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Commission des Marées Terrestres

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BIM 134

15 Décembre 2001

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BIM 134

Special Issue

The 14th International Symposium on Earth Tides (ETS2000)

August 28 - September 1, 2000
Mizusawa Cultural Hall ("Z Hall")
Mizusawa, Iwate, Japan

Jointly Organised:

International Association of Geodesy, Commission V
National Committee for Geodesy, Science Council of Japan
Geodetic Society of Japan
National Astronomical Observatory, Japan

Session Program

Monday 28 August, Room A
AM 09:30-10:45 Opening Session

AM 11:00-12:45
Session 1: Tidal instrumentation
Conveners: M. Van Ruymbeke and T. Tsubokawa

S1I00, WESTERHAUS, M. and Zuern, W.,
On the use of earth tides in geodynamic research
S1O01, EL Wahabi, A., DUCARME, B. and Van Ruymbeke, M.,
Humidity and temperature effects on LaCoste & Romberg gravimeters
S1O02, FRANCIS, O. and Hendrickx, M.,
Calibration of the LaCoste-Romberg 906 by comparison with the superconducting gravimeter C021 in Membach (Belgium)
S1O03, Falk, R., Harnisch, M., HARNISCH, G., Nowak, I., Richter, B. and Wolf, P.,
Calibration of the superconducting gravimeters SG103, C023, CD029 and CD030
S1O04, RUOTSALAINEN, H.,
Modernizing the Finnish long water - tube tiltmeter.
S1O05, TSUBOKAWA, T., Tazawa, S. and Tsuruta, S.,
New type of a half - filled water - tube tilt meter

PM 14:15-15:45

S1O06 JAHR, T., Jentzsch, G. and Kroner, C.,
The geodynamic observatory Moxa / Germany : instrumentation and purposes
S1O07, DATE', S., Kumagai, N., Ohshima, T., Sasaki, S. and Takao, M.,
Earth tides in a large circular electron accelerator
S1O08,VAN RUYMBEKE, M., Beauducel, Fr. and Somerhausen, A.,
New developments of the EDAS concept dedicated to tidal monitoring

PM 16:00-17:45
Session 3: Tidal observations using space techniques
Conveners: H. Schuh and A. Sengoku

S3I00, HAAS, R.,
Tidal effects and space geodetic techniques
S3O01, IORIO, L.,
Effects of Earth tides on the orbital elements of LAGEOS and LAGEOS II SLR satellites
S3O02, WU, B., Peng, B., Zhu, Y. and Hsu, H.,
Love numbers determined by Satellite Laser Ranging
S3O03, SCHMITZ-HUBSCH, H., Schuh, H. and Weber, R.,
Investigation of high-frequency tidal and non-tidal variations Of the Earth rotation parameters.
S3O04, AOKI, S., Ozawa, T., Shibuya, K. and Masuyama, A.,
Ocean tide observed with differential GPS technique in LützowHolm Bay, Antarctica
S3O05, PETROV, L.,
Determination of Love numbers *h* and *l* for long-period tides using VLBI

Tuesday 29 August, Room A
AM 09:15-10:45
Session 3: Tidal observations using space techniques (continue)

S3O06, FURUYA, M. and Okubo, S.,
Imaging oceanic tidal loading deformation by SAR interferometry - analysis of ERS data over South Korea
S3O07, HATANAKA, Y., Sengoku, A., Sato, T., Johnson, J., Rocken, C. and Meertens, C.,
Detection of the tidal loading signals from GPS permanent array of GSI Japan
S3O08, Varga, P., Zavoti, J., GROTEN, E. and Arfa-Kaboodvand, K.,
Tidal observations derived from GPS based length of day and polar motion data

S3O09, SHIRAI, T. and Fukushima, T.,
The detection of free core nutation
S3O10, Molodensky, S.M. and GROTEN, E.,
On the upper bound of the liquid core viscosity

AM 11:00-12:45 (105 min)

Session 7: Superconducting gravimetry

Conveners: D. Crossley and Y. Imanishi

S7I00, MEURERS, B.,
Superconducting gravimetry in geophysical research today
S7O01, DUCARME, B., Sun, H.P., Casula, G., Crossley, D., Francis, O., Harnisch, M. & G., Hinderer, J., Imanishi, Y., Merriam, J., Meurers, B., Neumeyer, J., Richter, B., Sato, T., Takemoto, S., Van Dam, T. and Virtanen, H.,
Tidal gravity results from GGP network in connection with tidal loading and Earth response
S7O02, NEUMEYER, J., Brinton, E., Fourie, P., Ritschel, B., Dittfeld, H.-J. and Pflug, H.,
Installation and first results of the dual sphere SG at the South African Geodynamic Observatory Sutherland
S7O03, ZUERN, W., Laske, G., Widmer-Schnidrig, R., Gilbert, F. and Kleinert, S.,
Observation of low order toroidal free oscillations of the Earth with gravimeters
S7O04, HARNISCH, M. and Harnisch, G.,
Study of long - term gravity variations based on data of the GGP cooperation

PM 14:00-15:45

S7O05, IMANISHI, Y., Higashi, T. and Fukuda, Y.,
Calibration of superconducting gravimeter T011 by one month parallel observation with absolute gravimeter FG5 #210
S7O06, VIRTANEN, H.,
Hydrological studies at the gravity station Metsähovi in Finland
S7O07, AMALVICT, M., Hinderer, J., Boy, J.-P. and Gegout, P.,
A 3 year comparison between a superconducting gravimeter (GWRC026) and an absolute gravimeter (FG5 – 206) in Strasbourg (France)
S7O08, SATO, T., Asari, K., Tamura, Y., Plag, H.-P., Digre, H., Fukuda, Y., Kaminuma, K. and Hamano, Y.,
Continuous gravity observation at Ny-Alesund, Svalbard, Norway with a superconducting gravimeter CT#039
S7O09, SUN, H.-P., Hsu, H.-T., Wang, Y., Chen, X.-D., Xu, J.-Q., Hao, X.-H. and Zhang, W.-M.,
Determination of the new tidal parameters obtained with superconducting gravimeter at Wuhan/China
S7O10, RICHTER, B., Zerbini, S., Negusini, M., Simon, D., Romagnoli, C. and Domenichini, F.,
Height and gravity variations by continuous GPS, gravity and environmental parameter observations in the Southern Po Plain (Medicina, Italy)

PM 16:00-17:30

S7O11, TAMURA, Y., Sato, T., Aoyama, Y., Matsumoto, K. and Asari, K.,
Free core resonance parameters obtained from gravity tide observations at Esashi Earth Tides Station
S7O12, KRONER, C.,
Hydrological effects in the gravity data of the geodynamic observatory Moxa
S7O13, MANSINHA, L. and Hayes, T.,
A search for the gravitational wave from earthquakes
S7O14, SMYLIE, D.E., Francis, O. and Merriam, J. B.
Beyond tides - determination of core properties from superconducting gravimeter observations
S7O15, CROSSLEY, D., Hinderer, J. and Amalvict, M.,
A spectral comparison of absolute and superconducting gravimeter data

PM 17:30-19:00, Room B

Poster Core Time (Sessions 1, 3, 4, 6, 7)

Session 1:

S1P01, D'OREYE, N., Klein, G., Celli, G. and Harpes, P.,
WALLACE: from the integrated data acquisition system to the database, the full remote control and management of the Walferdange Underground Laboratory

S1P02, IMANISHI, Y.,
Development of a high-rate and high-resolution data acquisition system based on a real-time operating system

S1P03, OHYA, F., Teraishi, M., Furuzawa, T. and Sonoda, Y.,
Measurement of tidal tilt with half-filled type water-tube tiltmeter

S1P04, VAN RUYMBEKE, M., Ducarme, B. and Somerhausen, A.,
Determination of the scale factor of the tidal parameters at the Brussels station

Session 3:

S3P01, RICHTER, B., Schwahn, W., Simon, D. and Falk, R.,
Proposal for a gravity network in Europe to verify observations from satellite missions

S3P02, HATANAKA, Y., Sengoku, A. and Sato, T.,
GPS permanent array as a tool for measuring tidal signals

Session 4:

S4P01, MATHEWS, P.M.,
Love numbers and gravimetric factor for diurnal tides

Session 6:

S6P01, DUCARME, B. and Venedikov, A.P.,
Special analysis of long tidal series of cryogenic gravimeters

S6P02, MORII, W.,
A new method of spectral analysis based on the technique of the AM receiver

Session 7:

S7P01, VAN RUYMBEKE, M., Somerhausen, A. and Mansinha, L.,
Meteorological effects observed in Europe during the eclipse of August 11, 1999

S7P02, MANSINHA, L., Ducarme, B., Hinderer, J., Meurers, B. and Van Ruymbeke, M.,
Gravitational shielding observations in Europe during the eclipse of 1999 August 11

S7P03, RICHTER, B., Brinton, E.W., Reineman, R. and Warburton, R.J.,
Superconducting gravimeters for remote deployment and array measurements

S7P04, WARBURTON, R.J., Lee, T.-C., Damiata, B., Jentzsch, G., Van Dam, T., Francis, O. and d'Oreye, N. and Richter, B.,
Applications for arrays of superconducting gravimeters

S7P05, MEURERS, B.,
Tidal and non-tidal gravity variations in Vienna - a five years' SG record

S7P06, NAWA, K., Suda, N., Fukao, Y. and Sato, T.,
Observation of the Earth's background free oscillations: comparison of superconducting gravimeter, LaCoste Romberg Gravimeters and STS-1V seismometers

S7P07, KRONER, C., Jahr, Th. and Jentzsch, G.,
Comparison of data sets recorded with the dual sphere superconducting gravimeter CD 034 at the Geodynamic Observatory Moxa

S7P08, OGASAWARA, S., Higashi, T., Fukuda Y. and Takemoto, S.,
Calibration of a superconducting gravimeter with an absolute gravimeter FG-5 in Kyoto

S7P09, RITSCHEL, B., Neumeyer, J., Hönow, B., Dittfeld, H.-J. and Pflug, H.,
Sutherland SG data acquisition and multi media monitoring and information system

S7P10, AOYAMA, Y., Sato, T., Fukuda, Y. and Ooe, M.,
Earth's gravity response to the Chandler Wobble

S7P11, MCQUEEN, H., Sato, T., Tamura, Y., Asari, K. and Lambeck, K.,
Instrumental drift and site stability at Canberra Gravity Station

S7P12, AMALVICT, M., McQueen, H. and Govind, R.,
Absolute gravity measurements and calibration of SG CT #31 at Canberra, 1999-2000

S7P13, MERRIAM, J.B., Pagiatakis, S. and Liard, J.,
Reference level stability of the Canadian superconducting gravimeter installation

S7P14, FUKUZAKI, Y., Aoki, S., Yamada A., Tamura, Y., Sato, T. and Shibuya, K.,
Coherent variation between SG and GPS in Syowa station, Antarctica

Wednesday 30 August, Room A
AM 09:15-10:45
Session 6: Data processing
Conveners: A. Venedikov and Y. Tamura

S6I00, ISHIGURO, M.,
Tidal data analysis and information criteria
S6O01, VENEDIKOV, A.P., Arnoso, J. and Vieira, R.,
Program VAV/2000 for tidal analysis of unevenly spaced data with irregular drift and colored noise
S7O02 DITTFELD, H.-J.,
About the validity of environmental parameters in gravimetric tidal analyses
S6O03, HSU, H.T., Liu, L.T. and Sun, H.P.,
Wavelet-characterized approach to harmonic analysis of tide gravity observations

AM 11:00-12:45
Session 4: Modeling of solid earth tides and related problems
Conveners: P.M. Mathews and S. Okubo

S4I00, SCHERNECK, H.-G.,
Solid Earth model with liquid core and ocean loading in application to ground water tides in deep wells
S4O01, FUKUSHIMA, T.,
Longitude origins on a moving equator
S4O02, KOPAEV, A. and Ducarme, B.,
Large-scale tide gravity anomalies: modelling and analysis of observations
S4O03, MATHEWS, P.M.,
Consistent modeling of effects of the tidal potential
S4O04, Tsuji, D. and OKUBO, S.,
Complex green's function for diurnal/semidiurnal loadings

Thursday 31 August, Room A
AM 09:15-10:45
Session 2: Results of ground based observations
Conveners: G. Jentzsch and S. Nakao

S2I00, AGNEW, D.C.,
Nominal and actual precision and accuracy in earth-tide observations
S2O01, ARNOSO, J., Vieira, R., Velez, E.J., Van Ruymbeke, M. and Venedikov, A.P.,
Analysis of tidal and long term variations of three gravity meters installed at station Cueva de Los Verdes (Lanzarote, Spain)
S2O02, ISHII, H., Yamauchi, T., Matsumoto, S., Hirata, Y., Nakao, S., Sano, O. and Hirano, T.,
Three-dimensional strain and stress continuous observation in Kamaishi mine in the northeast Japan
S2O03, BAKER, T.F. and Bos, M.,
Tidal gravity observations and ocean tide models
S2O04, NAKAO, S., Hirata, Y., Jentzsch, G., Ramatshi, M. and Araya, A.,
Comparative observation of pendulum type tiltmeters in Nokogiriyama observatory, Japan

AM 11:00-12:30

S2O05, JENTZSCH, G., Zadro, M., Braitenberg, C., Latynina, L.A., Verbitzkiy, T.Z., and Tichomirov, A.V.,
Relations between different geodynamic parameters and seismicity in areas of high and low seismic hazards
S2O06, DAL MORE, G., Ebblin, C. and Zadro, M.,
The FEM in the interpretation of tilt-strainmeter observations in a cave; air pressure loading effects
S2O07, BRAITENBERG, C. and Zadro, M.,
Modeling the hydrologic induced signal in geodetic measurements
S2O08 RYDELEK, P.A., Eguchi, T., Watabe, I., Iwasaki, S., Fujinawa, Y. and Fujita, E.,
Tidal analysis of data from pressure sensors located at the Sagami Trough, Central Japan

AM 12:30-13:00
Session 8: Tidal studies in tectonic active regions
Conveners: R. Vieira and K. Fujimori
S8I00, KASAHARA, J. and Sato, T.,
An implication on the relation among tides, hydrothermal activity and volcanic earthquakes observed by ocean bottom seismometers
PM 14:00-16:00
S8O01, FUJIOKA, K., Kobayashi, K., Kato, K., Aoki, M., Mitsuzawa, K., Kinoshita, M. and Nishizawa, A.,
Tide-related variability of hydrothermal activity at the TAG hydrothermal mound, Mid - Atlantic Ridge
S8O02, AOKI, Y. and Kato, T.,
Tidal triggering of seismic swarms off the Izu Peninsula, Japan
S8O03, OMURA, M., Otsuka, S., Fujimori, K. and Yamamoto, T.,
Tidal strains observed in the Rokko-Otsuki fault, Kobe, Japan, before occurrence of the 1995 Hyogoken-Nanbu Earthquake
S8O04, WESTERHAUS, M.,
No clear evidence for temporal tidal tilt modification prior to large earthquakes and volcanic eruptions
S8O05, SUGIHARA, M., Ishido, T., Nishi, Y. and Tosha, T.,
Geoelectric tides observed at Ohgiri geothermal field, Japan
S8O06, D'OREYE, N. and Fonseca, J.,
About the use of long- and short-base tiltmeters for active zone monitoring : water-tube test in Walferdange and electronic spirit levels on Fogo Volcano (Cape Verde)
S8O07, ARNOSO, J., Vieira1, R., Velez, E.J., Cai, W.-X., Tan, S.-L., Jun, J. and Venedikov, A.P.,
Monitoring tidal and nontidal tilt variations in Lanzarote Island (Spain)
S8O08, HEKI, K.,
On the seasonal change in the strain build - up in the northeast Japan
PM 16:15-17:30
Session 5: Atmospheric and oceanic loading effects
Conveners: O. Francis and A. Mukai
S5I00, SCHENEWERK, M.S., Marshall, J., Dillinger, W. and Weston, N.,
Vertical ocean - loading deformations derived from a global GPS network
S5O01, BOGUSZ, J.,
Detection of tidal effect in the air pressure changes
S5O02, AOYAMA, Y. and Naito, I.,
Atmospheric wind and pressure variations have complementarily maintained the observed Chandler wobble
PM 17:30-19:30, Room B
Poster Core Time (Sessions 2, 5, 8, 9)
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S2P01, KOPAEV, A., Milyukov, V. and Yushkin, V.,
Tide gravity and strain observations near the Mt. Elbrus, Central Caucasus
S2P02, DUCARME, B. and Van Ruymbeke, M.,
Tidal gravity observations along the Atlantic coast of France with LCR G906
S2P03, Berrino, G. and RICCARDI, U.,
Gravity tide at Mt. Vesuvius (Southern Italy): correlations with different geophysical data and volcanological implications
S2P04, Bos, M. and BAKER, T.F.,
Tidal gravity observations and modelling in the near coastal zone
S2P05, YOSHIKAWA, S. and Yamamoto, T.,
Strain measurement by double coaxial borehole strainmeters at Odawara, Japan
S2P06, YAMAMOTO, T., Kamigaichi, O., Naito, H., Yoshikawa, S. and Ishikawa, Y.,
Strain observations at Tsuruga and Imazu stations, Northern Kinki District, Japan
S2P07, NAGAO, T., Kudo, T. and Aoyama, Y.,
Tidal components detected in long span telluric current data
S2P08, ASAI, Y., Aoki, H., Tanaka, T., Kitagawa, Y. and Azuma, S.,
Comparison of tidal changes of ground strain, tilt and groundwater observed in boreholes

S2P09, ONOUE, K., Mukai, A. and Takemoto, S.,
Tidal strain enhancement observed with extensometers in Donzurubo Observatory, Nara, Japan

S2P10, ISHII, H., Yamauchi, T., Matsumoto, S., Hirata, Y. and Nakao, S.,
Multi-component borehole instrument developed by E.R.I. and some interesting results

S2P11, NAKAI, S., Sugihara, M. and Tamura, Y.,
Evaluation of tidal and non-tidal gravity change from continuous readings of Scintrex CG-3M gravimeters

S2P12, DITTFELD, H.-J.,
Tidal results of neighboring stations ("Part III" of an old investigation)

S2P13, Ishii, H., JENTZSCH, G., Nakao, S., Ramatschi, M. and Graupner, S.,
Observatory Nokogiriyama/Japan: comparison of different tiltmeters

Session 5:

S5P01, BOGUSZ, J. and Chojnicki, T.,
Seasonal changes in atmospheric tidal waves

S5P02, AGNEW, D.C.,
Map projections to show the effects of surface loading

S5P03, NIWA, Y. and Hibiya, T.,
Spatial distribution of internal tides in the North Pacific predicted using a three-dimensional numerical model

S5P04, MUKAI, A., Takemoto, S., Higashi, T. and Fukuda, Y.,
Effect of viscosity in oceanic tidal loadings estimated from gravity observations in Kyoto and Bandung.

S5P05, BOY, J.-P., Gégout, P. and Hinderer, J.,
Gravity variations and global atmospheric pressure loading

Session 8:

S8P01, VAN RUYMBEKE, M., Somerhausen, A., Ducarme, B., Vieira, R., Arnoso, J. and Velez, E.,
Projects of the Royal Observatory of Belgium (ROB) at the Lanzarote laboratories

S8P02, MUKAI, A. and Fujimori, K.,
Elastic constants in fault zone determined using strain changes obtained at an 800M borehole

S8P03, MATSUMOTO, N. and Roeloffs, E.,
Time-varying hydraulic and mechanical properties estimated by responses of ground-water level to Earth tides

S8P04, HARADA, M., Furuzawa, T., Ohya, F., Morii, W. and Yamada, M.,
Measurement of Earth tidal strain at Amagase Observatory

S8P05, YAMAMURA, K., Sano, O., Utada, H., Fukao, Y., Nakao, S. and Takei, Y.,
Long-term observation of tidal variation of in situ seismic velocity and attenuation

S8P06VIEIRA, R., Weixin, C., Arnoso, J., Vélez, E., Xiling, T. and Jun, J.,
Tidal and nontidal observations in a volcanic active region, review of the cooperation between Spain and P. R. China in the Geodynamics Laboratory of Lanzarote

Session 9:

S9P01, YANG, Z.,
Non-tidal term in secular variation of Earth rotation

S9P02, TAKANEZAWA, T., Matsumoto, K., Ooe, M. and Naito, I.,
Effects of the long-period ocean tide on Earth rotation, gravity and crustal deformation predicted by global barotropic model - periods from Mtm to Sa -

S9P03, TAKANEZAWA, T., Matsumoto, K., Ooe, M. and Naito, I.,
Non-equilibrium charateristics of the long-period ocean tide in dynamics and energetics

S9P04, IWATA, T., Takahashi, M., Namiki, N., Hanada, H., Kawano, N., Heki, K., Matsumoto, K. and Takano, T.,
Mission instruments for lunar gravity measurements using SELENE sub-satellites

S9P05, MANABE, S.,
Possibility of astrometric detection of stellar motions due to the tidal effects of the nearby galaxies

S9P06, TAKANEZAWA, T., Hanada, H., Kono, Y., Tsuruta, S., Tsubokawa, T., Kawachi, M., Funazaki, K. and ILOM research group,
Possibility of detecting the lunar tidal signal by ILOM (In-situ Lunar orientation measurement) telescope

S9P07, HEKI, K., Hanada, H., Iwata, T., Ooe, M., Matsumoto, K., Araki, H. and ILOM research group,
In-situ measurement of the physical libration and tidal deformation of the Moon

S9P08, YANG, Z., Zhu, Y. and Shum, C.K.,
The possible effect on rotational evolution of Venus due to the Venusian non-zonal gravitational field

S9P09, PING, J.-S., Kono, Y., Kawano, N. and Hanada, H.,
How S/C tip-off and free nutation effect doppler tracking in SELENE

Friday 1 September, Room A

AM 09:15-10:30 (75 min)

Session 5: Atmospheric and oceanic loading effects (continue)

S5O04, MATSUMOTO, K., Sato, T., Takanezawa, T. and Ooe, M.,
GOTIC2: a software for computation of oceanic tidal loading effect

S5O05, VAN DAM, T., Wahr, J., Milly, C., Samakin, A. and Francis, O.,
Hydrological loading and gravity observations

S5O06, RAY, R.D.,
The problematic $\square_1$ tide

S5O07, RICHTER, B., Simon, D., Zerbini, S. and Negusini, M.,
Seasonal vertical density variation in the atmosphere and their consequences for gravity and GPS measurements

S5O08, FUJIMOTO, H., Mochizuki, M., Mitsuzawa, K., Matsumoto, K. and Sato, T.,
Long-term observation of ocean bottom pressure across the spreading axis of the southern East Pacific Rise

AM 10:30-11:00 (30 min)

Session 9: Tides on planet

Conveners: C.K. Shum and H. Hanada

S9I00, YODER, C.F.,
Detection of tides on planets and satellites using orbiting spacecraft and landers

AM 11:15-PM 13:15

S9O01, YANG, Z.,
Atmospheric circulation of Venus and its rotation evolution

S9O02, WU, X., Yoaz, B.-S., Folkner, W., Williams, J. and Zumberge, J.,
Europa's tides and possible hidden liquid ocean

S9O03, ARAKI, H.,
Focal processes of deep moonquakes

S9O04, ABE, M., Ooe, M.,
Tidal history of the Earth-Moon dynamical system

S9O05, HANADA, H., Kawano, N., Hosokawa, M. and Imae, M.,
Possibility of observations of rotational fluctuations and tidal deformations of planets by the inverse VLBI method

S9O06, SHUM, C.K., Yu, N. and Morris, C.,
Accuracy assessment of contemporary Earth ocean tide models

PM 14:30-15:00 Closing Session (30 min)

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Japan

Opening Address of the 14th International Symposium on Earth Tides

(on behalf of Prof. N. Kaifu, Director General of National Astronomical Observatory)

Shoken Miyama

Associate Director of General of National Astronomical Observatory, Japan

Good morning, ladies and gentlemen.

I am Shoken Miyama, the executive vice director of National Astronomical Observatory of Japan, NAOJ. As the representative of the host institute, I would like to say it is my great pleasure to welcome to you to Japan, and welcome to Mizusawa and to the 14th International Symposium on Earth Tides.

First of this symposium, on behalf of the Director, Norio Kaifu, I wish to extend our heartiest welcome to the scientists, secretarial staff and others who have come to this symposium from many countries. Especially we are honored by so many distinguished guests, the president of International Association of Geodesy, Special Commission 3, Professor Groten and the president of IAG Commission V, Professor Takemoto.

This city, Mizusawa is the birthplace of geodetic study in Japan. About a century ago, in 1899, the International Latitude Observatory of Mizusawa was founded under the program of the International Latitude Service in this city. After that as the center of Japanese Earth-Geodynamics, there have been many famous scientists and their works. Especially the work by the first director of the observatory, Professor Kimura, is World famous by the Z-term of Polar motion of Earth. The name of this city hall, "Z-Hall," comes from his discovery.

NAOJ was established in 1988, integrating the Tokyo Astronomical Observatory of the University of Tokyo, the International Latitude Observatory of Mizusawa, and the solar radio group of the Research Institute of Atmospherics, Nagoya University. Because the proper combination between the astronomy and the geodynamics will make good effects for both fields. In order to promote open-use of the observatory facilities for country-wide researchers, these three research centers were reorganized as NAOJ. After the establishment of NAOJ, in the Mizusawa, as a branch of NAOJ there are the Earth Rotation Division and the Mizusawa Astrogeodynamics Observatory. There are about 30 scientists. They are studying about Radio Geodynamics, Earth Rotation, Geodynamical data processing, Earth Deformation, Earth Tides and Gravity. Especially in the field of Earth Tides, we have Observation Facilities, The Esashi Earth Tides Station. That is located about 20 km east of the Mizusawa campus and consists of an observation tunnel and a gravity measurement room. In the near future we have some planes to investigate planet and moon tides also. In Mizusawa Astrogeodynamics Observatory there are young scientists from several Universities and some graduate students who are actively studying about Earth Tides.

Therefore that the 14th International Symposium on Earth Tides is held at this city and recent developments, instrumentation, observation and theory about the earth tide can be discussed here is very meaningful from the historical viewpoint as well as the educational viewpoint.

Before end of my opening address, I would like to say special thanks to the Sponsors, International Association of Geodesy, Commission V: Earth Tide Commission, National Committee for Geodesy, Science Council of Japan, and Geodetic Society of Japan. And also thanks to Cosponsors, Iwate Prefecture and Mizusawa City. In conclusion, I offer to this Symposium my best wishes for success and to each of the participants a happy and meaningful stay in this city. Thank you very much for your kind attention.

Welcome Address of the Chairman of LOC

Masatsugu Ooe

National Astronomical Observatory, Mizusawa, Japan

Welcome all of you to the 14th International Symposium on Earth tides.

It is my great honor to meet you in Mizusawa as chairman of the LOC of the Symposium. We realized, in rapid development of instrumentation and observations, such as VLBI and GPS, and also in development of new theories, the fields of Earth tide researches were widely expanded into related fields. The applications of tidal instrumentation to detection of crustal motions are well known. Superconducting gravimeters also are becoming powerful tools to investigate into the Earth's interior.

We experience many volcanoes and earthquakes since Japanese Islands is very active region. Many reports are brought to us in relation to tides. Also many reports are coming to you dealing with tides on the Moon and planets. We in Mizusawa had a centennial anniversary last year since starting the latitude observations and we stand on the turning point to the next century. NAO Mizusawa has joint SELENE project to research into the origin of the Moon and to possibly initiate new sciences on the Moon. Now in worldwide the techniques of geodesy are expanding to the space.

We discussed how to focus the symposium. After that we came to the point to propose to add new sessions to the symposium. One is 'tidal studies in tectonic active regions' and another is 'tide on plants' as you know. All sessions other than these, however, are sure bases for farther development of researches.

I, in behalf of LOC, express sincere thanks to the president of IAG and the president of 5th Commission of IAG and all colleagues, for their invaluable supports to the symposium. We announced in the circulars, papers presented in this symposium will be published in the Journal of Geodetic Society of Japan. I am now talking about details of it with colleagues of invited coeditors. I wish you discuss freely and obtain fruitful results through this symposium and also wish the great progress be brought to IAG.

Thank you.

IAG Presidential Address

(on behalf of IAG President Prof. F. Sanso)

Erwin Groten

Darmstadt University of Technology, Germany

The Commission on Earth Tides of the International Association of Geodesy (IAG) is one of the most active Commissions of IAG since long time. I am attending the ETC Symposium now for the sixth time; The first ETC Symposium I had the honour to attend was the fourth Symposium of that commission held at Brussels in 1961 which was organized under the presidency of Prof. R. Tomaschek, and Prof. P. Melchior headed its organizing committee as secretary of the commission which was still called "Commission Permanente" at that time. Prof. Melchior soon celebrates his 75th birthday; he was a young scientist in 1961; so you realize the long tradition of the Earth Tide Commission.

The work of the commission at the edge between astrometry, geophysics, geodesy and geodynamics has since been extremely fruitful. There are only few fields and disciplines in geophysics where the generating forces are so well and exactly known and predictable as in earth tides. By observing the reaction of solid and fluid earth on land and at the ocean we may treat the tidal problem as an inverse filter problem where the parameters of the earth models are determined from known input and observed output. M.S. Molodensky was one of the first scientists who derived in the late fifties reliable fluid outer core models and stimulated the detailed research of various wobbles (such as NDFW) of the earth, where wobble means the variations of the earth rotation in an earth-fixed frame of reference. Meanwhile our observations also give extremely valuable information on the solid inner core. Earth tide observations generally fill a gap of the spectrum where little other observation is available.

The fact that tides and precession-nutation are generated by the same system of acceleration or forces intensified the interrelations of astrometry and geophysics. Discussions on nearly diurnal free wobble and similar perturbations led to a variety of improved insight into the earth deep interior. The use of global systems and the installation of very precise instrumentation in terms of superconducting gravimeters, various extensometers, particularly in Japan, inspired earth tide research. So tidal research and the Commission can be proud to cover a broad spectrum of geoscientific activities from atmosphere, to ocean and to a great variety of solid earth geophysics.

Also the practical impact of earth tide research besides its scientific aspect gained recently great recognition. From VLBI to SLR, GPS, gravimetry and various other disciplines of geophysics, geodesy and engineering earth tide results are of interest and importance and their further progress strongly depends on progress made in earth tide research.

