

From the very earliest days of the space era, scientists realized that artificial satellites could offer a powerful tool to researchers interested in mapping the gravity field and shape of the Earth. The science dealing with these measurements is referred to as *geodesy*. Geodesy is conveniently considered to divide into *physical geodesy* and *geometrical geodesy*. The former comprises the study of the Earth's gravitational field and its relationship to the solid structure of the planet, while the latter seeks by geometrical and astronomical measurements to determine the precise size and shape of the Earth and to locate positions accurately on the Earth's surface. In practice, of course, geometrical and physical geodesy is intimately related.

The first idea to use satellite geodesy was by the planetary scientist *J. A. O'Keefe*, in 1955, as part of the proposal to the National Space Foundation "On the Utility of an Artificial Unmanned Earth Satellite." O'Keefe had proposed an inflated satellite to be illuminated by searchlights or radar. Tracking of such a spacecraft would permit precise measurement of intercontinental distances and mapping of gravity field of Earth. A satellite can in fact be regarded as a moving target at high altitude and, with the triangulation technique, be used for positioning. Because its orbit is affected by the gravitational field of the Earth, the satellite may also serve as a sensor for gravitation. Therefore, since the

launch of *Sputnik 1*, artificial Earth satellites have been used to define the size and shape of Earth and determine its gravity and rotation parameters. Thus was born the *satellite geodesy*, geodesy based on the use of satellites. Soon were sent into orbit special spacecrafts designed exclusively for geodetic applications that, in addition to determine more precisely the dimensions of Earth, also allowed to measure the location of points on Earth's surface with great accuracy, act as reference for mapping, and for monitoring of geodynamic phenomena, such as crustal motion, Earth rotation, and polar motion.

Geodetic satellites are usually equipped with various devices that facilitate their location: transmitters of radio signals of stable frequency that are tracked through the Doppler effect, light sources that emit flashes of light of great intensity, corner reflectors or prisms of polished quartz that reflect beams of laser light sent from Earth, radar altimeters used to measure the distance between the satellite and ground surface, and also accelerometers for measuring gravity. Techniques of satellite geodesy may be classified by instrument platform: A satellite may be observed with ground-based instruments (*Earth-to-space methods*); carry an instrument or sensor as part of its payload to observe the Earth (*space-to-Earth methods*), or use its instruments to track or be tracked by another satellite (*space-to-space methods*).

2.1 The Shape and the Size of the Earth

Seen from space, the Earth looks perfectly round. *Pythagoras* and his school were the first, in the sixth century BC, to realize that the Earth was round and three hundred years later *Eratosthenes* accomplished a quite accurate calculation of the radius of the Earth with a method based on the determination of the length of an arc of meridian delimited by two places of well-known latitude. *Eratosthenes* measures, however, were rather approximate because it is not easy to determine the linear distance between two widely separated points on the Earth's surface. Indeed, its direct measurement is made impossible by natural obstacles (mountains, rivers, forests ...). It can be easily determined instead the length of a meridian arc using a special method that requires direct measurement of relatively small distances, named *bases*, and some angles. This method, on which is based the geodesy, is called *triangulation* and was applied for the first time by *Willebrordus Snellius* in 1615 for the measurement of an arc of a meridian in the Netherlands (Fig. 2.1). During that time, it was assumed that the Earth was a sphere.

This made the geodetic problem quite simple, because defining the size of the Earth was sufficient to determine the radius of the terrestrial sphere and the rest came out as a result of simple geometry. But in the seventeenth century, it became clear that the Earth was not spherical. In his *Principia*, published in 1687, *Newton* observed that, due to the daily rotation of the Earth around its North–South axis, the centrifugal forces had to produce a bulge at the equator so the Earth would look like a flattened sphere or *spheroid*. *Newton* went on his way by calculating the flattening of the Earth, defined as the ratio $f = (a - b)/a$, where a is the equatorial radius and b the polar radius. *Newton* obtained the value of $1/230$, that is to say that, according to its calculations, the equatorial radius was greater than the polar of one part in 230. From this period on, the Earth was visualized as essentially an *ellipsoid of revolution*, with its major axis in the equatorial plane and minor axis along the Earth's axis of rotation.

Subsequently, numerous attempts were made to verify experimentally the flattening expected from theory: If the Earth were a perfect sphere, a degree of latitude on the Earth's surface should correspond to an arc of constant length, whereas if the Earth is flattened at the poles, then we should expect that in the vicinity of the pole, the arc length corresponding to one degree of latitude is greater than the length of an equivalent arc at the equator. In the eighteenth century, in order to verify this hypothesis, several expeditions were organized, which resulted often lengthy and very difficult. So it is hardly surprising that confusion arose in the early days. The French astronomer *Gian Domenico Cassini* and his son even went so far as to conclude that the Earth was flattened at the equator and bulging at the poles, having obtained a negative value of flattening, equal to $-1/95$. Later estimates had largely verified the prediction of *Newton* regarding an equatorial bulge, but they showed that the flattening was not as relevant as he had thought. The methods used for the measurement of f included not only the comparison between the measurements of the lengths of the arcs, but also studies on the perturbations of lunar motion, examination of the precession of the Earth's rotation, and detailed inquiries of the changes of the gravity on the Earth's surface. By the mid-twentieth century, the equatorial radius of the reference ellipsoid had been determined as 6,378,388 m, while the flattening was put as $1/297$. The tasks of modern geodesy grew out of this historical background.

The launch of satellites, since 1957, has also provided a new and powerful tool with which to investigate the shape of the Earth. Analyzing the orbits of satellites allowed to perform the calculation of the flattening of the Earth much more accurately than was possible before and has also provided a wealth of new data on abnormalities of the spherical shape of the Earth very less noticeable than the equatorial bulge. There is no exaggeration in affirming that the satellites have revolutionized our knowledge about the shape of the Earth. If the Earth was perfectly spherical and has no lateral variations in density, any satellite would travel in an elliptical orbit of constant size



Fig. 2.1 a, b The spherical shape of the Earth is evident in photographs taken from space since the 1960s. c The method of *triangulation*: The territory is divided into adjacent triangles until covering the entire land with a network that will serve as a track to draw the map of the territory and determine the relative distances between its points. d Stamp dedicated by the former Soviet Union to the 15th General Assembly of the International Union of Geodesy and Geophysics. Geodesy is usually divided into two parts: *geometrical geodesy* and *physical geodesy*. The former relates with positioning, mapping, and surveying of the entire Earth's surface, while the latter relates to the gravity fields of the Earth and how these fields affect its shape. Geodesists also study geodynamical phenomena such as crustal motion, tides, and polar motion. When these measurements are carried out from space, they form what is known as *space geodesy*. The satellite depicted on this stamp reminds one of the many configurations of the *Cosmos* series. e This stamp, belonging to one series dedicated to the space collaboration between the Soviet Union and India, illustrates the technique of *satellite triangulation* which consists in photographing the object in orbit simultaneously from three stations: two with the

known coordinates, while the third is that of which the position is to be determined. The three photographs show the satellite in different positions against the background of stars. The triangle that forms the three images of the satellite is similar to that consisting of the three stations; knowing the distance that separates two of them, it is possible to calculate the other elements of the figure and deduce the coordinates of the unknown point. At bottom right is showed a high luminosity camera (i.e., *Baker-Nunn* type) that allows to follow a satellite and take pictures of it against the background of the stars. The star fields enable scientists to define the position of the satellite with respect to each station and then to determine their distances on Earth's surface. f Stamp dedicated to the fifth anniversary of the founding of the European Laboratory of Geodynamics of Luxembourg. *Geodynamics* is a subfield of geophysics dealing with dynamics of the Earth. Generally, it is concerned with processes that move materials throughout the Earth, in particular way with the mantle convection which leads to plate tectonics and geologic phenomena such as seafloor spreading, mountain building, volcanoes, earthquakes, and faulting

and remain in a plane immobile with respect to the fixed stars (neglecting the drag action of the air surrounding the Earth and disturbance by the Sun and Moon). But the Earth is not a perfect sphere: The main imperfection is the bulge of the equator which forms the disturbance that most affects the orbits of the satellites. This bulge is the cause of two important effects: First, the orbital plane of the satellite does not remain fixed in space but rotates constantly (precession) with respect to the terrestrial axis of a few degrees per day; in the second place, the point of perigee of the orbit moves along this in the orbital plane with a period that may vary from a few months up to several years. The flattening of the Earth can be calculated starting from measurements of both these effects. *Sputnik*, the first satellite, was tracked by British scientists who used the measurements of its orbit by comparison with previously made measurements based on land distances. The ellipticity of the Earth was confirmed and measured independently in this way. *Merson* and *King-Hele* studied since 1958 the orbits of *Sputnik 2* and so they recalculated the value of the flattening of the Earth, obtaining a value of $f = 1/(298.24 \pm 0.02)$, instead of the $1/297$ value widely accepted until the advent of the space age. Also *Buchar* in Czechoslovakia was able to make an estimate of the Earth's flattening. From the measured rate of precession of the *Sputnik 2* orbit, he obtained the value $f = 1/(297.90 \pm 0.18)$. It was thus found that the Earth was a little less flattened than it had thought before, while the flattening was calculated with much greater precision (Fig. 2.2).

