MAREES TERRESTRES

BULLETIN D'INFORMATIONS

INTERNATIONAL CENTER FOR EARTH TIDES
CENTRE INTERNATIONAL DES MAREES TERRESTRES

ICET

Federation of Astronomical and Geophysical Data Analysis Services
(FAGS)

International Association of Geodesy - International Gravity Field Service
(IAG – IGFS)

Publié avec le soutien de l'Observatoire Royal de Belgique

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SCIENTIFIC PAPER

International Association of Geodesy

15th International Symposium on Earth Tides

2-6 August 2004

Ottawa, Canada

Conveners

International Association of Geodesy & IAG Earth Tides Subcommission

The 15th international Symposium on Earth Tides will was held in Ottawa, Canada's Capital, from 2-6 August 2004. Ottawa is the heart of Canada, and much more than just a beautiful and spectacular city. With its neo-Gothic style and spirit, Ottawa straddles the border of the provinces of Ontario and Quebec exactly where Ottawa, Gatineau and Rideau rivers converge. Ottawa is the cultural and festival city with the highest concentration of museums in Canada. Parklands, gardens, trails, recreational pathways, historic monuments and grounds, and the Rideau Canal offer visitors an unsurpassed blend of national pride and French and English culture.

The National Arts Centre (NAC) was the venue of the conference. It is among the largest performing arts complexes in Canada and is situated in the heart of the nation's capital across from Confederation Square and Parliament Hill, right next to Rideau Canal. NAC is unique, for it is the only multidisciplinary and bilingual performing arts centre in North America and features one of the largest stages on the continent.

Local Organizing Committee

Dr. Spiros Pagiatakis (Chair, York University, spiros@yorku.ca)
Dr. Joseph Henton (Geodetic Survey Division, NRCan, jhenton@nrcan.gc.ca)
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Welcome address

15th International Symposium on Earth Tides

Robert Ryerson
Director General of the Canadian Centre for Remote Sensing

Introduction and Objective

It is an honour to be asked to address this 15th International Symposium on Earth Tides. It is to your credit that the Earth Tides Commission (ETC) of the International Association of Geodesy is a highly successful collaboration of national agencies, universities and research institutions representing over 24 nations. As someone who has been involved in many international collaborative efforts, it never ceases to amaze me, how much is done in these voluntary organizations.

A key objective of this meeting is to encourage dialog and further promote campaigns to develop, compare and calibrate instrumentation for earth tide observations, techniques of operation and data analysis procedures. So I encourage all of you to take advantage of this beautiful setting, establish a rapport with your fellow scientists and use this as a springboard for your future collective success.

I commend each of you and your organisations for your dedication to the ETC and welcome you to this Symposium.

My staff has prepared some detailed notes on the size of our country the importance of natural resources to Canada, and our department's role. I think that this is worth sharing with you.

Canada and the Federal Department of Natural Resources (NRCan)

Canada is the world's second-largest country, larger than the continent of Europe (excluding Russia), and covers six time zones. Yet only 33 million of us call this vast land home. Given this, it is not surprising that the natural resources sector is a very important part of the Canadian economy, amounting to over 12 percent of Canada's GDP. Nearly a million Canadians are directly involved in forestry, mining and energy.

Natural Resources Canada, also known as NRCan, is a Canadian federal government department specializing in the sustainable development and use of natural resources, energy, minerals and metals, forests and earth sciences. NRCan conducts leading-edge science and technology to provide Canadians with ideas, knowledge and technology. This helps us use our resources wisely, reduces costs, protects the environment and creates new products and services.

We build and maintain a national knowledge infrastructure of Canada's land and resources, so all Canadians can easily access the latest information about our landmass and our resources. International partnerships and exchanges such as these help NRCan meet its commitments related to natural resources, and keeps access open to Canadian and global markets for products, services and technology.

NRCan Support of Gravity Efforts

Gravity is one of the supporting sciences in our department and Canada has a long, successful history in gravity studies. Two years ago we commemorated the 100th Anniversary of the first precise gravity measurements performed by Canada. These were carried out by the Dominion Observatory which later established our Geodetic Survey Division.

The 1902 experiments and the early gravity apparatus marked the Canadian beginning of a series of scientific observations and formed the basis for the National Gravity Program. And the evolution has continued through generations of improved instrumentation, now relying on state-of the-art absolute gravity meters. The original equipment is now a part of our history and is preserved in the collection of the National Museum of Science and Technology here in Ottawa. And to tell you how old I am, some of the first systems I was involved in developing are also in that museum!

Geodetic Survey Division is located within the Canada Centre for Remote Sensing. Under the stewardship of Geodetic Survey, the Canadian National Gravity Program now forms an integral part of a modern spatial positioning framework for Canada, called the Canadian Spatial Reference System (CSRS). Gravity contributions to international gravity programs serve Canadian science and technology and ensure global consistency of national spatial reference standards.

The measurements support NRCan commitments towards the sustainable development of natural resources and contribute to other government priorities. For example, tools to generate sea level GPS heights along with data for vertical crustal motion and post-glacial rebound studies are used in addressing environmental issues as well as for economic development through contributing to identifying potential oil- and mineral-bearing regions.

But I think we need to do better to get our story out and ensure the lasting support our science deserves.

NRCan's Science that Serves Canadians

This meeting here is of particular importance as the micro-gravity community prepares to expand its expertise into environmental monitoring efforts. For NRCan this expertise could be applied to projects investigating effects related to climate change processes, to variations in groundwater storage, and to natural hazards such as crustal deformations found in seismic regions.

With Canada's vast territory, it is incumbent on us to take advantage of the opportunities presented by emerging technologies such as satellite systems. Remote sensing, for example, already helps us to manage our forests and our crops better and enables summer shipping through the ice packs of Arctic waters.

Many of you are getting involved with a new breed of remote sensing as satellite missions such as CHAMP, GRACE and the upcoming GOCE produce unprecedented coverage and accuracy for monitoring changes in gravity. All of this bodes well for our collaborative understanding of the Earth's systems as we all face unsettling changes in our natural environment.

Closing Remarks

If I leave you with only one message, it would be a challenge to do your utmost to help us all face the issues of today. Help us to focus our limited resources efficiently on understanding and mitigating the effects of climate change and natural hazards, on building strong and safe communities and developing healthy economies. Science is helping to take us there, but our collective choices along the way will influence our success.

I hope you have time to visit some of the sites around our beautiful capital city, take in some of its capital attractions, such as the traditional Changing the Guard ceremony. If this is your first visit to our country, I hope that Ottawa will provide you with lasting memories of the quiet charm of Canada. We certainly extend a welcoming hand and look forward to seeing you in Canada in the future.

The local organizing committee is available to address any specific questions you may have about the city or your visit. Don't hesitate to ask for their help. Once again thank you and I hope you have a very productive meeting.

ETsC Presidential Address Ottawa 2004

Mr. Chairman, dear colleagues, ladies and gentlemen,

I welcome you to the 15th International Symposium on Earth Tides held in Ottawa, Canada. I thank you for your participation! Special thanks go to Dr. Robert Ryerson as our Canadian host: He is Director General of the Canadian Centre for Remote Sensing (CCRS), Earth Sciences Sector, of the Department of Natural Resources Canada. I thank you for your welcome address.

I also thank the Local Organising Committee for the preparations! We meet in an interesting city and in an attractive meeting place. After the symposia in New York, 1981, in Beijing, 1993, and Mizusawa, 2000, it is the fourth symposium outside Europe and, consequently, the second symposium in North-America.

During the last General Assembly of the IUGG in Sapporo, 2003, I was appointed President of the Earth Tide Commission. But, more importantly, in Sapporo the structure of IAG was changed: Now the ETC belongs to Commission 3 (former Comm. 5) of IAG with the topic Geodynamics and Earth Rotation, chaired by Veronique Dehant. The ETC is *sub-commission 3.1*, and the other two are *3.2 Tectonics and Crustal Deformation* chaired by Markku Poutanen, and *3.3 Geodynamics (including loading and post-glacial rebound)* chaired be Richard Gross. We are – as before – encouraged to name working groups on specific problems which have to report to ETC.

Commission 3 also promotes the *Global Geodynamics Project* chaired by David Crossley, and it relies on the IERS (International Earth Rotation and Reference System Services) as well as on ICET (International Center of Earth Tides, Brussels). Finally, it is related to Commission 19 of the IAU (International Astronomical Union), chaired by Veronique Dehant.

The program of this symposium reflects the present state of our research area: We condensed earlier classical experimental and theoretical topics to (1) Earth based instrumentation, as well as (5) Tilt, strain, connected to aperiodic and long period signals, and (3) Earth and ocean tides. We also kept (2) Space geodetic techniques and tides. In continuation of the ideas of our Japanese colleagues responsible for the symposium in Mizusawa, we now put emphasis to (4) Interplanetary tidal interactions and gravity, as well as to (6) Environmental processes and gravity, and (7) Geodynamics. We also added a workshop on the Global Geodynamic project.

New is the Open Forum scheduled for this afternoon with the title: *Earth Tides Research on the Crossroads*. This title reflects the fact that, in the meantime, most of our work is related to non-tidal effects. Therefore, we feel the need for a re-definition of tidal research with regard to the scientific problems we work on, and, thus, to put our activities on an improved basis. One proposal we have to discuss also in the resolution committee is the completion of the name of our commission with a term that reflects our activities, like *temporal gravity variations* or *geodynamics*.

I would like to report about a very pleasant duty which I had to fulfil: Our friend and former President of the Earth Tide Commission, Prof. Houtze Hsu, celebrated his 70th birthday; I should better say, the Chinese Academy of Sciences celebrated his birthday in Wuhan, and it was a great festival which showed the power and success of modern China. I was invited to present a talk on modern developments in Earth Tide research which was also printed in a 11-hundred pages birthday volume.

Although tidal research started during the second half of the 19th century, which means it is more than 125 years old, the tidal community was born 1954 with the first Symposium on Earth Tides organised by Prof. Paul Melchior in Brussels. This means, this year our fairly small Earth Tides community now celebrates 50 years of successful co-operation. On the other hand, this also means that at every symposium we have to deplore the loss of valuable colleagues who passed away. To my knowledge came the names of four colleagues: Christian Le Provost, Christian Poitevin, Tadeusz Chojnicki, Hans-Jürgen Dittfeld. We will keep their memory.

I wish all of us an interesting and successful symposium. Thank you very much.

Gerhard Jentzsch
Friedrich-Schiller-University
Jena, Germany

Earth Tides subCommission Medal

International Union of Geodesy and Geophysics'
International Association of Geodesy

Commission III: Geodynamics and Earth Rotation
Sub-Commission I: Earth Tides Commission

The Earth Tides Commission of the International Association of Geodesy awards the Third

EARTH TIDES COMMISSION MEDAL

to

Professor John Goodkind

for his outstanding contribution to earth tides research.
This presentation is made the 3rd day of August, 2004 at the 15th International Symposium on Earth Tides in Ottawa, Canada.

Gerhard Jentzsch
President

Spiros Pagiatakis
Vice President

Olivier Francis
Secretary

Centre International des Marées Terrestres
International Centre for Earth Tides

SCIENTIFIC ACTIVITY REPORT
for the period 2000-2004

by
B.Ducarme, ICET Director
ducarme@oma.be

The staff of ICET, which is completely supported by the Royal Observatory of Belgium, our host Institution, is composed as follows:
Prof. B.Ducarme, Director(part time)
Mrs. L.Vandercoilden, technician(full time)
Mr. M.Hendrickx, technician(part time)

The Royal Observatory of Belgium is hosting ICET since 1958 and continues to provides numerous administrative and scientific facilities especially for the publication of the " Bulletin d'Information des Marées Terrestres" (BIM), for the tidal data processing and, between 1997 and 2004, for the maintenance of the ICET/GGP data base.

1. Terms of reference

The terms of reference of the International Centre for Earth Tides(ICET) can be summarised as follows:
- as World Data Centre C, to collect all available measurements on Earth tides;
- to evaluate these data by convenient methods of analysis in order to reduce the very large amount of measurements to a limited number of parameters which should contain all the desired and needed geophysical information;
- to compare the data from different instruments and different stations distributed all over the world, evaluate their precision and accuracy from the point of view of internal errors as well as external errors;
- to help solving the basic problem of calibration by organising reference stations or realising calibration devices;
- to fill gaps in information and data;
- to build a data bank allowing immediate and easy comparison of earth tides parameters with different Earth models and other geodetic and geophysical parameters ;
-to ensure a broad diffusion of the results and information to all interested laboratories and individual scientists.

These goals are achieved essentially by the diffusion of information and software, the data processing, the training of young scientists and the welcome of visiting scientists.

2. Main Commitments

It appears first that most geodetic measurements are affected by earth tides, as at the centimetric level the tidal displacement of the station is no more negligible. It will thus remain an important task for ICET to provide algorithms for tidal computation or analysis. For example the geophysicists, such as seismologists or volcanologists, who are measuring crustal deformations for natural hazards monitoring, are now conscious of the necessity of dealing properly with the tidal signals. In a similar way absolute gravity measurements require accurate tidal corrections that should take into account the local tidal parameters. These parameters have to be computed including oceanic tidal loading effects or even require in situ tidal gravity observations.

On the other hand the earth tidal scientific community is limited. The last International Symposium on Earth Tides, held in Mizusawa, Japan from August 28 to September 1st, 2000 , brought together only a bit more than one hundred and twenty participants. The groups are always very small and often marginally involved in tidal research. The papers dealing specifically with tidal studies are not fitting so well to international journals. It is thus very important to keep a specialised diffusion and information medium. It is the vocation of the "Bulletin d'Information des Marées Terrestres"(BIM). ICET is generally publishing two eighty pages issues per year.

Besides this basic activity, which is the scientific challenge for the beginning of this century?

The mathematical modelisation of the astronomical tidal forces as well as the elastic response of the Earth made decisive progress. It is now possible to model the astronomical tidal forces to within 5 nanogal in the time domain. The different mathematical techniques for the evaluation of the tidal response of the Earth do agree now to better than 0.1%. The most recent models include inelasticity in the mantle.

The last problems to be solved are linked to the fluid elements of our planet: liquid core resonance, oceanic loading, meteorological effects, underground water.

Among the ground based observations only gravity tides are able to give informations valid at the regional level. The other components (tilt, strain, volume change) are heavily depending of the local parameters of the crust, including cavity or topography effects. These observations should be mostly used to monitor tectonic deformations after removing the tidal phenomena.

Tidal gravity observations are able to provide constrains on the liquid core resonance by means of very precise observations in selected sites. The same is valid also for the selection of the most realistic model for the elastic or inelastic response of the Earth. For that purpose it is essential to improve the calibration methods in order to achieve a 0.1% accuracy in amplitude and a 0.01° accuracy in the phase determination. It is also necessary to use up to date oceanic tides models for tidal loading corrections. Recently it became possible to determine precisely the frequency of the NDFW and its Q factor using superconducting gravimeters data. The determination of the amplitude factor of the polar motion effect on gravity will constrain the Earth viscosity at low frequency.