One particular aspect is certainly luni-solar triggering of earthquakes. This is only one aspect of typical side-effects of earth-tidal research which demonstrates how relatively small effects can have substantial consequences in a relatively broad spectrum.
From the very beginning Japan, the host country of this Symposium, played an eminent

role in earth tidal research. When I wrote my thesis on earth tides, more than 38 years ago, Japanese tidal work played a leading role; the names of Shida, Nishimura, Takeuchi etc. are unforgettable. IAG adopted its important decision on permanent tides in 1982 at Tokyo during the General Meeting of IAG. The important research results achieved in Japan and the relevant colleagues who initiated that progress are too numerous to be listed here.

Earth tide research has made tremendous progress in recent years. Japanese researchers took substantially part in it and locations like Mizusawa, Kyoto and Tokyo have gained world-wide recognition in earth-tidal and tide related research.

In view of all these interrelations mentioned before I think Mizusawa is the right location for this Symposium; on behalf of IAG I express my good wishes for a successful meeting which certainly also represents the long tradition as well as the outstanding new results of world-wide earth tidal research.

ETC Presidential Address

Shuzo Takemoto

Kyoto University, Kyoto, Japan

Mr. Chairman, Professor Groten the IAG Representative and ladies and gentlemen, to all of you present here, I take pleasure in expressing sincere thanks for your attendance at this Symposium.

The first International Symposium on Earth Tides was held at Brussels in 1957. Since then thirteen meetings were held during 4 decades. We are now about to begin our 14^{th} International Symposium on Earth Tides here in Mizusawa. It should be noticed specially that this is the first time the Symposium is held in Japan.

In Japan, studies on Earth tides began in the early part of the 20^{th} century. The late professor Toshi Shida of Kyoto Imperial University first observed tidal tilts in Japan using an E. von Rebeur-Paschwitz tiltmeter of horizontal pendulum type at the Kamigamo Geophysical Observatory in Kyoto. The name of Shida is famous as the Shida Number in tidal studies. As well known, the tidal response on the Earth's surface can be represented by three dimensionless parameters. They are Love number h and k, and Shida number l. After the pioneering work by Shida, many researchers continued Earth Tides observations in Japan. I have believed that Japan has enough potential to organize the highest standard Symposium on Earth tides.

At the 13^{th} International Symposium on Earth Tides held in Brussels three years ago, we discussed on seven topics of (1) Tidal instrumentation, (2) Space geodetic observations (3) Ground based observation, (4) Tidal models, (5) Tidal data processing, (6) Ocean tide models and (7) Superconducting Gravimeters. Now in this Symposium, we added two sessions: one is "Relation between the tidal and tectonic phenomena" and the other is "Observation and theory for tides on the Earth and planets". The former is by the reason that this Symposium is held in the tectonically active region Japan and the later is based on recent development of space geodetic techniques and the planetary tides will be one of the main targets of our Commission in the 21st century.

In this opportunity I would like to express my sincere thanks on behalf of the Earth Tide Commission to members of the Local Organizing Committee, especially to Prof. Ooe, Prof. Sato and colleagues in the National Astronomical Observatory of Japan for their excellent work in organizing this Symposium. I also express my deep appreciation to Prof. Sanso IAG President and Prof. Tscherning IAG Secretary General who kindly allocated a part of IAG fund to this Symposium and five persons could be awarded IAG travel fund.

Finally, we sincerely hope that all who participate in this Symposium will report fully on the results of their continuing research and thus contribute to the progress of Earth tide studies in the 21st century.

Thank you very much.

Report of the Earth Tide Commission (1999-2000)

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Abstract
The 14th International Symposium on Earth Tides (ETS2000) was successfully held in Mizusawa, Japan, during the period from August 28 to September 1, 2000. 138 participants (including 10 accompanying persons) from 21 countries reported fully on their results of continuing researches on Earth tides and thus contributed to the progress of further research of Earth and Planetary Tides. As the President of the Commission, it is my duty and honor to present a brief report of the Earth Tide Commission for the period 1999-2000.

1. Objective of the Commission

The objective of the Commission is to promote international cooperation and coordination of investigations related to the observation, preprocessing, analysis and interpretation of earth.

By earth tides, we understand all phenomena related to the variation of the Earth's gravity field and to the deformation of the Earth's body induced by the tide generating forces, i.e. the forces acting on the Earth due to differential gravitation of the celestial bodies as the Moon, the Sun and the nearby planets.

The Commission will collaborate with all international and national organizations concerned with the observation, preprocessing,.

The Commission will encourage and promote campaigns to develop, compare and calibrate instrumentation for earth tide observations, techniques of operation, procedures for data preprocessing and data analysis.

The Commission makes standard software for the prediction of earth tide phenomena and for the processing of earth tide observations available to the scientific community by an Electronic Information Service, started in November 1st 1995.Note that the ftp information service is no longer available, because since May 1997, the Electronic Information Service of the Earth Tide Commission is directly accessible from this home page.

The Commission will organize the 14th International Symposium on Earth Tides at Mizusawa/Japan in 2000.

2. Officers of the Commission

The President of the IAG Commission V (Earth Tides) was elected by the Council of IAG at the IUGG/IAG General Assembly held in Birmingham, UK, in July 1999.

After discussion and deliberation with some colleagues, the President appointed in autumn 1999 Jacques Hinderer (France) as Vice-President and Olivier Francis (Belgium, now Luxembourg) as Secretary of the Commission until the first regular meeting of the commission, i.e., the 14th International Symposium on Earth Tides (ETS2000). Before the opening session of the ETS2000, the President consulted opinion of the National Representatives of the Commission on proposal to ask Jacques Hinderer and Olivier Francis to continue their office until the next IUGG/IAG General Assembly to be held in Sapporo, Japan, in July 2003, and obtained their approval. At the opening session of ETS2000, the Commission elected J. Hinderer as Vice-President and Francis as Secretary without a dissenting voice. Congratulation to Jacques Hinderer and Olivier Francis, and the best wishes for their future work.

3. National Representatives to the IAG Commission V: Earth Tides

The National Representatives to the IAG Commission V: Earth Tides were appointed from the National Delegates of IAG in Member Countries of the Union (IUGG). The updated list of the National Representatives is given below.

* Demitris Arabelos (Greece), ARAB@ENG.AUTH.GR
* Tevor Baker (UK), tfb@pol.ac.uk
* John Beavan (New Zealand), J.Beavan@gns.cri.nz
* Tadeusz Chojnicki (Poland), tch@cbk.waw.pl
* Ricardo Vieira Diaz (Spain), vieira@iagmat1.mat.ucm.es
* Bernard Ducarme (Belgium), Bernard.Ducarme@ksb-orb.oma.be
* D. El-Naggar (Egypt),
* Jean Flick (Luxembourg), nicolas.doreye@ecgs.lu
* Casula Giuseppe (Italy), casula@ibpgfs.df.unibo.it
* Jacques Hinderer (France), jhinderer@eost.u-strasbg.fr
* Jussi kaariainen (Finland), jussi.kaariainen@fgi.fi
* Emile Klingele (Switzland), klingele@geod.ethz.ch
* Jim Merriam (Canada), jim.merriam@usask.ca
* Sergey Molodensky (Russia), msm@uipe-ras.scgis.ru
* Jose Pereira Ossrio (Portugal), posorio@oa.fc.up.pt
* Hans-Peter Plag (Norway), hans.peter.plag@statkart.no
* Bernd Richter (Germany), richter@ifag.de
* Tadahiro Sato (Japan), tsato@miz.nao.ac.jp
* Zdenek Simon (Czech Republic), gope@asu.cas.cz
* Peter Varga (Hungary), varga@ggki.hu
* John Wahr (USA), wahr@lemond.colorado.edu
* R. T. Wonnacott (South Africa), rwonnacott@sli.wcape.gov.za
* Yaozhong Zhu (P.R.China), zyz@asch.whigg.ac.cn

4. ETC Homepage

The ETC Homepage can be seen through the following address,

http://www-geod.kugi.kyoto-u.ac.jp/iag-etc/

5. 2nd ETC Medal

The ETC steering committee (S. Takemoto, J. Hinderer, O. Francis, B. Richter, M.van Ruymbeke, H. Schuh and. G. Jentzsch) decided to award the 2nd ETC Medal (ETC Medal 2000) to the late Prof. Hans-Georg Wenzel for his outstanding contribution to international cooperation in earth tide research.

Hans-Georg Wenzel was born on February 3, 1945 at Hahnenklee, country of Goslar/Germany. After graduated the Technical University of Hannover in 1972, Hans-Georg Wenzel workd in Institut fur Erdmessung, University of Hannover as scientific assistent, chief engineer and senior scientist. He received the Doktor-Ingenieur degree with a thesis on the accuracy of gravimetric earth tides observations (1976), and his Dr.-Ing. habil. thesis dealt with high resolution spherical harmonic models for the gravitational potential of the earth (1985). In 1988, he became Professor at the Geodetic Institute, University of Karlsruhe, and Director of the Schiltach Geodynamical Observatory (Black Forest Observatory). In March 1999, he accepted a call from the University of Hannover to become Professor for physical geodesy at the Institut fur Erdmessung, and suddenly passed away on November 11, 1999 at Hannover without any recognizable warning. His contribution to gravity and Earth tides researches is so well known through the papers more than 150. He is famous by development of a new tidal potential catalogue, a worldwide synthetic gravity tides model, and the Earth tides data processing package so called ETERNA.

In the world wide geodetic community, he chaired the IAG special study group "Global Gravity Field Approximation" (1987 - 1991) and the International Gravity Commission working group "Computation of Mean Gravity Anomalies" (1989 - 1991). He served as Secretary (1987 - 1991) and President (1991 - 1995) of IAG Section 3 "Gravity Field Determination" and as President of the Earth Tides Commission (1995 - 1999). His management abilities were acknowledged in the Directing Board of the Bureau Gravimetrique International (1987 - 1995), and as Secretary of the Federation of the Astronomical and Geophysical Data and Analysis Services FAGS, since 1996.

With grateful appreciation for the numerous services rendered by Prof. Hans-Georg Wenzel during his lifetime, all participants of ETS2000 paid one-minute's tribute to him with deepest sympathy.

The Commission awarded the 2nd ETC Medal (ETC Medal2000) to Ms Marion Wenzel at the Opening Session of ETS2000 on August 28 2000 at Mizusawa, Japan.

6. ETC Working Groups

At the opening session of ETS2000, chairpersons of following Working Groups reported their activities,

Working Group 4 "Calibration of Gravimeters", (M.van Ruymbeke),
Working Group 5 "Global Gravity Monitoring", (B. Richter),
Working Group 6 "Earth Tides in Geodetic Space Techniques, (H. Schuh),
Working Group 7 "Analysis of Environmental data for the interpretation of gravity measurements", (G. Jentzsch).

The Commission thanks all members and chairpersons of WGs which have been active during the last period, for their fruitful work. ETC accepted the conclusions of the reports of the Working Groups and decided according to their wishes:
*To close Working Groups 4 and 5.
*To extend for another 4 year term the activities of the Working Group 6 (Earth Tides in Geodetic Space Techniques) under the new chairperson-ship.
*To extend for another 4 year term the activities of the Working Group 7 (Analysis of Environmental data for the interpretation of gravity measurements) under the new chairperson-ship.

*To create Working Group 8 on "Gravitational Physics" under the chairperson-ship of Prof. Lalu Manshinha to tackle among others the following scientific problems:

The Problem of Aberration:

Modern tidal position catalogs assume that the true position of the tide causing body is responsible for the tidal forces, rather than the apparent position, as in optical astronomy. The problem may have consequences, as it may imply relative velocities between the gravity and optical signals. This is a case for experts in Celestial Mechanics and in Earth Tides.

The Gravitational Shielding:

There is currently no accepted theory of gravity that incorporates or predicts gravitational shielding. The problem is possibly different from the absorption of gravitational radiation by matter. The Earth Tide community should think about, and search for, the consequences of shielding.

7. Directing Board of the International Center for Earth Tides (ICET)

The ICET Directing Board (S.Takemoto (Chair), B.Ducarme, T.F.Baker, D.Crossley, H.T.Hsu and O. Francis (Non-voting member)) met together on August 29, 2000 at the Z-hall in Mizusawa. The main subject for discussion was "Future activity of ICET and re-organization of the IAG services". ICET-DB discussed on the GFFS (Gravity Field and Figure of the Earth Service) proposed by Prof. F. Sanso, which is a new Service including activities of BGI, IGeS and ICET. Because of a restriction of time, ICET-DB could not draw a conclusion at Mizusawa and decided to continue our discussion by E-mail. ICET-DB will draw a conclusion not later than the end of October 2000.

8. Resolution Committee

The Resolution Committee (J. Hinderer(Chair), O. Francis, B. Ducarme, B.Richter, M.van Ruymbeke, H. Schuh and. G. Jentzsch, H. Hsu, L. Manshinha, M.Ooe and S. Takemoto,) was held on August 31, 2000. The Earth Tide Commission has adopted the 11 resolutions at the closing session of the 14th International Symposium on Earth Tides, August 28 - September 1, 2000, Mizusawa, Japan.

9. IAG Travel Awards

The following 5 persons are winners of IAG Travel Award for the ETS2000.
Alexander Kopaev, (Moscow, Russia), Janusz Bogusz, (Warsaw, Poland), Carla Braitenberg, (Trieste, Italy), Sun He-Ping (Wuhan, P.R. China), Zhigen Yang (Shanghai, P.R. Chin)

10. Publication of the ETS2000

Proceedings of scientific papers will be published as a special issue of the Jour. Geod. Soc. Japan. Other Report on the ETS2000 including the list of participants will be appeared in the next issue of BIM (BULLETIN D'INFORMATIONS MAREES TERRESTRES).

11. Next Symposium

During the ETS2000, Canadian Colleagues (Profs. D. Smylie, L. Mansinha and S. Pagiatakis) kindly offered to have the next (15th) International Symposium on Earth Tides in Canada in 2004. The Earth Tide Commission acknowledges the receipt of this invitation.

ETC

International Association of Geodesy

Commission V : EARTH TIDE COMMISSION

The Earth Tide Commission of the International Association of Geodesy awards the

EARTH TIDES COMMISSION MEDAL

for the second time at the 14th International Symposium on Earth Tides, August 28 – September 1, 2000, Mizusawa to

Late Professor Hans-Georg Wenzel

for his outstanding contribution to international cooperation in earth tide researches.

Mizusawa, August 28, 2000

(Shuzo Takemoto)
President

(Jacques Hinderer)
Vice President

(Olivier Francis)
Secretary

Centre International des Marées Terrestres
International Centre for Earth Tides
(ICET)

Report to the
Earth Tides Commission
for the years 1997- 2000

B.Ducarme, ICET Director
ducarme@oma.be

The staff of ICET, which is completely supported by the Royal Observatory of Belgium, is composed as follows:
Prof. B.Ducarme, Director(part time)
Dr. O.Francis, Vice-Director(part time, until November 1998)
Mrs. L.Vandercoilden, technician(full time)
Mr. M.Hendrickx, technician(part time)

The Royal Observatory of Belgium is hosting ICET since its creation and continues to provides numerous administrative and scientific facilities especially for the publication of the " Bulletin d'Information des Marées Terrestres" , for the tidal data processing and more recently for the maintenance of the ICET/GGP data bank.

Introduction

This XIVth International Symposium on Earth Tides is a good opportunity to recall the challenges ICET has been facing since its creation more than 40 years ago and the new perspectives for the XXI century.
Earth Tide is affecting gravity and positions at the surface of the Earth at the 10^{-7}-10^{-8} level and requires a multidisciplinary approach including Astronomy, Geodesy, physics of the Earth interior, physical Oceanography, atmospheric sciences…
The tidal observations are providing information for the study of the Earth nutations as well as of the anelasticity in the mantle. Tidal prediction is required to correct gravity observations as well as precise positioning.
The beginning of concerted observations goes back to the International Geophysical Year. At that time one thought that it would be possible to determine the Love numbers from ground observations. It was indeed too optimistic due to the well known perturbing effects such as :
- the indirect effect of the oceanic tides that can reach 10% of the observed tidal phenomena;
- a coloured aperiodic geophysical noise mainly from atmospheric origin (more than 5%);
- the limited accuracy of the calibration of the instruments (typically 1%);
- site effects such as strain-tilt coupling.

It was thus necessary to work on all these problems in a concerted way and it was the task of ICET through:
- the dissemination of information by means of the "Bulletin d'Information des Marées Terrestres" (BIM);

- the constitution of data banks;
- a technical support to users including data reduction, analysis and interpretation, improvement of observation techniques (VM pendulum, calibration) and tidal prediction;
- its participation to coordinated observation campaigns such as Astro-Geo Project Spitsbergen (1969-70), Trans European tidal gravity Profiles(1971-1973) and finally Trans World tidal gravity Profiles(1973-1993).

The main goal of these observation campaigns was to check the validity of the oceanic tidal loading corrections (Schwiderski, 1979) and of the models for the Earth response to the tidal forces (Molodenskii, 1965; Wahr, 1981).

Since 1990 there is a renewed interest from seismologist and volcanologist for continuous gravity, tilt and strain recording as part of a multiparameter approach. Monitoring of the tidal signal is requested to see if the transfer function is modified on one hand or to eliminate properly the tides in order to obtain clean records in search for aperiodic signals. For ICET it means a renewed pedagogic effort involving technical help for the calibration of instruments and the elimination of perturbing effects from the records as well as the organisation of training sessions for data preprocessing, analysis and interpretation.

The Brussels symposium in 1997 coincides with the opening of new perspectives in tidal research:

- The different models describing the Earth response to the tidal forces achieve an agreement at the level of a few parts in 10^{-3}.
- Thanks to satellite altimetry, several new and more precise oceanic tides models are now available.
- Improved methods have been developed to correct the atmospheric attraction and loading effects.
- Efficient software for tidal data preprocessing are now available such as PRETERNA or T-soft and it becomes thus easy to work directly on minute sampled data.

Moreover the Global Geodynamics Project (GGP consortium) was launched in July 1997 for a 6 years time span. More than 15 superconducting gravimeters located all around the world (figure 1) are recording tidal gravity changes following standard procedures. Much attention is paid to the calibration as well in amplitude as in phase. The world-wide coverage will help to discriminate the global phenomena.

For ICET It was an unique opportunity to handle high quality tidal data that will help for example to

- improve the determination of the core resonance and compare the results with the models;
- recover global phenomena of very tiny amplitude (10^{-11}g);
- evaluate the quality of the new cotidal maps for tidal loading correction;
- determine the so called "pole tide" due to the polar motion.

ICET proposed thus to keep the GGP data bank and assist GGP as computing centre for data preprocessing and routine data analysis in order to check the quality of the stations (integrity monitoring). The main advantage is that a standard procedure is applied to the data. Moreover each year ICET is preparing a CD-ROM with the raw and preprocessed data.

Diffusion of Information

From 1997 to 2000 eight issues of the "Bulletin d'Information des Marées Terrestres" (BIM) have been published, numbers 126 to 133. We wish to thank here Dr. Olivier Francis who acted as editor up to number 130. The ICET director resumed this task.

The ICET WEB site is continuously improved. It contains now:

- 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 published BIM and starting from BIM 133 an electronic version of the papers;
- tidal analysis and preprocessing softwares available from different WEB sites or on request from ICET.

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 softwares. 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 have been requested from ICET since May 2000. Other softwares such as Tsoft for tidal data processing and VEN98 for tidal data analysis are currently available from the WEB.

Data processing

ICET is still receiving regularly earth tides data. *All data received are checked and recompiled.* Some Institutes are still sending clinometric and extensometric records but most of the activity is now devoted to gravity tides. Among the recently participating countries we should mention, besides GGP member countries : Belgium, China, Czech Republic, France, Germany, Hungary, Indonesia, Italy, Grand Duchy of Luxembourg, Poland, Russia and Spain.

Most of our computing activities are now connected to the GGP project. ICET is responsible of the "Global Geodynamics Project-Information System and Data Centre" (GGP-ISDC). The GGP original minute sampled data are carefully preprocessed at ICET using T-soft. The data are corrected for tares and spikes. The data are then decimated to one hour and analysed. This is the main task of Mrs.L.Vandercoilden. 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 sets and insure their homogeneity.

The archiving of the data is rather complex as 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 software provided for the gestion of this data bank by the GeoForschungZentrum Potsdam is fully operational since April 1999. The implementation of this software required to purchase new informatic equipments. Although he resigned his position in ICET, Dr. O. Francis from the Royal Observatory of Belgium agreed to supervise the installation of the software. The routine work is assumed by Mr. M.Hendrickx.

The one minute sampled raw data of each gravimeter represents 1.6 Mbytes per month. For fifteen operational stations we have thus 24 Mbytes per month or 300 Mbytes per year. It represents only one CD-ROM. We do also archive the preprocessed minute data ready for tidal analysis.

According to the internal GGP rules we produced already 4 CD-ROMS containing the raw(#1 and #2) and processed(#1a and #2a) minute data of the two first years, 97/07 to 99/07, of the project.

New structures inside IAG

In the framework of the reorganisation of the IAG structures a proposal has been put forward by Prof. F.Sanso, director of the IGeS to create a confederation of the IAG Services dealing with the gravity vector i.e. the International Centre for Earth Tides(ICET), the International Gravimetric Bureau(IGB) and the International Geoid Service(IGeS). A first draft proposal was established during a meeting of the three directors in Milan on May 3. Other entities, such as new IAG Service dealing with Digital Terrain Modelling, could join this group. The official name of this new composite body will be International Gravity Field (IGFS).

As the statutes of the contributing entities are very different, some being FAGS member or WDC other not, each partner will keep his own governing bodies and structures. There will be an « Advisory board » organising the co-operation between Centres and their representation at IAG level. Individuals wishing to contribute actively to the IGFS may obtain the status of « Fellows » and will be represented inside the Advisory Board.

At the meeting of the Gravity and Geoid Commission in Banff(CDN) in August 2000 it was decided that IGB and IGeS will unite inside IGFS. At the meeting of ICET Directing Board during the 14[th] International Symposium on Earth Tides it was stressed that the advantages of IGFS for ICET are not evident, the most obvious one being a better representation at IAG level. The new structures seemed unduly complicated. Directing Board members insisted on the fact that in any case the publication of BIM should continue under its present form. Finally, after additional consultations, it was decided that the ICET director was allowed to appreciate by himself the opportunity of joining IGFS.

Visitors

Year 1997

We welcomed as trainees Dr. J.J.Alonso del Rosario(Cadiz, Spain), Dr. U.Riccardi(Napoli, Italy), Mrs. S.H.Schwab(Curitiba, Brasil), Dr. T.Van Dam(Boulder, USA). Each participant brought his own data to process using the new preprocessing software T-SOFT.

Dr. H.P.Sun(Wuhan, China) was staying three months to work on superconducting gravimeters data and atmospheric pressure effects.

Year 1998

Prof. A.P.Venedikov of the Geophysical Institute, Academy of Sciences of Bulgaria, stayed from February 9 to March 2. He developped a new version NSV98of his tidal analysis program. He also worked on the long series of data of the superconducting gravimeter of Brussels.

Dr.V.Timofeev, Geophysical Institute, UIGGM, RAS (Siberian branch) at Novosibirsk, stayed from November 15 to December 5. He reanalysed the clinometric and extensometric data registered since 15 years at the Talaya underground laboratory near Baikal lake. He also worked on the transformation by electromagnetic feedback of the russian made Gridniev horizontal pendulums.

Dr. Ph.Jousset, in postdoctoral stay in Japan, visited us on April 22-23 to prepare the publication in BIM of the gravimetric tidal records made on Mount Merapi in Indonesia.

Geophysicist Maria M.Caamaño, Observatorio Astronomico de la Plata, Argentina, came for training from April 27 to June 19. She worked on the tidal gravimetric data of Buenos Ayres in connexion with the swells in the Rio de la Plata estuary. She was trained in the use of the Tsoft for data processing and got informations concerning the oceanic tides along the coasts of Argentina.

Year 1999

Dr. Mark Davis from the Open University, Great Britain came from May 17 to 20 to get training on tidal data preprocessing and analysis. He brought with him the tidal gravity observations registered on Mount Etna. His main goal is to get rid from tidal, pressure and other environmental effects in order to try to identify the effects of volcanic activity on the gravity residuals.

Dr. G. Casula was staying from May 27 to July 10. He brought his data of the Brasimone cryogenic gravimeter in order to practice with TSOFT and the new softwares of Prof. A.P. Venedikov.

Dr. H.P.Sun stayed at ROB from beginning of September to end of November. He treated the observations obtained at the GGP station Wuhan using the softwares developped at ROB(T-soft). He also prepared communications presented at ETS2000.

Dr. V.Timofeev stayed at ROB from October 20 to December 23, 1999.
During these two months at ROB we finished the analysis of the tidal data recorded at Talaya, (Baikal, Siberia) and at Ala-Archa/Bishkek (Kirghizstan). At Talaya we have now analysed ten years(1988-1998) of clinometric records in NS and EW direction as well as five extensometers.

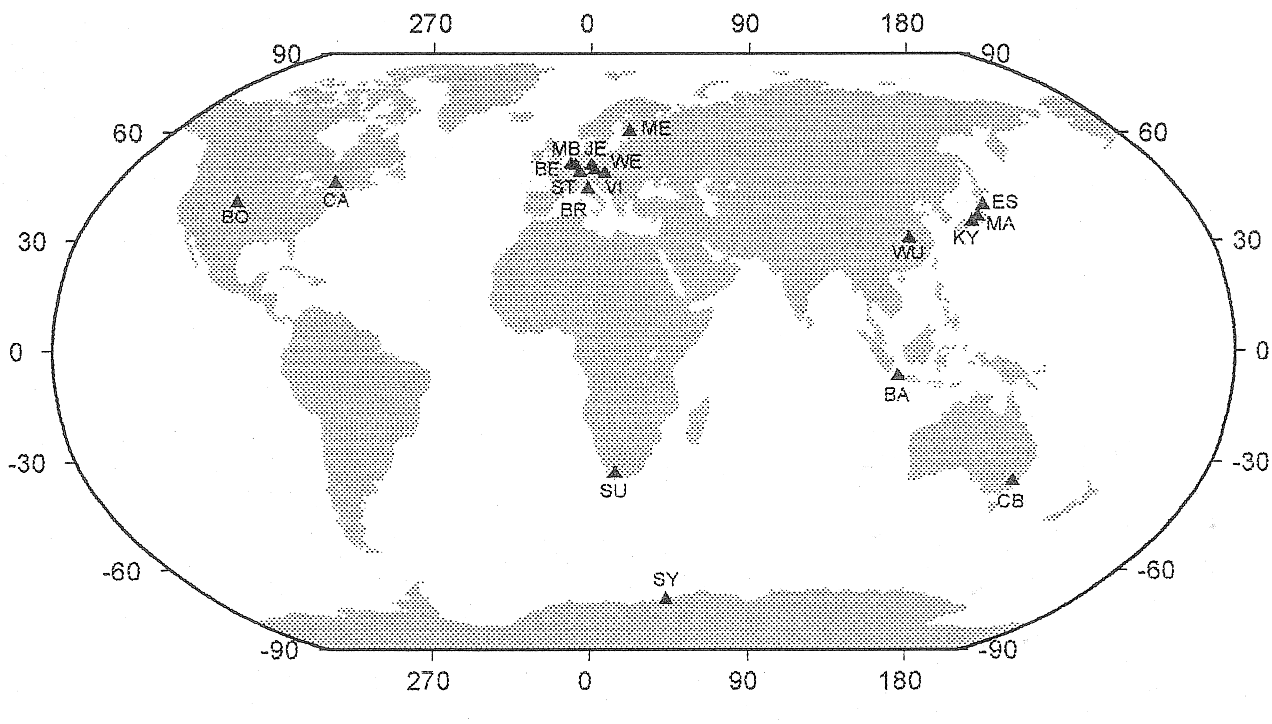
Year 2000

Dr. Alexander Kopaev from Sternberg Astronomical Observatory, Moscow University, stayed one month to work on the ICET data bank and prepare papers presented at the ETS2000.

Prof. David Crossley and Jacques Hinderer, respectively President and Secretary of the GGP consortium, visited ICET to discuss of the current status of the GGP data bank at ICET. They met Dr. Bernd Ritschel who is developing the GGP data base software.

Dr. Ernst Boyarski and Ludmila Latinina, from Institute of Physics of the Earth of Moscow will stay from September 22 to 29. They bring clinometric and extensometric data from stations Medevo/Almaty(Kazakstan) Protvino/Serpoukov(Russia).

Figure 1. GGP Network of Superconducting Gravimeters



Report of Activities of the IAG/ETC Working Group 4 « Calibration of the Gravimeters »

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Introduction:
During the meeting organized in Jena for the Working Group 7 [this issue of the BIM], G. Jentzsch has accepted to welcome our proposition to discuss about the problems concerning the calibration of gravimeters. It was an opportunity to analyse the present situation and we can formulate some general remarks. We are looking for methods which could achieve an accuracy better than 0.1% [Baker T.,1998].

Description of the problem:
We are concerned by the scale factor of gravimeters recording gravity variations, mainly tidal ones.

For the metrologist, any measurement aims to obtain the ratio between a quantity to scale and an another one selected like «standardized unit ».

For the tidal gravimeters, the situation is the same. A well known variation of gravity is induced and recorded by the instrument. The admittance between the signal and the modulation of gravity gives the scale factor as well as the phase characteristics of the instrument. It is sometimes interesting to determine the transfer function independently of the scale factor. When it is possible to modulate externally the restoring force of a gravimeter one can determine directly its transfer function by injecting a step function or sinusoidal signals[Richter & Wenzel, 1991; Wenzel H.-G., 1994; Van Camp & al., 1999].

What kind of processes could modify the acceleration felt by the gravimeter mass?
<1> The attraction of a moving mass is an obvious way to modify the gravitational field of the Earth and calibrate gravimeters. However it is a very weak action and a sufficient signal to noise ratio exists only for superconducting gravimeters.
<2> A second method consists to move the gravimeter in selected locations with different gravity values. This is the principle of the «Calibration lines ». Modulations of the gravity values can be very large and the signal to noise ratio does not limit of the accuracy.
<3> A third method consists to tilt the gravimeters to change the moment of force applied to the instrument. Systematic errors occur due to the changes of the gravimeter mechanical equilibrium and the 0.1% accuracy does not seem to be accessible through this technique[Kopaev A.,1998].
<4> A fourth method is based on the physical equivalence between the gravitational mass and the inertial mass. It is thus possible to calibrate a gravimeter by inertial forces e.g. those induced by sinusoidal motions.

The calibration processes <2>,<3> and <4> require to move the gravimeters. Additional mechanical systems are required for processes <1> and <4>.

