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Edited by Somdev Bhattacharji, Gerald M. Friedman, Horst J. Neugebauer and Adolf Seilacher

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E. Groten R. Strauß (Eds.)

GPS-Techniques Applied to Geodesy and Surveying

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Prof. Karl Rinner
dedicated on the occasion of his

76 birthday.

Prof. Rinner had planned to attend this meeting but was finally unable to do so because of illness.

C O N T E N T S

Appendix: Field Measurements

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Opening Address

Opening address

by E. Groten

Local Organizing Committee

On behalf of the Local Organizing Committee, I welcome you all to the first International Workshop on GPS-techniques in surveying and geodesy held at this university. This workshop is designed to bring together experts from various countries and also scientists who carry out, analyze and interpret such measurements with those who work on instrumental and theoretical problems. The workshop focuses hereby on high-precision applications with emphasis on monitoring time-dependent phenomena such as those relevant to geodynamics as well as men-made constructions as those in civil engineering and similar fields. It is astonishing to see how, in spite of all earlier satellite work over the last two decades, GPS-methods became so fast a relevant new technology, in its proper sense, in modern geodesy and surveying besides VLBI and Satellite Laser Ranging (SLR). With the recent development of new dual-frequency receivers the role of GPS-procedures in monitoring large-scale phenomena over big distances will still expand; and the application of kinematical GPS-approaches is of utmost interest in solving high-precision problems. It is indeed fascinating to realize how GPS-methods have become in such a short time a surprisingly efficient and effective, this means : fast, precise and easy to apply, tool which is able to replace already now, after a few years of existence and with an incomplete set of a few out of the 18 satellites (of the final stage), at least partially some expensive, slow and cumbersome classical surveying methods.

On the other hand, it cannot be overemphasized that GPS-procedures are still at their beginning and the full spectrum of their capabilities still has to be explored. In Europe, for example, where excellent classical surveying systems do exist the situation is quite different from the situation in other countries such as Canada or the USA. Even within Europe the application types of GPS-methods will vary; for example, in Norway the situation is quite different from central European countries.

It is often forgotten, that together with GPS we will have to introduce new concepts and a new thinking in combination with other modern satellite procedures. GPS itself can resolve only a small part of the problems to be solved by modern geodesy but it will open the way to a great variety of new applications and capabilities. Modern global tectonics is just one of the new disciplines of high interest and great practical impact. I could continue in citing other similarly important new fields. GPS is, however, of special importance because it replaces old technologies and fills gaps where modern and efficient tools are most needed.

Consequently, also the optimal combination of GPS-methods with new auxiliary and also classical high-precision techniques is of great importance, mainly under the european conditions outlined above. Moreover, the real-time or almost-real-time use of GPS in combination with photogrammetry, inertial geodesy, gravity gradiometry or even classical surveying is of substantial interest.

It is indeed important to realize the new concepts in modern satellite and space methods and I, therefore, spoke above of a new "technology" which should be optimally developed as there is a worldwide need of such capabilities and tools.

In view of the few active NAVSTAR-satellites in sky in 1988 this is perhaps not the best year for GPS-applications but the right time for a review of the experience gained until now and using it as a base for the planning of the future.

This meeting is designed as a typical workshop with about 48 presentations and only a small informal opening session, a few social events in order to enable the participants to exchange ideas even in the evening and practical demonstrations and measurements. Thus, we face a heavy program.

I express my sincere thanks to the sponsoring organizations, who made this meeting of scientists from 18 countries possible. I am particularly thankful to the president of the host university, Prof. H. Boehme, that he found time to welcome you here. I also appreciate that IAG is represented here by its 1st Vice-president Prof. W. Torge. Furthermore, I am indebted to the Hessisches Landesvermessungsamt for the efficient technical support in view of the field demonstration.

Moreover, I welcome the representatives of the industry who help to make this a real application-oriented but truly scientific workshop with a lot of practical demonstrations.

Finally, I welcome especially the colleagues from developing countries such as Brazil, China, etc. I am also happy that many young scientists are here.

We have here speakers from 14 nations and an audience consisting of about 20 nations. As we are still at the beginning of a new era in modern geodesy it is so important to lead these new efforts into the right direction in order to make them as efficient as possible. We focus here on a particularly sensitive and crucial part of this approach. I wish a good, fruitful and enjoyable meeting to all of you!

Welcome Addresses

Ladies and Gentlemen,

it is a great pleasure for me to welcome you here on behalf of the Technische Hochschule Darmstadt. We are proud to be host to the International Workshop on Global Positioning System Techniques in Geodesy, and I express my warmest thanks to my colleague, Professor Groten, and his collaborators for preparing, organizing and leading this important meeting. Under the protection of the International Association for Geodesy you will discuss during the next few days quite new possibilities of measurement-methods by satellite and their applications which promise your science interesting and various aspects for the future. I hope that this workshop will be very successful and increase the scientific understanding.

You have come to Darmstadt from many nations all over the world, and with a few words I'll try to introduce you our town. Surrounded by the recreational areas of the Odenwald and the Bergstraße, the Taunus and Spessart, Darmstadt is favoured not only by nature, having a mild climate and fertile countryside, but is also particularly conveniently placed for travel, being in the centre of the Federal Republic, between the industrial regions of the Rhein-Main and Mannheim-Ludwigshafen, with easy access to the cities of Wiesbaden, Mainz and Frankfurt. The town, with 135.000 occupants, compact and friendly, promotes itself with the ambitious slogan, "the arts live in Darmstadt". Its air of culture as well as its predominantly white collar nature are a legacy from its past as a grand ducal residence. There is much which bears witness to this: the Art Nouveau ensemble at Mathildenhöhe; the Rosenhöhe artists' quarter, home of painters, sculptors and writers; the high-quality collections and museums; the educational system, highly developed at all levels, and the Land Theatre, whose prestige extends far beyond the city limits, and which is regarded as a springboard to the very top.

However, science is also well represented in Darmstadt. The Technische Hochschule Darmstadt counts more than 16.000 students and about 1.500 scientists. Besides the THD two Technical Colleges are well-respected centres of education. Darmstadt is home to the technical facilities of the Post Office. The accelerator of the Society for Heavy-lon Research - situated in the woods outside the city - is the workplace for many scientists from near and far. Finally, on a truly international note, there is the Europeans Space Operations Centre - likewise in Darmstadt. At ESOC the take offs of the European carrier rockets and the functioning of geostationary satellites are monitored. Among other things, ESOC provides German television companies with satellite photographs of the weather.

Research and Development are however not a concern only of scientific bodies, but also of industry. Darmstadt is the site of some particularly future-orientated branches of industry. The chemical industry occupies first place with several multinational companies. Reputedly the specialized engineering firms can produce here free of competition. A great deal of innovative force is behind the young enterprises working in the fields of telecommunications and computer science. After 1945 the graphic trades (publishing, printing, paper processing) settled in Darmstadt. Naturally there is a great deal of very varied contact between the University and local business and industry, to their mutual benefit.

Ravaged in the war - in a single night of bombing in September 1944, the whole of the city centre was laid to waste - Darmstadt is once more a lively, cosmopolitan community with an air of innovation. Progressiveness is the factor uniting the city's "great sons", predecessors to which the city readily refers, even if they did not have it easy here in their own time: Justus Liebig, the founder of agricultural chemistry and reformer of scientific education; Georg Christoph Lichtenberg, the physicist and aphorist; and Georg Büchner, the doctor, poet and revolutionary. They all straddled the border between the exact sciences and the fine arts, and set standards to which the University also feels a commitment: the endeavour - to be taken up time and again - to reconcile engineering and the humanities, the union of technology and society.

I hope you will like your visit in Darmstadt and its Technische Hochschule.

Prof. Dr. H. Böhme

President of the Technische Hochschule Darmstadt

MORE THAN FIVE YEARS OF GPS-EXPERIMENTS - RETHINKING OF GEODESY

by

Wolfgang Torge

Dear Colleagues,

since GPS installation started 15 years ago, and with geodetic GPS-experiments performed over more than 5 years, we all are aware of the possibilities which this space based positioning system offers to geodesy, and we foresee - at least partially - the changes which classical geodetic dogmas valid for more than 100 years, are going to experience. The geodetic community has early recognized the challenge of this new technique, as documented by numerous research activities and GPS related scientific meetings, attracting geodesists from research and application orientated institutions, as we see here.

It is a great pleasure for me, to sketch in this introduction the impetus of GPS to geodesy, and to indicate some of the problems which you will discuss later in more detail. But before, I should like, as the first Vicepresident of the International Association of Geodesy, to deliver you the greetings and best wishes for a successful meeting, from the IAG President and IAG Bureau. As the Chairman of the German Geodetic Commission at the Bavarian Academy of Sciences, I add the welcome greetings of that representative body of geodesy in the Federal Republic of Germany. We are thankful to Professor Groten for his initiative to organize this workshop in our country, where intensive GPS research is under way since some years, and we are happy about this positive response, from inside our country and from abroad.

Now, let me try to indicate how the potential possibilities of GPS-techniques are going to change geodesy, although we certainly do not yet know the final result of the presently occuring collision between classical and modern concepts.

Since the first establishment of classical control networks for position and height, about 100 years ago, the pre-satellite era which lasted approximately until the 1960s , was characterized by

- employment of time-consuming terrestrial observation techniques, with days to weeks per first order trigonometric point determination, and 5 to 10 km first order levelling progress per day, direct line of sight between neighbouring stations being necessary,

- changing orientation provided by the local plumb line direction, corresponding to the use of numerous local astronomical systems,

- separation of position and height control systems, with geometric (ellipsoid) resp. physical (geoid) reference surfaces, thus in a clever manner minimizing the effect of the gravity field on the derived parameters, as a first order approximation allowing to neglect them,

- relative accuracies referring to the station distance of $\pm 10^{-5}$ for positions, only in local high-precision networks observed with electro-optical distance measurement equipment $\pm 10^{-6}$ has been reached, while $\pm 10^{-6}$ to $\pm 10^{-7}$ for heights could be obtained by first order levelling,

- global orientation through astronomic methods for position networks, and through oceanographic information for height networks, with discrepancies up to ± 10^{-4} in position resp. ± 10^{-7} in height with respect to a common global system,

- monitoring time variations of the orientation of a global reference system with a relative accuracy of ± 10^{-6} , by an astronomic control system.

With these features, position and height control networks met, for more than 100 years, the needs of administration and development in countries being at the transition from rural to industrial societies, and even served most of the requirements in more industrialized regions. A number of severe drawbacks became obvious with the rapid changes which human society experienced after the 1950s.

These drawbacks of the classical geodetic control are:

- the extremely slow progress at the establishment of control networks, especially if a dense station distribution (e.g. 1 to 5 km) is demanded,

- the complex error accumulation at larger networks, leading to changes in network scale and orientation, and to unpredictable network distortions, and causing severe problems at subsequent surveys in highly developped and densely populated areas,

- the weak ties of the national position control systems to a common global reference, with discrepancies no longer acceptable for modern navigation,

- the inability to investigate recent crustal movements at global and regional scales, being the strongly required geodetic contribution to geodynamics research, and needed for monitoring movements in connection with seismic and volcanic events, as well as those produced by man-made environment changes.

The following pre-GPS satellite era from approximately 1960 to 1980 already brought partial improvements to this situation, first through optical and then - more effective - through Doppler satellite positioning methods. Main characteristics have been

- the more rapid point determination, taking few days per station at high accuracy demands, with no need for visibility between stations,

- the common orientation in a global reference system with ± 10^{-6} to 10^{-7},

- absolute point determination accuracies of 1 to 5 meters, and relative accuracies of some ± 10^{-6} for distances from 100 to 500 km.

Consequently, classical control networks could now be controlled at distances larger than 100 km, and transformed to a global reference system. With absolute point positioning accuracy, control point requirements for topographic mapping could be fulfilled now. But probably most important was that threedimensional satellite technology forced geodesy to a threedimensional way of thinking, and corresponding modelling of geodetic observations and parameters.

After that transition epoch from classical to space techniques, space geodesy era started about 1980, covering now local, regional, and global scales. For most users of geodetic products, GPS-results are of special interest, as for local and regional problems with distances between 1 and some 100 km, this technique now offers rapid solutions with accuracies sufficient for most purposes. The main characteristics of this space geodesy era may be described as follows:

- monitoring the motions of the global geodetic reference frame in space and of large-scale tectonic plate movements through advanced space techniques, with approximately $\pm 10^{-8}$ to 10^{-9} (Satellite Laser Ranging, Very Long Base-Line Interferometry) relative accuracy, but with still large investments in hardware and operational costs,

- three-dimensional positioning through GPS-methods, delivering within short time (few minutes to hours) relative accuracies of $\pm 10^{-6}$ to 10^{-7} for distances from 10 km to some 100 km, and with cm-accuracy at 1 to 10 km distances,

- employment of GPS-techniques in the kinematic mode, giving relative navigation accuracies of ± 1 m in position, and ± 0.1 m/s in velocity.

As one example of the high efficiency of GPS-methods, I mention the European north-south-GPS-traverse, which has been proposed for regional geoid control few years ago by a IAG-Special Study Group chaired by Professor Birardi. The central and northern part of this traverse, between Austria and northern Norway, has been observed in 1986/1987, under direction of our Institute, and in cooperation with Geodetic agencies and institutes of Austria, Denmark, Norway, Sweden, and the Federal Republic of Germany. Using two or more TI-4100 receivers, and simultaneously observing adjacent (appr. 50 km station distance) and overlapping connections, the evaluation was performed with the Hannover-software. Preliminary height results have been compared with the normal heights obtained from the Unified European Levelling Network, and the gravimetric geoid heights of our EGG1-solution. For the 3600 km long traverse part, the r.m.s. discrepancy was only ± 0.67 m, which reduced after a tilt (-0".13 corresponding to -0.6 m/1000 km) to ± 0.27 m, thus revealing a high accuracy of GPS heights and of the European geoid.

We have to state some consequences of this recent developments:

- highly efficient space techniques now have reached and, at regional and global scales, far exceeded the accuracies of classical geodetic methods,

- geodetic control systems established through space methods are a priori three-dimensional, with global geocentric orientation, and may be subdivided into a global reference network monitoring time variations of global character, and regional/global networks, eventually composed of a base network (GPS reference stations) and densification nets,

- with navigation potential offered by GPS,kinematic survey methods of operational or experimental stage may get a substantial support, with eventual drastic change of methods; this refers to inertial surveying (position updating and gravity vector separation), photogrammetry (orientation), and airborne gravimetry and gravity gradiometry (orientation, Eötvös-correction, separation of gravity and disturbing accelerations),

- geodetic contributions to geodynamics research become more efficient now, as high resolution data aquisition in space and time is possible, with the chance of eventual continuous monitoring the earth surface, at least in areas where large movements occur.

But, before handling the new tools with maximum efficiency, taking the boundary conditions of existing survey systems into account, a lot of problems still has to be solved. Let me mention some of them, which are related to GPS:

- optimal GPS-network design, with optimization strategies for observation time per station, satellite constellation, and network configuration including the question of optimum station distance and overlapping connections, and use of one- and two-frequency-receivers,

- optimum combination with existing classical control networks, and available terrestrial survey methods, as electronic distance measurements, levelling, and inertial surveying, or eventual superseding of them,

- software improvements for functional and stochastic models, in order to get reliable results at least at the "cm"-level, and realistic accuracy estimates, including the cycle-slip problem, closely connected to site selection,

- implication for the classical philosophy of "geometric" position and "physical" height control systems, including the question of site coincidence of the control points, and high-precision geoid determination,

- additional measures as improved orbit determination at regional geodynamics investigations including investigations about the long-time stability of the GPS-system,

- implication for kinematic survey methods, which eventually in further future may enable these methods also to monitor time variations of the earth surface and gravity field.

Many of these problems will be discussed here, and I hope that at least for some problem areas, the outcome of this workshop will set one step further to new concepts in operational geodesy. I wish you fruitful discussions and full success for the workshop.

Welcome

Robert Strauß

President of the "Arbeitskreis Triangulation of the "Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland"

Ladies and gentlemen,
dear colleagues,

It is a great pleasure to me to welcome you on behalf of all those colleagues, who are responsible for the control network of the Federal Republic of Germany. You certainly will know, that there is no central administration, which is responsible for the surveys in our country. Instead of that we have a working group which is called "triangulation" and which was established in 1949 by the gouvernments of the federal states. It is the task of this working group to achieve standard regulations for keeping the field of trigonometric points in a similar type in all the federal states. The last result of our cooperation is a rough draft for applications of GPS in the control network of the Federal Republic of Germany. You can read it in number 2 1988 of the Zeitschrift für Vermessungswesen. For that reason I dropped my report, which I prepared for this workshop. The essential goal of our draft is to prevent the establishment of additional new reference systems by private users of GPS. We suppose that this is possible by the establishment of a GPS-basenetwork and the determination of precise transformation parameters between the reference system of the GPS, the World Geodetic System 1984 and the official reference system, represented by our first order network. We think that a world-wide or at least an european cooperation is necessary. That is why we are very interested to discuss problems like orbit determination or threedimensional reference systems. The program of this workshop shows that these are not only problems to be solved. We should take time by the forelock until the 18. satellite starts developing theory and gathering practical experience. There ist not a shadow of a doubt that then GPS-applications will spread out. The working group I am representing here then no longer will be diveded into two parts, some already using GPS and others being eaten up with envy.

I wish three days of effective work, good results, a pleasant stay to all participants and the expected success to Professor Groten.

First session: General Aspects

Chairman: Prof. Kakkuri, Helsinki

GEODETIC APPLICATIONS WITH GPS IN NORWAY AS PART OF A GLOBAL COOPERATION

by

K. Aksnes, P. H. Andersen, S. Hauge

and

B. Engen

Abstract

The Norwegian Defence Research Establishment (NDRE) and the Norwegian Mapping Authority (NMA) have undertaken a joint project in satellite geodesy in cooperation with several geodetic groups in Europe and the U.S. Simultaneous GPS tracking is now being routinely performed with TI-4100 receivers located in Tromsø and at Onsala, Wettzell and five North-American VLBI stations. In Norway, NMA is in charge of data collection and is operating GPS reference stations in Tromsø and at Onsala. An orbit computation service is also being planned. NDRE is responsible for development, testing, and special applications of the GPS data analysis tools. At the core of these applications is a computer program,GEOSAT, for high-precision calculation of orbits and associated geodetic parameters, based on a variety of satellite tracking data. Results are presented from use of this program on a TI-4100 data set acquired at three VLBI stations in the U.S., 3-7 June 1986.