To achieve these goals it will be necessary to tackle three main questions: oceanic tidal loading, atmospheric pressure effects, underground water. It is only possible through a coordinated effort and a multidisciplinary approach including Astronomy, Geodynamics, physical Oceanography, Hydrology and Climatology.

3. Ongoing project

These objectives are now directly addressed by the "Global Geodynamic Project"(GGP). A network of 20 stations equipped with cryogenic gravimeters is in operation since July 1997, using a similar hardware and the same procedures for data acquisition. It is an unique opportunity to obtain high quality well calibrated tidal observations. It is a reason why ICET fully supported GGP activities since the beginning and considers GGP as an ICET "project". A first 6 years term finished in July 2003 (GGP-Phase 1) and a second term 2003-2007 (GGP-Phase 2) started immediately after.

Besides tidal research, an important objective of GGP is to study the residues after elimination of the tidal contribution in order to detect inertial accelerations such as free oscillations of the Earth core and mantle with periods larger than 50 minutes, which are difficult to observe by means of conventional seismometers. In fact the cryogenic gravimeters are extra-large band instruments covering phenomena with period ranging from one second to more than one year.

- During the Phase 1 of the project, ICET was responsible of the "Global Geodynamics Project-Information System and Data Centre" (GGP-ISDC, http://etggp.oma.be/), with the technical support of the Royal Observatory of Belgium. The software provided for the management of GGP-ISDC by the GeoForschungZentrum Potsdam was continuously updated.

The data owners can upload themselves the original minute sampled data. The data are carefully preprocessed at ICET using a standard procedure, to correct for tares and spikes. The data are then decimated to one hour and analysed. The analysis results are directly communicated to the data owners. This follow up is required to detect quickly the anomalies that could affect the data. Each year CD-ROM's are edited with the raw and corrected minute data as well as the log files and the auxiliary data, when available.

The data are only released according to a strict time table. The data are sent to ICET only one year after their production. During one additional year the data are only available to the GGP members and can be freely accessed only after two years. The second GGP observation period started immediately after the first one. This GGP Phase 2 is limited to a four years period starting July 1,2003.

- During Phase 2 the GGP groups producing data agree to send to ICET for access by other GGP groups their uncorrected 1-minute data within a 6 month period from the time of its collection and to release it for open access within a 1-year period.

During Phase 2 the GGP data Centre is administrated jointly by ICET and the GFZ-Potsdam. An official agreement was signed between ICET and GFZ for that purpose. The data base is physically at GFZ but ICET will continue its task of data evaluation and analysis.

With the collaboration of guest scientists ICET pushed forward researches using the GGP data sets and concerning the liquid core resonance, the determination of the pole tide and the detection of the inner core oscillations known as Slichter's mode. We have now more than 20 high quality data sets with a minimum length of three year and we can provide on request not only tidal parameters, oceanic loading corrections according to different models but also tidal residues to study non tidal effects such as core modes. These series, if they are well constrained by absolute measurements, will be also useful in the interpretation of satellite gravity data.

4. Ongoing Activities

The "Bulletin d'Information des Marées Terrestres"(BIM) is printed in 300 copies. Some 275 copies are sent to libraries and individual scientists all over the world. It is devoted to scientific papers concerning tidal research. From May 2000 until the end of 2003, six issues n° 132 to 138 have been published with a total number of 770 pages. BIM139 is under preparation. In 2002 we had the opportunity to publish the proceedings of the "Third Workshop of the Global Geodynamics Project (GGP) on superconducting Gravimetry" and of the "Meeting of the ETC-Working Group 7 on Analysis of Environmental Data", held in Jena, Germany, from March 11 to 15,2002. For the first time all the published papers were immediately available on the ICET WEB site.

ICET made an agreement with Marion Wenzel, wife of late Prof.H.G.Wenzel, who inherited the property rights on the ETERNA tidal analysis and prediction software. ICET is now authorised to distribute freely this software among the scientific community for non commercial purposes. This initiative met a great success as some forty CD-ROMS with ETERNA software are requested from ICET each year since May 2000.

The ICET WEB site (http://www.astro.oma.be/ICET/) has been updated and developed. Besides general information including historical aspect and last ICET reports, it proposes to the visitors an access to:
- the general bibliography on Earth Tides from 1870-1997 either by alphabetical order of the first author or following the decimal classification introduced by Prof. P.Melchior;
- the table of content of all the previous BIM, n° 1-138, and starting from BIM 133 an electronic version of the papers;
- tidal analysis and preprocessing software available from different WEB sites or on request from ICET.

Most of the information requests (one per week minimum) concerned softwares Most of them followed the consultation of the WEB site. This site is one of the most frequently consulted among the pages of the Royal Observatory of Belgium (ROB), which is the host agency.

According to the internal GGP rules ICET is preparing annually CD-ROM's, with the raw and processed minute data. We already edited CD-ROM's for the 5 first years, 1997/07 to 2002/06, of the project. We are now preparing the sixth year.

5. Visitors

ICET welcomed more than 25 visitors. Besides visitors coming only for a short stay we must consider also guest scientists and trainees.
The guest scientists bring their own know how or data to work at ICET during several weeks or even months. Some of them worked on the ICET and GGP data banks, as Dr. A.Kopaev(Sternberg Astronomical Institute, Moscow), Prof. H.P. Sun and his assistants (Institute of Geodesy and Geophysics, CAS, Wuhan, China), Prof. V.Timofeev (Institute of Geophysics, UIGGM, Novosibirk, Russia) and Prof. A.P. Venedikov (Institute of Geophysics Sofia). Others brought their own data sets to perform tidal analyses using the ICET software and computing facilities, as Dr. E.Boyarski and Prof. L.Latynina (Institute of Physics of the Earth, RAS, Moscow), Prof. L.Brimich (Geophysical Institute, SAS, Bratislava Slovakia), Prof Silvia S.Schwab ("Universidade Federal de Parana", Curitiba, Brazil), Dr. V.Timofeev(Institute of Geophysics, UIGGM, Novosibirk, Russia). Mrs P.Beddows (School of Geographical Sciences, Bristol University, UK), Mr. M. Harrop (Open University, UK) and and Mrs. E.Zapreeva (Institute of Geophysics, UIGGM, Novosibirk, Russia) came to receive intensive training on earth tide data processing and analysis.

5. Schools

In the framework of the International Gravity Field Service (IGFS) recently created inside IAG, a summer course on "Terrestrial Gravity Data Acquisition Techniques" has been organised jointly by ICET and the "Bureau Gravimétrique International" (BGI), with the

support of IAG and FAGS. Some 45 students from 27 countries took part to this school that took place on the campus of the Catholic University of Louvain in Louvain-la-Neuve, Belgium from September 4 to 11. A CD-ROM with all the teaching material was published.
The aim of this summer school was the training in *gravimetric techniques* of people involved in geodesy, geodynamics, geophysics or geology. At the end of the school, they were able to operate relative gravimeters and handle gravity data in order to realise gravity networks, densification surveys or microgravimetric studies. Special attention was paid to the tidal gravity corrections. There were three different types of activities: lectures, field practice and case studies. The case studies were talks given by specialists who are using the gravimetric techniques in Geodesy and Geophysics or for civil engineering applications.

The ICET Director took part to the "International Seminary on the Applications of the Computer Program VAV-03 for Tidal Data Processing" organised in Madrid from October 21 to 24 by the "Instituto de Astronomia y Geodesia" (CSIC-UCM). He presented two lectures. A CD-ROM will be edited and a manual of VAV method, including applications, will be printed in BIM139 with a CD-ROM attached.

6. Implementation of the new IAG structures

During the 23rd General Assembly of the IUGG, the new IAG structures have been implemented. As a member of the of the International Gravity Field Service (IGFS), ICET has a strong link to the new Commission 2 (Gravity Field), but it is also associated with Commission 3 (Geodynamics and Earth Rotation), to which the new Earth Tides Sub-commission is attached. In the new structure the Services will be represented at the level of the IAG Executive Committee. For ICET this representation will become effective through the IGFS.
A new Directing Board for ICET has been installed (Annex 1). Besides the ex-officio members, the other members have been elected during the last meeting of the former Earth Tides Commission
The Global Geodynamics Project (GGP) is now recognised as an Inter-commission Project between Commissions 1 and 3, reporting to Commission 3.
After the common organisation of the 2002 Summer School, ICET continued to tighten its links with the "Bureau Gravimétrique International" (BGI) in the framework of the "International Gravity Field Service (IGFS). The two services made a common bid for funding to the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) for the merging of their bibliographic data bases. This work is in progress.

7. Future Perspectives

Besides its usual activities for the diffusion of information, the training of young scientists, or the management of the GGP data bank, ICET wants to pay more attention to the development of its WEB site by putting on line the results of all the stations kept in our data bank.
ICET asked to the Earth Tides sub-commission to create a working Group on "Precise Tidal Prediction Methods" in order to be able to provide updated tidal prediction programs on its WEB site.
With an improved WEB site it will be possible also to convert partly the "Bulletin d'Information des Marées Terrestres" into an electronic journal. It will speed up the

publication of the papers, which are generally dedicated to ongoing researches, and reduce drastically the costs.

Following the creation inside IAG of the International Gravity Field Service (IGFS), ICET will deepens its cooperation with the other confederated bodies. ICET will continue its cooperation with BGI for the preparation of a CD-ROM with standard software for gravity measurements, including tidal gravity predictions and for the organisation of a second summer school on "Micro-gravimetric techniques: static and dynamics aspects".

Another possibility offered inside IGFS is to appoint "Fellows", who are individual scientists wishing to contribute to the Service activities. It will be possible to develop a network of contributors who can provide their expertise to ICET in answering to very specialised questions, developing new software and so on.

ANNEX 1

ICET DIRECTING BOARD

ICET Directing Board is composed as follows

Ex officio members

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GGP Stations 1997 - 2003

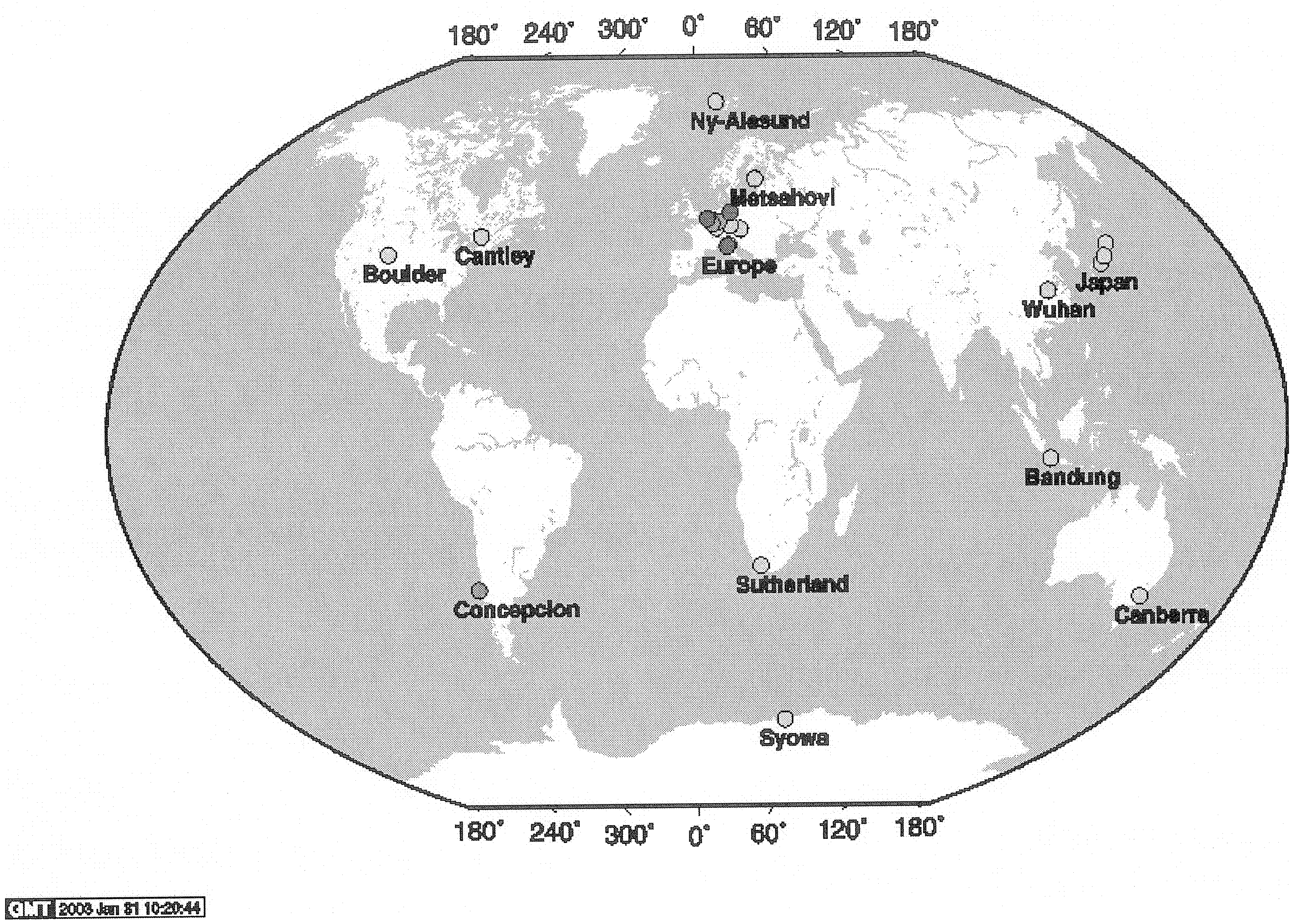

Figure 1 : Network of stations equipped with superconducting gravimeters and contributing to the Global Geodynamics Project
Red dots: closed stations Brasimone (I), Brussels (B) and Potsdam (D)
Yellow dots: active stations
Europe Membach (B), Moxa (D), Strasbourg (F), Vienna (A) and Wettzell (D)
Japan Esashi, Kyoto and Matsushiro
Green dots: stations recently implemented Conception (Chile) and Walferdange (Luxembourg)

OTTAWA, AUGUST 4, 2004

ICET Directing Board meeting

Present: G. Jentzsch, N. Anderson, T. Baker, B. Ducarme, O. Francis, H. Schuh, S. Takemoto,

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Agenda

A) Activity report
Terms of reference
Ongoing projects
Ongoing activities

B) Prospective- Future of ICET

C) Pending problems
IAG Affiliation
January 2008: Replacement of Director

D) Next meeting

A) Terms of reference:
B. Ducarme read the terms of reference. No modifications were proposed

Ongoing projects:

ICET is working on only one project due to the lack in manpower. It concerns the maintenance of the GGP database. The database is being moved from Brussels to Potsdam.

Scientific activity:
- Mostly with guest scientists
- Lot of financial support from the ROB

Ongoing activities:
- Editions of the BIM
- Distribution of the software Eterna
- No more bibliography of Earth Tide since 1997

B) <u>Prospective:</u>

- Request people to send other data than only gravity observations to ICET
- New GGP CD-Roms: problems due to the changes in the calibration factors
- Web site improvement
- Gravity summer school with BGI in 2005
- BGI CD-Rom for tidal gravity corrections
- BIM will become an electronic journal
- Distribution of ETERNA through the web page with a password
- Director of ICET should propose a procedure for the nomination of the Directory Board (selection of fellows from IGFS President of the WGs, of the Commissions, ...)