The calibration process <2> is generally used to calibrate an intermediate standard of the field gravimeters the so called « micrometric screw ». The instruments using a feedback system can use calibration lines to calibrate directly the feedback force if the range of the first ones does not exceed the range of the second one.

It should be pointed out that the intercomparisons in one station of several gravimeters is not a « calibration » "senso strictu".

The tidal gravimeters:
Nowadays the principal types of instruments able to record tidal gravity signals are :

-the superconducting gravimeters (SCG)
-the LaCoste-Romberg spring gravimeters (LCR)
-the Scintrex gravimeters (SCI)
-the Askania gravimeters (ASK)

Recently some authors used also

-the absolute gravimeters (ABS)

No calibration is required for absolute instruments(ABS) which are directly referenced to the wavelength of a laser beam and the time scale of an atomic clock. This type of gravimeter is the best one to measure the gravity values along a calibration line. Its use to record tides during a long time [Francis O., 1997] will remain marginal. It is generally used for intercomparisons with tidal instruments during a few days to calibrate them.

For spring gravimeters (LCR) & (ASK), a mechanical system modulates the elastic restoring force proportionnally to the rotation of a micrometer. After determination of its scale factor by intercomparisons on « calibration lines », the micrometer is used to determine the sensitivity of the gravimeters during tidal registration.

To record tides with (LCR) or other astaticized gravimeters it is necessary to use a restoring force working in the feedback mode in order to minimize the elastic after-effects inherent to the astatisation.

Some (ASK) are also equipped with a system allowing to put additional masses (balls) on the beam. The equivalent force was scaled against gravity by the maker. The precision of the method is poor as it is necessary to tilt the instrument in order to put and remove the ball.

For the (SCI), it is not possible to modulate the feedback force directly. However the scale factor seems to be very stable[Ducarme & al., 1997]. So the « maker calibration » checked on « calibration lines » can be used for tidal records.

For (SCG), it is not possible to move the instruments on « calibration lines » and no internal modulation of the restoring force is possible with the required accuracy. The so-called « electrostatic calibration » gives only apparent changes of sensitivity. Direct calibration is possible only through methods <1> and <2>.

Sources of errors:
The scale factor of an instrument has to be related to absolute units.

During the transfer process, two kinds of errors could exist which are systematic or random.

The first kind defined as systematic, is directly affecting the scale factor. This error is constant independantly of the number of calibrations.

The second kind which is defined like a random noise, is limiting the precision of the calibration. This kind of error decreases with the increase of the number of determinations.

We can have a very high repeatability of the results of calibration, meaning a low level of random noise, associated with very large systematic errors.

This risk is especially important for frequency dependent processes when the excitation periods are short like in process <4>. The slope of adjustment could be modified by an attenuation of amplitude due to low pass filtering of the mechanical or the parts of the system. As this effect is frequency dependent like the acceleration itself, the systematic errors have to be corrected by determinining the transfer function of the filters. It becomes thus possible to compensate the damping of the filters at different frequencies.

Systematic errors could exist in the process of transfer from the micrometer to the gravimeter itself of the scale factor (dead zone in the mechanichal transmission, long term drift, ...).
For process <1>, the gravimeters need sufficiently heavy mass to obtain significant signals. The risk exist of systematic errors induced by the mechanical effects due to the displacement of large masses.

Finally it is very important to know how the calibration process itself can modify the gravimeter records, altering its sensitivity and/or drift.

Selection of the methods:
It is clear that some methods are obsolete or will never reach the required accuracy. We shall try to summarize here some of the most promizing approaches.

<u>Cryogenics instruments(SCG)</u>
-Interesting results have been already obtained with mass calibration <1>,[Achilli & al., 1995; Casula & al.,1998]. However this experiment requires a special geometry for the instrument and is thus not applicable everywhere. It does not provide the transfer function as it is working at zero frequency.

-The most popular method has been so far the intercomparison with another relative instrument during a few months [Francis & al.,1997], or with an absolute gravimeter during a few days [Hinderer & al.,1998]. The precision is close to the required 0.1% one. The accuracy is equivalent to the precision when the primary standard is an absolute gravimeter. When using a relative instrument you should take into account the additional uncertainty on its calibration. Attention should be paid to the difference between the transfer functions of the instruments involved in the intercomparison.

-A special inertial device has been realised and tested [Richter B., 1991; Richter & al.,1995].Very high accuracy is claimed but no convincing results have been published so far.

Spring gravimeters

Much more calibration effort has been devoted recently to (LCR) than to (ASK) or (SCIN). We shall thus focus our attention on the first type of instrument.

-The signal to noise ratio is generally not sufficient to apply the mass calibration method <1> at the 0.1% accuracy level [Czapo, Szatmari,1995].

-The most popular method for (LCR) is the use of the micrometric screw which in turn has been calibrated using calibration lines. The calibration of the micrometer is better than 0.01%. The problem is to extrapolate results obtained in the several hundred milligal range to the tidal range. It is why special base lines of a few milligal range have been established in Germany and China[Wenzel H.G.,1995]. The second problem is to calibrate accurately the tidal records using the micrometric screw. Recent tests show that the apparent changes of sensitivity are accurately followed by the calibrations[van Ruymbeke M.,1998].

-Inertial platforms have been successfully tested[van Ruymbeke M.,1989], but much effort has still to be devoted to reach the required accuracy.

Conclusions:

The 0.1% of accuracy on a phenomenon which has a so small amplitude as the tides is at the limit of instrumentation and any method to improve calibration is useful to improve the gravimeters themselves.

We suggest to organize a meeting of people concerned by the determination of the scale factor of the gravimeters to overview the different approaches, including realistic evaluation of the accuracies. An intercomparison of results obtained by various ways is essential to eliminate the risk of systematic errors which are different in the various methods.

Bibliography:

Achilli V., Baldi P., Casula G., Errani M., Focardi S., Guerzoni M., Palmonari F., Raguni G., *A calibration system for superconducting gravimeters*. Bulletin Geodesique, **69**, 73-80.

Baker T.,*Tidal gravity observations and Earth tide model.* Proc.13th Int. Symp.on Earth Tides, Brussels july 22-25,1997, Observatoire Royal de Belgique, Serie Geophysique, 287-294, 1998

Casula G., Baldi P., Salemi G., *Tidal Analysis of daea recorded by a superconducting gravimeter in Italy*. Proc.13th Int. Symp.on Earth Tides, Brussels July 22-25,1997, Observatoire Royal de Belgique, Serie Geophysique, 611-616, 1998

Csapo G., Szatmari K.G., *Apparatus for moving mass calibration of LaCoste-Romberg feedback gravimeters.* Metrologia, **32**, 225-230.

Ducarme B., Somerhausen A., *Tidal gravity recording at Brussels with a SCINTREX CG3-M gravity meter*. Bull. Inf. Marees terrestres, **126**, 9611- 9634, 1997.

Francis O., *Calibration of the C021 superconducting gravimeter in Membach (Belgium) using 47 days of absolute gravity measurements*. IAG Symposia: Gravity, Geo · and Marine Geodesy, Springer Verlag, **117**, 212-219, 1997

Francis O., Ducarme B., van Ruymbeke M., *One year of registration with the C021 cryogenic gravimeter at station Membach*. IAG Symposia: Gravity, Geo · and Marine Geodesy, Springer Verlag, **117**, 336-342,1997

Hinderer J., Amalvict M., Florsch N., Francis O., Makinen J., *On the calibration of superconducting gravimeters with the help of absolute gravity measurements*. Proc.13th Int. Symp.on Earth Tides, Brussels july 22-25,1997, Observatoire Royal de Belgique, Serie Geophysique, 557-564, 1998

Kopaev A., Yushkin V., Ducarme B., *Tide gravity recording with a quartz gravimeter Sodin-209 at ORB, Brussels*. Proc.13th Int. Symp.on Earth Tides, Brussels july 22-25,1997, Observatoire Royal de Belgique, Serie Geophysique, 51-57, 1998

Richter B., *Calibration of superconducting gravimeters*. Cahiers Centre Europ. Geodyn. et Seismologie, **3**, 99-107

Richter B., Wenzel H.-G., *Precise instrumental phase lag determination by the step response method*. Bull. Inf. Marees Terrestres, **111**, 8032-8052.

Richter B., Wilmes H., Nowak I., *The Frankfurt calibration system for relative gravimeters*. Metrologia, **32**, 217-223, 1995

Van Camp M., Wenzel H.-G., Schott P., Vauterin P., Francis O., *Accurate transfer function determination for superconducting gravimeter*. Submitted to Geoph. Research Letters, 1999

van Ruymbeke M., *A Calibration system for gravimeters using a sinusoidal acceleration resulting from a vertical periodic movement*. Bull. Geod., **63**, 223-235, 1989

van Ruymbeke M., *Internal precision of calibration for la Coste&Romberg gravimeters equipped with a feedback system*. Proc.13th Int. Symp.on Earth Tides, Brussels july 22-25,1997, Observatoire Royal de Belgique, Serie Geophysique, 59-68, 1998

Wenzel H.-G., *Accurate instrumental phase lag determination for feedback gravimeters*. Bull. Inf. Marees Terrestres, **118**, 8722-8734, 1994

Wenzel H.-G., *Die Vertikale Gravimetereichlinie Karlsruhe*. H.Draheim 80Geburstag, E.Kuntz 70Geburstag und H.Malzer 70Geburstag; Geod. Inst. Univ. Karlsruhe, 273-282, 1995.

Report of Activities of the IAG/ETC Working Group 5 «Global Gravity Monitoring Network (g-gramophone)»

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Objectives:

This working group has been a forum to tighten existing global gravity networks e.g. Network of Superconducting Gravimeters (GGP), the International Absolute Gravity Base station Network (IAGBN), which are observed with instruments at the highest technical level. Methods shall be discussed to complement the techniques mainly used for the observations. The idea shall be supported to intensify the combined observations of superconducting gravimeters with repeated absolute gravity measurements at stations which are suitable for such comparisons.

The combined data sets should be the base for studies of the performance of the instruments, the influence of environmental parameters on gravity from local up to global effects, the history respectively the long term stability of fundamental gravity base stations.

The results of these studies will support the knowledge of the variability of gravity stations in order to improve the overall error budget of gravity measurements and to increase the possibility to complement measurements performed with other techniques like space geodetic techniques to study local, regional and global height variations or mass redistributions.

Within the group, the information shall be exchanged by circular e-mails and faxes. Business meetings at major gravity conferences shall be used for direct communications and discussions. Besides the discussion of internal matters, results and ideas, interesting papers and articles touching the basic ideas of the working group shall be distributed. All information will be stored in an information board which can be the base of a comprehensive archive for precise gravity networks as well as a documentation of the state of the art for the used gravity techniques and models.

Members:

T. Baker, G. Casula, O. Francis, J. Hinderer, H. Hsu, J. Maekinen, I. Marson (president Gravity Commission), B. Meurers, T. Sato, T. van Dam, B. Richter (chair),

Guests:

D. Crossley (chairperson of GGP),
H.-G. Wenzel (president Earth Tide Commission),
I.Marson (president Gravity Commission)

Meetings:

1. Tokyo, Japan GraGeoMar 96 Symposium October 3, 96
2. Brussels, Belgium 13th International Symposium on Earth Tides, July 23, 1997
3. Munsbach, Luxemburg 2nd GGP workshop, March 25, 1999

Statements worked out within the working group:
To improve the high precision gravity observations with absolute and Superconducting gravimeters the responsible working groups in Austria, Belgium, Canada, China, Finland, France, Germany, Italy, Japan, USA are stimulated to use the two techniques as complementary tools.

The intensive inter-comparisons of absolute and Superconducting gravimeters as well as repeated observations at dedicated stations as Membach (Belgium), Strasbourg (France), Wettzell & Bad Homburg (Germany), Medicina (Italy), Boulder (USA), demonstrate the high level of the gravity recordings. The present day gravity instrumentation is capable to pick up long-term variations in the gravity signal at the 10 nms-2 level.

The combined analysis enables an operational control for both gravimeter types, the detection of instrumental drifts and offsets and the determination of calibration factors for the Superconducting gravimeter. But not all groups who are potentially capable make use of the great benefits of intensive inter-comparisons.

Results
From this working group there is no intention to set up in addition to existing monitoring global networks a new one. But the findings within this working group have already influenced the work of other groups like GGP where the combination of absolute and relative gravity data extended the spectrum for scientific investigations to the long term gravity variations.

Future needs
Local gravity time series are collected and handed by various groups e.g. GGP. Absolute gravity measurements are mainly used to determine the static gravity field e. g. set up gravity networks. The upcoming space gravity missions will improve the knowledge of the global gravity field, the static and the time varying part.

The space borne gravity information should be combined with the earth borne ones. The static gravity measurements on Earth are strongly locally biased e.g. by the topography respectively the density distribution. The long term time variations in the gravity field caused e.g. by annual signals are more regular and regional persistent. So those are more likely candidates for the combination or validation of the two types of gravity information.

The stations in the GGP network are not well distributed globally, there are clusters in Japan and Europe. The large gaps in the network will restrict global information. In Europe 8 stations equipped with Superconducting Gravimeters form a basis network. For long term gravity variations frequently repeated absolute gravimeter measurements at selected stations will give additional information. With the absolute gravimeter available in the region it should be possible to improve the European network so that 15 to 20 stations ("data point") well distributed in a radius of 1000 km will supply information. These stationary information on the local variations in the gravity field have to be combined to an areal function e.g. expression in spherical functions which can be compared with the signals seen by the satellite for that region.

Proposal

To set up within section III or the gravity commission a SSG to deal with the combination of terrestrial data with the high quality time varying gravity data derived from the planned space missions. The terrestrial data have to be prepared in a manner that they are comparable with the space borne gravity data. It has to be investigated what regional gravity signals (sources, frequencies, quantities) are seen from the ground in contrast to those seen from the space. As a test area the "relatively" dense European Network should be chosen. As a final goal a kind of service should be established which provide the ground information on a regularly schedule.

Report of Activities of the IAG/ETC Working Group 6 «Solid Earth Tides in Space Geodetic Techniques»

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1. Introduction

The IAG/ETC Working Group 6 'Solid Earth tides in space geodetic techniques' was established at the XIIIth International Symposium on Earth Tides, Brussels, July 1997. The general goal of the WG is to strengthen the links between researchers of the tidal community and those who work in space geodetic techniques. The cooperation shall take place in both directions:

- The tidal experts provide precise models for the displacements of observation sites on the Earth's crust due to the tides and for the tidal variations to the gravitational field of the Earth.
- The space geodetic techniques are used to validate and possibly to improve the tidal models, e.g. the tidal parameters.

For the investigation of the solid Earth tides it is necessary to take also into account other geophysical influences, e.g. those of the oceans, of the atmosphere and of the pole-tide. Thus, oceanic and atmospheric loading, oceanic and atmospheric effects on the geopotential and the pole-tide are regarded by the WG, too.

Chairman, members and correspondents of WG 6 (status August 2000) are:

Chairman: Harald Schuh (DGFI, München, since April 2000 TUW, Wien)
Members: Per-Helge Andersen (NDRE, Kjeller)
Trevor Baker (POL, Bidston)
Veronique Dehant (ROB, Brussels)
Richard Eanes (UTEX, Austin)
John Gipson (GSFC, Greenbelt) (till 1999)
Ruediger Haas (OSO, Onsala)
P.M. Mathews (Univ. Madras, Chennai)
Jürgen Mueller (TUM, München)
Richard Ray (GSFC, Greenbelt)
Hans-Georg Scherneck (Chalmers Univ. of Techn., Göteborg)
Oleg Titov (Univ., Sanct-Petersburg)
Correspondents: Duncan C. Agnew (Scripps Inst. of Oceanography, La Jolla)
Richard Biancale (CNES, Toulouse)
Karen Bruyninx (ROB, Brusells)
Robert C. Bostrom (Univ. of Washington, Seattle)
Jean Chapront (PO, Paris)
Shailen Desai (JPL, Pasadena)

Robert Dill (DGFI, München)
Olivier Francis (ROB, Brusells)
Pascale Gegout (IPG, Strasbourg)
Michael Gerstl (DGFI, München)
Michael B. Heflin (JPL, Pasadena)
Maria Mareyen (BKG, Potsdam)
Jürgen Neumeyer (GFZ, Potsdam)
Ron Noomen (TU, Delft)
Markuu Poutanen (FGI, Masala)
Burghard Richter (DGFI, München)
Judit G. Ries (UTEX, Austin)
Ernst Schrama (TH Delft)
Tonie M. VanDam (NOAA, Boulder)
Peter Varga (GGRI, Sopron)
John Wahr (Univ. Colorado, Boulder)
Robert Weber (TUW, Wien)
Pascal Willis (IGN, Paris)
Wu Bin (IGG, Wuhan)
Xi Qinwen (State Seism. Bur., Beijing)
Kahled Zahran (Univ., Karlsruhe)

2. Terms of Reference (ToR)

The following Terms of Reference (ToR) were agreed upon by the members of WG 6 on Oct., 24th, 1997:

1. Extension of the recommendations concerning the tidal influences given in the IERS Conventions (1996) to facilitate their practical use for space geodetic techniques.
2. Evaluation and comparison of the potential of different space geodetic techniques to monitor tidal effects and to determine tidal parameters. Techniques such as VLBI, SLR, LLR, GPS and GLONASS, DORIS and PRARE, satellite altimetry will be covered.
3. Determination of parameters of the tidal models by space geodetic techniques. This requires a priori corrections due to atmospheric and oceanic influences on the Earth‘s surface and on the geopotential and precise models for tidal influences on the Earth orientation parameters. The effect of pole-tide has also to be considered. The results will have to be compared and interpreted.

3. Activities of Working Group 6 from 1997 till 2000

Activities for the 1. **Term of Reference** started in February 1998 by establishing sub-groups which worked on ‘supplements‘ to the IERS Conventions (1996). The goal was to work on an extension of the recommendations concerning the tidal influences given in the IERS Conventions (1996) to facilitate their practical use for space geodetic techniques. Dennis D. McCarthy, editor of the IERS Conventions (1996), was informed.

These are the subgroups with the chairpersons given in bold:

Chapter 6 of the IERS Conventions (1996) 'Geopotential'

- Effect of Solid Earth Tides (**Eanes**, Dehant, Mathews, Ray,...)
- Solid Earth Pole Tide (**Andersen**, Müller, Schuh, ...)
- Treatment of the Permanent Tide (**Mathews**, Dehant, Eanes, ...)
- Effect of the Ocean Tide (**Ray**, Eanes, Baker, Müller, Scherneck, ...)
- Conversion of tidal amplitudes defined according to different conventions (**Dehant**, Gipson,...)

Chapter 7 of the IERS Conventions (1996) 'Site Displacement'

- Local Site Displacement due to Ocean Loading (**Scherneck**, Baker, Haas, Müller, ...)
- Effects of the Solid Earth Tides (**Dehant**, Gipson, Haas, Mathews, Schuh, Titov, ...)
- Rotational Deformation Due to Polar Motion (**Andersen**, Müller, Schuh)
- Antenna Deformation (**Haas**, Schuh, Titov, ...)
- Atmospheric Loading (**Gipson**, Baker, Haas, MacMillan, Scherneck, Schuh, Titov, Vauterin)
- Postglacial Rebound (**Ray**, Scherneck, ...)

An Explanatory Supplement to the IERS Conventions (1996) Chapters 6 and 7 was elaborated which was published as *DGFI Report 71*:

http://www.dgfi.badw.de/dgfi/DOC/report71.pdf (1999).

The activities for the **2. and 3. Term of Reference** started in summer 1999. New subgroups were established in September 1999, now to evaluate the different space geodetic techniques with respect to their potential to monitor tidal effects and to determine tidal parameters. The subgroups were also open for non-members of the WG. The following questions were addressed by the subgroups:

1. Which tidal effects have to be considered in the particular space technique?
2. How is the 'permanent tide problem' handled?
3. What is the capability of the particular space technique to investigate tidal effects (including oceanic and atmospheric tides) and to determine tidal parameters, e.g. the Love numbers?
4. What are the newest results?
5. What are the limitations?
6. What are the future perspectives?

Each subgroup presented its results in a draft report between 1 and 15 pages before the ETS2000 in Mizusawa and it was agreed that the final report should be finished till end of 2000. Subgroups for ToR 2 and 3 are:

WG 6/1 (VLBI): R. Haas, P.-H. Andersen, O. Titov, H. Schuh, P.M. Mathews, V. Dehant
WG 6/2 (SLR: Wu Bin, R. Eanes, J. Müller, P.-H. Andersen
WG 6/3 (LLR): J. Müller, J. Chapront, J.G. Ries, J. Williams
WG 6/4 (GPS/GLONASS): R. Weber, T. van Dam, K. Bruyninx, P.-H. Andersen, T. Baker, M. Rothacher, H.-G. Scherneck
WG 6/5 (DORIS): R. Biancale, J.G. Ries, P. Willis
WG 6/6 (Satellite Altimetry): S. D. Desai, R.D. Ray, E.J.O. Schrama

Results of the work of the subgroups on different space geodetic techniques

- all space geodetic techniques provide interesting information about tidal effects;
- comparison of the treatment of tidal effects in different software packages revealed considerable discrepancies (e.g. between GPS software packages, between VLBI software packages, between LLR software packages, ...);
- new results for the tidal parameters were obtained for:

  VLBI: h, l (for individual tides and also for tidal bands: semi-diurnal, diurnal, long-period, second degree and third degree, including phase lags, *Haas and Schuh, 1996; Schuh and Haas, 1998*)

  DORIS: h_2, k_2 (*R. Biancale, 2001*)

  LLR: secular tidal acceleration, lunar tidal parameters, h_2, l_2 (*Müller and Tesmer, 2000*)

  SLR: k_2, h_2 incl. phase lags (for M_2, S_2, K_1, O_1) (*Wu Bin et al., 2001*)

  GPS: planned

  Sat. Altimetry: h_2 for four tides (*Ray et al., 1995*), ocean tidal models

For the work on the Terms of Reference and to achieve the results briefly summarized above three meetings of WG6 took place from 1997 till 2000, additionally to several thousands of email communications. Each of the meetings was attendend by about 20 participants.

1st Meeting, during EGS, Nice, April 23rd, 1998
2nd Meeting, during IUGG, Birmingham, July 22nd, 1999
3rd Meeting, during EGS, Nice, April 26th, 2000

4. Outlook

The following questions for the future of Working Group 6 were risen:

- What else should the WG 6 deliver? (bibliography related to tidal effects and space geodetic techniques?)
- What could be future activities after ETS2000?

- Should WG 6 finish its activities, continue in the present form, continue with different or
- additional goals?

The following proposals for future tasks of WG 6 were made:

- Cooperation with the analysis coordinators of the new IAG international services, e.g. IGS, IVS, ILRS, IDS, ... and the Working Groups which exist within these services,
- Comparison of tidal parameters obtained from the different techniques,
- Comparison of results obtained by space geodetic techniques and ground-based tidal measurements.

5. References

Explanatory Supplement to the IERS Conventions (1996) Chapters 6 and 7, ed. by H. Schuh, *DGFI Report 71*: http://www.dgfi.badw.de/dgfi/DOC/report71.pdf, 1999.

Final Report of the IAG/ETC Working Group 6 for the years 1997-2000, ed. by H. Schuh, with contributions by Biancale, Desai et al., Haas et al., Müller et al., Weber et al., Wu Bin et al., BIM, 2001.

Haas, R. and Schuh, H.: Determination of frequency dependent Love and Shida numbers from VLBI data. Geophys. Res. Lett., Vol. 23, No. 12, 1509-1512, 1996.

Müller, J. and Tesmer, V.: Investigation of Tidal Effects in LLR. subm. to Journal of Geophysical Research, 2000.

Ray, R.D. et al.: Geometrical Determination of the Love number h_2 at four tidal frequencies. Geophys. Res. Lett., Vol. 22, No. 16, 2175-2178, 1995.

Schuh, H. and Haas, R.: Earth Tides in VLBI Observations. Proc. of the 13th International Symp. on Earth Tides, Brussels, 1997, ed. by B. Ducarme and P. Paquet, Série Géophysique, Obs. Royal de Belgique, 101-110, 1998.

Report of Activities of the IAG/ETC Working Group 7 «Analysis of Environmental Data for the Interpretation of Gravity Measurements»

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This working group was established during the 13th Earth Tide Symposium in Brussels, 1997. Following the tradition of the former WG meetings at Bonn University ('Bonn – Meeting') we organised a workshop in Jena, September 1 – 4, 1998, at which Michel van Ruymbeke spent one afternoon for a meeting of his WG on CALIBRATION OF GRAVIMETERS. In all, 25 scientists from 9 countries participated.

The objectives of the WG are:
- Systematic investigation of effects of environmental parameters on the gravity vector, such as air pressure, air humidity, wind, seasonal effects of vegetation, ground water level variations, soil moisture;
- Understanding of the relation between the individual sources and their effects on the gravity vector, both in different periods, and different amplitudes:
- Development of models for the correction of environmental effects and recommendations for the recording of environmental parameters, and recommendations for the application of the corrections.

In a first step, the basic task at the workshop was to collect experiences gained by the different groups and to work out recommendations to be presentes at the 14th Earth Tide Symposium.

We refer to the papers presented by the participants at the working group meeting, printed by the International Center, Bulletin d'Information Mareés Terrestres, volume 131, May 1999.

The recommendations and proposals submitted to the 14th Earth Tide Symposium cover the topics discussed:

(1) Parameters to be recorded:

- Standard parameters to be monitored should be barometric pressure, temperature, precipitation, and ground water level. The sampling rate for the recording of environmental parameters should correspond to the sampling rate of the geodynamic data observed. A sufficient resolution and accuracy of the measurements of the environmental parameters should be granted.

- Although the difficulties of monitoring soil moisture are recognized, the working group recommends to undertake efforts to realize a continuous monitoring of this parameter.

- The monitoring of wind is also recommended because wind might produce short-period noise as well as long-period modulations.

(2) Area that enters into the correction:

- For studies of long-period effects it is recommended to correct gravity data for local (diameter: 100 km), regional (diameter 2000 km), and global pressure signals as all three produce significant effects in ths spectral range.
- All other environmental parameters should be monitored directly at the station.

(3) Models to be developed:

- Effects due to ground water table variations should be investigated more closely and models for the correction of gravity and tilt measurements should be developed.
- The influence of snow and rain on gravity should be studied.
- The application of precipitation functions and statistical models for correcting gravity, tilt, and strain should be tested.
- With respect to soil moisture a reliable method for a continuous monitoring needs to be found and models for correction should be developed.
- The effect of stress resulting from temperature variations on tilt and strain needs to be studied.
- The correlation between precipitation, barometric pressure, and ground water table should be investigated in order to develop transfer functions. For this special events should be studied, disturbing signals should be compared and correlated to different inputs. In addition, experiments should be done.

(4) Data handling / data bank:

- There should be free access to global meteorological barometric pressure charts for the 'earth tide' community.
- If the International Center (ICET) agrees, global barometric pressure data should be collected by the center.

September 1, 2000

ETS2000 RESOLUTIONS

1/ Recognising the importance of the observation of tidal effects and of the determination of tidal parameters by space geodetic techniques,
the ETC recommends
to continue this observational effort;
to compare the results obtained by different space geodetic techniques between each other and with the results of ground based tidal measurements.

2/ Recognising the importance of the new international services on space geodetic techniques,
the ETC recommends
that WG6 establishes or intensifies the cooperation with the analysis coordinators of these international services concerning the tidal modelling.

3/ Considering the new fields of tidal research in lunar and planetary geodesy,
the ETC recommends
that the tidal community should take an active part in space missions related to lunar and planetary geodesy ;
requests a proper archiving of the data and metadata acquired during those missions and normal access to the world-wide geodetic community.

4/ Considering the increasing interest of the tidal community to lunar and planetary researches,
the ETC recommends
that a session on tides on the planets should be included in the future earth tides symposia.

5/ Recognising the importance of a global Earth coverage with superconducting gravimeters
for the study of weak geophysical signals,
for the determination of the liquid core resonance parameters,
for the study of the polar motion effects on gravity,
for the intercomparison of the load vectors derived from recent ocean tides models,
for the study of global and regional gravity changes to validate the results of the dedicated satellite missions,
the ETC recommends
to extend the GGP observation period for an additional 6 year period starting July 2003,
to maintain the existing sites and to encourage the installation of new GGP stations especially in the Southern hemisphere and in polar regions.

6/ Recognising the fact that presently the calibration of the superconducting gravimeters participating to the world-wide GGP project is not homogeneous,
the ETC recommends
that systematic calibration campaigns with absolute gravimeters should be planned and realised before the end of the current GGP observation period,
through an international cooperative effort.

7/ Recognising the importance to keep in operation several calibration techniques for gravimeters to allow a mutual accuracy control,
the ETC recommends
that inertial calibration platforms and moving mass calibration devices should continue to be developed or maintained besides more usual calibration methods such as intercomparison with absolute or well-calibrated relative instruments.

8/ Recognising the importance of environmental data for the interpretation of tidal measurements,
the ETC recommends:

a/ to record the following parameters:
- The barometric pressure, temperature, precipitation, and ground water level. The sampling rate for the recording of environmental parameters should correspond to the sampling rate of the geodynamic data observed. A sufficient resolution and accuracy of the measurements of the environmental parameters should be granted.
- Although the difficulties of monitoring soil moisture are recognised, its is recommended to undertake efforts to realize a continuous monitoring of this parameter.
- The monitoring of wind is also recommended because wind might produce short-period noise as well as long-period modulations.

b/ to correct gravity data in long term studies for local (diameter 100km), regional (diameter 2000 km), and global atmospheric pressure signals as all three produce significant effects.

c/ to develop correction models for gravity, tilt, and strain related to:
- ground water table variations
- snow, rain and soil moisture
- stress resulting from temperature variations

9/ Noting the importance for tidal measurements of accurate error estimates and appreciating that such estimates can be made only if the power spectral density of the noise is known,
the ETC recommends
to show noise spectra as Power Spectral Density expressed in unit 2/ frequency.

10/ On behalf of all participants of the 14th International Symposium on Earth Tides, the ETC thanks the Japanese National Committee for Geodesy, the Science Council of Japan, the Geodetic Society of Japan, the National Astronomical Observatory of Japan, the City of Mizusawa and the Iwate Prefecture for their generous support to the Symposium.

11/ ETC thanks the Local Organising Committee : Masatsugu Ooe (Chairman), Tadehiro Sato (Secretary) , Jiro Segawa (President of Geodetic Society of Japan) and the staff, for their wonderful welcome and their many efforts in making the 14th International Symposium on Earth Tides a great scientific success.