1. Introduction

Even during its current experimental phase, the Navstar Global Positioning System (GPS) has already become an important tool for ship navigation and marine charting with the ice-going vessel R/V Lance of the Norwegian Hydrographic Service. GPS is also rapidly replacing other methods used by private surveying companies for precise offshore positioning of oil rigs and of vessels engaged in towing, pipe-laying or oil exploration on the Norwegian continental shelf.

The usefulness of GPS was rather dramatically highlighted a few years ago when sea level measurements indicated that the oil rig Ekofisk in the North Sea was sinking at a rate of several decimeters per year. By means of differential GPS, it was found that this subsidence amounted to about 40 cm per year relative to a nearby oil rig which was believed to be stable. It would have been much more desirable to refer the Ekofisk motion to the Norwegian mainland some 300 km away, but to achieve a relative positioning accuracy of, say, 3 cm over this baseline length would have required a 0.1 ppm performance. This can only be done based on very precise Navstar satellite ephemerides. This and other high precision positioning needs of vital importance to the offshore oil industry incited an early interest in GPS tracking and orbit improvement in Norway.

But Norway also has a need for GPS to solve a much more fundamental problem; namely the establishment of an improved national first order geodetic network and its representations in local, regional, and global datums, respectively NGO-48, ED-50, and WGS-84. NGO-48 and ED-50 are based on essentially the same first order points in Norway determined astronomically and by triangulation. NGO-48 suffers from scaling errors up to 40 ppm, but ED-50 is more uniform. Maps and coordinates for offshore navigation and positioning are based on ED-50. Under the auspices of the RETRIG subcommission of IAG, improvements have been made in the ED-50 system by means of trilateration and satellite techniques. However, the time now seems ripe to switch to an entirely new European Datum based on VLBI, SLR, and GPS techniques (Landau and Hein 1986, Boucher and Altamimi 1986).

In Norway the most stringent demands for accurate geodetic reference systems come from oceanographers interested in tracking currents, eddies and storm surges by means of altimetry in satellites. This requires very precise knowledge of the marine geoid, which is also of interest to oil prospecting because of the relationships between the shape of the geoid, gravity anomalies, and oil bearing structures below the oceans.

2. National Cooperation and Goals

The main responsibility for establishing and maintaining geodetic reference systems and for charting and map production on Norwegian territory and in territorial waters lies with the Norwegian Mapping Authority (NMA). This includes both civilian and military applications. NMA has recently acquired five TI-4100 receivers and has partime access to two more. With this equipment NMA is now engaged in an international measurement campaign to be described later.

The Norwegian Defence Research Establishment (NDRE) is responsible for developing and testing algorithms and software for high precision analysis of GPS data. Initially most data processing will be done at NDRE, but routine data processing will later be taken over by NMA. At the NDRE Mathematics Section, a computer program (GEOSAT) for precise analysis and simulation of satellite tracking data has been under development for several years (Andersen 1986). A brief description of the GEOSAT program along with some test results are given later.

NDRE is heading a joint Norwegian geodetic experiment aimed at using laser, PRARE and altimetry data on ESA's ERS-1 satellite for point positioning and orbit and geoid determination. GPS measurements are an important pre-launch part of this experiment. The joint GPS and ERS-1 goals include

- differential GPS positioning relative to VLBI sites of designated GPS and ERS-1 reference stations in Tromsø, Stavanger, Jan Mayen, and Svalbard
- orbit calculations for GPS and ERS-1 and precise positioning of secondary geodetic points by means of differential GPS and PRARE measurements relative to the reference stations
- calulation of precise geoid, datum parameters and transformations between local (NGO-48), regional (ED-50), and global (WGS-84) reference systems

3. International GPS Tracking

Since December 1987, two of NMA's TI-4100 receivers together with six such receivers owned by other nations have been in permanent operation at the following seven VLBI sites plus Tromsø Satellite Station:

Westford, Massachusetts
Richmond, Florida
Austin, Texas
Mojave, California
Yellowknife, Canada
Onsala, Sweden
Wettzell, W. Germany
Tromsø, Norway

Additional VLBI sites on Hawaii and in Japan, Australia, S. Africa, Spain and China will or may take part during October 30 to November 19, 1988 in a campaign (Mader 1988) referred to as the first GPS Global Orbit Tracking Experiment (GOTEX-1). During this campaign there will be locally organized regional campaigns in secondary reference networks. The main goals of the campaign are :

- the evaluation of the primary Mark III VLBI network for the determination of GPS orbits

- the comparison of regionally determined orbits to these global orbits

- the first epoch measurements of new primary fiducial sites and the establishment of secondary reference networks

- a more accurate relationship between the WGS-84 and the VLBI systems.

In March 1988 representatives from the geodetic communities in Norway, Greece, and Spain met in Norway and issued a Memorandum of Understanding (MOU) concerning a European Tracking Experiment (EUTREX) with GPS receivers in Tromsø and at the Dionysos SLR station and the Madrid VLBI station. During an initial experiment in the second half of 1988, NMA will station three of its TI-4100 receivers at these three sites. The MOU also invites participation from other nations. At the time when the MOU was issued we were unaware of the GOTEX-1 campaign which, however, fits nicely in with our initial experiment. NDRE's GEOSAT software will be used for data analysis.

4. <u>The GEOSAT software system</u>

The GEOSAT system has been described elsewhere (Andersen 1986) and we shall therefore mention only a few of the main features. GEOSAT is implemented on a Norwegian manufactured computer, ND-570, and it consists of approximately 70000 FORTRAN statements.

The system can be applied in three different modes : estimation, simulation (in which synthetic observations are generated) or for error analysis. The GEOSAT system includes what we believe are the best available mathemathical models (generalizations of the MERIT standard) formulated in a general relativistic PPN-framework.

The system is a multi-station and multi-satellite tool which can handle several types of modern tracking data, including laser and microwave range, doppler, phase and altimetry, in a simultaneous manner. Single, double and triple differences can be generated for most of these measurement types. In the future also satellite gradiometry and possibly surface gravimetry will be implemented.

The estimation scheme is a three-level partitioned Bayesian weighted least squares method in which the model parameters can be treated as either "solve-for" or "consider" global parameters (fixed values for the whole dataset), arc parameters (fixed values for a part of the dataset) or local parameters (fixed values for each observation set).

Among the parameters that can be treated as either solve-for or consider parameters are orbital elements, surface scaling parameters for radiation pressure modelling, polynomial coefficients and trigonometric amplitude and phase for modelling empirical accelerations, gravity parameters, station and satellite oscillator parameters, earth rotation parameters, phase biases and rates, tropospheric scaling, baseline vectors, absolute coordinates and tidal parameters.

4.1 The Dataset

The GPS dataset consisted of pseudorange and phase measurements on both L1 and L2 from three TI-4100 receivers located in Westford, Richmond and Fort Davis during five days in June 1986. The receivers were equipped with Hydrogen-Maser oscillators. The available dataset is presented in Table 4.1. Note that the D-passes (day) usually involve only one or two satellites during a short time period.

PASS	1001						1002						1003						TEST		
	6	8	9	11	12	13	6	8	9	11	12	13	6	8	9	11	12	13	A	B	C
154N	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	A	B	
154D			*		*				*		*						*		A		C
155N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	A		C
155D									*		*						*		A	B	
156N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	A	B	
156D			*		*				*		*						*		A		C
157N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	A		C
157D			*		*				*		*						*		A	B	
158N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	A	B	
158D			*		*				*		*						*		A		C

Table 4.1 The dataset

Since GEOSAT is a general-purpose software system not restricted to any specific satellite system, the TI-measurements were preprocessed by a program called PREPARE. This program re-formats the data and calculates station oscillator polynomials and, optionally, also preliminary station coordinates using pseudorange. PREPARE also corrects the phase measurements for cycle-slips, and it can generate normal points at the frequency chosen by the program operator. Normal points were generated every 10 minutes in this investigation.

For the purpose of getting some realistic knowledge about the accuracy of the calculated orbits, we performed three separate tests denoted A, B and C (see Table 4.1). Note that test A contains all data and that the datasets of B and C are independent. Furthermore, note that test B contains three N-passes (night) and C only two N-passes during a period of five days. Only SV9 and SV12 are present in the D-passes.

4.2 Data Processing Strategy

There are several problems connected with the reduction of GPS measurements. Multipath is reported by many authors to be a significant problem (Evans 1986) for pseudorange measurements obtained with the standard TI-antenna. The RMS due to multipath on pseudorange is reported to be around 1.3 m or worse. We have used normal points every 10 minutes to try to smooth high-frequency multipath effects. So far, this procedure does not seem to give any major improvement, so we think that the dominant multipath effects must be of lower frequency. Papers presented at a GPS workshop at JPL in March 1988 seem to be consistent with this hypothesis.

Another very serious problem is that the TI-receivers sometimes lose lock on the satellite signal and this causes cycle-slips. Most of these cycle-slips are corrected in PREPARE to an accuracy which is always better than five cycles, and usually better than two cycles. The cycle-slips are detected by comparison of the pseudorange rate of change with the corresponding phase rates. Also single differences between stations are used in this process. The corrections are obtained by polynomial prediction and interpolation. The cycle corrections are usually checked on a graphical display, and in a very few cases it is necessary to do some manual editing. If necessary, it is possible to correct for earlier erroneous cycle-slip corrections in each iteration in GEOSAT. In the last few iterations, the model parameters are well determined and the conditions for sucessful cycle-slip correction are the very best.

In the first few iterations of GEOSAT, only pseudoranges are used to calculate orbital elements, radiation pressure parameters, ionospheric corrections, satellite oscillator polynomial coefficients (1. order polynomial) and station oscillator polynomial coefficients (2. order polynomial) using known reference stations. Then pseudorange and phase on both L1 and L2 are processed simultaneously to solve also for phase biases and improved ionospheric corrections. This procedure seems to reduce the RMS due to ionospheric errors by a factor of two.

The arc length was five days and the oscillator parameters for both stations and satellites were updated on every pass. Only raw measurements were applied with no differencing.

In this investigation we applied models for the earth gravity field (8 x 8, part of the WGS84 standard) and the MERIT models for ocean and solid earth tides. The station coordinates were supplied by NGS in the WGS72 system. We transformed the coordinates to WGS84 by adding a 4.5 m correction in the z-direction. Due to this procedure, the coordinates might be in error by several decimeters with respect to WGS84.

4.3 Results

We have determined the orbits for test sets A, B and C. The calculated orbits were stored on files and compared globally. Table 4.2 columns A-B, A-C and B-C shows the RMS of the corresponding orbit differences. Comparing A-C and B-C, we see that the numbers are quite similar. The A-B column shows small numbers and since test set A is expected to give the best results, we conclude that test C gives good orbits only for SV11 and SV13. Even though set B contains approximately 50 % of the data from set A, we believe that both A and B give orbits better than 10 meters (1 σ). We also see that the formal errors from the A, B and C tests are very realistic when compared with the "actual" orbit error. This leads us to conclude that the orbit errors for solution A might be in the range 2- 5 meters for all satellites, except possibly SV6 and SV8 for which there is only a small number of measurements.

SV	FORMAL ORBIT ERROR (M)			ACTUAL ORBIT ERROR (M)		
	A	B	C	A-B	A-C	B-C
6	4.99	5.86	85.94	11.58	99.55	98.18
8	9.77	13.03	37.97	5.96	29.65	29.50
9	2.67	3.46	4.67	3.06	12.04	13.98
11	2.72	3.30	12.99	5.44	3.51	7.97
12	2.61	4.16	3.71	4.95	25.77	27.78
13	3.35	4.10	8.11	4.43	4.49	8.01

Table 4.2 Orbital results

The a priori standard deviation of all the measurements were assumed to be 1 meter when used to calculate the formal errors.

Figures 4.1 - 4.3 show the orbit differences for test A and B in the radial, along-track, and cross-track directions. Note the short-period differences with a period of 12 hours and also the secular drift both in the along-track and in the radial directions. The "hairy" high-frequency oscillations starting at 100000 seconds are due to roundoff in the output of GEOSAT.

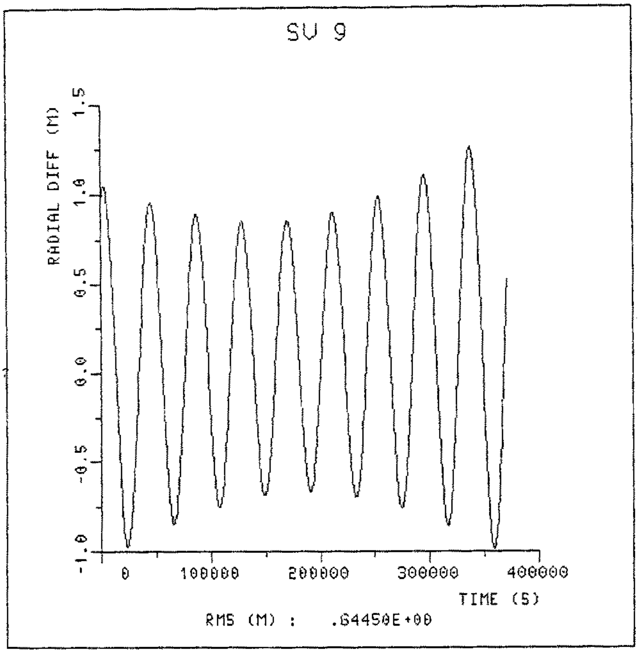

Figure 4.1 <u>Radial orbit difference between test A and B for SV9</u>

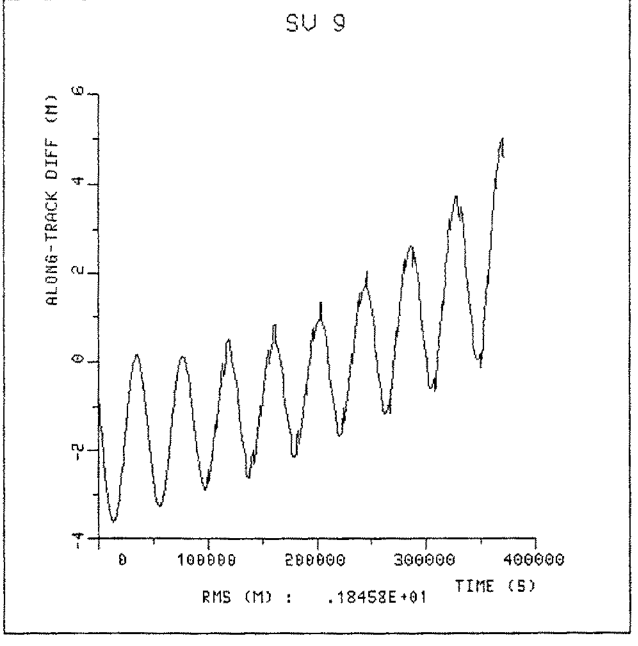

Figure 4.2 <u>Along-track orbit difference between test A and B for SV9</u>

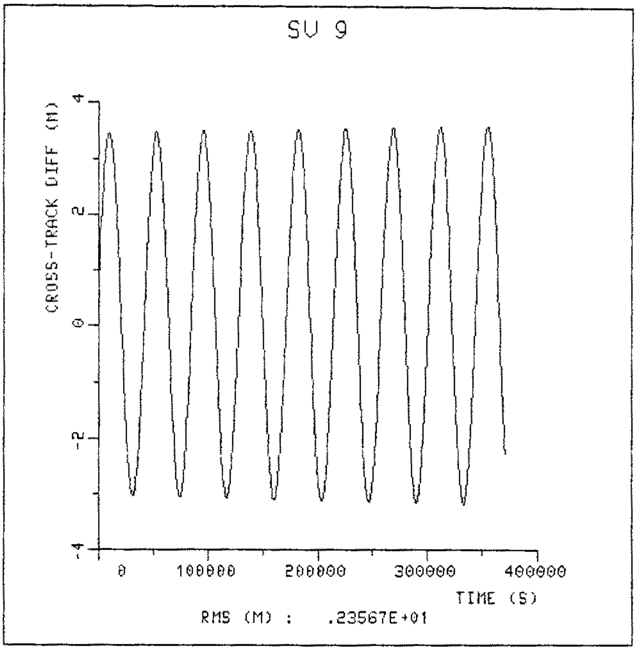

Figure 4.3 Cross-track orbit difference between test A and B for SV9

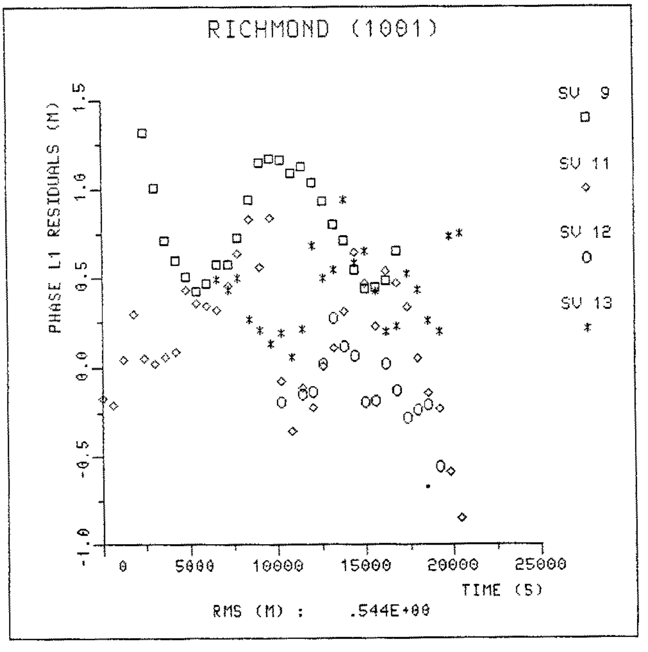

Figure 4.4 L1 phase residuals for Richmond

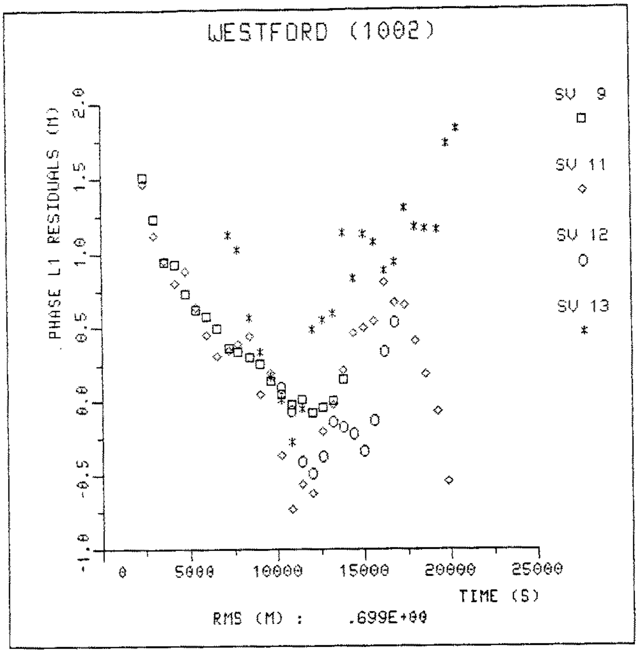

Figure 4.5 <u>L1 phase residuals for Westford</u>

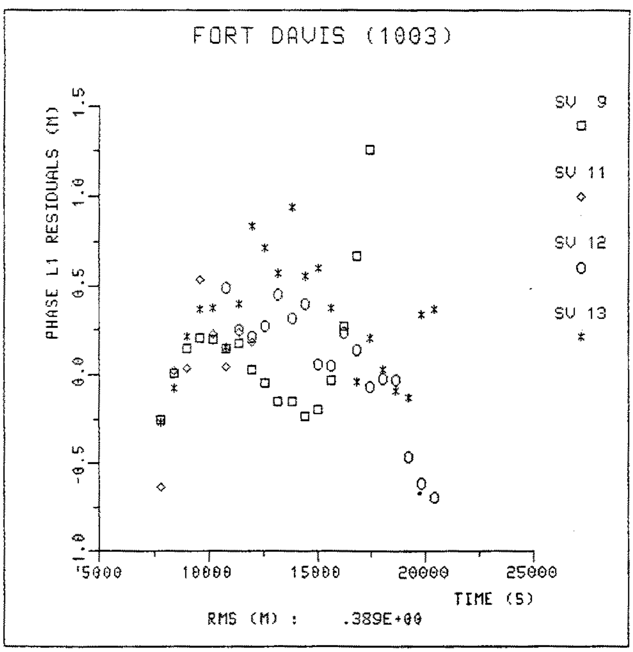

Figure 4.6 <u>L1 phase residuals for Fort Davis</u>

Typical undifferenced residuals are shown in Figures 4.4-4.6 for the L1 phase.