B) Director retirement:

B. Ducarme will retire in a few years. One needs to find a new director for ICET. Up to now; there is no candidate.

The new director has to be proposed by IAG

- A proposal should be ready for the IUGG XXIV General Assembly in Perugia, Italy
- An open call should be advertised

C) Next meeting in Vienna, EGU, April 25-29, 2005

O. Francis
ETsC Secretary

Report

of the

Working Group

on

‚Analysis of Environmental Data for the Interpretation of Gravity Measurements'

Kroner, C. and Jentzsch, G.

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This working group, in which the influence of the environment on terrestrial geodynamic observations is studied, is now in its seventh year of existence. During this period two developments have emerged: 1. an increasing number of effects due to the environment need to be considered, and 2. even known effects still need to be studied more closely as the observations become more refined. These developments became esp. clear during a workshop in Jena, March 11 – 15, 2002, which was shared by the working group and the Global Geodynamics Project. In all, 39 scientists from 16 countries participated. Papers presented by the participants are published by the International Center for Earth Tides' Bulletin d'Informations des Marées Terrestres, vol. 135 - 137. The importance of environmental influences in geodynamic observations was likewise topic of a number of presentations and discussions during the 15th Earth Tide Symposium in Ottawa this year. At the business meeting of the conference it was decided to change the working group into a study group of the IAG Sub-commission 3.1 Earth Tides, as the understanding of environmental effects is a dynamic research topic which requires long-term studies and cannot be finished within a defined period.

Whereas the first term of report was characterised by the studies focusing on effects due to mass movements in the atmosphere, within the recent term the importance of hydrological influences on observations was recognized. This is also reflected in the recommendations and proposals by the working group. Main results of the discussions were:

- Concerning the barometric pressure influence on gravity indications exist that vertical density variations could be of importance.

- At a number of gravimeter stations located in bedrock hydrological effects on gravity can be observed. It is not entirely clear, where these effects originate from as usually clefts and fissures are too small to allow larger hydrological variations.

- The influence of hydrological fluctuations on gravity needs to be studied more closely. It is recommended that at least precipitation measurements are carried out at each station. A fundamentally better understanding of the hydrological situation at an observatory can be obtained if precipitation, groundwater table, and soil moisture changes are observed.

- For studies of long-periodic gravity variations fluctuations in the continental water storage and in the water mass of the oceans need to be considered in addition to large-scale barometric pressure variations.

- It was recommended to ask the recently established 'Special Bureau for Loading' to provide global barometric pressure corrections and corrections for continental water storage and water mass in the oceans for all GGP stations, thus making a standard correction available for these effects. This contact has been made.

- The monitoring of soil moisture variations is a problem, because either soil moisture variations of different depths or an integrated soil moisture value seems to be needed. In addition, it is not clear up to which extend such a value is representative for its surroundings. Regarding these two issues principle studies are required.

- The physical mechanism between environmental variation and signal in tilt or strain often is still uncertain, for at a single station already quite a number of different effects due to the same environmental parameter can be observed. Therefore it is recommended that observatories, in which gravity, tilt, strain, and a number of environmental parameters are monitored, should carry out case studies.

Studies regarding the last item are already carried out by some observatories suitable for this. With regard to the monitoring of hydrological parameters it is necessary to collect information from groups already carrying out this kind of observations in order to give recommendations for an adequate monitoring.

15th International Symposium on Earth Tides
2-6 August 2004
Ottawa, Canada

SCIENTIFIC PROGRAM

FOREWORD:
The abstracts of the scientific papers can be found on the ICET web site (http://www.astro.oma.be/ICET/), under BIM140.

Monday August 2: (ETS-2) Space Geodetic Techniques and Tides
Conveners: R. Haas, S. Bettadpur

Oral Presentations

ETS-2-01 The significance of tides in GRACE gravity field determination
R. Eanes, S. Bettadpur, J. Bonin, J. Ries, M. Cheng

ETS-2-02 Seasonal time changes of the Earth's gravity field from GRACE: a comparison with ground measurements from superconducting gravimeters and with hydrology models prediction
J. Hinderer, O. Andersen, F. Lemoine, D. Crossley, J.-P. Boy

ETS-2-03 Effect of high-frequency mass variations on GOCE recovery of Earth's gravity field
S.-C. Han, C. K. Shum, C. Kuo, P. Ditmar, P. Visser, E. J. O. Schrama, C. Van Beelen

ETS-2-04 Oceanic mass constraint studies in East Antarctica ocean
C. Y. Kuo, A. Braun, S.-C. Han, C. K. Shum, Y. Yi

ETS-2-05 Combined analysis of VLBI and superconducting gravimeter
L. Petrov, J. Hinderer, J.-P. Boy

ETS-2-06 Geodynamics from Space – VLBI observations of the free core nutation
D. E. Smylie, A. Palmer

ETS-2-07 Constraints on mantle anelasticity from geodetic observations: some implications
D. Benjamin, J. M. Wahr, S. Desai

ETS-2-08 Deficiencies in monitoring global crustal deformations with GPS
P. J. Mendes Cerveira, R. Weber, H. Schuh

ETS-202-09 Global tidal displacements measured by GPS
X. Wu, M. B. Heflin, D. C. Jefferson, F. H. Webb, H.-G. Scherneck

Posters

ETS-2-11 GPS observations of ocean tide loading in the British Isles
C.R. Allinson, P. Clarke, M. A. King, S.J. Edwards, T. F. Baker, P. Cruddace

ETS-2-12 Kinematic and static GPS techniques for estimating tidal displacements with application to Antarctica
M. A. King

ETS-2-13 Deficiencies in monitoring global crustal deformations with GPS
P. J. Mendes Cerveira, R. Weber, H. Schuh

ETS-2-14 Subdiurnal Earth rotation variations from VLBI CONT campaign
R. Haas, J. Wünsch

ETS-2-15 Comparison of superconducting gravimeter and GRACE satellite derived temporal gravity variations
J. Neumeyer, P. Schwintzer, C. Reigber, F. Barthelmes, O. Dierks, F. Flechtner, J. Hinderer, Y. Imanishi, C. Kroner, B. Meurers, S. Petrovic, R. Schmidt, H.-P. Sun, M. And G. Harnisch

Tuesday August 3, AM: (ETS-1) Earth based instrumentation
Conveners: G. Jentzsch and O. Francis

Oral Presentations

ETS-1-01 Superconducting gravimeters: current production models and future developments
E. Brinton, R. Warburton

ETS-1-02 A new data series observed with the remote gravimeter GWR C038 at the geodetic fundamental station TIGO in Concepción (Chile)
H. Wilmes, A. Boer, B. Richter, P. Wolf, M. Harnisch, G. Harnisch, H. Hase

ETS-1-03 Validation of the Frankfurt calibration system for superconducting gravimeters
B. Richter, I. Nowak, H. Wilmes, R. Falk, M. Harnisch, G. Harnisch

ETS-1-04 Some recent results of the gravimetric tidal station Pecny, Czech Republic
V. Palinkas

ETS-1-05 The very-broad-band digital data acquisition of the long base tiltmeters of Grotta Gigante (Trieste, Italy)
C. Braitenberg, G. Romeo, Q. Taccetti, I. Nagy

ETS-1-06 A 100m laser strainmeter system in Kamioka (Japan) for precise observations of tidal strain
S. Takemoto, A. Araya, W. Morii, J. Akamatsu, M. Ohashi, H. Momose, A. Takamori, S. Miyoki, T. Uchiyama, D. Tatsumi, T. Higashi, Y; Fukuda

ETS-1-07 Results of the international comparison of absolute gravimeters in Walferdande (Luxembourg) of November 2003
O. Francis

Posters

ETS-1-08 The automated Burris gravity meter : a new instrument for surveying and continuous operation
J. Adams, L. Burris, G. Jentzsch, A. Kopaev, H. Valliant

ETS-1-09 Tidal gravity observations in eastern Siberia at Khabarovsk/Zabaikalskoe and along the atlantic coast of France at Chizé
V. Y. Timofeev, M. van Ruymbeke, G. Woppelmann, M. Everaerts, E. A. Zapreeva, P. Y. Gornov, B. Ducarme

ETS-1-10 Vertical and horizontal seismometric observations of tides
S. Lambotte, L. Rivera, J. Hinderer

ETS-1-11 The "wth2o" water tube tiltmeter
N. d'Oreye de Lantremange, W. Zürn

ETS-1-12 A new design of the long water-tube tiltmeter of FGI
H. Ruotsalainen

ETS-1-13 On modern developments of strainmeters and tiltmeters in Russia
I.Vasiliev, L. Latynina, G. Jentzsch

ETS-1-14 Tidal water level changes in deep wells: implications on the determination of the elastic parameters of the aquifer
V. Y. Timofeev, B. Ducarme, E. A. Zapreeva, G. N. Kopylova, P. Y. Gornov, L. Vandercoilden, S. V. Boldina

ETS-1-15 Calibration and reference level stability of the Canadian superconducting gravimeter installation
J. B. Merriam, J. Liard, S. Pagiatakis

Tuesday August 3, PM: (ETS-5) Tilt, strain: aperiodic and long period signals
Conveners: T. Jahr, J. Arnoso, G. Mentes

Oral Presentations

ETS-5-01 Aperiodic and long period signals from crustal deformation observations at the NE border of the Adria plate
C. Braitenberg, I. Nagy, S. Papacchioli

ETS-5-02 Quarter-diurnal waves observed with a long base water-tube tiltmeter in the Grand Duchy of Luxembourg
N. d'Oreye de Lantremange, W. Zürn

ETS-5-03 Well level data analysis in Hungary near a fault region
Rotár-Szalkai, L. Ó. Kovács, I. Eper-Pápai, G. Mentes

ETS-5-04 The ASKANIA borehole tiltmeter array at the KTB location in Germany
T. Jahr, H. Letz, G. Jentzsch

ETS-5-05 Earth tide tilt measurements in Canada revisited
P. M. Rouleau

ETS-5-06 Observing long term FCR variations by using Esashi strainmeters
J. Ping, T. Tsubokawa, Y. Tamura, K. Heki, T. Matsumoto, T. Sato

ETS-5-08 Tidal strain observations in Chu-Chi, Taiwan
S. Takemoto, Min Lee, Chih-Yen, Chen, Ming-Chien Kao, A. Mukai

Posters

ETS-5-09 Parallelism of regional tectonic and climatic processes for 1400-2000
B. L. Berry

ETS-5-10 Parallelism of global tectonic and climatic processes for 1600-2000
B. L. Berry

ETS-5-11 Strainmeter observations at Moxa
T. Jahr, C. Kroner, A. Walther

ETS-5-13 On relation of ground deformation observed at Donzurubo observatory to sea level changes
K. Onoue

ETS-5-15 Long term thermal effects on strain measurements at the Geodynamics Laboratory of Lanzarote
A. P. Venedikov, J. Arnoso, R. Vieira, W. Cai

Wednesday August 4, AM: (ETS-3) Earth and Ocean tides: theory and analysis
Conveners: T. Baker and H. T. Hsu

Oral Presentations

ETS-3-01 What have we really learned about the Earth from tidal gravity, tilt and strain observations?
W. Zürn

ETS-3-02 An estimation of the errors in the gravity ocean tide loading computations
M. S. Bos, T. F. Baker

ETS-3-03 Design of local ocean tide model in the nearby of El Hierro (Canary Islands)
J. Arnoso, M. Benavent, B. Ducarme, F. G. Montesinos

ETS-3-06 Tidal gravity and oceanic loading obtained with a single and a double sphere SG at stations Wuhan and Sutherland
H. P. Sun, J. Neumeyer, X. D. Chen, O. Dierks, J. C. Zhou, H. Z. Hsu

ETS-3-07 Validation of long period oceanic tides with superconducting gravimeters
J.-P. Boy, M. Llubes, R. Ray, J. Hinderer, N. Florsch

ETS-3-08 Accuracy assessment of ocean tide loading computations for precise geodetic observations
K. H. Zahran, G. Jentzsch, G. Seeber

ETS-3-09 Analysis and prediction of ocean tides by the computer program VAV
B. Ducarme, A. P. Venedikov, R. Vieira, J. Arnoso

ETS-3-10 A modern, analytical approach to the harmonic development of the tide-generating potential
S. Casotto, F. Biscani

Posters

ETS-3-11 A comparison of ocean tide loading models with tidal gravity observations in the Canaries
J. Arnoso, R. Vieira, F. G. Montesimos, M. Benavent

ETS-3-12 Data processing of the Membach SG
M. Van Camp, O. Francis, M. Hendrickx

ETS-3-13 Surface deformation due to non-linear tides in the North Sea
S. A. Khan, J. Wahr, O. B. Andersen

ETS-3-14 World wide synthetic tide parameters for gravity, vertical and horizontal displacements
K. H. Zahran, G. Jentzsch, G. Seeber

ETS-3-15 Analysis of SG tidal data by the programs ETERNA and VAV
B. Ducarme, L. Vandercoilden, A. P. Venedikov

ETS-3-16 Advances in Southern Ocean tide modelling
Y. Yil, K. Marsumoto, A. Braun, C. K. Shum, Y. Wang

Wednesday August 4, PM: Global Geodynamics Project (GGP) Workshop
Convener: D. Crossley

Oral Presentations and discussions

Welcome and Introduction
D. Crossley, J. Hinderer

Review of installations
SG representatives

Review of GGP agreements
Open discussion

Comparison of observations with dual sensor superconducting gravimeters
C. Kroner, O. Dierks, J. Neumeyer, H. Wilmes, P. Wolf

What are precision accuracy and noise level?
Open discussion

Contribution of SGs to normal mode seismology
J. Hinderer

GGP data for seismology
Open discussion

GGP as repository for AG data
Open discussion

GGP-ISDDC at the GFZ Potsdam: system reinstallation and integration into the GFZ-ISDC services
B. Ritschel, S. Freiberg, H. Palm, M. Hendrickx

New ideas for GGP Phase 2
Open discussion

Thursday August 5, AM: (ETS-7) Global Geodynamics
Conveners: J. Merriam, A. Lambert, J. Hinderer

Oral Presentations

ETS-7-01 Highlights of GGP "Gedanken Experiments" with SGs: what new can be realized?
D. Crossley, J. Hinderer

ETS-7-02 Improvement of two stacking methods used in Slichter mode detection
Y. Guo, O. Dierks, J. Neumeyer, L. Potts, C. K. Shum

ETS-7-03 The Slichter triplet in the superconducting gravimeter series
S. D. Pagiatakis, H. Yin

ETS-7-04 Product spectra of gravity observations at Canberra, Australia
H. Wondimu, D. E. Smylie

ETS-7-05 Study of long term gravity variations based on data of the GGP cooperation continued
M. Harnisch, G. Harnisch

ETS-7-06 Long term monitoring by absolute gravimetry: tides to postglacial rebound
A. Lambert, N. Courtier, T.S. James

ETS-7-08 Global analysis of GGP superconducting gravimeters network for the estimation of the polar motion effect on gravity variations
B. Ducarme, A. P. Venedikov, J. Arnoso, R. Vieira