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Final Report for 1997-2000
of the
IAG/ETC Working Group 6
Solid Earth tides in space geodetic techniques

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Foreword

Within the Earth Tides Commission (ETC) of the International Association of Geodesy (IAG) the Working Group 6 'Solid Earth tides in space geodetic techniques' was established at the 13[th] International Symposium on Earth Tides, Brussels, July 1997. The general goal of the WG was to strengthen the links between researchers of the tidal community and those who work in space geodetic techniques. The cooperation had to be taken place in both directions:

- The tidal experts provide precise models for the displacements of observation sites on the Earth's crust due to the tides and for the tidal variations to the gravitational field of the Earth.

- The space geodetic techniques are used to validate and possibly to improve the tidal models, e.g. the tidal parameters.

For the investigation of the solid Earth tides it is necessary to take also into account other geophysical influences, e.g. those of the oceans, of the atmosphere and of the pole-tide. Thus, oceanic and atmospheric loading, oceanic and atmospheric effects on the geopotential and the pole-tide were regarded by the Working Group, too. Chairman, members and correspondents of WG 6 (status August 2000) are given in the Activity Report of WG 6 (Schuh, BIM 2001).

The following Terms of Reference (ToR) were agreed upon by the members of WG 6:

1. Extension of the recommendations concerning the tidal influences given in the IERS Conventions (1996) to facilitate their practical use for space geodetic techniques.

2. Evaluation and comparison of the potential of different space geodetic techniques to monitor tidal effects and to determine tidal parameters. Techniques such as VLBI, SLR, LLR, GPS and GLONASS, DORIS and PRARE, satellite altimetry will be covered.

3. Determination of parameters of the tidal models by space geodetic techniques. This requires a priori corrections due to atmospheric and oceanic influences on the Earth's surface and on the geopotential and precise models for tidal influences on the Earth orientation parameters. The effect of pole-tide has also to be considered. The results will have to be compared and

interpreted.

The work on the 1. Term of Reference was summarized and published in: Explanatory Supplement to the IERS Conventions (1996) Chapters 6 and 7, ed. by H. Schuh, *DGFI Report 71*: http://www.dgfi.badw.de/dgfi/DOC/report71.pdf, 1999.

The activities for the 2. and 3. Term of Reference started in summer 1999. Subgroups were established in September 1999 to evaluate the different space geodetic techniques (VLBI, SLR, LLR, GPS/Glonass, DORIS, satellite altimetry) with respect to their potential to monitor tidal effects and to determine tidal parameters. The subgroups were also open for non-members of the WG. The following questions were addressed by the subgroups:

1. Which tidal effects have to be considered in the particular space technique?
2. How is the 'permanent tide problem' handled?
3. What is the capability of the particular space technique to investigate tidal effects (including oceanic and atmospheric tides) and to determine tidal parameters, e.g. the Love numbers?
4. What are the newest results?
5. What are the limitations?
6. What are the future perspectives?

The results of the individual subgroups on six different space geodetic techniques of WG 6 (VLBI, SLR, LLR, GPS/Glonass, DORIS, satellite altimetry) for the years 1997 till 2000 are presented in this Final Report. They show that all space geodetic techniques provide interesting information about tidal effects. Comparison of the treatment of tidal effects in different software packages revealed considerable discrepancies even within the same technique (e.g. between GPS software packages, between VLBI software packages, between LLR software packages, ...). New results for the tidal parameters were obtained for all techniques.

Finally, the chairman (for 1997-2000) wants to express his gratitude to all individuals who contributed to the success of Working Group 6. At the 14th International Symposium on Earth Tides in Mizusawa, Japan (September 2000) it was decided that Working Group 6 will continue its activities for another term and Dr. Wu Bin (Wuhan, China) was determined as the new chairman. As the former chairman I'd like to wish him and the WG 6 all the best for the future.

Harald Schuh (Vienna, June 2001)

Report of the IAG/ETC/WG6/1 (VLBI)

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1. Introduction

The Working Group 6 (WG6), 'Solid Earth Tides in Space Geodetic Techniques', of the Earth Tide Commission (ETC) of the International Association of Geodesy (IAG) has the following three Terms of Reference (ToR):

1. Extension of the recommendations concerning the tidal influences given in the IERS Conventions (1996) to facilitate their practical use for space geodetic techniques.

2. Evaluation and comparison of the potential of different space geodetic techniques to monitor tidal effects and to determine tidal parameters. Techniques such as VLBI, SLR, LLR, GPS and GLONASS, DORIS and PRARE, satellite altimetry will be covered.

3. Determination of parameters of the tidal models by space geodetic techniques. This requires a priori corrections due to atmospheric and oceanic influences on the Earth's surface and on the geopotential and precise models for tidal influences on the Earth orientation parameters. The effect of the pole-tide has also to be considered. The results will have to be compared and interpreted.

ToR 1 has been worked on during 1998/1999 and the results have been compiled and published. The Working Group 6 was separated into smaller subgroups during the last working meeting at the IUGG General Assembly, July 1999. These smaller subgroups are directly related to the specific space geodetic techniques and have the task to address ToR 2 and ToR 3. The following report concludes the work done by subgroup 1 (VLBI) with respect to these two ToRs.

2. Tidal effects to be considered in geodetic VLBI

Geodetic VLBI uses radio telescopes on the earth's crust to observe extragalactic radio sources. The microwave signals of the radio sources are received and recorded together with precise time information on magnetic tapes. The basic observations of geodetic VLBI are the time delays between the arrival of the radio signals at two telescopes forming a baseline. These time delays are obtained in a correlation process.

In order to analyse the geodetic VLBI data, a model has to be implemented that describes the geometric situation during the observation precisely. Thus, the three-dimensional positions of the radio telescopes and the rotation of the earth have to be modeled. This requires to include the tidal influences on either of the latter.

The solid earth tides are the most important tidal effect for the modeling of the station positions. Crustal loading due to redistribution of oceanic mass is the second largest effect and accordingly has to be modeled. The deformation effect caused by polar motion, the so-called pole-tide, has also to be accounted for. A further crustal loading effect to be considered is the deformation due to the changing atmospheric pressure, though it is not a tidal effect. Furthermore, the thermal deformation of the radio telescopes has to be modeled which does not belong to the tidal effects either. The two last mentioned effects do not belong to the category of tidal effects but show similar temporal behaviour and therefore are included in the list at this point.

Concerning the modeling of earth rotation the solid earth tide effects on polar motion and UT1 have to be modeled. Also the oceanic effects on the latter have to be considered.

2.1. Solid earth tides

Most of the analysis software packages for geodetic VLBI data today follow the model for solid earth tides as recommended by the IERS Conventions (1996) (IERS, 1996). The only exception is the permanent tide where the actual treatment does differ from the recommendations of the IERS Conventions (1996). VLBI data analysis programs neither reduce the data to the so-called 'mean-crust' that includes the permanent, zero-frequency deformation of the earth which is called 'permanent tide', nor do they reduce the data to the so-called 'tide-free-crust' which describes an earth without any tidal deformation (Mathews, 1999). This is done by purpose in order to keep consistency with the way the permanent tide was treated during the last decade in space geodesy and to avoid any discontinuity of the VLBI results and an irritation of their users. However, the IERS Conventions (1996) recommend to use the concept of the 'mean-crust'.

2.2. Ocean tide loading

Ocean tide loading is modeled according to the recommendations of the IERS Conventions (1996) in most VLBI analysis software packages. This means the application of the ocean tide loading model according to Scherneck (1991) based on the ocean tide model by Schwiderski (1980) and Le Provost *et al.* (1994). There are more recent ocean tide loading models and some VLBI analysis groups use for example models by Scherneck (1996) and Scherneck (2000) which are based on ocean tide models by Eanes and Bettadpur (1995) and Ray (1999). Some of the VLBI analysis groups also apply refined ocean loading models by introducing a large number of interpolated tides using addmittance calculations.

2.3. Pole-tide

The so-called pole-tide describes the rotational deformation effect of the earth due to polar motion. It has been discussed by Wahr (1985) and Gipson (1998). The topic was also treated by Andersen *et al.* (1999) in detail.

2.4. Atmospheric loading

The effect of atmospheric loading for the vertical site displacement is accounted for by some VLBI analysis groups via an admittance coefficient to be multiplied with the local pressure. There also exists an extensive database of three-dimensional atmospheric loading effects calculated by global convolution of atmospheric pressure data from the European Centre for Medium Weather Forecast (ECMWF) with loading Green's functions (Scherneck *et al.*, 2000). However, so far no VLBI analysis group uses these atmospheric loading effects based on global convolution calculations in routine analysis.

2.5. Thermal deformation of radio telescopes

A model for thermal deformation of radio telescopes has been described by Haas *et al.* (1999). For the application of this model the outside air temperature as logged in the VLBI databases and the dimensions of the radio telescopes are needed to calculate the thermal expansion effects. The radio telescope dimensions are collected by Nothnagel and Haas for all VLBI telescopes structures worldwide on the webpage http://giub.geod.uni-bonn.de/vlbi/thermal-ex/parameters.html . Currently the model is being tested based on the invar-rod measurement systems at Onsala and Wettzell which directly measure the vertical change of the radio telescopes due to temperature influences.

2.6. Solid earth tide and ocean tide effects on earth rotation

The periodic variations in UT1 due to solid earth tides are described by Yoder (1981) and modeled accordingly in the VLBI analysis programs. Dickman (1993) added the long period influence of ocean tides on earth rotation. Models for diurnal and subdiurnal earth rotation variations due to ocean tides are applied in routine VLBI data analysis by most VLBI analysis groups. The model by Brosche *et al.* (1989) is based on theoretical considerations while the model by Ray *et al.* (1994) is based on results from satellite altimetry observations. Latter is recommended in the IERS Conventions (1996). Besides these models derived either from pure theory or external information there are also extensive empirical models, e.g. by Gipson (1996), which are derived from VLBI observations themselves.

3. Results from geodetic VLBI

Already during the eighties, first results for Love and Shida numbers derived from geodetic VLBI were presented by Herring *et al.* (1983) and Ryan *et al.* (1986). During the last years more recent results analysing more extensive VLBI data sets were obtained.

Mitrovica *et al.* (1994) determined complex Love numbers for seven diurnal tides and resolved the Free Core Nutation (FCN) resonance frequency and phase lag.

Herring and Dong (1994) estimated frequency dependent Love and Shida numbers for eleven diurnal and eleven semi-diurnal tides from the analysis of eight years of VLBI data.

Results for Love and Shida numbers in the diurnal and semi-diurnal frequency bands have also been presented by Haas and Schuh (1996), Haas and Schuh (1997) and Schuh and Haas (1998). The investigations covered real and imaginary Love and Shida numbers and more than 16 years of VLBI data. The resonance period of the Free Core Nutation (FCN) and its quality factor have been reported by Haas and Schuh (1996) Haas and Schuh (1997) and Schuh and Haas (1998).

Gipson and Ma (1998) investigated the pole-tide effect and determined real and imaginary Love numbers associated with the deformations. They also studied the influence of the polar motion induced ocean loading effect.

Recently, Petrov (2000) derived complex Love and Shida numbers for long-period tides, using an extensive data set of 20 years of VLBI data.

Estimates of vertical ocean tide loading parameters have been presented by Sovers (1994) and Haas and Schuh (1998). Furthermore, three-dimensional ocean tide loading amplitudes and phases have been determined from VLBI data by Haas and Scherneck (1999) and Scherneck *et al.* (2000) for a number of VLBI sites and ocean loading tides. It was shown at the example of the VLBI station Westford that the refinement of global ocean tide models by regional models leads to an improved agreement of theoretical and empirical ocean loading parameters.

Results for atmospheric loading effects investigated using VLBI data have been reported by VanDam and Herring (1994), MacMillan and Gipson (1994) and Haas *et al.* (1997). Admittance coefficients between vertical site displacement and local atmospheric pressure have been determined.

A model for the thermal deformation effect on radio telescopes has been presented by Haas *et al.* (1999). Using a very simple approach taking only a mean temperature for each 24 hours VLBI experiment, the change of the vertical position of the telescopes at Onsala and Wettzell can be modeled with an agreement of about 0.5 mm with respect to the vertical changes as observed by the invar-rod measurement systems. Further refinements and test of the model are ongoing.

Titov and Yakovleva (2000) presented an investigation on seasonal variations in VLBI baseline length measurements based on VLBI data up to 1995.

Tidal effects on earth's rotation have been studied already in the eighties using geodetic VLBI and concentrated first on the tidal periods as predicted by Yoder *et al.* (1981). During the nineties the investigations focused then on high frequency variations in earth's rotation.

Campbell and Schuh (1986) determined tidal variations in UT1 with periods of 9.1 and 13.6

days from intensive VLBI observations. Luo *et al.* (1987) and Schuh (1988) reported variations in UT1 for several tidal periods between seven and 35 days.

Brosche *et al.* (1991) detected short period UT1 variations from VLBI in the diurnal and semi-diurnal tidal bands and compared them to the predictions of their theoretical model for ocean tide effects on earth's rotation (Brosche *et al.*, 1989).

Sovers *et al.* (1993) determined ocean tidal effects for four diurnal and four semi-diurnal frequencies in both, polar motion and UT1, in a direct approach analysing VLBI data.

Herring *et al.* (1994) determined high frequency tidal signals in polar motion and UT1 for 22 frequencies analysing eight years of VLBI data.

The tidal effects on high frequency earth orientation variation have been studied in great detail by Gipson (1996) analysing a VLBI data set of 15 years.

Scherneck and Haas (1999) showed the importance of ocean tide loading for the investigation of high frequency earth orientation variations. Neglect of horizontal ocean tide loading in the analysis of space geodetic data leads to a rotation of the space geodetic network used. In turn these disturbances are absorbed in the estimated results of high frequency earth orientation variations. There is also a second order effect due to the differences in the currently existing theoretical ocean tide loading models.

4. Limitations of geodetic VLBI

Geodetic VLBI is sesitive to all tidal effects mentioned before, i.e. tidal effects on site displacements and earth's rotation. Thus the VLBI technique can be used to investigate tidal effects and to determine tidal parameters. However, one effect that is beyond the possible investigation is the permanent tide. No space geodetic method is sensitive to the permanent tide.

Since VLBI is a geometric method and does not use artifical satellites orbiting the earth, it is not sensitive to tidal effects on the geopotential.

A limiting factor in geodetic VLBI is the geometry of the current international VLBI network. There is a concentration of geodetic VLBI telescopes in the northern hemisphere, while the southern hemisphere is equipped with only few telescopes.

The investigation of the latitude depedence of the Love and Shida numbers may suffer from this uneven distribution of VLBI sites. However, the investigation of global tidal parameters, e.g. the frequency and quality factor of the Free Core Nutation resonance, are not affected.

The uneven distribution restricts to some extend the investigation of ocean tide loading effetcs, since the ocean models are not sensed equally well by the current distribution of the VLBI sites.

The uneven distribution might create a problem to separate plate tectonic motion and earth rotation for the long frequency range. But since tidal effects on earth rotation are mainly in the short frequency rage, there is no limitation for the study of tidal influences on earth rotation.

Another limitation of geodetic VLBI is that there are no permanent obervations. Geodetic VLBI is conducted on the basis of single experiments of usually 24 hours length. Since the observing process still requires human interaction, it has to be more automised before permanent observations will be possible. There are breaks in the observing program and so the temporal distribution of the VLBI results is not evenly spaced in time. The only automised VLBI system today is the Keystone Project in the metropolitan area of Tokyo, Japan (Kiuchi *et al.*, 1999). But even there, the observations are conducted every second day only. The problem of non-permanent observations will be solved partly when the CORE program (MacMillan *et al.*, 1999) comes to full implementation during the year 2003. There will be observations every week day with at least one intercontinetal VLBI network of four to five participating stations.

Geodetic VLBI does not allow real-time analysis of the observed data. Usually the magnetic tapes with the recorded data have to be transported to a central correlator first. Then the correlation process has to be performed and the resulting delay observations to be distributed to the analysis centres. Today the fastest turn-around times between conducting a VLBI experiment and analysing the data are 3–5 days. In contrast to this standard routine, the VLBI data from the Keystone network in Japan get available for the data analysis in near real-time, i.e. 1 hour after the end of an observing session of 24 hours length. However, for the investigation of tidal effects, a real-time or near real-time availability of the data is not of major importance.

5. Future perspectives

The full implementation of the Mark IV technique will improve the precision of the VLBI system. This will in turn also lead to higher accuracy of the tidal results derived from VLBI data.

With the start of the routine CORE program, VLBI data will be available more regularly. This will lead to improved temporal resolution of the VLBI results.

The installation of the transportable integrated geodetic observatory (TIGO) (Hase, 1999) in the southern-hemisphere at Concepcion, Chile (Schüter *et al.*, 2000), will improve the geometry of the international VLBI networks.

The application of high speed data links for VLBI will possibly become reality in a few years and speed up the turn-around time between the actual observations and the data analysis. Thus, results from VLBI data will be available sooner.

All technical improvements mentioned so far will lead to higher precision of the VLBI data and in turn to improved accuracy of the results derived from VLBI data. Thus, the investigation of tidal effects and the determination of tidal parameters will benefit in particular.

Besides the purely technique oriented improvements, there are also the analysis aspects. The routine introduction of three-dimensional atmospheric loading effects in the VLBI data analysis, the application of recent ocean tide loading models and the inclusion of thermal deformation effects in the VLBI data analysis will lead to improved results for tidal parameters derived from VLBI.

Using all VLBI data available, one challenge will be to investigate solid earth tides and ocean tide loading effects simultaneously. A separation of the tidally driven effects seems to be possible by exploiting the site-specific, complicated phase behaviour of the ocean tide loading effects. A further point of investigation is to continue the studies of seasonal variations in baselength and station components.

Geodetic VLBI links directly the terrestrial and celestial reference frames and is the only space geodetic technique that contributes to earth orientation investgations by delivering nutation corrections. Latter are affected by the Free Core Nutation resonance effect, so are the tidal deformations. A combined approach to investigate the FCN effect from these two sides by using VLBI data seems very interesting. This will become possible by introducing a new nutation model and a new solid earth tide model that both are expressed in the frequency domain.

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References

Andersen, P. H., H. Schuh and J. Müller: Explanatory Supplement to the Sections 'The solid Earth pole tide effect on the geopotential' and 'The site displacement caused by rotational deformation due to polar motion' of the IERS Conventions (1996), *DGFI Report Nr. 71*, H. Schuh (ed.), Deutsches Geodätisches Forschungsinstitut (DGFI), 13–18, 1999.

Brosche, P., U. Seiler, J. Sündermann and J. Wünsch: Periodic Changes in earth's rotation due to oceanic tides, *Astron. Astrophys.*, **220**, 318–320, 1989.

Brosche, P., J. Wünsch, J. Campbell and H. Schuh: Ocean tide effects in universal time detected by VLBI, *Astron. Astrophys.*, **245**, 676–682, 1991.

Campbell, J. and H. Schuh: Short-period Variations of Earth Rotation Determined by VLBI, *Proc. of the Xth Int. Symp. on Earth Tides, Madrid, July 1985*, 943–951, 1986.

Dickman, S. R.: Dynamic ocean-tide effects on earth's rotation, *Geophysical Journal International*, **112**, 448–470, 1993.

Eanes, R. J. and S. Bettadpur: The CSR 3.0 global ocean tide model, *Technical Memorandum, CSR-TM-95-06*, Center for Space Research, 1995.

Gipson, J. M.: Very long baseline interferometry determination of neglected tidal terms in high-frequency Earth orientation variation, *Journal of Geophysical Research*, **101**(B12), 28051–28064, 1996.

Gipson, J. M. and C. Ma: Site displacement due to variation in Earth rotation, *Journal of Geophysical Research*, **103**(B4), 7337–7350, 1998.

Haas, R. and H. Schuh: Determination of Frequency Dependent Love and Shida Numbers From VLBI Data, *Geophysical Research Letters*, **23**(**12**), 1509–1512, 1996.

Haas, R., H.-G. Scherneck and H. Schuh: Atmospheric Loading Corrections in Geodetic VLBI and Determination of Atmospheric Loading Coefficients, *Proc. of the 12th Working Meeting on European VLBI for Geodesy and Astrometry*, B. R. Pettersen (ed.), 122–132, Hønefoss, Norway, ISBN 82-90408-41-2, 1997.

Haas, R. and H. Schuh: Determination of Tidal Parameters by VLBI, *Bulletin d'Information Marées Terrestres*, **127**, 9778–9786, 1997.

Haas, R. and H. Schuh: Ocean Loading Observed by Geodetic VLBI, *Proc. of the XIIIth Int. Symp. on Earth Tides, Brussels, July 1997*, Ducarme (ed.), 111–120, Observatoire Royal de Belgique, 1998.

Haas, R., A. Nothnagel, H. Schuh and O. Titov: Explanatory Supplement to the Section 'Antenna Deformation' of the IERS Conventions (1996), *DGFI Report Nr. 71*, H. Schuh (ed.), Deutsches Geodätisches Forschungsinstitut (DGFI), 26–29, 1999.

Haas, R. and H.-G. Scherneck: Ocean loading tides in VLBI and perturbation of earth orientation parameters, Poster at the XXII General Assembly of the International Union of Geodesy and Geophysics (IUGG), Birmingham, July 1999, A.443, 1999.

Hase, H.: Theorie und Praxis gobaler Bezugssysteme, Dissertation, *Mitteilungen des Bundesamtes für Kartographie und Geodäsie*, **13**, 1999.

Herring, T. A., B. E. Corey, C. C. Counselman, I. I. Shapiro, A. E. E. Rogers, A. R. Whitney, T. A. Clark, C. A. Knight, C. Ma, J. W. Ryan, B. R. Schupler, N. R. Vandenberg, G. Elgered, G. Lundqvist, B. O. Rönnäng, J. Campbell and P. Richards: Determination of Tidal Parameters from VLBI Observations, *Proc. IXth Int. Symp. Earth Tides, New York, August 1981*, 205–214, 1983.

Herring, T. A. and D. Dong: Measurement of diurnal and semidiurnal rotational variations and tidal parameters of Earth, *Journal of Geophysical Research*, **99**(**B9**), 18051–18071, 1994.

IERS: IERS Conventions (1996), *IERS Technical Note*, **21**, D. D. McCarthy (ed.), Paris, 1996.

Kiuchi, H., T. Kondo, M. Sekido, Y. Koyama, M. Imae, T. Hoshino and H. Uose: Real-Time VLBI system, *Journal of the Communications Research Laboratory*, **46**(**1**), 83–89, 1999.

Le Provost, C., M. L. Genco, F. Lyard, P. Vincent and P. Canceil: Spectroscopy of the world ocean tides from a finite element hydrodynamic model, *Journal of Geophysical Research*, **99**(**C12**), 24777–24797, 1994.

Luo, S., D. Zheng, D. S. Robertson and W. E. Carter: Short-Period Variations in the Length of Day: Atmospheric Angular Momentum and Tidal Components, *Journal of Geophysical Research*, **92**(**B11**), 11657–11661, 1987.

MacMillan, D. S. and J. M. Gipson: Atmospheric pressure loading parameters from very long baseline interferometry observations, *Journal of Geophysical Research*, **99**(**B9**), 18081–18087, 1994.

MacMillan, D. S., W. E. Himwich, C. C. Thomas, N. R. Vandenberg, J. M. Bosworth, B. Chao, T. A. Clark and C. Ma: CORE: Continous, High-Accuracy Earth Orientation Measurements, *Proc. of the 13th Working Meeting on European VLBI for Geodesy and Astrometry*, W. Schlüter and H. Hase (eds.), 166–171, Viechtach, Germany, 1999.

Mathews, P. M.: Explanatory Supplement to the Section 'Treatment of the Permanent Tide' of the IERS Conventions (1996), *DGFI Report Nr. 71*, H. Schuh (ed.), Deutsches Geodätisches Forschungsinstitut (DGFI), 9–12, 1999.

Mitrovica, J. X., J. L. Davis, P. M. Mathews and I. I. Shapiro: Determination of tidal h Love number in the diurnal band using an extensive VLBI data set, *Geophysical Research Letters*, **21**(**8**), 705–708, 1994.

Petrov, L.: Determination of Love numbers h and l for Long-Period Tides Using VLBI, *Proc. of the XIVth Int. Symp. on Earth Tides, Mizusawa, August 2000*, in press, 2000.

Ray, D. R., D. J. Steinberg, B. F. Chao and D. E. Cartwright: Diurnal and semidiurnal variations in the earth's rotation rate induced by oceanic tides, *Science*, **264**, 830–832, 1994.

Ray, D. R.: A Global Ocean Tide Model From TOPEX/POSEIDON Altimetry: GOT99.2, *NASA/TM-1999-209478*, Goddard Space Flight Center, Greenbelt, Maryland, 1999.

Ryan, J. W., T. A. Clark, R. J. Coates, C. Ma, W. T. Wilders, C. R. Gwinn, T. A. Herring, I. I. Shapiro, B. E. Corey, C. C. Counselman, H. F. Hinteregger, A. E. E. Rogers, A. R. Whitney, C. A. Knight, N. R. Vandenberg, J. C. Pigg B. R. Schupler and B. O. Rönnäng: Geodesy by Radio Interferometry: Determinations of Baseline Vector, Earth Rotation, and Solid Earth Tide Parameters With the Mark I Very Long Baseline Radio Interferometry System, *Journal of Geophysical Research*, **91**(B2), 1935–1946, 1986.

Schuh, H.: Analysis of UT1 Determinations by VLBI Within Project IRIS, in: *The Earth's rotation and reference frame for geodesy and geodynamics*, IAU, 171–180, 1988.

Schuh, H. and R. Haas: Earth tides in VLBI observations, *Proc. of the XIIIth Int. Symp. on Earth Tides, Brussels, July 1997*, Ducarme (ed.), 101–110, Observatoire Royal de Belgique, 1998.

Scherneck, H.-G.: A globalized solid earth tide model and ocean tide loading effects for global baseline measurements, *Geophysical Journal International*, **106**, 677–694, 1991.

Scherneck, H.-G.: A comprehensive and tentatively complete summary of oceanic effects in space geodetic baseline measurements, *Proc. of the 11th Working Meeting on European VLBI for Geodesy and Astrometry*, Chalmers Research Report 177, G. Elgered (ed.), 122–133, Onsala, Sweden, 1996.

Scherneck, H.-G. and R. Haas: Effects of horizontal displacements due to ocean tide loading on the determination of polar motion and UT1, *Geophysical Research Letters*, **26**(4), 501–504, 1999.

Scherneck, H.-G., R. Haas and A. Laudati: Ocean Loading Tides for, in and from VLBI, *Proc. of the First IVS General Meeting*, N. R. Vandenberg and K. D. Baver (eds.), *NASA/CP-2000-209893*, Goddard Space Flight Center, Greenbelt, MD 20771 USA, 128–132, 2000.

Schlüter, W., H. Hase, A. Böer, St. Riepl, J. Alvarez, A. Cecioni: Progress of the TIGO-Project, *CSTG Bulletin*, **16**, Deutsches Geodätisches Forschungsinstitut (DGFI), 2000.

Schwiderski, E. W.: On charting global ocean tides, *Rev. Geophys. Space Phys.*, **18**, 243–268, 1980.

Sovers, O. J., C. S. Jacobs and R. S. Gross: Measuring Rapid Ocean Tide Earth Orientation Variations With Very Long Baseline Interferometry, *Geophysical Research Letters*, **98**(B11), 19959–19971, 1993.

Sovers, O. J.: Vertical Ocean Loading Amplitudes from VLBI Measurements, *Geophysical Research Letters*, **21**(5), 357–360, 1994.

Titov, O. and H. G. Yakovleva: Seasonal variations in radial components of VLBI stations, *Astronomical and Astrophysical Transactions*, **18**, 591–603, 2000.

VanDam, T. M. and T. A. Herring: Detection of atmospheric pressure loading using very long baseline interferometry measurements, *Journal of Geophysical Research*, **98**(B3), 4505–4517, 1994.

Wahr, J. M.: Deformation induced by polar motion, *Journal of Geophysical Research*, **90**(B11), 9363–9368, 1985.

Yoder, C. F., J. G. Williams and M. E. Parke: Tidal variations of earth rotation, *Journal of Geophysical Research*, **86**(B2), 881–891, 1981.

Contributions of satellite laser ranging to the studies of Earth tides

IAG/ETC WG6 SLR subgroup report

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Satellite laser ranging (SLR) contributes to the studies of Earth tides in the following aspects:
1. Determination of potential love number k2 by analyzing related tidal parameters from satellite orbit perturbations
2. Determination of Love number h2 and l2 by analyzing tidal displacements of SLR sites.
3. Determination of tidal geocenter variations.

SLR observable, the range from a satellite in orbit to a station, is a function of tidal displacements of site and tidal geopotential variations, which perturbate the position of a satellite in its orbit. Hence the signals of tidal variations in satellite position and station position can be recovered from SLR data analyzing. For example, for K1 tide wave, solid Earth tide causes the variation of Lageos inclination 43 meters with the period of 1050 days and maxim radial site displacement 0.08 meter with diurnal period compared with 4 meters in inclination and 0.015 meter in maxim radial site displacement by ocean tide. It is worth to note that SLR is a such technique that is used to determine not only the Love number h2 and l2 from the site tidal displacements but also the Love number k2 from the orbit tidal perturbations, which is quite different from the VLBI or gravimeter.

In order to obtained the high precise Love numbers from SLR analyzing, sophisticated models, especially the ocean tide models are crucial because the solid Earth, ocean and atmosphere affect the geopotential variations and site displacements at same frequency associated with any tide constitute. Although using SLR to derived displacement Love numbers h and l is less precise than VLBI, it has proven from recent studies that SLR is a more precise tool to determine potential Love number k2 with high precision from semi-diurnal period to 18.6 year.

In precise SLR data analyzing, second and third solid Earth tide model, and ocean tide model at least up to 6th degree and order must be included for precise orbit determination. Second degree solid Earth tide to geopotential variations and displacements with liquid core flattening correction and ocean tidal displacement correction must be applied. Polar tide correction is advisedly to add to geopotential and site displacement. Permanent tide effects on geopotential and site displacement are important when objectives are to determine the gravity model including SLR data and to realize the terrestrial reference frame using SLR data.

With enhancement the global distributed SLR station tracking network and centimeter or better precision of ranging measurement, the tidal variations in the geopotential and coordinates of stations have been recovered by SLR technique more accurately. These tidal variations contain all of the solid Earth, oceanic and atmospheric tide contributions and provide a unique method to directly to estimate Love number independently from traditionally ones. By adopting the recent ocean tide model and some small corrections of atmospheric tides, SLR data can be used to estimated the second degree Love numbers for the semi-diurnal (M2,S2), diurnal (K1,O1), monthly (Mm, Mf) and 18.6 year waves. The geocenter tidal variations can also be recovered by parameterized estimation from SLR data analyzing.