After the orbits were obtained, the coordinates of Richmond were fixed (thereby defining the terrestrial system), and the coordinates of the other two stations were solved for together with all the other parameters. This is the way the fiducial technique works. The results are shown in Table 4.3. The B/C column shows the mean values of test B and C, and we see that the mean values are very close to the values calculated for test A. Furthermore, the formal standard deviation compares quite favourably with the empirical repetition accuracy in the range 16-24 cm. Note that this is <u>absolute</u> positioning with only one reference station. Wendel et al (1986) have calculated absolute station positions for sites involved in the Spring 1985 GPS precision baseline test. They obtained the following average errors : 1.07 m east, 0.96 m north and 2.06 m vertical. Since our dataset is very small, we want to emphasize that the results presented here are preliminary, but they indicate that GEOSAT will be able to produce very good results with GPS data.

STATION	TEST	SOLUTION (M)			ERROR (M)	
		X	Y	Z	FOR	EMP
WESTFORD	A	1492398.35	-4457293.19	4296818.17	0.18	
WESTFORD	B	1492398.28	-4457292.99	4296818.03	0.24	
WESTFORD	C	1492398.46	-4457293.38	4296818.24	0.26	
WESTFORD	B/C	1492398.37	-4457293.19	4296818.14		0.24
FT DAVIS	A	-1324206.15	-5332058.60	3232043.60	0.23	
FT DAVIS	B	-1324206.01	-5332058.50	3232043.59	0.30	
FT DAVIS	C	-1324206.23	-5332058.56	3232043.38	0.36	
FT DAVIS	B/C	-1324206.12	-5332058.53	3232043.49		0.16

Table 4.3 <u>Absolute positioning results</u>

4.4 Future Improvements

In order to take full advantage of the high accuracy of the phase measurements, the time must be modeled to an accuracy of about 30 ps. As an alternative, the oscillator effects can be dramatically reduced using differencing techniques. Clock modelling to the required accuracy is very difficult even for Hydrogen-Masers. Thus the next obvious step is to use doubly differenced phase measurements in the last few iterations. In addition, software must be developed for taking advantage of the integer nature of the doubly differenced biases. JPL and other institutions have demonstrated that improvement by a factor 1.4 to 4 in relative positioning can be achieved with properly fixed integer biases. A corresponding improvement can be expected in the calculated orbits.

Some of the errors inherent in the results presented are due to inconsistencies in the applied reference system. A new set of coordinates with an internal consistency of about 10 cm has already been implemented (Murray and King 1988) together with a new gravity field GEM-T1 (Marsh et al 1988) and improved models for ocean and solid earth tides. The ROCK 4 radiation pressure model has been acquired but it is not implemented yet. It might also be necessary to include models for earth albedo and thermal radiation pressure in order to be able to model the orbits to a few decimeter level.

When data from a globally distributed network become available, it will be possible to solve for variations in the earth rotation and polar motion (ERP). ERP-values and nutation corrections determined from VLBI can be applied as an alternative.

5. Conclusions

GPS tracking and data analysis are well underway both on a national and international scale. It is hoped that the European Tracking Experiment 1988 (EUTREX-88) and the first GPS Global Orbit Tracking Experiment (GOTEX-1) in the second half of 1988 will evolve into permanent cooperative programs for inter-European and international GPS tracking, orbit determination, and reference system improvement. In Europe, the Bernese software (Gurtner et al 1985) is already well proven for this computational task and the GEOSAT software (Andersen 1986) is also very promising. Independent but coordinated GPS data analysis with these two software systems should be encouraged.

6. Acknowledgement

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GPS GEODESY WITH CENTIMETER ACCURACY

by

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Abstract

Centimeter-level accuracy is crucial for Global Positioning System (GPS) baseline measurements to be useful for many geophysical applications. This implies that baseline vector accuracy must be of the order of a few parts in 10^8 of baseline length for regional geodesy. The latest techniques developed at JPL for analyzing GPS data have indeed resulted in centimeter-level agreement with solutions determined by Very Long Baseline Interferometry (VLBI) in California, for baseline lengths of up to 1000 km.

The techniques we have found most promising for high accuracy geodesy are: (1) carrier phase ambiguity resolution, (2) multi-day orbit determination, (3) stochastic estimation of the zenith tropospheric delay, and (4) simultaneous use of carrier phase and pseudorange. The order of importance depends upon the scale of the network, and the approaches are often synergistic. For example, ambiguity resolution can depend upon the ability of the other techniques to improve precision.

The future of GPS looks bright if one considers that these results have been acheived despite a partial GPS constellation, no global tracking network, and pseudorange data plagued by multipath. A full GPS constellation and a global tracking network will not be realized until the 1990's, but steps are being made in the right direction. A new receiver/antenna prototype at JPL is showing promise of producing pseudorange observables accurate to 5 cm. Two of these receivers participated in the January 1988 CASA UNO experiment, which was managed by JPL in cooperation with about 30 other institutions. The purpose of this experiment was to accurately measure geodetically interesting baselines in South and Central America. Precise orbit determination for this experiment was enabled by tracking the GPS satellites from Australia, New Zealand, Hawaii, American Samoa, North America, and Europe. Results from this experiment should give valuable information on the potential of GPS.

1. Introduction

The Global Positioning System (GPS) data analysis team at the Jet Propulsion Laboratory (JPL) has recently estimated geodetic baselines which agree with Very Long Baseline Interferometry (VLBI) solutions at the level of 2 parts in 10^8 (2 cm per 1000 km of baseline length). Moreover, it has since been learned that there is a scaling difference between the GPS and VLBI solutions which arises from the use of inconsistent VLBI-inferred fiducial coordinates. It is expected that GPS and VLBI baselines will agree at the level of 1 part in 10^8 when this inconsistency is corrected. These results reflect the effectiveness of recently developed estimation techniques, which include new approaches to carrier phase ambiguity resolution, multi-day GPS orbit determination, stochastic troposphere estimation, and the use of simultaneous group and phase delay.

The goal of achieving centimeter-level geodesy has thus been realized for regional-sized GPS networks with good fiducial control. For networks of dimensions greater than 1000 km, centimeter-level GPS accuracy should be achievable anywhere on the globe considering forseeable upgrades in hardware, software, experimental design, and tracking networks.

2. State of the Art Techniques

2.1 Carrier Phase Ambiguity Resolution

The GPS carrier phase delay data are biased by an integer number of wavelengths. Resolving these biases is the well-known problem of "ambiguity resolution." Covariance studies show that if the biases are not resolved and are simply estimated as real-valued parameters, there is about a factor of 3–5 degradation in baseline precision [Melbourne, 1985].

Previous ambiguity resolution techniques have been limited by the ability to model the ionospheric delay. Our method uses the valuable information inherent in the simultaneous measurements of the pseudorange and carrier phase observables [Melbourne, 1985; Wubbena, 1985]. We start by using a time-average of a linear combination of the pseudorange data (P_1 and P_2) and carrier phase data (L_1 and L_2) to first determine the integer offsets, n_Δ, between the two carrier channels:

$$\begin{aligned} n_\Delta &\equiv (n_1 - n_2) \\ \hat{n}_\Delta &= \frac{L_1(\mathrm{cm})}{19.029} - \frac{L_2(\mathrm{cm})}{24.421} - \frac{P_1(\mathrm{cm})}{153.35} - \frac{P_2(\mathrm{cm})}{196.80} \end{aligned} \tag{1}$$

where n_Δ can be inferred from the real-valued estimate, $\hat{n}_\Delta$. Using currently available TI-4100 receivers, it appears that half an hour is sufficient time to average down the pseudorange noise to a level at which these "widelane" biases are resolvable. With future high precision pseudorange receivers and antennas, widelane resolution should be possible in less than a minute.

We then proceed to form the ionosphere-free linear combination of the phase data:

$$\begin{aligned} L_C &= L_1 + \alpha\,(L_1 - L_2) \\ L_C(\mathrm{cm}) &= \rho + 48.444\,n_\Delta + 10.695\,n_C + \nu \end{aligned} \tag{2}$$

where $\alpha \simeq 1.5457$, ρ is the non-dispersive delay, and ν is the data noise. Each phase connected data arc is now biased by n_C, an integer number of 10.695 cm wavelengths.

In order to resolve these "narrowlane" biases, we estimate them simultaneously with ρ, which is modeled in terms of station coordinates, satellite ephemerides, clocks, and tropospheric delays. An algorithm based on the square-root information formalism (SRIF) is then applied which sequentially adjusts the biases to the nearest integer value in such a way that the global solution is updated at each step. In this way, ambiguity resolution over longer baselines can be achieved by using the information contained in resolving the biases on the shorter baselines.

Based on our experience [Blewitt *et al.*, 1987] and that of others [Councelman, 1987; Dong and Bock, 1988], a well designed GPS network should contain several shorter length baselines (100–200 km) if ambiguity resolution is to be acheived over longer baselines. We have demonstrated ambiguity resolution on baselines up to 2000 km in length [Blewitt, 1988]. Network design to ensure ambiguity resolution should be an important consideration when planning GPS experiments.

2.2 Multi-Day Arc GPS Orbit Determination

The GIPSY software used at JPL for GPS data processing uses a pseudo-epoch state process noise filter to estimate all geodetic and orbital parameters simultaneously [Bierman, 1977; Thornton and Bierman, 1980]. Spacecraft motion is modeled in geocentric J2000 coordinates with a numerical integration of the variational equations and equations of motion. The GEM-L2 geopotential harmonic expansion (complete to degree and order 8 for GPS models) and effects from solar, lunar, and planet point masses are modeled. The ROCK4 solar radiation pressure model is used. General relativistic corrections for clock models and gravitational bending are included, and with this degree of model sophistication, satellite motions can be realistically and accurately estimated and propagated over arcs of two weeks or more.

The GPS filtering strategy for multi-day arc orbit determination has evolved at JPL in the past two years based on experience with the data taken during the 1985 and 1986 GPS experiments in North America [Lichten and Border, 1987]. Three solar pressure coefficients (including the Y-bias parameter) are estimated as constant parameters along with the orbital states.

Preliminary solutions indicate that with arcs of longer than two weeks results improve when the solar pressure coefficients are estimated stochastically. We believe that this may be evidence for unmodeled forces on the GPS satellites and this possibility is being intensively studied at this time.

2.3 Stochastic Troposphere Estimation

Water vapor radiometers (WVR's) can be used to calibrate GPS data for the wet tropospheric delay under certain meteorological conditions (e.g., when it is not raining) [Elgered *et al.*, 1987; Tralli *et al.*, 1988]. However, these conditions are not always available, and WVR's are bulky, expensive, and few in number. Consequently, most GPS data do not have the luxury of accurate tropospheric calibrations. Standard models using surface meteorological data are of limited value, and can be in error by more than ten centimeters.

At JPL, the tropospheric zenith delay can be estimated at every station. For stations with WVR calibrations, a tightly constrained constant calibration bias is estimated from the GPS data; typical corrections are 1-3 cm at zenith. We have found that estimating the tropospheric delays using a random walk stochastic model be very successful when WVR's are not available. The stochastic model is tuned so that the tropospheric delay can wander ~ 4 cm over an 8-hour daily tracking session. From one day to the next, the troposphere zenith delay is reset to be independent from the previous day's value.

Daily repeatability for baselines and mapped orbit solutions are consistently improved by factors of up to 2 as compared to simply estimating a constant residual zenith delay [Lichten and Border, 1987; Tralli *et al.*, 1988]. We are currently investigating the application of stochastic troposphere estimation in Central America and the Caribbean.

2.4 Simultaneous Group and Phase Delay

Although the pseudorange group delay data type is typically two orders of magnitude noisier than phase delay, it provides an unambiguous differential range measurement. If

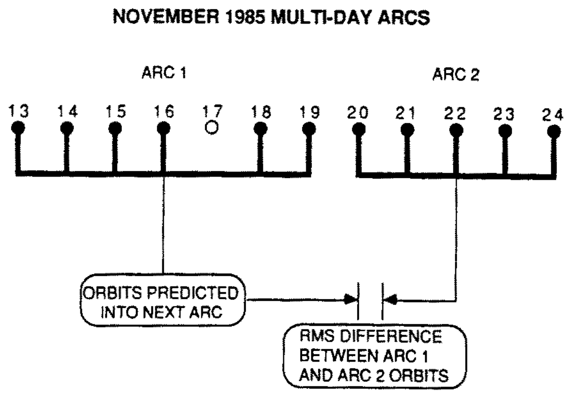

Figure 1. Definition of orbit repeatability for November 1985 multi-day arc test. Orbit solutions from arc 1 are mapped forward, and the RMS difference is taken at beginning of arc 2.

we assume that the pseudorange and carrier phase data are sampled simultaneously (to within 1 μsec), the pseudorange strengthens the carrier phase solution in two ways: (1) it allows for precise estimates of receiver synchronization offsets; (2) it constrains the carrier phase bias estimates.

Baseline accuracy is improved by about a factor of 2 with meter-level pseudorange from current TI-4100 receivers [Lichten and Border, 1987; Tralli and Dixon, 1988]. This factor will improve with the advent of high precision pseudorange receivers and antennas. Also, the phase biases are estimated more accurately, thus enabling ambiguity resolution with greater confidence. Covariance studies performed at JPL show that if carrier phase is combined with high precision pseudorange ($<$ 10 cm for 6 minute points), it is nearly as effective as using carrier phase with the ambiguities resolved [Lichten and Border, 1987]. This may be important for longer baselines where ambiguity resolution is difficult.

3. GPS Accuracy

3.1 Daily Repeatability

One measure of system performance is repeatability of solutions. Strictly, only a lower bound on accuracy can be inferred from repeatability; however it is useful to compare baseline precision with that expected from formal errors. Moreover, GPS accuracy cannot be directly assessed on baselines which have not been previously estimated using VLBI, or satellite laser ranging.

We have analyzed data from 18 sites in the western U.S.A. which were occupied for up to 4 days in June 1986 [Blewitt *et al.*, 1987; Skrumeda *et al.*, 1987]. Station locations and satellite orbits were estimated independently for each day. Using combined carrier phase and pseudorange data, we stochastically estimated the residual zenith tropospheric delay and resolved 94% of the carrier phase ambiguities in the network. This resulted in subcentimeter baseline repeatability in the horizontal plane for all baselines up to 600 km in length. Repeatability is improved by a factor of 3 when compared to solutions without ambiguity resolution. In the vertical direction, repeatability is at the 3 cm level.

Multi-day orbit determination has proved to be important for improving the precision of longer baselines [Bertiger and Lichten, 1987]. Well-tracked GPS orbits show sub-meter repeatability when compared to orbits determined from separate, independent measurement

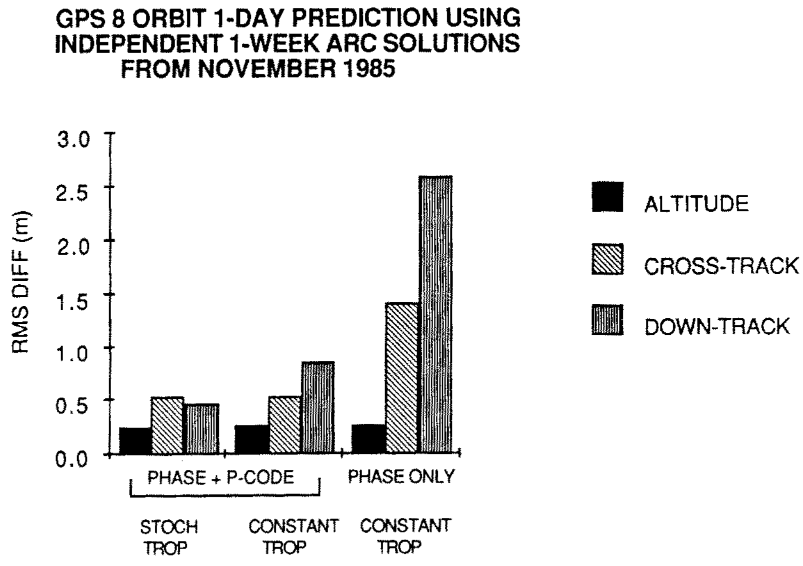

Figure 2. Orbit repeatability of GPS 8 for three estimation strategies. The best strategy uses combined carrier phase with pseudorange, and stochastic troposphere estimation.