Posters

ETS-7-09 Absolute gravity and vertical motion: results from observations along a profile crossing the Rhine graben from the Vosges to the Black Forest
M. Amalvict, J. Hinderer, S. Rosat

ETS-7-10 Analysis of the free oscillation signal from the long term records of tidal gravimeter ASKANIA GS15 at station Pecny (Czech Republic)
P. Lukavec, A. Zeman

ETS-7-11 Investigation of long period seismic normal modes and the Slichter triplet with SGs: impact on deep Earth's properties
S. Rosat, J. Hinderer, L. Rivera, G. Roult

ETS-7-12 New observations of Q quality factors of a few gravest normal modes from the GGP project
G. Roult, S. Rosat, J. Hinderer, R. Millot-Langet, E. Clévédé

ETS-7-13 Regional radial rates of Earth's geometric figure by VLBI and non-tidal secular acceleration in Earth rotation
Z. Yang

Friday August 6, AM: (ETS-6) Environmental processes and gravity
Conveners: C. Kroner, J. Henton, M. S. Bos

ETS-6-01 Effect of underground water on gravity observed at Matsushiro (Japan) and detection of coseismic gravity change caused by 2003 Tokachioki earthquake
Y. Imanishi

ETS-6-02 Study of the seasonal gravity signal in superconducting gravimeter data
J.-P. Boy, J. Hinderer

ETS-6-03 On the contributions of local environmental effects to gravity at Metsähovi
H. Virtanen

ETS-6-04 Gravity tides and the seasonal gravity variation at Ny-Ålesund, Svalbard in the Artic
T. Sato, H.-P. Plag, Y. Tamura, K. Matsumoto, K. Asari, O. Francis

ETS-6-05 Integrated approach to understand local gravity variations
B. Richter, H. Wilmes, R. Falk, S. Zerbibi, M. Harnisch, G. Harnisch, A. Reinhold

ETS-6-06 Comparison of barometric pressure induced noise in horizontal components: results from numerical modeling for the observatories Moxa and Schiltach, Germany
H. Steffen, S. Kuhlmann, T. Jahr, C. Kroner

ETS-6-07 Semi-diurnal and diurnal atmospheric tides in gravity variations
J.-P. Boy, R. Ray, J. Hinderer

<u>Posters</u>

ETS-6-10 Investigation of meteorological effects on strain measurements at two stations in Hungary
Gy. Mentes, I. Eperné-Pápai

ETS-6-11 Two hydrological experiments at Moxa observatory
C. Kroner, T. Jahr

ETS-6-12 Application of a distributed hydrological model to detect hydrological effect on gravity
S. Hasan, J. Boll, P. A. Troch, C. Kroner

ETS-6-13 Hydrological influences on in long gravimetric data series
G. Harnisch, M. Harnisch

ETS-6-14 Hydrological effects on the superconducting gravimeter observation in Bandung
M. Abe, S. Takemoto, Y. Fukuda, T. Higashi, Y. Imaishi, S. Iwano, S. Ogasarawa, Y. Kobayashi, H. Takigushi, S. Dwipa, D. S. Kusuma

ETS-6-15 3-D atmospheric pressure correction on gravity data
J. Neumeyer, J. Hagedorn, J. Leitloff, C. Stöber

Friday August 6 AM/PM: (ETS-4) Interplanetary tidal interaction and gravity
Conveners: X. Wu, C. K. Shum, S. Takemoto

Oral Presentations

ETS-4-01 Gravity fields and interior structure for equilibrium bodies in the outer solar system
J. D. Anderson

ETS-4-02 Solar system oscillations and models of natural processes
B. L. Berry

ETS-4-04 Tides, subsurface oceans and Jupiter icy moons orbiter
X. Wu, J. G. Williams

ETS-4-05 Temporal variation of geodynamical properties due to tidal friction
P. Varga, Gy. Mentes

ETS-4-07 Estimation and validation of non-tidal oceanic contributions on annual polar wobble
M. Zhong, H. Yan, Y. Zhu

Posters

ETS-4-08 Space-time classification of mountainous and glacier relief
B. L. Berry

Proceedings Earth Tide Symposium Ottawa, Canada, August 2004

Special issue of Journal of Geodynamics: "Earth Tides and Geodynamics"

ETS-1: Earth Based Instrumentation

ETS-1-02
H. Wilmes, A. Boer, B. Richter, P. Wolf, M. Harnisch, G. Harnisch, H. Hase
A New Data Series Observed with the Remote Gravimeter GWR C038 at the Geodetic Fundamental Station TIGO in Concepción (Chile)

ETS-1-04
V. Palinkas
Some Recent Results of the Gravimetric Tidal Station Pecny, Czech Republic

ETS-1-06
S. Takemoto, A. Araya, W. Morii, J. Akamatsu, M. Ohashi, H. Momose, A. Takamori, S. Miyoki, T. Uchiyama, D. Tatsumi, T. Higashi and Y. Fukuda
A 100m laser strainmeter system in Kamioka, Japan, for precise observations of tidal strains

ETS-1-09
V.Yu. Timofeev, M. van Ruymbeke, G. Woppelmans, M. Everaerts, E.A. Zapreeva, P.Yu. Gornov, B. Ducarme
Tidal gravity observations in eastern Siberia at Khabarovsk/Zabaikalskoe and along the Atlantic coast of France at Chize

ETS-1-10
Lambotte, S., L. Rivera, and J. Hinderer
Vertical and horizontal seismometric observations of tides

ETS-2: Space Geodetic Techniques and Tides

ETS-2-02
J. Hinderer, O. Andersen, F. Lemoine, D. Crossley, and J.-P. Boy
Seasonal time changes of the Earth's gravity field from GRACE: a comparison with ground measurements from superconducting gravimeters and with hydrology model predictions

ETS-2-03
S.-C. Han, C.K. Shum, P. Ditmar, P. Visser, E.J.O. Schrama, C. van Beelen, and E.J.O. Schrama
Aliasing effect of high-frequency mass variations on GOCE recovery of the Earth's gravity field

ETS-2-12
M. A. King
Kinematic and static GPS techniques for estimating tidal displacements with application to Antarctica

ETS-2-13
P.J. Mendes Cerveira, R. Weber, H. Schuh

Deficiencies in monitoring global crustal deformation with GPS

ETS-2-14
R. Haas and J. Wünsch
Subdiurnal Earth rotation variations from VLBI CONT campaigns

ETS-3: Earth and Ocean Tides: Theory and Analysis

ETS-3-03
J. Arnoso, R. Vieira, F.G. Montesinos, M. Benavent
A new ocean tide loading model in the Canary Island region

ETS-3-07
J.-P. Boy, M. Llubes, R. Ray, J. Hinderer and N. Florsch
Validation of long period oceanic tides with superconducting gravimeters

ETS-3-09
B. Ducarme, A. P. Venedikov, J. Arnoso, R. Vieira
Analysis and prediction of ocean tides by the computer program VAV

ETS-3-16
Y. Yi, K. Matsumoto, C. K. Shum, Y. Wang, R. Mautz
Advances in Southern Ocean Tide Modeling

ETS-4: Interplanetary Tidal Interactions and Gravity

ETS-4-02
Boris L. Berry (Berri)
Solar system oscillations and models of natural processes.

ETS-4-05
P. Varga
Temporal variation of geodynamical properties due to tidal friction

ETS-5-06
J. Ping, T. Tsubokawa, Y. Tamura, K. Heki, K. Matsumoto, T. Sato
Observing Long Term FCR Variation Using Esashi Extensometers

ETS-5: Tilt, Strain: Aperiodic and Long Period Signals

ETS-5-01
C. Braitenberg, G. Romeo, Q. Taccetti, I. Nagy, S. Papacchioli
The very-broad-band long-base tiltmeters of Grotta Gigante (Trieste, Italy): Secular term tilting and the great Sumatra-Andaman Islands earthquake of December 26, 2004

ETS-5-02
N. d'Oreye de lantremange and Walter Zürn: Quarter-diurnal tides observed with the long baseline water-tube tiltmeter

ETS-5-03
Á. Rotár-Szalkai, I. Eper-Pápai, Gy. Mentes
Well level data analysis in Hungary near a fault region

ETS-5-04
T. Jahr, H. Letz, G. Jentzsch:
The ASKANIA borehole tiltmeter array at the KTB location / Germany.

ETS-5-08
S. Takemoto, Min Lee, C.-Y. Chen, M.-C. Kao, A. Mukai, T. Ikawa, T. Kuroda, T. Abe:
Tidal strain observations in Chu-Chi, Taiwan

ETS-05-11
T. Jahr, C. Kroner, A. Lippmann
Strainmeters observations at Moxa

ETS-05-15
A.P. Venedikov, J. Arnoso, W. Cai, R. Vieira, S. Tan, E.J. Velez:
Separation of long term thermal effects on strain measurements at the Geodynamics Laboratory of Lanzarote

ETS 6: Environmental Processes and Gravity

ETS-6-01
Y. Imanishi, K. Kokubob, H. Tatehatab
Effect of underground water on gravity observation at Matsushiro, Japan

ETS-6-02
J.-P. Boy and J. Hinderer
Study of the seasonal gravity signal in superconducting gravimeter data

ETS-6-04
T. Sato, J.P. Boy,Y. Tamura, K. Matsumoto, K. Asari, H.-P. Plag, O. Francis
Gravity tide and seasonal gravity variation at Ny-Ålesund, Svalbard in Arctic

ETS-6-06
H. Steffen, S. Kuhlmann b , T. Jahr, C. Kroner
Comparison of barometric pressure-induced noise in horizontal components – results from numerical modellings for the observatoriesMoxa and Schiltach

ETS-6-07
J.-P. Boy, R. Ray and J. Hinderer
Diurnal atmospheric tide and gravity variations

ETS-6-10
Gy. Mentes and I. Eper-Pápai
Investigation of meteorological effects on strain measurements at two stations in Hungary

ETS-6-11
C. Kroner, T. Jahr

ETS-6-13
G. Harnisch and M. Harnisch

Hydrological influences in long gravimetric data series

ETS-6-14
M. Abe, S. Takemoto, Y. Fukuda, T. Higashi, Y. Imanishi, S. Iwano, S. Ogasawara, Y. Kobayashi, H. Takiguchi,, S. Dwipa and D.S. Kusuma
Hydrological effects on the superconducting gravimeter observation in Bandung

ETS-7: Global Geodynamics

ETS-7-08
B. Ducarme, A.P. Venedikov, J. Arnoso, X.D. Chen, H.P. Sun, R. Vieira
Global analysis of the GGP superconducting gravimeters network for the estimation of the pole tide gravimetric amplitude factor.

ETS-6-02
J.Y. Guo, O. Dierks, J. Neumeyer, C.K. Shum
Weighting algorithms to stack superconducting gravimeter data for the potential detection of the Slichter modes

ETS-7-05
M. Harnisch, G. Harnisch
Study of long-term gravity variations, based on data of the GGP co-operation

ETS-7-06
A. Lambert, N. Courtier and T.S. James
Long-term monitoring by absolute gravimetry: Tides to postglacial rebound

ETS-7-11
S. Rosat, Y. Rogister, D. Crossley, J. Hinderer
A search for the Slichter Triplet with superconducting gravimeters: Impact of the density jump at the inner core boundary

ETS-7-12
G. Roult, S. Rosat, E. Clévédé, R. Millot-Langet, J. Hinderer
New determinations of Q quality factors and eigenfrequencies for the whole set of singlets of the Earth's normal modes ${}_0S_0$, ${}_0S_2$, ${}_0S_3$ and ${}_2S_1$ using superconducting gravimeter data from the GGP network

RESOLUTIONS
Of the 15thInternational Symposium on Earth Tides
On behalf of the Eart Tide sub-Commission (EtsC)
Commission 3 of IAG

1. **Considering** that earth tides phenomena must now be included in all fields of geodynamics, **recognizing** the success of the sessions dedicated to space geodetic techniques and planetary studies and **wishing** to attract scientists from all fields of geodynamics, the EtsC **recommends** that the next symposium be organised in collaboration with the other sub-commissions within Commission 3 (including inter-commission committees) and that the title of the symposium better fits the new developments of Earth tidal research within Commission 3 "Earth Rotation and Geodynamics".

2. **Considering** the potential interest of the Global Geodynamics Project (GGP) database for several fields of geodesy and geophysics besides Earth tidal studies and **considering** that a rapid access to the data is now of primary importance in scientific research, the EtsC **recommends** that greater publicity should be given to the data base and that new products should be developed and made available in widely used formats.

3. One of the tasks of the International Centre on Earth Tides (ICET) is to provide software for tidal prediction. Several software programs have been developed for precise evaluation of the astronomical tides. However, the computation of tidal effects on the real Earth is much more complex and, in the absence of in situ tidal observations, requires the use of models of the Earth's response to tidal forces and a precise evaluation of the oceanic loading effects. Therefore the EtsC **recommends** the formation of a *Working Group on Precise Tidal Predictions.*
   This working group should evaluate existing software for tidal prediction (ETERNA, BAYTAP-G, VAV03 and others) and provide synthetic tidal parameters at a global scale on the basis of existing models of the Earth's response and of tidal loading.

4. **Considering** the importance of ground based observations in quantifying climate change, the EtsC **recommends** including our geodetic observations into the Global Geodetic Observing System (GGOS) project.

5. **Realising** the importance of Earth tides in space geodesy, the EtsC **recommends** the creation, jointly with Commission 1, of a new
   Inter-commission Study Group on Earth Tides in Space Geodetic Techniques,
   replacing the former working group 3.1.2 and reporting to Commission 3. The chairman of this study group will be Rüdiger Haas (Onsala Space Observatory).

6. **Recognising** the increasing importance of modelling environmental effects in the evaluation of tidal records and **acknowledging** the successful efforts of the working group on Environmental effects, the EtsC **recommends** to continue the activities of this group as a
Study Group on Environmental Effects in Tidal Records,
chaired by Corinna Kroner.

7. **Realising** the continuing importance of the resolutions made at ETS2000, the EtsC **recommends** to continue following the ETS2000 resolutions, namely: Res (1) concerning the comparison of ground based and space based observations; Res (3) regarding the participation of the tidal community in lunar and planetary geodesy; Res (4) to include sessions on planetary tides in future meetings; Res (9) concerning the computation of noise spectra. The resolutions are published in BIM 134, Dec. 2001, p. 10529-10530.

8. **Recognising** the uniqueness of the 10 years time series of the GGP station Syowa, the EtsC **appreciates** the distribution of the raw data on CDs to the participants of the ETS2004, with special thanks to the GGP-Japan group and Prof. Kazuo Shibuya.