In recent years, partly excited by recently important results of ocean tide studies from satellite altimetery and Earth tide studies from VLBI, SLR community has been very active in studying the Earth tide. As an important base, more precise ocean models (e.g. CSR3.0) and ocean tide displacement models (e.g. HGS's model) were used for precise orbit determination in SLR data analyzing which made it possible to extend the studies of tidal parameter determination to the Love numbers determination. There we try to give a brief summery directly related to the topics of SLR subgroup of WG6 after 1997.

1) Watkins and Eanes (1997) studied Geocenter tidal variations. Their solution using nearly 18 years of Lageos data indicated 'geocenter motions at few millimeter level compare well with predicted values from theoretical ocean models and from TOPEX/Poseidon radar altimetry'

2) After Ray et al (1996), the earth tide phase lag was re-studied for M2 and K1 by Wu et al (1999) using SLR or satellite tracking data with phase lag(M2)=0.16 ±0.09 and phase lag(K1)=0.06±0 .12 (degree)

3) Cheng et al (1997) using multi-satellite SLR data, Peng (1998) and Peng and Wu (1999) using Lageos SLR data studied 18.6 year Love number k2 and phase lag and had the following results:

By Cheng ea al	k2=0.3265 ,	phase lag=0.62 (degree)
By Peng and Wu	k2=0.3152(0.0070)	phase lag=3.1(2.0) (degree) ,

4) Wu et al (1997,1999) studied how to precisely determine semi-diurnal and diurnal Love number k2. Using tidal parameter results of SLR and satellite tracking data with the following result:

k2				
M2	S2	K1	O1	
0.3017	0.3014	0.2573	0.2968	SLR (delta h2 corrected)
(0.0004)	(0.0004)	(0.0013)	(0.0029)	
0.3019	0.3022	0.2581	0.2961	SLR (delta h2 =0)
0.302	0.302	0.256	0.298	Wahr model
0.3012	0.3012	0.2574	0.2975	IERS recommended

5) Wu et al (1999) and Peng et al (1999) studied solid Earth tidal displacement Love number h2 and l2 by SLR and by both gravity tide results and SLR result with the result:

h2

M2,	S2,	K1,	O1	
0.6062	0.6114	0.5234	0.6024	SLR combined
(0.0004)	(0.0004)	(0.0013)	(0.0029)	
0.606	0.599	0.502	0.618	SLR
(0.001)	(0.004)	(0.002)	(0.002)	
0.600	0.592	0.512	0.612	Haas and Schuh (VLBI)
0.6078	0.6078	0.5232	0.6026	IERS recommended

l2= 0.071(0.001)M2, 0.069(0.002)S2, 0.065(0.002)K1, 0.095(0.002)O1

6) Wu et al (1999) studied the Love number k2 at Mm and Mf waves using SLR and the variation of length of day and obtained:
k2=0.3032+i0.0028 (Mf),0.3026+i0.0012 (Mm)， SLR
k2=0.3083-i0.0100 (Mf),0.3014-i0.0010 (Mm)， LOD

Further prospects: Previous researches, especially in recent four years, SLR have demonstrated that it is a one of the most useful techniques for the studies of Earth tides. Different from the long history of the ground gravimetric tidal ones, SLR just began to contribute the precise Earth tides research for a short time. There are left many detail problems to be refined and solved. One of the most limitations using SLR to study solid Earth tide mainly exists in sparse SLR data acquisition, error of ocean tide models. With the advancement of SLR hardware, SLR data accumulation, more precise orbit determination of SLR tracking satellites and the more precise oceanic and atmospheric tide models, SLR will be a powerful tool to study the Earth tides.

Recent publications

1. Cheng M.K., K.C. Shum and B.D., Tapley Determination of long-term changes in the Earth'gravity field from satellite laser ranging observations, JGR, Vol. 102 , No. B10, p22377-22390, 1997
2. Watkins M., and R. J. Eanes Observations of tidally coherent diurnal and semidiurnal variations in the geocenter, GRL, vol.24, No.17, p2231-2234, 1997
3. Peng B.B Application of satellite laser ranging to geodynamics , Ph.D thesis, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, 1998 (in Chinese)
4. Peng B.B and B. Wu Acta Geodaetica et Cartogrphica Sinica (in Chinese),1999 in press
5. Wu B. Pen B. B. and Y. Z. Zhu Determination of the Earth's body tide love number and phase lag by space geodesy , IUGG/IAG, Proceeding of International symposium on current crustal movement and hazard reduction in east Asia and south-east Asia, Nov. 1997, Wuhan, China.
6. Wu. B., Y. Z. Zhu and B. B. Peng, Determination of the Earth's body tide phase lag by space geodesy， Chiness Science Bulletin, 1999, vol.44,No.5
7. Wu. B., B. B. Peng and Y. Z. Zhu, Determination of the Earth's body tide Love numbers by space geodesy., The 2nd Meeting of the IAG/ETC Working Group 6 'Solid Earth Tides in Space Geodetic Techniques', July 1999, Birmingham, U.K.
8. Wu. B., B. B. Peng and X. H. Hao, Determination of Love number k2 on Mm and Mf from space geodesy, Acta Astronomica Sinica , 1999, vol. 41, No.3 (in Chinese)

LLR and Tidal Effects

Subgroup on LLR of the IAG/ETC Working Group 6

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1 Introduction

The analysis of Lunar Laser Ranging (LLR) data enables the determination of many parameters of the Earth-Moon system like lunar gravity coefficients, station and reflector coordinates, Earth Orientation Parameters (EOP) or quantities which parameterise relativistic effects in the solar system. The big advantage of LLR is the long time span of lunar observations (1970 - 2000). The accuracy of the normal points nowadays is about 1 cm.
At this time, year 2000, centres are analysing LLR data and contribute to the ILRS (International Laser Ranging Service). A fifth LLR centre, at the Shanghai observatory, submits EOP solutions to the IERS, but does not contribute to the ILRS and is not considered here in detail. A general problem of LLR is that funding is minimal and, if at all, thus covers only very small scientific investigations (e.g. relativity, lunar physics). Therefore many modelling activities or LLR analyses have to be performed beside the normal work. This is not a satisfactory situation, but LLR research has to be continued somehow.
In this paper, the tidal models used in the various LLR software packages of the four lunar analysis centres are listed/compared.

2 Tidal Effects in LLR

In principle, all tidal effects affecting the Earth-Moon distance at the mm-level should be considered, because the accuracy of the observations reaches the sub-cm level and an insufficient modelling causes systematic errors which affect the accuracy of other parameters to be determined, e.g. site coordinates or the EP parameter η. According to the IERS Conventions (1996), one should implement models of solid Earth tides, ocean loading, atmospheric loading, polar tides, diurnal and semi-diurnal tidal effects in UT1 (also those automatically contained in the nutation series) and polar motion.
Additionally one has to consider the secular tidal acceleration of the Moon (i.e. the Moon raises a tidal bulge on the non-ideal elastic Earth which in turn accelerates the Moon). Here the product $k_2\tau$ can be estimated where k_2 is the Love number of the Earth and τ is the lag angle (often expressed in time units). The secular tidal acceleration is responsible for the increase of the Earth-Moon distance of about 3.8 cm/year.
Like the Earth, the Moon behaves as an (an-)elastic body. That means one has to use an appropriate model with the lunar Love number k_m and the dissipation parameter τ_m as typical model parameters. Both quantities can be determined in the global adjustment of the LLR data.

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The four lunar analysis centres have implemented the various tidal effects with different accuracies, some effects have even been neglected. Those which have been dealt with in totally equivalent ways in each software are not mentioned here explicitly. For example, no one uses Eq. 17 of Chapter 7 of the IERS Conventions (1996) for the correction of the permanent tide; or considers short periodic tidal effects in polar motion. Also effects considered inherently e.g. by taking a nutation series, are not addressed here. The following tide-related models are considered in the respective software:

JPL (J. Williams)
Solid Earth tides are computed according to Eq. 8 of Chapter 7 of the IERS Conventions (1996), which models the degree 2 part. Additionally, a correction is applied to consider the different Love number for the K_1 tide with a maximum amplitude of about 1.2 cm (see e.g. IERS Standards (1992), p. 57). The pole tide effect and high-frequency variations in UT1 have also been implemented.
No attempt was made to determine Earth tidal parameters. Estimations had shown that the LLR observation time is correlated with the M_2 period which means this effect can hardly be determined by LLR. But solar tides or smaller lunar tides might be obtainable (Williams, 1999).
The (secular) tidal acceleration of the lunar orbit, $k_2\tau$, has been modelled and can be solved-for, including the diurnal ($k_{20} = 0.34$, $k_{21} = 0.3$, $\tau_{21} = 0.012956$ days) and semi-diurnal ($k_{22} = 0.3$, $\tau_{22} = 0.006925$ days) terms. The result for the value of τ given here has been determined using the ephemeris DE330 (Williams, 1998).
The Moon is modelled as an elastic, dissipative body. The corresponding terms affect the librations of the Moon. The two parameters k_m (= 0.0287) and τ_m (= 0.11523 days) have been determined during the global adjustment.

UTXMO (J. Györgyey Ries)
The effect of the solid Earth tides is computed following the work of Alsop and Kuo (1964), which was based on Bullen's model. The Love numbers of the tidal displacement are $h_2 = 0.618$ and $l_2 = 0.088$, which are hardcoded and cannot be estimated without substantial effort. Tides raised on the Moon by the Earth and the Sun are coded, but usually not used. Although the software is capable of estimating the lunar Love number, k_2, and $k_2\tau$, it has not been attempted. Additional tidal effects and ocean loading are not considered. At present, streamlining of the analysis process takes higher priority than estimation of tidal effects.

OBSPM (J. Chapront)
Solid Earth tides are computed according to Eq. 8 of Chapter 7 of the IERS Conventions (1996). The Love numbers of the tidal displacement are $h_2 = 0.609$ and $l_2 = 0.0852$.
The (secular) tidal acceleration of the lunar orbit has been modelled, including the effect of both the diurnal ($k_{20} = 0.34$, $k_{21} = 0.3$, $\tau_{21} = 0.0138569$ days) and semi-diurnal ($k_{22} = 0.3$, $\tau_{22} = 0.0068254$ days) terms, where the numerical values have been adopted from the JPL ephemeris DE245. The secular lunar tidal acceleration, $k_2\tau$, is fitted. The effect of ocean loading at the sites has been considered, but without corrections due to the lunar node (IERS Conventions (1996), p. 53). Atmospheric loading is modelled using a simplified version of the formula given in the IERS Conventions (1996), p. 67: $\Delta r_{al} = -0.9\ pr$ [mm], where $pr = p_0 - 1013$ mbar and p_0 is the local pressure reduced to sea level.
The Moon is modelled as an elastic, dissipative body where the two parameters k_m (= 0.0299) and τ_m (= 0.16485 days) have been included in the computation of the lunar librations.

FSG (J. Müller)
Previous model:
Solid Earth tides were computed according to Eq. 8 and 9 (displacements due degree 3 tides) of Chapter 7 of the IERS Conventions (1996). The Love numbers of the tidal displacement are $h_2 =$

0.603, $l_2 = 0.083$, $h_3 = 0.292$ and $l_3 = 0.015$. A correction was applied to consider the different Love number for the K_1 tide (see IERS Standards (1992), p. 57). Also the pole tide effect and high-frequency variations in UT1 have been implemented. The effect of ocean loading at the sites has been considered, following the recommendations of the IERS Conventions (1996), Chapter 7.
The secular tidal acceleration of the lunar orbit has been modelled, but only the semi-diurnal term ($k_2 = 0.3$, $\tau_2 = 0.006939$ days) which is also solved-for during each adjustment.
Again, the Moon is modelled as an elastic, dissipative body where the two parameters k_m (= 0.0267) and τ_m (= 0.1709 days) are determined.

Tidal modelling since 2000:
The main parts of the model are the same as before. We detected and corrected a small error (wrong phase angle) in the term which models the K_1 tide effect. We implemented a new solid Earth tide model given by Mathews et al. (1997). This model considers further frequency- and latitude-dependent terms. The difference between the previous (but K_1 corrected) and the new models is less than 5 mm in radial direction and almost 0.1 mas (= 3 mm) transversal (Figure 1). Furthermore, we implemented a model to consider atmospheric loading which is similar to that of OBSPM.

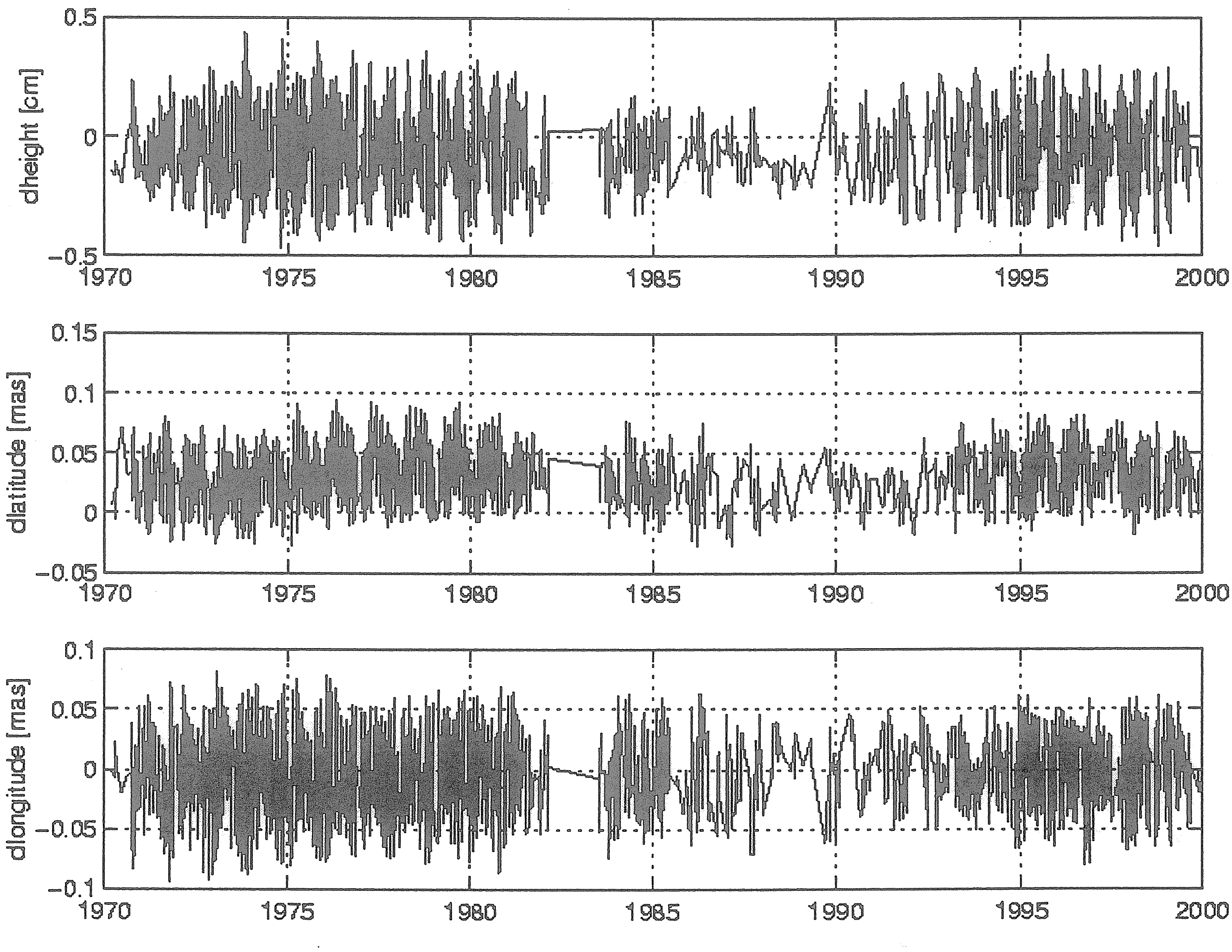

Figure 1: The difference between the previous and new solid Earth tide models at FSG.

The software implementations of the various tidal effects at the four lunar analysis centres are summarised in Tables 1a and 1b. There we have also indicated whether tidal parameters are determined or not.

	JPL (J. Williams)	UTXMO (J. Györgyey Ries)	OBSPM (J. Chapront)	FSG (J. Müller)	FSG 2000
Earth tides (no corr, of the permanent tide, Eq. 17)	IERS Conv. 1996, Eq. 8 (degree 2) + corr. of K_1	Alsop and Kuo (1964)	IERS Conv. 1996, Eq. 8 (degree 2)	IERS Conv. 1996, Eq. 8, 9 (degree 3) + corr. of K_1	Matthews et al. (1997)
Ocean loading	?	-	IERS Conv. 1996 (without corr. due to lunar node)	IERS Conv. 1996	
Atmospheric loading	?	-	IERS Conv. 1996 (p_{t0} vs p_0, simplified)	-	IERS Conv. 1996 (p_t vs p_{avg}, simplified)
Pole tide	yes	-	?	yes	
(Sub-)diurnal UT1 variations	yes	-	?	yes	

Table 1a: Tidal effects implemented in the various lunar analysis softwares (recommended by the IERS Conventions 1996).

	JPL (J. Williams)	UTXMO (J. Györgyey Ries)	OBSPM (J. Chapront)	FSG (J. Müller)
Secular tidal eccleration of the moon (+ 3.8 cm/y) potential Love$_{earth}$ k, lag angle τ	diurnal (k_{20}, k_{21}, τ_{21}), subdiurnal (k_{22}, τ_{22}) (det. with eph. DE330)	-	diurnal (k_{20}, k_{21}, τ_{21}), subdiurnal (k_{22}, τ_{22}) (det. with eph. DE245)	diurnal (k_2, τ_2)
estimation	$k_{21}\tau_{21}$; $k_{22}\tau_{22}$	-	$k_2\tau$	$k_2\tau$
Moon as an elastic, dissipative body potential Love$_{moon}$ k_m, dissipation parameter τ_m	yes	-	yes	yes
estimation	yes	-	?	yes

Table 1b: Tidal effects implemented in the various lunar analysis softwares (relevant for LLR).

3 Conclusion

The comparison of the software packages shows that the various tidal effects are handled very differently at the lunar analysis centres. The (solid) tidal effects not yet considered may still reach the mm-level and should be implemented. As a first step, the tidal modelling could be improved and homogenised. However, the general funding of geophysical research is a big problem.
All analysis centres estimate the secular tidal acceleration and the lunar tidal parameters. The results differ slightly depending on the parameterisation, the ephemeris used or other modelling properties. The comparison of the differences and the possible effect for solid Earth physics and/or lunar physics should be further investigated. Some aspects of this are discussed in Dickey et al. (1994). Also, the capability of LLR to determine additional tidal parameters has to be investigated separately. A first step in this direction is carried out by Müller and Tesmer (2000).

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References

Alsop and Kuo, Ann. Geophys., Vol. 20, P.286, 1964.
Dickey et al., Science, Vol. 265, P. 482-490, 1994.
IERS Standards (1992), IERS Technical Note 13, ed. by D. McCarthy, Paris 1992.
IERS Conventions (1996), IERS Technical Note 21, ed. by D. McCarthy, Paris 1996.
Mathews P., Dehant V., Gipson J., JGR, Vol. 102, No. B9, P. 20,469-20,477, 1997.
Müller J. and Tesmer V., paper presented at IAG/ETC WG6 meeting in Nice, 2000.
Williams J., LLR results from JPL, private communication, December 1998.
Williams J., private communication, 1999.

GPS / GLONASS and Tidal Effects

Subgroup on GPS / GLONASS of the IAG/ETC Working Group 6
(Solid Earth Tides in Space Geodetic Techniques)

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Introduction

Considering the present quality of modelling satellite orbits the microwave space-techniques GPS and GLONASS are in principle sensitive to a variety of tidal effects. This holds especially for GPS, claiming an almost unbelievable orbit precision level of about 5cm (Kouba,Springer, 1999). This report covers a list of tidals signals which have to be considered, followed by a survey of how different Analysis Center of the IGS handle these effects within their routine data processing. Chapter 2 discusses the still unsolved problem on how to treat the permanent tide. On the one hand there is the demand to be consistent with recommendations of IAG or IERS and on the other hand the convention has to fulfil practical needs. Then we state some ideas on how tidal parameters might be determined (e.g. Love numbers) from GPS/GLONASS data and give subsequently a brief summary of the current limitations in determing these quantities. Remarks on future perspectives as well as a number of recommendations conclude this report.

Tidal effects to be considered in the GPS/GLONASS data processing

In the first place **local site displacements** due to **solid earth tides** and **ocean loading** have to be taken into account. The effect of solid tides is discussed extensively in (McCarthy , 1996). Application of the given equations describe the radial motion as well as the transverse diplacements at the 1mm level. A two step procedure is recommended, accounting in step one for motions by means of nominal real love numbers h and l common to all degree 2 tides. The second step corrects for the frequency dependence of these numbers (diurnal band, long periods). An improved precision demands in addition the calculation of diplacements due to degree 3 tides. Movements induced by ocean loading may reach the range of a few centimeters in the vertical (Scherneck, 1996) based on the models FES94 (Le Provost et al., 1994), CSR4.0 (Eanes and Bettadpur,1999), or, alternatively GOT99.2 (Ray, 1999). Displacements are available now for almost all global stations of the IVS, ILRS, IGS, DORIS services.

Although **atmosphere loading** may cause vertical diplacements of several (up to some tens of) millimeters, an adequate correction is not applied by the IGS Analysis Centers at the moment (see list below). This goes together with the discussion about the reliability of the available models and the question at which periods the inverted/non-inverted barometer assumption for the response of the oceans due to changes in air pressure is valid.

As part of the **orbit model**, the **tidal forces** are most conveniently described as variations in the standard geopotential coefficients. The tidal contributions are expressible in terms of the potential Love number k. Modelling the solid earth tides usually starts with frequency independent Love numbers up to degree and order 3. Subsequently frequency dependent corrections are applied for up to 34 constituents. The effects of ocean tides are also incorporated by periodic variations in the Stokes' coefficients. Coefficients used in GPS orbit modelling were obtained in most cases from the UT CSR3.0 (Eanes et al., 1996) ocean tide height model or from the model of Schwiderski (Schwiderski, 1983).

Ocean and atmosphere tides induce a motion of the coordinate frame of tracking stations of all satellite techniques relative to the Earth's center of mass. Viewed from the rigid crust-fixed frame, the motion of the coordinate system origin is known as 'geocenter-motion' and the tidal induced components as '**geocenter tides**'. Presently, these centimeter-size motions may not be seen in GPS/GLONASS analyses, thinking of the current accuracy of the orbits. However, in SLR the terms are clearly resolvable and in order to foster a uniform data processing for all techniques, these variations should be taken into account.

Ocean tides (matter and motion terms) induce variations in the axial (LOD) as well as in the equatorial **earth rotation components** (polar motion) in three frequency bands: semidiurnal, diurnal and long-periodic. The former can be monitored very precisely by satellite techniques like GPS. Apriori correction for daily and subdaily tidal variations in the Earth rotation and polar motion by means of the Ray model (Ray, 1996; 8 constituents) has become standard in IGS data processing since 1997.

Below (see Table 1) an overview (extract from the analysis center log files available at the IGS Central Bureau System: July 2000) is given of how the different IGS analysis centers correct for tidal effects. At first glance the results of this survey look not very homogeneous, but we should keep in mind that in some cases this information does not mirror the current situation. An update, where necessary, has been requested by this Working Group. Nevertheless, the situation is and has been inconsistent over years.

	CODE	EMR	ESOC	GFZ	JPL	NOAA	SIO	USNO
Solid Earth Displacement	Model IERS96 nominal h_2 / l_2 0.6078/0.0847 +corrections	Model IERS92 nominal h_2 / l_2 0.609/0.085 $dh_2(K1)$:0.089	Model IERS92 nominal h_2 / l_2 0.609/0.085 $dh_2(K1)$:0.089	Model IERS92 nominal h_2 / l_2 0.609/0.085 $dh_2(K1)$:0.089	Williams	nominal h_2 / l_2 0.6067/0.0844 +corrections	Model IERS92 nominal h_2 / l_2 0.609/0.085 $dh_2(K1)$:0.089	Williams
Force	frequ. indep. Love's Nr: $k_2 = 0.300$	frequ. indep. Love's Nr: $k_2 = 0.300$	frequ. depend. Wahr; nominal $k_2 = 0.300$	frequ. depend. Wahr; nominal $k_2 = 0.300$	nominal $k_{2(0-2)}$ 0.299/0.3/0.302 $k_{3(0-3)}$=0.093 +34 frequ.dep corrections	frequ. depend. Wahr; nominal $k_2 = 0.300$	frequ. indep. Love's Nr: $k_2 = 0.300$	nominal $k_{2(0-2)}$ 0.299/0.3/0.302 $k_{3(0-3)}$=0.093 +34 frequ.dep corrections
Perm. Tide Displacement	not applied	not applied	no info	applied	no info	not applied	no info	no info
Force	applied	applied		applied		applied		
Pole Tide	appl. / IERS96 mean m1/m2 0.033/0.331	appl. / IERS92	not appl.	appl. / IERS92	appl. / IERS92	not appl.	not appl.	appl. / IERS92
Ocean Loading Displacement	Scherneck	Pagiatakis	Scherneck	Scherneck	Scherneck	not appl.	not appl.	Pagiatakis
Force	UT CSR 3.0	UT CSR 3.0	Schwiderski	Schwiderski	UT CSR 3.0 + TEG-2B data	not appl.	UT CSR 3.0	UT CSR 3.0 + TEG-2B data
Atmosphere Loading	not applied	not applied	not applied	not applied	not applied	not applied	not applied	not applied

Table 1: Tides related part of the Analysis Strategy Summaries of the IGS ACs

Treatment of the 'permanent tide problem' within GPS/GLONASS data processing

Basically, in order to allow intercomparison and combination of the solutions of different techniques the recommendation is that every technique handles the permanent tide in the same way.

The current working standard is to subtract a permanent tide from the individual ((quasi-) instantaneous) observations of the station position. The amplitude of this permanent tide displacement is governed by the elastic Love numbers at semi-diurnal frequencies. An additional simplification implies is that a spherical earth is a sufficient model for this tide and that linear superposition holds. The model taken into account contains the full effect of the solid earth tides, but using unfortunately the nominal (semidiurnal,diurnal) Love-number ($h_2 \approx 0.60$) for the secular part (instead of the secular Love-number 1.94).

A zero-tide definition including a permanent tide in a fluid approximation could be chosen to derive a physically plausible tide-free reference frame. However, no independent observation method exists which could uniquely separate the permanent tidal flattening of the earth from the rotational flattening without additional assumptions (finite elasticity in the crust for instance) which are again difficult to verify contemplating the fact that we deal with an infinite-time response.

There is a recommendation of the IAG to work on the Earth's crust. This implies, that the correction of the permanent tide should not be applied. We have to apply the nominal correction not taking into account the secular term.

If station positions have to be expressed on the 'tide-free' crust, they must be corrected for the complete response of the earth to tidal force. Thus, again we have to apply the nominal correction and afterwards account for the difference between the semidiurnal and the secular Love number. Both proposals (recommendations) are satisfying the scientific point of view but they are in conflict with the present practice.

Analysis experts insist on their 'working position', because it would be extremely dangerous to change the convention. If the transition has to be performed, each site coordinate file would have to be firmly ear-marked as to what definition is implied. Also, during the transition phase incompatible versions of analysis procedures and subroutines might coexist. Therefore, it appears viable to (continue to) stipulate the implication of a purely conventional permanent elastic tide in the computed tide displacement of a station in the reduction of space geodetic observations.

If in future more exact formulations of tide displacements come about (which would employ the frequency response method based on a harmonic expansion of the tide potential in the tradition of Doodson), we propose to

(1) exclude the zero-frequency term delivered by this method, and
(2) include instead the conventional zero-frequency term.

With sufficient accuracy, this term is

u = -0.6026 * 0.19844 * (1/2)(3\sin^2 \theta -1)
v = -0.0831* 0.19844 * (3/2)\sin(2\theta)

where u is vertical and v north displacement in meters, and theta is the geocentric latitude. The numbers in front are the basic Love numbers of the 1996 Conventions, and the second factor is the amplitude coefficient. In the IERS Standards (McCarthy, 1992) these quantities were h_2 = 0.6090, l_2 = 0.0852 and the amplitude coefficient was 0.19841.

In order not to introduce jumps in station coordinates each time the response parameters are changed, the tide model must recreate the original permanent tide.

The Determination of Tidal Parameters

Last but not least we should discuss the capability and limitations of the microwave satellite techniques to investigate tidal effects (including oceanic and atmospheric tides) and to determine tidal parameters ?

First of all we may distinguish between longer periods and the diurnal/subdiurnal band. In terms of periods of several days and more three formal approaches can be considered :

(1) Do not correct for the long period solid earth tides within the data analysis, but correct for ocean (and atmospheric) loading. Then, the 13.66 days, 27 days and one year periods will show up in the residuals. This should allow to extract information about the Love numbers for these frequencies for the solid earth tides (using the known tide generating potential).

(2)Correct in the data analysis as completely as possible for the solid earth tides (and for atmospheric loading), extract ocean loading from residuals.

(3)Correct in the data analysis as completely as possible for the solid earth tides and correct for ocean loading, extract atmospheric loading from residuals.

Preliminary results using Precise Point Positioning (PPP) as well as differencing schemes when processing regional continuous GPS networks show that atmospheric loading effects are somewhat attenuated (in Scandinavia effects are found that are a factor of three smaller than predicted using load convolution methods; the inverted barometer assumption does not seem to be the critical factor). Together with earlier results (van Dam, Herring, 1994), the resolution of atmospheric loading effects is expected at the 1-3 mm level (implying that vertical motion is better resolved than horizontal).

In terms of daily and subdaily periods we may conclude that:

(1) studying (ocean) tidal effects from a series of 2-hourly ERP values, based on 3 years of data of the global GPS network of the IGS, has shown (Rothacher et al., 2000) that tidal amplitude models, currently available from VLBI, SLR, GPS and Altimetry, agree within

$10\,\mu as$ in Polar Motion and $1\,\mu s$ in UT1.

