The Changing World of Geodesy and Surveying

K.P. Schwarz
Department of Geomatics Engineering
The University of Calgary
Calgary, Alberta, Canada T2N 1N4
E-mail: schwarz@ensu.ucalgary.ca

Summary

Change in the field of geodesy and surveying has been rapid during the past twenty-five years. It was driven by major advances in space geodesy resulting in new measurement systems. These systems have had a profound effect on the practice of geodesy and surveying and it is likely that their impact will become even broader and more pronounced during the next decade. Four major trends that developed over the past twenty-five years are briefly discussed in this paper and their impact on the major tasks of geodesy - the representation of the Earth's surface and its gravity field - are evaluated. The paper concludes with an outlook on a possible integration of geodetic techniques and data into an Earth Observing System that will more accurately describe the evolution of the Earth in time and space.

1. Twenty-five Years in Retrospective

Understanding change requires interpretation of the present in terms of the past. In this first chapter some developments of the past 25 years are interpreted as technological trends in the field of geodesy and surveying. Trends express continuity over a given time period. They offer therefore a limited amount of predictability which is dependent on the linearity of the observed phenomenon. Looking at the state of geodesy and surveying in 1974, few of the developments mentioned below were predictable in terms of the trends dominant during the period 1949-1974. The development was not linear and, only in hindsight, are we able to see some of the trends. This should be kept in mind when talking about 'The Changing World of Geodesy and Surveying'. Understanding change does not mean that the future can be predicted by extrapolating the past. Understanding change can, however, prepare us for the future. Golo Mann's remark that *"those who do not know the past will not get a handle on the future"* should serve as a reminder and an antidote against too much blue-eyed optimism.

What then are some of the major changes in our field at the end of this century? Disregarding general technological trends, such as the still rapid development of computer technology, the trend towards miniaturization of sensors and systems, and the rapid emergence of complex information systems, there are a number of specific developments which are changing the world of geodesy and surveying as we have known it. Four of them will be discussed here:

- The implementation of a time-varying reference frame of unprecedented accuracy which for the first time, allows the measurement of global and regional changes of the Earth and their modeling in space and time.
- The capability to operate the measurement systems directly in the reference frame using satellite orbits as the link and thus eliminating the need for networks and dense ground control point monumentation.

- The capability to solve the vertical datum problem by a combination of satellite and airborne gravimetry.
- The increasing trend towards integrated kinematic measurement systems with high data rates and the resulting changes in automated data acquisition, modeling and algorithm development.

Before discussing these trends in more detail, conventional approaches to solving the task of geodesy will be briefly reviewed in order to provide a framework for the rest of the paper.

2. Views on How to Solve the Task of Geodesy

More than 100 years ago, Helmert defined geodesy as the science of measuring and mapping the Earth's surface. Although methods have considerably changed since then, the definition is still useful if one adds the temporal variations of the Earth to the definition. Figure 1 illustrates the change in measurement systems and techniques that has taken place in the past 25 years and that is still in progress. Especially the development of kinematic techniques of mapping the Earth surface and gravity field are remarkable and will be discussed further in chapter 6. Helmert's seemingly simple definition has been interpreted in rather different ways by the groups involved in surveying and mapping. Part of this difference came about because of differences in the surface itself. Those who measured the ocean surface - by far the largest part of the Earth's surface - obviously faced different problems than those who measured the land surface. However, even among those who measured on land, there were vast differences in concept and approach. Figures 2 to 4 indicate some of these differences.

Figure 2 illustrates the view of the surveyor/geodesist who typically considers the measurement of the Earth's surface as a point positioning problem. The accurate determination and monumentation of points on the surface of the Earth is therefore seen as the major task. In order to express these points in a consistent coordinate system over larger parts of the Earth's surface, networks are established and the datum problem must be solved. Once this has been done, the network points can be used for point densification in local areas. The resulting representation of the surface by a more or less regular cluster of points is considered as sufficient. Mapping is done as pointwise mapping. In a way, the concept behind this approach is that the higher the point accuracy, the better the mapping. This is true for pointwise mapping, but obviously not for surface mapping. Simple interpolation between network points will for instance create large errors in a topographic map. Thus, the accuracy of the surface representation will not be uniform. In addition, although networks may stretch over a large part of the Earth's surface, they are globally disconnected when established by conventional procedures. This means that the datum problem cannot be solved without extraterrestrial measurements. This method has therefore to be supplemented by other techniques in order to solve the task of geodesy as defined by Helmert.

Figure 3 illustrates the view of the photogrammetrist who considers the measurement of the Earth's surface as an imaging problem. It is solved by deriving a model of the surface from digital or photographic images. In this case, patches of the Earth's surface are actually measured and mapped in accordance with Helmert's definition. The concept behind this method is that the surface of the Earth can be presented by pixels measured in projected images. The smaller the pixel size and the more uniform the geometry, the better the mapping. In this case, the accuracy is more or less uniform across the image and interpolation of specific image features is possible with high accuracy, once the image has been properly georeferenced. This is done by solving the datum problem using geodetic ground control in the survey area. Comparing the view of the surveyor/geodesist with that of the photogrammetrist shows that they are essentially complementary. The surveyor/geodesist provides highly accurate point positions in an adopted reference system which then can be used by the photogrammetrist to georeference measurements and solve the datum problem for the precise local maps derived from images.

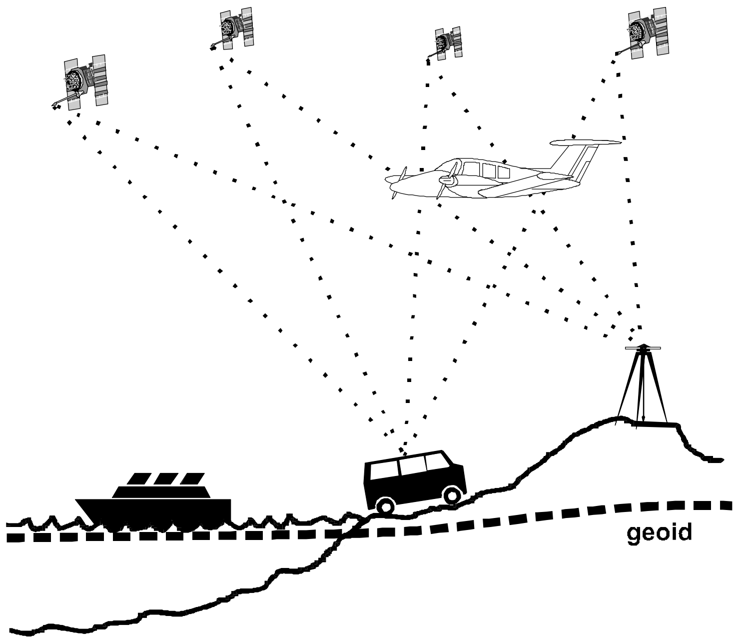
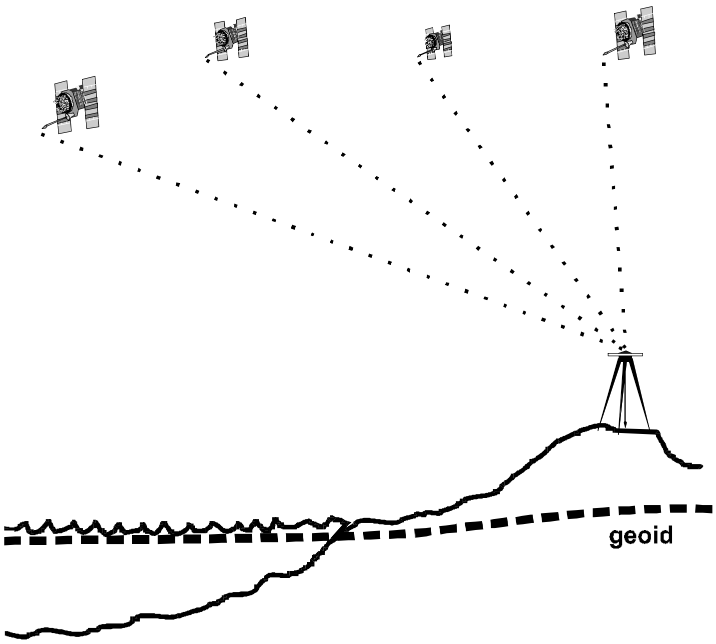


