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# 1 **The Interdisciplinary Role of Space Geodesy – Revisited**

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8

9 **Abstract.** In 1988 the interdisciplinary role of space geodesy has been discussed by  
10 a prominent group of leaders in the fields of geodesy and geophysics at an  
11 international workshop in Erice, (Mueller I I, S Zerbini, 1989). The workshop may be  
12 viewed as the starting point of a new era of geodesy as a discipline of Earth  
13 sciences. Since then enormous progress has been made in geodesy in terms of  
14 satellite and sensor systems, observation techniques, data processing, modelling  
15 and interpretation. The establishment of a Global Geodetic Observing System  
16 (GGOS) which is currently underway is a milestone in this respect. Wegener served  
17 as an important role model for the definition of GGOS. In turn, Wegener will benefit  
18 from becoming a regional entity of GGOS.

19 What are the great challenges of the realisation of a  $10^{-9}$  global integrated observing  
20 system? Geodesy is potentially able to provide – in the narrow sense of the words –  
21 “metric and weight” to global studies of geo-processes. It certainly can meet this  
22 expectation if a number of fundamental challenges, related to issues such as the  
23 international embedding of GGOS, the realisation of further satellite missions and  
24 some open scientific questions can be solved. Geodesy is measurement driven. This  
25 is an important asset when trying to study the Earth as a system. However its

26 guideline must be: “What are the right and most important observables to deal with  
27 the open scientific questions?”

28

29 **Key words:** geodesy, satellite geodesy, global observing system, global geodetic  
30 observing system

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32

33 **Historical introduction.** Since about 150 years geodesy can be regarded as an  
34 independent discipline of science. BAEYER’s memorandum about the size and figure  
35 of the Earth “Über die Größe und Figur der Erde” (1861) may be seen as a starting  
36 point, even though important geodetic work had been done before by famous  
37 scientists such as NEWTON, LAPLACE, GAUSS, BESSEL. But their work was not referred  
38 to as geodesy and they did not regard themselves as geodesists. BAEYER’s initiative  
39 resulted in an extension and unification of existing triangulation and levelling  
40 networks covering central Europe. This work was then expanded to the whole of  
41 Europe, before its transition to an international effort with the aim to determine the  
42 global figure of the Earth. It was one of the first international projects in science and  
43 the root of what is today the International Association of Geodesy (IAG), cf. (TORGE,  
44 2001).

45 Last year, in 2007, 50 years of space age was celebrated. With the launch of Sputnik  
46 1 on October 4, 1957 (and shortly after of Sputnik 2) modern space age began.  
47 Already these two satellites had a fundamental effect on geodesy. Almost  
48 instantaneously a large part of 100 years of diligent geodetic work dedicated to the  
49 determination of the figure of the Earth became out-dated. From measuring the  
50 precession of satellite orbits the Earth’s flattening could be determined much more  
51 accurately than with classical astro-geodetic work, compare e.g. King-Hele, 1992.

52 Satellites opened new horizons for geodesy and no other discipline is known to me  
53 that has benefited more profoundly from space techniques. Positioning, gravity field  
54 determination, Earth rotation monitoring and geodetic remote sensing can be done  
55 much more accurately, completely and efficiently from space. Geodesy became truly  
56 global and three dimensional. Oceans, a “terra incognita” of the classical times  
57 turned with satellites into an area of great geodetic activity. Classical geodetic  
58 techniques did not allow the accurate measurement of zenith angles, due to  
59 atmospheric refraction. From space the vertical dimension of the Earth’s surface can  
60 be determined almost as accurately as the horizontal components. Progress of space  
61 geodesy was fast and had a great impact. Hand in hand with the rapid development  
62 of geodetic space techniques geosciences became more and more interested in  
63 geodetic work.