(2) On the other hand, tides with periods close to 12 and 24 hours (S1, $\psi 1$; K1, S2, K2) seem to be biased because of orbit errors. The residual spectrum, that remains after removal of the main tidal terms contains non-tidal signals up to $50\,\mu as$ in polar motion and $3\,\mu s$ in UT1. These effects might be due to the resonance effect (12 hour revolution period of the GPS satellites) or, alternatively, due to atmospheric or oceanic normal modes. To add GLONASS data seems to be a very promising way to overcome some model deficiences. First of all, the revolution period of $11^h\,15^m$ is not in resonance with earth rotation and, moreover, the increased orbital inclination reduces the impact of along track orbit errors on LOD estimates.

Future perspectives

Future perspectives are of course closely tied to modelling improvements in the non-gravitational forces acting on the satellites and to tropospheric effects. Another important point is the impact of improved ocean loading tides (altimetry models) on orbits and subsequently on the ERP estimation or for the accurate determination of water vapour from GPS measurements. Advantages of analyzing data from different satellite navigation systems were discussed above. Last but not least the steady increasing time series ERPs and station coordinates leads to decreasing formal errors in the derived tidal parameters.

Recommendations

1) In order to foster an uniform data processing for all techniques, geocenter motion models as well as atmosphere loading models should be taken into account.

2) A long-term solution concerning the treatment of the permanent tide has to be presented in the near future. Opportunities are either to stay at the (IERS,1992) model or to move to the Earth's crust (IAG).

3) We recommend an exact review of the current situation of modelling tidal effects at the IGS Analysis Centers in order to create a fully coherent situation across the field. The results of this survey have to be forwarded to the IGS Analysis Center Coordinator.

Bibliography

Baker, T.F., Curtis D.J., Dodson A.H., 1995
Ocean Tide Loading and GPS
GPS World, March, pp.54-59.

Bos,M.S., Baker T.F., 2000
Ocean tides and loading in the Nordic Seas,
Memoirs of National Institute of Polar Research (Japan), Special Issue, No.54.

Eanes R.J., S.V. Bettadpur, 1996,
The CSR 3.0 global ocean tide model,
Center for Space Research, Techn. Memorandum,CSR-TM-96-05.

Eanes R.J., S.V. Bettadpur, 1999,
The CSR 4.0 global ocean tide model

Kouba J., T. Springer, 1999
Analysis Activities,
International GPS Service; IGS Annual Report 1998, pp.13-17,
IGS Central Bureau, JPL.

Le Provost C., M. Genco, F. Lyard, P. Incent, P. Canceil, 1994,
Spectroscopy of the world ocean tides from a finite element hydrological model,
JGR, Vol. 99, pp. 24777-24798.

McCarthy D.D. (editor), 1992,
IERS Standards,
IERS Technical Note 13, Observatoire de Paris.

McCarthy D.D. (editor), 1996,
IERS Conventions,
IERS Technical Note 21, Observatoire de Paris.

Ray R.D., 1996,
Tidal Variations in the Earth's Rotation,
in 'IERS Conventions', McCarthy D.D. (editor)
IERS Technical Note 21, pp. 76-77, Observatoire de Paris.

Ray R.D., 1999,
A Global Ocean Tide Model from TOPEX/POSEIDON Altimetry:GOT99.2
NASA/TM-1999-209478; National Aeronautics and Space Administration,
Goddard Space Flight Center, Greenbelt,MD.

Rothacher M., G. Beutler, R. Weber, J. Hefty, 2000,
High Frequency Earth Rotation Variations from three Years of Global Positioning System Data,
Submitted to the Journal of Geophysical Research.

Scherneck, H.G., 1991,
A parameterized solid earth tide model and ocean tide loading effects
for global geodetic baseline measurements,
Geophys. J. Int., 106, pp. 677-694.

Scherneck, H.G., 1996,
Site displacement due to ocean loading,
McCarthy D.D.(editor): IERS Technical Note 21,.pp. 52-56.

Scherneck H.-G., J.M. Johansson, F.H. Webb, 2000,
Ocean Loading Tides in GPS and Rapid Variations of the Frame Origin,

in Schwarz K.P. (editor): Geodesy beyond 2000, The Challenges of the First Decade, IAG Symposia, Volume 121,Springer, pp. 32-40.

Schwiderski,E., 1983,
Atlas of Ocean Tidal Charts and Maps
Marine Geodesy, Vol. 6, pp.219-256

Van Dam T.M., T.A. Herring, 1994,
Detection of Atmospheric Pressure Loading using Very Long Baseline Interferometry Measurements, JGR, Vol.99, pp.4505-4517.

Van Dam T.M., G. Blewitt, M.B. Heflin, 1994,
Atmospheric Pressure Loading Effects on GPS Coordinate Determinations,
JGR, Vol.99, pp.23939-23950.

Weber R., 1999,
The Ability of the GPS to Monitor Earth Rotation Variation
in 'Acta Geodaetica et Geophysica Hungarica',
Vol. 34, Number 4, pp. 457 – 473, Akademiai Kiado, Budapest.

Love's number adjustment from DORIS and SLR

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The "Groupe de Recherches de Geodesie Spatiale" (GRGS) has developped for many years the GINS/DYNAMO software package for precise orbit computation and model computation (e.g. the geopotential GRIM models) or reference system computation (e.g. station coordinates and velocities).

First GINS performs a numerical integration of the satellite's equations of motion using Cowell's method. It is based on a predictor-corrector type scheme with a fixed time step. The force model includes: the Earth gravity field, luni-solar and planetary gravitation, solid and ocean tides, atmosphere gravitation, direct and Earth-reflected radiations and atmospheric drag for the main forces. This numerical integration is performed either in the instantaneous celestial reference frame or in the inertiel J2000 reference frame.

Through an iterative process based on a first order Taylor's expansion of residuals and a root-mean-squares technique, GINS is able to adjust many parameters depending on the orbit, on some force models, on reference systems, on the measurements used ...; it can also create normal equation sets (in an additional iteration) which are afterwards processed by the DYNAMO software chain for combining, reducing, weighting, inverting, solving for all parameters.

So far, angular (optical), range (SLR, PRARE, altimetric), doppler (TRANET, PRARE, DORIS), GPS data have been considered as measurement functions. VLBI has then been recently introduced although an orbit computation is not needed. This fulfils the multi-disciplinarity of this software package and offers of course new possibilities in the combination of techniques for Earth parameters recovery.

This software package has been recently used for testing the capabilities of SLR and DORIS techniques to investigate tidal effects through the recovery of the Love's numbers k_2 and h_2. The initial values have been based on the IERS recommended values and models (IERS convention, 1996). The adusted values are summarized in the following table according to tracking technique and satellite and show very homogeneous results between both techniques. However it is to notice that DORIS results are slightly above the SLR results and in fact closer to the initial values : k_2= .3019, h_2= .6078. Of course results in h_2 are depending on the distribution of the station network. From this point of view DORIS benefits of a better worldwide distribution of the beacons .

Satellite/ Technique	Processed period	Data number	Residuals	Arc numb.	Arc length	k_2	h_2
STARLETTE/ SLR	Feb. 90-May 99	203 950	5.3 cm	279	8 d	.3016 ± .0001	.5948 ± .0013
STELLA/ SLR	Nov. 93-June 99	81619	4.6 cm	159	8 d	.3012 ± .0001	.5971 ± .0018
SPOT2/ DORIS	Jan. 93-Dec. 95	2 572 863	.512 mm/s	156	5 d	.3026 ± .0005	.6026 ± .0016
SPOT2/ DORIS	Jan. 96-Dec. 98	2 511 837	.481 mm/s	150	5 d	.3020 ± .0002	.6004 ± .0015

Report from Subgroup 6 on Satellite Altimetry of the IAG/ETC Working Group 6 'Solid Earth Tides in Space Geodetic Techniques'

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July 7, 2000

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1 Introduction

The International Association of Geodesy Earth Tide Commission (IAG/ETC) Working Group 6, 'Solid Earth tides in space geodetic techniques', was established in July 1997. Initially, three terms of reference were established to define the goals of the working group. The first of these three terms of reference is aimed at extending the recommendations relating to tidal influences that are given in the IERS conventions [*McCarthy*, 1996]. This first term of reference been addressed by *Schuh* [1999]. The remaining two terms of reference are aimed at evaluating and comparing the potential of different space geodetic techniques to monitor tidal effects and to determine tidal parameters, and at determining parameters of the tidal models by space geodetic techniques. It was decided to separate working group 6 into subgroups, with each subgroup having the task of addressing the two remaining terms of reference as they pertain to a specific geodetic technique. This report summarizes the conclusions and recommendations of subgroup 6 on satellite altimetry with respect to these two terms of reference.

The report begins by describing the tidal effects that should be considered in satellite altimetry and the methods that are being used to treat these individual effects. Specific emphasis is then placed on describing the treatment of the permanent tide in satellite altimetry, particularly with regards to the definition of the mean sea surface, geoid, and geopotential. A summary of the capabilities and limitation of satellite altimetry to determine various tidal effects and parameters is then provided.

2 Tidal Effects That Should be Considered

Satellite altimeters measure the range between the satellite and the ocean surface that lies nadir to the satellite. The geocentric sea surface height, h, of the ocean surface observed by satellite altimeters is determined as the difference between the geocentric altitude of the host satellite, r, and the range measurement from the satellite altimeter, ρ.

$$h = r - \rho \tag{1}$$

The observed geocentric sea surface height can then be decomposed into a static surface, most often referred to as a mean sea surface height, h_{mss}, and the geocentric dynamic sea surface height, h_d.

$$h = h_{mss} + h_d \tag{2}$$

The geocentric dynamic sea surface height can then be decomposed into radial tidal displacements, h_t, and non-tidal oceanic variations that include the response to atmospheric forcing and the general circulation of the oceans, h_c.

$$h_d = h_t + h_c \tag{3}$$

Observing the non-tidal variations of the oceans is generally the primary goal of most satellite altimeter missions. However, it is the tidal displacements that provide the dominant signal in the geocentric dynamic sea surface heights observed by satellite altimeters. These tidal effects must first be considered before observing the non-tidal variations of the oceans. Those tidal displacements that must be considered include the body tides, h_{bt}, the ocean tides, h_{ot}, the associated load tides, h_{lt}, and the pole tide, h_{pt}.

$$h_t = h_{bt} + h_{ot} + h_{lt} + h_{pt} \tag{4}$$

Satellite altimeters only observe radial displacements of the ocean surface, so only radial tidal displacements need to be considered for satellite altimetry applications. Since satellite altimeters actually observe the total displacement at the sea surface that results from both the ocean tide and the associated load tide, many satellite altimeter applications and data products often combine the ocean tide and load tide displacements over the oceans into a total displacement that is sometimes referred to as the geocentric ocean tide. For clarity, here this total displacement is simply referred to as the (ocean+load) tide, h_{oplt}.

$$h_{oplt} = h_{ot} + h_{lt} \tag{5}$$

On average, the tidal displacements, excluding any contributions from the permanent tide, account for approximately 80% of the geocentric dynamic sea surface height, with the (ocean+load) tides having the largest contribution, followed by the body tides, and a very small (<0.1%) contribution from the pole tide.

3 Treatment of Tidal Effects

3.1 Satellite Altimetry Data Products

Data from satellite altimeter missions are accumulated by the individual institutions that manage the particular mission. These data are processed by the managing institutions and then distributed to the scientific community in data products referred to as Geophysical Data Records (GDRs). The GDRs provide the data that is necessary to derive the observed sea surface height that is inferred by each individual range measurement from the altimeter, and also provide quantities that predict certain geophysical contributions to the observed sea surface height. The GDRs usually provide the following quantities for each range measurement data point.

1. Time tag of the range measurement from the satellite altimeter.
2. Geolocation of the range measurement.
3. Range measurement from the satellite altimeter after applying various instrument corrections.
4. Altitude of the satellite above a reference ellipsoid.
5. Various instrument corrections that were applied to the raw range measurement.
6. Environmental corrections that should be applied to the observed range measurement to account for the effects of tropospheric and ionospheric delays, and the observed sea state roughness.
7. Geophysical quantities that contribute to the individual sea surface height measurement, such as the mean sea surface, the geoid, the ocean tide, the load tide, the body tide, the pole tide, and the inverse barometer response of the ocean surface to atmospheric pressure.

The geolocation and altitude associated with each range measurement are determined from the precise orbit determination (POD) of the satellite. Models are usually used for the environmental corrections. However, dual frequency altimeters are able to implicitly measure the ionospheric delay, and some missions such as the TOPEX/POSEIDON (T/P) mission also have a radiometer on the satellite that measures the wet tropospheric delay. Models are always used to generate each of the geophysical quantities that are associated with each individual sea surface height observation. It should be emphasized that only radial displacements of the observed sea surface are provided for all of the geophysical quantities.

3.2 Body Tides

Satellite altimetry data products most often, if not always, model the body tides by a purely radial elastic response of the solid Earth to the tidal potential. The elastic response is usually modeled using frequency independent Love numbers, h_n, for each degree n of the adopted tidal potential. The tidal potential is one that has been decomposed into its individual spectral components [e.g. *Cartwright and Edden*, 1973, *Tamura*, 1987]. The permanent tide (zero frequency) spectral component is specifically removed from the adopted tidal potential so that the model of the total body tide displacement that is provided on the satellite altimeter data products does not include the contribution from the permanent body tide displacement. As an example, the T/P GDRs model the body tides by applying Love numbers $h_2 = 0.609$, and $h_3 = 0.291$ to a *Cartwright and Taylor* [1971] tidal potential (excluding the permanent tide component) that has been extrapolated to the T/P era.

Although frequency independent Love numbers are used to model the body tides, the effects of the free core nutation (FCN) resonance in the diurnal tidal band are sometimes accounted for by simply scaling the tide potential amplitude of the K_1 spectral line and some neighboring spectral lines by an appropriate scale factor. Multiplication of the scale factor by the adopted frequency independent Love number provides the Love number that accounts for the FCN resonance. Again using the T/P GDRs as an example, the effects of the FCN resonance are simply modeled by scaling the tide potential amplitude of the K_1 spectral line and the neighboring nodal lines by a factor $0.52/0.609 = 0.854$, since the appropriate Love number at the K_1 tidal frequency is approximately 0.52.

The use of frequency independent Love numbers, and especially the simplistic approach towards the FCN resonance in the diurnal band certainly introduces errors to the modeled body tides. However, these errors are considered to be much smaller than the instantaneous accuracies of the altimetric sea surface height measurements which are likely to be no better than approximately 4 cm. For example, the elastic semidiurnal Love number specified by *Mathews et al.* [1997], $h_2 = 0.6026$, implies a maximum error in the amplitude of the elastic M_2 body tide modeled on the T/P GDRs that ranges from 0.16 cm at the equator to 0.03 cm at $\pm 66°$ latitude. It should be realized that any errors in the body tide model are likely to be absorbed into any (ocean+load) tide models that are empirically determined from altimetric sea surface height data that remove body tide effects with the provided body tide model.

3.3 Ocean Tides and Load Tides

With the recent advances in modeling the ocean tides [e.g. *Shum et al.*, 1997], present altimetric missions sometimes provide for one empirically derived ocean tide model and one hydrodynamic ocean tide model on their data products. The benefit of providing both types of models on the data products is that the ocean tide effects can be removed from the sea surface height data with the use of either a data-dependent ocean tide model, or a data-independent ocean tide model. Furthermore, the hydrodynamic ocean tide models tend to provide better representations of the ocean tides in regions where the ocean tides have shorter wavelengths than can be observed by the spatial sampling characteristics of the altimeter ground track.

The models are usually provided on the data products as a field for the (ocean+load) tides, and a corresponding separate field for the associated radial load tide that was actually used to generate the (ocean+load) tide field. At least in the case of the T/P GDRs, the (ocean+load) tide fields provide radial (ocean+load) tide displacements using the diurnal and semidiurnal (ocean+load) tide heights as is provided by the chosen models, and adding to them a long-period pure ocean tide height that models the long-period ocean tides with a classical equilibrium response. Load tide displacements from the long-period ocean tides are ignored and not included in either of the (ocean+load) tide or load tide fields on the data products.

Here, the classical equilibrium long-period ocean tide response refers to a representation of the long-period ocean tide height as the product of the Love number factor $\gamma_n = (1 + k_n - h_n)$, and the long-period tidal potential. As with the body tide displacements provided on the data products, the permanent ocean tide is also excluded from the long-period ocean tide heights that are computed for the satellite altimetry data products by specifically removing the permanent tide (zero frequency) spectral component from the long-period tidal potential. The Love numbers used to compute the classical equilibrium long-period ocean tide are also assumed to be frequency independent. Again using the T/P GDRs as an example, the model for the long-period equilibrium ocean tides use the *Cartwright and Taylor* [1971] long-period tidal potential (excluding the permanent tide term), along with the Love numbers, $h_2 = 0.609$, $k_2 = 0.302$, $h_3 = 0.291$, and $k_3 = 0.093$.

The treatment of the long-period ocean tides is erroneous in many ways. Of most importance is the fact that the true long-period ocean tides probably do not have an equilibrium response to the tidal potential particularly at the periods of the two principal monthly and fortnightly tidal components. However, the equilibrium response for the long-period ocean tides is adopted because the long-period ocean tides are thought to have only small departures from an equilibrium response, and because the long-period ocean tides are an area of continuing investigation. Only very recently have models been developed that appear to model the long-period ocean tides better than the equilibrium response, and these models are still under evaluation. Indeed, data products for the upcoming Jason-1 altimetry mission will have fields for both the traditional classical equilibrium model of the long-period ocean tides, and a non-equilibrium model of the long-period ocean tides.

Nevertheless, even if the Earth's ocean tides did have an equilibrium response, the classical equilibrium model that has historically been adopted by the satellite altimetry data products ignores the effects of the loading and self-gravitation of the long-period ocean tides, and the requirement that the ocean tides conserve mass. The self-consistent equilibrium model of the long-period ocean tides, introduced by *Agnew and Farrell* [1978], would take these effects into account. Also, while the data products provide (ocean+load) tide heights from the diurnal and semidiurnal band, only pure ocean tide heights are being provided from the long-period band. It should however be conceded that those effects that are being ignored in the classical equilibrium representation of the long-period ocean tides are small enough ($<$ 1.0 cm) to ignore for most oceanographic applications of the altimetry data. More importantly, these effects are likely to be smaller than the actual departures of the true long-period ocean tide response from an equilibrium response.

3.4 Pole Tide

Those satellite altimetry data products that provide a model for the pole tide do so by assuming that the period of the oscillating rotation axis is long enough for the pole tide displacement of the solid Earth and the oceans to be in equilibrium with the centrifugal potential that is generated by the oscillating rotation axis [e.g. *Wahr*, 1985]. The data products provide a single field for the radial geocentric pole tide displacement of the sea surface, and includes the radial pole tide displacement of both the solid Earth and the oceans. The radial geocentric pole tide at a point on the surface with latitude ϕ and longitude λ is computed as the elastic equilibrium response to the centrifugal potential, V_c.

$$h_{pt} \quad = \quad (1 + k_2)\frac{V_c(\phi, \lambda)}{g} \tag{6}$$

$$V_c = -\frac{a^2\Omega^2}{2}\sin 2\phi\,[(x - x_{av})\cos\lambda - (y - y_{av})\sin\lambda] \quad (7)$$

The mean radius of the Earth, the mean rotation rate of the Earth, and the mean gravitational acceleration at the Earth's surface are denoted by a, Ω and g, respectively. The instantaneous location of the rotation axis, in units of radians, along the 0° meridian and 90°W meridian are denoted by x and y respectively, and x_{av} and y_{av} are the respective coordinates of the mean pole. Certainly, the Love number k_2 should be consistent with the long periods of 12 and 14 months that almost entirely describe the oscillation of the rotation axis, and IERS conventions [*McCarthy*, 1996] recommend using $k_2 = 0.2977$ for an elastic Earth. The pole location varies from its mean location by at most 0.8 arcseconds, which corresponds to a maximum geocentric pole tide displacement of approximately 5.5 cm. Any errors caused by ignoring anelastic effects are likely to be smaller than 1 mm and are therefore insignificant for altimetry applications. The use of equation (6) to model the pole tide is analogous to the use of the classical equilibrium response to model the long-period ocean tides. As such, it also ignores the self-gravitation and loading effects of the pole tide in the oceans.

Using T/P GDRs again as an example, the pole tide is computed using a value $k_2 = 0.302$ that is consistent with the Love number used to compute the long-period equilibrium ocean tides, and a mean pole location of $x_{av} = 0.042$ and $y_{av} = 0.293$ arcseconds. The difference between the Love number adopted for the T/P GDRs and that recommended in the IERS conventions implies a maximum error in the radial elastic geocentric pole displacement of less than 1 mm, which again is small enough to ignore.

4 Treatment of the Permanent Tide

4.1 Tidal Reference Frames

When describing the treatment of the permanent tide in geodetic quantities it become useful to define the various tidal reference frames to which the geodetic quantities refer. The following terminology which is most often used in discussions of the permanent tide [e.g. *Rapp et al.*, 1991; *Mathews*, 1999] is also used in this discussion of the permanent tide.

1. "Tide-free" values refer to values which exclude all tide effects.
2. "Mean" values refer to values which include both the direct and indirect permanent tide effects.
3. "Zero" values refer to values which include the indirect permanent tide effects only, and exclude the direct permanent tide effects.

Rapp et al. [1991] provide recommendations for the treatment of the permanent tide on the T/P GDRs and that discussion is extended here for general satellite altimetry applications.

4.2 The Permanent Tidal Potential and Deformations

In order to quantify the treatment of the permanent tide in satellite altimetry consider the direct permanent tide potential at the surface of the Earth, represented here by $\overline{V}$,

$$\overline{V} = \left(\frac{5}{4\pi}\right)^{1/2} H g P_{20}(\sin\phi) \quad (8)$$

$$P_{20}(\sin\phi) = (1.5\sin^2\phi - 0.5) \quad (9)$$

where P_{20} is the second degree unnormalized Legendre polynomial, and H is the permanent tide potential amplitude. The value of the permanent tide potential amplitude varies slightly in the literature where for example *Cartwright and Edden* [1973] have H = -0.31446 meters, or more recently *Tamura* [1987] has H = -0.314593 meters, while T/P algorithm specifications extrapolate the *Cartwright and Edden* [1973] tide potential to the T/P era and define H = -0.31458 meters.

The direct permanent tide potential causes the solid Earth to deform, with the radial component of this body tide deformation defined by $\overline{h}_b$.

$$\overline{h}_b = h_2(\omega_0)\frac{\overline{V}}{g} \tag{10}$$

The redistribution of mass associated with the permanent body tide results with an indirect permanent tide potential, $k_2(\omega_0)\overline{V}$. The total permanent tidal potential at the surface of the Earth and the geocentric equipotential surface of the permanent tide are then defined by $\overline{V}_t$ and $\overline{h}$, respectively.

$$\overline{V}_t = [1 + k_2(\omega_0)]\,\overline{V} \tag{11}$$

$$\overline{h} = \frac{\overline{V}_t}{g} = [1 + k_2(\omega_0)]\,\frac{\overline{V}}{g} \tag{12}$$

Here, $h_2(\omega_0)$ and $k_2(\omega_0)$ are used to explicitly indicate the requirement that second degree Love numbers at the zero frequency, ω_0, must be applied to the permanent tide.

The Love numbers at the zero frequency are presently unknown and are a subject for further investigation. However, present IERS conventions [*McCarthy*, 1996] use the fluid limit Love numbers, h_s and k_s, sometimes also referred to as the secular Love numbers, to define the tidal response at the zero frequency, $h_2(\omega_0) = h_s$ and $k_2(\omega_0) = k_s$. The fluid limit Love numbers are adopted at the zero frequency only because of a lack of observational evidence or any other theory that would indicate otherwise. The secular Love numbers are derived for a rotating Earth in hydrostatic equilibrium [*Lambeck*, 1980] and have the following important relationship.

$$h_s = (1 + k_s) \tag{13}$$

Lambeck [1980] defines k_s = 0.94, while *Mathews* [1999] defines k_s = 0.933 for the Preliminary Reference Earth Model (PREM). Use of the fluid limit Love numbers implies that the surface of the permanent body tide is coincident with the equipotential surface of the permanent tide, with $\overline{h}_b = \overline{h}$. This suggests that the solid Earth and the oceans react in tandem, as fluids, to the permanent tide potential.

If no specific relationship between the Love numbers $h_2(\omega_0)$ and $k_2(\omega_0)$ is assumed, then the classical equilibrium theory that is often applied to the long-period ocean tides might also be extended to the permanent ocean tide. Classical equilibrium theory derives the ocean tide displacement with respect to the ocean bottom, $\overline{h}_o$, by subtracting the body tide from the surface of the tide-generating potential.

$$\overline{h}_o = \overline{h} - \overline{h}_b = \mathcal{O}\,[1 + k_2(\omega_0) - h_2(\omega_0)]\,\frac{\overline{V}}{g} \tag{14}$$

Here, $\mathcal{O}$ defines the ocean function [e.g. *Munk and Macdonald*, 1960] which has a value of 1 over the oceans and 0 over land. Equation (14) further emphasizes that there is a zero net displacement of the ocean surface with respect to the ocean bottom if the fluid limit Love numbers are applied at the zero frequency, since $(1 + k_s - h_s) = 0$.

4.3 The Mean Sea Surface

From equations (2) and (3), and using $< X >$ to denote the mean value of a time dependent parameter X, the mean of the geocentric sea surface heights observed by satellite altimeters, $\langle h \rangle$, is:

$$\langle h \rangle = \langle h_{mss} \rangle + \langle h_t \rangle \tag{15}$$

For the purposes of this discussion it is assumed that $\langle h_c \rangle = 0$. If h_{bt} and h_{ot} are defined to include the respective indirect permanent tide deformations, then the mean deformation of all tidal quantities $\langle h_t \rangle = \overline{h}$, since over the oceans $\langle h_{bt} \rangle + \langle h_{ot} \rangle = \overline{h}_b + \overline{h}_o = \overline{h}$, and $\langle h_{lt} \rangle = \langle h_{pt} \rangle = 0$. The quantity h_{mss} would be considered to be the "tide-free" mean sea surface and $\langle h \rangle$ would be the "zero" or "mean" mean sea surface since $\langle h \rangle$ would include the indirect permanent tide deformation $\overline{h}$. In this case the "zero" and "mean" values are equivalent since there are no direct permanent tidal deformations. However, if h_{bt} is defined to exclude the indirect permanent tide deformation, then $\langle h_t \rangle = 0$, and $\langle h \rangle = h_{mss}$ and the mean sea surface h_{mss} would be the "zero" or "mean" value, defined to include the indirect permanent tide deformation, $\overline{h}$.

Rapp et al. [1991] recommend that reported sea surface heights "should have permanent tide effects included when the values are reported". In accordance with this recommendation, the zero frequency spectral line (permanent tide) component of the tidal potential is ignored when generating the radial body tide height and the classical equilibrium representation of the long-period ocean tide height for tidal fields on the T/P GDRs [*Benada*, 1997], such that $\langle h_t \rangle = 0$. The philosophy behind this recommendation appears to be based on the assumption that most users of satellite altimetry data subtract tidal effects from the observed geocentric sea surface heights. Since the subtracted tidal effects do not include the permanent tide then the residual geocentric sea surface heights are considered to be "zero" (or "mean") values since they include the indirect permanent tide deformation, $\overline{h}$. As a consequence of these recommendations, a mean sea surface generated from the "zero" valued geocentric sea surface heights would therefore be considered to be a "mean", or equivalently "zero", mean sea surface, and the observed geocentric dynamic sea surface heights with respect to that mean surface would be "tide-free" values.

4.4 The Geopotential and Geoid

The treatment of the permanent tide with respect to the POD of the satellite, and the definition of a geoid height are also of particular importance to satellite altimetry. The POD of the satellite is necessary to derive the geocentric satellite altitude, and to subsequently derive the geocentric sea surface height that is observed by the altimeter. The geoid height is sometimes used as an alternative to the mean sea surface as the reference for the geocentric dynamic sea surface heights. Both of these applications require knowledge of the Earth's geopotential and the treatment of the permanent tide with respect to the adopted geopotential is necessary to ensure that the complete altimetric system is in a consistent tidal reference frame.

The Earth's geopotential, W, is represented here by the usual spherical harmonic expansion,

$$W = \frac{GM}{a} \sum_n \sum_m \left(\frac{a}{r}\right)^{n+1} P_{nm}(\sin\phi)\,[C_{nm}\cos(m\lambda) + S_{nm}\sin(m\lambda)] \tag{16}$$

where GM is the product of the gravitational constant and the mass of the Earth, and r, λ, and ϕ are the spherical coordinates of a point external to the surface of the Earth. For simplicity, here unnormalized spherical harmonic coefficients C_{nm} and S_{nm} are used. Also pertinent to this discussion is the oblateness term $J_2 = -C_{20}$. The direct permanent tide potential in equation (8) can be rewritten in a form that is easily compared to the spherical harmonic coefficients in equation (16) by considering the potential W at the surface of the Earth ($r = a$).

$$\overline{V} = \frac{GM}{a} C_{20}^{pt} P_{20}(\sin\phi) \quad (17)$$

$$C_{20}^{pt} = \left(\frac{5}{4\pi}\right)^{1/2} H g \frac{a}{GM} \quad (18)$$

Using constants from the IERS conventions [*McCarthy*, 1996], and the permanent tide potential amplitude from *Tamura* [1987], then C_{20}^{pt} = -3.10555 e-8. For the following discussion a corresponding oblateness coefficient for the the permanent tide, $J_2^{pt} = -C_{20}^{pt}$, is also defined.

The question arises as to which tidal reference frame is being referred to by the C_{20} geopotential coefficient. In order to distinguish between the three tidal reference frames, three different values of J_2 are explicitly defined here, with J_2^{tf}, J_2^{m}, and J_2^{z} being the "tide-free", "mean", and "zero" values respectively.

$$J_2^m = J_2^{tf} + [1 + k_2(\omega_0)]\, J_2^{pt} \quad (19)$$

$$J_2^z = J_2^{tf} + k_2(\omega_0) J_2^{pt} \quad (20)$$

Of course, without any better knowledge the fluid limit Love number k_s should also be applicable for the geopotential and in fact section 6 of the IERS conventions [*McCarthy*, 1996, p. 47] states that "...to obtain the effect of the permanent tide on the geopotential, one can use the same formula as equation (6) using the fluid limit Love number which is $k = 0.94$".