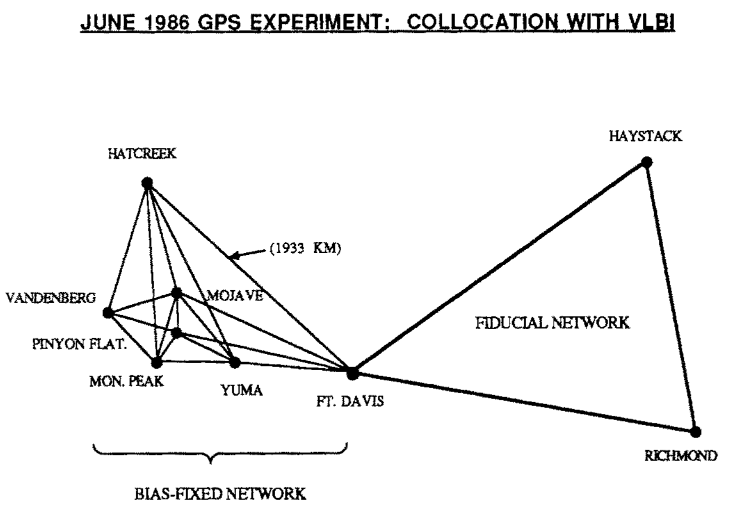

Figure 3. Network configuration of June 1986 GPS experiment for sites collocated with VLBI. The fiducial network was held fixed at the VLBI-inferred coordinates, and the other station locations were estimated using ambiguity resolution.

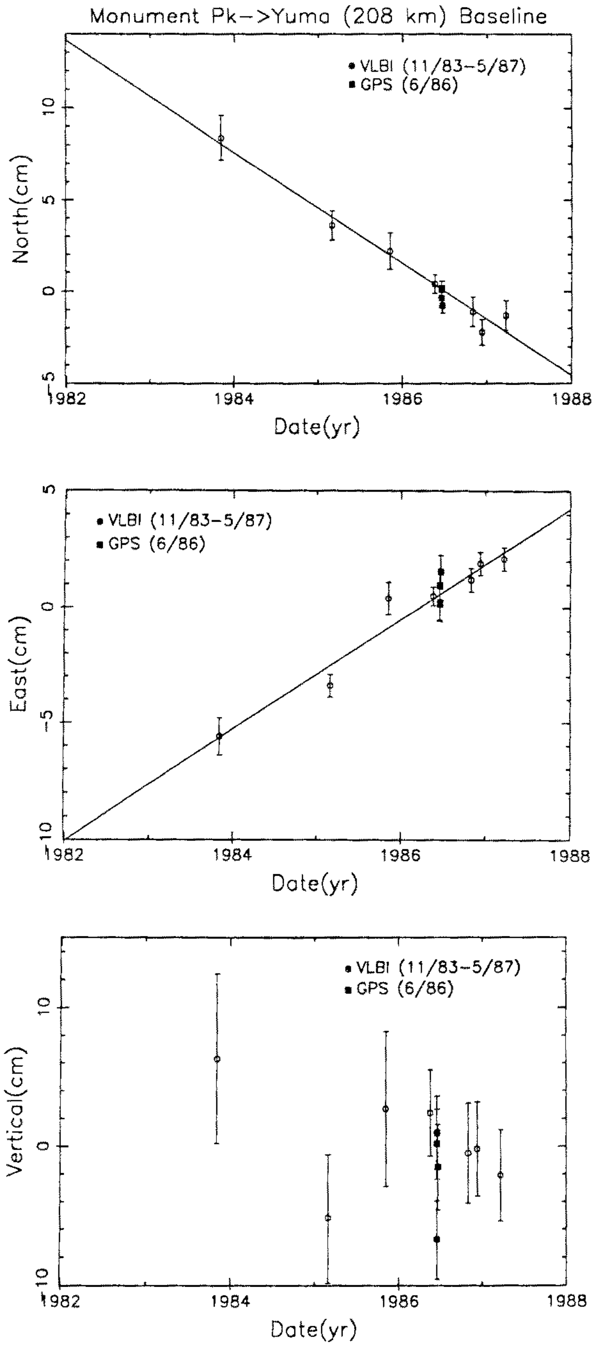

Figure 4. Example of daily GPS baseline solutions from the June 1986 test superimposed on a history of VLBI solutions for Monument Peak to Yuma (208 km).

sets [Lichten and Border, 1987]. Orbit repeatability is explained in Figure 1. Figure 2 shows the effect of various strategies on orbit repeatability. Using multi-day arcs for GPS orbits, stochastic troposphere estimation, and combined carrier phase and pseudorange, the daily repeatability is better than 3 cm in all components for baselines up to 2000 km in length (better than 2 parts in 10^8).

We are currently implementing carrier phase ambiguity resolution for solutions with simultaneously estimated multi-day arcs and station locations. Using all the inherent information in the system to accomplish this task is not trivial due to the large number of bias parameters (several hundred) which must be adjusted.

3.2 Comparison with VLBI

A comparison of GPS with both mobile and fixed VLBI baselines in the western U.S.A. [Skrumeda *et al.*, 1987] shows a root-mean square (RMS) difference of 2 cm for the horizontal components of 15 baselines up to 1086 km in length (Hatcreek, California to Yuma, Arizona). The network configuration is shown in Figure 3. Taking the mean over all baselines, the RMS difference between GPS and VLBI coordinates is 1.4 cm (east), 1.6 cm (north), 3.6 cm (vertical), and 1.2 cm (length). This agreement includes a factor of 2 improvement by ambiguity resolution. In Figure 4, we show representative examples of GPS baseline solutions along with the time-series of VLBI solutions.

The GPS length solutions are systematically longer than VLBI by an average of 0.8 cm. Although less well determined, the longer baselines in the range 1000–2000 km from Fort Davis, Texas, to stations in California, also show a systematic offset. Figure 5 shows (GPS-VLBI) baseline length solutions. It appears that there is a scaling difference at the level of about 1 to 2 parts in 10^8. We believe that these scaling differences arise from the use of coordinates at the fiducial sites (Ft. Davis, Richmond, Haystack) which were derived from an outdated VLBI analysis. This inconsistency is understood and will be corrected in future analyses.

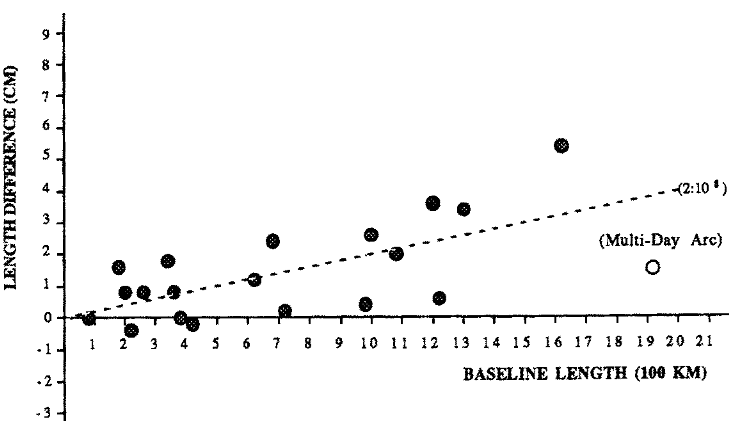

Figure 5. GPS-VLBI length comparison for single-day arc, bias-fixed solutions. Also shown is a multi-day arc solution for comparison. A scaling difference of 1–2 parts in 10^8 can be accounted for by the use of inconsistent fiducial coordinates.

For centimeter-level long baseline accuracy, multi-day GPS orbit determination is currently required. The comparison of GPS with VLBI is currently limited by the uncertainties in the VLBI-inferred fiducial baselines used to define the GPS reference frame. Nevertheless, baselines of 2000 km determined with these orbits agree with VLBI at the level of 0.3–5 cm in all vector components. The 1933 km GPS baseline between Hatcreek, California, to Fort Davis, Texas, agreed with VLBI to better than better than 2.6 cm for all components using data taken in November 1985 (see Figure 5). This solution was a result of a 6 day arc fit to the GPS orbits.

4. Future Prospects

4.1 JPL Receiver/Antenna Development

A GPS receiver has been developed for NASA at JPL expressly for making high quality geodetic measurements [Meehan *et al.*, 1987a]. The ROGUE GPS receiver is based on a digital design that leads to very high accuracy phase and pseudorange measurements. The error contribution from the receiver itself is submillimeter for the carrier phase data, and is at the centimeter level for 2 minute P-code pseudorange.

In practice, however, pseudorange measurements are greatly degraded by multipath signals at the antenna [Meehan *et al.*, 1987b]. This leads to a situation where centimeter level pseudorange error contributions from system noise and other receiver errors are overshadowed by multipath error contributions of up to a meter. Earlier studies of multipath effects done at JPL and elsewhere determined that, for a given multipath environment, certain antenna/backplane configurations could significantly reduce the errors due to multipath.

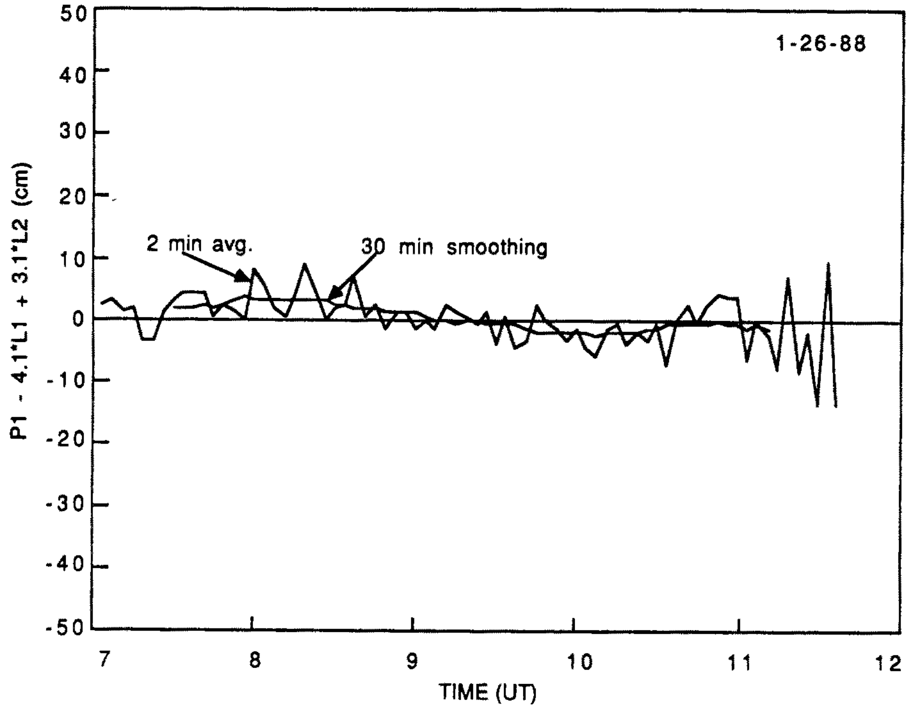

Figure 6. A sample of single-band pseudorange noise from data taken at Owens Valley by the ROGUE receiver with a choke-ring backplane. Long-term multipath signatures are below the 5 cm level.

Field tests have shown that one such configuration, developed at JPL by D.J. Spitzmesser, can reduce long term multipath errors on pseudorange to about 5 cm. This configuration uses a drooped cross-dipole antenna to receive the L_1 and L_2 satellite signals and a conducting "choke-ring" backplane. Two prototype antenna/backplane combinations were used in conjunction with ROGUE receivers at the Mojave and Owens Valley Radio Observatory sites in California during the recent CASA UNO experiment. Figure 6 shows a sample of the pseudorange noise for data taken at Owens Valley. A linear combination of the data, which removes all signatures except for multipath and noise, is plotted with time. These preliminary results are encouraging, and more tests are in progress.

4.2 Global Tracking: The "CASA UNO" Experiment

The "CASA UNO" experiment provided three weeks of GPS data for an initial epoch measurement of a geodetic network in Central and South America managed by JPL, the CASA UNO experiment involved participants from about 30 institutions worldwide. In all, 24 sites in Central and South America were occupied by 16 receivers. An additional 13 receivers in the U.S.A. occupied 20 sites during the experiment. To provide effective fiducial control for such an extended network, a near-global tracking network of 12 receivers, most of which were collocated with VLBI sites (Figure 7). The locations of the non-collocated sites will be estimated simultaneously with the GPS orbit parameters. Covariance studies show that the consequences of not collocating all tracking sites with VLBI are insignificant due to the strong GPS data strength [Freymueller and Golombek, 1987]. In all, about 600 station-days of data are now being reduced.

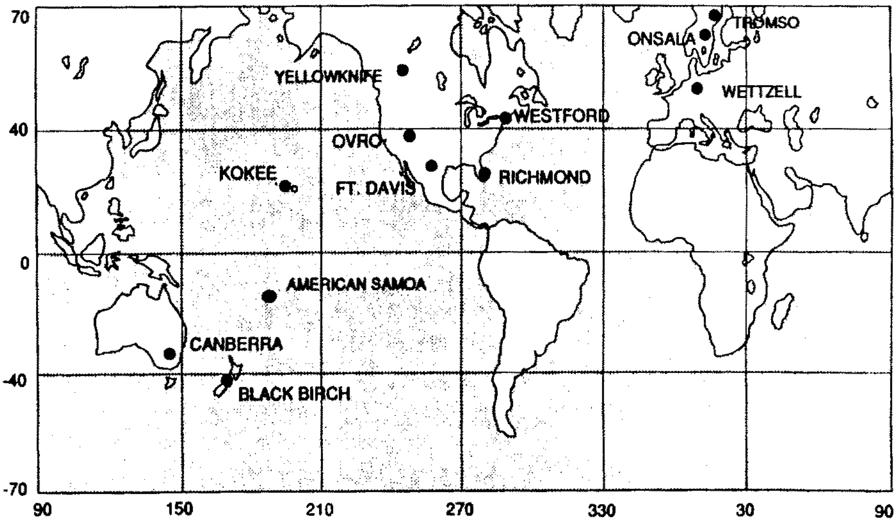

Figure 7. This near-global tracking network of 12 receivers acquired 3 weeks of GPS data during the CASA UNO experiment, January 1988.

The experiment provides a unique opportunity to investigate the benefits of global tracking using real data. So far, fiducial networks have been limited to sizes of the order of 3000 km. Results from CASA UNO will provide a valuable benchmark to calibrate covariance studies, so that we can reliably predict the performance of future global tracking systems.

Investigations are being undertaken to study the best estimation strategy applicable to global networks. Preliminary studies into the potential of GPS to determine earth orientation and the geocenter will be pursued with this data set.

5. Conclusions

GPS-based geodesy has reached the point where centimeter-level accuracy for regional baselines (< 1000 km) can be done routinely in areas of good fiducial control. Accuracies of 2 parts in 10^8 have been demonstrated for baselines up to 2000 km in length. This level of accuracy requires careful modeling of the GPS observables, resolution of carrier phase ambiguities, multi-day arc orbit determination, and stochastic estimation techniques.

Accuracies of 1 part in 10^8 of baseline length should become routine worldwide in the 1990's, as various aspects of GPS-based systems are improved. Important developments are precise pseudorange, receiver/antenna designs, global tracking networks, experiment design to enable ambiguity resolution, and the continual improvement of estimation strategies.

Acknowledgements

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RELATIVISTIC EFFECTS IN GPS

by

S. Y. Zhu[1] , E. Groten

Abstract

Relativistic effects in GPS are twofold: first is the effect on orbit and signal propagation, second is that on the clock. The first part has an effect of up to 0.001 ppm in positioning. The second part affects the clock frequency on the order of 10^{-10}, but only the periodic fluctuation in it is of interest. This term is completely canceled out by between-station differences, hence it is harmless for relative positioning, but it directly affects the clock synchronization and causes substantial error in single point positioning. By adopting a Keplerian orbit, most of this fluctuation can be corrected. The ammount of non-Keplerian part is estimated to be less than 0.6 ns (18 cm).

1. Introduction

GPS is applied in geodetic positioning and in time transfer. Relativistic effects on both of them are discussed here, with emphasis on positioning.

There are two kinds of positioning by GPS, point positioning and relative positioning. The accuracy of the first is worse than 1 ppm, that of the latter is much higher. Recently, Bertiger and Lichten (1987) have demonstrated 5×10^{-9} repeatability for a continental baseline which was estimated using multi-day GPS orbits. Interstingly and fortunately, the magnitudes of relativistic effects are in agreement with the relevant accuracy; the relativistic effects on point positioning are pretty large (~1 ppm), those in relative positioning are much smaller ($\sim 10^{-9}$). This correspondance between positioning accuracies and magnitudes of effects can be thought of as a major feature of relativistic effects in GPS positioning.

The earth's gravitation exerts direct relativistic effects on the orbital motions of satellites (relativistic perturbation) and on phase measurements (propagation correction); these effects are treated in section 2. The satellites carry high accuracy clocks on orbit; due to the gravitation of the earth and orbit motion of satellites the clocks will give time which is different from time given by the same kind of clocks at rest at the earth's surface. Its impact on time transfer and positioning is the topic of section 3.

Only the main results and relevant explanations are presented in this paper; all derivations are omitted. The results are based on general relativity. The treatment is carried out in the terrestrial (earth's center) system, see Zhu et al. (1987). The Schwarzschild metric of the earth is good enough for such considerations. Neglecting the effects of quadrupole of the earth's potential and the effects of the sun and other solar system bodies only causes errors in positioning of 10^{-5}ppm (or less) and errors in frequency of 10^{-14} (or less).

2. Relativistic dynamic effect and propagation correction

The relativistic perturbation reads (Zhu et al., 1987) :

$$\delta\ddot{\underline{r}} = GE\,\underline{r}\,[(4GE/r)-\dot{\underline{r}}^2]/c^2r^3+4GE(\underline{r}\cdot\dot{\underline{r}})\dot{\underline{r}}/c^2r^3, \qquad (1)$$

where $\underline{r}$ is the geocentric vector of the satellite. $\dot{\underline{r}}$ is its velocity. $\delta\underline{r}$ is about 0.5×10^{-9} the Newtonian acceleration and amounts to 0.3×10^{-9} m/sec^2 for the Navstar satellite. Table 1 compares this effect with other Newtonian perturbations, the latters are taken from (Rizos and Stolz, 1985). From that table one sees that the relativistic perturbation is nearly as important as that of the earth's tidal potential or that of albedo pressure.

