep-sea tides.

At present, the deep oceans are virtually unexplored geodetically. It is clear that both types of instrument will help to extend geodetic measurements to the deep oceans.

3.4 MOON AND PLANETS

The variations in the gravity field and surface elevations of the moon and planets are important indicators of their levels of tectonic activity and degree of crustal differentiation, as they are for the earth. In addition, a mean radius combined with the mass from flyby or natural-body perturbations yields the mean density, an important constraint on bulk composition, while the dynamical oblateness combined with either a precession rate due to a torque or (for a rapidly spinning body) the hydrostatic assumption gives the moment of inertia.

The NASA Planetary Exploration Program, together with the great radars at Arecibo, Goldstone, and Haystack, have led to a significant increase in our geodetic knowledge of the moon and planets in recent years.

The great variety in the inherent characteristics of the planets, the degree of detail of which has been measured and the prospects for future measurements make a planet-by-planet discussion appropriate. For a general summary, see Anderson (1975).

3.4.1 The Moon

By virtue of Doppler tracking of close lunar satellites, there exists a rather detailed gravity map of the near side of the moon, with resolution varying from 100 to 300 km. The most pronounced features of the map are gravity highs associated with ringed maria, impact-created basins filled with lava flows. Estimates of the far-side gravity field require a rather complex process of indirect inference from longer-term orbital perturbations. The accuracy of determination of the longer-wavelength variations of the gravity field further indicate that the moon is closer to hydrostatic equilibrium than is the earth, the stresses implied by the gravity field being only one third as much (Kaula, 1975).

Rather accurate elevations of about 20 percent of the moon's surface were obtained by the mapping cameras on the later Apollo missions. Lower-accuracy information about topography is inferred for other regions by radar, laser altimetry, and reconnaissance photography. Combination of this altimetry with the gravimetric map enables the extrapolation from seismometry in the Apollo landing-site area to obtain global estimates of crustal thickness. The mean crustal thickness is estimated to be about 75 km, a striking difference from that of the earth; this is a major constraint on theories of lunar origin. An appreciable offset of the center of figure from center of mass, about 2 km, is also inferred.

Laser ranging from the earth to retroreflectors at three Apollo sites enables measurement of the moon's wobble, which in turn can be used to estimate the moment of inertia. The degree of central densification of the moon indicated thereby is very slight.

A major improvement in knowledge of the moon's shape and gravity field would be obtained by a Lunar Polar Orbiter, as proposed by NASA in, but deleted from, the fiscal year 1977, 1978, and 1979 budgets. It was planned to incorporate a relay satellite in this project, in order to measure variations in the gravity field on the far side of the

Some INS are so accurate that unmodeled gravity anomalies are the limitation in their performance.

Litton has used frequent velocity updates by stopping a carrier vehicle every 3 to 4 min (Huddle, 1977). The Draper Laboratory Aerial Profiling of Terrain System (APT) has analyzed an airborne system that would use position fixes with an on-board laser tracking and ranging from three corner reflectors placed around the region to be surveyed. In each case, the velocity or position updates calibrate the inertial system (fit the parameters in the model of the instruments), as well as provide initial conditions for the navigator.

In addition, the gyros can provide a stable mount for a gravimeter or gravity gradiometers.

Status

The art is mature but still marked by change as new instruments are developed. Most recent changes have been to reduce cost and improve reliability as adequate accuracy is available for most navigation missions.

Performance

The Litton system provides 1-m accuracy for ranges up to approximately 50 km. Its performance is currently limited by a combination of accelerometer scale-factor errors and instrument noise.

Future Performance

Modest improvements could be achieved with the velocity update system with improved instruments that are still within the state of the art. The APT proposal would give 3:1 improved horizontal position. In the vertical axis, with the addition of a laser altimeter, accuracy of ±0.15 m (±0.5 ft) is predicted over a local survey area of 3 x 30 km (2 x 20 miles).