The POD of satellites requires use of both a geopotential and a background body tide model to determine the total potential acting on the satellite. It should be emphasized that very often the direct and indirect potential arising from the body tides are not derived from spectrally decomposed tide potentials, but rather from lunar and solar ephemerides, as is the case in the IERS conventions [Section 6, *McCarthy*, 1996]. In doing so, a constant Love number k_{nm} is usually assumed across each degree (n) and order (m) of the tide potential. For the second degree zonal term ($n = 2, m = 0$), a Love number k_{20} of approximately 0.3 is usually used. In such cases the indirect permanent tide contribution is then restored to the geopotential either beforehand by removing a term $k_{20}J_2^{pt}$ from the complete indirect tide potential that is computed from the luni-solar ephemerides to ensure use of only the time varying part of the indirect tide potential, or after the fact by adding a term $k_{20}J_2^{pt}$ back into the applied or estimated geopotential. In doing so, the geopotential is always defined in the "zero" tidal reference frame.

The potential for confusion, particularly with regards to the defined terminology, when restoring the geopotential to its "zero" value should be quite evident. For example, *Lemoine et al.* [1998, pp. 3-14, eq. 3.3.1-5], have adopted what they refer to be a "zero" J_2 value for that project that is defined as follows:

$$J_2(\text{zero}) = J_2(\text{tide-free}) + (0.3 \times 3.11080e - 8) \quad (21)$$

Evidently, the terms "tide-free" and "zero" are inconsistent with each other in this equation since the Love number applied to the permanent tide is a value of 0.3. A similar conflict with terminology appears to be evident in *Rapp et al.* [1991], where the J_2 value from the GEM-T2 model is referred to be the "tide-free" value, and the "zero" value is restored with the use of a Love number of 0.3. It is likely that the defined "zero" value is consistent with the defined terminology, but what has been referred to as the "tide-free" value is probably not consistent and is instead some "pseudo-tide-free" value that is really $J_2^{tf} + [k_2(\omega_0) - k_{20}]J_2^{pt}$. Namely, the "zero" value is simply restored by adding the adopted background indirect permanent tide potential, $k_{20}J_2^{pt}$ to the "pseudo-tide-free" value, as is described above.

The geoid is an equipotential surface that very closely represents the mean sea surface. The geoid is another commonly used reference surface that is provided in the satellite altimeter data products. Denoting W (see equation (16)) as the Earth's geopotential, and U as the normal potential defined by an equipotential reference ellipsoid, then a disturbing potential T is determined as:

$$T = W - U \tag{22}$$

The geoid height, N can be computed from Bruns' formula [*Heiskanen and Moritz*, 1993]:

$$N = \frac{T}{\gamma} \tag{23}$$

where γ is the normal value of gravity. For clarity, "tide-free", "mean", and "zero" geopotentials, W^{tf}, W^m, and W^z, and normal potentials, U^{tf}, U^m, and U^z, are explicitly defined here, where:

$$W^m = W^{tf} + [1 + k_2(\omega_0)]\,\overline{V} \tag{24}$$
$$W^z = W^{tf} + k_2(\omega_0)\overline{V} \tag{25}$$
$$U^m = U^{tf} + [1 + k_2(\omega_0)]\,\overline{V} \tag{26}$$
$$U^z = U^{tf} + k_2(\omega_0)\overline{V} \tag{27}$$

Similarly, the corresponding "tide-free", "mean", and "zero" valued geoid heights with respect to the respective reference ellipsoid are defined as follows:

$$N^{tf} = \frac{(W^{tf} - U^{tf})}{\gamma} \tag{28}$$
$$N^m = \frac{(W^m - U^m)}{\gamma} \tag{29}$$
$$N^z = \frac{(W^z - U^z)}{\gamma} \tag{30}$$

As long as the geopotential and the normal potential are defined in identical tidal reference frames, the geoid height with respect to the equipotential reference ellipsoid would itself be tide-free in the strictest sense, with $N^{tf} = N^z = N^m$. Meanwhile the geocentric geoid surface, $N_g = W/\gamma$, would be in a tidal reference frame that is identical to that used for the two potentials U and W. As such, it is really the tidal reference frame of the equipotential reference ellipsoid that is important.

With the nomenclature defined above, the "tide-free", "mean", and "zero" geocentric geoid surfaces would then be defined by N_g^{tf}, N_g^m, and N_g^z.

$$N_g^{tf} = N^{tf} + \frac{U^{tf}}{\gamma} \tag{31}$$
$$N_g^m = N^m + \frac{U^m}{\gamma} = N_g^{tf} + [1 + k_2(\omega_0)]\,\frac{\overline{V}}{\gamma} \approx N_g^{tf} + \overline{h} \tag{32}$$
$$N_g^z = N^z + \frac{U^z}{\gamma} = N_g^{tf} + k_2(\omega_0)\frac{\overline{V}}{\gamma} \tag{33}$$

By making the approximation $\gamma \approx g$, and inserting equation (12) into equation (32) it should be realized that the "mean" geocentric geoid surface is consistent with the "mean" mean sea surface in the sense that both surfaces include the permanent body and ocean tide displacement. Therefore, for satellite altimetry applications, which usually define the mean sea surface in the "mean" tidal reference frame, the geocentric geoid surface should also be provided in the "mean" tidal reference frame. In this way, geocentric dynamic sea surface heights that are referenced to the "mean" geoid would be "tide-free" values, just as they would be if referenced to the "mean" mean sea surface. Given a "zero" geocentric geoid surface N_g^z, the "mean" geocentric geoid surface is simply derived as follows:

$$\begin{aligned} N_g^m &= N_g^z + \frac{\overline{V}}{g} \\ &= N_g^z + \left(\frac{5}{4\pi}\right)^{1/2} H P_{20}(\sin\phi) \end{aligned} \tag{34}$$

where the approximation $\gamma \approx g$ is made. Note that equation (19) of *Rapp et al.* [1991] is an equivalent expression to equation (34).

Rapp et al. [1991] recommend adopting the "mean" geoid on the T/P GDRs in order to have the provided geoid surface and mean sea surface both defined in the identical "mean" tidal reference frame. They recommend generating this geoid height with respect to the reference ellipsoid by adding the term $[(5/4\pi)^{\frac{1}{2}} H P_{20}(\sin\phi)]$ to the "zero" geoid height N^z. Of course, this adjustment to the "zero" geoid height is only appropriate if the reference ellipsoid is defined to be in the "zero" tidal frame. However, it is unclear from T/P documentation whether or not the adopted reference ellipsoid is in the "zero" tidal reference frame, and the reference ellipsoid is simply defined by an Earth radius of 6378.1363 km and a flattening of 1/298.257. Nevertheless, this adjustment to the geoid height has been adopted in the T/P GDRs.

5 Capability of Determining Tidal Effects and Parameters

Recent satellite altimeter missions, and in particular the Geosat Exact Repeat Mission and the T/P mission, have provided significant improvements to our knowledge of the Earth's ocean tides, and particularly our knowledge of the diurnal and semidiurnal ocean tides. This is due in large part to the fact that the ocean tides are the dominant signal in the geocentric dynamic sea surface heights observed by satellite altimeters. Our knowledge of the Earth's long-period ocean tides has also been somewhat improved from satellite altimetry. However, investigation of the Earth's long-period ocean tides is still very much a subject of continuing investigations that are likely to continue to improve our knowledge of these ocean tides as longer durations of high accuracy altimetric data become available.

The first three years after the T/P mission saw significant interest in modeling the ocean tides with more than 20 new models becoming available during that period [e.g. *Andersen et al.*, 1995; *Shum et al.*, 1997]. These models ranged from purely empirical models that were derived from the new generation of altimetric data, to purely hydrodynamic models whose goal was to model the ocean tides for oceanographic use of the altimetric data, and subsequently to hybrid models that either assimilated empirical models into hydrodynamic equations of motion or estimated empirical adjustments to apriori hydrodynamic models. The empirical and hybrid ocean tide models agree with each other to within 2-3 cm [*Shum et al.*, 1997], and are likely to have similar accuracies at least in the deep oceans [e.g. *Desai et al.*, 1997]. This should be of no surprise as all of the models are somewhat dependent on the same T/P sea surface height observations.

Some of the most recent global ocean tide models, among the many that are available, include those from *Eanes* [1999], *Ray* [1999], and *Le Provost et al.* [1998]. Each of these three models might be considered to be hybrid models that in some fashion take advantage of the higher spatial resolution that is available from hydrodynamic models while using the satellite altimetry data to constrain the long wavelength response of the ocean tides. The high accuracy and long duration of the T/P altimetry data has also sparked interest in the so called overtides which principally occur in shallow water regions. They are caused by the nonlinear interaction between the principal ocean tides. *Andersen* [1999] has used T/P altimetry data to observe the M_4 and M_6 ocean tides in the northwest European shelf region, where in some cases the amplitude of the M_4 constituent can exceed 50 cm. Certainly, such large ocean tides should have associated load tide effects on neighboring regions and future analyses should probably be extended to include investigations of load tide effects from the overtides.

The new generation of ocean tide models that have been developed from the T/P sea surface height data have been used to predict the effects of the ocean tides on the Earth's polar motion and rotation rate. For example, a comparison by *Chao et al.* [1995] of VLBI observations of the diurnal and semidiurnal tidal variations of the Earth's rotation rate to respective variations that are predicted by T/P-derived ocean tide models shows good agreement to within 2-3 microseconds. A similar comparison by *Chao et al.* [1996] for diurnal and semidiurnal tidal variations in polar motion also shows good agreement to within 10-30 microarcseconds for the largest tides. *Desai and Wahr* [1999] used a T/P-derived model of the monthly and fortnightly ocean tides to predict the effects of these long-period ocean tides on the Earth's rotation rate. This analysis indicates that the predicted fortnightly variations of the Earth's rotation rate are fairly well determined from the T/P ocean tide model, but that there is potential for improvement of the the predicted monthly variations of the Earth's rotation rate, particularly in the component that results from tidal currents.

The high accuracy of the ocean tide models that have recently been determined from satellite altimetry also allows use of these models to place observational constraints on the anelasticity of the Earth at the tidal periods. This is particularly useful since observations of the anelasticity of the Earth have usually been limited to the seismic periods of approximately 1 hour and the Chandler wobble period of 14 months, while the tidal periods principally range from 12 hours to 28 days. Ocean tide models that are derived from satellite altimetry, and the spherical harmonic coefficients of the ocean tides that are determined from satellite tracking data, are both usually based on elastic Earth tide models. Therefore, the ocean tide coefficients that are determined from each of the two geodetic techniques actually include the effects from the anelasticity of the Earth, although the coefficients derived from satellite altimetry data are far less sensitive to the Earth's anelasticity than those derived from satellite tracking data. Reconciling the coefficients from the two geodetic techniques provides an estimate of the anelasticity in the solid Earth. *Ray et al.* [1996] have performed such a comparison using a T/P-derived model of the M_2 ocean tide, which has a period of 12.4 hours. Their estimates of the lag in the body tide due to anelasticity agrees well with theoretical estimates. In a similar fashion, observational constraints on the Earth's anelasticity at periods of 5-30 days can also be determined by reconciling observed long-period tidal variations of the Earth's rotation rate with the predicted contributions to these variations from the respective elastic body tides and ocean tides. The residual in the observed variations after removing the respective contributions from the elastic body tide and the ocean tide is explained by mantle anelasticity. A preliminary analysis by *Desai and Wahr* [1998] that determines this residual at the fortnightly period by using a T/P-derived ocean tide model to predict the contribution from the ocean tides, also shows good agreement between this residual and theoretical estimates of the contribution from mantle anelasticity.

Satellite altimetry also has the capacity to place constraints on the Love number h_2. A preliminary analysis by *Ray et al.* [1995] provides estimates of h_2 at the M_2, N_2, O_1, and K_1 frequencies by combining tidal estimates from satellite altimetry with in situ measurements of the ocean tides. They use the satellite altimeter data to determine the total tidal displacement of the sea surface.

A model for the load tides is used to determine the load tide contribution, and the ocean tide contribution is determined from in situ tide gauge measurements. The remaining tidal displacements at the location of the tide gauge sites results from the body tides as observed by the satellite altimeter. The results from *Ray et al.* [1995] clearly indicate the effect of the FCN resonance at the K_1 frequency, and also provide good agreement with VLBI observations and theoretical estimates of h_2 at the M_2 frequency.

6 Limitations

The finite sampling of the ocean surface by satellite altimeters limits observations of the Earth's ocean tides to only the response which is of longer wavelength than the spatial sampling interval of the neighboring ground tracks. This means that it becomes difficult to observe and model the ocean tides from altimetric data in those areas where the ocean tide response has relatively large gradients. Fortunately, areas with large gradients usually occur in shallow water and coastal areas, which only account for a minor part of the Earth's oceans. As a consequence, the altimetric ocean tide models have already provided significant advances to global geodetic applications that only require knowledge of the long-wavelength response of the ocean tides. However, more localized geodetic applications still have the potential for significant future improvements both from longer durations of altimetric data and from the combination of data from multiple altimetry missions. For example, limitations in the accuracy of load tide models that are derived from the altimetric ocean tide models should be evident in regions both over land and the oceans that lie near areas with large gradient ocean tides, such as near coastlines.

Indeed, most of the recent ocean tide models show good agreement (within 2-3 cm) in the majority of the oceans, but can differ from each other by more than 10 cm in some shallow water areas. This limitation is especially significant in purely empirical ocean tide models that are derived exclusively from the altimetric data without any apriori assumptions about bathymetry or hydrodynamics. On the opposite end of the spectrum, purely hydrodynamic models are limited by poor knowledge of bathymetry and friction. It is the hybrid models that generally provide a good compromise by allowing the altimetric data or models to constrain the hydrodynamic equations of motion with the observed long wavelength response of the oceans, while applying the hydrodynamic model at a higher spatial resolution than is available from the sampling characteristics of the satellite ground track.

Satellite altimetry also has the fundamental limitation that results from the fact that radar altimeters cannot be used over ice sheets. As such, most oceanographic satellite altimeters have orbits that are configured to limit sampling over ice sheets while maximizing sampling of areas not covered by ice. This limits the use of satellite altimetry to observing the Earth's tides only in those areas within latitudes of approximately ± 70 degrees. Hydrodynamic ocean tide models still provide the best method of modeling the ocean tides in polar regions that are usually covered by ice sheets. This limitation is particularly important in tidal components such as the long-period ocean tides whose principal spherical harmonic component, the second degree zonal component, is particularly sensitive to the response in the extreme polar latitudes.

7 Future Perspectives

The current treatment of tidal effects in satellite altimetry data products appears to be sufficient for the accuracies that are presently available from satellite altimetry sea surface height measurements. However, as the accuracy of future satellite altimeters improves to the level of 1 cm (or better) it is likely that closer attention will need to be given to some of the finer details that are involved with modeling the tidal effects. In particular, the treatment of the body tides would probably need to be brought closer in tune with the IERS conventions, particularly with regards to the use of frequency dependent Love numbers. The treatment of the long-period ocean tides also has the potential for improvement, by using non-equilibrium models for the shorter period (< 30 days) constituents, by adopting a self-consistent equilibrium representation of the longer period constituents that are more likely to have an equilibrium response, and by accounting for the long-period load tides.

Certainly, data from multiple altimeter missions and longer durations of altimetry data are likely to continue to provide improvements to our knowledge of the Earth's ocean tides and consequently the load tides. In particular, there is potential for improvement in the spatial resolution of the altimetric ocean tide models particularly in high gradient areas such as shallow water and coastal regions. Indeed there are plans to have the soon to be launched T/P follow on satellite, Jason-1, and the T/P satellite fly on interleaving ground tracks. Meanwhile the accuracies of the smaller amplitude tidal components are likely to improve as longer durations of data become available. Improved accuracies in the long-period monthly and fortnightly ocean tide models are especially anticipated, while expanded interest in observing and modeling the overtides should also be expected. The improvements to the spatial resolution and accuracies of the altimetric tidal observations are likely to be accompanied by revised analyses of other geophysical applications of the altimetric tidal observations, many of which have so far only been preliminary analyses.

From the discussion on the treatment of the permanent tide it becomes evident that the actual values of the Love numbers at the zero frequency are neither important or necessary in satellite altimetry. The geopotential can always be defined in the "zero" tidal reference frame with knowledge of the Love number that has been adopted in the background body tide model that is used when generating the geopotential, and without explicit knowledge of the Love number $k_2(\omega_0)$. It is the tidal reference frame of the adopted reference ellipsoid that is of most importance to satellite altimetry. This is particularly true since all parameters including the altitude, sea surface height, mean sea surface, and geoid are usually provided with respect to the reference ellipsoid. Perhaps the least confusing method of dealing with the permanent tide would be to define the reference ellipsoid in the "mean" tidal reference frame. This only requires knowledge of the "zero" geopotential and the permanent tidal potential. In this way, the physical representation of the reference ellipsoid would include the deformation that results from the permanent body and ocean tides. The altimetric sea surface height, the mean sea surface height, and the geoid height with respect to this ellipsoid would then all be "tide-free", while the respective geocentric values would all be in the "mean" tidal frame. No adjustment of the geoid height as is defined by equation (34) would be necessary, and any potential for confusion that might arise from such adjustments would be removed, particularly with regards to the consistency of this adjustment with the defined reference ellipsoid.

Acknowledgements

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8 References

1. Agnew, D. C., and W. E. Farrell, Self-consistent equilibrium ocean tides, *Geophys. J. R. Astro. Soc.*, 55, 171-181, 1978.

2. Andersen, O. B., P. L. Woodworth, and R. A. Flather, Intercomparisons of recent ocean tide models, *J. Geophys. Res.*, 100 (C12), 25261-25282, 1995.

3. Andersen, O. B., Shallow water tides in the northwestern European shelf region from TOPEX/ POSEIDON altimetry, *J. Geophys. Res.*, 104 (C4), 7729-7741, 1999.

4. Benada, J. R., Physical Oceanography Distributed Active Archive Center, PO.DAAC, Merged GDR (TOPEX/POSEIDON) Generation B, MGDR-B, Version 2.0, June 23, 1997.

5. Cartwright, D. E., and A. C. Edden, Corrected Tables of Tidal Harmonics, *Geophys. J. R. Astro. Soc.*, 33, 253-264, 1973.

6. Cartwright, D. E., and R. J. Taylor, New computations of the tide-generating potential, *Geophys. J. R. Astro. Soc.*, 23, 45-74, 1971.

7. Chao, B. F., R. D. Ray, and G. D. Egbert, Diurnal/semidiurnal oceanic tidal angular momentum: Topex/Poseidon models in comparison with Earth's rotation rate, *Geophys. Res. Lett.*, 22, 1993-1996, 1995.

8. Chao, B. F., R. D. Ray, J. M. Gipson, G. D. Egbert, and C. Ma, Diurnal/semidiurnal polar motion excited by oceanic tidal angular momentum, *J. Geophys. Res.*, 101, (B9), 20,151-20,163, 1996.

9. Desai, S. D., J. M. Wahr, Y. Chao, Error analysis of empirical ocean tide models estimated from TOPEX/POSEIDON altimetry, *J. Geophys. Res.*, 102 (C11), 25157-25172, 1997.

10. Desai, S. D., and J. M. Wahr, Monthly and fortnightly ocean tide models empirically estimated exclusively from TOPEX/POSEIDON altimetry with implications for mantle anelasticity, *EOS Trans. AGU*, 79, 1998.

11. Desai, S. D., and J. M. Wahr, Monthly and fortnightly tidal variations of the Earth's rotation rate predicted by a TOPEX/POSEIDON empirical ocean tide model, *Geophys. Res. Lett.*, 26 (8), 1035-1038, 1999.

12. Eanes, R. J., An improved ocean tide model from satellite altimetry, *EOS Trans. AGU*, 80(46), 1999.

13. Heiskanen, W. A., and H. Moritz, Physical Geodesy, reprint, Institute of Physical Geodesy, Technical University, Graz, Austria, 1993.

14. Lambeck, K., The Earth's variable rotation: Geophysical causes and consequences, Cambridge University Press, 1980.

15. Lemoine, F. G. et al., The development of the joint NASA GSFC and the national imagery and mapping agency (NIMA) geopotential model EGM96, NASA Tech. Memo. 206861, 1998.

16. Le Provost, C., M. L. Genco, F. Lyard, P. Vincent, and P. Canceil, Tidal spectroscopy of the world ocean tides from a finite element hydrodynamic model, *J. Geophys. Res.*, 99 (C12), 24777-24798, 1994.

17. Le Provost, C., F. Lyard, J. M. Molines, M. L. Genco, and F. Rabilloud, A hydrodynamic ocean tide model improved by assimilating a satellite altimeter-derived data set, *J. Geophys. Res.*, 103 (C3), 5513-5529, 1998.

18. Mathews, P. M., V. Dehant, J. M. Gipson, Tidal station displacements, *J. Geophys. Res.*, 102 (B9), 20,469-20,477, 1997.

19. Mathews, P. M., Explanatory Supplement to the Section "Treatment of the Permanent Tide" of the IERS Conventions (1996), Deutsches Geodatisches Forschungsinstitut, Report 71, editor H. Schuh, pp 9-12, 1999.

20. McCarthy, D. D., IERS Conventions (1996), IERS Technical Note 21, July 1996.

21. Munk, W. H. and G. J. F. Macdonald, The Rotation of the Earth, a Geophysical Discussion, Cambridge at the University Press, 1960.

22. Rapp, R. H., R. S. Nerem, C. K. Shum, S. M. Klosko, R. G. Williamson, Consideration of permanent tidal deformation in the orbit determination and data analysis for the TOPEX/ POSEIDON mission, NASA Tech. Memo. 100775, January, 1991.

23. Ray, R. D., S. Bettadpur, R. J. Eanes, E. J. O. Schrama, Geometrical determination of the Love number h_2 at four tidal frequencies, *Geophys. Res. Lett.*, 22 (16), 2175-2178, 1995.

24. Ray, R. D., R. J. Eanes, and B. F. Chao, Detection of tidal dissipation in the solid Earth by satellite tracking and altimetry, *Nature*, 381, 595-597, 1996.

25. Ray, R. D., A global ocean tide model from TOPEX/POSEIDON altimetry: GOT99.2, NASA Tech. Memo. 209478, 1999.

26. Schuh, H., Explanatory Supplement to the IERS Conventions (1996), Chapters 6 and 7, An Overview, Deutsches Geodatisches Forschungsinstitut, Report 71, editor H. Schuh, pp 5-8, 1999.

27. Shum et al., Accuracy assessment of recent ocean tide models, *J. Geophys. Res.*, 102 (C11), 25173-25194, 1997.

28. Tamura, Y., A harmonic development of the tide-generating potential, *Bulletin d'Informations Marees Terrestres*, 99, 6813-6855, 1987.

29. Wahr, J. M., Deformation Induced by Polar Motion, *J. Geophys. Res.*, 90 (B11), 9363-9368, 1985.

Gravity Monitoring with a Superconducting Gravimeter in Vienna

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Introduction

Since August 1995 the superconducting gravimeter GWR C025 is operating in the seismic laboratory of the Central Institute of Meteorology and Geodynamics in Vienna (Austria). The laboratory is situated in the basement of the institute's main building where a concrete pillar is founded deeply in Alluvial sediments. The main goal of research is the determination of both tidal and non-tidal gravity variations by combining continuous records with repeated absolute gravity measurements. The latter will be performed by using an upgraded Jila-g type absolute gravimeter. All these investigations will contribute to the Global Geodynamics Project (GGP) started in July 1997.

The SG gravimeter has been set up at a preliminary site and will be moved to its final position at the new Conrad Observatory that will be constructed 60 km SE of Vienna next year. This station is far away from sources of industrial noise in contrast to the actual site which is situated at the margin of Vienna. Nevertheless, the results obtained from a 2 years' observation are of high quality. The instrument exhibits a linear and very small drift of about 30 nms^{-2}/a only. Therefore, it is especially suited to monitor non-periodic and long period gravity variations.

The data acquisition is carried out with CSGI software (Dunn 1995) running on a PC with a QNX operating system. All data samples are triggered by a GPS time signal. The high resolution gravity output channel (HR-GRAV) is read by a HP3457A digital multimeter with 1 Hz sampling rate. The air pressure signal is sampled with 0.1 Hz by a Keithley 2000 digital scanner that also monitors in one minute intervals additional instrumental and environmental parameters like the tide filter output signal, two tilt signals, the neck temperatures at the 11 K and 70 K stage, the room and electronics temperature and the liquid Helium flow rate. Since September 1997 a new gravity card (Warburton 1997) is operating that meets the GGP requirements.

Calibration

The initial calibration has been performed by comparing the filtered gravimeter signal with the synthetic earth tide model of Timmen and Wenzel (1995) including the ocean effects. In

1996 the instrument has been calibrated by comparison with absolute gravity measurements performed by Jila g-6 (Figure 1). The absolute gravity has been observed during 2.5 days. After elimination of outliers, about 9000 single drops could be used for the linear regression analysis. Unfortunately the drop to drop scatter is rather high at the station in Vienna which limits the calibration accuracy. In addition, the observation period is probably too short to get more accurate results (Hinderer et al. 1997, Francis 1997), but further calibrations could not be performed till now because of remaining instrumental problems after servicing and an absolute gravimeter's upgrade. Of course calibrations will be repeated regularly in future.

The initial calibration factor turns out to be correct within the error band, but because of the high seismic noise level the accuracy is not better than 0.7%. Additionally the calibration factor is confirmed by comparing tidal analysis results with those obtained at the same station in 1986 (Figure 2) by analyzing a 6 months observation period of LaCoste-Romberg D-9 (Meurers 1987) equipped with an electronic feedback system SRW-D (Schnüll et al. 1984). The feedback has been calibrated at the precise vertical calibration line in Hannover (Kanngieser et al. 1983). In order to check the temporal stability of the SG's calibration factor several successive and non-overlapping data sets covering a 83 day interval have been investigated. The instrumental time lag being changed since installation of the new gravity circuit card has been considered accordingly. Figure 3 shows the adjusted tidal parameters for the main tidal waves O_1 and M_2. The standard deviation of the amplitude factors amounts for both components 0.0002 only.

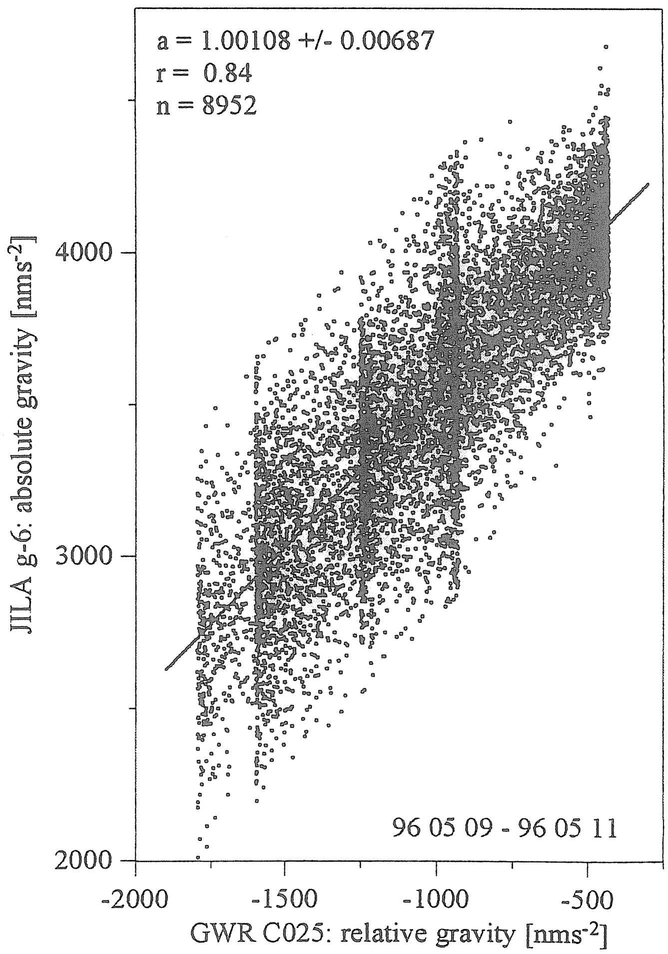

Fig. 1: Linear regression analysis of absolute gravity data (Jila g-6) and relative gravity obtained from GWR C025 (a = regression coefficient, r = correlation coefficient, n = number of samples).

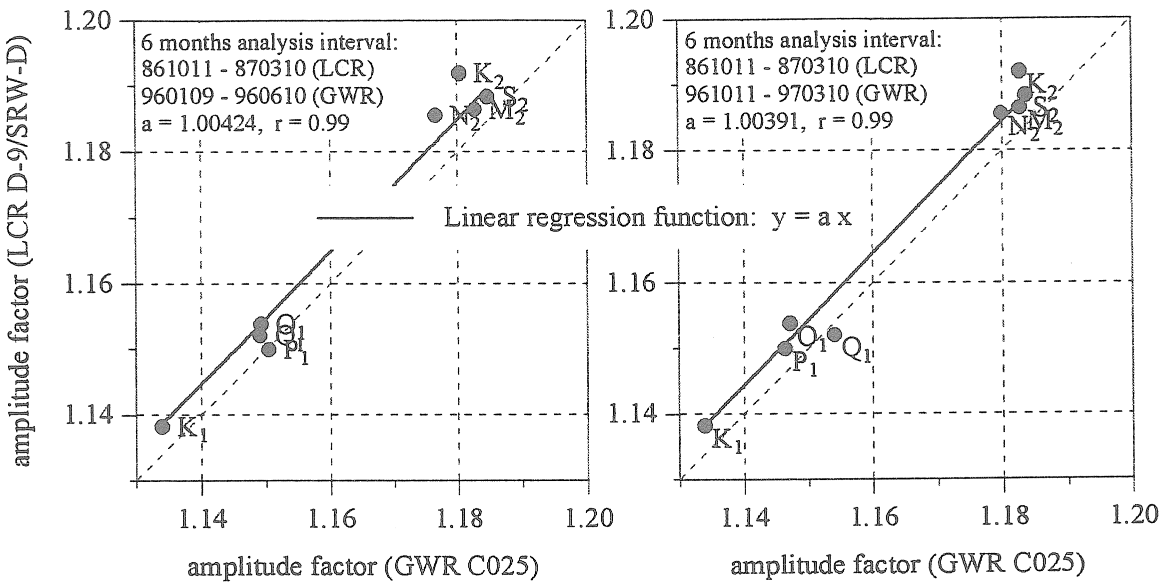

Fig. 2: Comparison of tidal parameters obtained by analyzing 6 months' observation periods from data of LCR D-9 (equipped with electronic feedback system SRW-D) and GWR C025. The regression analysis (a = regression coefficient, r = correlation coefficient) yields same results for independent GWR time series proving the time stability of the calibration factor.