Table 1 Effect of Perturbing Forces on GPS Satellites

Source	Acceleration (m/sec^2)
Earth's non-sphericity :	
(a) C_{20}	5×10^{-5}
(b) other harmonics	3×10^{-7}
Point-mass effects of sun and moon	5×10^{-6}
Earth's tidal potential :	
(a) earth tides	1×10^{-9}
(b) ocean tides	1×10^{-9}
Solar radiation pressure	1×10^{-7}
Albedo pressure	1×10^{-9}
Relativistic effect	0.3×10^{-9}

Taking phase measurements as an example, the relativistic propagation correction is (cf. Holdridge, 1967).

$$\delta t = (2GE/c^3) \ln [(r + R + \rho)/(r + R - \rho)]. \qquad (2)$$

in which r and R are geocentric distances of satellite and station, respectively. ρ is the range distance. The corresponding correction for range measurement is $c\delta t$. For single phase measurement, the maximum value for $c\delta t$ is 19 mm.

This propagation correction depends on the geometry between station, satellite and geocenter. The combination of observations (differences) could hardly be of any help to reduce this error in a relative sense. Table 2 gives the order of magnitude of this error.

Table 2 Relativistic propagation error

Types of observation	max absolute error (mm)	max. relative error (ppm)
single observation	19	10^{-3}
differences between:		
- satellites	7*	10^{-3}
- stations	7*	10^{-3}
- epoches	**	10^{-3}

* with baseline length ~7000 km
** depends on the time interval of the two adjacent epoches

Both dynamic and propagation effects cause errors up to 0.001 ppm in positioning. These errors can not be eliminated (from relative point of view) by any kind of differences. To ensure ultimate 0.01 ppm accuracy, they should better be taken into account, although for most present applications they can be ignored.

3. Effects on clock frequency

If the transmitting satellite clock frequency is f_t, when received at the station receiver it is shifted into f_r; after the usually Doppler shift has been accounted for, the relation between f_t and f_r becomes [cf. Table 1-1 of (Spilker, 1980); note that some printing errors in this reference should be corrected] :

$$f_r/f_t = 1-(\phi_t+\underline{v}_t^2/2 - \phi_o + (\phi_o - \phi_r - \underline{v}_r^2/2))/c^2 \quad (3)$$

where ϕ_t = GE/r, ϕ_r = GE/R, $\underline{v}_t = \dot{\underline{r}}$ is the velocity of satellite. $\underline{v}_r$ is the velocity of the station (due to the earth rotation). ϕ_o is the value of $(\phi_r + \underline{v}_r^2/2)$ on the geoid. It is introduced since the International Atomic Time (TAI) is defined on the geoid. The last part in eq. (3) is the frequency offset of the station clock with respect to TAI, which is constant at each station and could be easily corrected. $(\phi_t + \underline{v}_t^2/2)/c^2$ contains a constant part ($\sim 2.5 \times 10^{-10}$) and a periodic fluctuation, the latter is mostly due to the non-zero eccentricity. $(\phi_o/c^2) - <(\phi_t + v_t^2/2)/c^2>_{const.}$ is about 4.465×10^{-10}, which can be calculated from the semi-major axis of the orbit and has already been removed by offsetting the GPS clock frequency prior to launch. A residual constant offset due to an off nominal semi-major axis of the actual orbit can be corrected as constant time and frequency offset. Only the periodic part is problematic; which could be as large as 46 ns for eccentricity e = 0.002; the corresponding range error is about 14 m. This effect must be taken into account.

Currently this periodic effect is calculated by considering the orbit as Keplerian cf. (Van Dierendonck et al., 1980; Jorgensen, 1986; Ashby, 1987). The result is

$$\Delta t_{sv} = -4.4428 \times 10^{-10} \text{ (sec/}\sqrt{\text{meter}}\text{) } e\sqrt{A} \text{ (sin } E(t) - \sin E(t_{oc})) \quad (4)$$

where A is the semi-major axis, E(t) is the eccentric anomaly at time t. $E(t_{oc})$ is the value at a certain initial epoch t_{oc}. The $\sin E(t_{oc})$ term is a constant bias which can be corrected by a given time and frequency offset of the satellite clock with respect to GPS time. The only correction in the user's equipment is

$$\Delta t'_{sv} = -4.4428 \times 10^{-10} \text{(sec/}\sqrt{\text{meter}}\text{)} e\sqrt{A} \sin E(t) \doteq -2290 e \sin E \text{ (ns)} \quad (5)$$

The actual orbit is certainly not Keplerian. However, generally speaking perturbations of GPS orbits are small. But one should be aware that perturbations such as C_{20} in Table 1 may cause secular changes in Ω, ω and M, hence actual $E(t) - E(t_o)$ may significantly differ from its Keplerian value after a long time span. If we express the actual Δt_{sv} as

$$\Delta t_{sv} \text{ (actual)} = \Delta t_{sv} \text{ (Keplerian)} + \Delta t_{sv} \text{ (perturbation)} \quad (6)$$

then the amount of Δt_{sv} (perturbation) depends on the time span of $(t - t_{oc})$. t_{oc} is an epoch of time at which the time and frequency offsets of the satellite clock relative to GPS time are redetermined. If the offset is redetermined every two weeks, then the largest value of (t-

t_{oc}) is 604800 sec (Van Dierendonck et al., 1980). For e = 0.02 the perturbation Dt_{sv} is estimated as 1.2 ns (this equals 36 cm in range measurement), which is negligible in comparison to the current accuracy of point positioning.

For relative positioning Dt_{sv} is completely canceled out in the between-station differences and it is therefore harmless.

This periodic fluctuation not only causes a time offset Dt_{sv}, which affects the range measurements but also frequency offsets which affect the range rate measurements. From eq. (4) the average value of $\phi Df/f\phi$ is 2.1×10^{-12} and the maximum value of it is 6.7×10^{-12} which appears at perigee and apogee. Corresponding average and maximum range rate effects are 0.6 and 2 mm/sec, respectively, Again it is negligible for point positioning, and vanishes in relative positioning. Since the in-orbit stability of a satellite clock is better than 1×10^{-13}, this offset might be harmful for future high accuracy time and frequency transfer. To estimate and correct it, one must use the ephemeris message.

Table 3 Relativistic effect on clock

Secular drift :	
- nominal drift	$\sim 4.45 \times 10^{-10}$, calculated from nominal orbit parameters, corrected prior to launch
- residual drift	$<1 \times 10^{-12}$, due to an off nominal semi-major axis of the orbit, is a constant time and frequency offset, correctable
Periodic time offset :	
- initial value (Keplerian)	$- k \sin E (t_{oc})$, $k \mp 46$ ns for e = 0.02, constant time offset, correctable
- time variable (Keplerian)	$k \sin E (t)$, can be corrected by using GPS Navigation Message (a_o, a_1, a_2 coefficients)
- Non-Keplerian	<1.2 ns (36 cm) for e=0.02 $(t-t_{oc}) < 604800$ sec.
Periodic frequency offset	for e=0.02 $\phi Df/f\phi$ ave$=2.1\times10^{-12}$ range rate:0.6mm/sec $\phi Df/f\phi$max$=6.7\times10^{-12}$ range rate: 2 mm/sec

4. Scale problem in comparison with other techniques

When comparing GPS baseline solutions with those of other techniques one should be aware of the scale differences caused by the adoption of different relativistic models. For instance, LLR and VLBI data are usually treated in the solar system barycetric coordinate system, while SLR and GPS data are processed in the geocentric system. By definition the station coordinates and baselines in the barycetric system are different from those in the geocentric system. The difference may amount to $1.5*10^{-8}$. Some LLR and VLBI data analysing centers have already taken this into account, but other centers have not yet removed this definition discrepancy. In addition, sometimes the orbit of GPS satellite is determined by using the observations on a fiducial network which takes VLBI station coordinates as a priori, the scale error of these VLBI stations will affect the GPS baseline determination.

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RELATIVISTIC MODELS OF PHASE AND DOPPLER OBSERVATIONS OF ELECTROMAGNETIC SIGNALS

by

Elke Stöcker-Meier

Abstract

The paper deals with special definitions of phase and Doppler observations of electromagnetic signals and their modeling in four-dimensional space times of general relativity with an earth related metric. Particular attention is paid to phase measurements in GPS and, in addition, to possible contributions of clock transports. After a short explanation of the most essential fundamentals of physical theories and observations with standard clocks solutions of the direct and inverse geodetic problems in media are treated, which are directly or indirectly important for all observation equations concerning coordinate determinations. Then, based on the theory of electromagnetic wave propagation in a refractive medium the observation equations for phase measurements with standard clocks (oscillators) are derived. Finally, the observation equations of clock transports along terrestrial paths, directly resulting from the fundamental form of general relativity, are discussed. It can be shown that their application yields a valuable improvement in the accuracy of coordinate determinations.

1. Preliminary remarks

Producing of earth related observations and mapping them into physical models are the main topics of geodesy. Thereby, the objective functions consist of coordinates of points of the earth's surface and parameters for describing its extrinsic gravitation field. Now as before, classical Newtonian mechanics based on three-dimensional Euclidean space and absolute time dominates in geodetic modeling. Generally, we leave this physical concept when

- electromagnetic signals are used for observations, (1-1)
- test bodies attain high relative velocities compared with the velocity of light or/and (1-2)
- strong gravitation fields exist. (1-3)

Then we have to replace Newtonian mechanics by general relativity, which involves a consistent theory of mechanics and electrodynamics in four-dimensional (pseudo-) Riemannian space. Observations with so-called standard clocks play an important role in general relativity. They are the fundamental observables in the theory of relativity and can be used for measuring the travel time of electromagnetic signals as well as for phase and Doppler observations. In addition, rigid measuring rods, which are the fundamental observation instruments of Euclidean geometry, can still be used in relative small spacetimes.

At present, the presuppositions of (1-1) to (1-3) for leaving classical physics are especially fulfilled in VLBI and GPS brought about first of all by great accuracy in observations combined with (1-2). Formulations of observation equations for phase measurements based on general relativity is one of the two objectives of the following representations. The other concerns with problems of terrestrial clock transport as an essential procedure for the synchronization of standard clocks in general relativity.

2. Fundamentals of geometrical optics in general relativity

Geometrical optics is that part of electrodynamics dealing with the propagation of electromagnetic waves in the approximation for very short wave lenghts.

In general, electromagnetic waves are solutions of Maxwell's equations or the wave equation of electrodynamics. Let A be a component of an electric or a magnetic wave field, then

$$A = a\, e^{-i\phi}, \quad \phi = \phi_o + \int d\phi = \phi_o + \int k_\alpha\, dx^\alpha , \qquad (2\text{-}1a)$$

$$a(x^\alpha) = \text{amplitude}, \qquad \phi(x^\alpha) = \text{phase}, \qquad (2\text{-}1b)$$

$$x^\alpha = (ct\ ,\ x^i) = \text{4-coordinates}, \qquad c = \text{velocity of light}, \qquad (2\text{-}1c)$$

$$k_\alpha = (\omega/c,\ k_i) = \text{wave 4-vector}, \qquad \omega = \text{angular frequency}; \qquad (2\text{-}1d)$$

$$\alpha, \beta, \gamma, \ldots \in \{0, 1, 2, 3\}, \qquad i, j, k, \ldots \in \{1, 2, 3\} \qquad (2\text{-}1e)$$

is true. The phase of the wave is an invariant, i.e., it is independent of the reference system caused by the fact that it results as the inner product of the wave 4-vector k_α and the coordinate differentials dx^α.

The wave 4-vector is normal to the wave front ϕ = constant which follows from

$$k_\alpha = k_\alpha(x^\alpha) = \phi_{,\alpha} \ . \tag{2-1f}$$

In case of geometrical optics amplitude and wave 4-vector are nearly constant. In a medium of refractive index n relativistic geometrical optics can be based on <u>Fermat's principle</u>:

$$\int_{ray} k_\alpha dx^\alpha = \text{extremal} \tag{2-2a}$$

under the side-condition:

$$k_\alpha k^\alpha = K_o^2(1-n^2) \ , \tag{2-2b}$$

$$K_o = k_\alpha u^\alpha/c \quad = \text{frequency in the rest frame of the medium} \ , \tag{2-2c}$$

$$u^\alpha = u^\alpha(x^\beta) \quad = \text{4-velocity of the medium} \ , \tag{2-2d}$$

$$n = n(x^\alpha, K_o) = \text{refractive index of the medium} \ . \tag{2-2e}$$

The <u>characteristic equations of geometrical optics</u> describe the propagation of an electromagnetic wave. They follow from the Euler equations of the variational principle (2-2a); see E. STÖCKER-MEIER:

$$dx^\alpha/dq = \ (k^\alpha - (u^\alpha/c)K_o(1-n^2-nn'K_o))\lambda \ , \tag{2-3a}$$

$$\begin{aligned} Dk_\alpha/dq &=: dk_\alpha/dq - \Gamma^\beta_{\alpha\gamma}k_\beta(dx^\gamma/dq) \\ &= \ (-K_o^2 nn_{,\alpha} + (u^\beta{}_{;\alpha}k_\beta/c)K_o(1-n^2-nn'K_o))\lambda \ , \end{aligned} \tag{2-3b}$$

$$\lambda \ =: C/(nK_o((n+ n'K_o)^2 - 1)^{1/2}) \ , \tag{2-3c}$$

$$n' = \ \partial n/\partial K_o \ . \tag{2-3d}$$

If the refractive index is a function of frequency (2-3d), we call the medium dispersive. q is an affine coordinate, defined by

$$g_{\alpha\beta}(dx^\alpha/dq)(dx^\beta/dq) = C^2 = \text{constant} \ . \tag{2-3e}$$

The two ordinary differential equations (2-3a,b) determine not only the coordinates but also the wave 4-vector at each point of the ray. One equation depends on the other so that it is necessary to solve them together. It is also possible to eliminate the wave 4-vector by differentiation of (2-3a) with respect to q and insertion of (2-3b). Accordingly the characteristic equations (2-3a,b) reduce to an ordinary differential equation of second order:

$$D^2x^\alpha/dq^2 =: d^2x^\alpha/dq^2 + \Gamma^\alpha_{\beta\gamma}(dx^\beta/dq)(dx^\gamma/dq) = (dt/dq)^2 R^\alpha \ , \tag{2-4a}$$

$$R^\alpha = R^\alpha(n, n', n_{,\alpha}, u^\alpha, u^{\alpha;\beta}, g_{\alpha\beta}, dx^\alpha/dq) \ . \tag{2-4b}$$

R^α is called disturbing function. In vacuum we obtain:

$$R^\alpha = 0 \quad \text{for} \quad n = 1 = \text{constant} \ , \tag{2-4c}$$

so that the world lines of the signals in vacuum are <u>geodesic lines</u> in the four-dimensional Riemannian spaces. Considering the equations (2-4a) we have to eliminate the coordinate q and to write the equations as functions of coordinate time t:

$$d^2x^i/dt^2 = G^i + \bar{R}^i \ , \qquad (2\text{-}5a)$$

$$G^i = ((1/c)\Gamma^o_{\beta\gamma}(dx^i/dt) - \Gamma^i_{\beta\gamma})(dx^\beta/dt)(dx^\gamma/dt) \ , \qquad (2\text{-}5b)$$

$$\bar{R}^i = R^i - (1/c)R^o(dx^i/dt) \ . \qquad (2\text{-}5c)$$

The 3-acceleration of the signal is composed of a gravitational part G^i and a disturbing part $\bar{R}^i$. We formulate initial-value and boundary-value problems to solve the differential equations by numerical integrations or series expansions. In case of the propagation of electromagnetic signals through the atmosphere the initial-value and boundary-value problems are called <u>direct or inverse geodetic problems</u>. They are directly or indirectly important for all observation equations concerning coordinate determinations. Without the effects of refraction and gravitation electromagnetic signals propagate along straight lines. With respect to the straight lines in Euclidean spaces we define the so-called <u>reduction of travel time</u> δt:

$$\delta t = \Delta\bar{t} - \Delta t \ , \qquad (2\text{-}6a)$$

$$\Delta t = \text{observed travel time} \ , \qquad (2\text{-}6b)$$

$$\Delta\bar{t} = \text{Euclidean travel time} \qquad (2\text{-}6c)$$

$$= (\Delta_{ij}((x^i)_b - (x^i)_a)((x^j)_b - (x^j)_a))^{1/2}/c \ .$$

For a distance of 20000 km we obtain a reduction of 1-2 cm as a result of the earth gravitational field, which ought to be taken into account.

