SURVEY ON STATUS AND PROSPECT OF EARTH GRAVITY MODELS FOR PRECISE ORBIT DETERMINATION IN CONNECTION WITH GEODYNAMIC APPLICATIONS

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ABSTRACT

The ability to monitor geodynamic phenomena, e.g. earth rotation or tectonic motion, through satellite tracking depends on the accuracy of the orbits which in turn depend fundamentally on the accuracy and resolution of the earth gravity field models. From many data sources of varying quality improved gravity models have been derived over the last ten years in the USA and Europe.

The paper gives a brief description of these fields, of their accuracy and usability for geodynamic mission applications. Existing problems with these models, in particular in connection with the precision orbit determination are identified and on-going activities for further improved models are described.

Keywords: Satellite geodesy, geodynamics, gravity models, orbit determination

1. INTRODUCTION

Geodynamics is the branch of geoscience concerned with the forces and processes which act upon the solid and non-solid parts of the planet Earth consisting of the crust, the mantle, the outer liquid and the inner solid core.

Manifestations of such forces and processes are variations in the orientation of the Earth in space, variations in the rotational speed, vertical and horizontal changes in the Earth's surface structure, the anomalous gravity field, the solid Earth tides as well as the anomalous magnetic field. These phenomena cannot be regarded as single features in isolation, rather, they have to be considered in the light of how they influence and react with one another, with the atmosphere and hydrosphere in order to obtain a meaningful overall picture of the processes taking place on and inside the Earth's body and of the forces which drive these processes.

Satellite geodesy with it's broad spectrum of already existing systems or systems under development for (i) target tracking from ground to space, s tellite-to-ground or satellite-to-satellite (i remote sensing of the ocean and ice surfaces wit satellite borne altimeters and (iii) measuring gravity sensor components with satellite borne gradiometer sensors has already contributed significantly in the last 5-10 years to harden the concept and provide additional evidence of plate tectonics and will continue to contribute to the explosive increase in our understanding of the structure and evolution of the Earth with improved observation techniques and new missions.

Those aspects of the overall complex solid earth physics which have profited most from the rapid development in satellite geodesy are:

- structure of the global Earth gravity field and temporal variations of the field
- precise point positioning and determination of motions
- motion of the pole and variations in rotational velocity

To make meaningful contributions to the many up to now unresolved questions in geodynamis extremely high accuracies are required for the various parameter subgroups: (i) relative positioning of points over distances ranging from a few tens to many thousands of kilometers with an accuracy of at least 1-2 centimeters and rates of motion at sampling intervals of some months with an accuracy of less than one centimeter per year, (ii) earth rotation parameters at intervals of one day with accuracies of 1 mas for the pole position and 0.1 ms for the rotational rate, (iii) longest wavelength features of the geoid (degree and order 6) with subdecimeter precision and a high-resolution (100 km wavelength) global gravity field with an accuracy of a few milligals.

Laser ranging and microwave interferometry techniques have demonstrated in the last few years their capability to achieve at least partly the goals mentioned under items (i) and (ii). Satellite laser range measurements and satellite altimetry observations have very much enhanced our knowledge of the Earth's gravity field structure. Two of these tracking techniques, namely the satellite laser ranging (SLR) and satellite altimetry (SA), make observations to or from a near earth satellite and are therefore with one endpoint of the observed quantity directly linked to the satellite's orbital motion. This orbital motion is primarily affected by the earth gravitational field. The accuracy with which geodetic-geodynamic parameters can be

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derived from this type of tracking data by applying dynamic methods is therefore very much dependent on the accuracy of the gravity field. This report gives a short survey on the existing gravity models, their use for orbit computations in geodynamic applications and describes shortly the on-going activities for model improvements.