Figure 1: Measuring the Earth's Surface by Static and Kinematic Systems



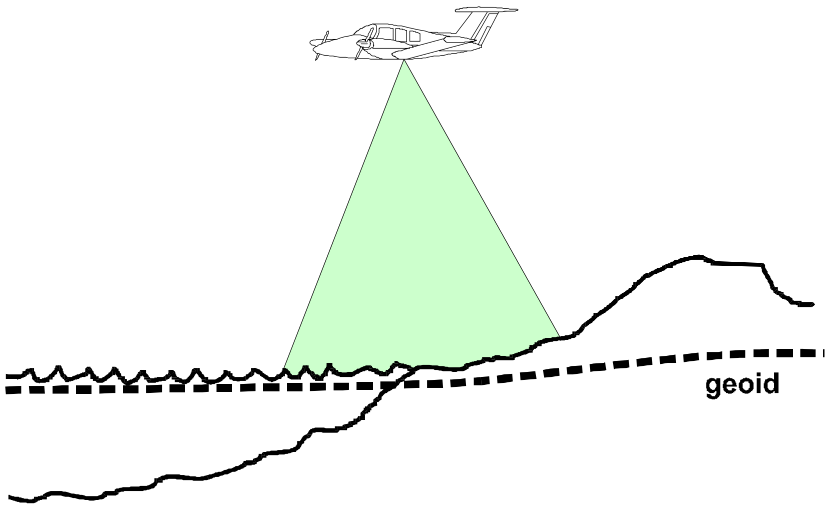
The surface of the Earth is defined by point measurements.

The higher the accuracy of point determination, the better the mapping.

Figure 2: Point Positioning – The Surveyor's View

Figure 4 illustrates the view of the geodesist who considers the surface of the Earth as a boundary surface to be determined by gravimetric measurements. This corresponds closely to the definition of geodesy given by Bruns in 1878 stating that ”the task of geodesy is the determination of the potential function W(x,y,z)”. The connection to the positioning problem is given by the fact the W is defined as a function of position (x,y,z). Thus, once W(x,y,z) is determined with sufficient accuracy, the Earth’s surface can in principle be derived and the mapping problem solved. The practical problem in this approach is the determination of the potential function from discrete measurement (gravity anomalies, deflections of the vertical, etc). Data density and consistency will strongly influence the accuracy with which the surface can be determined. In other words, the denser the gravimetric data, the better the surface mapping. Currently, the measurement accuracy is still orders of magnitude better than the interpolation accuracy. In addition, the datum problem has to be solved. Thus, on a global scale the best models are still about two orders of magnitude away from the accuracy level that would make them consistent with the point positioning accuracy currently achieved by GPS and other satellite methods.

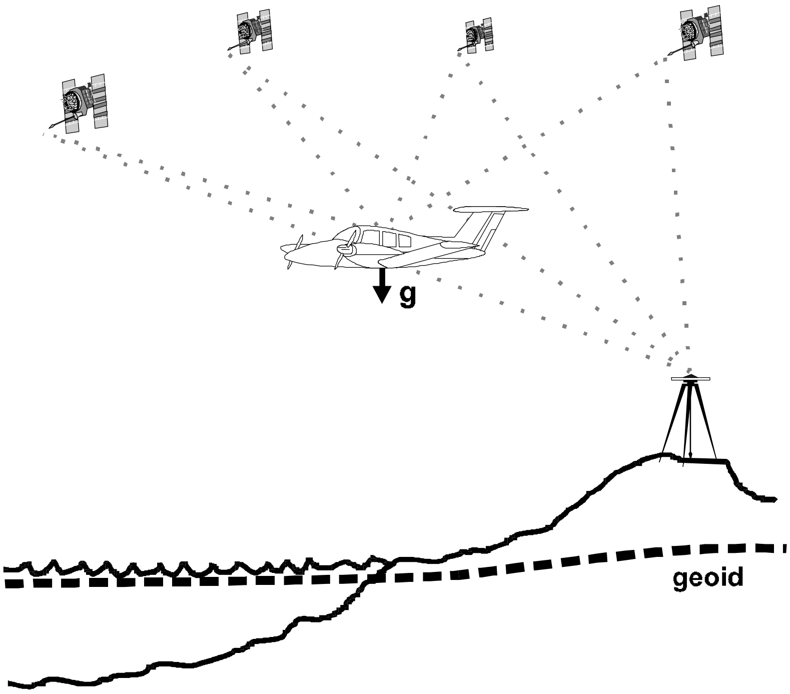
All three classical solution approaches have one drawback in common: they approximate the global situation by patching together those pieces of the Earth’s surface which are covered by measurements. This leaves big gaps generated by ocean areas and by poorly surveyed parts on the continents. To improve the patchwork, a consistent global frame is needed and a methodology to transform isolated surface patches onto this frame. Looking at the current efforts in Europe to patch together the different reference systems, different DEMs, and diverse geoid patches, gives an appreciation of the size of the task for just one well-surveyed continent.



The surface of the Earth is defined by pixels measured in projected images.

The smaller the pixel size, the better the mapping.

Figure 3: Image Modelling – The Photogrammetrist’s View



The surface of the Earth is defined by a gravimetric boundary value problem.

The denser the gravity measurements, the better the mapping.

