INTERNATIONAL
SPACE
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ISSI/HISPAC Forum on “Understanding Gravity”

3/4 December 2013 at ISSI premises in Bern, Switzerland

FINAL REPORT

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Understanding Gravity

Executive Summary

The physics of Gravity spans all the activities of ESA from Science to Technology and Earth Observation to Communications. It is also a field of science in which major intellectual challenges are driving enormous technical developments. A discussion forum (see Annex) held at ISSI in December 2013 brought together scientists and technologists to review the possibilities for cross -fertilisation between the programmes in different ESA directorates, propose mechanisms to improve the transfer of technology and suggest detailed topics for immediate development through focussed workshops. The recommendations from the ISSI meeting were as follows:

1. The wide ranging discussions during the meeting demonstrated that there are large benefits to be gained by detailed transfer of technical information between the different areas of science within ESA. The technical issues concerning gravity could include accelerometry, inertial sensors, atomic interferometers, atomic clocks and navigation/clock comparison methods. Novel analysis techniques and software developments are not to be excluded from such activity. Mechanisms should be sought for this transfer of information and actively pursued as a means of maintaining an efficient programme of science delivery.
2. The opportunities for cross fertilisation of technical progress between science areas as diverse as Fundamental Physics and Earth Observation presents a major opportunity for ESA. In particular the techniques of interferometry, either using lasers or cold atom sources, may contribute substantially to new levels of performance in the study of the Earth via gravimetry.
3. The many extremely novel aspects of instrumentation for fundamental physics require considerable care in allocating hardware development tasks between industry and academic institutes. At present the administrative processes for space mission management favour technical developments in industry where high risk development programmes are expensive and time consuming. The allocation of early stage development work needs to be made by analysing where the risks and costs are best managed.
4. Whenever possible ESA should make available opportunities for small secondary payloads to maximise the science outcomes from missions. These might be fundamental physics experiments benefiting from deep space orbits in planetary missions or small payloads on Galileo platforms where multi-point measurements could be effective.
5. An active watch should be maintained for synergy between other fast growing technical sectors (such as telecoms, for example) in which ESA could benefit from developments leading towards flight hardware of value to the science programme.
6. ESA may wish to build upon the ISSI meeting reported in this note by organising further workshops on the detailed transfer of single items of technology between different programmes within the agency. Some suggestions for workshop topics are made below.
7. The role of scientists in ESA is crucial to the success of all science missions. These scientists must maintain their knowledge base and community contacts by having formally allocated time for their own research in order to carry out their agency function effectively and act as a channel of communication between ESA and the scientific community. It has been proposed that the ESA Director General establish an inter-directorate scientific structure within which ESA scientists from all program areas could meet and foster scientific synergy across the Agency.

8. A series of topics for future ISSI workshops was generated including:
    a. High Performance Clocks in Geodesy and Geophysics
    b. Quantum Tests of the Einstein Equivalence Principle
    c. Synergies and limitations of Space Gravity Sensors for Earth Observation and Fundamental Physics
    d. Planetary Metrology with New Technology

Introduction

In 2010 it was suggested by the ESA Director General that ISSI would be well positioned in terms of scientific expertise, available organisational structures, international reputation and level of independence to support the High Level Science Policy Advisory Committee (HISPAC) in its tasks. In responding to this suggestion, ISSI and ESA decided to organise a series of ISSI events. The first of these has been devoted to the topic of Gravity, already selected by ESA as one of its strategic scientific themes and embodied in the selection of a gravitational wave mission for L3. This is a subject which spans many activities within ESA, throughout all its program directorates.

Scientific Context

Gravity is the most fundamental force. It is believed to govern the evolution of the Universe, enables the formation of planets, stars and galaxies and is critical to life on Earth in many ways. The Newtonian formulation of Gravity was sufficient to predict everything that observers could measure for nearly 200 years. Einstein's formulation of Gravity has lasted for 100 years, and while no experimental test has challenged this theory of General Relativity, a profound theoretical challenge has existed for most of that time in the difficulty of quantising the gravitational interaction. The fact that the two most fundamental physical theories may not be compatible on all scales is driving a programme of experimental and theoretical research which has developed sophisticated techniques of measurement, some of which rely on the fundamental laws of quantum mechanics and quantum field theory e.g. atomic clocks, optical and atomic interferometers. These advanced techniques now offer the possibility of using Gravity to explore the structure and dynamics of the Earth, detect the rate of climate change and study the use of terrestrial resources. Thus the subject of Gravity spans a wide range: from theory to experiment and vital practical application. In December 2013 the International Space Science Institute hosted a meeting, at the suggestion of HISPAC, of space scientists to explore the many areas in the European space programme which touch upon Gravity and the methods being developed to study it. The object of the meeting was to encourage and improve the transfer of knowledge between the branches of ESA.