2. NEEDS FOR HIGH PRECISION GRAVITY MODELING

Dynamic methods as used by most analysts for the derivation of geodynamic parameters, make explicit use of the satellite motion around the earth under the attraction exerted on it by conservative and non-conservative forces of different origin. Observations made from ground-based stations are used to relate the motion of the satellite in space to the crust-fixed set of tracking stations in a linear least squares best fitting sense. The orbit - if modelled properly - defines a good approximation of a quasi-internal reference, whereas the set of globally distributed tracking stations establishes a mean terrestrial reference frame at epoch T. The connection between these frames involves the currently adopted theory for the orientation of the Earth in inertial space, that is precession and nutation and the observationally determined variations of the Celestial Ephemeris Pole with respect to the aforementioned terrestrial frame, that is polar motion and UT1 variations. It is rather obvious from the above that a great diversity of parameters and very accurate too have to be known in order to relate in a frame convenient for the data reduction process (e.g. true of date system) the motion of the observatory to the motion of the satellite through the acquired and preprocessed tracking data. To add those main effects which were not mentioned in the above and which also need precisely to be modeled: Earth gravity and its variations due to earth and ocean tides, third body attraction (sun, moon, planets), apparent forces, non-conservative forces such as atmospheric drag, solar radiation, plate tectonic motions, tidal uplift and loading effects and last but not least physical and geometric reductions of the observations. Most of these affect the motion of the satellite in a periodic or time proportional manner and the length of the analysed data set and data distribution therefore determines wether these effects can be estimated from the data themselves or some "best" parameter values have to be adopted in the solution. For instance when it comes to determine station position variations from a several year long record of observations on a single satellite like LAGEOS, earth orientation parameters can and have to be determined simultanously, but not all required constituents of the gravity field. These have to be taken from a seperate gravity field model solution for which long observation records on a variety of satellites evenly distributed in inclination have been analyzed. Fixing such a gravity model - which still contains model errors - for instance in a station position and orientation parameter solution allows the gravity mismodelling to propagate through the orbit into the adjusted parameters. Considering the few centimeter accuracy which is required for the positioning and orientation parameters to make them valuable for geodynamic investigations makes it clear that a very precise gravity field modeling is required at least in the spectral domains to which the satellite in question is sensitive. For LAGEOS because of it's high altitude this domain is limited to terms up to degree and order 10 in the spherical harmonic expansion of the field plus some additional zonal, resonant and side-resonant terms. So a total of less than 200 accurately determined geopotential coefficients is sufficient to model the gravity induced perturbations. For a low orbiting geodynamic satellite like STARLETTE or for a altimeter carrying spacecraft like SEASAT, GEOS3, ERS-1 the situation becomes much more complex. To reach decimeter orbit position accuracies required for geodynamic investigations a much larger portion of the gravity field development with roughly 2000 potential coefficients has accurately to be known. Besides these orbit determination aspects a detailed and accurate global description of the gravity field is of course required for the derivation of geopotential functionals such as geoid heights, gravity anomalies, deflections of the vertical etc.

3. EXISTING GLOBAL GRAVITY FIELD MODELS

For many years now American and European groups have been working on the theoretical and practical aspects of gravity field determination and have contributed significant advancements to the modelling of the Earth gravity field. Some most recent examples of gravity field models for the long- and short- wavelength structures of the field which are available in the open literature are given in Table 1.

Table 1: Description of recent Earth gravity field models

Model	Complete Harmonics	Field Resolution (km)	Data used	References
GEM9	20	1000	ST	Lerch et al., 1977
GEM10B	36	550	ST + SG + SA	Lerch et al., 1978
GEM – L2	20	1000	ST	Lerch et al., 1983
PGS – 1331*	36	550	GEM10B + ST + SA	Marsh et al., 1985
PGS – S4*	36	550	GEM10B + ST + SA	Lerch et al., 1982
GRIM3	36	550	ST + SG + SA	Reigber et al., 1983
GRIM3B*	36	550	GRIM3 + ST	Reigber et al., 1984
GRIM3 – L1	36	550	ST + SG + SA	Reigber et al., 1985
Rapp81	180	110	GEM9 + SG + SA	Rapp, 1981
GPM2	200	100	GEM – L2 + SG + SA	Wenzel, 1985