The measurement of the rotation speed of perigee along the orbit leads to less accurate results for f , although not in contrast with those obtained from observation of precession of the orbital plane. The latest results on the flattening of the Earth were therefore derived from the study of the orbital precession of the satellites. Observing the angle of rotation for many orbits, say for several months, its value will reach several hundred degrees. In these cases, the flattening can be evaluated with an error percentage of about 1 in 10,000.

The currently accepted value for f , obtained from the analysis of many orbits of satellites, is now $1/298.257$. This value defines the *reference ellipsoid*.

But satellites also showed that the Earth is not a perfect ellipsoid and presents small deformations distributed somewhat anywhere on its surface. For that reason, geophysicists have introduced the concept of *geoid*. The term *geoid* is used in this context to represent the actual figure of the Earth's surface. The geoid is essentially the figure of the Earth abstracted from its topographical features. It is defined as the shape that the surface of the oceans would take under the influence of Earth's gravitation and rotation alone, in the absence of other influences such as currents, tides, winds and air pressure variations. It is also assumed that the geoid is normal to the direction of gravity, but, because the mass of the Earth is not uniform, the shape of the geoid is irregular and cannot be mathematically defined.

2.2 *Vanguard 1* Discovers the “Pear Shape” of the Earth

What should have been the first satellite in the world, if there were not a certain “*Sputnik*,” and another “*Explorer*,” the *Vanguard 1* of the US Navy, was in a sense the first geodetic satellite. Launched March 17, 1958, it was followed constantly by the stations of the Minitrack network. From the analysis of its orbit, the researchers obtained a completely new and unexpected result: The Earth's surface reduced to sea level (geoid) has the shape of a pear with the petiole at the North Pole. More precisely, at the North Pole, the surface reduced at sea level resulted 40 m higher with respect to the equator than it was the surface of the South Pole (the geoid in the vicinity of the North Pole exceeds 16 m the reference ellipsoid, while the South Pole lies 24 m below the latter). Moreover, at middle latitudes, the Southern Hemisphere has a slight bulge, while the opposite happens in the Northern Hemisphere. The mass of the Earth is therefore asymmetrically distributed with



Fig. 2.2 a Satellite geodesy began shortly after the launch of first satellites in 1957. Due to the equatorial bulge of the Earth, the orbital plane of the satellite rotates constantly (precession) about rotation axis of the Earth. From observations of this precession, the amount of flattening of our planet could be determined mathematically b *Sputnik*, the first satellite. c, e *Sputnik 2*. d The *Vanguard 1* satellite was inserted into an elliptical orbit ranging in

height from 654 to 3969 km. From a more extensive analysis of its motion, workers at the US Army Map Service obtained a value of $f = 1/(298.38 \pm 0.07)$ very close to the result obtained by a US Naval Research Laboratory group. f, g Observations of *Explorer 1* and *Sputnik 3* in 1958 allowed for an accurate determination of Earth's flattening

respect to the equatorial plane and assumes a “pear-shaped.” This means that the distance of a satellite’s perigee from the Earth’s center is less when it is located in the Northern Hemisphere than when it is located in the Southern. From the observation of this effect and from other analysis of other satellite orbits, also numerous other small distortions of the geoid have been derived, and it was seen that the geoid is actually a complex surface with numerous deformations with respect to a flattened spheroid (Fig. 2.3).

After the *Vanguard 1*, many subsequent orbital spacecraft have been tracked very

carefully, and the perturbations in their orbits have been used to calculate some of the characteristics of the geoid and for refined Earth model computations. From a detailed analysis of the orbital perturbations of five satellites (*Vanguard 2*, *Vanguard 3*, *Echo 1*, *Explorer 9*, and *Midas 4*), followed with a total of 7234 Baker-Nunn camera observations, it was then possible to derive a map of the departures of the geoid above and below the reference ellipsoid. This map, produced by W. Kaula of Goddard Space Flight Center, reports the two hemispheres of the Earth in which are traced some contour lines that

describe the geoid heights referred to an ellipsoid of $1/298.24$ flattening. The contour lines marked with positive numbers indicate elevations of the geoid in meters above the reference ellipsoid while those with negative values indicate depressions. The maximum value of 52 m above the ellipsoid is located in the North of Australia, while the minimum value is 59 m, to the west of India. In addition to providing indications about the distribution of mass within the Earth's crust, the elevations and depressions of the geoid shown in the equatorial belt strongly suggest that the Earth's equator is not a circle, but an ellipse. This is consistent with an analysis conducted by C. A. Wagner on data from the communications satellite *Syncom 2* in synchronous orbit over the Earth's equator. Wagner found a difference of 130 ± 4 m between the major and minor equatorial diameters, with one end of the major diameter at $19^\circ \pm 6^\circ$ west of Greenwich.

After this historic map, programs were developed to generate a more detailed geoid model by combining spacecraft measurements and the limited number of measurements of gravity variability over the surface of the Earth. The results led to numerous geoids. Up to now, more than 130 such models have been published, and their number is still growing. The first Earth model, the *Standard Earth of Smithsonian*

Astrophysical Observatory (SAO-SE), was published as early as 1966 and was based on more than 45,000 observations with Baker-Nunn cameras from 12 ground stations to 13 satellites. SAO-SE model consisted of a map of the Earth on which were drawn contour lines representing the differences in height in relation to a reference ellipsoid with semi-major axis = 6,370,165 m and flattening = $1/298.25$. The details of the anomalies are much greater in the Kaula's model and indicate that some areas such as the Antarctic, Turkestan, and especially the regions in South India are located below the surface of the ellipsoid of revolution (the minimum of—113 m is situated South of Ceylon) and the regions around Iceland and North of Australia are located above the ellipsoid (the maximum value of 81 m is in located in the New Guinea region). Following the publication of the SAO geoid, a long series of Earth models has been compiled also at the *NASA Goddard Space Flight Center (Goddard Earth Modes or GEM)*.

The first *GEM 1* was published in 1972, while the last model in the series based exclusively on satellites data, the *GEM 9*, appeared in 1979. In total, 840,000 observations to satellites were included (150,000 camera observations, 477,000 electronic observations, and 213,000 laser ranges).

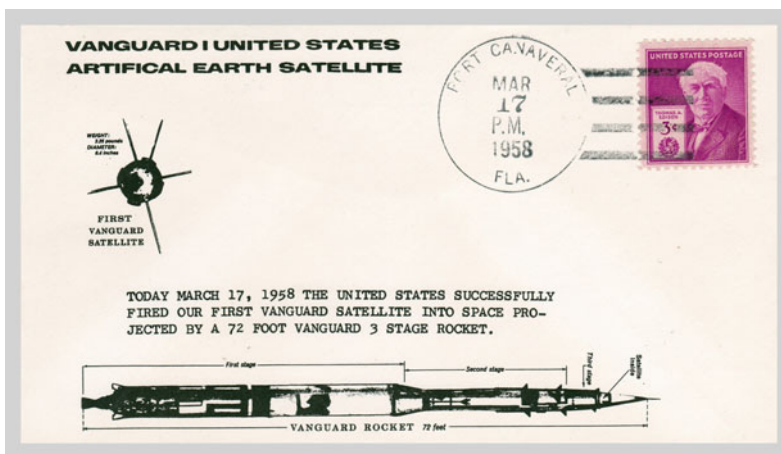


Fig. 2.3 Cover postmarked at Port Canaveral (in 1958 this was the post office nearest to Cape Canaveral) on the day of the launch of *Vanguard 1*, the second American

satellite. The envelope text provides the characteristics of tiny satellite: weight = 3.25 lb (1.47 kg), diameter = 6.4 inches (16.25 cm)

In the following years, using other satellites with different inclinations not previously used, further improvements were made and new geoid models increasingly refined were built. For example, the model *GEM 10B* published in 1981 used also the data coming from orbit observations of several Soviet *Cosmos* satellites. In this model, the sea level at the North Pole is 17.84 m above the reference ellipsoid and sea level at the South Pole is 27.23 m below the ellipsoid. So the pear-shaped tendency—the North polar radius minus the South polar radius—became 45.1 m as compared with 44.7 m used in a solution of 1974 and about 41 m in the 1969 SAO model (Fig. 2.4).

Subsequent satellite observations, combined with ongoing gravity measurements, have enabled refinement of the geoid. Satellite

altimetry, in particular, provides unprecedented details of around 2–3 cm. The *Earth Geodetic Model (EGM96)* was developed in 1996, using altimeter data from *TOPEX/Poseidon* satellite (launched in 1992). It involved computation of geoid (called undulations) to <1 m, except where gravity data were insufficient. This confirmed the broad pattern of geoid variation observed from previous analyses, indicating the lowest point, to the Southeast of India, 105 m below the reference ellipsoid, and a maximum point, in eastern Indonesia, 87 m above the ellipsoid.