3. <u>Observations with standard clocks</u>

Every <u>arbitrary clock $\tilde{U}_n$</u> is nothing else but an oscillator, that is a physical system, which changes its phase periodically:

$${}^n\Phi({}^n\tau) = {}^n\Phi({}^n\tau_o) + {}^n\omega_o({}^n\tau - {}^n\tau_o) = {}^n\Phi({}^n\tau_o) + 2\pi\,{}^nN + {}^n\varphi({}^n\tau) \ , \qquad (3\text{-}1a)$$

$${}^n\tau = \text{oscillator time} \ , \qquad (3\text{-}1b)$$

$${}^n\omega_o = d\,{}^n\Phi/d\,{}^n\tau = \text{constant angular frequency} \ , \qquad (3\text{-}1c)$$

$${}^nN = \text{cycle count} \ , \quad {}^n\varphi = \text{fractional phase part} < 2\pi \ . \qquad (3\text{-}1d)$$

As a rule the so-called <u>standard clocks U_m</u> are the observing instruments to measure travel times, phases and frequencies of electromagnetic signals. Standard clocks are able to measure proper time differentials, which correspond to the fundamental form of general relativity with the exception of constant scale factors ${}^mM$:

$$\overset{m}{M}\,d\overset{m}{\tau} =: d\tau = (g_{oo} + (2/c)g_{oi}v^i + (1/c^2)g_{ij}v^iv^j)^{1/2}\,dt\ , \qquad (3\text{-}2a)$$

$$\overset{m}{\tau} = \text{proper time}\ , \qquad \overset{m}{\omega}_o = \text{proper frequency}\ . \qquad (3\text{-}2b)$$

Recently the best approximations of standard clocks are atomic clocks. In general relativity it is only possible to compare two clocks, which are moving together on one and the same world line. In this case the physical

<u>hypothesis of consistency:</u> (3-3)

two standard clocks of the same type have same scale factors

$$\overset{1}{M} = \overset{2}{M} = \ldots \overset{m}{M} \qquad (3\text{-}3a)$$

and for two standard clocks of different types the ratios of the scale factors are constant:

$$\overset{1}{M}/\overset{2}{M} = \text{constant}\ , \qquad \overset{2}{M}/\overset{3}{M} = \text{constant}\ , \ \ldots \qquad (3\text{-}3b)$$

is assumed; see J.L. SYNGE. Arbitrary clocks $\tilde{U}_n$ have scale factors, which depend on time:

$$\overset{n}{M} = \overset{n}{M}(\overset{n}{\tau})\ . \qquad (3\text{-}4)$$

The <u>observables of standard clocks U_m</u> are:

cycle counts $\overset{m}{N}$, (3-5a)

fractional phase parts $\overset{m}{\varphi} < 2\pi$ and (3-5b)

proper time intervals $\Delta\overset{m}{\tau}$. (3-5c)

Compared to the phases of an arbitrary clock $\tilde{U}_n$ we obtain

phase differences $\Delta\overset{m}{\Phi}_{mn}(\tau) = \overset{m}{\Phi}(\overset{m}{\tau}) - \overset{n}{\Phi}(\overset{m}{\tau})$. (3-5d)

4. <u>Phase and Doppler observations</u>

Phase differences are used in NAVSTAR-GPS to measure electromagnetic waves by means of a local standard oscillator U_m (3-2a,b) in the terrestrial receiving station P_m. The transmitter is a standard clock U_n in the GPS-satellite P_n. It generates the electromagnetic wave, which travelles to the receiver and controls there an arbitrary oscillator $\tilde{U}_n$. The output of the GPS-receiver is the <u>difference between the phases of U_m and $\tilde{U}_n$</u>:

$$\Delta\Phi_{mn}(t_m) = (\overset{m}{\Phi}(t_m))_m - (\overset{n}{\Phi}(t_m))_m + 2\pi N_{mn}\ . \qquad (4\text{-}1a)$$

The

integer cycle count N_{mn} (4-1b)

represents the number of full cycles in the observed phase. With respect to the <u>phase variation in time and in space</u> we yield the <u>observation equations</u> for phase measurements:

$$\Delta\Phi_{mn}(t_m) = \overset{m}{(\Phi(t_m))_m} - \overset{n}{(\Phi(t_m))_n} + 2\pi N_{mn} + \omega_o(\Delta t_{nm} + G_{mn}(t_m) + R_{mn}(t_m)) \ , \tag{4-2a}$$

$$G_{mn}(t_m) = \int_{t_n}^{t_m} d(\overset{n}{\tau(t)}) - dt \quad = \text{gravitational reduction} \ , \tag{4-2b}$$

$$R_{mn}(t_m) = (1/\omega_o) \int_{(x^\alpha)_m}^{(x^\alpha)_n} k_\alpha dx^\alpha = \text{refractive} \quad \text{reduction} \ , \tag{4-2c}$$

$$\Delta t_{nm} = t_m - t_n = \text{coordinate travel time} \ . \tag{4-2d}$$

The gravitational reduction (4-2b) follows from the difference between proper time of the satellite-oscillator and coordinate time used in the problem. To see what influence gravitation has, the reduction (4-2b) is computed with an earth related metric. It results 1-2 cm due to the potential difference between satellite and receiver. With the observation equation (4-2a) it is possible to determine the time difference (4-2d). To calculate the

spatial coordinate differences $(x^i)_n - (x^i)_m$ (4-2e)

we have to solve a direct geodetic problem and to introduce (4-2d) as initial-values.

Because of inaccurate satellite orbits and refraction models we have to use <u>relative coordinates</u>. The observations which belong to relative positioning are the <u>station differences $D\Delta\Phi_{ab}$</u>. They are defined as the differences between the phase measurements made by the two receivers U_a and U_b in case of simultaneously emitted signals:

$$D\Delta\Phi_{ab} =: \Delta\Phi_{an}(t_a) - \Delta\Phi_{bn}(t_b) \ . \tag{4-3a}$$

Inserting (4-2a) into (4-3a) the <u>observation equation</u> can be expressed as:

$$D\Delta\Phi_{ab} = \overset{a}{(\Phi(t_b))_a} - \overset{b}{(\Phi(t_b))_b} + 2\pi N_{ab} + \omega_o((t_a - t_b) + \Delta G_{ab} + \Delta R_{ab}) \tag{4-3b}$$

$$\Delta G_{ab} = \text{gravitational anomaly} \ , \tag{4-3c}$$

$$\Delta R_{ab} = \text{refractive} \quad \text{anomaly} \ . \tag{4-3d}$$

ΔG_{ab} and ΔR_{ab} follow from the gravitational and refractive effects, which are different in both stations. The observation equation (4-3b) yields

$$N_{ab} =: N_{an} - N_{bn} \quad , \quad t_a - t_b \ , \tag{4-4a}$$

$$(\overset{a}{\Phi}(t_b))_a - (\overset{b}{\Phi}(t_b))_b \ , \tag{4-4b}$$

whereby the coordinate time difference $t_a - t_b$ can be transformed into the

baseline vector $(x^i)_b - (x^i)_a$, (4-4c)

by solving a direct geodetic problem. (4-4b) depends on the

clock offset $(\overset{a}{\Phi}(t_o))_a - (\overset{b}{\Phi}(t_o))_b$ (4-4d)

and the

clock scale rate $\overset{a}{M}/\overset{b}{M}$ (4-4e)

between both receivers. t_o is a reference time. It is shown in chapter 5, that it is also possible to determine the phase difference (4-4b) by means of a <u>clock transport</u>. A transport of clocks is a good completion to simultaneous phase measurements and it should be carried out additionally, because this method reduces the unknowns.

The time derivatives of phase measurements (4-1b) are defined as <u>Doppler displacements</u>:

$$\Delta\overset{m}{\omega}_{mn}(\overset{m}{\tau}) = \overset{m}{\omega}_o - \overset{n}{\omega}(\overset{m}{\tau}) = (d\Delta\overset{m}{\Phi}_{mn}/d\overset{m}{\tau})_{\overset{m}{\tau}} \ . \tag{4-5a}$$

Differentiating equation (4-2a) with respect to $\overset{m}{\tau}$ gives in the local observing system of the receiver:

$$\Delta\overset{m}{\omega}_{mn}(\overset{m}{\tau}) \approx \overset{m}{\omega}_o - \overset{n}{\omega}_o(\overset{m}{M}/\overset{n}{M})(1+(v_n/c)\cos\varphi$$
$$+(1/2)(v_n/c)^2(\cos^2\varphi - \sin^2\varphi) - W_n/c^2 + R\omega) \ , \tag{4-5b}$$

v_n = velocity of the satellite , (4-5c)

φ = angle between wave propagation and direction of satellite motion , (4-5d)

W_n = potential difference between satellite and receiver (4-5e)

$R\omega$ = refractive reduction . (4-5f)

In addition to the longitudinal and transversal Doppler effects the gravitational potential influences the Doppler observations with the order of 30 cm in case of measurements to a TRANSIT-satellite. The refractive reduction depends on the direction of the gradient of the refractive index relative to the velocity of the satellite.

5. Clock transports

The transport of clocks is a terrestrial method measuring phase differences to synchronize earth related clocks within the scope of general relativity. The basis of a clock transport reads as follows:

One standard clock is positioned in each of two terrestrial observation stations:

$$U_1 \text{ in } P_a\text{, measuring proper time } \overset{1}{\tau}\text{,} \tag{5-1a}$$

$$U_2 \text{ in } P_b\text{, measuring proper time } \overset{2}{\tau}\text{.}$$

A third transportable standard clock

$$U_3 \text{ in } P_c\text{, measuring proper time } \overset{3}{\tau}\text{,} \tag{5-1b}$$

is located in P_c moving along a path C_{ab} from P_a to P_b. The observations are the proper times of U_3:

$$\Delta\overset{3}{\tau}_{ab} = \overset{3}{\tau}_b - \overset{3}{\tau}_a\text{,} \quad \overset{3}{\tau}_p = \text{arbitrary times for } P_c \equiv P_p,\ p \in \{a,b\}, \tag{5-2a}$$

and the phase differences between U_3 and U_m in P_a and P_b:

$$\Delta\Phi_{m3} = \overset{m}{\Phi}(\overset{m}{\tau}) - \overset{3}{\Phi}(\overset{m}{\tau})\text{,} \quad m \in \{1,2\}\text{.} \tag{5-2b}$$

Integrating the fundamental form (3-2a) yields the observation equation for the transport of the clock U_3 (5-2a):

$$\overset{3}{M}\Delta\overset{3}{\tau}_{ab} = \int_{t_a}^{t_b} \left((g_{oo} + (2/c)g_{oi}v^i + (1/c^2)g_{ij}v^iv^j)^{1/2}dt\right)_{C_{ab}}\text{.} \tag{5-3a}$$

If the gravitational field and the velocity v^i of U_3 are known sufficiently accurate along the path C_{ab} it is possible to determine the coordinate time difference:

$$\Delta t_{ab} = t_b - t_a\text{.} \tag{5-3b}$$

In the earth related system S_E the difference between (5-2a) and (5-3b) can be splitted into three parts. K_1 depends on height h above a reference station P_B, K_2 is a function of velocity v and K_3 results from Coriolis's acceleration:

$$\Delta t_{ab} - \Delta\overset{3}{\tau}_{ab} =: K_1 + K_2 + K_3\text{,} \tag{5-4a}$$

$$K_1 = \int_{\overset{3}{\tau}_a}^{\overset{3}{\tau}_b} (1/c^2)\ \left(((gh)_B - gh)\ d\overset{3}{\tau}\right)_{C_{ab}}\text{,} \tag{5-4b}$$

$$K_2 = \int_{\overset{3}{\tau}_a}^{\overset{3}{\tau}_b} (1/2) \quad ((v/c)^2 \, d\overset{3}{\tau})_{C_{ab}} \ , \tag{5-4c}$$

$$K_3 = \int_{\overset{3}{\tau}_a}^{\overset{3}{\tau}_b} -(1/c^2) \ (\omega \, \epsilon_{3jk} v^j x^k \, d\overset{3}{\tau})_{C_{ab}} \ , \tag{5-4d}$$

g = absolute value of gravity acceleration of the earth , (5-4e)

ω = absolute value of angular velocity of the earth . (5-4f)

The values (5-4b,c,d) were calculated for a transport of clocks through the area of the Eifel with v≈50 km/h. The results are shown in table 1.

Comparing two standard clocks the <u>observation equations of phase measurements</u> (5-2b) reduce to:

$$\Delta\Phi_{m3}(\overset{m}{\tau}) = \overset{m}{\Phi}(\overset{m}{\tau}_o) - \overset{3}{\Phi}(\overset{m}{\tau}_o) + (\overset{m}{\omega}_o - \overset{3}{\omega}_o \overset{m}{M}/\overset{3}{M})(\overset{m}{\tau} - \overset{m}{\tau}_o) \ . \tag{5-5a}$$

(5-5a) is called the clock equation, which allows to determine the clock offsets and the scale rates:

$$\begin{aligned} &\overset{1}{\Phi}(\overset{1}{\tau}_o) - \overset{3}{\Phi}(\overset{1}{\tau}_o) \ , \quad \overset{1}{M}/\overset{3}{M} \ , \\ &\overset{2}{\Phi}(\overset{2}{\tau}_o) - \overset{3}{\Phi}(\overset{2}{\tau}_o) \ , \quad \overset{2}{M}/\overset{3}{M} \ . \end{aligned} \tag{5-5b}$$

The objective of the <u>clock synchronisation of general relativity</u> is to compare coordinate times in different places. With the assumption

$$(v^i)_a = (v^i)_b = 0 \ , \quad g_{\alpha\beta,o} = 0 \tag{5-6a}$$

(3-1a) and (3-2a) gives in P_a and P_b:

$$\begin{aligned} &(\overset{m}{M}/\overset{m}{\omega}_o)(\overset{m}{\Phi}(\overset{m}{\tau}) - \overset{m}{\Phi}(\overset{m}{\tau}_{oa})) = (g_{oo})_a^{1/2}(t_a - t_{oa}) \ , \quad m \in \{1,3\} \ , \\ &(\overset{n}{M}/\overset{n}{\omega}_o)(\overset{n}{\Phi}(\overset{n}{\tau}) - \overset{n}{\Phi}(\overset{n}{\tau}_{ob})) = (g_{oo})_b^{1/2}(t_b - t_{ob}) \ , \quad n \in \{2,3\} \ . \end{aligned} \tag{5-6b}$$

t_{op} are the coordinate times belonging to τ_{op}. If t_{oa} is a known quantity, we can determine

$$t_{ob} = t_{oa} + \Delta t_{ab} \tag{5-6c}$$

by means of (5-3b). t_a and t_b are given functions of the observed phases in P_a and P_b on the basis of (5-6b) provided that we have

$$\overset{m}{\Phi}(\overset{m}{\tau}_{oa}) - \overset{n}{\Phi}(\overset{n}{\tau}_{ob}) \ , \quad \overset{m}{M}/\overset{n}{M} \tag{5-6d}$$

additionally from the compa:ision of the standard clocks (5-5b). It is also possible to describe with (5-6b) the phase differences (4-4b) as functions of coordinate time.

path	component	reductions for the path: $C_1 \rightarrow C_2$ (ns)	$C_2 \rightarrow C_1$ (ns)
C_1	K1	-0.37218	-0.37218
	K2	0.00968	0.00968
	K3	-0.09894	0.09894
C_2	K1	-0.25502	-0.25502
	K2	0.01443	0.01443
	K3	0.08909	-0.08909
total reductions		-0.61294	-0.59322

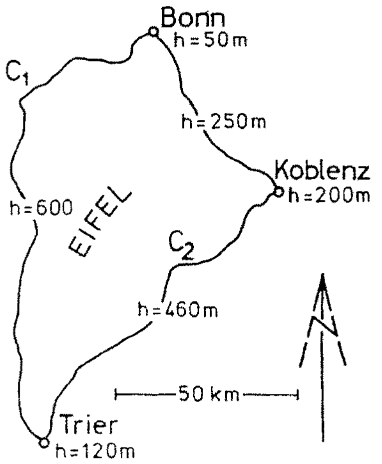

TABLE 1: clock transports: $C_1 \rightarrow C_2$ = Bonn-Trier-Koblenz-Bonn,
$C_2 \rightarrow C_1$ = Bonn-Koblenz-Trier-Bonn

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Second session: Application of GPS

Chairman: Prof. Pâquet, Brussels

THE USE OF GPS AT IGN : GEODESY, GEOPHYSICS, ENGINEERING

by

Claude Boucher, Pascal Willis

Abstract

The Institut Géographique National has purchased since 1985 four GPS receivers (TR5S from SERCEL, 5 channels, single frequency type). For research and production purpose, a specific software, called GDVS, was then developed. This software is now operational and has been used with success to process several GPS campaigns.

Two major campaigns were performed in 1986 : one between France and England and the second one between France and Italy. One of the main topic of these campaigns was to connect tide gauges in the Channel area or in the Mediterranean Sea area, to a global reference frame.

GPS was also used to provide very shortly local geodetic network of a few tens of kilometers for geodetic or geophysical purposes. Some examples of such campaigns are the following : Djibouti, Pyrénées, Provence.

For the future, the IGN intends to continue these uses of GPS and also to continue the development of GPS for photogrammetry (airborne GPS) and kinematic GPS.

1. Introduction

Since 1985, the French Institut Géographique National has been involved in GPS and its possible applications. GPS receivers have been purchased and a specific research software called GDVS (*Géodésie par mesures de Distances et Variations de distances sur Satellites)* has been developed. Several applications of the GPS technology have been investigated for science or production purposes. For the Institut Géographique National, being both a geodetic Institute and a mapping Agency, these applications are very numerous : geodesy (small size specific geodetic network, national geodetic network), geophysics (active zones surveys, volcanoes surveys, tide gauges connections) or engineering (photogrammetry with airborne GPS receivers).

We summarize here the latest examples of use of GPS at IGN, giving at the same time a large range of possible applications of this highly accurate tool for geodesists. It should be noticed that the accuracy of GPS strongly depends on the way it is used : absolute or relative positioning, using the pseudo-ranges or the carrier beat phases [WELLS (1986)], type of receiver, real time or post-processing solution, software capabilities. Table 1 gives a summary of the possible use of GPS and the typical achievable accuracy.

Type	Accuracy
Navigation	20 m
Differential navigation	2 m
Trajectography	0,5 m
Geodesy (L1 receiver)	3 ppm
Geodesy (L1/L2 receiver)	1 ppm
Kinematic	0,01m
High accuracy	0,02 ppm

Classes of applications of GPS

Table 1

The Institut Géographique National has presently 4 TANS (TRIMBLE) for navigation, 4 TR5S (SERCEL) for geodesy (single frequency receivers) and plan to purchase in 1988 3 dual frequency receivers (to be determined) : 2 for surveying and one for satellite tracking.

2. Navigation

The initial purpose of the development of GPS for the U.S. military agencies was to provide at any time and anywhere an absolute position (in a precise global reference frame). This application only requires low cost GPS receivers that can perform pseudo-range measurements on the L1 frequency. The Institut Géographique National possesses four receivers of this type : TANS from TRIMBLE. A simple software is needed to obtain a real-time position from the pseudo-ranges measurements. The accuracy of this basic use of GPS is about 20 metres. Figure 1 shows an example of this type of positioning using a TR5S (SERCEL) equipment at Hasparren (Netherlands). Every point represents an independent position estimated every 0,6 second. This figure shows a good consistency of the result (internal precision at a few metres level). The dots seem to scatter in two different populations. This difference is due to the change of ephemerides.

In this type of positioning, the quality of the broadcast orbit is essential and may be degraded in a near future (block II satellites). This real time navigation can be used with profit for the fast determination of a large number of points, for instance to locate a gravity survey. The I.G.N. is achieving such a large project in Africa (Mali : 640 points, Guinea Bissau : 30 points, Guinea Konakry : 737 points, Togo : 74 points, Benin : 150 points, Ivory Coast : 167 points, Central African Republic : 710 points, ...). GPS navigation can also be used for very small scale stereopreparation, for example for the SPOT images.

3. Differential navigation

In the navigation accuracy (20 metres), a large part comes from the precision of the orbit. This effect is in fact a regional effect and will cause a more or less common bias on the estimated position of the receiver in the same area.