ST... Satellite Tracking; SG... Surface Gravity; SA... Satellite Altimetry
* Tailored Gravity Models

These models and their resolution are characterized by the types of data which went into the solution, the relative weighting of the heterogenous data sources and the analysis approach. Whereas the Goddard Space Flight Center "satellite only" solutions GEM9 (Lerch et al., 1979) and GEM-L2 (Lerch et al., 1983) are solely based on satellite tracking data, the GSFC GEM10B (Lerch et al., 1981) and the German (DGFI/SFB78) - French (GRGS/CNES) GRIM3 (Reigber et al., 1983) and GRIM3-L1 (Reigber et al., 1985) "combination" solutions are derived from a combined weighted least squares solution of satellite tracking, terrestrial mean free air gravity anomalies and satellite altimetry data. These combination solutions, based on a balanced weighting of the various data types and trying to avoid aliasing effects, are aiming at a good global representation of the long-wavelength geopotential structures or of it's functionals. In contrast to this, models like the PGS-1331, PGS-S4, GRIM3B are aiming at an optimal representation of a specific satellite by highly weighting of the tracking data of this satellite in a combination solution. These models are so-called"tailored" models for the STARLETTE (PGS-1331), SEASAT (PGS-S4) and LAGEOS (GRIM3B) satellites and they take advantage of aliasing effects. The high resolution gravity fields OSU81 (Rapp, 1981) of the Ohio State University and GPM2 (Wenzel, 1985) of the University Hannover represent weighted combinations of the satellite derived long-wavelength geopotential information with the medium- and short-wavelength information resulting from an analysis of $1^{\circ} \times 1^{\circ}$ continental and oceanic gravity data, with the oceanic data coming mostly from satellite altimetry. These models primarily serve for geodetic applications and geodynamic interpretations.

The sucessive GEM- and GRIM-solutions given in table 1 don't all represent real iterations of the previous solution. The last real iteration for the GEM and PGS solutions has been GEM9 in 1977 and GRIM3 in 1981 for the GRIM solutions. Later solutions are all based on the satellite normals of GEM9 and GRIM3, respectively. These later solutions have benefitted from additional and higher quality data, improvements in data pre-processing and force field modeling and from continous upgradings of the analysis software. But because these sucessive solutions still include the "old" GEM9 and GRIM3 satellite normals, respectively, and the data reduction of the newer satellite tracking measurements was not always totally consistent with the reduction of the old satellite data no dramatic improvements in long-wavelength gravity field modeling has been achieved over the last years. For the latest GRIM models for instance the major improvements were achieved for the longest wavelengths portion of the field through the inclusion of a great deal of precise LAGEOS SLR observations and for the middle degree portion through the use of a more recent and more reliable terrestrial gravity data set and the applications of a modified weighting scheme.

As one possible option for a model intercomparison table 2 shows for the whole spectrum up to degree and order 36 of the spherical harmonic expansion the comparison of the GEM10B and GEM-L2 fields with the GRIM3-L1 field in terms of rms coefficient differences, geoid undulation and gravity anomaly differences. What becomes apparent from this table is the the fact, that the last model of the GRIM series, GRIM3-L1, agrees very well with the two GEM models for the very low degrees 2 to 4. The greatest differences occur for the middle degrees with maximum values predominantly for degrees 7 to 11. This is also the region where the estimated errors of the various models tend to be large.