64 **The Erice workshop about the interdisciplinary role of space geodesy.** Twenty  
65 years ago some of the most outstanding geodesists, Earth scientists and physicists  
66 were invited to a workshop in Erice/ Sicily. It dealt with the interdisciplinary role of  
67 space geodesy and was organized by Ivan I MUELLER and Susanna ZERBINI (1989).  
68 At this workshop the role of space geodesy for Earth sciences was carefully analysed  
69 and recommendations formulated for the future. The introductory chapter to the book  
70 by W M KAULA is especially worthwhile to read. He discusses five selected fields of  
71 Earth science and the possible role of space geodetic techniques for them. The five  
72 fields are (1) Earth rotation and core-mantle interaction, (2) mantle convection, (3)  
73 regional tectonics and earthquakes, (4) ocean dynamics and (5) Venus-Earth  
74 differences. The workshop in Erice marks the beginning of the era of space geodesy  
75 as being a discipline of Earth sciences.

76 **Developments of the recent past.** In recent years the general emphasis of Earth  
77 sciences has moved towards Climate Change and Earth System Science.

78 Awareness grew that we need a much better understanding of the Earth as a system,  
79 of solar radiation as its driving force, of the thermal back radiation and how it is  
80 affected by even tiny changes in chemical composition of the atmosphere, and last  
81 not least of the impact of man. One fundamental deficiency became particularly  
82 evident in the course of the preparation of the last report of the Intergovernmental  
83 Panel on Climate Change (Climate Change, 2007) and has been addressed in  
84 several articles in Science and Nature, see (Hogan, 2005) and the articles quoted  
85 there: There is a clear lack of observations (ibid, 2005). Space geodesy is able to  
86 provide important new and unique data to Global Change research by measuring  
87 mass and energy transport processes in the Earth system. Ben CHAO (2003) wrote:”  
88 After three decades and three orders of magnitude of advances, space geodesy is  
89 poised for prime time in observing the integrated mass transports that take place in  
90 the Earth system, from the high atmosphere to the deep interior of the core. As such  
91 space geodesy has become a new remote sensing tool, in monitoring climatic and  
92 geophysical changes with ever increasing sensitivity and resolution.” One can claim  
93 that geodesy, by merging geometry, Earth rotation, gravity and geoid, is in a position  
94 to provide “metric and weight” to Earth system research. Before this background the  
95 establishment of the Global Geodetic Observing System (GGOS) is the right step at  
96 the right time. The underlying concept is simple and well described by the scheme  
97 shown in figure 1 and due to ROTHACHER, see (RUMMEL et al., 2005; see also PLAG &  
98 PEARLMAN, 2007).

99

100 Figure 1

101

102 GGOS will combine the three fundamental pillars of geodesy: the measurement of  
103 the shape of the Earth, Earth rotation and the Earth’s gravity field and geoid. The

104 objective is to realize this with a relative precision level of  $10^{-9}$  in one unified Earth  
105 fixed reference system and to keep this system stable over decades. Where does  
106 such a demanding requirement come from? In geosciences one usually deals with  
107 estimates accurate to only a few percent. Global change parameters are small and  
108 their temporal changes are slow and even smaller. In general they cannot be  
109 observed directly but have to be derived from a combination of several measurement  
110 systems and models. In order to be able to analyze them as a global process they  
111 have to be scaled relative to the dimension of the Earth. Let us take an example. Sea  
112 level at an arbitrary tide gauge may vary by a few meters, due to tides and storm  
113 surges. Measurement of sea level change with a precision of a few mm requires  
114 therefore a relative precision of  $10^{-3}$  at this particular station. Local sea level  
115 monitoring can be transformed into a global monitoring system by satellite systems  
116 such as altimetry and GPS. Only then a global process can be deduced from local  
117 tide gauge records. In order to achieve cm- or mm-precision with satellite systems  
118 globally, orbit determination and altimetric measurements have to be delivered with a  
119 relative precision of 1 ppb.

120 In order to meet the goals set for GGOS a series of rather fundamental geodetic  
121 problems have to be dealt with. The three pillars of geodesy, geometry, Earth rotation  
122 and gravity have to be expressed in one and the same Earth fixed reference system  
123 with millimetre precision and stability (of the frame) has to be guaranteed over  
124 decades. This requires the space as well as the ground segments to function as one  
125 homogeneous entity as if all observations were done in one observatory  
126 encompassing the Earth. Each observation contains a superposition of a variety of  
127 effects, related to ionosphere, atmosphere, oceans, ice shields and solid Earth. In  
128 order to employ them for Earth system research strategies have to be developed for  
129 their separation and quantification by analysing their spatial, temporal and spectral