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POLAR MOTION AND NON TIDAL SIGNALS IN THE SUPERCONDUCTING GRAVIMETER OBSERVATIONS IN BRUSSELS

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ABSTRACT

Through the analysis of 13½ years of tidal gravity observations the gravity effect of the polar motion is estimated, that is, the amplitude factor δ_{pole} of the pole tide. This data set is extracted from the complete series of 18 years (from 21.04.1982 till 22.09.2000) tidal data obtained in Brussels (Royal Observatory of Belgium) with the GWR T003 Superconducting Gravimeter (SG), from which a non-reliable initial part has been discarded. Very important precondition of success of this work is that the length of 13½ years allows a good separation of the annual components of the data and the Chandler wobble. The analysis has been performed with the computer program VAV/2002 (Venedikov et al., 2001, 2003) for tidal data processing. Some options have been specially developed for this task. The analysis has taken into account the tidal signal, including a rather efficient determination of the LP (long period) tides, seldom well estimated, as well as the effect of the air-pressure. We build then a model of the non tidal part of the signal often called "drift", directly orientated towards the estimation of δ_{pole}. We include the theoretical pole tide, estimated from the IERS observations, multiplied by δ_{pole}, a piecewise polynomial representation, an annual components at 1cpy (cycle per year) with its harmonics till 6 cpy and a model of the temperature effect. The result obtained for the polar motion tidal factor is $\delta_{pole} = 1.181 \pm 0.008$. This is higher value than the value $\delta = 1.158$ theoretically predicted for periods near one year by a model including mantle inelasticity. The difference is due to the tidal loading effect of the ocean pole tide. It appeared impossible to get a good estimate of δ_{pole} when the water table is included in the drift model due to a strong interference with the polynomials, approximating the instrumental drift. Nevertheless, the effect of the water table, i.e. the corresponding regression coefficient c_{WT}, has been separately estimated, so to say, as a

byproduct of the main task. The regression coefficient obtained for the water table $c_{WT} = -149.5 \pm 2.7$ nms^{-2}/m which is in reasonable agreement with previous determination.

1. INTRODUCTION

The Superconducting Gravimeter (SG) GWR model T003 recorded tidal variations of gravity at station Brussels, situated in the Royal Observatory of Belgium, from 21.04.1982 till 22.09.2000, i.e. some 18 years. This is the longest set of SG tidal data ever obtained.

In principle, SG instruments have a very low drift, especially in comparison to other tidal instruments, namely spring gravimeters, tiltmeters and extensometers. This makes the SG data very interesting with respect to the study of low frequency phenomena, in particular the gravity effect of the polar motion, the so-called "pole tide".

The pole tide is dominated by the 430-day Chandler wobble and an annual component. A major problem in studying the pole tide is that the tidal data also contain an annual component of meteorological origin, coinciding with the long period tide Sa (solar annual tide). This makes it necessary to separate the pole tide from the spurious annual contribution. Such a process needs records of at least 6.6 years, the longer – the better.

In July 1997 started (Crossley et al., 1999) Global Geodynamics Project (GGP) observation campaign. It involves stations with the new generation of SG, namely the Compact-Tidal (CT) instruments. The latter have better performances than the T model in Brussels. Nevertheless, due to the need for series larger than 6.6 years, the data of Brussels remain most promising with respect to the pole tide, as it covers several commensurability intervals between the Chandler and annual periods.

In the following parts of this paper we shall consider the study of the pole tide through specially developed analysis of the SG data of Brussels.

Section 2 introduces a general model of the gravity effect of the polar motion. In analogy with the long period tides, a polar amplitude δ factor is defined, which relates the theoretical pole tide with the observed one.

Section 3 is a brief description of the SG data from Brussels.

Sections 4 and 5 discuss with the method of analysis, which is applied by the computer program VAV for tidal data processing. In section 4 the drift is modeled as a stepwise function, remaining a constant during 24 hours. The values of the drift are included in the observational equations as unknowns, which are estimated by MLS (Method of the least squares). Further, in Section 5, the drift is represented as a combination of purely instrumental drift, observed pole tide, temperature effects, annual component and the effect of the water table.

In subsections 5.1 an initial part of the data is abandoned and the finding of an optimum initial point is shown. Subsections 5.2 through 5.6 deals with finding concrete components of the general drift function. The models involve series of parameters, whose values are not defined a priory. Some optimum values are found in a Bayesian approach, though variations of the models and selection of optimum variants on the basis of statistical criteria.

Most sophisticated and thus most vulnerable may look the polynomial model of the drift, discussed in subsection 5.2. In principal, polynomials are used as a most flexible tool for the approximation of non-periodical functions. Since the drift has obviously discontinuities, as jumps, and discontinuities in its derivates, manifested as sudden changes of the drift behavior, it was impossible to get a good approximation by a single model over the whole data interval of 13 years. Therefore the data series has been partitioned in 4 blocks and the drift has been approximated by different polynomials in every block. It is shown how the points of the discontinuities are found and how the power of the polynomials is chosen.

Subsections 5.3, 5.4 and 5.5 deal with the models of the annual, temperature and water table components. The last subsection 5.6 deals with the pole tide. Here a more general model is used than the model in section 2. Namely, a possibility of a time lag between the theoretical and the observed pole tide is accepted. Nevertheless, the estimated time lag appeared to be insignificantly low (advance of 4 days).

The final results, actually obtained in section 5, are presented in section 6.

2. POLE TIDE AND LONG PERIOD TIDAL COMPONENTS

Let $\Delta g(T)$ is the theoretical tidal gravity signal at given place and time T, generated by the tide generating potential of degree 2. This means that $\Delta g(T)$ is a variation of the gravity which would be observed on an ideal non-deformable (absolute rigid) Earth.

According to the classical theory of Love, in the case of static deformation of the Earth, the observed tidal gravity variations are

$$\Delta G(T) = \delta \Delta g(T) \tag{1}$$

I.e., due to the deformation, $\Delta g(T)$ is multiplied by a coefficient, often called delta or amplitude factor.

In the actual case, the picture is not so simple. The expression (1) is considered in the frequency domain with a frequency dependent δ factors and it is necessary to introduce phase lags, which are also frequency dependent.

Nevertheless, for the tidal constituents with very low frequencies or the LP (long period) tides, especially those at frequencies 1 cpy (cycle per year) the expression (1) works quite well. There are at least three reasons for this: (i) the deformation is very slow, (ii) the amplitudes of the ocean tides, whose loading effect may affect (1), have very small amplitudes and (iii) generally, the precision of all estimations at the low frequencies is very low and small deviations from (1) cannot be distinguished, being under the level of the noise.

Due to the polar motion the geographic latitude of a given point (a tidal station, for instance) and thus its distance to the Earth rotation axis are varying. This is changing the centrifugal force associated to the angular speed of the Earth rotation Ω. Moreover, the variations of the length of the day, LOD(t) produce additional inertial forces modifying the gravity value.

By using the instantaneous pole coordinates $(x(t), y(t))$ at time t in arc seconds and the variation of the length of the day dt in seconds per day, the theoretical pole tide $\Delta g_{\text{pole}}(t)$ (Melchior, 1986) at point with geographic coordinates (φ,λ) can be computed through

$$\Delta g_{\text{pole}}(t) = \Omega^2 r \left\{ \left(x(t)\cos\lambda + y(t)\sin\lambda \right) \sin 2\varphi + (\cos^2\varphi / 43200) dt \right\} \tag{2}$$

where r is the geocentric radius.

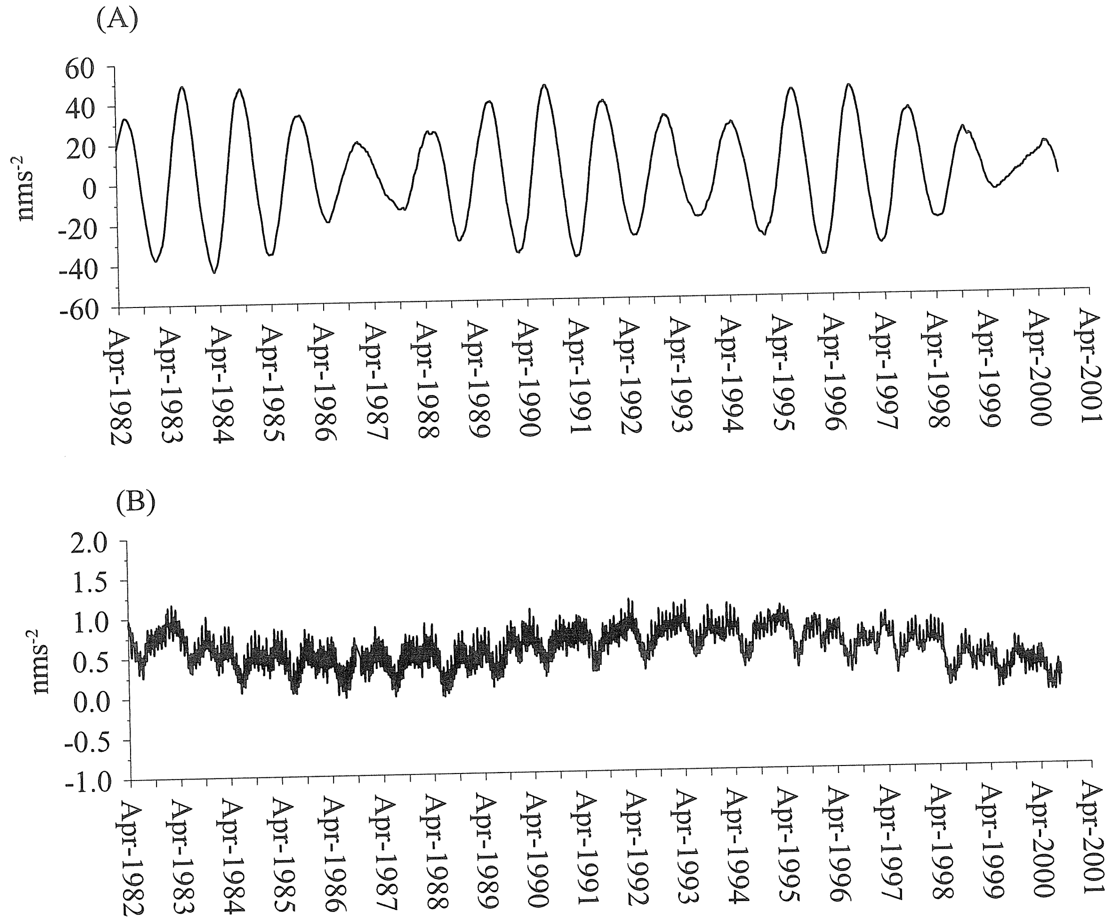

Figure 1. (A) The first term in (2) of the theoretical pole tide $\Delta g_{\text{pole}}(t)$ for station Brussels. (**B**) The second term in (2) of the theoretical pole tide $\Delta g_{\text{pole}}(t)$ for station Brussels.

Figures 1A and 1B represent the two components of $\Delta g_{\text{pole}}(t)$ at station Brussels. The first one is, so to say, the theoretical effect of the proper polar motion, while the second one is the effect of LOD. Obviously, the effect of LOD is considerably lower, practically negligible.

The effect (2) can be called "theoretical" because it is computed for an ideal no deformable Earth, just like the theoretical tide $\Delta g(T)$ in (1). At the same time the polar motion causes a deformation of the real Earth, which has an effect on the gravity variations. Thus, instead of the theoretical pole tide $\Delta g_{\text{pole}}(t)$ we shall observe a modulated pole tide $\Delta G_{\text{pole}}(t)$.

Nearly all LP tides are generated by the spherical harmonic of the tide generating potential of degree 2, order 0 (zonal). The polar motion is also producing a potential field of degree 2, order 0 (zonal), the LP tides. Hence, the pole tide is amplified by the elastic response of the Earth in a similar way as the LP tidal waves. I.e., in analogy with (1), we can define an amplitude factor δ_{pole} through the relation

$$\Delta G_{\text{pole}}(t) = \delta_{\text{pole}} \Delta g_{\text{pole}}(t) \qquad (3)$$

This definition is in accordance with Dehant et al. (1999) for the δ factor (called tidal gravimetric factor): *"In the frequency domain, the tidal gravimetric factor is the transfer function between the tidal force exerted along the perpendicular to the ellipsoid and the tidal gravity changes along the vertical as measured by a gravimeter"*.

For a purely elastic Earth, Dehant et al. (1999) computed a latitude dependent δ value, which for Brussels (50°48') was $\delta = 1.15534$. Inelasticity in the mantle increases the δ value for longer periods (Table 1).

The usual methods for tidal analysis are not able to provide valuable determination of LP tides like the annual Sa wave or its harmonic the semiannual Ssa, as they are always strongly affected by meteorological effects. Therefore, our unique possibility to investigate the Earth deformation at very low frequencies and thus to check the theoretical values in Table 1 is to try to determine the amplitude factor δ_{pole} of the pole tide.

Table 1 Tidal gravity factors for the long period waves. Model DDW99, inelastic, non hydrostatic.

Wave	Angular speed (°/h)	Period (days)	Amplitude Factor δ
MQm	2.18678245	6.86	1.15598
MsQm	2.11392880	7.10	1.15599
MTm	1.64240775	9.13	1.15608
MsTm	1.56955409	9.56	1.15609
Mf	1.09803304	13.66	1.15622
Msf	1.01589576	14.77	1.15625
Mm	0.54437471	27.55	1.15649
Msm	0.47152105	31.81	1.15655
Ssa	0.08213728	186.62	1.15738
Sa	0.04106668	365.26	1.15778
18 years	0.00220641	7267.09	1.15996

As shown by Figure 2, the Chandler wobble is clearly distinguished in both the gravity data and the theoretical pole tide. This is an indication, that the gravity data can be used to study the pole tide. An annual component with 1 cpy also exists in both types of data, but the annual gravity component is much stronger and it is accompanied by a sub-harmonic of 2 cpy. Strong energy can also be seen in the gravity spectrum at frequencies lower than 0.5 cpy which are actually related with the drift.

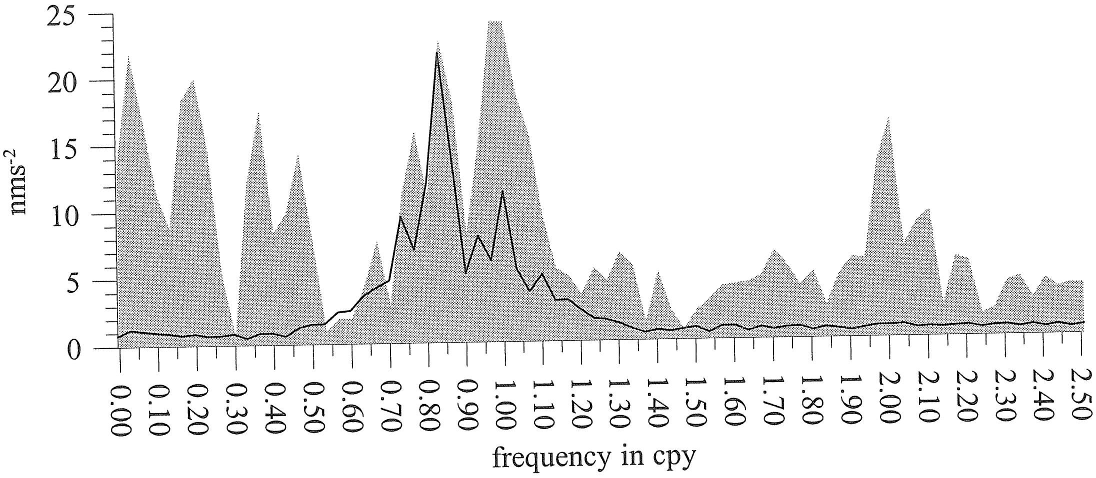

Figure 2. Very long period spectrum of the observed gravity signal (filled curve) and the theoretical pole tide. showing the complex structure around 1 cpy (cycles per year) and the Chandler period (0.85 cpy). The superimposed spectrum of the polar motion indicates that the Chandler term is very well recorded but that the annual one is largely contaminated. There is also significant energy in periods larger than 750 days (frequencies lower than 0.5 cpy) that we try to model by a piecewise polynomial representation.