To the many model intercomparisons and comparisons with external data which have been described in the literature (Lerch et al., 1985 a, b, Reigber et al., 1984, Reigber et al., 1985) only one addition should be made. A comparison of model derived geoid heights with doppler derived geoid heights at 481 Doppler points on the globe (Africa, Asia, Australia, Europe, Greenland, North- and South America). As can be seen from table 3 the smallest rms differences are obtained with the high resolution

Table 2

GEM10B - GRIM3-L1				
DEGREE	COEF. .NE.0	RMS-DIFF *10**8	UND-DIFF (METER)	ANOM-DIFF (MGAL)
2	3	.49	.05	.01
3	7	1.08	.18	.06
4	9	.38	.07	.03
5	11	1.60	.34	.21
6	13	.92	.21	.16
7	15	1.82	.45	.42
8	17	1.88	.49	.53
9	19	2.31	.64	.79
10	21	2.03	.59	.82
11	23	2.00	.61	.94
12	25	1.26	.40	.68
13	27	1.48	.49	.91
14	29	1.46	.50	1.00
15	31	1.16	.41	.89
16	33	1.10	.40	.93
17	35	.80	.30	.74
18	37	1.13	.44	1.14
19	39	.89	.36	.98
20	41	1.05	.43	1.25
21	42	.84	.35	1.06
22	43	.90	.33	1.22
23	47	.76	.33	1.12
24	49	.53	.30	1.08
25	51	.67	.30	1.12
26	53	.64	.30	1.15
27	54	.71	.33	1.32
28	56	.59	.28	1.17
29	58	.66	.32	1.39
30	60	.69	.34	1.52
31	62	.54	.27	1.26
32	65	.51	.26	1.25
33	66	.50	.26	1.27
34	67	.55	.29	1.45
35	70	.53	.23	1.49
36	72	.46	.25	1.35

GEML2 - GRIM3-L1				
DEGREE	COEF. .NE.0	RMS-DIFF *10**8	UND-DIFF (METER)	ANOM-DIFF (MGAL)
2	3	.23	.03	.00
3	7	.59	.10	.03
4	9	.54	.10	.05
5	11	1.27	.27	.16
6	13	1.10	.25	.19
7	15	1.89	.47	.43
8	17	2.07	.54	.59
9	19	2.85	.79	.98
10	21	2.46	.72	.99
11	23	2.60	.80	1.22
12	25	1.41	.45	.76
13	27	1.86	.62	1.14
14	29	2.55	.38	1.75
15	31	1.44	.51	1.10
16	33	1.78	.65	1.51
17	35	1.52	.57	1.41
18	37	1.26	.49	1.28
19	39	1.21	.48	1.33
20	41	1.31	.54	1.57
21	31	1.30	.46	1.42
22	31	1.29	.46	1.48
23	11	1.27	.27	.91
24	11	1.08	.23	.81
25	11	.81	.17	.63
26	5	.91	.13	.50
27	9	1.01	.19	.78
28	11	.79	.17	.69
29	7	1.17	.20	.85
30	2	2.17	.20	.57

models. This comparison again classifies the GEM-L2 and GEM9 models as good satellite only gravity models and GEM10B and GRIM3-L1 as the best long-wavelength combination solutions presently available.

Table 3: Comparison with Doppler derived Geoid Heights
(481 globally distributed stations)

Model	RMS difference (m)	Maximum (m)	Minimum (m)
GRIM3	4.28	12.4	−15.3
GRIM3B	4.53	12.6	−22.5
GRIM3−L1	3.25	11.1	−12.0
GEM9	3.51	12.6	−16.4
GEM10B	3.15	11.2	−14.6
GEM−L2	3.55	12.7	−16.9
Rapp81	2.68	10.8	−12.8
GPM2	2.60	11.4	−12.3