Although the principal causes of variation are anomalies in lithospheric mass, these suggest simply that, at least in these regions, there must also be significant anomalies in the lower mantle (Fig. 2.5).

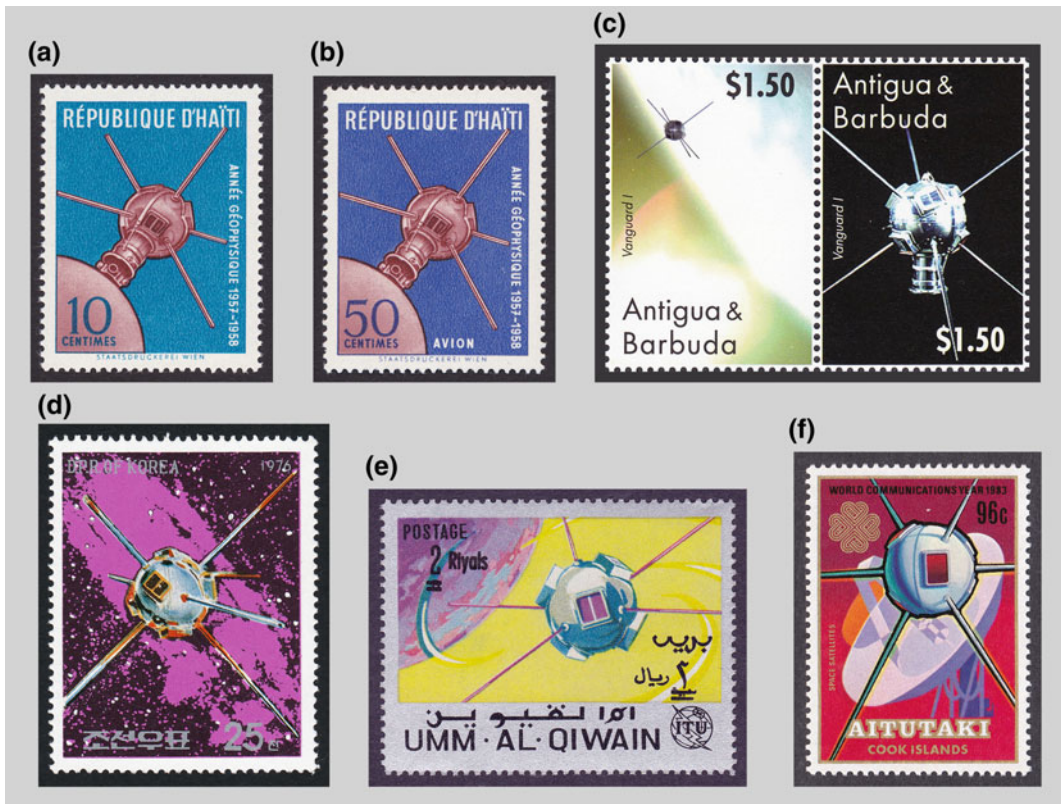


Fig. 2.4 Some of the many philatelic issues dedicated to the *Vanguard 1* satellite. The satellite radio continued to transmit until 1964, and tracking data obtained revealed that Earth is not quite a perfect sphere: It is slightly

pear-shaped, elevated at the North Pole and flattened at the South Pole. It corrected ideas about the atmosphere's density at high altitudes and improved the accuracy of world maps



Fig. 2.5 At the top is an image of *GFZ-1*, a passive geodetic microsatellite launched on April, 19 1995, with the objective to improve our knowledge of the Earth's gravity field. In the background, you see the so-called *Geoid 1995*, a representation, highly exaggerated, of the

irregular gravitational field of the Earth, become known as the "Potsdam Gravity potato." The geoid model was built on the basis of data from 37 satellites launched since 1960 and other older methods of measurement, plus surface data (airborne gravimetry and satellite altimetry)

2.3 The ANNA Program

The first satellites used for geodetic applications supported a relatively passive role since, ultimately, the main part was carried out by the ground stations and from the centers of processing and calculation. In the case of satellites tracked optically, an accuracy problem was related to the synchronization of satellite observations. Also, it was not possible to place expensive stations on all points of the Earth surface. So the Americans had the idea of launching satellites detected optically by means of simple, precise instruments. Then, it was no longer necessary to have ground complex tracking system, because some good camera and some accurate clock would have been sufficient for observations. In this way, the project *ANNA* (*Army, Navy, National Aeronautics and Space Administration*,

and *Air Force*) was born. As the name suggests, the program was a collaboration between the civilian space agency NASA and the three major American armed forces. In fact, if in the early 1960s we had maps of the Earth that could be considered accurate, their accuracy was no longer comparable with what the technique of missiles demanded. So the military were in a paradoxical situation because of possessed intercontinental missiles whose accuracy was higher than that of the maps available. It seemed then useless to increase the accuracy of the missiles, at least as long as the accuracy of the objectives was not known with more precision. The ANNA project had to meet precisely these requirements. The technique inaugurated by the ANNA project in 1962 consisted of making a satellite to emit a sequence of powerful flashes (with an electronic flash lamp) at a time determined with great precision. The photographs were thus exposed

Fig. 2.6 Imperforate souvenir sheet issued in 1964 by *Sharjah*, one of the seven *Trucial States*, and dedicated to some of the best-known American satellites of the 1960s. Are depicted in fact the meteorological satellites *Tiros 3* and *Nimbus 1*, the communication satellite *Relay 1*, the space probe *Pioneer 5*, and a geodetic ANNA satellite



simultaneously at all points of the world from which the satellite was visible. On May 10, 1962, a first launch attempt was carried out at Cape Canaveral. The *ANNA-IA* satellite, carrying on board the first of the US Army's *SECOR* (*Sequential Collation of Range*) instruments, did not achieve orbit due to a failure of the second stage of the *Thor-Able Star* carrier rocket. But on October 31, 1962, the satellite *ANNA-IB* was successfully placed in an orbit having an inclination of 51° whose period, apogee, and perigee were, respectively, 107.8 min, 1078, and 1172 km (Figs. 2.6 and 2.7).

2.4 Tracking of the “Echo” Balloons

While many researchers were concerning themselves with physical, or dynamical, geodesy, others were working on the problems of mensuration and mapping. Since the seventeenth century, by means of triangulation, the specialists could get the exact locations of the points of the Earth and construct highly detailed maps of its surface. In the course of several centuries, they also built geodetic networks that allowed the construction of very precise maps of countries

and entire continents. But if it was rather easy to connect the networks of the neighboring countries and thus establish a quite accurate system for mapping on a continental scale, however remained an unsolved problem: the connection of two networks separated by an ocean, since triangulation is necessarily stopped on the shore or on some island visible from the coast. This is the reason for which, until the middle of last century, the distance between Rome and New York was known only to within a few kilometers: It was really a situation too deficient to be able to meet the requirements of most applications. The exact determination of the distances between different points of the Earth was one of the first and most brilliant contributions of artificial satellites. An artificial satellite provides an ideal point of reference: Its height makes it visible from very distant points on the surface of the Earth. With clear skies, it can be photographed with special telescopic cameras, or with the cloudy sky, it can be tracked by radio. The only drawback is that a satellite is a moving point and this considerably complicates the calculations.

However, the position of the satellites along their orbit can be determined with extreme precision by means of the various techniques used

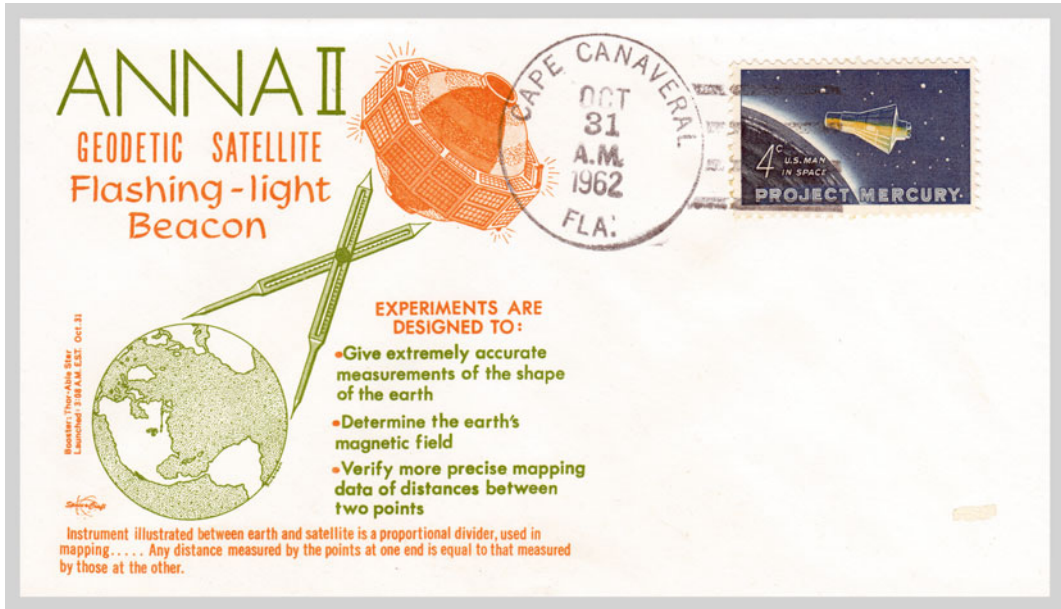


Fig. 2.7 The ANNA satellites were the first all-geodetic research satellites designed to mark positions on Earth, locate the center of Earth's mass, and measure the strength and direction of the Earth's gravitational field. *ANNA-1B* was a sphere of 91.44 cm dia and 157.50 kg weight with a collar of solar cells mounted equatorially that powered four powerful flashes. In obedience to a remote control, at a specific time, the four flashes lit up for five times in a row, with an interval of 5.6 s. The specialists could then photograph the lights that, being visible on the background of well-known stars, enabled to do triangulation calculations relatively simple. This "firefly" allowed many experiences for two years that showed that many of the