3. THE SUPERCONDUCTING GRAVITY DATA IN BRUSSELS

As said above, the superconducting gravimeter T003 recorded at the Royal Observatory of Belgium between 21.04.1982 and 22.09.2000. The series is split in two main parts.

A first period extending from April 1982 to October 1986 has been extensively studied in De Meyer and Ducarme (1991). The long term behavior of the instrument was seriously disturbed until May 1986 by the so called "getter" effect. As there was a slight leak of helium gas in the vacuum can separating the core of the instrument from the liquid helium bath, the heating voltage of the thermostat had to increase steadily to compensate the increasing loss of energy by convection of the helium gas. After 6 months the maximum possible heating power has been reached and thus it became necessary to insert a "getter", that is, a small porous ceramic crystal able to fix the helium gas. The voltage has then decreased to its minimum in one hour and a new cycle started. The voltage drop was accompanied by a jump in the gravimeter curve of the order of 3μgal/V (1μgal = 10^{-8} ms^{-2} = 10 nms^{-2}) and followed by a slow upward drift during 6 months. The net result was to introduce an artificial 6 months periodicity in the data obscuring the annual term and the polar motion signal.

Since May 1986 (day 1500 in Figure 3) a permanent getter has been installed in order to solve that problem. However, the characteristics of the annual term as well as of the thermal effects concentrated in the S_1 term (frequency $\nu(S_1) = 1$ cpd) were modified. For example the annual term, evaluated to 30 nms^{-2} in De Meyer and Ducarme (1991), increased up to 60nms^{-2} after the introduction of the permanent "getter". It is thus difficult to study simultaneously the data obtained before and after May 1986. Moreover, an instrumental failure occurred in October 1986 and the ball had to be relevitated.

The second recording period, extending from November 1986 up to September 2000, is homogeneous and quite undisturbed, except at the beginning. After relevitation of the ball a strong drift occurred and a final adjustment of the parameters was performed in the spring of 1987. In section 5.1 we shall investigate the best initial epoch from a statistical point of view. We have found namely that it is in April 1987. This is the reason why we shall consider hereafter the data between April 1987 and September 2000 (13½ years) only.

4. DETERMINATION OF THE DRIFT IN SG DATA

The basic algorithm of VAV is related with the following model of the drift.

The data set is partitioned into a sequence of time intervals or blocks of equal length. We shall denote by $I(T)$ an interval with central epoch T. In an earlier computation we used intervals of length $L = 48^{\mathrm{h}}$. Now we have used $L = 24^{\mathrm{h}}$ with better results.

The intervals are without overlapping. Between the intervals may remain arbitrary gaps, as well as strongly perturbed and doubtful data. We have thus a set of intervals

$$I(T) \text{ with central epochs } T = T_1, T_2, T_3, \ldots \text{ where } T_{i+1} - T_i \geq L = 24 \text{ hours.} \tag{4}$$

Let $Y(T+t)$ be an ordinate or tidal observation at time $T+t$ within $I(T)$, where t is time, measured within $I(T)$ with origin $t = 0$ at the central epoch T. According to our model the drift $D(T+t)$ at the point $T+t$ is represented by the polynomial

$$D(T+t) = \sum_{l=0}^{k} d_l(T) t^l \text{ in a given } I(T). \tag{5}$$

Here $d_l(T)$ are $k+1$ unknown constants in a given $I(T)$. In the same time $d_l(T)$ may get arbitrarily different values in the different $I(T)$, i.e. $d_l(T)$ are functions of the epoch T. It is very essential that $d_0(T) = D(T)$ is the value of the drift (according to the model) at the central epoch T.

We shall use the following general model or observational equations

$$Y(T+t) = G_{\mathrm{D,SD}}(T+t) + G_{\mathrm{LP}}(T+t) + G_{\mathrm{AP}}(T+t) + D(T+t), \; T = T_1, T_2, T_3, \ldots \tag{6}$$

The G terms are components of the tidal record, different from the drift, namely

$G_{\mathrm{D,SD}}(T+t)$ is the usually treated tidal signal at the D, SD, ... frequencies
$G_{LP}(T+t)$ is the long period (LP) tidal signal
$G_{\mathrm{AP}}(T+t)$ is the effect of the air-pressure and, eventually, other meteorological signals.

In this way the drift term D can be considered as the unexplained long-term part of the signal.

Every one of the components in (6) involves a set of unknowns. The **statistically correct** processing of the data by using MLS (Method of the Least Squares) is to solve this system of equations **with all unknowns**, including the drift unknowns $d_k(T)$. According to this principle VAV provides MLS estimates $\tilde{d}_l(T)$ of $d_l(T)$ and thus the estimated values $\tilde{D}(T+t)$ of the drift, in particular the estimated drift $\tilde{D}(T) = \tilde{d}_0(T)$ at the central epochs $T = T_1, T_2, T_3, \ldots$.

The tidal analyses methods, when we are not interested in the LP tides, usually ignore the term G_{LP}, the LP being well approximated and represented by the drift polynomials or filtered out as in ETERNA.

We have worked in another way. We have established for the SG data that in short intervals, e.g. during 24 hours, the drift properly said, i.e. without the LP tides, is practically a constant.

I.e., if the LP term is kept in (6), it is possible to consider the drift in $I(T)$ as a constant, choose the power $k=0$ in (5) and thus replace $D(T+t)=d_0(T)$. In such a way the drift is represented by a stepwise function, remaining a constant with a step of 24 hours.

This allowed us to use (6) as

$$Y(T+t)=G_{D,SD}(T+t)+G_{LP}(T+t)+G_{AP}(T+t)+d_0(T) \tag{7}$$

Then the drift is obtained as a series of estimates of the unknowns $d_0(T)$ for $T=T_1,T_2,T_3,\ldots$ Figure 3 represents the drift curve obtained in such a way.

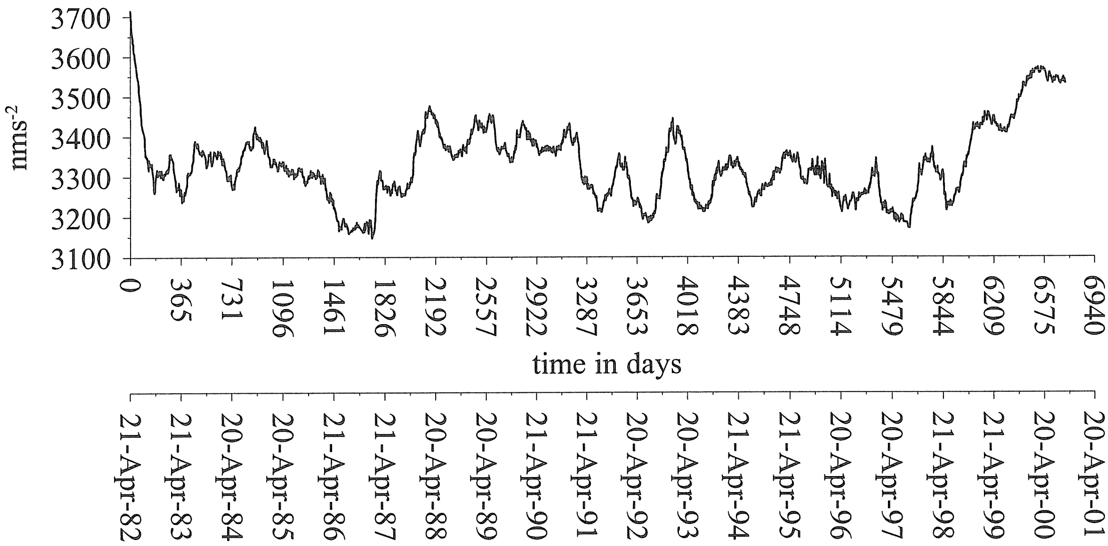

Figure 3. Complete curve of the estimated drift over the time interval of 18.4 years, from 21.04.1982 till 22.09.2000 and points every 24 hours (with the exception of two small gaps).

The model of the drift as a stepwise function, used here, also has been used for the determination of the LP tides (Ducarme et al., 2004 (Journal of Geodynamics, in press)). The results obtained, according to our knowledge, are with the highest precision ever reached, which confirms the reasonability of this model.

The solution of the system (7) by VAV, according to MLS, passes through a transformation of the data in a time/frequency domain. For every $I(T)$ we get a set of quantities, obtained by the application of orthogonal pass-band filters amplifying bands at frequencies 1, 2, … cpd, and low-pass filtered quantities, related with the estimation of $d_0(T)=D(T)$.

The tidal data are charged by a red noise. This is the reason VAV uses frequency dependent filtered data. Through their residuals we get frequency dependent estimates of the precision, always lower at the lower frequencies. The estimates of the precision of $d_0(T)$ and all quantities, related with $d_0(T)$, are obtained through the residuals of the low-pass filtered quantities, having the most unfavorable effect of the noise. I.e., the precision of $d_0(T)$ is estimated in the most severe way.

Partitioning in blocks of $L=24$ hours has been used by Doodson (1928, 1941) for the analysis of ocean data, as well as by Pertsev (1958). Lecolazet (1958) has used blocks with $L=43$. The method of Venedikov (1966) has used $L=48$ which have been implemented in the first successful application of MLS.

The determination of LP by the programs ETERNA and ANALYSE of Wenzel () uses a partitioning of the data in blocks, considerably longer than our intervals $I(T)$. Within the blocks the drift is approximated by polynomials with different coefficients in the different blocks. Gaps and jumps are available between the blocks. The VAV model (7) can be considered as a particular case of the scheme of Wenzel, namely when the blocks are of fixed length of 24 hours and the power of the polynomials is the lowest possible, i.e. $k = 0$.

5. MODEL OF THE DRIFT AS NON-TIDAL COMPONENT OF THE DATA

Further the drift curve in Figure 3 will be considered as non-tidal component of the data, involving an "instrumental drift" properly said, as well as signals, in which we shall be mainly interested. Thus we shall use a model like

$$d_0(T) = D_{\mathrm{ID}}(T) + \Delta G_{\mathrm{annual}}(T) + \Delta G_{\mathrm{temper}}(T) + \Delta G_{\mathrm{WT}}(T) + \Delta G_{\mathrm{pole}}(T), \quad T = T_1, T_2, T_3, \ldots \quad (8)$$

The ΔG components are known geophysical signals, namely

$\Delta G_{\mathrm{annual}}$ - annual component, mainly of meteorological origin

$\Delta G_{\mathrm{temper}}$ - effect of the slow temperature variations

ΔG_{WT} - effect of the water table and, finally,

ΔG_{pole} - observed gravity variations due to the polar motion (wobble) .

The component D_{ID} denotes the instrumental drift can also be considered as representing the zero line of the record. It is not excluded D_{ID} to include some geophysical signals, which we do not know. A typical characteristic of D_{ID} is that there are not obvious periodic components.

As shown in the following, the expression (8) can be considered as a regression with unknown regression coefficients. E.g. the δ_{pole} in ΔG_{pole}, defined by (3) is such a regression coefficients. Hence, (8) can be treated by MLS as a system of observational regression equations. Actually, VAV proposes a more strict application of MLS. Namely, $d_0(T)$ from (8) is replaced in (7). Then MLS is applied on the new (7), providing estimates of all unknowns, including the regression coefficients of (8).

In the following parts of this section the models of all components of (8) are discussed. The models depend on parameters, which are not a priori defined and which cannot be estimated by MLS as unknowns. This imposes to use a kind of Bayesian approach, namely to let vary the parameters and choose optimum cases according to a reasonable criterion.

The main criterion used is the minimum of the MSD (mean standard deviation) of δ_{pole}, denoted as $\sigma(\delta_{\mathrm{pole}})$. The Akaike Information Criterion AIC (Sakamoto et al., 1986), based on the principle of the maximum likelihood, has also been taken into account.

In the set of components we have a number of parameters and models, which may be denoted as $A, B, C, D, \ldots$ Let their optimum variant is $A_{\mathrm{opt}}, B_{\mathrm{opt}}, C_{\mathrm{opt}}, D_{\mathrm{opt}}, \ldots$ This variant has been obtained "manually", through many hundreds of analyses. For instance, we let vary A for some fixed $B, C, D, \ldots$ until we find a promising variant of A'_{opt}. Then we fix $A = A'_{\mathrm{opt}}, C, D, \ldots$ and let vary B until we find a promising variant $B = B'_{\mathrm{opt}}$. Afterwards we return to A looking for new optimum at condition $B = B'_{\mathrm{opt}}$, etc.

In the examples hereafter, if we discuss the variation of, say A, this is done at the condition of already found $B_{opt}, C_{opt}, D_{opt}, \ldots$ Thus the examples demonstrate only the final stage of the optimization procedure.

The attempts to give "equal rights" to ΔG_{WT} with all components in (8), have failed. The reason is that there is the interference between ΔG_{WT} and the polynomials, representing D_{ID}. Therefore our final results were obtained without ΔG_{WT}. As compensation, ΔG_{WT} is separately studied in section 5.5.

It is logically expected (8) to include the air-pressure, but all attempts to do this appeared to be useless. The reason is that the spectrum of the air-pressure does not include clear annual or other low frequency components.

5.1. Starting point of the data.

According to the events, discussed earlier in section 3, a portion of the initial data is not convenient for our purposes. So that the first problem we had to solve is to determine how many of the initial data must be discarded.

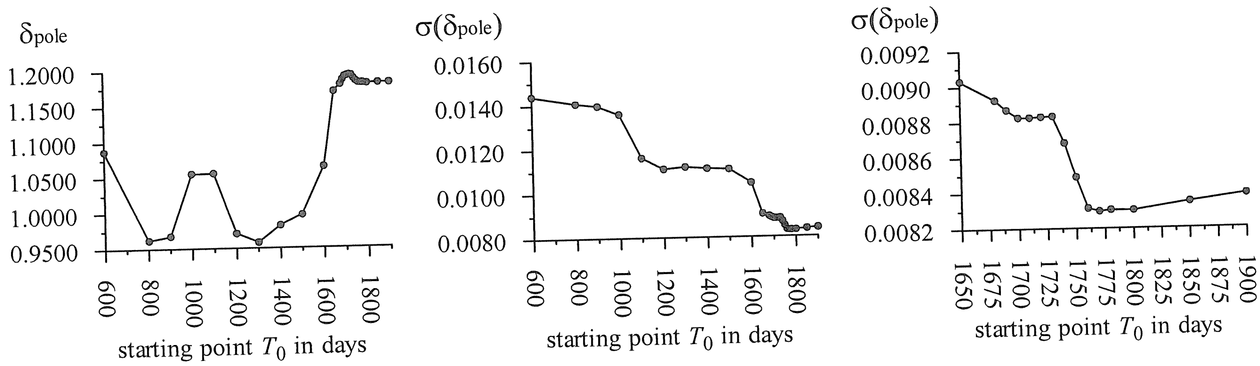

Figure 4. The factor δ_{pole} and its mean square deviation (MSD) $\sigma(\delta_{pole})$ as functions of the starting point T_0.