Of particular interest in the context of this paper is the question of the quality of these models for orbit determination purposes. Of course such quality tests very much depend on the orbital characteristics of the satellite in question, because they (in particular the altitude) determine the sensitivity of the satellite orbit to the anomalous geopotential constituents or their mismodeling. A harmonic analysis approach based on a first order solution of the Lagrange planetary equations allows to compute for each term in the spherical harmonic expansion the along-track, radial, and cross-track oscillations associated with the specific frequency which are impressed on the motion of the secularly precessing ellipse. In the same way the estimated geopotential coefficient errors can be introduced to compute the orbit position uncertainties associated with the estimated model errors. Taking the estimated errors of the GEM-L2 model given in (Lerch et al., 1985) and those of the GRIM3-L1 model given in (Reigber et al., 1985) which result from the formal errors of the solutions scaled by a factor $5^{1/2}$ and 2, respectively, the rss orbit position uncertainties as given in table 4 are obtained for the two geodynamic satellites LAGEOS (altitude ≈ 5900 km), STARLETTE (altitude ≈ 950 km) and for the planned European altimeter carrying satellite ERS-1 (altitude ≈ 800 km).

Table 4: Total (rss) position component errors (separated into m-daily and short period perturbation errors) due to estimated errors in potential coefficients.

Satellite	radial [m]	cross-track [m]	along-track [m]
LAGEOS			
GEM-L2 o's	0.1/0.0*	0.1/0.0	0.2/0.1
GRIM3-L1 o's	0.2/0.1	0.1/0.1	0.3/0.1
STARLETTE			
GEM-L2 o's	2.8/1.2	2.8/1.4	6.1/2.9
GRIM3-L1 o's	3.2/0.9	3.1/1.1	7.4/1.8
ERS-1			
GEM-L2 o's	3.9/1.8	3.3/2.0	8.3/7.8
GRIM3-L1 o's	4.0/1.2	3.3/1.8	9.2/4.0

* m-daily/short period

Thus one can conclude from the estimated potential coefficient errors that at least for arc lengths for which uncertainties in modeling long period zonal and resonant effects are not critical, LAGEOS orbits should be determinable with an accuracy of about 0.3-0.4 m, (somewhat better with GEM-L2 than with GRIM3-L1). For lower orbiting satellites such as STARLETTE and ERS-1 gravity induced orbit uncertainties can be 20 to 30 times larger. Only tailored models or new gravity models drastically improved in the tesseral harmonics allow or will allow to reduce considerably these orbit errors.

That the potential coefficient errors of the two considered models provide a rather pessimistic than optimistic picture of the achievable orbit accuracies can be verified by orbital fits to tracking data as obtained from the GEM-L2 and GRIM3-L1 model parameters. For a reasonable comparison of such data fits it is of sourse necessary to use the same constants (GM, a_e), to scale the potential coefficients, station positions and earth rotation parameters to these constants or adjust the station positions and earth rotation parameters in the orbit determination process.

The orbital fit results to 30 days LAGEOS laser ranging data in January 1986 are shown in table 5. All station positions and earth rotation parameters were adjusted in this case.

Table 5: Comparison of Gravity Models with Lageos Laser Data: January 1986 solution

Model	Orbital Fit [cm]	Mean baseline error [cm]
GEM-L2	6.3	1.7
GRIM3-L1	9.8	2.7
RMS Difference of baselines	7.0 cm	

Using LAGEOS determined station positions and earth rotation parameters orbital fits for 5 day STARLETTE orbits are typically 2-4 m using the GEM-L2 model and 3-5 m with GRIM3-L1. With the tailored STARLETTE model PGS 1331 rms fits of the order of 50-100 cm are obtained.

From these figures and the many intercomparisons performed by other investigators (e.g. Lerch et al., 1985, Marsh et al., 1985, Cheng et al., 1985) it can be concluded that at present the best published gravity models for orbit determination of geodynamic satellites are GEM-L2 for LAGEOS, and PGS 1331 for STARLETTE. With GEM-L2 station positions and pole coordinates can be derived with an accuracy of 2-5 cm from annual LAGEOS solutions. This is verified by the results of the various SLR analysis centers for MERIT (Mueller (ed.), 1985). The same parameters derived from STARLETTE tracking data using the PGS 1331 model have an about 10 times higher uncertainty.