Figure 4: Boundary Surface Determination – The Geodesist's View

3. Reference Frames and the Solution of the Datum Problem

One of the advantages of applying space methods to geodesy is the establishment of a highly accurate reference frame for positioning. The centre of mass of the Earth, as well as the direction of the axes of the conventional terrestrial frame can be established with an accuracy that, in a relative sense, is at the part per billion level and is thus superior to most practically applied positioning techniques. Comparing this to the best available global frame 25 years ago shows that reference frame implementation has been improved by more than two orders of magnitude. For much of the following discussion, the detailed technical background can be found in the proceedings of the recent IGGOS (1998) symposium.

A Conventional Terrestrial Reference Frame (CTRF) is implemented by tying the frame definition to the positions of fundamental observing stations which are continuously measured. The measurements are either made with respect to satellites or with respect to extraterrestrial sources. If only one technique is used for the determination of the coordinates, small biases may remain in the frame definition. Comparing independently determined conventional reference frames offers therefore a means to detect and eliminate such biases. Such comparisons have been made by the International Earth Rotation Service (IERS), established by the IAG, and have shown that the origins of these different reference frames agree at the level of a few centimeters and that the directions of the axes agree at the level of a few milliarcseconds. Thus the stability of current global reference frames is such that time changes in the coordinates of the fundamental stations have to be taken into account. The IERS has therefore added a plate tectonic motion model to its ITRF94 reference frame, making it a four-dimensional frame. It is planned to extend this model to include regional motions, once estimates of sufficient accuracy are available; for an overview see Blewitt et al (1997). Twenty-five years ago that would have been impossible because the existing reference frames did not have the accuracy nor the stability to reliably determine such small motions by measurement.

Besides the ITRF94 which uses a combination of observational techniques to determine the reference frame, there are a number of reference frames which make use of one observational technique only. The best known is the WGS84 which is based on the GPS tracking station network and uses observations to GPS satellites only. The IGS network operated by the International Geodesy and Geodynamics Service, established by the IAG, is another GPS-based reference frame with a much larger tracking station network, almost 200 stations by now. It will be used to measure and model regional motions. Similar reference systems exist for satellite laser techniques and VLBI. Each of these techniques has its own set of tracking stations to define the reference frame. Each of these reference frames can be considered as an implementation of the underlying reference system. Figure 5 illustrates in a schematic way the weakness of implementing a reference frame by only one type of measurements using GPS as an example. The GPS tracking network is indicated by three widely spaced stations on the surface of the Earth (triangle). Each of these stations can be determined by range measurements to at least four satellites, indicated by the heavy lines between one of the network stations and five of the satellites. The underlying assumption of this approach is that the satellite positions at the time of measurement are precisely known. This is not the case and therefore the range measurements are also used to improve the satellite orbits. This can be done reliably if the positions of the tracking stations are accurately known. Thus, one ends up with a typical bootstrap procedure: To improve orbits, accurate positions of tracking stations are needed - to get tracking station coordinates, precise orbits are needed. This problem is solved in an iterative way by matching the accuracy of tracking station coordinates with the accuracy of orbit determination. The results are excellent because of the measurement precision and the continuous observation schedule. However, because of the bootstrapping operation, small systematic errors in scale and orientation may remain in a reference frame derived in this way. It is therefore important to compare and improve reference frames derived from only one technique.

To do that, fundamental stations with more than one observational technique are included in the network to derive transformation parameters from the specific network to the ITRF94. Figure 6 shows in a schematic way how the reference frame derived from GPS observations could be improved in its orientation accuracy by VLBI measurements. The tracking network is again indicated by the triangle of fundamental stations on the Earth which are now simultaneously observed by VLBI and GPS. The dotted lines indicate VLBI measurements between the tracking stations and the quasar sources. They provide precise orientation of the CTRF within an inertial frame of reference. This technique has been used for the WGS84 for instance and the results are shown in Table 1 which gives the translations in cm and the rotations in milliarcseconds (mas); for details see Slater and (1997). Both the transformation parameters and their standard deviations indicate that the differences between the two systems is at the level of a few parts per billion.

Table 1: How Good is the GPS Reference?
Transformation of WGS 84 (G873) on ITRF94

Origin	Orientation of axes
$\Delta x = -0.1 \pm 2.9$ cm	$\varepsilon = 0.0 \pm 0.3$ mas
$\Delta y = -0.2 \pm 2.3$ cm	$\psi = 0.4 \pm 0.2$ mas
$\Delta z = 0.1 \pm 1.4$ cm	$\omega = 0.6 \pm 0.4$ mas
Scale Factor Accurate to:	
$s = -0.5 \pm 0.2$ parts per billion	

With a reference system of this accuracy and stability, the datum problem for positioning can be considered as solved for all practical requirements. The only remaining problem is the transformation of the existing network information onto this global reference frame. As the ongoing EUREF and REUN campaigns in Europe show, this is not a trivial task. While the global reference frame is a consistent three-dimensional coordinate system, this cannot be said for the reference systems used in the conventional network approach. Horizontal and vertical networks are essentially disconnected. They have few or no overlapping points and are based on different datums and are therefore not consistent. To transform the vertical network information to the global reference frame, the geoid is needed with high global accuracy. This will be further discussed in chapter 5. To transform the horizontal network information to the global reference frame, network distortions have to be eliminated first, before the relatively simple geometric transformation can be applied. Network distortions are due to a variety of causes, such as the observational procedure, the insufficient knowledge of the geoid used for reductions, and geodynamic changes of the Earth's surface during the long time periods over which networks were established. Whether these transformations can be determined with an accuracy sufficient to reliably transform existing networks into the global reference, will be answered by the ongoing investigations. If the answer is positive, an enormous amount of valuable observational material will be preserved for scientific investigations. Even in this case, however, their practical value as ground control will be very limited due to reasons discussed in chapter 4.

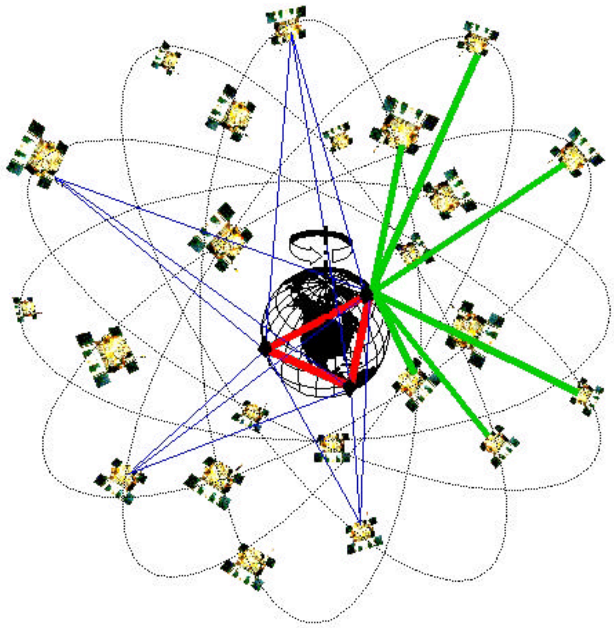


Figure 5: The GPS Bootstrap Operation: Tracking Stations vs. Orbits

4. Positioning in the Age of GPS - Satellites Replace Ground Control

Although GPS is now extensively used for a broad spectrum of survey tasks, it is widely seen as a highly accurate relative positioning method. Interstation vectors are the output of differential GPS methods and, in this sense, GPS is viewed as a sophisticated replacement of a total station for longer distances. In this scenario, a dense network of ground control points is still needed to tie the output of the receiver to the existing network. What is lost in this view of GPS positioning is the fact that the receiver output is directly connected to the global reference system by way of satellites. In principle, it should therefore be possible to determine globally referenced positions without access to networks or dense ground control.