Forum Presentations and Discussions

Gravity affects all particles equally and is a local phenomenon, coupling to the particle mass. On the other hand, Quantum mechanics is non-local and every particle reacts to the presence of every other particle, seemingly over large distances. While quantum phenomena characteristically depend on Planck's constant in some way, the formula for the phase change in an Atomic Interferometer does not include Planck's constant. If Gravity really is completely a phenomenon of space-time curvature (a metric theory) then a profound test of this concept is the Equivalence Principle test-the comparison of free fall for bodies of different composition.

A key outcome from the theory of General Relativity was the prediction in 1915 that gravitational waves would propagate as a spin-2 waves at the velocity of light. In objects predicted only by General Relativity such as binary systems formed of Black Holes, the gravitational wave emission provides a means of studying these objects with considerable precision. The higher harmonics available from a full GR calculation give more information on binary astrophysics including the spin and orientation of the binary partners. Some systems such as the stellar clusters around galactic centres evolve for most of their lifetime in the Newtonian gravitational regime with stellar orbital interactions determining the rate at which objects enter the inner regions close to the central black hole. The later stages of orbital evolution are dominated by gravitational wave emission forming the inspiralling Extreme Mass Ratio binaries- an important group of sources for space-based GW detectors such as LISA. The event rates indicate that a wealth of data will be available from space based detectors when they become available.

Ground based detectors aimed at neutron star and stellar mass black hole emission are already under construction and upgrade and they will improve by a factor of about 10 in the period from 2016 to 2019. The first detection of GW's is expected in that time frame, probably at low signal to noise ratio. In contrast, space based detectors are needed to search for low frequency signals from super massive black holes, implicated in galaxy formation, and eLISA will detect sources out to z=7 and beyond, because the signal to noise ratio in such detectors will be so high.

Another prediction of General Relativity is the dependence of clock rates on the gravitational potential in which they operate. Very precise tests of GR have therefore used the most stable clocks available and have motivated the development of clocks with lower and lower instability, these being subsequently available for other applications. Atomic clocks on the ground are now achieving an instability of 2e-18 while the flight model for ACES achieves 1e-16 and will be launched to the ISS in 2016. These very high precision clocks will enable the study of General Relativity with an accuracy ten to a hundred times greater than presently available. Clocks on their own are limited unless there is an accurate means of time transfer between clocks on the ground and clocks in space. As the clock technology approaches an instability of 1e-18 there will be problems using them on ground due to the uncertainty in geopotential affecting the clock rate through GR. Conversely, such clocks on the ground may be used to study the geopotential and investigate the geometry, geology and hydrology at their location.

Developed from the technology of Atomic clocks, Atom interferometers are now being used in drop towers tests of the Equivalence Principle lasting a few seconds, both for immediate science outcomes and in preparation for longer sounding rocket flights. The current drop tower programme aims to simulate the performance of interferometers in extended free fall and to demonstrate a single-shot sensitivity for inertial forces of 6e-11 m/s2√Hz for matter waves of potassium and rubidium. The limited repetition rate is expected to constrain drop tower tests of the equivalence principle at a level of about 1e-11. On ground, equivalence principle tests using only quantum objects constrained the inaccuracy in the Eötvös parameter to 1e-07 in lab based experiments compared to 1e-13 for the best ground based tests using macroscopic masses. New initiatives realising very long baseline atom interferometers (VLBAI) target inaccuracies beyond this limit. The possibility of performing Equivalence Principle tests using interferometry with Rubidium isotopes onboard a satellite is being studied in the STE-QUEST project with the aim of reducing the inaccuracy in the Eötvös parameter to 2e-15. A test with the same level of accuracy is going to be performed with classical test-masses by the MICROSCOPE mission due to fly in 2016. Apart from experiments probing the foundations of quantum mechanics and gravity with quantum objects, atomic quantum sensors are nowadays commercialised for gravimetric applications. In space, these devices gain enormously from the extended free fall and may serve on satellites in future geodesy missions.

GR effects can be detected in electromagnetic emission from neutron stars and black holes and include spectral changes to iron lines and quasi periodic oscillations produced by matter orbiting in the innermost regions of accretion disks. Fast X-ray variability and quasi periodic oscillations down to sub-millisecond timescale, together the extremely broadened profiles of iron lines and their variations, provide powerful means of investigating GR in these strong field regions. The study of these effects can be important in testing GR using X-ray data. Very large X-ray detector areas are needed to explore these effects in Active Galactic Nuclei. The LOFT mission proposes a technological advance to enhance this study.

ESA has a world leading programme of fundamental physics in space and gravitational missions. Large advances in limits on GR violation will come from currently planned missions such as ACES, MICROSCOPE and Bepi-Colombo. New technology is being developed with higher performance but even the use of current technology in different orbits would increase sensitivity to GR substantially. Scientific progress can often be made using rather small Fundamental Physics payloads on planetary missions which explore different gravitational environments across the Solar System. The new technologies are accelerometers, inertial sensors, atomic clocks and atomic interferometers and these will find application in enhanced science from Planetary Physics missions but also in Earth Observation and Navigation.