If it obvious from the above that existing gravity models are not accurate enough in particular when precise trajectories of lower orbiting satellites have to be determined for précise point positioning, earth kinematics and ocean dynamics studies. This is, as summarized in table 6, partly a problem of inconsistencies in the data reduction, of constants, transformation parameters and force model components not representing our present better knowledge in physical modeling, but primarily a problem of the observation material and the treatment of the various old and new data sources.

Table 6: Problems with existing Gravity Models

• Iteration:		Sucessive solutions don't represent true iterations (last real iterations: GEM9 (1977), GRIM3 (1983))
• Data:		Older SLR data much less accurate; Many unreliable surface gravity data in older sets; Older Sea Surface Height models less accurate
• Initial Model	– Reference Frame:	Old precession, nutation, GMST expressions, Less accurate initial positions, survey ties, datum connections No plate motion model
	– Forces:	Only luni – solar attraction (GRIM), No ocean tides (only in Lageos arcs (GRIM)), Only Love tides ($k_2 = 0.3$)
• Adjustment:		Truncation of satellite normals according to varying sensitivity and data precision; Only one drag and solar radiation factor adjusted for; In a number of systems geodetic parameters held unadjusted (e.g. earth rotation, GM)
• Software:		S/W adopted to older and less efficient computers

4. NEW GRAVITY MODEL DEVELOPMENTS

The situtation with regard to observations and geometric and dynamic model developments has changed a great deal over the last years and in view of the pressing need for better gravity models for the up-coming altimetric missions ERS-1 and TOPEX/POSEIDON more money has been made available in the U.S.A. and Europe for model improvement work. Groups in the U.S.A. (GSFC, CSR), in Germany (DGFI) and France (GRGS) have started thorough reanalyses of data and new iterations of their models. We at DGFI are working along the following lines

- o Select from complete historical data set best tracking arcs and evaluate data
- o Examine newest surface gravity and sea surface height data sets. Apply proper corrections and eliminate unreliable data
- o Create initial position set in properly defined terrestrial frame
- o Use consistent set of constants
- o Apply best earth and ocean tide models
- o Better model non-conservative forces
- o Adjust for additional geodetic parameters
- o Adapt s/w system to vector machines
- o Develop system for model quality assessment and calibration

Along similar baselines the other groups work. The GSFC team has derived in the meanwhile two interim gravity fields, PGS-T1 and PGS-T2, (Marsh, et al., 1986) exclusively from satellite tracking observations. Both models give the spherical harmonics coefficients complete to degree and order 36, the GPS-T2 model in addition 66 terms for the ocean tides. As first test results, using orbital tracking data, indicate (Marsh et al., 1986) the PGS-T2 model out-performs even tailored models in orbit computation. A publication of the model coefficients is expectable for 1987. Results for the other models indicated in table 7 are foreseen in the 1987 to 1988 time frame.

Table 7: New Gravity Models in Preparation

Agency	Model	Data	Status
GSFC	PGS – T1	Laser, Camera, Doppler	Comp., Unpubl.
GSFC	PGS – T2	Laser, Camera, Doppler	Comp., Unpubl.
UT/CSR	8604 PTGF – 1	Laser, Camera, Doppler	In Preparation
DGFI/GRGS	GRIM4	Laser, Camera, Doppler Surface Gravity, Altimetry	In Preparation
DGFI/DFVLR	PEGM1	Laser, Camera, Doppler	Start in 1987

5. CONCLUSION

All things considered a new gravity field modeling era on the basis of existing observation material has started on both sides of the atlantic ocean. It can be expected that improvements by a factor of 2 to 4 are achievable. This would be already a big step forward for the processing of data from geodynamic and altimetric satellites. Laser and/or microwave tracking data from up-coming missions (SPOT, ERS-1, TOPEX) will contribute to further improvements.

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