During the campaign presented in figure 1, another TR5S receiver was present at Saint-Mandé (France). The results obtained were very similar, showing the same skip due to the change of ephemerides. Figure 2 represents the result of the differential positioning (real-time difference of estimated three-dimensional coordinates every 0,6s). In this differential positioning, there is no more break if the achievable accuracy is at the level of 2 metres. A very important aspect of the method is that the receiver observes simultaneously the same configuration of satellite. Only L1 pseudo-range receivers and real-time single point processing software are needed [NARD et al. (1987)]. The final solution is obtained in a post processing mode by differentiating the real time navigation solution.

When another system is available to transmit information from one receiver to another, this relative positioning can also be obtained in real time. Two solutions are possible : differentiating the estimated position (as described before) or differentiating the raw pseudo-ranges.

Figure 1

USE OF GPS FOR NAVIGATION

JUNE 1986 SERCEL GPS CAMPAIGN
SITE "HASPARREN"

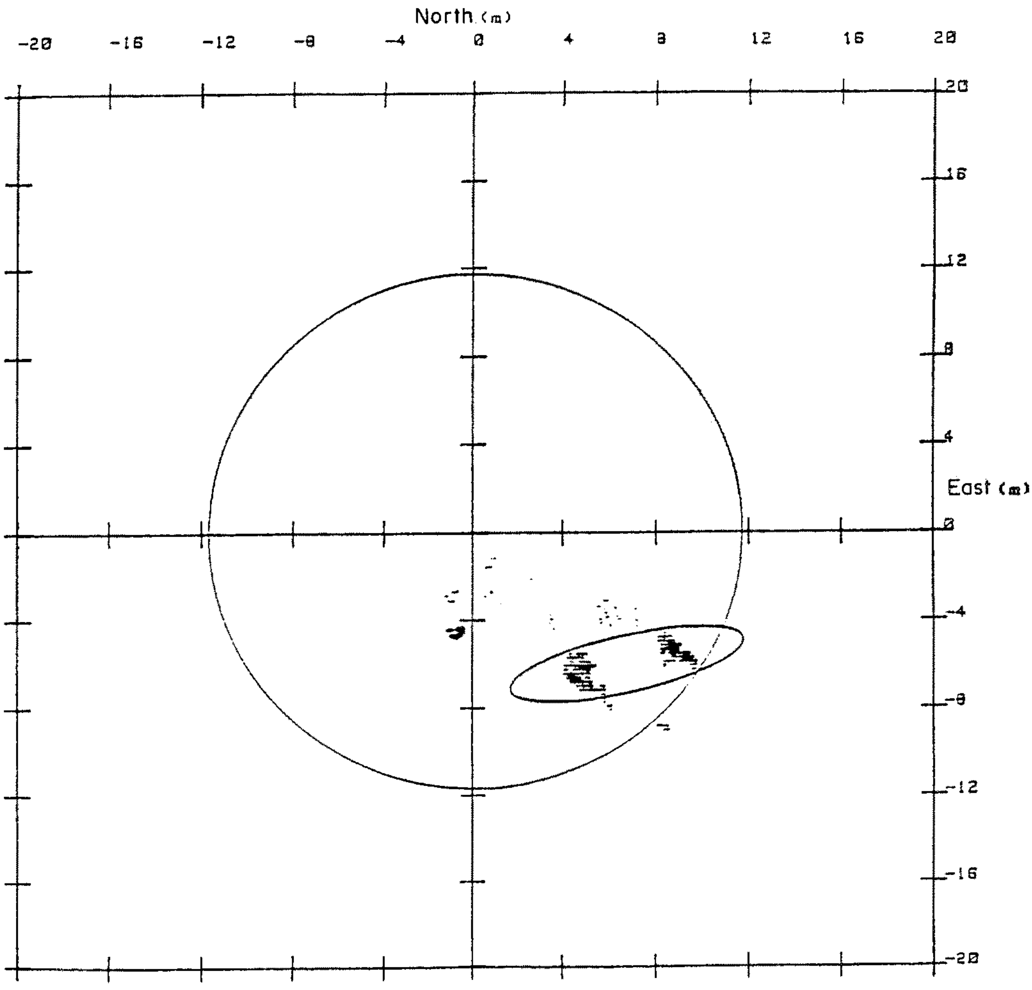
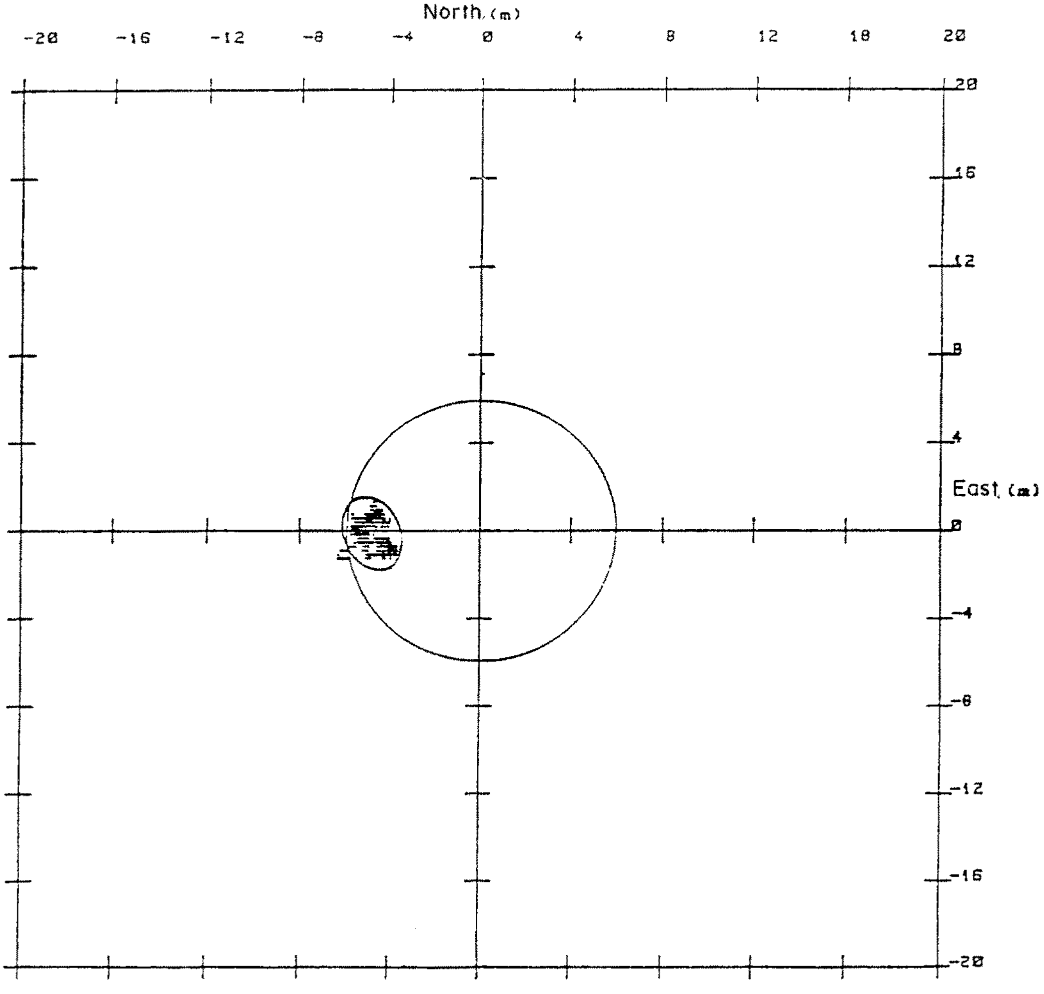


Figure 2

USE OF GPS FOR DIFFERENTIAL NAVIGATION

JUNE 1986 SERCEL GPS CAMPAIGN
RELATIVE POSITIONING SAINT MANDE-HASPARREN



4. Trajectography

At this point, the limit of accuracy is due to the noise of the raw pseudo-range measurement. When Doppler measurement exists (carrier beat phase or Doppler Integrated measurement), it is possible to use these measurements to smooth the pseudo-ranges and then decrease the noise level of this observable that we could call Doppler Integrated Pseudo-Ranges.

For this application, a L1 code and phase multichannel receiver is needed, and the data analysis is performed in an off-line mode. Figure 3 shows an example of this type of positioning applied to an airborne receiver. The data were recorded on an aircraft (Caravelle) and were processed, using a specific software developed by SERCEL. This figure shows the difference between the estimated position (every 0,6 second) and the STRADA estimation. Several tests on roads and on aircrafts have proved a 0,5 metre achievable accuracy, or better.

Two major uses of the GPS trajectography are investigated at I.G.N. : photogrammetry and roads data base. For photogrammetry, the major goal is to use this GPS positioning on a plane able to recover the photogrammetric perspective. Several tests have been realized [R. BROSSIER et al. (1986)] : Amiens (1986) with only one receiver, Lunel-Vichy (1987) with two receivers. Another interest for our Institute is to be able to precisely position a car in order to realize, in a very short time, a road data base. Several production GPS campaigns will take place in 1988 (metropolitan France, Martinique, Guadeloupe, ...).

5. Geodesy with single frequency receivers

In order to improve the accuracy from 1 or several metres to centimetres or millimetres, the GPS carrier beat phase must be used. Presently, the I.G.N. possesses 4 single frequency TR5S from SERCEL (5 channels, code and phase measurements). To solve ambiguities, it is necessary to obtain simultaneous observations for at least one hour with 4 or 5 satellites. The processing is not a real-time processing and requires a phase capability off-line software.

The data analysis software used is GDVS using the double difference technique. When using single frequency receivers and broadcast orbits, the relative positioning accuracies are at the level of 3ppm (part per million) for distances ranging to several tens of kilometres. Table 2 shows typical results obtained by the GDVS software. These data were recorded during a geodetic evaluation test realized by SERCEL near Nantes (Brittany). Every line corresponds to an independent estimation of the baseline (difference of coordinates in the three dimensions) obtained from one session of observations (5 GPS satellites during 1 hour). The mean value and the standard deviation were estimated from this set of independent estimated differences of coordinates.

In this case, the agreement (internal consistency) is at a 4 millimetres level (at 1σ) for a distance of 2,7km. This type of application of geodetic GPS has been used in production since 1986 and several campaigns already mentioned were carried out. Let us give some examples of such realizations.

Figure 3

GPS profile of a landing aircraft
Comparison in meters with STRADA reference
SERCEL Results

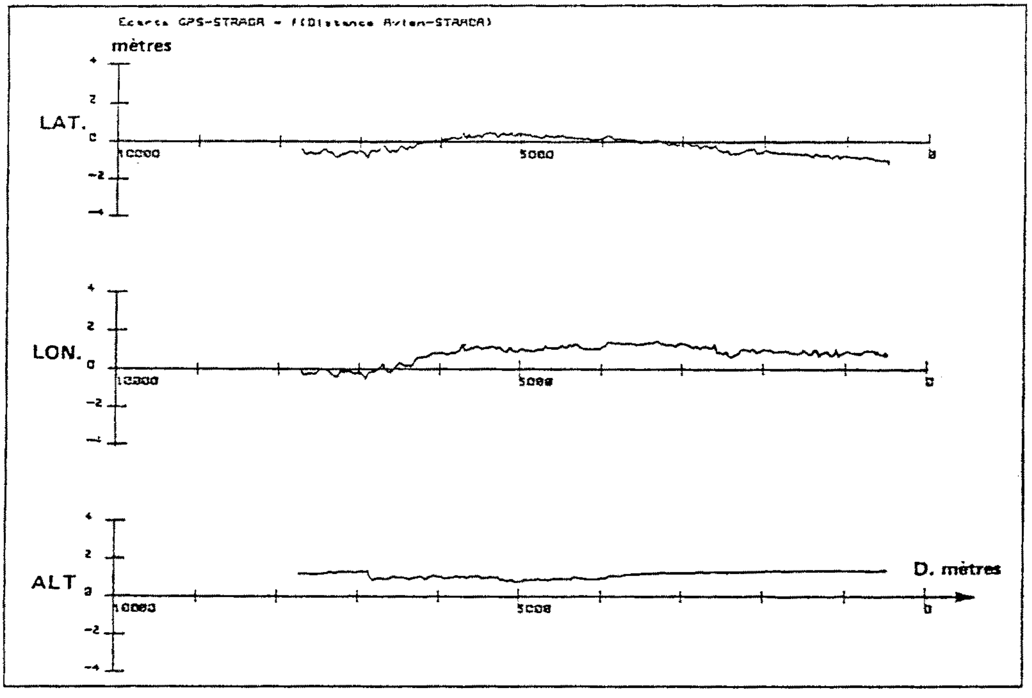


TABLE 2

GDVS results for the baseline SERCM001-AGFA (2.7km)

SERCEL test campaign (January-February 1988)

Session	Day	DX (m)	DY (m)	DZ (m)	D (m)
1	28-01-1988	-1385.034	-2011.471	1217.832	2729.002
2	28-01-1988	-1385.029	-2011.466	1217.839	2728.999
3	29-01-1988	-1385.027	-2011.471	1217.832	2728.998
4	29-01-1988	-1385.022	-2011.460	1217.846	2728.993
5	30-01-1988	-1385.026	-2011.470	1217.837	2728.999
6	30-01-1988	-1385.021	-2011.464	1217.847	2728.997
7	31-01-1988	-1385.024	-2011.470	1217.837	2728.998
8	31-01-1988	-1385.023	-2011.463	1217.843	2728.995
Mean value		-1385.026	-2011.467	1217.839	2728.998
Standard deviation		0.004	0.004	0.005	0.003

For small scale geodetic networks, this type of use of GPS is specially valuable : high accuracy geodetic network at CERN (1985 and 1986), TURTMANN (1985), CASSINO (1986), Channel (1986) in cooperation with Ordnance Survey, Zottegem (1987) for the Institut Géographique National de Belgique, Channel (1987) in cooperation with Ordnance Survey for Trans-Manche Construction. We must also mention that in 1988 the national geodetic network will be entirely done with GPS in Martinique Island. For geodynamic purposes, several networks were surveyed by GPS : Djibouti (1987) under the coordination of the IPGP, Pyrénées (1987) for GRGS-Toulouse, Provence 1987, as a joint IGN-IPGP project.

Since the beginning, the Institut Géographique National has also been involved in the connection of tide gauges to a very precise global reference frame by GPS [see P. WILLIS, C. BOUCHER (1987)]. Several major campaigns were organized : France-Italy (1986), Channel (1986). Figure 4 shows the geographic location of the tide gauges and of the SLR and VLBI sites in the area of the Channel. This activity will continue in the future and there are plans for such campaigns in Spain and Portugal in 1988 and in the Pacific zone in 1989.

6. Geodesy with dual frequency receivers

In order to improve the ionospheric correction, it is necessary for large distances (greater than several tens of km) to use dual-frequency equipment. Presently, the I.G.N. has no receivers of this type. During 1988, we plan to buy 3 of these receivers (two for surveying and one

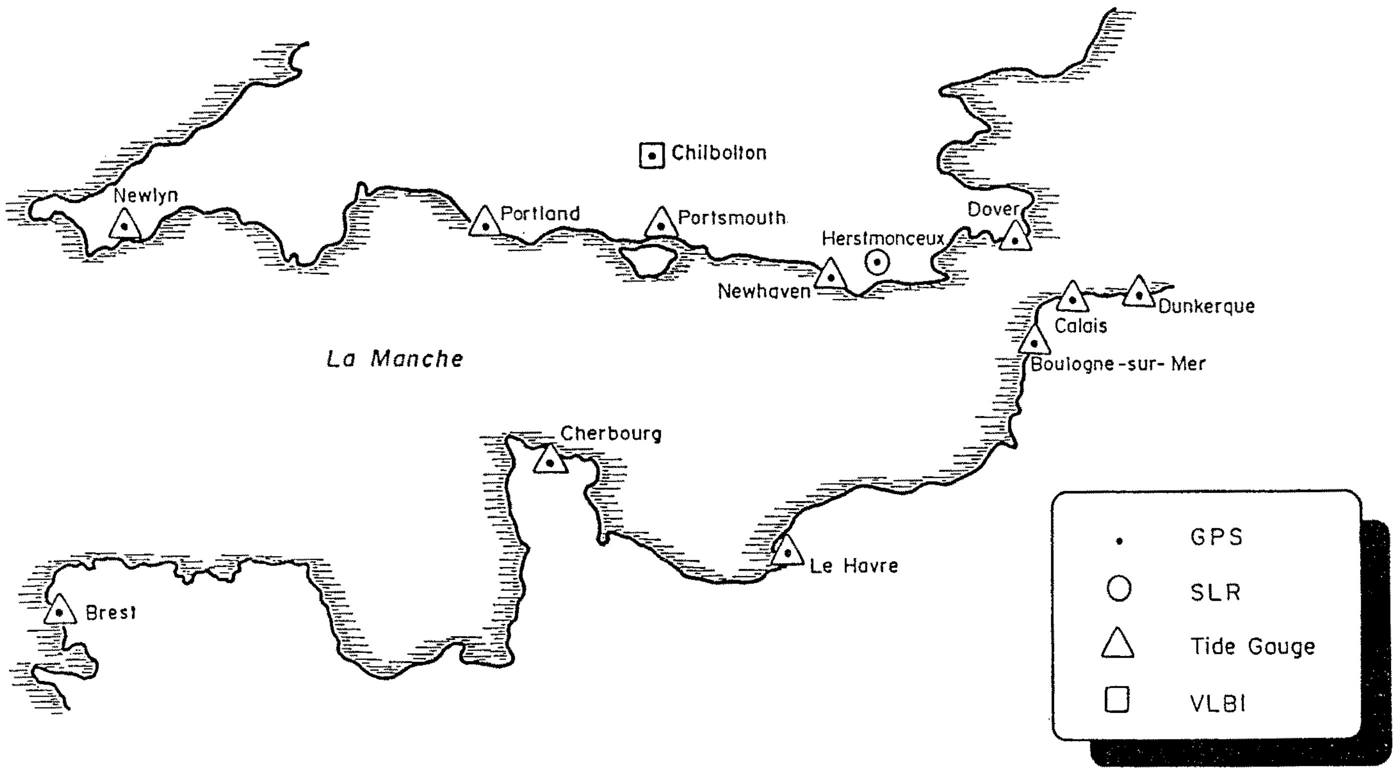


Figure 4 - **IGN-OS Joint Campaign August 1986**

for satellite tracking. The expected accuracy of the relative positioning is presently at the order of 1 ppm for distances up to one or two hundred km. The limiting factor of this precision is the quality of the broadcast orbit when using a software package. It must be noted that it is possible to improve the single frequency results when they are combined with dual frequency measurements. In 1987, the I.G.N. has realized, in collaboration with Ordnance Survey, a specific geodetic network for the future Channel tunnel, using both dual frequency (4 TI 4100 from TRIMBLE) and single frequency (4 TRIMBLE 4000 S and 4 TR5S from SERCEL). Figure 5 shows the colocation between single and dual frequency instruments. The combination of all the observations, and also the previous terrestrial geodetic observations, allowed us to obtain an homogeneous network RTM 87 (Réseau Trans Manche 1987) of the quality of 1 ppm.