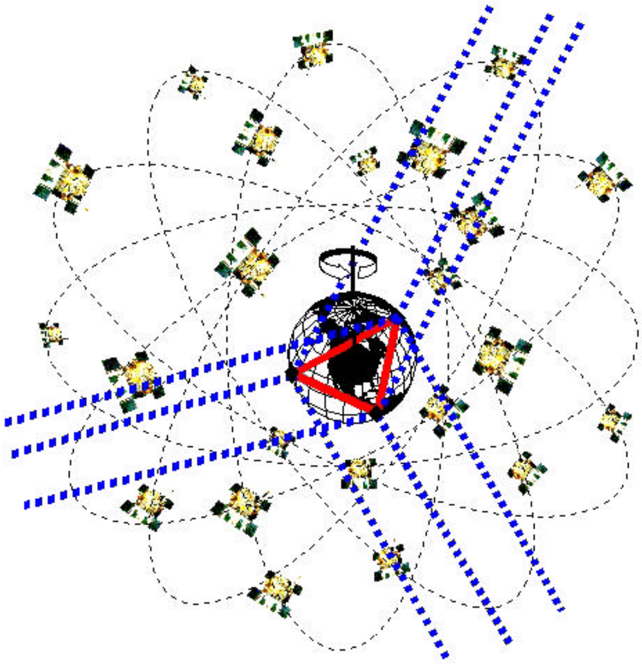


Figure 6: Connecting GPS to VLBI

This means that in the long run networks and monumented control will lose their importance because it will be possible to establish accurate global positions within a relatively short observation period. Part of this future is already with us in both static and kinematic positioning. Currently, the accuracy of the results is not good enough for all applications. To make it the standard method for most applications, it will be necessary to improve the availability of precise orbits, to better model or eliminate atmospheric effects, to improve the clock technology, and to further advance real-time algorithm development. Many of these improvements are discussed in the NAPA/NRC (1995) report where specific recommendations are given. Further details can be found in the technical literature. As an example likely developments in the area of orbital modeling will be briefly discussed in the following.

A major difference between GPS and traditional positioning methods is the replacement of ground control by sky control. Instead of tying into monumented control points one links into satellites which, in their orbital positions, carry accurate reference system information with them. This is possible because satellites are tied by measurement to the ground tracking stations which define the reference system. The accuracy of the orbital information depends on its age and on the density of the tracking network. The age of the orbit information is important because the broadcast ephemeris is predicted for a 36 hour period, computed from previous satellite observations. Their accuracy gets poorer with time which means that the accuracy of the reference information stored in the satellites deteriorates with time. This will affect real-time results, but not post-mission processing which can make use of orbital information that was derived from measurements during the observation period. While broadcast ephemeris may contain errors of up to 2m, post-mission orbits are typically better than 0.2m. The accuracy of broadcast ephemeris could be considerably improved by shortening the prediction period. Studies have shown that this is not a computational problem any more. The information could be available with relatively short time lags. The remaining

problem is efficient data distribution. It may be possible to upload the orbital information at a higher rate than the current 12 hour rate. Otherwise, some way of automatically updating the receivers would be needed.
Another way of improving the long-term prediction accuracy is the use of GPS crosslinks, i.e. of direct measurements between GPS satellites. Figure 7 shows this concept in a schematical way. Instead of using only measurements from the Earth to the satellites for orbit determination, measurements between satellites could be used to create a kinematic network on the GPS-satellite envelope. While Earth-satellite observations are optimal in fixing the radial orbit component, between-satellite observations would strengthen the along-track and across-track components. Thus, the ground tracking network would be supplemented by a sky tracking network. Technically, the capability for crosslink measurements is available in the Block IIR GPS satellites and can be activated, once enough of these satellites are in orbit. It is interesting to note that in such an approach the separate orbital planes, resulting from the gravity field model employed, are tied together by geometric measurements, essentially defining a potential surface at satellite altitude.

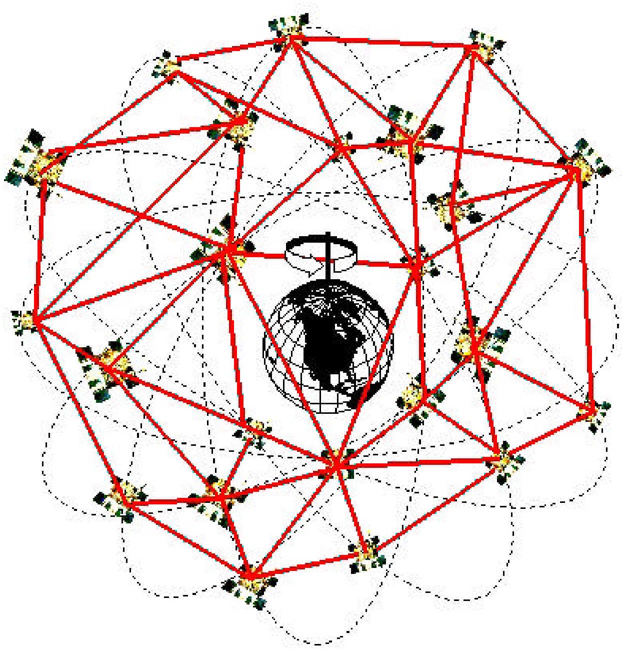


Figure 7: Skynet from GPS Crosslinks

The current trend towards the development of wide-area networks or active control networks is an intermediate step between relative positioning which requires dense ground control point information (DGPS), and absolute positioning which is based on satellite orbits only and does not require ground control for the measurement process. Compared to conventional control networks, the station distribution of wide-area networks is much sparser. These stations transmit orbit information and atmospheric corrections for the area covered by the network to improve real-time static and kinematic positioning. All active stations are at the same time permanent tracking stations and are tied into a global reference frame, such as the IGS. They can therefore be considered as a high-accuracy regional representation of the global reference frame. To which extent this accuracy can be transferred to the receivers operating within such a wide-area network depends largely on the station spacing, the accuracy of the transmitted information, the measurement mode (static or dynamic) and the operational procedures applied. It is likely that such networks will be operated for a considerable time to come. They will also prepare the way for precise absolute GPS positioning by improving orbital and atmospheric modeling techniques and pioneering data transmission to large numbers of users.