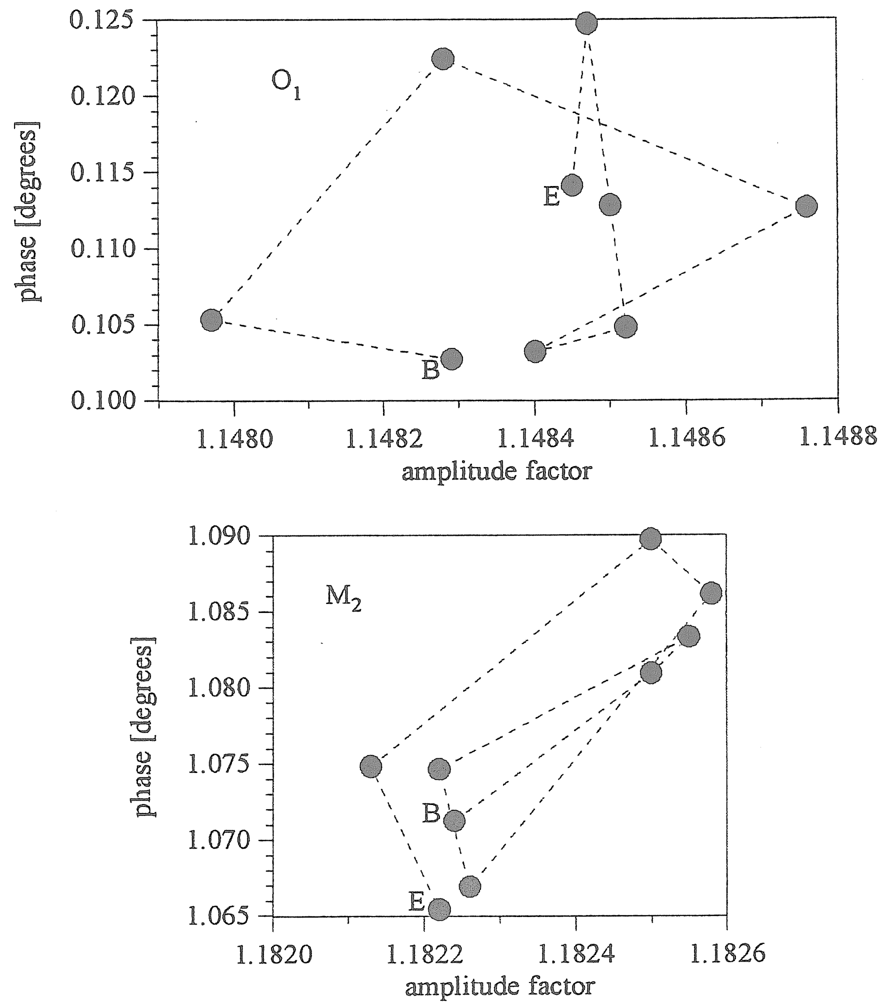

Fig. 3: Tidal parameters (O_1 and M_2) obtained by analyzing successive non-overlapping intervals of 83 days each. B: first observation period, E: last interval, the only one with the new gravity card installed.

Frequency transfer function

During the installation of the new gravity circuit card in September 1997 the frequency transfer function of the complete recording system has been determined for both the original and the new gravity card by applying the step response method. The step response data have been analyzed by Wenzel's (1994) program ETSTEP using discrete Fourier transform of their time derivative.

Because of the improved filter characteristics of the new card the results are much more sensitive to the microseismic noise than those of the old gravity card. This is a severe problem at noisy stations like Vienna. In order to reduce the random noise contribution the data of up to 10 single steps have been averaged after detiding. Figure 4 shows the differentiated step response functions of about ten single steps and their average for two experiments performed with the old and the new card respectively. Averaging is obviously effective. However, small amplitude disturbances still remain in the case of the new card. Therefore the desired accuracy of 10 ms could not be obtained because of the high noise level at the station in Vienna. Table 1 compares the results of time lag determination and the errors within the tidal band. The statistical evaluation was done in two different ways. First a mean time lag has been calculated using the results from all single steps in upward and downward direction respectively. Afterwards the averaged step response data has been analyzed separately for each step direction. Table 1 shows that the final average values of the time lag do not depend on the evaluation method. The transfer function seems to be well determined which is confirmed by the tidal analysis results. Both the amplitude factors and phases did not change significantly since the new gravity card has been installed. This is shown in Figure 3 where the symbol E marks the results obtained with the new configuration.

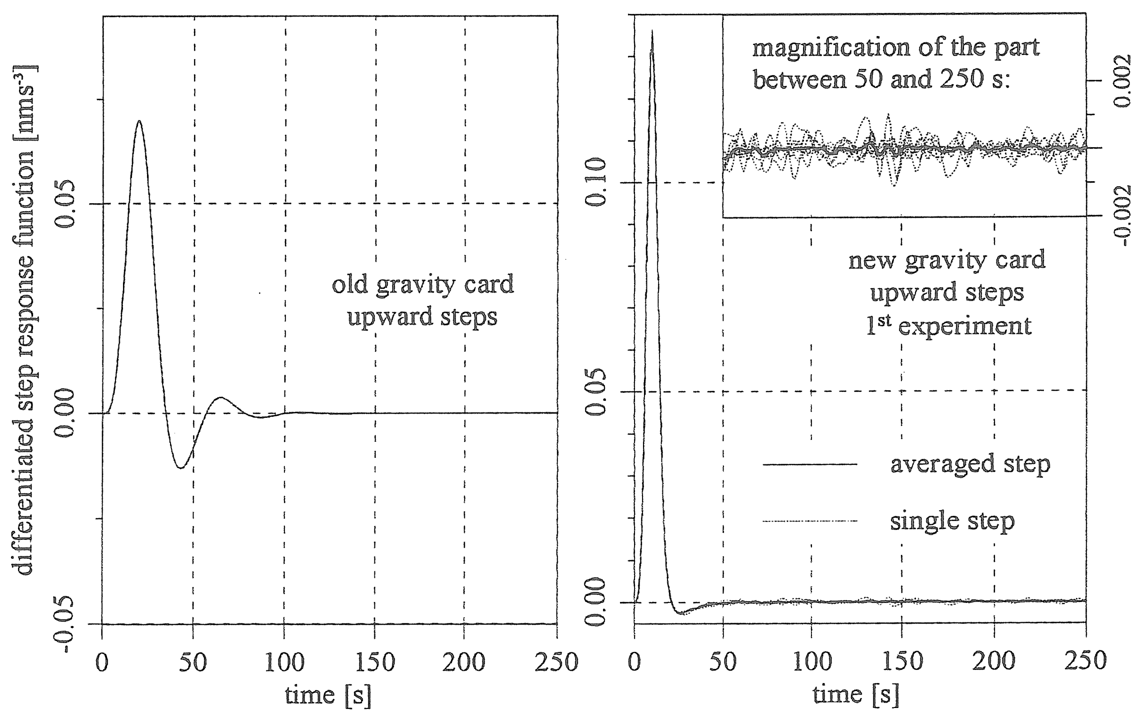

Fig. 4: Step response of the recording system with the old (left) and the new (right) gravity circuit card. Small disturbances remain after averaging the step response data in case of the new card (see details at the top of the graph).

old gravity card					mean
step direction	upward	downward			
number of single steps	10	10			
single step statistics:					
average	17.005	16.994			16.999
standard deviation	± 0.041	± 0.039			± 0.039
mean error	± 0.013	± 0.012			± 0.009
averaged steps	17.005	16.999			17.002
standard deviation					± 0.004
new gravity card					**mean**
step direction	upward	downward	upward	downward	
number of single steps	10	9	9	10	
single step statistics:					
average	9.401	9.374	9.366	9.267	9.349
standard deviation	± 0.102	± 0.204	± 0.081	± 0.034	± 0.126
mean error	± 0.032	± 0.068	± 0.027	± 0.010	± 0.020
averaged steps	9.402	9.374	9.366	9.255	9.349
standard deviation					± 0.065

Tab. 1: Time lag [s] of the recording system in the tidal band.

Tidal analysis and residual determination

Preprocessing and tidal analysis of the raw data sampled with 1s interval has been performed by applying the ETERNA v3.3 software package of Wenzel (1996) and the programming module GSOFT of Vauterin (1997). Only a few big disturbances caused by earthquakes had to be removed manually. Also, two manual offset corrections were necessary in order to remove two steps caused by a power supply interruption (190 nms^{-2}) and the exchange of the gravity card (−16 nms^{-2}) respectively. These step corrections have been determined precisely by adjusting low degree polynomials to small portions of the raw data separately for both sides of the step. Further, despiking and destepping has been performed automatically applying thresholds of 2 and 5 nms^{-2} respectively for spike and step detection. Intensive test calculations with different despiking and destepping limits show adjusted tidal parameter to be almost independent on the thresholds applied. This justifies the application of automatic preprocessing. Within the more than 2 years long observation period only three small steps (< 40 nms^{-2}) have been removed by this automatic procedure.

Table 2 summarizes the analysis results based on the Tamura (1987) tidal potential. The noise estimate of the amplitude spectrum is less than 0.03 nms^{-2} in the diurnal and less than 0.02 nms^{-2} in the semidiurnal band. The pressure admittance factor results to −3.538±0.005 nms^{-2}/hPa.

The procedure of residual calculation starts with subtraction of the tidal effect from the hourly data applying the same tidal parameters and the same model as obtained by and adopted for tidal analysis. For these computations the tidal prediction program supplied by the ETERNA package has been used. The air pressure effect is removed using the admittance factor mentioned above.

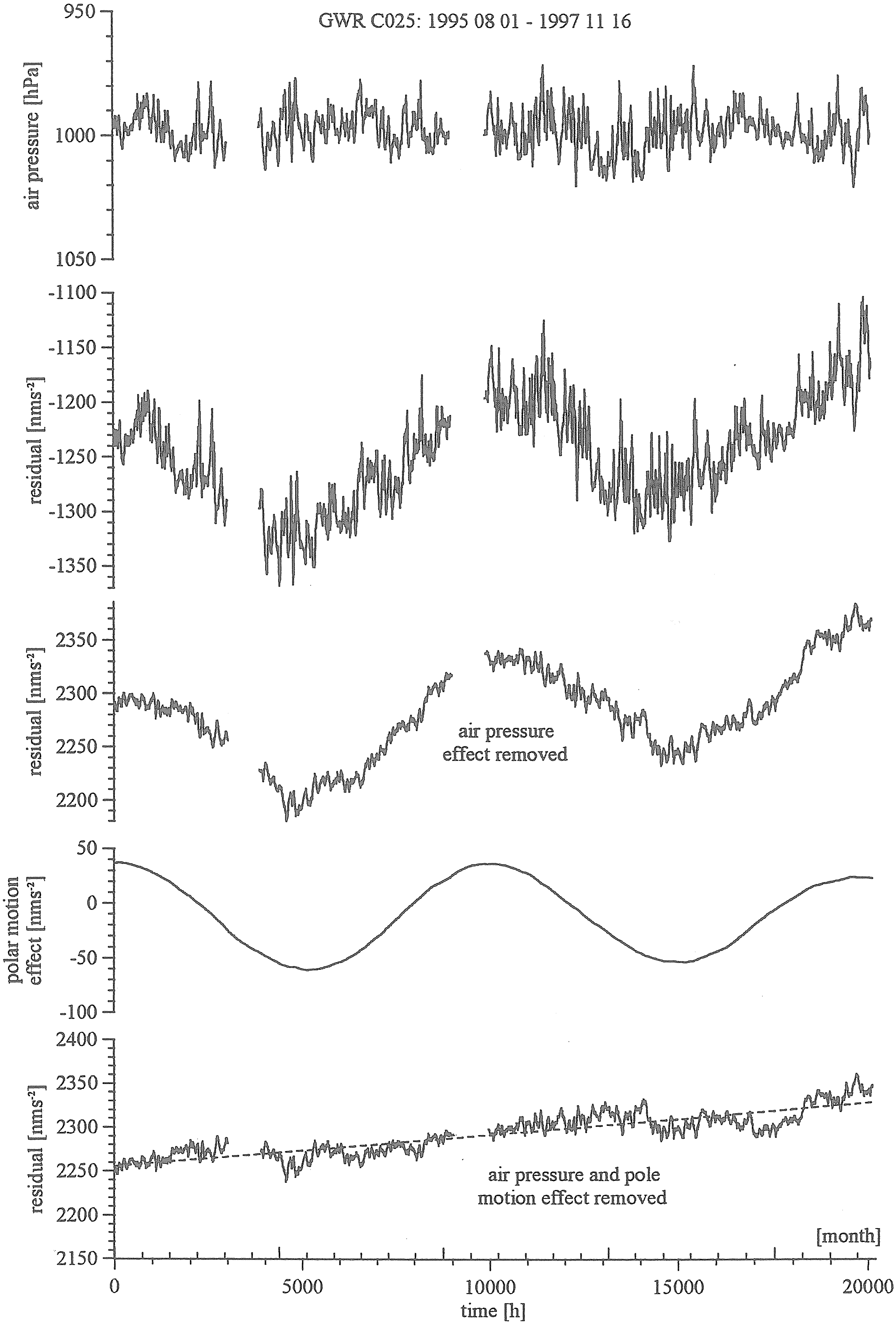

Fig. 5: Residuals after subtracting the gravity effect of the adjusted tidal model, the air pressure contribution assuming a frequency independent admittance factor and the pole motion effect.

The final residuals result from removing the pole motion effect based on IERS data calculated without taking an amplitude factor into account. The residuals are characterized by a very small and linear drift of about 30 nms^{-2}/a. Even immediately after instrumental set up there is no exponential drift behavior. Figure 5 demonstrates the different steps and the result of residual calculation.

The residuals are clearly correlated with the air pressure because of the dependency of the pressure admittance function on frequency. Figure 6 presents in more detail the hourly residuals after removing a linear drift and the air pressure effect calculated with the frequency independent pressure admittance factor derived from tidal analysis. A distinct anti-correlation can be observed proving the assumed admittance factor to be too high in the frequency range below 1 cpd. This anti-correlation is clearly visible also in the long period components fitted by high degree polynomials. A frequency dependent pressure admittance function (Figure 7) has been calculated by applying standard methods (e.g. Neumeyer and Pflug 1997).

wave group	amplitude [nms^{-2}]	amplitude factor	standard deviation	phase lead [deg]	standard deviation
Q1	67.6720	1.14498	0.00027	−0.1121	0.0134
O1	354.5094	1.14842	0.00005	+0.1121	0.0027
M1	28.0418	1.15505	0.00055	+0.1028	0.0275
P1	164.7970	1.14733	0.00010	+0.1462	0.0051
S1	3.7412	1.10145	0.00611	+9.5364	0.3163
K1	492.4439	1.13429	0.00004	+0.1927	0.0019
PSI1	4.3145	1.27027	0.00433	+0.9492	0.1952
PHI1	7.2635	1.17492	0.00234	+0.0098	0.1141
J1	28.0220	1.15427	0.00073	+0.0536	0.0362
OO1	15.2927	1.15124	0.00170	+0.2662	0.0845
2N2	11.8813	1.16629	0.00060	+1.8057	0.0297
N2	75.2188	1.17914	0.00012	+1.5424	0.0060
M2	393.9436	1.18236	0.00002	+1.0775	0.0011
L2	11.0831	1.17686	0.00057	+0.2576	0.0278
S2	182.8325	1.17945	0.00005	+0.0879	0.0026
K2	49.7444	1.18044	0.00024	+0.2992	0.0117
M3M6	4.6693	1.07046	0.00084	+0.1563	0.0450

Tab. 2: Tidal parameters obtained by analyzing the GWR C025 data between 1995 08 01 and 1997 11 16.

Performance control

The performance of the SG gravimeter was permanently controlled by monitoring some additional instrumental and environmental parameters like the electronics and room temperature, the temperatures at the 11 K and 70 K stages and the liquid Helium loss rate. The corresponding time series were compared with the hourly residuals in order to detect instrumental effects in the gravity signal. No significant correlation could be found.

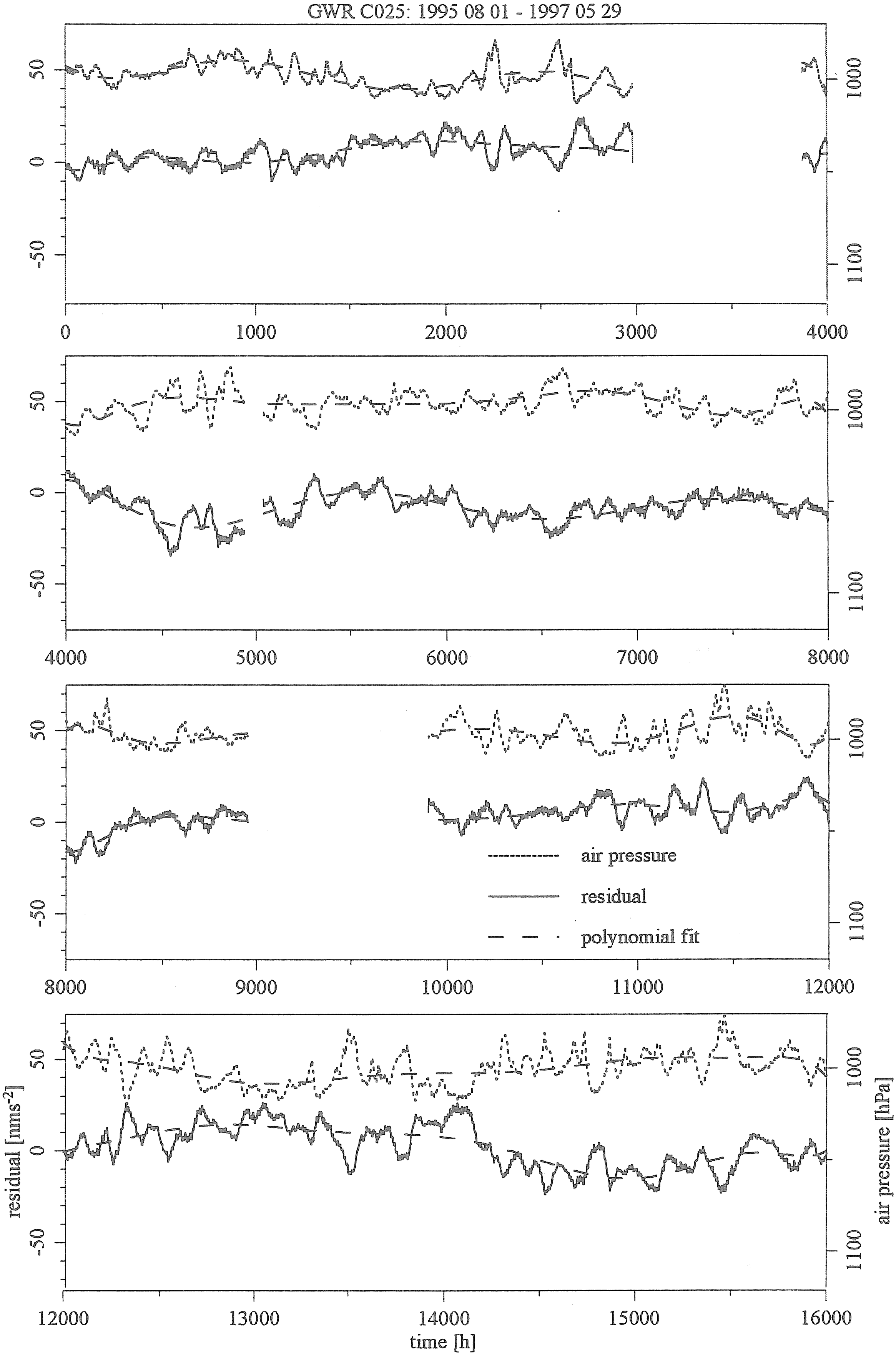

Fig. 6: Comparison of the trend reduced residuals with the observed air pressure showing the frequency dependency of the air pressure admittance function. Air pressure and residuals are distinctly anti-correlated in the frequency band < 1 cpd.

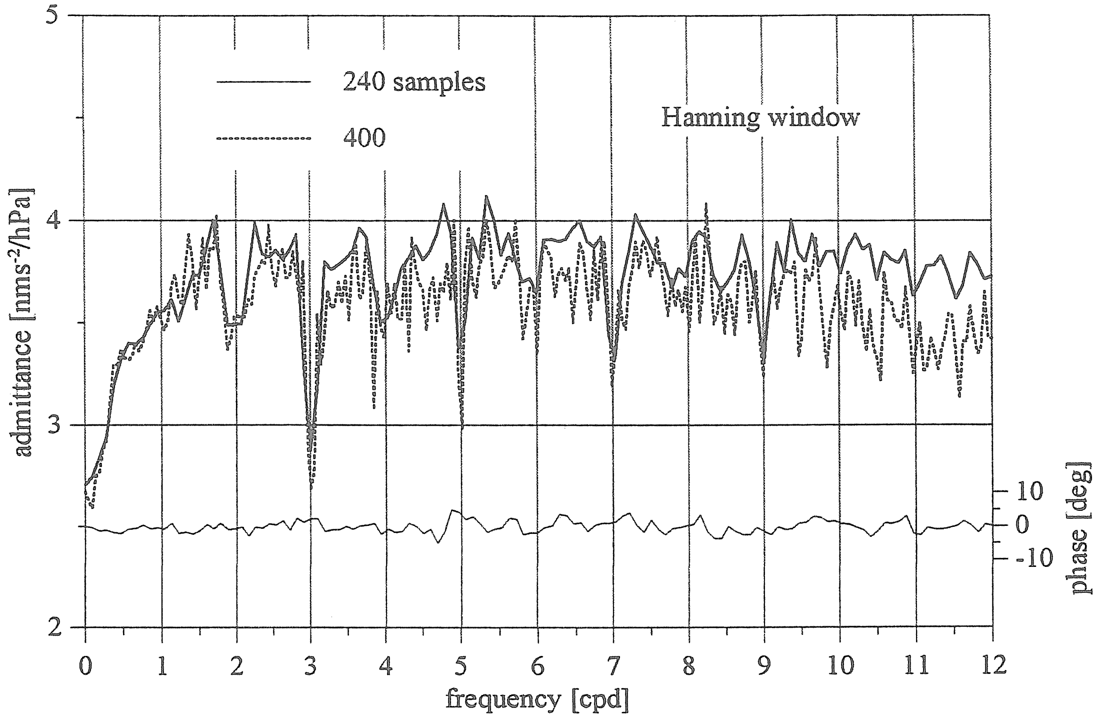

Fig. 7: Air pressure admittance function obtained by averaging over the whole observation period. The method of Neumeyer and Pflug (1997) has been applied.

Additionally the differences between the signals of the GWR air pressure sensor and an external high quality sensor implemented in a semi-automatic climate monitoring station (TAWES) at the site in Vienna have been investigated. A distinct correlation with the room temperature could be observed proving the GWR air pressure sensor being not accurate and stable enough. The differences are of the order of 1-2 hPa. These instabilities consequently introduce errors of about 3-6 nms^{-2} when removing the air pressure effect for residual determination.

Conclusion

The GWR C025 superconducting gravimeter has proven to be an excellent instrument for monitoring tidal and non-tidal gravity variations. The drift behavior is almost linear with a small drift rate of 30 nms^{-2}. Analyzing successive and independent time series of about 3 month period shows the high temporal stability of the instrument. The residuals can be explained mainly by air pressure effects that remain when a frequency independent admittance factor obtained from tidal analysis is applied for air pressure correction. In spite of the high noise level at the station in Vienna the frequency transfer function of the complete recording system could be determined successfully by the step response method for both the original and the new gravity card recommended for GGP. The interpretation of non tidal phenomena will be supported by combining the continuous record with regularly performed absolute gravity measurements.

References

Dunn, B., 1995: CSGI software reference manual. Dept. Earth Sciences, University of Western Ontario, Canada.

Francis, O., 1997: Calibration of the C021 superconducting gravimeter in Membach (Belgium) using absolute gravity measurements. 13th International Symposium on Earth Tides, Brussels.

Hinderer, J., Amalvict, M., Francis, O. and Maekinen, J., 1997: On the calibration of superconducting gravimeters with the help of absolute gravimeters. 13th International Symposium on Earth Tides, Brussels.

Kanngieser, E., Kummer, K., Torge, W. and Wenzel, H.G., 1983: Das Gravimeter-Eichsystem Hannover. Wiss. Arb. Fachrichtung Vermessungswesen, Univ. Hannover, 120.

Meurers, B., 1987: Comparison of Earth Tide Observations in Vienna. Bulletin d'Informations Mareés Terrestres, 100, 6942-6953.

Neumeyer, J. and Pflug, H., 1997: ADMITT - a program for determination of the atmospheric pressure admittance. Bulletin d'Informations Mareés Terrestres, 127, 9851-9855.

Schnüll, M., R.H. Röder and H.-G. Wenzel, 1984: An improved electronic feedback for LaCoste-Romberg gravity meters. BGI, Bulletin d'Information, 55, 27-36.

Tamura, Y., 1987: A harmonic development of the tide-generating potential. Bulletin d'Informations Mareés Terrestres, 99, 6813-6855.

Timmen, L. and Wenzel, H.G., 1995: Worldwide synthetic gravity tide parameters. In: Sünkel, H., Marson, I., (eds): Gravity and Geoid. IAG Symposium 113, Springer Verlag, 92-101.

Vauterin, P., 1997: Graphical interactive software for the analysis of earth tide information. 13th International Symposium on Earth Tides, Brussels.

Warburton, R., 1997: GWR developments. 1st GGP Workshop, 21 July 1997, Brussels.

Wenzel, H.-G., 1994: Accurate instrumental phase lag determination for feedback gravimeters. Bulletin d'Informations, Marees Terrestres, 118, 8735-8752.

Wenzel, H.-G., 1996: The nanogal software: Earth tide data processing package ETERNA 3.30. Bulletin d'Informations Mareés Terrestres, vol. 124, 9425-9439.

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First Announcement

Joint BGI/ICET Summer School 2002 on

TERRESTRIAL GRAVITY DATA ACQUISITIONS TECHNIQUES

September 4-11 2002, Louvain-La-Neuve, Belgium

Organised by

The Bureau Gravimetrique International (BGI)

The International Center for Earth Tides (ICET)

Preliminary Program of the School

Lectures:

Wednesday p.m.	Earth gravity field: introduction
Thursday	Gravimeters and reference systems
Friday	The positioning methods and tide corrections
Saturday	Gravity nets
	Gravity anomalies and topographic corrections
Monday	Processing of gravity anomalies
	Applications in civil engineering
Tuesday	Applications in volcanology - Geoid modeling

Field work

- Scintrex/Lacoste-Romberg gravimeters settings
- Determination of the vertical gradient
- Positioning
- Profile acquisition with a Scintrex or a Lacoste-Romberg gravimeter
- Data reduction (vertical gradient or profile)
- Network adjustment

Software dedicated to the data corrections, data adjustment and data validation will be distributed free of charge to the participants.

Registration fee: 550 $ (including accomodations)

Attendance is limited to 40 persons, on a first come, first served basis.

Financial support could be provided to people from developping countries, after submission of a grant application.

http://bgi.cnes.fr

ANNOUNCEMENT

The data from the third year 1999-2000
of the **Global Geodynamics Project** (GGP)
are now available on the CD-ROM's

ETGGP3 raw minutes files, log reports and auxiliary files

and

ETGGP3a calibrated and corrected minutes files, hourly data ready for analysis

Copies of the previous CD-ROM's ETGGP1/ETGGP1a (1997-1998) and ETGGP2/ETGGP2a (1998-1999) are still available

For any request

Please contact the "International Centre for Earth Tides"
C/O Observatoire Royal de Belgique
Avenue Circulaire 3
B-1180 Brussels
Belgium
e-mail ducarme@oma.be
tel 32 2 3730248
fax 32 2 3749822

Global Geodynamics Project - ETGGP #3

Type of data on this CD ETGGP #3:
MINUTE: raw minutes files with gravity and air pressure measurements
LOG: reports of events concerning the SG and the station
AUX: auxiliary data, esp. groundwater level
Stations:BA:Bandung,BE: Brussels, BO: Boulder, BR: Brasimone, CA: Cantley, CB:Canberra,ES: Esashi, KY: Kyoto, MA: Matsushiro, MB: Membach, ME: Metsahovi,MO: Moxa, ST: Strasbourg,SY:Syowa, VI: Vienna, WE: Wettzell, WU: Wuhan

GGP

The Global Geodynamics Project is a consortium of SG Institutions who agreed to put their data in common.
Chairman: D. Crossley (crossley@eas.slu.edu)
Secretary: J. Hinderer (jacques.hinderer@eost.u-strasbg.fr)

ICET

The International Centre for Earth Tides supplies a scientific supervision of the database, as well as a control of the data by computing analyses and provides assistance to the stations.
Director: B. Ducarme (bernard.ducarme@oma.be)

The Royal Observatory of Belgium is the host institution who is in charge of the technical maintenance of the GGP database and provides assistance to the stations for the use of the database.
Head of Dpt. Geodynamics: R. Verbeiren (roland.verbeiren@oma.be)
Contact person: M. Hendrickx (marc.hendrickx@oma.be)

GFZ POTSDAM

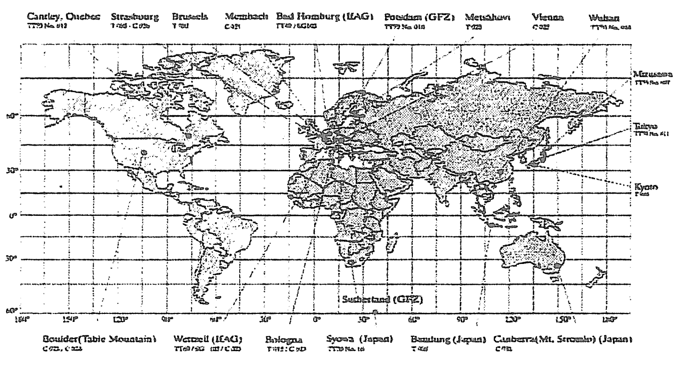
The ISDC of the GeoForschungZentrum in Potsdam has designed the database http://etggp.oma.be and cares for the software maintenance as well as for the needed updates and adaptations.
Head of data center: J. Wächter (wea@gfz-potsdam.de)
Software architect: B. Ritschel (rit@gfz-potsdam.de)

Global Geodynamics Project - ETGGP #3

GGP

Global Geodynamics Project

Site of Superconducting Gravimeters



CD-ROM ETGGP #3

This CD-ROM contains the data files from the GGP databank
http://etggp.oma.be (July 1999 till June 2000)