7. Kinematic positioning using the carrier beat phase

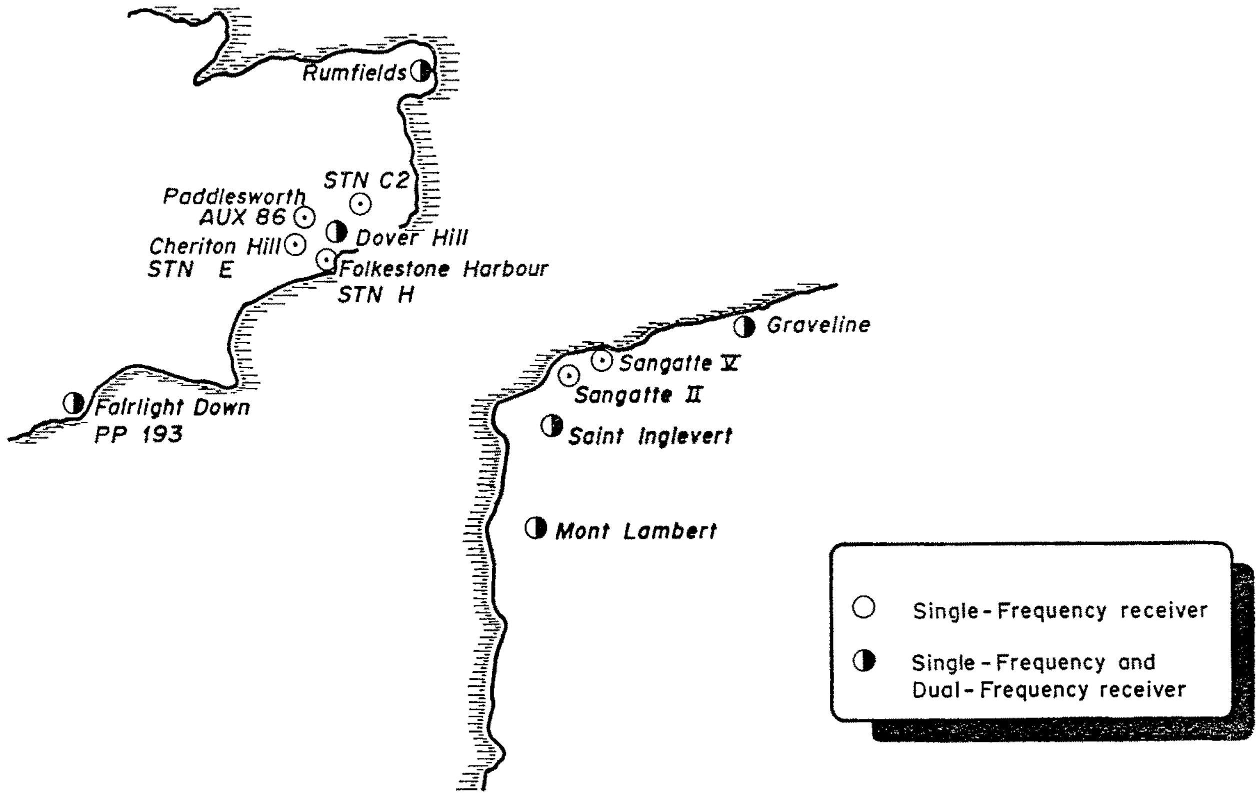
For the surveys described below, it is necessary to record one hour (at least) of GPS observations, in order to distinguish (in a least squares sense) the signature of the ambiguities with the signature of the position parameters. When these ambiguities are known, in a way or another, it is possible to use the phase observation in a non-ambiguous mode, as it is done with pseudo-range, as long as there is no cycle slip in the data.

Several techniques are possible to estimate the ambiguities : calibrate the ambiguities on a well known baseline, use the switching antenna technique [B.W. REMONDI (1986)], for example. The estimated accuracy is at the level of 2 centimetres for baselines smaller than a few kilometres [G. MADER (1986)]. This kinematic GPS using the phase must be distinguished from the trajectography (paragraph 4) when the observable is the smoothed pseudo-range and not the carrier beat phase. Some preliminary tests were performed at I.G.N. using the GDVS results and will be presented soon. In 1988, the I.G.N. plans to realize estimation tests for this method on a near production basis. This technique can be of great use for photogrammetry in providing a large number of control points at 1 centimetre level for large scale aerotriangulation.

8. High accuracy

Finally, the millimetric precision of the GPS measurement can be used, when using dual-frequency receivers and a specific software including orbit determination. This concept of "fiducial network", developed by J.M. DAVIDSON (1986), has proved to give excellent results by several authors [Y. BOCK et al. (1986)]. Presently, when an orbit determination is realized (using as fiducial points the VLBI and/or the SLR sites), it is possible to achieve accuracies of 2×10^{-8} in relative positioning for baselines of a hundred km to a few thousands km. The I.G.N. has not yet obtained this capability but is willing to improve its experience on the orbit determination problems in a near future.

Figure 5 - IGN-OS Joint Campaign October 1987



9. Conclusions

Since 1985, the Institut Géographique National (France) has been involved in the GPS. Several receivers were bought and plans for a new equipment exist. A specific software (GDVS) has been developed. A large range of applications of the Global Positioning System have been tested or developed and actually demonstrated on the field for science or production purposes. Some investigations must be continued, specially for high accuracy GPS and for orbit determination.

The Global Positioning System will probably obtain a very large number of different users interested in one or several aspects of the above described applications of GPS.

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GPS APPLICATIONS OF CTS

by

Barbara Kolaczek

Abstract

An outline of present conventional terrestrial systems and posibility of applications of GPS to the CTS improvement are presented.

Introduction

GPS achieving a high accuracy in determinations of relative station positions and base lengths have been succesfully applied to regional Earth crust motions but it has not been applied yet to reference CTS determinations. Some suggestion of GPS applications to the improvement of the BTS is presented here.

The problem of definition and practical realization of the terrestrial and celestial coordinate systems was always the basic problem in geodetic and astronomic investigations. It became crucial when the new observational techniques, such as VLBI, lunar and satellite laser ranging and GPS achieved accuracies of the order of 1 mas and of a few centimeters in determinations of radiosource positions, of lengths and directions of terrestrial bases and of station positions, respectively. At this level of accuracy station positions can no longer be assumed motionless in relation to each other due to the Earth crust motions. Anyhow there seems to be a general agreement that the best way of the practical realization of a reference terrestrial coordinate system is the determination of a conventional terrestrial system - CTS consisting of a number of stations with accurately determined geocentric coordinates. Conceptionally the definition of CTSs presently used in the process of evaluation of the Earth rotation parameters is similar to the definition of the Conventional International Origin - CIO or BIH 1968 and BIH 1979 coordinate systems based on classical astrometric stations. The new CTSs consist of ten to several tens of stations carrying on observations by VLBI, laser and Doppler techniques, but their geocentric coordinates are not connected with local verticals as it was in the case of astrometric stations. Independent CTSs are determined in the process of ERP evaluations by different techniques but also in determinatiions of the Earth gravitational field. The homogeneous BIH reference terrestrial system BTS for all observational techniques was computed in 1984 and improved later. The problem of the reference terrestrial system has been discussed and reviewed at many meetings (B. Kolaczek, G. Weiffenbach, 1974; E. Gaposchkin, B. Kolaczek, 1981; I. I. Mueller, 1985; G. A. Wilkins, A. Babcock, 1987).

Outline of present CTSs and the BTS

CTSs consisting of sets of stations with the most accurately known geocentric positions which are presently determined in the evaluation process of the Earth rotation parameters - ERP depend not only on a set of participating stations and on the applied observational technique but also on the applied model of computations, adopted constants etc. Several different CTSs were determined from different sets of observational data by different analysing centers evaluating ERP series especially during the MERIT Campaign (BIH, 1986; Boucher, Altamimi, 1986, 1987). The accuracy of station coordinates of the laser station network (73) determined for instance by the Center for Space Researches - CSR and the VLBI station network (13) determined by the National Geodetic Service - NGS range from several to 20 centimeters (BIH, 1986).

Since 1984, the BIH Terrestrial System - BTS, the reference CTS for all observational techniques participating in ERP observations has been computed (C. Boucher, M. Feissel, 1984). The BTS consists of stations at which observations by the use of at least two observational techniques (VLBI, laser, Doppler) were carried out. The BTS (1986) consists of 51 stations participating in evaluation of 6 ERP series, see Tables 1 and 2 (BIH, 1986; C. Boucher, Z. Altamimi, 1986).

Differences of station coordinates determined in BTS (1985) and BTS (1986) ranging from 1 to 20 cm (Table 1) and the transformation parameters of these two systems (Table 3) show that the accuracy of station coordinates of the BTS (1986) is of the order of a few centimeters. A higher accuracy of the reference terrestrial system is required.

The BTS (1986) has other drawbacks. Distribution of the BTS (1986) stations in longitudes and latitudes is very unhomogeneous. They are located mostly on the North American (23) and European-Asian plates (16). Only 12 stations are located outside Europe and North America. Nearly half of these stations are located in the vicinity of plate tectonic boundaries. 6 stations move with the velocity greater than 2cm/year due to the tectonic plate motions. 40 stations move with the velocity of the order of 1 - 2 cm/year (BIH, 1986). At the plate tectonic boundaries some irregular crust motions are possible.

There are only 16 VLBI stations in the BTS (1986). Therefore the present BTS (1986) is based mostly on laser and Doppler station networks. Transformation parameters between the individual terrestrial systems and the BTS (1986) given in Table 4 (BIH 1986) show the biggest discrepancies of the Doppler station coordinates.

Applications of GPS to CTS improvements

In this situation the application of the GPS technique to the improvement of the BTS ought to be considered. First of all the GPS technique could be applied as the additional observational technique at the laser nad VLBI sites of the BTS (1986), especially at its European and North American sites. Repetitions of these GPS measurements which are easier than the repetitions of laser or VLBI collocations could check the stability of the BTS network.

GPS mobile receivers achieving such a high accuracy in determinations of relative station positions and base lengths could be used for connections of the present BTS sites located in the vicinity of tectonic plate boundaries with well chosen sites located on the stable parts of the tectonic plates. It could allow to check motions of the BTS sites and to create consistent continental networks.

The application of the GPS technique to the ERP determinations is expected (Pâquet, Louis, 1987, Zelensky et al. 1987). In order to ensure the highest accuracy of CTS determinations in the process of evaluation of the ERP about 20 - 30 stations well distributed in latitude and longitude ought to be taken into account (Mueller et al., 1982). In the case of small number of stations participating in ERP determinations the geometric conditions of a solution and the influence of errors of station coordinates are important. It is well known fact in the case of IRIS-VLBI series of the ERP based on observations of several stations (IRIS, 1987). Bad geometric configuration of VLBI stations increases errors of ERP determinations or eliminates one of pole coordinates from determinations. Errors of station coordinates participating in ERP determinations in the order of a few centimeters can introduce similar errors in ERP determinations in the case of ten or smaller number of stations not well distributed in latitude and longitude.

In the near future new systems of satellite observations such as DORIS - Doppler Orbitography and Radiopositioning Integrated by Satellite (Doner et al., 1985) and PRARE - Precise Range and Range Rate Equipment (Hartl et al., 1985) will be introduced in practice. Some coordination of activities is needed in order to use all observational techniques for improvement of the reference CTS.

Table 1. BTS (1986) sites (BIH, 1986).

SITE	NETWORKS	COORDINATE DIFFERENCES BTS(1986) - BTS(1985)			PLATE
		dX (cm)	dY (cm)	dZ (cm)	
Algonquin	2 7	- 7	+ 4	- 7	NOAM
American Samoa	5 6 7	+ 3	-23	+ 3	PCFC
Arequipa	5 6 7	-10	+ 3	+ 7	SOAM
Bear Lake	5 6 7	-19	+14	- 5	NOAM
Bermuda	5 7	-12	+12	+ 4	NOAM
Canberra	3 5 7	-	-	-	INDI
Cerro Tololo	5 6	-	-	-	SOAM
Chilbolton	1 2 7	+ 2	-15	- 9	EURA
Dionysos	5 7	+58	-12	-18	EURA
Effelsberg	1 2 7	+ 3	-19	- 9	EURA
Flagstaff	5 6	-	-	-	NOAM
Fort Davis	1 2 4 5 6 7	-15	- 6	- 7	NOAM
Goldstone	1 2 3 5 6 7	-13	+11	- 4	NOAM
Grand Turk	5 7	-10	+ 5	- 6	NOAM
Grasse	4 5 6 7	- 8	- 3	0	EURA
Graz	5 6 7	- 2	- 3	-13	EURA
Greenbank	1 2 7	-18	0	- 8	NOAM
Haystack	1 2 3 5 6 7	-18	- 4	- 8	NOAM
Helwan	5 6	-	-	-	AFRC
Herstmonceux	5 6 7	- 3	+ 2	-11	EURA
Johannesburg	1 2 7	-	-	-	AFRC
Kootwijk	5 6 7	- 1	- 3	- 3	EURA
Kwajalein Atoll	2 5 6 7	+13	+43	+ 3	PCFC
Madrid	2 3 7	-	-	-	EURA
Maryland Point	1 2 7	-21	0	- 3	NOAM
Matera	5 6	-	-	-	EURA
Maui	4 5 6 7	+ 6	+ 6	-11	PCFC
Mazatlan	5 6	-	-	-	NOAM
Metsahovi	5 6 7	-174	-16	-74	EURA
Monument Peak	5 6	-	-	-	NOAM
Motu Hiumoo	5 6	-	-	-	PCFC
Mount Hopkins	5 7	-23	- 5	-12	NOAM
Natal	5 6 7	+ 1	-24	- 2	SOAM
Onsala	1 2 7	- 8	-14	-10	EURA
Owens Valley	1 2 3 5 6 7	-13	+11	- 9	NOAM
Pasadena	5 6 7	-12	+13	- 4	NOAM
Patrick Afb	5 7	-21	+ 5	- 2	NOAM
Platteville	5 6	-	-	-	NOAM
Potsdam	5 6	-	-	-	EURA
Quincy	5 6 7	- 5	+15	-12	NOAM

Table 1 cont.

SITE	NETWORKS	COORDINATE DIFFERENCES BTS(1986) - BTS(1985) dX (cm)	dY (cm)	dZ (cm)	PLATE
Richmond	1 2 7	-19	+ 1	- 8	NOAM
San Diego	5 6 7	+12	+18	- 5	NOAM
Santiago	5 6	-	-	-	SOAM
Shanghai	5 6 7	-	-	-	EURA
Simosato	5 6	-	-	-	EURA
Vernal	5 6	-	-	-	NOAM
Washington	5 6 7	-12	+11	- 4	NOAM
Wettzell	1 2 5 6 7	- 7	+15	-11	EURA
Yarragadee	5 6 7	+19	-12	-14	INDI
Yuma	5	-	-	-	NOAM
Zimmerwald	5 6 7	+11	0	-24	EURA

Table 2. Networks and series of the Earth rotation parameters contributing to the BTS (1986) (BIH, 1986).

Contributing Networks				Series of ERP	
Nr	Set of station coordinates	Time span	Nb of coloc. sites	ERP Label	Time span
1	SSC (NGS) 87 R 01	1980-1986	12	NGS 87 R 01	1984.0-1987.0
2	SSC (GSFC) 87 R 01	1979-1986	15	NGS 87 R 01	1984.0-1987.0
3	SSC (JPL) 83 R 05	1971-1983	5	JPL 83 R 01	1984.0-1987.0
4	SSC (JPL) 87 M 01	1983-1986	3	JPL 87 M 01	1984.0-1987.0
5	SSC (CSR) 86 L 01	1976-1986	42	CSR 86 L 01	1984.0-1986.7
6	SSC (DGFII) 87 L 01	1980-1984	37	DGFII 87 L 01	1984.0-1985.0
7	SSC (DMA) 77 D 01	1975-1984	38		

Jet Propulsion Laboratory - JPL, Pasadena, USA
NASA Goddard Space Flight Center - GSFC, Greenbelt, USA
National Geodetic Survey - NGS, Rockville, USA
Center for Space Research - CSR, Austin, USA
Deutsches Geodatisches Forschunginstitut - DGFI, Munich, FRG
Defence Mapping Agency - DMA, Washington, USA.

Table 3. Transformation parameters between the three realizations of the BTS (the uncertainties are given in the second lines) (BIH, 1986).

BTS	T1 m	T2 m	T3 m	D 10^{-6}	R1 "	R2 "	R3 "
1984/1985	0.023	0.044	0.037	-0.0021	-0.0002	-0.0014	-0.0042
	0.020	0.020	0.020	0.0029	0.0008	0.0007	0.0007
1985/1986	0.051	-0.023	0.070	-0.0089	-0.0025	-0.0006	-0.0069
	0.022	0.022	0.022	0.0032	0.0009	0.0008	0.0008

Table 4. Transformation between the individual terrestrial systems and the BTS (BIH, 1986).

Network	SSC	T1 cm	T2 cm	T3 cm	D 10^{-8}	R1	R2 0".001	R3	A3
SSC (NGS)	87 R 01	10.8	12.5	5.8	-2.4	-4.5	10.3	-1.8	0.6
SSC (GSFC)	87 R 01	153.5	-96.1	45.0	-2.7	-4.1	10.4	10.3	0.9
SSC (JPL)	83 R 05	5.5	-27.6	-15.8	-1.6	-4.8	-2.6	4.9	1.4
SSC (JPL)	87 M 01	.0	.0	.0	-2.2	1.9	3.7	-10.6	
SSC (CSR)	86 L 01	.0	.0	.0	.0	-4.5	3.1	-4.4	
SSC (DGFI)	87 L 01	.3	-3.3	6.2	1.3	8.0	-6.0	120.6	
SSC (DMA)	77 D 01	-16.7	-21.2	-431.4	57.1	36.1	8.4	-795.1	

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