Pacific islands were badly located on the maps, with errors of several kilometers. They also revealed depressions and reliefs of a few hundred meters on the Earth's crust. Using simultaneous photographic observations of ANNA-1B taken from different stations, Air Force workers measured distances between stations separated by about 1000 km with an accuracy better than 10 m. They concluded that their geodetic stellar camera system was operationally capable of extending geodetic control to proportional accuracy of better than 1/100,000 when cameras in a network simultaneously observe a flashing satellite beacon. The independent flashing light and Doppler measurement systems agreed within 20 m or better

by ground stations. Knowing the height of a satellite at a well-defined instant and measuring the angle under which it is seen simultaneously by two points far apart on the ground, it is easy to determine the distance that separates the two points, whatever the natural obstacles placed in the way between them: oceans, mountains, and, of course, the same sphericity of the Earth. To be easily photographed from the ground, the satellite must be illuminated by sunlight, by laser pulses or by some internal flash devices, while the observation station must be located in darkness on the night side of Earth (Fig. 2.1c).

And therefore, why not use a satellite visible to the naked eye for the entire duration of its path in the night sky, such as the giant spheres of the two communications satellites *Echo 1* and *Echo 2*, which reflected sunlight very effectively (Figs. 2.8 and 2.9) ?

This is what the French scientists did in May 1964 using the first of the two balloons, then four years old, a little worn but still visible. Observing *Echo 1* satellite, which had a diameter of 30-m satellite, French geodesists undertook a program that would enable to connect the network of triangulation of France with that of North Africa.

Fig. 2.8 a, b The two *Echo* satellites, launched in 1960 and 1964, were so bright that it was possible for anybody to watch them visually with the naked eye and to follow their motion across the stars. In the early 1960s, several million people watched and acquired a personal physical feeling for the existence of satellites and became aware that we were entering the Space Age. The visual observations were not just curiosities; networks of amateurs observed with some optical instruments and provided directions, elevation and azimuth of satellites to the appropriate centers: The result was the first models of the Earth’s gravity field and of the upper atmosphere density

(a)



(b)



The space group of the *IGN* (*National Geographic Institute*) and *CNES* brought to a successful conclusion, for a fortnight, several series of measures which proved essential for the French and European space programs. Indeed, the creation of a series of effective stations for tracking and telemetry requires a precise knowledge of the location of these stations.

Even the Soviets had used *Echo 1* from May 1961 to establish the position of a ground station in Kharkov, using as points of reference the Pulkovo, Tashkent, and Nikolayev stations. And this was done to within 70 m. A new campaign of observations was carried out between May and June 1963, using stations positioned in Uzgorod (central Russia) and Kabarosk (Far East) and several

other neighboring countries (Poland, Romania, Czechoslovakia, and East Germany), bringing the extension of the network to more than 10,000 km away. The measures gave results comparable to those obtained by radio geodetic methods.

2.5 Laser Satellite Ranging: Beacon Explorer and GEOS

The year 1964 saw a greater awareness in space technicians on the contribution they could give to the knowledge of the shape and the size of Earth. At a meeting on space geodesy, held in Paris in September, NASA pointed out its programs and introduced two new types of geodetic satellites



Fig. 2.9 Initially, passive large balloon satellites were used as targets such as the first experimental telecommunication satellites *Echo 1* (a–d) and *Echo 2* (e–h) or

PAGEOS (*P*Assive *G*EOdetic *S*atellite), the first dedicated satellite geodetic balloon

that were to be launched in the immediate future: the *Beacon Explorer* (*BE*) and *GEOS*, both pertaining to the *Explorer* series.

The main purpose of *Beacon Explorer* satellites was to obtain worldwide observations of total electron content of the ionosphere in a vertical cross section between the spacecraft and the Earth under quiet and disturbed conditions and study its diurnal and seasonal variations. Another objective was to test the recently

devised laser tracking system. In particular, the mission of the last *BE* was also to study the perturbations in the satellite orbit by means of radio Doppler tracking techniques in order to refine knowledge of the Earth's gravitational field (Fig. 2.10).

Between 1964 and 1965, two *Beacon Explorer* were launched: *Explorer 22* and *27*, while a third satellite failed to reach the orbit on March 18. The equipment mounted on these new

Fig. 2.10 *Explorer 22* was the second of three identical satellites of the *Beacon Explorer (BE)* series. *BE-A*, launched March 18, 1964, had failed, while the *BE-C* or *Explorer 27* was launched on April 29, 1965



satellites would allow the use of different positioning and tracking methods: *optical tracking*, *Doppler techniques*, and, mainly, *laser ranging*.

Doppler positioning involves recording the Doppler shift of a radio signal of stable frequency emitted from a satellite as it approaches and recedes from the observer.

The observed frequency depends on the radial velocity of the satellite relative to the observer, which is constrained by orbital mechanics. If the observer knows the orbit of the satellite, then recording the Doppler profile determines the observer's position. Conversely, if the observer's position is precisely known, then the orbit of the satellite can be determined and used to study the Earth's gravity. Consequently, in addition to being provided with three basic transmitting systems (ionospheric beacons at 20.005, 40.010, 41.010, and 360.090 MHz; Doppler beacons at 161.987 and 323.974 MHz; and a telemetry and tracking transmitter at 136.740 MHz), the *BE* satellites carried also a mosaic of corner reflectors mounted on the top of spacecraft to reflect laser beams transmitted by ground stations (Fig. 2.11).

Corner reflectors, as the name suggests, are reflectors or mirrors that reflect radiation back in the original direction from where it came. Satellites carrying corner reflectors make use of *laser ranging* for geometrical geodesy applications (*Satellite Laser Ranging, SLR*). In *SLR*, a

global network of observation stations measures the round-trip time of flight of ultrashort pulses of light sent to satellites. In this case, the geographical position of the ground stations is not determined by the photograph but by the measure of the elapsed time between the emission of the laser beam and the return of the reflected signal. This provides instantaneous range measurements of millimeter level precision which can be accumulated to provide accurate orbit parameters, gravity field parameters (from the orbit perturbations), Earth rotation parameters, tidal Earth's deformations, coordinates and velocities of *SLR* stations, and other substantial geodetic data.

The *GEOS* (*Geodetic Earth Orbiting Satellite*) satellites were the first of the NASA Explorer series designed exclusively for geodetic studies. Between 1965 and 1968, there were launched two satellites: *GEOS 1* and *2* (*Explorer 29* and *36*, respectively) (Fig. 2.12).

The two *GEOS*, weighing 176 and 210 kg, were far more equipped with geodetic measuring systems than the *Beacon Explorers* that weighed only 54 kg. They carried five types of systems: a flashing light beacon, similar to that used by *ANNA*, which can be photographed against the background stars; cube-corner quartz reflectors similar to those on *Beacon Explorers*; a *SECOR* range transponder to fix the satellite's position relative to that of the interrogating ground



Fig. 2.11 *Explorer 27* or *BE-C*. A laser reflector consisting of 160 quartz corner reflectors was mounted on the top of each *BE* spacecraft so that the north-seeking end of the satellite magnet would be oriented toward Earth as the spacecraft passed over the Northern Hemisphere. Telemetered responses of the laser detector in the orbiting satellites provided the desired confirmation that laser

reflections observed on Earth were indeed from the spacecraft. The 41° inclination of the *BE-C* satellite's orbit was selected to increase geodesy coverage. Since previous satellites had provided Doppler data from orbital inclinations of 32° , 50° , 67° , 80° , and 90° , the placement of *BE-C* midway in the gap between 32° and 50° was highly desirable

stations; a radio Doppler system; and a radio range/rate system to determine the range and radial velocity of the satellite. The *GEOS 2* carried also a C-band radar transponder.