The emphasis in this chapter has been on possible developments in GPS positioning. It should not be misunderstood as an advertisement for GPS as a panacea for all positioning ills. GPS, as all other positioning methods, has advantages and drawbacks. Some of the advantages have been discussed above. Limitations are ‘line-of-sight’ problems between satellite and receiver which will be especially serious in urban centres, forested areas, and in steep mountainous terrain. Thus, other methods will not only continue to exist, but will be more economical and more effective in numerous situations. It will be the task of the practitioner to select the right positioning tools for a given task.

5. Towards a Solution of the Vertical Datum Problem - The Decade of Gravity Satellites

As outlined in chapters 2 and 3, the reference surfaces in the conventional approach are not consistent. Horizontal coordinates refer to the ellipsoid, while height coordinates refer to the geoid. This is somewhat surprising because the measurement systems, theodolites and levels, both refer to the local astronomic frame and, thus, the geoid should be the surface of choice. It was not used as a reference for horizontal coordinates, however, because measurements could be reduced to the ellipsoid by deriving deflections of the vertical from astronomic observations. Since computations were much simpler on the ellipsoid, the methodology was not changed, even when a global representation of the geoid became available. On the other hand, in leveling the line of sight is essentially parallel to the equipotential surface and thus almost parallel to the geoid. Therefore, the height differences are very close to orthometric height differences which are defined with respect to the surface of the geoid. To transform such height differences into ellipsoidal height differences, the geoidal undulations along the leveling line must be known. This is usually not the case and it is the main reason why two different reference surfaces came about.

When GPS was introduced as a three-dimensional positioning system, all three coordinates became available in a consistent reference frame which could be either Cartesian or curvilinear. Usually an ellipsoid was chosen as the curvilinear reference surface and, thus, a direct comparison between the GPS-derived coordinates and the conventional horizontal coordinates was possible. It was not possible, however for ellipsoidal heights and orthometric heights. To transform one height system into the other, an accurate geoid representation was needed in the measurement area. The situation is shown in Figure 8 where, in first approximation, the orthometric height H is the difference of the ellipsoidal height h and the geoidal undulation N. To transform the GPS-derived height into an orthometric height of equal accuracy, the geoid representation had to be accurate to a few centimeters. This is still not the case in many parts of the world. On a global scale the height transformation problem remains therefore an unsolved problem. The best global geoid models are not better than 1-2 m in areas with poor gravity coverage and between 0.3 an 0.5m in areas with good gravity coverage. Thus, the CTRF can be defined with an accuracy of a few centimeters by GPS, it cannot be transformed, however, with the same accuracy into a global reference frame with an orthometric height system. To solve the vertical datum problem, the geoid must be globally known with an accuracy of a few centimeters. In that case, the CTRF will be consistent independent of the height system used.

A number of different techniques are currently used to determine the global geoid model. They are shown in conceptual form in Figure 9. Each technique contributes to a specific part of the gravity spectrum. Because of the attenuation of gravity with height, the spectral range resolved by every technique is dependent on the height of the sensor above the attracting masses. Therefore, measurements on the surface of the Earth or airborne measurements typically give better short-wavelength resolution than satellite measurements. The only exception is satellite altimetry which determines the geoid from direct measurements to the sea surface. Its wavelength resolution mainly depends on the size of the footprint. To resolve the whole spectrum, all techniques have to be combined. For the long-wavelengths the analysis of satellite orbit perturbations is still the most important method. Satellite altimetry resolves long and medium wavelengths over the oceans if a good model for sea surface topography is available. Mean gravity values cover the medium wavelength range on land. Finally, densely spaced point gravity measurements on land allow the resolution of short wavelengths. Absolute gravimetry is used on selected points to guarantee measurement consistency. Data from all these techniques are used for current global geoid models.

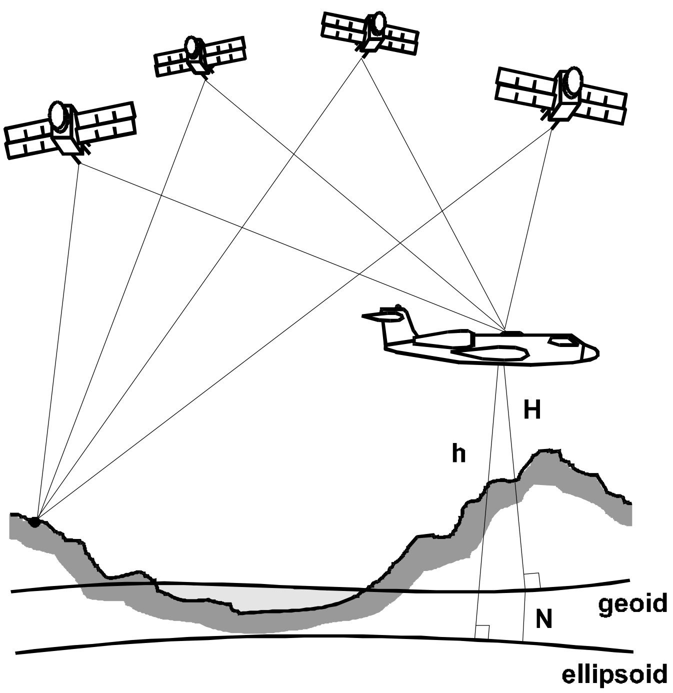


Figure 8: Heights in the Age of GPS – The Datum Problem (N)