We have applied the analyses with different starting points T_0 between 400^d and 1900^d. As shown in Figure 13, we have got a minimum of $\sigma(\delta_{pole})$ at $T_0 = 1770^d$, which has been accepted as a start of the data to be used.

5.2. Polynomial components, approximating the instrumental drift.

Generally, a universal tool for the approximation of an unknown function like $D_{ID}(T)$, which has not evident periodic components, is a polynomial of T with appropriately chosen power k and unknown coefficients (polynomial regression). In particular cases exponential functions can be useful (Richter et al., 1995, Loyer et al., 1999). Namely, the drift may have an exponential character during a certain time after its installation. Such is the initial part of Figure 3, which, by the way, has been discarded in section 5.1. Due to the complicated behavior of the data we preferred the polynomial approximation.

An intuitive study of Figure 3 clearly shows that there are several important changes in the tendencies of the curve, as well as some fast displacements, looking like jumps. Hence $D_{ID}(T)$ has to be considered as a discontinuous function at the jumps or as a continuous function with discontinuous derivatives at some time points. Hence, it is senseless to use an approximation by a single polynomial, as well as by an exponential function, efficient only for continuous functions with continuous derivatives.

Due to this, we have decided to partition the curve in several segments or blocks and represent $D_{ID}(T)$ by different polynomials in every segment. I.e., we accept that there are some discontinuities, which should separate the segments. In a way this is an approximation of the drift similar to its approximation in the blocks of Wenzel (see Section 4).

The search of the discontinuities has started by the partitioning of the data in two segments, separated by a variable point T_{break} (breaking point). Within every segment $D_{ID}(T)$ has been represented by a polynomial of power $k=1$. We have let vary T_{break} from 2400 till 6400 days. The main results from these analyses are shown in Figure FNN_Tbreak_01. The relative minimums indicate possible discontinuities at about $T_{\text{break}} = 3200^{\text{d}}$ and, more clearly, at about $T_{\text{break}} = 5700^{\text{d}}$. Refining the search algorithm allowed to better localize these two points and to identify a third break point at about $T_{\text{break}} = 4000^{\text{d}}$.

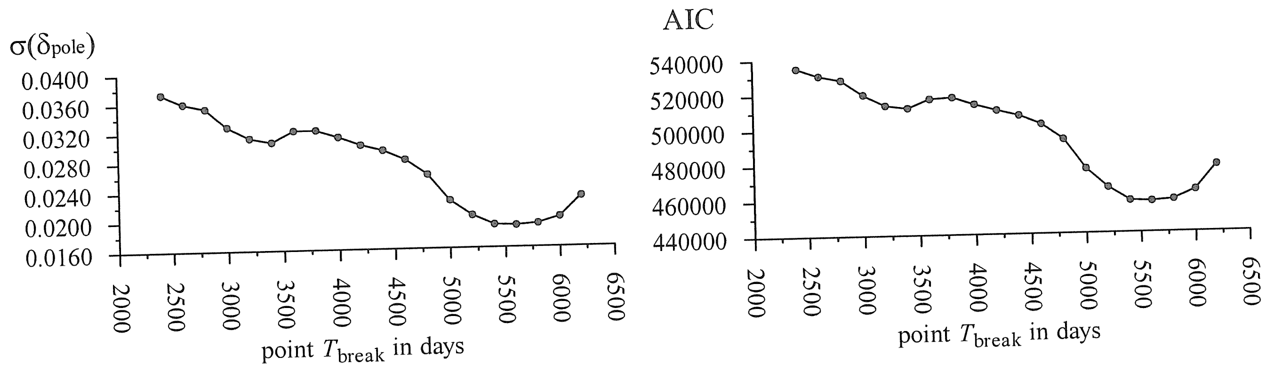

Figure 5. Experimental analyses for finding points of discontinuities of the instrumental drift.

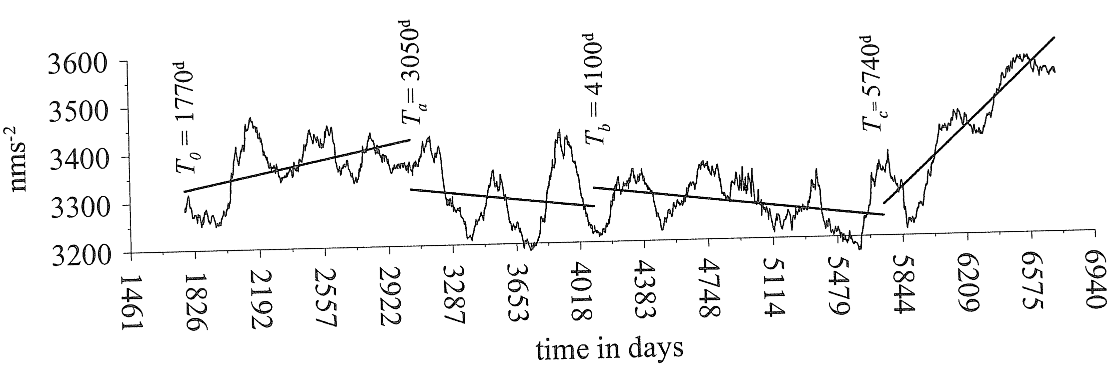

Figure 6. Points T_a, T_b and T_c of discontinuities, which define the partitioning of the data set in 4 segments.

Figure 6 shows the final selection of the discontinuity points and segments. The D_{ID} is approximated by linear functions with the only aim to illustrate the real changes in the character of the drift from segment to segment. Break points T_a (day 3050) and T_c (day 5740) correspond to a change of the slope of the instrumental drift and break point T_b (day 4100) - to a jump.

The points T_a, T_b and T_c have been found after multiple experiments, looking for the minimum of $\sigma(\delta_{pole})$ and AIC. Figure 7 is an example of the final selection of the third point $T = T_c$. It is related to an abrupt change in the behavior of $D_{ID}(T)$ due to building activities at the Observatory including large excavations. They started in September 1997, at about $T = 5630^d$ but it is impossible to know a priori when started the real effect of the building. The minimum has been found at $T_c = 5740^d$, some 100 days later than $T = 5630^d$.

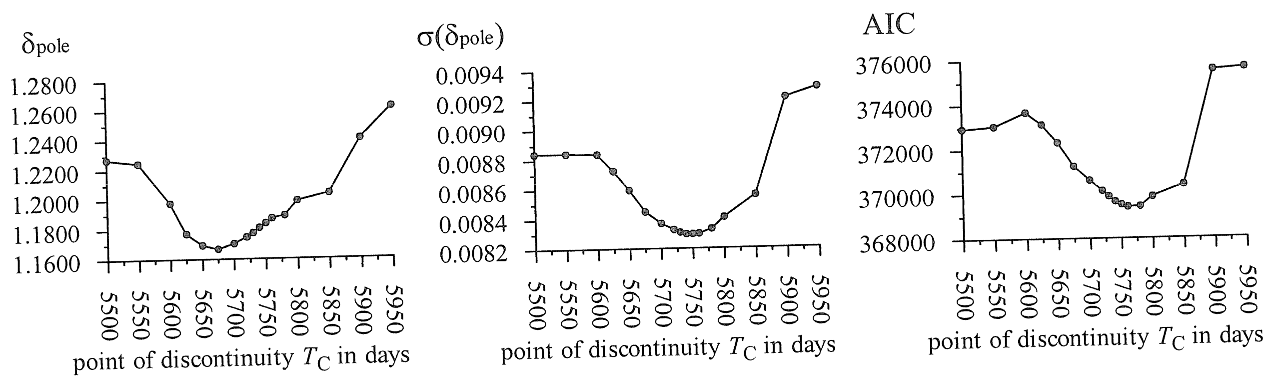

Figure 7. Estimated δ_{pole}, MSD of $\sigma(\delta_{pole})$ and the criterion of Akaike AIC as functions of the point $T = T_c$ of discontinuity.

Figure 8 shows the selection of the power k of the polynomials, which is common to all the segments. It appeared to be an easy problem because we have got a clear minimum of $\sigma(\delta_{pole})$ for $k = 4$. It is interesting that the curve of AIC does not stop decreasing at $k = 4$. Nevertheless, due to the principle of parsimony, we have chosen $k = 4$ on the basis of $\sigma(\delta_{pole})$.

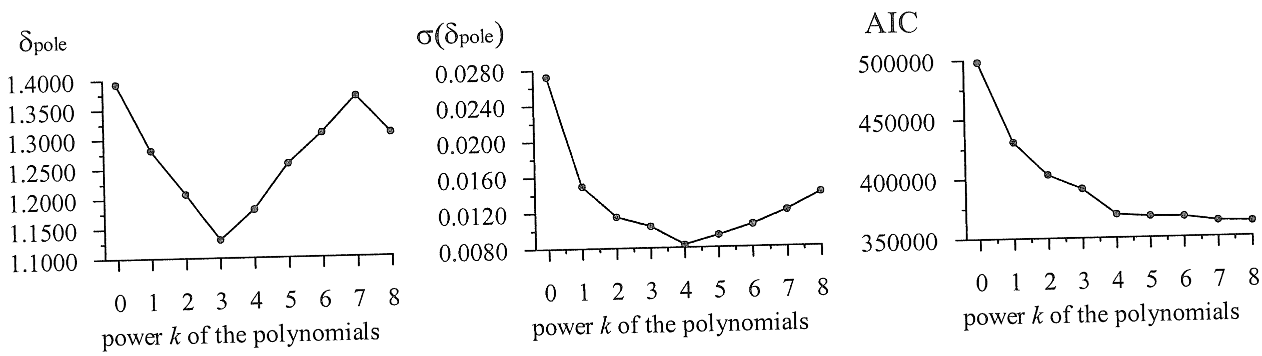

Figure 8. Estimated δ_{pole}, its MSD $\sigma(\delta_{pole})$ and AIC as functions of the power k of the polynomials in every segment.

5.3. Annual component.

It is very natural to represent ΔG_{annual} by a discrete Fourier expansion with basic period one year, namely

$$\Delta G_{annual}(T) = \sum_{j=1}^{J} h_j \cos\left(\frac{2\pi j}{a}T + \Phi_j\right), \text{ where } a = 1 \text{ year in days and } T \text{ is also in days.} \quad 9)$$

Here h_j is amplitude and Φ_j is phase at frequency j cpy. The regression unknowns are $h_j \cos\Phi_j$ and $h_j \sin\Phi_j$. The parameter of the model to be chosen is the order J.

The curves in Figure 9 have been obtained through analyses with different values of J. We haven't got a minimum of $\sigma(\delta_{\text{pole}})$, as well as of AIC. With good enough imagination, an effect can be seen till $J = 8$, but we have decided not to exaggerate and choose a final value $J = 6$, by keeping in mind the mentioned principle of parsimony. Moreover δ_{pole} becomes stable after $J = 6$ and $\sigma(\delta_{\text{pole}})$ as well as AIC are no more decreasing significantly.

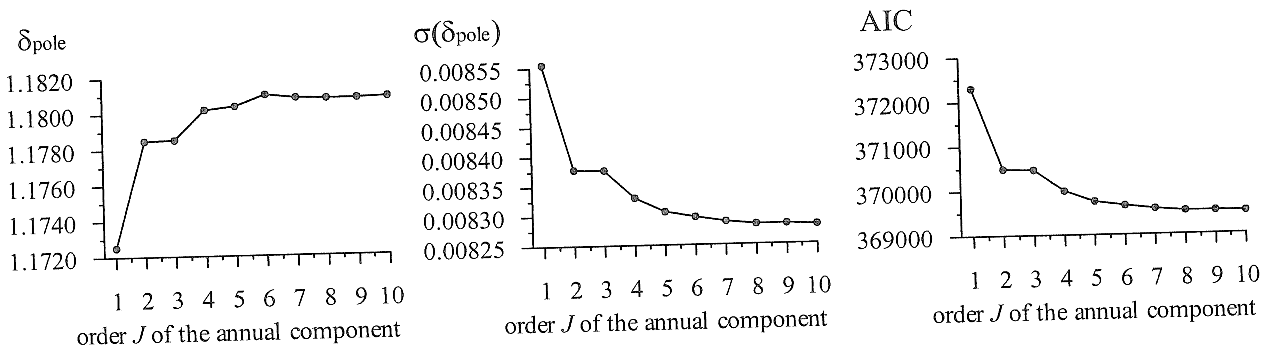

Figure 9. Estimated δ_{pole}, its MSD $\sigma(\delta_{\text{pole}})$ and AIC as functions of the order (highest frequency) J of the annual component.

As shown in the next section, the attempts to work without the annual component are to be categorically rejected.

5.4. Temperature component.

The effect of the temperature has been represented through

$$\Delta G_{\text{temper}}(T) = c_{\text{temper}}\left(C(T - \tau_{\text{temper}}) - \overline{C}\right), \tag{10}$$

where $C(T)$ is mean daily temperature in °C (degrees Celsius) at time T, $\overline{C}$ is mean of all used values of $C(T)$, c_{temper} is an unknown regression coefficient and τ_{temper} is a time lag (retardation for $\tau_{\text{temper}} > 0$) of the effect of the temperature.

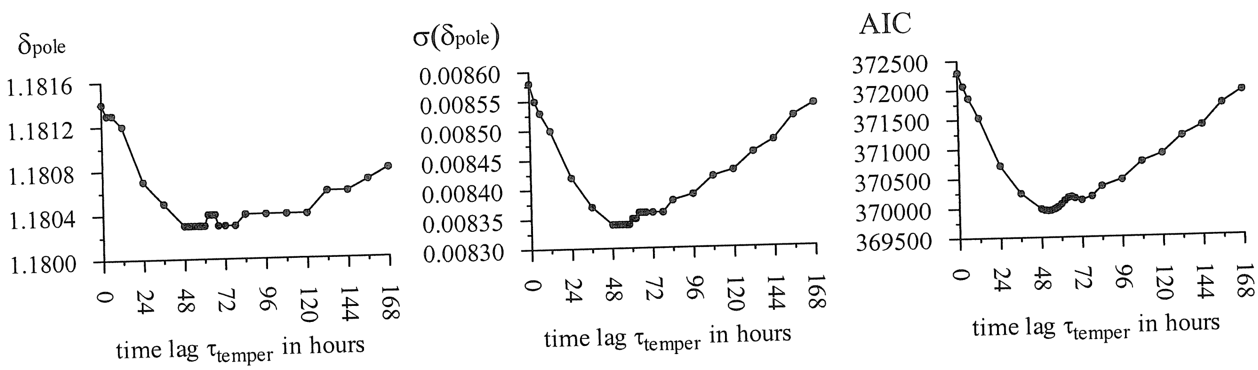

Figure 10. Estimated δ_{pole}, its MSD $\sigma(\delta_{\text{pole}})$ and AIC as functions of the time lag τ_{temper} (retardation) of the temperature effect on the observed gravity.