A third *GEOS* satellite, much more complex, was launched in 1975 out of the *Explorer* series and was named *GEOS 3* (*Geodynamics Experimental Ocean Satellite 3*).

2.6 French Geodetic Satellites

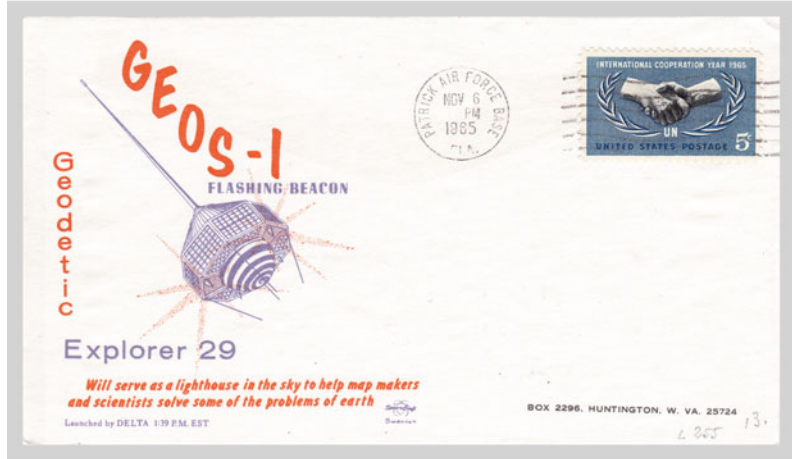
After the USA, France, too, has brought a great contribution to satellite geodesy, first with *D1-A* or *Diapason*, controlled by the Doppler effect, and then with the *D1-C*, *D1-D*, and *Peole* satellites equipped with laser reflectors. *D1-A* is the name given to second French artificial satellite. It

was launched in February 17, 1966, by a *Diamant-A* rocket from Hammaguir in Algeria. The satellite, developed by CNES, had a scientific mission of geodesy, by measuring the Doppler effect on radio transmissions at very stable frequency. With a mass of 18.5 kg, it carried on a low orbit a scientific payload consisting of two radio transmitters; it is the stable frequency emissions of these transmitters that have given the name *Diapason* to the satellite (Fig. 2.13).

Ground stations measured the Doppler effect of these emissions to deduce their positions. To carry out the mission, two stations have been set up in Nice and Beirut. *Diapason* has made interesting measures including the ability to determine the Nice–Beirut distance with an uncertainty of only 60 m. A second identical satellite was built to be used in case of failure of

Fig. 2.12 a, b The two satellites *GEOS 1* and 2 have provided a means to determine point positions on Earth to an accuracy of 10 m. They also determined structure of the Earth gravity field to 5 parts in 10^8 and precisely defined the position of some isolated islands. Finally, they provided a means for the measurement of the geometry of geodetic triangulation networks. One feature of the *GEOS Explorer* is an 18-m boom which provides gravity-gradient attitude stabilization, so that the optical beacons and radio antennas point eastward at all times

(a)



(b)



Fig. 2.13 France celebrated its second satellite, *D 1*, the day after the launch, as evidenced by this *First-Day Cover* (FDC) canceled on February 18, 1966





Fig. 2.14 a, b The satellite *D1-A Diapason*. c–g The satellite *D1-C*, or *Diademe 1*

the first launch but, given the success of *D1*, it has never been used. The *Diapason* satellite was followed by *Diadème 1* and 2, two operational geodetic satellites (Figs. 2.14 and 2.15).

Diadème 1 D1-C and *Diadème 2 D1-D* were launched one week apart in February 1967 into elliptical orbits. *Diademe* had the following instrumentation onboard: a dual frequency

Doppler transmitter and a retroreflector array (RRA) consisting of 2 flattened truncated cones with a total of 144 cube corners that provided a target for laser tracking measurements from the ground.

Subsequently, France has then also participated with a satellite to the *ISAGEX* program (International Satellite Geodesy Experiment). The

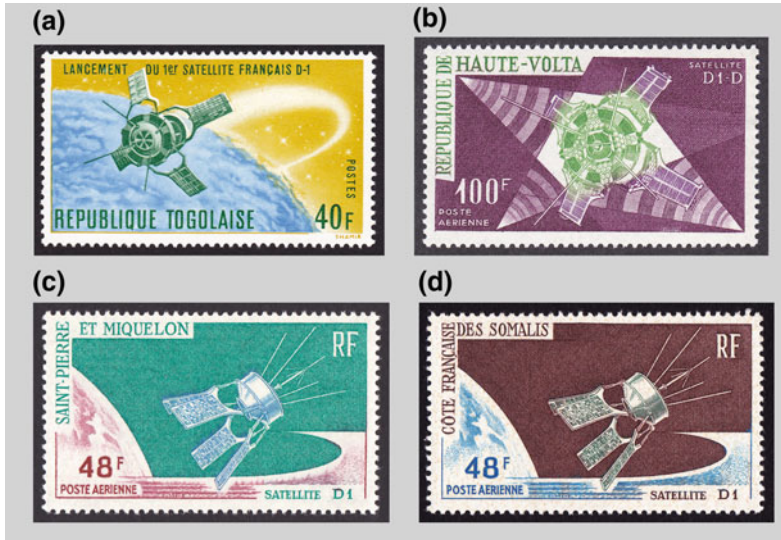


Fig. 2.15 a–b Two images of French satellite *D1- A* or *Diapason*. b The satellite *Diadème 2 (D1- D)*. c–d After France, in the following months, also the French overseas territories (the Comoros, French Polynesia, French

Southern and Antarctic Territories, Saint Pierre and Miquelon, Wallis and Futuna, French Somali Coast issued the same stamp with different colors and values



Fig. 2.16 The laser reflectors of *Peole* satellite made contributions in the international program *ISAGEX (International Satellite Geodesy Experiment)* whose objective

was to test the capabilities of the laser reflection for the definition of the trajectory of the satellites and géodynamique

objective of the program was to collect a set of homogenous and well-distributed precise laser and camera satellite observations for the purpose of dynamic and geometric geodesy. The ISAGEX experiment involved seventeen countries and over

fifty tracking stations. On 12 December, 1970, France launched the satellite *Peole*, equipped with laser reflectors which, given its nearly equatorial orbit ($i = 15^\circ$), provided a unique opportunity for the geodetic observations of the ISAGEX

program (Fig. 2.16). The satellite was the prototype of the *Eole* weather satellite to be launched the following year.

2.7 PAGEOS: Return to Balloons

The third type of geodetic satellites launched by NASA after the establishment of the 1964 program denotes a return to the “Echo” type balloons. After all, NASA has entrusted the study and the construction of new geodetic satellites precisely to the Schjeldahl company, mylar specialist, and manufacturer of the first *Echo*. The name of the new satellites, *PAGEOS*, recalls their mission (*geos* for geodetic satellite) and their formula (*pa* for passive). In fact, satellites of this type will not have even the smallest radio signal. But their lack of instruments is greatly rewarded by the size (30 m in diameter) that allows to follow them easily with the naked eye (they shine like the star *Polaris*) and to make accurate measurements with optical telescopes relatively simple. However, ultimately, it was launched one satellite of this type, the *PAGEOS 1*.

PAGEOS 1 was launched on June 1966 and inflated in orbit to serve as a giant reflector of sunlight that could be photographed from more than 40 ground stations (Fig. 2.17).

The satellite was able to reflect about 85 % of visible light and 97 % of incident radiative energy and could be observed simultaneously, e.g., from Europe and America appearing as a slow-moving star. Because of its high orbit and polar inclination, it could avoid the Earth’s shadow and be observed any time of the night (low-orbit satellites are only observable shortly after sunset and before sunrise). The satellite suffered a first disintegration in July 1975, closing one of the most successful satellite projects of the twentieth century. *PAGEOS* enabled the determination of the precise location of continents, islands, and other land masses.

2.8 Secret Geodesy: Military Geodetic Satellites

In early 1964, a member of the US Department of Defense revealed that among the many satellites launched discreetly by Vandenberg, there were some geodetic vehicles. They were part of the *SECOR* (*Sequential Collation of Range Satellite*) program, the first success of which had been preceded by three failures. The *SECOR* system was an all-weather, mobile, geodetic tool which was employed by the Army to collect more accurate data for determining relative



Fig. 2.17 *PAGEOS 1* was a 30-m-diameter sphere made from 1.27 μm Mylar externally coated with a 0.22 μm vapor-deposited aluminum weighing 54 kg. The

PAGEOS orbit was a polar one (inclination 84.4°) of 2953×5207 km and an orbital period of approximately three hours

locations of continents, islands, and other landmarks separated by large bodies of water or by inaccessible terrain. Geodetic *SECOR* was in operational use for several years, establishing a global survey network. It used the successive positions of artificial satellites in space to determine locations on the Earth's surface with exactness over long distances. The system consisted of a satellite and four ground stations, three at geographical points where the coordinates had been surveyed accurately and the fourth at an unknown location. Radio waves were flashed from the ground stations to the satellite and returned.