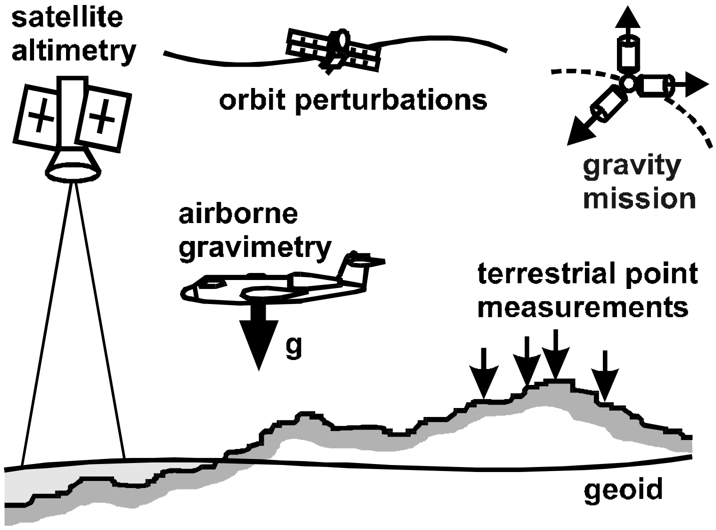


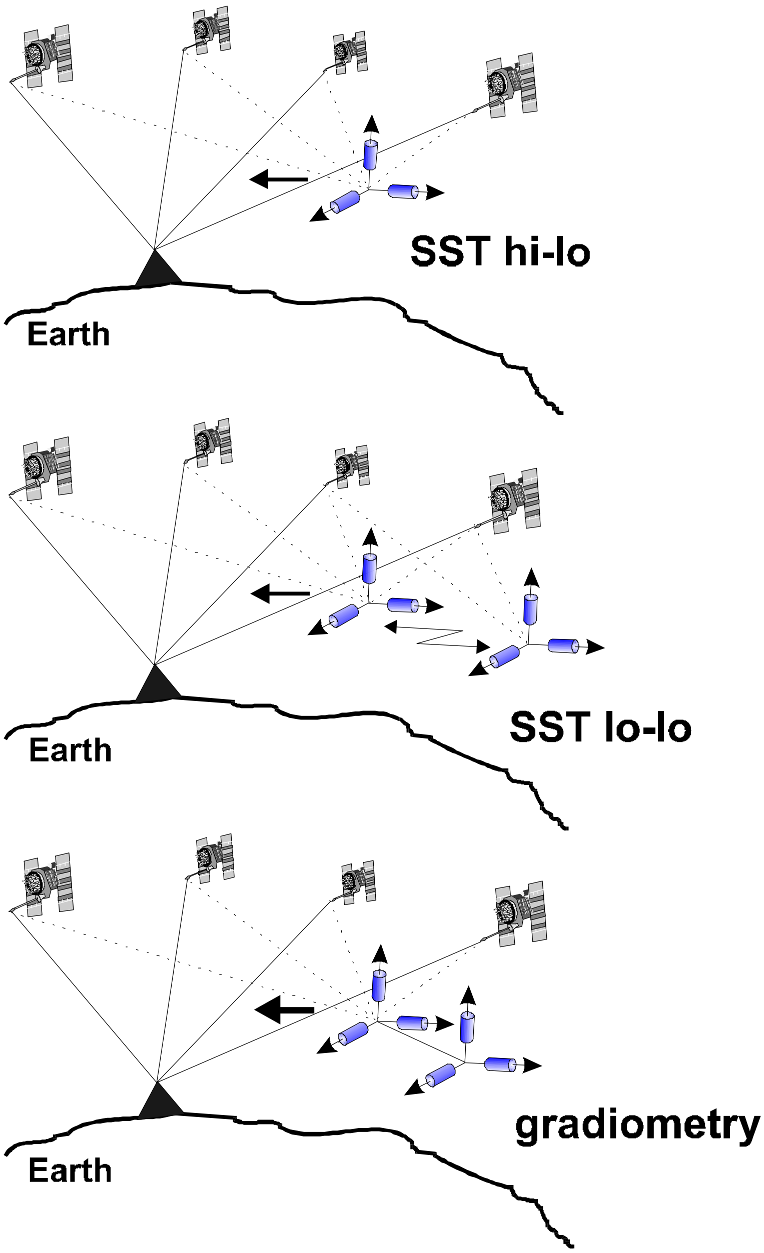
Figure 9: How is N Determined – Current and Future Gravity Methods

To improve current geoid models, new measurement techniques are needed. The most promising ones are airborne gravimetry and gravity satellite missions. The first is a local or regional technique, the second a global technique. In airborne gravimetry the acceleration output of DGPS and INS is differenced, resulting in filtered gravity along flight profiles. This method covers areas of up to 1000 km by 1000 km with gravity profiles and thus resolves half wavelengths between 8 km and 500 km. Dedicated gravity satellite missions use low-orbiting satellites to resolve the gravity spectrum to half wavelengths of about 80 km in the best case and about 300 km in the worst case. The two methods are therefore complementary with airborne methods covering the high frequency spectrum which cannot be resolved by satellite methods and part of the medium frequency spectrum where satellite methods are weak, and satellite methods covering the long and medium spectral ranges.

Currently three specific gravity satellite missions have been proposed, two of which are in an advanced stage, see Ilk (1998) for details. They are shown in schematic form in Figure 10. The first is the microsatellite CHAMP which will be launched this year by Germany and which will operate in a high-low mode. This means that the low-orbiting CHAMP satellite will be tracked by GPS satellites, thus eliminating one major error source, namely atmospheric effects. The perturbation analysis of the CHAMP satellite orbit will be supported by the output of an accelerometer triad on the satellite which will allow a better separation of non-gravitational forces. It is expected that this mission will improve the current global solutions by better decorrelating the medium wavelengths. It will not add decisively, however, in terms of minimum wavelength resolution. The second planned mission is GRACE, which will be launched in 2002 by the USA and will use a satellite-to-satellite tracking technique to resolve the gravity field spectrum. The distance between two low-orbiting satellites will be monitored by an interferometric microwave link. Variations in the measured range will be used to detect temporal variations in the gravity field spectrum and to improve its minimum resolution to half wavelengths of about 150 km. The third mission GOCE is planned by ESA and is scheduled to be launched in 2005. It will use satellite gradiometry to directly measure gravity gradients over a very short base in the satellite. The minimum wavelength resolution could be as low as 80 km. If all three missions go ahead, the complete gravity spectrum to half wavelengths of about 80 km and its major temporal variations will be determined. The combined solution would provide a much better global resolution of the gravity field and especially of the geoid than is currently available. The next decade would then rightfully be called the decade of gravity satellites.

Figure 11 shows the impact of the two new measurement techniques, airborne gravimetry and satellite gravimetry, on the accuracy of global geoid determination. Figure 11a compares four possible scenarios where the dark column indicates the worst case in each scenario and the white column the best case in each scenario. Starting with the currently best global model, the EGM 96, global standard deviations range from about 0.4 m to 1.5 m. As mentioned before these differences are mainly due to the differences in gravity coverage in different parts of the world. The second scenario shows the impact of the gravity satellite missions only. The range of values is much smaller now, between 0.35 m and 0.5 m, and is mainly due to the difference between the optimistic and the more guarded predictions. The accuracy in this case is more or less uniform over the globe. It would not be sufficient, however, to give the geoid transformation with centimeter accuracy. The third scenario shows the combination of the current global model with airborne gravimetry. It gives slightly better results than the previous scenario and has the advantage that it could be implemented right now. The difference between the best and the worst scenario is again due to the difference in EGM 96 accuracy in different parts of the world. The final scenario is the combination of airborne and satellite gravimetry which clearly gives the best results and achieves the accuracy required for height transformation. This means that the required accuracy in the geoid representation will most likely be reached in the next five to seven years, but only in areas where airborne gravity has been obtained or consistent ground gravity coverage is available.

Figure 11b gives best (dotted) and worst (solid) accuracy projections for the next six years assuming that the planned satellite missions are on schedule. Some improvements of the current global models can be expected around the middle of 2000 when the CHAMP data are integrated into the global solution. After that, improvements will be mainly due to the maturing of airborne gravimetry, until GRACE data come on line in about 2003. This will result in major improvements in geoid accuracy because of the better wavelength resolution. GOCE data will add to the high and medium frequency spectrum and, together with airborne gravity data, finally provide the accuracy required in the height transformation.