The time lag τ_{temper} is a parameter of the model whose value has to be obtained through a variation procedure. As shown in Figure a minimum of $\sigma(\delta_{\text{pole}})$ at τ_{temper} = 52 hours. The minimum of AIC happened to be nearly at the same point.

Table 2. The effect of the temperature and the annual components.

Case	Components used		Regression coefficients		Amplitudes ΔG_{annual} (nms^{-2})		AIC
	ΔG_{temper}	ΔG_{annual}	δ_{pole}	c_{temper} (nms^{-2}/K)	At 1 cpy	at 2 cpy	
1	Yes	Not	0.9608 ±0.0115	-5.142 ±0.0385			403 383
2	Not	Yes	1.1839 ±0.0088		53.21 ±0.26	6.52 ±0.26	375 007
3	Yes	Yes	1.1810 ±0.0083	-1.735 ±0.047	40.72 ±0.37	5.22 ±0.24	369 653

Since the temperature has a seasonal annual component, it is interesting to investigate whether ΔG_{temper} cannot replace ΔG_{annual} and, vice-versa, whether ΔG_{annual} cannot replace ΔG_{temper}. The results from these attempts are given in Table 2.

The case 1 without ΔG_{annual} is obviously very poor, compared to cases 2 and 3 with ΔG_{annual}, i.e. ΔG_{annual} is absolutely necessary.

In case 1 we have c_{temper} considerably higher (in absolute value) than in case 3. Thus ΔG_{temper} is partly taking the role of ΔG_{annual} but not enough. It is probably due to the fact that the semi-annual component is very weak in the temperature, in contradiction with what is observed in the gravity signal. A separate evaluation of both terms gives thus better results.

The comparison between cases 2 and 3 shows that ΔG_{temper} has a small, but useful effect on δ_{pole}. It is also evident that the inclusion of ΔG_{temper} decreases the amplitude of ΔG_{annual}. It can be explained by the fact that the amplitude of the annual wave in our residues is not perfectly stable as it is also the case for the annual temperature variations. The variable part of the annual gravity signal is effectively taken into account by the annual temperature wave, while the semi annual is not affected.

5.5. Effect of the water table

Figure 11 shows the observed curve of the water table $W(T)$ in Brussels. Following the experience of (Richter et al., 1995) and (Delcout-Honorez, 1991) we have accepted that the effect of $W(T)$ can be modeled by

$$\Delta G_{\text{WT}}(T) = c_{\text{WT}}\left(W(T) - \overline{W}\right) \tag{11}$$

where c_{WT} is an unknown regression coefficient and $\bar{W}$ is the mean of all used values of $W(T)$.

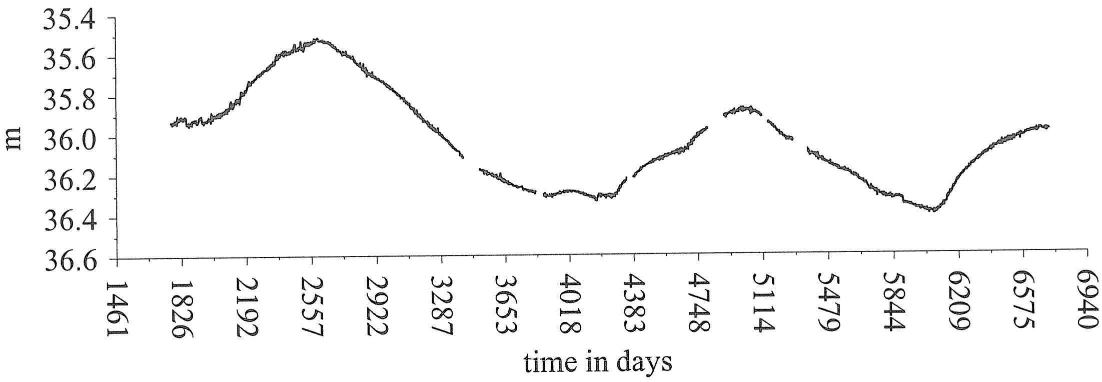

Figure 11. Observed variations $W(T)$ of the water table (descending vertical scale).

Unlike the other ΔG constituents of (8), $W(T)$ is a slowly varying function without clearly manifested periodic components. Due to this there appeared problems to use in parallel $W(T)$ in parallel with the polynomial model of D_{ID}.

The use of (11) and D_{ID} represented by polynomials of power $k=4$, as shown in section 5.2, has given

$$\delta_{\mathrm{pole}} = 1.1730 \ \pm 0.0130 \ \text{ and } c_{\mathrm{WT}} = 29.3 \ \pm 13.8 \ \mathrm{nms}^{-2}/\mathrm{m}\,. \tag{12}$$

This value of δ_{pole} is not so bad, although it has a lower precision than the final value obtained without ΔG_{WT} (Table 4 in Part 6). Much more disastrous is the estimated c_{WT}, being a completely abnormal quantity - positive instead of negative, with extremely low precision.

Due to this the use of $W(T)$ as a tool for finding the estimate of δ_{pole} has been abandoned Instead, we have attempted finding a reasonable estimate of c_{WT} by simplifying the use of the polynomials. After a series of experiments, it appeared reasonable to use the same points of discontinuities as in section 5.2, but decrease the power of the polynomials to $k=1$. The other two phenomena, temperature and annual component, remained in use as above.

The analysis in such a way has provided

$$c_{\mathrm{WT}} = -149.5 \ \pm 2.8 \ \ \mathrm{nms}^{-2}/\mathrm{m} \tag{13}$$

This value is in reasonable agreement with Delcout-Honorez (1991), who obtained $c_{\mathrm{WT}} = -128\,\mathrm{nms}^{-2}/\mathrm{m}$. In the same time, we have got $\delta_{\mathrm{pole}} = 1.315 \ \pm 0.0221$, which is obviously not satisfying.

5.6. Effect of the polar motion.

The theoretical model of ΔG_{pole} for static deformation has been given by the expression (3). It implies that the theoretical effect Δg_{pole} on an absolute rigid (non-deformable) Earth and the observed effect ΔG_{pole} on the real Earth are in phase.

One way to study the phase difference is to use a decomposition of ΔG_{pole} in series of periodic constituents (Loyer et al., 1999), with frequencies known from the study of the polar motion. Then we obtain the δ_{pole} factor (actually factors) in the frequency domain.

We preferred to remain entirely in the time domain. The real spectral structure of the polar motion is complicated and the frequencies are not very clearly defined. E.g., in the ancient data of Vondrak, one can find a double peak at the Chandler period.

For that reason the phase problem has been solved by using, instead of (3), the model

$$\Delta G_{\text{pole}}(T) = \delta_{\text{pole}} \Delta g_{\text{pole}}(T - \tau_{\text{pole}}) \tag{14}$$

with time lag of the effect τ_{pole}, positive for retardation.

In this model τ_{pole} is a parameter of the model, which should be estimated through its variation. Figure 12 shows the result from the experiments. The minimum of $\sigma(\delta_{\text{pole}})$, as well as the minimum of AIC happened at τ_{pole} = - 96 hours = -4 days, i.e. for an advance of the effect with 4 days.

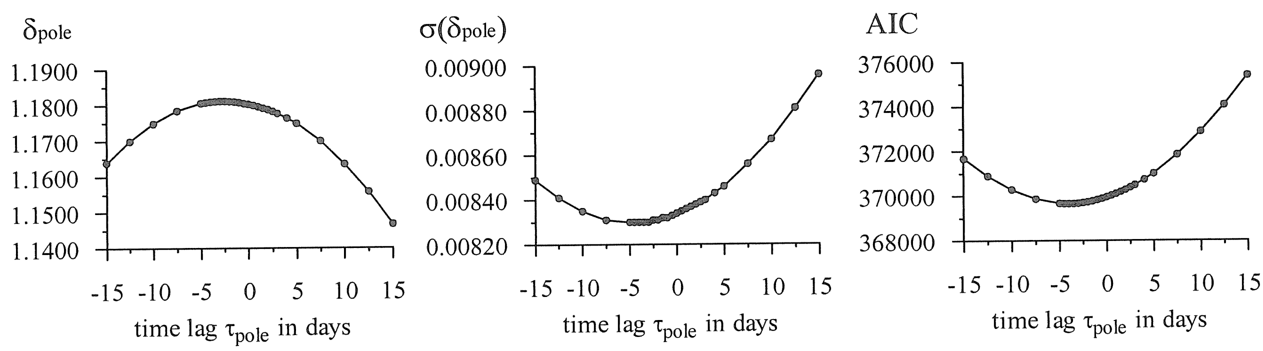

Figure 12. Estimated δ_{pole}, its MSD $\sigma(\delta_{\text{pole}})$ and AIC as functions of the time lag τ_{pole} (positive for retardation).

In the same time, as shown in Table 3, the differences between the results for $\tau_{\text{pole}} = 0$ hours and $\tau_{\text{pole}} = -96^{h}$ are extremely small. So that the results $\tau_{\text{pole}} = 0^{h}$ and $\tau_{\text{pole}} = -96$ hours cannot be accepted as significantly different quantities. By the way, for the Chandler period the quantity $\tau_{\text{pole}} = -96^{h}$ corresponds to a phase advance of only 3°.35.

Table 3. Effect of the time lag $\tau_{\text{pole}} = -96^{h}$.

τ_{pole} (hours)	δ_{pole}	$\sigma(\delta_{\text{pole}})$	AIC
-96	1.1810	0.00830	369653
0	1.1803	0.00834	369955

The observed δ_{pole} value is much too large compared with the theoretical models, e.g. the DDW99 model for a non hydrostatic anelastic Earth model. However Boy & al. (2000) computed an amplitude factor $\delta_{\text{pole}} = 1.19$ taking into account the oceanic loading at the Chandler period. The phase advance too, which seems indeed not accurately determined, could also be explained by the oceanic loading.

6. FINAL RESULTS

Table 4 is a summary of our results.

Table 4. Final results.

Component	Parameter	Numerical estimates	unit
Pole tide	δ_{pole}	**1.1810 ± 0.0083**	
	τ_{pole}	**-96 (advance)**	hours
Annual components (only amplitudes of the first harmonics)	(1 cpy)	39.05 ±0.52	nms^{-2}
	(2 cpy)	5.10 ±0.34	nms^{-2}
Temperature	c_{temper}	-1.735 ±0.047	$nms^{-2}/^{o}C$
	τ_{temper}	52 (retardation)	hours
Water table	c_{WT}	-149.54 ±2.75	nms^{-2}/m

Figure 13 is a graphical illustration of the approximation process.

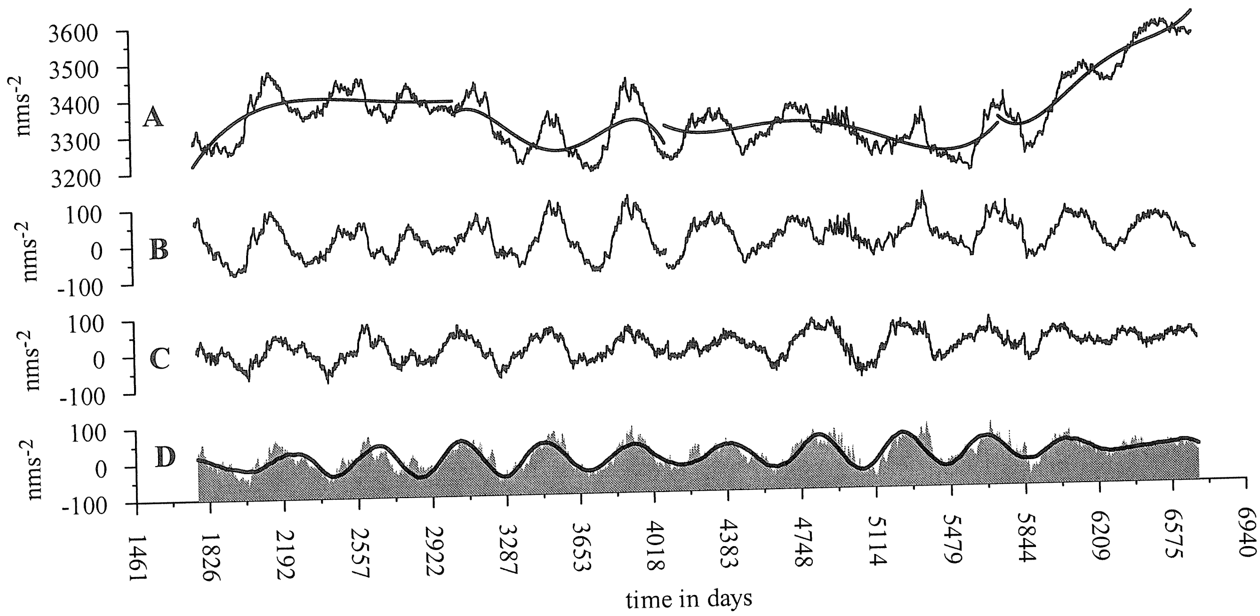

Figure 13. (A) Estimated drift $d_0(T)$ & polynomial approximation of the instrumental drift $D_{ID}(T)$ in 4 blocks, (B) $d_0(T)$ reduced by the approximation of the instrumental drift, (C)

$d_0(T)$ reduced by the approximation of the instrumental drift as well as by the effects of the annual and the temperature components and (D) estimated effect of the polar motion $\Delta_{pole}G(T) = \delta_{pole}\Delta g_{pole}(T - \tau_{pole})$ (bold line), compared with the observed effect in (C) (the filed grey curve).

7. CONCLUSIONS

From a 13½ years observation period performed in Brussels with the GWR T003 Superconducting Gravimeter we tried to determine the amplitude factor δ_{pole} of the pole tide by modeling the effect of different perturbing factors. We used the VAV/2002 program to evaluate simultaneously in the signal the tidal part and the non tidal one, often referred as "drift", as well as residual gravity. The spectral content of this drift signal shows beside the polar motion effect, strong annual and semi-annual oscillations, as well as aperiodic fluctuations. As auxiliary signals we can use pressure, temperature and water table variations. The aperiodic fluctuations in the drift are partly explained by the water table with a coefficient δ_{pole} close to -150nms^{-2}/m. However the aperiodic signal includes jumps and it was necessary to use a polynomial representation though a partition of the data in 4 blocks. The temperature signal is explaining only a part of the annual gravity signals and it was necessary to introduce an a priori annual wave and its harmonics of higher order. To find the optimal adjustment we tried to minimize the RMS error or MSD on the δ_{pole} factor as well as the AIC criterion. The best estimated value seems to be $\delta_{pole} = 1.1810 \pm 0.0083$. This large increase of the tidal amplitude factor at periods close to one year with respect to recent models of the Earth response including inelasticity in the mantle is essentially due to the ocean pole tide. It will be necessary to compute an ocean loading correction based on the modeled ocean pole tide by Desai (2002).

It is obvious that the stacking of different superconducting gravimeter data from various stations could produce a more robust evaluation of δ_{pole} as the perturbations will not build up unlike the pole tide signal. As we have now some series close to 10 years a composite solution is already possible.

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