5.2 OCEAN INSTRUMENTATION

5.2.1 Direct Gravity Measurements at Sea

Principle

Gravity measurements at sea require the overcoming of two environmental problems: (1) vertical accelerations of the ship, which can be considered high-frequency noise for the gravity sensor, and (2) rotations and horizontal accelerations of the platform. The problem of the vertical acceleration (most gravity systems are designed to cope with accelerations of up to 1 to 2 m sec^{-2} in a period range of 6 to 20 sec) is handled by adequate filtering. In spring instruments (Graf Askania and LaCoste and Romberg) a part of the filtering is provided by damping of the gravimeter beam. In force rebalance (Bell) and vibrating string instruments (Bosch Arma) the filtering is provided almost entirely external to the basic sensor by using appropriate low-pass filters. The problem of rotations and horizontal accelerations is handled by employing gyro-stabilized platforms. Most platforms are utilized only with respect to the vertical (no azimuth stabilization). The gyroscopes are slaved to primary vertical references (so that gyroscope drift is inconsequential). The primary vertical references are short-period pendulums (horizontal accelerometers). In order that the primary vertical references respond to tilt but not to accelerations, a filtering network is interposed between the reference and the gyroscope, which filters out the short-period horizontal accelerations.

Since the Eötvös acceleration (the vertical component of the Coriolis acceleration) due to the east-west velocity V (km/h) at a latitude ϕ of the ship contributes an acceleration signal of approximately $4V \cos \phi$ mgal, a determination of ship velocity to 0.25 km/h is necessary in order to obtain the Eötvös correction to 1 mgal at the equator.

Status

Shipboard gravimeters and stable platforms are routinely available (Graf Askania, LaCoste and Romberg, VSA, and Bell) for normal shipboard gravity work. Adequate stable platforms are supplied by LaCoste and Romberg, Bell, and Aeroflex Company.

Cost

Approximately $150,000 for gravimeter and approximately $150,000 for stable platform.

Performance

Since gravity measuring errors due to ship accelerations are nonlinear, the performance is highly dependent on sea conditions. Under good sea conditions (accelerations less than 0.5 m sec^{-2}) measurements to an accuracy of 1 mgal can be obtained. Often the larger uncertainties arise from navigation, which leads to errors in the calculation of the Eötvös acceleration.

We recommend that developments be undertaken to improve moving platform gravimetry cost and reliability.

Additional Reference

A comprehensive review of gravimetry at sea is given by Talwani (1970).

5.2.2 Tide Gauges

Principle

Tide gauges are maintained at coastal tidal stations by the National Ocean Survey, NOAA, in the United States and by other agencies in other countries. They consist of a float or an automatically recording pressure gauge in a vertical tube or box called a stilling well, whose purpose is to dampen the effect of wind-driven waves. The gauges are routinely resurveyed into adjacent benchmarks of the U.S. National Vertical Control Network. Pressure gauges have been temporarily deployed in offshore shelf water for periods of up to a year to obtain the tides on the shelf. They are not tied to the U.S. National Vertical Control Network.

Status

Primary tidal stations are maintained over an extended period of time to provide a long series of continuous observations. There are 30 such stations on the Atlantic Coast, 8 on the Gulf Coast, 15 on the Pacific Coast, and 8 in Alaska. Measurements over shorter periods are made on the coast and shelf with pressure gauges that can vary in cost from \$500 up to \$20,000, depending on the depth, pressure expected, and duration of time that pressure is to be recorded.

Performance

Ocean surface heights are monitored to a precision of better than 1 cm in tidal stations and in the shelf waters. The shelf gauges suffer from a small drift of a centimeter over a year presumably because of gas absorption in the bellows.

Future Performance

Oceanographically ruggedized recorders will permit more and longer observations away from the primary stations. Laser ranging has made absolute leveling offshore feasible.

Additional References

Works on tidal measurements are Marmer (1951), Swanson (1974), and Beardsley *et al.* (1977).

5.2.3 Oceanic Pressure Measurements

Principle

Vibrating Crystal Transducer. The frequency of oscillation of a quartz crystal changes with pressure. Accompanying temperature sensors with sensitivities of 10^{-5} C are used to correct for temperature effects on the transducer. Pressure variations rather than absolute pressure is measured.

Bourdon Tube. A curved tube bent in an arc straightens when its internal pressure increases relative to the external pressure. The displacement is measured as the indication of pressure difference. A sealed, evacuated case makes the instrument an absolute pressure gauge.