The position of the satellite at any time was fixed by the measured ranges from the three known stations. Using these precisely established satellite positions as a base, ranges from the satellite to the unknown station were used to compute its position (Fig. 2.18).

Geodetic *SECOR* allowed continents and islands to be brought within the same geodetic global grid. There were two types of *SECOR* satellites: the spherical Type I *SECOR* and the cubic Type II *SECOR* version. The earliest *SECOR* satellites were of the Type I variety. This version was of *Solrad/Grab*-type spherical construction, 50.8 cm in diameter, designed to be as simple as possible and to take maximum advantage of proven satellite techniques and

existing hardware. This reflecting spacecraft was designed for a 1-year lifetime and was capable of being photographed by *Baker-Nunn* cameras.

Six circular solar cell plaques, about 20 cm in diameter, were spaced equidistant from the satellite's surface. The first two *SECOR* satellites were allowed to locate with unrivaled precision some references in Okinawa and some islands in the Ryukyu archipelago. Experiments with these satellites led to *Timation* satellites and finally to the *GPS Navstar* system. A satellite of the Type II *SECOR*, named *TOPO I*, was launched on April 8, 1970, piggyback with the *Nimbus 4* meteorological satellite.

Another important series of military spacecraft used in geodesy is Transit satellites. The *Transit satellite system* was used extensively for Doppler surveying, navigation, and positioning. Observations of satellites in the 1970s by worldwide triangulation networks allowed for the establishment of the *World Geodetic System* (Fig. 2.19).

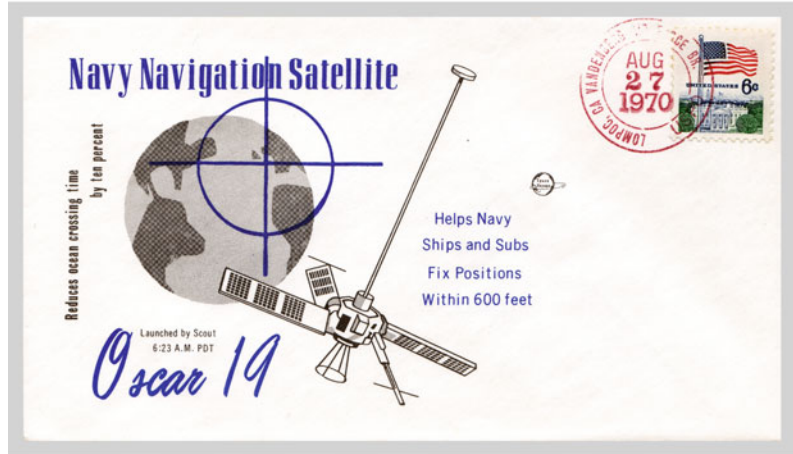
Finally, the development of GPS by the USA in the 1980s allowed for precise navigation and positioning and soon became a standard tool in surveying. In the 1980s and 1990s, satellite geodesy began also to be used for monitoring geodynamic phenomena, such as crustal motion, Earth rotation, and polar motion (Fig. 2.20).

Fig. 2.18 *SECOR 5* was a US Army geodetic satellite used to precisely determine points on the Earth



Fig. 2.19 **a** Envelope produced to mark the launch of the *Transit-O 19* (*Oscar 19*) satellite.
b *TOPO 1*, the US Army Topographic Command's first satellite, was used primarily for research and development in determining the accuracy of SECOR system. The 18.14 kg satellite was based on the *SECOR Type II* satellite and was shaped like a rectangular box (0.36 m by 0.30 m by 0.23 m)

(a)



(b)



2.9 Satellite Altimetry

The mission of the *Skylab* space station in the early 1970s made it possible to test a new geodetic technique that allowed not only the direct mapping of the geoid, but also to study the ocean dynamics and the major features of its topography. This technique is called *satellite altimetry*, one of the more recently developed methods of satellite geodesy. The basic concept is very simple: A satellite transmits microwave pulses in the radar frequency domain to the ground and receives the return signals after reflection at Earth's surface; the round-trip flight time of the signal determines the distance

between the spacecraft and the Earth's surface. From this distance or height, the local surface effects such as tides, winds, and currents are removed to obtain the satellite height above the geoid (Fig. 2.21).

With a precise knowledge of the satellite position, it is then possible to compute the geoid height by subtracting the measured altitude from the ellipsoidal height. The difference between the ocean surface and the actual geoid also gives information on the ocean surface topography.

After the successful test during the *Skylab* missions, new and improved altimeter versions were flown on *GEOS 3* (1975) and *Seasat* (1978) (Fig. 2.22 and Fig. 10.1). *GEOS 3* was the third satellite and final satellite as part of NASA's



Fig. 2.20 The *global positioning system (GPS)* has become a widely used tool in geodetic studies of Earth. The data collected by GPS receivers and the analyzed results are used to study problems of global geodynamics with direct application to global plate tectonics and postglacial rebound and to studies of the excitation of variations in Earth's rotation. When the global data are combined with data collected in a local region, they can be used to study the deformation processes in that region. In the long run, analysis of these regional data will lend to improved dynamical models and to a better understanding of earthquakes and other deformation processes. In **a** and **b**, we see two examples of mapping based on the use of a GPS receiver that can provide position estimates (latitude, longitude, and altitude) with an accuracy to a few

millimeters for weekly averaged positions. **c** is shown a GPS receiver station installed on a glacier. The data collected in long intervals provide information on the movement of the ice, its thickness, and the formation of large icebergs. The cachet of the cover **d**, which bears the date of the launch of the satellite *Navstar II-26*, recalls some of the GPS applications that can save lives. For example, the problem of fires in remote areas. Using information from a GPS, a fire can be mapped fairly easily. A ground or air unit, using a GPS, travels the perimeter and records the coordinated points. The information is then fed into a GIS program, and a detailed map of the perimeter can be created as a map layer with other layer showing roads, houses, and any information useful for the rescues



Fig. 2.21 The technique of satellite altimetry was tested for the first time during the *Skylab* missions *SL-2*, *SL-3*, and *SL-4* between 1973 and 1974. The radar altimeter aboard *Skylab* has detected short-wavelength anomalies in sea surface topography, caused by the gravitational effects of major ocean bottom topographic features. Some features, such as deep ocean trenches, seamounts, and

escarpments, displace the ocean surface by as much as 15 m over 100 wavelength kilometer. This experiment demonstrates the potential of satellite altimetry for determining the ocean geoid and for mapping major features of the ocean bottom. **a, c** Two artistic renditions of the *Skylab*, compared with a photographic image (**b**)

Geodetic Earth Orbiting Satellite/Geodynamics Experimental Ocean Satellite program (NGSP) to better understand and test satellite tracking systems. For the first two satellites, *GEOS* referred to *Geodetic Earth Orbiting Satellite* but was changed to *Geodynamics Experimental Ocean Satellite* for the *GEOS 3* satellite.

GEOS 1 and *GEOS 2* had provided useful information about the structure of the Earth's gravitational field, but new technology was deemed necessary to gain a further understanding. *GEOS 3* was a multipurpose satellite: Its mission was designed to further an understanding of the Earth's gravitational field, size and shape of the terrestrial geoid, deep ocean tides, sea state, currents, structure of the Earth's crust, solid Earth dynamics, and remote sensing technology. Besides the altimeter, laser reflectors, Doppler transmitter, and a "satellite-to-satellite" tracking system were installed on the spacecraft (see Fig. 2.22).

2.10 Geodynamic Satellites

Earlier in this chapter, we have seen how the path followed by a satellite is not arbitrary but is completely determined by the initial conditions

(position and velocity at a given time) and the forces acting on it (gravitational forces due to the Earth's field, perturbation from the Moon and the Sun, atmospheric drag, and, possibly, pressure effects of solar radiation). Therefore, to obtain the highest precision, a geodetic satellite must be designed in such a way as to minimize all those influences on its movement not due to the Earth's gravitation. Since the attraction forces of the Sun and Moon are well known, it will be sufficient that the satellites are only insensitive to the atmospheric drag and solar radiation. One way to do this is to use the spherical shape, a heavy material, and a very high orbit. This is the case of the geodetic satellites of second generation, such as *Starlette*, launched by French CNES in 1975, and *Lageos*, launched by NASA the following year. Both satellites are spherical bodies with an aluminum shell wrapped around a very heavy nucleus (uranium for *Starlette* and brass for the *Lageos*).

Their design is a perfect compromise between several factors, including the need to be as heavy as possible to minimize the effect of non-gravitational forces, to be light enough to be placed in high orbit, to accommodate as many retroreflectors as possible, and to reduce the surface area to minimize the radiation pressure.