130 characteristics. Satellite measurements represent time series along their orbit. Via  
131 the Earth's rotation and the choice of the satellite orbit elements these time series are  
132 related to a spatial and temporal sampling of the Earth. The reconstruction of the  
133 temporal and spatial geophysical phenomena poses a complicated problem of  
134 aliasing and inversion. The current investigations of the global water cycle or of the  
135 ice mass balance in Greenland and Antarctica from GRACE gravimetry are exactly  
136 problems of this type. The inclusion of terrestrial and airborne data, such as surface  
137 loading, ocean bottom pressure, tide gauges, gravimetry or altimetry may certainly  
138 help. However, this step is not easy either, because terrestrial measurements are  
139 affected by local influences and exhibit a spectral sensitivity quite different from that  
140 of satellite observations. Probably the most effective support to de-aliasing and  
141 separation of geophysical phenomena is the inclusion of prior information, such as  
142 models of solid Earth and ocean tides, atmosphere, oceans, ice, hydrology or glacial  
143 isostatic adjustment, however only if they are introduced consistently for all  
144 techniques of the observing system. Important work towards these goals is currently  
145 underway and we see geodetic techniques used much more widely in the various  
146 Earth disciplines.

147 WEGENER developed over the years from an almost mono-disciplinary project to  
148 regional multi-disciplinary activity combining a large variety of geodetic and non-  
149 geodetic measurements techniques and involving all geo-disciplines relevant to its  
150 objectives. It is therefore an excellent example on how GGOS could operate on a  
151 global scale.

152 **A look into the future.** With an enormous pace space geodesy has made fantastic  
153 progress over the past 50 years. Do we have to fear this development to slow down  
154 in the near future? Let me try to look into the future..

155 Firstly, under what general boundary conditions will space geodesy have to operate  
156 in the years to come? Global Change activities are mostly organized on an  
157 intergovernmental level in international programs such as INSPIRE, IGOS or CEOS.  
158 GGOS must therefore strive to be integrated into such programs in order to attain the  
159 necessary impact and recognition. It is advisable that geodesy tries to activate its  
160 national governmental agencies towards this goal, in particular those agencies  
161 supporting already for years the geodetic scientific services under the umbrella of the  
162 International Association of Geodesy (IAG). Global Change is discussed nowadays in  
163 terms of so-called essential climate variables (ecv's). GGOS has to analyze in what  
164 way it can contribute to the determination and monitoring of the identified ecv's. To a  
165 large extent the major Earth oriented satellite programs of NASA and ESA are  
166 defined already for the next 5 to 10 years. If missions are missing which are essential  
167 for the progress of space geodesy, GGOS has to develop a strategy on how to get  
168 such missing elements approved by one of the space agencies.

169 What are the geodetic priorities and how can geodesy take advantage of non-  
170 geodetic space activities? Let me formulate a number of questions.

171 Several GNSSs will be available in parallel in the near future, the GPS, GLONASS,  
172 GALILEO, COMPASS and the associated augmentation systems. What can we gain  
173 from their combined use, what for example from their improved clocks? If one could  
174 establish inter-satellite ranging, one would get an orbiting precision polyhedron. What  
175 would we gain from such a constellation?

176 Let us assume geodesy would push for a third LAGEOS (e.g. counter rotating as  
177 proposed by Professor BERTOTTI a long time ago). Would it further strengthen our  
178 terrestrial reference system, e.g. its long term stability and the low gravity harmonics?

179 It would certainly be an important bridge to gravitational physics.

180 After the great success of GRACE further gravimetric satellite missions are urgently  
181 needed to secure continuity of the measured time series, if mass transport should  
182 remain a central gravimetric theme. How should such missions look like? Compare  
183 also, KOOP and RUMMEL, 2006. In parallel the development of significantly improved  
184 geophysical “background” models of ocean tides, and coupled atmosphere-ocean  
185 circulation must have high priority on the geodetic agenda. They would serve the de-  
186 aliasing and separation of geophysical effect. Only then one could fully benefit from  
187 improved technological concepts such as inter-satellite laser link, drag free system,  
188 proof mass-to-proof mass measurement and satellite configuration flights.