Status

The crystal transducers have been in use since 1972. With them, fluctuations in pressure may be recorded at the bottom of the deep seas for months. Units can be constructed for \$6000 that are suitable for use in the deep sea or on the continental shelf. A Bourdon tube made of metal was first used to measure absolute pressures in the ocean in 1971. A quartz device was used in a differential configuration in the MODE experiment (Baker, 1973) and more recently in the ISOS FDRAKE experiments for durations of one year. Units can be constructed for \$45,000 that are suitable for use in the deep sea or on the continental shelf.

Performance

Sensitivities of 0.01 mbar (corresponding to approximately 0.1 mm of sea-surface height) with duration of operation up to two months are now available. There is considerable long-term drift in the instruments of 10 mm per month (1 mbar/month), and thermal and other noise appears to lead to a meaningful sensitivity of 0.1 mbar. Deep-sea tides can be observed routinely with these gauges. Sensitivities of 0.1 mbar are obtainable with Bourdon tubes as differential gauges, but drift has been a limitation in either differential or absolute operation. The 1976 ISOS instrument had a drift of less than 2 mbar/month. The quartz construction, however, is fragile for deep-sea use.

Future Performance

Drift may be reduced in either instrument with the use of new materials and geometry. Recording times up to two years should be possible.

We recommend that there be developed deep-ocean pressure gauges with drift of less than 0.5 mbar/year.

Additional References

Ocean-bottom pressure gauges are discussed by Snodgrass *et al.* (1974) and Filloux (1971).

5.2.4 Bathymetry

Principle

An array of high-frequency narrow-beam sonar devices take bathymetric soundings from stable and quiet platforms by measuring the time of propagation to the ocean floor and return. Corrections are made for changes in the speed of sound through the ocean column.

Status

Much of the high-quality work has been done on the continental shelf or slope areas. In the deep basins, such surveys are not routinely done. The best bathymetry is about an order of magnitude better in horizontal resolution and a factor of about 4 better in vertical precision than routine scientific bathymetry. Effectiveness depends on the size of the array and the sophistication of the data reducing, so the best arrays can exceed $1 million in cost.

Performance

On continental shelves, features of the order of 1 m in breadth can be resolved, and depths (floor to transducer) on the order of 10 cm can be obtained. In the deep seas, contour maps good to 2 fathoms (approximately 4 m) at 4000 m can be obtained with a beam width of 1 degree.

Future Performance

The sonar techniques have received a lot of development in the past, and developments will occur in the future with more extensive arrays and data-reducing systems. Acoustically and photographically active submersibles or towed sleds may be refined to the point of producing the best bathymetry in the future.

Additional Reference

An example of scientific application of bathymetry is the work by Maley *et al.* (1974).

5.2.5 Positioning on Deep-Ocean Floor

Principle

To position ships or submersibles, three or more deep-sea transponders are deployed 5 to 10 km apart, each transponder set to emit a pulse of given frequency when it receives an appropriate signal. A shipboard pinger periodically activates these transponders in sequence, and shipboard receivers measure the time duration between the activation pulse and the transponder response. Computer solutions of sonar paths through the water column can then be used to determine the distance from the ship transponder to the pingers and to other devices with transponders.

Status

Shipboard computers in the 1970's enabled computation of sufficient sophistication to be done to make the procedure possible. Hardware is available at approximately $10,000 per transponder and $20,000 for the shipboard pinger activator, timers, and other instruments, exclusive of computer.

Performance

Rough topography or unusual sonar propagation paths can give echo problems. Under good conditions and calm sea state relative positions to 1 m can be obtained.

Future Performance

Refinement to decimeter accuracy for specialized applications appears to be possible. Requirements for knowledge of the time-varying temperature and salinity profiles along the acoustic paths can be reduced by operating the ship near the center of the array. Then only the horizontal gradients in the sound speed across the array will cause inaccuracies in the horizontal components of position. Procedures to fix the transponders and to avoid the effect of ship motion would be required, as well as more refined calculations of acoustic propagation. One use of decimeter ship-positioning accuracy with respect to transponder arrays would be to combine it with measurements by extraterrestrial techniques of the ship's position with respect to points on land on the other side of a subduction zone or to another ship on the other side of a midocean ridge or rise. By reoccupation of positions above arrays at intervals of several years, the motions of the ocean floor could be determined.