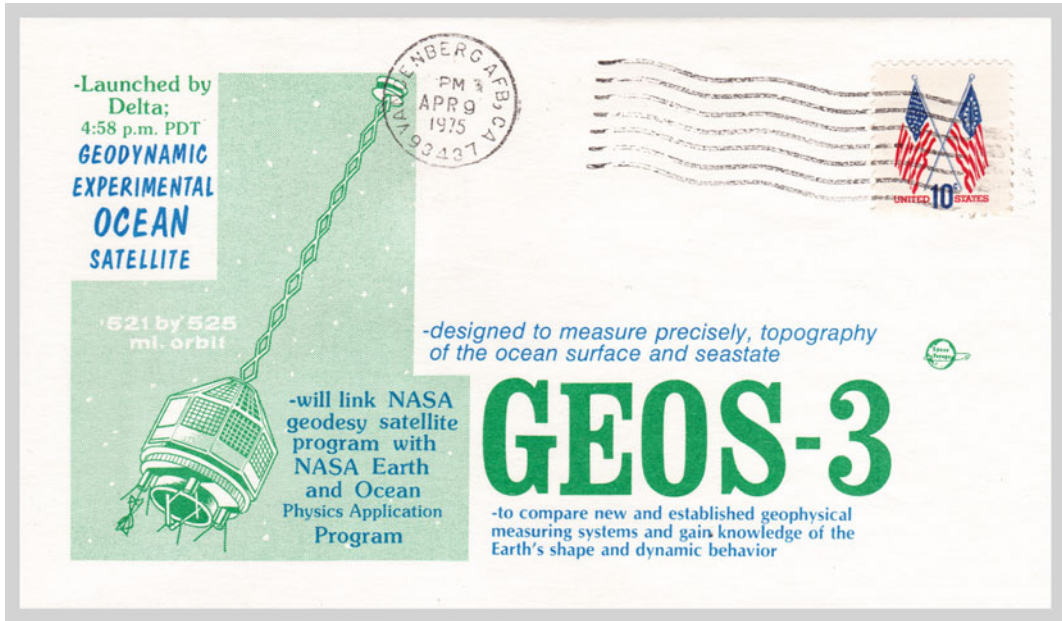


Fig. 2.22 *GEOS 3* was launched in April 9, 1975, and remained operational until late July 1979. The *GEOS 3* spacecraft was an octahedron, topped by a truncated pyramid, with a parabolic reflector for a radar altimeter on the flat bottom side. A metal ribbon boom with end mass extended upward approximately 6.1 m from the top of the pyramid. 264 laser retroreflector cubes were mounted in a ring around the parabolic reflector with the normal vector from each cube facing 45° outward from the direction of the Earth. One of the retroreflectors was designed for the infrared. Mission objectives were to perform a satellite altimetry experiment in orbit, to support further the calibration and position determination of NASA and other agency C-band radar systems, and to perform a SST experiment with the *ATS 6* spacecraft using an S-band

transponder system. The *GEOS 3* mission provided data that furthered scientific understanding in various fields. The ocean height data set from this mission provided the first comprehensive coverage in most areas of the world's oceans, providing a better understanding of the ocean geoid. Ocean height also provided information about quasi-stationary departures from the geoid, for events such as currents, eddies, and storm surges. The return waveform data were used to better understand the sea state at a level that was comparable to buoy-collected data. An unexpected result was the ability to use waveform data to derive surface wind speed and the ability to maintain track over terrain and ice. Altimeter data from *GEOS 3* has been utilized by many gravity models, including *GEM-T3*, *JGM-1*, and *JGM-2*.

In addition, their materials were chosen to reduce the effects of Earth's magnetic field on the spacecraft orbits.

Therefore, spacecrafts of this type allow to practically treat the problem of the movement of a satellite as if it were subject only to the Earth's gravitational field, the determination of which is also one of the objectives of geodesy (Figs. 2.23 and 2.24).

Starlette (*Satellite de Taille Adaptée avec Réflecteurs Laser pour les Etudes de la Terre*) is a small (only 24 cm in diameter) and massive (it weighs 47 kg) satellite placed in low orbit (about

800 km). Spherical and entirely passive, it is equipped with 60 *corner-cube reflectors* (retroreflectors that take the form of three equilateral triangles joined to make an open pyramidal shape) able to send back to the ground stations emitting sources (such as the Observatory of the Côte d'Azur) the laser beams received.

The *Lageos* (*Laser Geodynamics Satellite*) is a spherical 60-cm-diameter passive satellite that carries an array of 426 prisms. This sphere made of brass covered with aluminum, weighed about 411 kg, and is composed of a cubical inner core with six attached spherical caps. Each of the

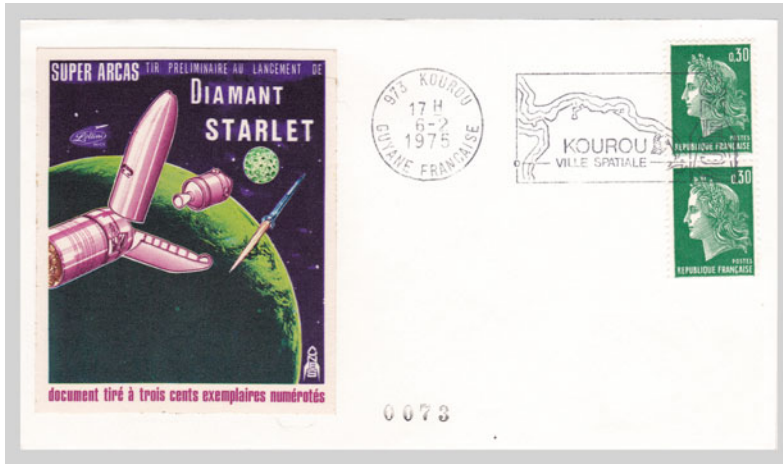


Fig. 2.23 Envelope commemorating the launch of the satellite *Starlette*, which occurred on February 6, 1975, from the French Space Center of Kourou



Fig. 2.24 The first localizations of the satellite using laser pulses have been carried out between 5 and 9 March. *Starlette* and *Stella* measured changes in the Earth's gravitational field, both statically (change in gravitational

field according to location) and dynamically (variations in gravitational field with time due to tidal forces). In the 1980s, *Starlette* results enabled scientists to develop a model of global ocean tides

spherical caps had machined cavities to accommodate the retroreflectors. The satellite was placed at a high orbital inclination at an altitude

of about 5000 km and tracked by a network of 13 laser stations operated by both US and foreign agencies.

Fig. 2.25 The two *Lageos* satellites. Laser retroreflectors covering a very dense spherical satellite were used to provide a permanent reference point in a very stable orbit for precision Earth dynamics measurements. It is estimated that the two satellites will remain in orbit for at least eight million years. The performance in orbit is limited only by degradation of the retroreflectors, and a minimum lifetime of 50 years is expected



The results from these first two satellites were very satisfactory: Their laser reflectors could determine movement or position within a few centimeters, which allowed scientists to track and analyze tectonic plate movement and continental drift. In the following years, several other satellites of this type were placed into orbit: *Stella* and *Lageos 2*, twins of the predecessors *Starlette* and *Lageos 1*, the German satellite *GFZ 1*, the Russian *Etalon* satellites, the Japanese *Ajisai* and the Italian *LARES* (Figs. 2.25, 2.26, 2.27, 2.28 and 2.29). *Etalon* is a geodetic passive satellite family of two identical spacecraft of Russia. *Etalon* is dedicated entirely to satellite laser ranging to permit solid Earth studies: geodynamic processes,

development of high-accuracy global references, long-period disturbances, geopotential modeling, etc. The spacecraft structure is a sphere with a diameter of 1.294 m, mass = 1415 kg. There are a total of 2140 fused quartz plus 6 germanium *corner-cube reflectors*. The germanium reflectors are intended for potential future infrared interferometric measurements.

The two *Etalon* spacecraft were built by the United Space Device Corporation, Moscow, Russia. The two satellites were placed in very high circular orbits (about 19,000 km), inclined at 65° in 1989, respectively, on 10 January and 31 May, with the names of *Cosmos 1989* and *Cosmos 2024*.



Fig. 2.26 *Lageos 1* contains a message plaque designed by *Carl Sagan* addressed to humans (or other beings) of the far future. The plaque is 10 cm by 18-cm stainless steel plate and contains three maps of the Earth's surface. The first map denotes the Earth 268 million years in the past with all the continents shown together in one mass. The middle map displays the present configuration of the

planet. The final map shows the Earth's surface 8.4 million years from now—very roughly the estimated lifetime of the *Lageos*. Whoever will be able to view the *Lageos* plaque needs only compare a current map of the Earth's geography with that in the lower two maps to calculate roughly the difference between his time and ours

The Japanese *Experimental Geodetic Satellite* (*EGS*) was launched on August 13, 1986, and was renamed *Ajisai* (*Hydrangea*) after reaching orbit. The objectives of the mission included a survey aimed at rectifying Japan's domestic geodetic triangular net, determining the exact position of many isolated Japanese islands, and establishing Japan's geodetic point of origin. Satellite laser ranging to *Ajisai* is used for precision orbit determination and is used to improve the gravity field. The design accuracy of laser reflectors corresponds to a range resolution of 1–2 cm.