189 Would mini-satellites be useful, e.g. for atmospheric sounding or for a satellite based  
190 synchronization of two or several techniques, such as GPS, DORIS, VLBI and laser  
191 ranging?

192 The GNSS signal emitters and receivers are distributed over three spatial layers: the  
193 GNSS satellites at high altitude, a large number of low Earth orbiters (LEO’s)  
194 equipped with GNSS receivers between 300 and 1000 km altitude and many  
195 permanent receiving stations on ground. Could this add, literally, a further dimension  
196 to GNSS atmospheric sounding and to the modeling of the wet troposphere?

197 Several space agencies are preparing missions to our moon. A lander mission could  
198 be used to deploy geodetic laser transponders. This would greatly facilitate and  
199 improve lunar laser ranging and strengthen its role among the geodetic space  
200 techniques and for gravitational physics. In addition, the far-side gravity field of the  
201 moon is still not known very well; thus any mission opportunity for satellite lunar  
202 gravimetry would be welcome.

203 What are the technological building blocks of future space geodetic missions? A new  
204 generation of ultra-high-precision clocks in space and on ground, such as optical  
205 clocks, active transponders for tracking systems, GNSS reflectometry and new types

206 of accelerometers may soon become available for space geodesy. These could have  
207 a tremendous impact on the development of geodesy.

208 This leads to the question about the challenges and opportunities of future space  
209 geodesy. The three traditional enemies are non-gravitational forces acting on  
210 satellites, atmospheric refraction and local ties.

211 Uncertainties and gross errors in local ties between measurements systems sound  
212 like a trivial question of diligence and organisation but strangely enough this problem  
213 is not yet globally resolved. Great progress has been made in measuring and  
214 modelling local tropospheric effects for the various ground receiver systems.  
215 However a uniform and consistent approach for all techniques is still not routine and  
216 should be pursued with high priority. Modelling of the satellite environment (residual  
217 air drag and solar radiation) is still far from solved and should also be given high  
218 priority. Possibly, low Earth orbiters without accelerometers might be used for gravity  
219 field monitoring in the future.

220 What about clocks, time measurement, synchronisation and transfer? The great  
221 progress of the past in space geodesy can be intimately linked to a corresponding  
222 progress in the measurement of travel times and time keeping. Important new  
223 developments have lead to optical clocks (and counters) at a precision level of  $10^{-18}$   
224 in the laboratory. Precisions better than  $10^{-16}$  can and will have important implications  
225 for geodesy. The materialisation of a global unified height system could be achieved  
226 using the relativistic dependence of time on the gravitational potential. Time  
227 synchronisation at this level of precision via satellites would open several new  
228 perspectives for geodesy. Time measurements made by satellites might be  
229 considered as real observables and not only as a device for "tick marking"  
230 measurements. One could start dreaming of the direct measurement of gravitational

231 potential differences between satellites as well as between satellites and ground  
232 stations.

233 During the pioneering days of satellite geodesy direction measurement with cameras  
234 to satellites against the stellar background was one of the primary techniques. With  
235 the advent of laser and radio tracking range and range rate replaced angular  
236 measurements which always suffered from the effect of atmospheric refraction. But  
237 are angular measurements really obsolete for ever? Should one not think about new  
238 concepts of angular measurement, e.g. with synchronised twin laser telescopes, and  
239 about what their impact would be?

240 Finally, considering all this amazing progress one can wonder whether there is not a  
241 natural limit of precision beyond which further progress of geodetic space techniques  
242 does not make sense anymore because the ever increasing precisions cannot  
243 anymore be reproduced in nature. Is  $10^{-9}$  already such a limit or  $10^{-10}$ ?