We recommend the development of an ocean-bottom ship-positioning system with a reproducibility of 10 cm over very long time intervals and the investigation of other possible uses of high-accuracy acoustic distance measurements in oceanography.

One other possible use is for direct distance measurements between acoustic devices near the ocean floor for determining movements across transform faults or across central rifts in ridge-rise systems. Another is for determining vertical motions of transponders on the ocean floor. The accuracy achievable in such measurements with the use of subsidiary temperature and salinity measurements should be investigated.

5.3 SPACE INSTRUMENTATION

5.3.1 Radio Doppler

Principle

The change in frequency (i.e., Doppler shift) of a transmitted radio signal is proportional to the time derivative of the range of the transmitter and receiver. If the relative range is decreasing with time, then the receiver frequency will be higher and vice versa.

In practice, with satelliteborne transmitters, the usual procedure is to count a fixed number of cycles of the Doppler frequency and record the time interval required. This procedure is continuously repeated while the satellite is above the ground station's horizon.

Similar techniques are used for the tracking of one satellite by another.

Status

As discussed in Section 4.2, Doppler tracking of near-earth satellites from ground stations has been applied to geodetic purposes for nearly 20 years, using as many as 37 worldwide locations. Satellite-to-satellite tracking has been applied for about 5 years.

Performance

The Navy Navigation Satellite System (NNSS) transmits the frequency pair 150–400 MHz. The measurement errors associated with a single pass of this Doppler system has been estimated at less than 5 m (Black *et al.*, 1975). This estimate assumes (1) two-frequency ionospheric refraction correction; (2) existing (Hopfield, 1969) tropospheric refraction model; (3) 50-μsec ground clock accuracy; and (4) satellite oscillator stability ($\Delta f/f$) of 10^{-11} rms. For geodetic accuracies approaching 0.5 m, many satellite passes are required.

The NASA Goddard Space Flight Center satellite-to-satellite tracking system uses a single frequency of 2000 MHz. It is estimated to have a bias of 0.2 cm sec^{-1} and a noise of 0.04 cm sec^{-1} with 10-sec averaging (Bryan and Lynn, 1973). This system also obtains range. Several satellites have been tracked by the geosynchronous satellite ATS-6, but the only one of low enough elevation to be sensitive to regional gravity variations was Apollo-Soyuz (Vonbun, 1975).

Future Performance

The technology currently exists to make significant improvements in the present Doppler systems. By transmitting higher frequency pairs (in the gigahertz range), ionospheric refraction errors could be reduced to the centimeter level. Also, by using rubidium atomic reference oscillators, frequency stabilities ($\Delta f/f$) of 5×10^{-13} rms would be available.

For positioning, the NNSS Doppler is already scheduled to be superseded by the Global Positioning System (GPS) (see Section 5.3.3). Further development of Doppler techniques is desirable, however, to measure the gravity field by satellite-to-satellite tracking, which escapes much of the ionospheric refraction effects. The above-stated frequency stability should obtain range rates of 0.15 mm sec^{-1}, and those using 200-km altitude satellites, a resolution better than 100 km of gravity field features.

5.3.2 Satellite Laser Ranging

Principle

Short pulses from a laser are sent up from the ground station to retroreflectors on an artificial satellite or on the moon. The roundtrip travel time up to the satellite and back is measured electronically. Corrections are made for the time delay due to the atmosphere, which is roughly 7 m at sea level for a 20° elevation angle. Calibration measurements are used to correct for any time delay differences in the electronics or photodetectors between the transmitted and received pulses.

Status

Roughly 15 "second-generation" laser ranging systems have been constructed. The laser pulse length generally is a few nanoseconds, and the largest source of uncertainty usually is associated with the electronic circuitry used to pick out the center of gravity of the returned pulse. Many of these systems are mobile, so that they can be moved from site to site (Smith *et al.*, 1977, 1978). Three "third-generation" systems with pulse lengths of the order of 0.2 nsec and energies per pulse of about 200 mJ are in operation.

Performance

The "second-generation" laser ranging systems have accuracies of 5 to 10 cm (Smith *et al.*, 1977, 1978; Vonbun, 1977a). With these systems, the main present limitations for most satellites are errors in the satellite orbits due to the gravity field uncertainties, radiation pressure effects, and atmospheric drag. For determining station positions, polar