Orbit perturbation analysis

GPS tracking of satellite in high-low mode

CHAMP (GER) - 1999

Satellite-to-satellite tracking

Interferometric microwave link between two low satellites

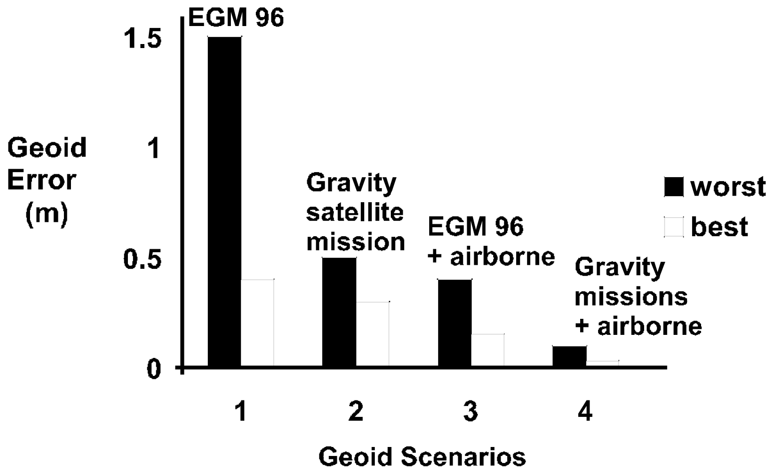
GRACE (US) - 2002

Satellite gradiometry

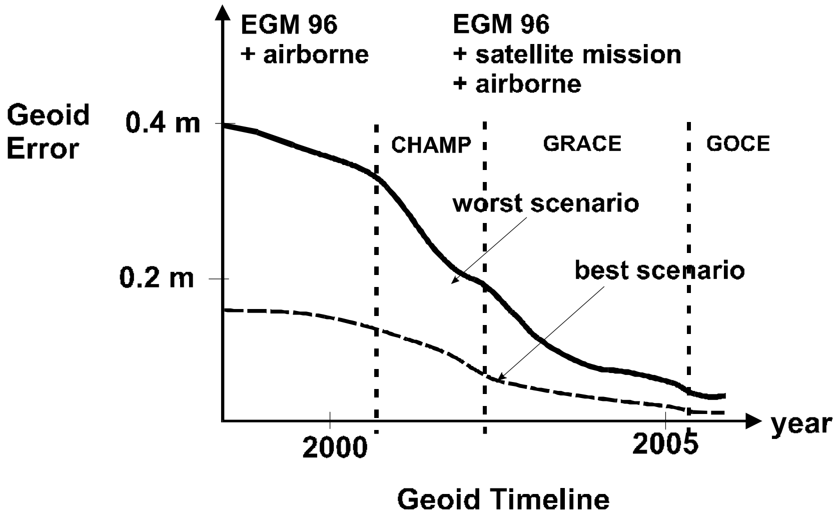
Direct measurement of gravity gradients

GOCE (EU) - 2005

Figure 10: The Decade of Gravity Satellites



(a) Near-Future Scenarios



(b) A Timeline for Geoid Accuracy

Figure 11: The Future of Geoid Determination

6. A Systems Approach to Helmert's Definition - Integrated Kinematic Mapping Systems

In chapter 2, three different views of interpreting Helmert's definition of geodesy have been outlined and some of their advantages and shortcomings have been pointed out. The resulting measurement and processing techniques, i.e. point positioning, photogrammetric mapping, and geoid determination, have been considered as essentially independent, even if their results were often combined in post mission. By combining the three methods, it is possible to come up with an integrated system to measure and map the Earth's surface that maximizes the advantages that each method offers without being affected by their drawbacks. It thus solves the problem contained in Helmert's definition. Such an integrated system can be designed in a number of different ways. The following conceptual discussion of an integrated airborne imaging system should therefore be seen as only one of a number of possible realizations. For more details and some results, reference is made to Schwarz (1998).

There are a number of theoretical and practical reasons why such an integration is advantageous. First of all, a highly accurate global reference frame now exists which can be accessed everywhere by using a GPS receiver as the measurement tool. Since GPS receivers work in kinematic mode, there is no reason to separate the positioning process from the imaging process. By operating in DGPS kinematic mode, with one receiver on the aircraft and one on the ground, there is no need to first establish control positions on the ground which then have to be identified in the images.

Instead, the perspective centre of the photogrammetric camera is determined by DGPS at the moment of exposure. This provides the first three parameters of exterior orientation in an accurate global reference frame (WGS 84). The other three parameters describing the orientation of the camera at the moment of exposure can be obtained by integrating an Inertial Measuring Unit (IMU) with DGPS and the camera. This has two major advantages. First, it is now possible to give each individual image its full set of exterior orientation parameters which means that any two images with overlapping image content can be directly used for mapping part of the Earth ‘s surface in a consistent coordinate frame. Thus, there is in principle no need for designing photogrammetric blocks and corresponding adjustment procedures to solve the problem. Second, such a system could also solve the vertical datum problem in an elegant way without the need for additional instrumentation. By differencing the output of the IMU and the DGPS, gravity at flight level can be determined from which a relative local geoid can be derived at ground level. By combining it with global information, as described in chapter 5, the transformation problem between ellipsoidal and orthometric heights can be solved. Thus, all measurements that are needed to map the Earth's surface in a consistent global frame can be taken from the same airborne platform. This will not only result in a much more homogeneous data acquisition process, but will also produce a much more efficient data processing procedure.

It has been mentioned already that an integrated kinematic mapping system is not restricted to photogrammetric techniques, nor to an airborne platform. Digital cameras have been used with a land vehicle-based system, and effective use of airborne geoid determination has been made in deriving orthometric DEMs by interferometric SAR. Figure 12 illustrates the latter application. Other systems use laser scanners, sometimes in conjunction with digital cameras, to solve the surface mapping problem.

In all these systems, the data acquisition and processing procedures are remarkably different from conventional methods. Because of the emphasis on point positioning and the type of equipment available for implementing it, conventional survey methods have always been sparse data techniques requiring considerable observational skill and attention to procedure. Since sparse data problems are best solved by least squares adjustment, this became the dominant, and in many cases the only, estimation method used in geodesy. All of this hardly applies to the new measurement systems. Instead of sparse data, redundancies in static positioning are enormous and data compression techniques are much more important in imaging than sparse data techniques. Bandpass filtering, wavelet methods and multi-scale estimation seem to offer much better solutions to these problems than least squares. Because of the large number of redundancies, not all of the data will be stored in the future and efficient and reliable methods of real-time data processing will replace current procedures. Similarly, observational skills have already now been largely eliminated from the measurement process and given way to automated procedures of real-time data checking. Because of the limited amount of automation currently implemented, much still depends on the knowledge of the system operator about the measurement process. It can be expected, however, that more of this know-how will be built into the software and human decision making and expertise will more and more shift to the planning and managing aspects of the problem. Since kinematic mappings systems either are or will be fully digital in the future, the pressure to produce results as fast as possible will result in much more emphasis on real-time data processing. It is conceivable, therefore, that real-time mapping systems for specific applications, such as forest fires, oilspill monitoring, etc, are a distinct possibility in the not too distant future.