GFZ-1 is the first satellite mission designed and funded by the *Geo Forschungs Zentrum* Potsdam, Germany. The mission objectives of *GFZ-1* were to determine variations in the rotational characteristics of the Earth and to measure changes in the Earth's gravity field. *GFZ-1* was a passive geodetic satellite with only one

instrument, a *RRA* consisting of 60 corner-cube retroreflectors placed in special holders that were recessed into the satellite's body. External metallic surfaces were covered with white paint for thermal control purposes and to facilitate visual observation in space. The satellite was built and launched by Russia. *GFZ-1* was transported to the *Mir* station aboard the Russian *Progress-M 27* spacecraft and from there put into a low Earth orbit in April 1995. For the high-resolution determination of the parameters of the gravity field, a satellite must be launched into the lowest possible orbit. At its altitude of 400 km, *GFZ-1* has been the lowest geodynamic satellite to be ranged by lasers and its results will lead to a significant improvement in the modeling of the gravity field. On June 23, 1999, *GFZ-1* completed its mission. The satellite burned up in the upper atmosphere. Since its spectacular start,



Fig. 2.27 The Japanese *Ajisai* was launched on August 13, 1986, into 1500 km high orbit, inclined 50°, with a period of 115.7 min. This spacecraft is well suited for laser ranging and for photographic camera observation. It is polyhedron-shaped with an effective diameter of 2.15 m which carries 318 mirror elements to reflect solar rays and 120 groups containing a total of 1436

retroreflectors for laser light. The total weight is approximately 685 kg. Due to satellite rotation around its axis, an observer on the dark side of the Earth can see about two short flashes per second with a duration of 5 ms and magnitude between 1.5 and 3.5. These flashes can be photographed against the background stars

GFZ-1 has orbited nearly 24,000 times around the Earth. As the vehicle's orbit decayed, the satellite's orbital motion was also used to calculate atmospheric densities.

2.11 Gravity Sensors and Accelerometers

During its mission, the *GEOS 3* position was measured with great precision with the technique of *satellite-to-satellite tracking* (SST) that used the geostationary satellite *ATS 6*. The concept of SST technique was proposed and tested in the 1960s. Since then, two different concepts of SST have developed and perfected: the *high-low concept*, involving a high-orbiting satellite (geostationary, GPS....) and a low-orbiting

spacecraft, and the *low-low concept*, based on two satellites following each other along the same orbit. For both concepts, the satellites in the low orbit are the sensors in Earth's gravity field.

One-way and two-way intersatellite tracking systems can be used to measure the relative velocities. The irregular variations of this velocity contain gravitational information. SST in the high-low mode was applied during the *Apollo* program for Earth-based control of lunar orbiter. With respect to Earth's gravity field, SST in the high-low mode was tested in 1975 with measurements between the geostationary satellite *ATS-6* and the low-orbiting vehicles *GEOS 3*, *Nimbus 6*, and *Apollo-Soyuz* (Fig. 2.30).

In the low-low concept of SST technique, two low altitude satellites can track one another observing mutual orbital variations caused by

Fig. 2.28 The *Stella* satellite was launched on September 25, 1993, with the Flight 59 of the Ariane rocket, along with other satellites (*SPOT 3*, *Kitsat*, *Itamsat*, *Posat*, *Healthsat*, *Eyesat*)



gravity field irregularities. A prime example of this is the *GRACE* (*Gravity Recovery And Climate Experiment*), based on two identical satellite placed on the same orbit. The GRACE satellites observe variations in gravity as they fly coupled over the Earth uneven surface (Fig. 2.31). The satellites' microwave ranging instruments can measure variations at the micron level. The GRACE mission determined a global gravity field model by circling the Earth and tracking the orbital perturbations of the satellite pair. Gravity is determined by mass. By measuring gravity anomalies, GRACE shows how mass is distributed around the planet and how it varies over time.

Data from the GRACE satellites is an important tool for studying Earth's ocean, geology, and climate.

Accelerometers are mechanical or electromagnetic devices used for measuring gravity and are used in onboard satellites for space gradiometry applications. One of the important satellite missions carrying accelerometers is the ESA's *GOCE* (*Gravity Field and Steady-State Ocean Circulation Explorer*).

GOCE was the first of ESA's *Living Planet Program* satellites intended to map in unprecedented detail the Earth's gravity field. GOCE

mapped the deep structure of the Earth's mantle and probed hazardous volcanic regions. It brought new insight into ocean behavior; this, in particular, was a major driver for the mission. By combining the gravity data with information about sea surface height gathered by other satellite altimeters, scientists were able to track the direction and speed of ocean currents produced by the geostrophic winds. The low orbit and high accuracy of the system greatly improved the known accuracy and spatial resolution of the geoid. The spacecraft's primary instrumentation was a highly sensitive gravity gradiometer consisting of three pairs of accelerometers which measured gravitational gradients along three orthogonal axes. The satellite's unique arrow shape and fins helped keep GOCE stable as it flew through the upper thermosphere at an altitude of 255 km. Additionally, an ion propulsion system continuously compensated for the variable deceleration due to air drag without the vibration of a conventional chemically powered rocket engine, thus limiting the errors in gravity gradient (Fig. 2.32).

In the 1970s, the French CNES had conducted a first experiment on the perturbations of the gravitational field with the satellite *Castor* (*D-5B*). The spacecraft had a 26-face polyhedron

(a)



(b)



Fig. 2.29 a Envelope marking the launch, from *Mir* station, of the *GFZ-1* satellite. During four years and 64 days in space, 5,402 passes of *GFZ-1* were observed by 33 stations of the global SLR network (see also Fig. 2.5). **b** *LARES* (*Laser Relativity Satellite*), the last of the small completely passive geodetic satellites, is an Italian Space Agency satellite launched from the ESA Guiana Space Centre of Kourou, by the maiden flight of the European launch vehicle *Vega* on 13 February 2012. It was inserted in an orbit with 1450 kilometres of perigee, an inclination of 69.5 degrees and reduced eccentricity.

LARES is made of tungsten alloy and houses 92 cube corner retro-reflectors that are used to track the satellite via laser from stations on Earth. The satellite is the densest known object orbiting in the Solar System: with a diameter of about 36.4 centimetres it weighs about 400 kilograms. The main scientific target of the *LARES* mission is the verification of an effect predicted by the theory of relativity.

Together with *LARES*, the new *Vega* rocket has orbited a further eight small satellites, including the *MaSat-1* (see Fig. 8.65a)

Fig. 2.30 The *GEOS 3/ATS 6* link was used to determine the *GEOS-3* range and orbit. From a comparison between measured and computed range rates, based on gravity models, some anomalous gravity structures of the Java Trench and the Himalayan mountains were clearly discernible



Fig. 2.31 The *GRACE* project is based on two identical satellite placed on the same orbit and separated by approximately 200 km along their orbit track so that their relative position can be measured with extreme accuracy



Fig. 2.32 The launch of the *GOCE* satellite took place by March 17, 2009, from the Plesetsk Cosmodrome in Russia (the envelope was canceled in Mirny in the Arkhangelsk region, where there are establishments for the assembly of satellites). After running out of propellant, the satellite began dropping out of orbit and made an uncontrolled reentry on November 11, 2013





Fig. 2.33 **a** A commemorative cover of the launch of the two French satellites *Castor* (D5-B) and *Pollux* (D5-A). **c** *Pollux* satellite and D2 (*Signe 3*) satellite. Several sets of retroreflectors were installed on the Moon as part of the American *Apollo* and Soviet *Lunokhod* space programs. These retroreflectors are also ranged on a regular basis, providing a highly accurate measurement of the dynamics of the Earth/Moon system. The time the laser beam takes to travel there and back serves to determine with high precision the distance between the Earth and the Moon. Such measurements are essential for the study of lunar

motion and also for the solution of geophysical and geodetic problems. Laser RRAs have been placed on the Moon by the US *Apollo 11*, *14*, and *15* missions and the French reflectors *Lunokhod 1* and *Lunokhod 2* deployed by the Soviet automatic probes *Luna 17* and *Luna 21* in 1970 and 1973. **b** The laser reflector of *Lunokhod 2* is placed on the far left under the conical antenna of the rover. **d** With Lunar Module in the background, is clearly visible the *Laser Ranging Retro-Reflector (LRRR)*, placed on the Moon by an *Apollo 14* astronaut

shape with a diameter of 80 cm. The primary mission objective was to study the upper atmosphere density variations. Secondary objectives included a study of gravity field perturbations and a study of micrometeorite impacts.

A three-axis magnetometer was used to provide attitude information. Each one of the spacecraft faces contained a laser reflector. The *Pollux* satellite (D5-A) carried a hydrazine propulsion system that was tested in space (Fig. 2.33).

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