244 **Concluding remarks.** In the quoted book “The interdisciplinary role of space  
245 geodesy” (MUELLER and ZERBINI, 1999), KAULA wrote on page 9: „...Theoreticians  
246 get the impression that experimenters operate according to problem definitions that  
247 are a decade or more obsolete, while experimenters probably think that theoreticians  
248 are sporadic in their attention and underestimate technical difficulties. Better  
249 communication is particularly important now that measurement capabilities can yield  
250 valuable constraints, provided that they are applied in sufficient detail”. This is a  
251 remark about the relationship between theory and experiment. KAULA, being both an  
252 outstanding geodesist and geophysicist, saw that there was a problem in this  
253 relationship at that time. Traditionally geodesy is very “measurement and technique  
254 driven”. Even during the definition phase of GGOS the underlying rationale started  
255 from the observing system and not so much from the Earth science problems that  
256 could be addressed with such a system. Such an approach may be logical but it is

257 essentially wrong. Experiments have to be derived from theory and new hypotheses  
258 from the experiments; to be successful an intimate relationship between the two must  
259 exist. From this I conclude that geodesy and geodesists have to get much deeper  
260 into Earth sciences. Geodesists have to have a profound understanding of the  
261 geophysical problems. Only then the fantastic tools of modern space geodesy will  
262 develop their full potential for the understanding of our Earth as a system. This poses  
263 a great challenge to geodetic education and science.

264 **Acknowledgement:** Several coffee time discussions with Gerhard Beutler and Urs  
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266

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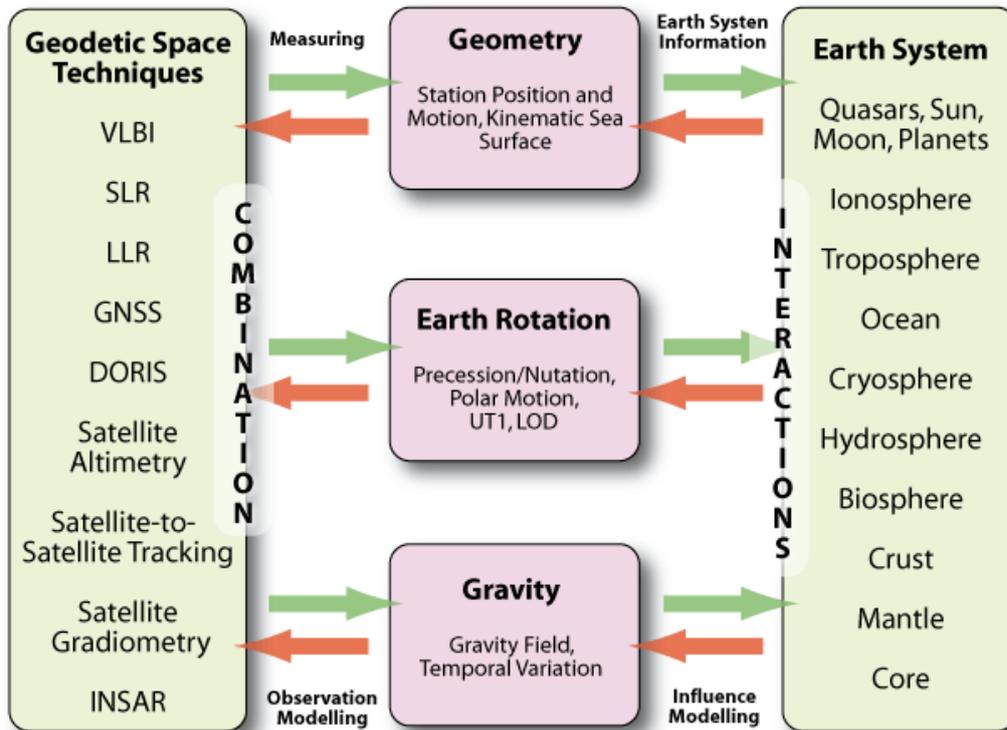
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288 Figure 1: Geodetic space techniques determine the shape of the Earth, Earth rotation  
289 and the Earth's gravity field and geoid. From these three geodetic entities a large  
290 variety of Earth system parameters are derived. In turn, any improvement of Earth  
291 parameters serves a better modeling of geometry, Earth rotation and gravity and a  
292 more accurate modeling of space geodetic measurements.

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Figure 1: Geodetic space techniques determine the shape of the Earth, Earth rotation and the Earth's gravity field and geoid. From these three geodetic entities a large variety of Earth system parameters are derived. In turn, any improvement of Earth parameters serves a better modeling of geometry, Earth rotation and gravity and a more accurate modeling of space geodetic measurements.