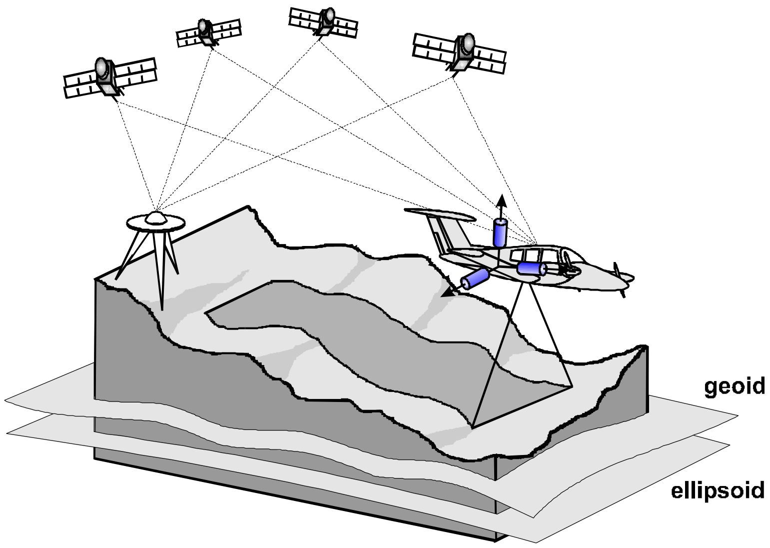


Figure 12: Interferometric SAR with a Geoid Reference

7. Towards an Integrated Geodetic and Geodynamic Observing System

In chapter 3, the establishment of an accurate Conventional Terrestrial Reference Frame (CTRF) and a corresponding motion model have been presented as one of the major contributions of space techniques to geodesy. The CTRF provides a framework in which spatial and temporal variations of the Earth can be precisely measured. How can these measurements be used in an enlarged concept of geodesy?

A couple of years ago, Rummel (1998) published a paper in which he proposed an integration of all geodetic data and techniques, conventional as well as space based, into a Global Integrated Geodetic and Geodynamic Observing System (GIGGOS). Such a system was meant to focus all current geodetic activities in such a way that they would become identifiable as geodesy's contribution to international science. The diagram presented as Figure 13 shows the major components of such a program and indicates the interactions that define it as one system. The following summary of some of the main characteristics of such a system is based on Rummel's original paper.

The four components, indicated as Frame, Earth rotation, Geometry and Kinematics, and Gravitational Field, will be briefly discussed. At the centre of this system is a well-defined and reproducible global terrestrial frame which provides the reference for the observing systems and a framework for modeling Earth processes. Its accuracy and stability affects the accuracy with which the other three components can be modelled. The establishment and maintenance of such a reference frame will be done by a combination of space techniques, such as VLBI, SLR, LLR, GPS, DORIS, PRARE. Closely related to the frame definition is the determination of Earth rotation as the integrated effect of all angular momentum exchange inside the Earth, between land, ice, hydrosphere and atmosphere, and between Sun, Moon, and planets. The measurement systems are the same as for the frame determination, but will be augmented by geodetic astronomy and emerging accurate ‘super-gyros’. The geometry of the Earth and its temporal variations would include models for the solid Earth, ice sheets, and the ocean surface and their change in time and space whether secular, periodical or instantaneous. All conventional and space point positioning techniques will contribute to this modelling process as well as surface measurement techniques, such as satellite altimetry, interferometric satellite techniques, and remote sensing. Finally, the gravity field of the Earth and its temporal variations will require models for mass balance, fluxes, and circulation patterns which put constraints on the geokinematic models. The required measurement systems have already been discussed in chapter 5. The largest future contribution to the global gravity field representation is expected from the proposed gravity satellite missions. For the numerous interactions between the components of GIGGOS indicated by arrows, the paper by Rummel (1998) should be consulted.

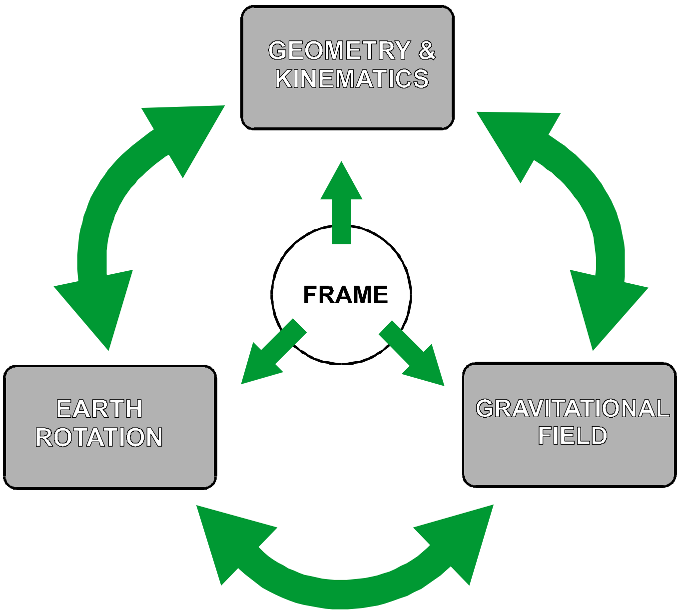


Figure 13: Towards a Global Integrated Geodetic and Geodynamic Observing System
Adapted from Rummel (1998)

The idea of coordinating and focusing geodetic activities under such a concept have generated a lively discussion inside the International Association of Geodesy. Some of this discussion is captured in Beutler et al (1998) and in some other papers of a recent IAG/Section II symposium in Munich (see IGGOS, 1998). Such a system is attractive to many researchers because it

- could become the focal point for research activities within the IAG, including much of the current research, and would accelerate the integration of classical and space measurement techniques.
- would more clearly identify the IAG contribution to Earth system science and show that the interaction of IAG with other Earth sciences goes well beyond data delivery.
- would recognize that the contribution of geodesy goes beyond solid Earth research.
- would, on the one hand, use the metrology tradition and strengths of geodesy and, on the other hand, open new vistas and challenges for young geodesists.

Such a program would emphasize the science tradition of geodesy which has been a strong component of geodetic activities since the Internationale Erdmessung was founded about one hundred years ago. With time, it would considerably extend the impact of geodesy on other branches of the Earth sciences and accelerate the cooperation between national agencies contributing to such an enlarged concept of geodesy. The engineering tradition of geodesy which also has strong roots in IAG would not be enhanced in the same way. This does not mean that its influence would dwindle. As indicated in the previous section, there are many challenging tasks in accurately representing the Earth’s surface and its temporal change for local applications. These applications will continue and will profit from a better understanding of the processes that are at the root of change. In the long term, they will be needed to describe the fine structure of the Earth’s temporal variations.

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