The ESA GOCE mission focused on the static gravity structure of the Earth at high spatial resolution (100km) and with an error at the level of 1-2 cm in terms of geoid height. The achievements of GOCE have been remarkable in that they provided, in just a few years, models of the static gravity field of a quality considerably superior to those derived from decades of orbital perturbation analysis. GOCE gave new insight into the physics of the Earth's interior, ocean currents and heat transport as well as improving the definition of the global height-reference system. The NASA/DLR twin satellite mission GRACE launched in 2002 was dedicated to measure, for the first time, temporal variations of the Earth's gravity field and hence mass transport in the Earth system. It achieved unprecedented spatial (~300km) and temporal resolution (1 month). This mission will allow more than a decade of monitoring of surface mass redistributions related to climate change and variability such as ice mass loss in Greenland and Antarctica. In addition, the monitoring of mountain glaciers, ocean mass increases and changes in land water storage will be studied allowing the effects of climate change and human activities to be explored.

Over terrestrial ice sheets GRACE has the advantage of directly measuring mass. This has added value to purely geometrical measurements from radar and laser (e.g. ICESAT) altimeters or SAR, because the gravitational signal reflects the actual mass present, independent of the packing density. One of the outcomes of the GRACE mission is that the polar ice mass is measured to be steadily reducing since the launch in 2002 and the effect seems to be accelerating since 2010. The analysis has to account for global isostatic readjustment - to the last glaciation (also detected by GRACE) in order to see the climate effects clearly - demanding additional information either from space based and in-situ measurements or modelling.

The terrestrial water cycle is another important application of GRACE data. This hydrological data shows that some regions of the Earth are losing water content with profound implications for the local population. To complete the interpretation of hydrological changes global runoff data is required but this is not uniformly available from all regions. The derived hydrological budgets in major river basins have impacts on meteorology, land management, and agriculture.

As these analyses benefit from longer time series, higher measurement precision and better spatial and temporal resolution, a follow-on mission (GRACE-FO) is being implemented by the German Centre for Geoscience (GFZ) and NASA. The mission is due for launch in 2017 and will carry a laser ranging interferometer based on LISA technology as a demonstrator. Optical gravimetry using laser interferometry offers the promise of substantial advances in the study of the Earth from orbit.

The GRAIL mission has performed these kinds of measurement on the Moon to provide a static gravity map of unprecedented accuracy and resolution. ESA has occasionally implemented reusable satellite designs which brought considerable cost savings by repeating missions with the same platform design. There are therefore opportunities to develop gravimetric missions for Venus and Mars using the GOCE or GRACE designs.

While GRACE had a nominal lifetime of about 5 years it has been in orbit for more than a decade but there is no guarantee that it will be operational up until the launch of the follow-on mission. It is likely that a break in the time series data will occur, interrupting the analysis of change patterns. For a number of applications, in particular land hydrology, increased spatial resolution will be needed from future space instruments- of order 100km or less and an improved temporal resolution of better than one week.

Both for Earth Observation and for Navigation a permanent long term measurement of the Earth geoid is required. The technology of gravimetry flown on GOCE and the microwave satellite ranging implemented on GRACE and GRACE-FO are at the limits of their performance and new technologies must be developed based on laser ranging, as will be demonstrated on GRACE-FO, or cold atom technology as proposed in STE-Quest. A combination of these technologies could also enable the observation of static and time-variable gravity fields simultaneously.

LISA Pathfinder, a technology precursor mission to eLISA, due to fly next year, will push the limit of gravitational gradient measurement 3 orders of magnitude beyond the limits of GRACE and GOCE, and that of differential acceleration measurements a couple of orders of magnitude beyond the limit predicted for MICROSCOPE and STE-Quest. The possibility of applying this enhanced sensitivity to a geodesy mission in the solar system at large will certainly be an important development after the flight of LISA Pathfinder.

Many effects need to be taken into account in order to achieve accurate navigation and orbit determination and these rely on accurate clocks. The NASA DSN currently uses Caesium clocks with an instability of 1e-14 or 5e-15. JPL is developing a small mass, mercury-ion clock with a mass of 5kg and requiring 20 w of power as a standard on-board clock. This should achieve instabilities of 1e-14 in 1000 seconds integration. There is the possibility of X-Ray navigation using the timing of X-ray pulsars but very large detectors are needed to obtain an adequate signal to noise ratio and this seems a distant prospect at present.

The Scope for Future Developments

The very rapid recent progress in the instrumentation required to measure and study gravity encourages innovation in both scientific objectives of future missions and greatly improved applications of the technology to current research objectives. Open discussion during the breaks in the meeting and during questions to the speakers generated many possible new scenarios for future study.

The reduction in the instability of atomic clocks might reach levels as low as 1e-20. When this is achieved clocks could not be based on the ground but would have to be on space platforms to ensure a stable gravitational potential. At these levels of performance clocks might be employed to directly measure gravitational waves possibly placed at distant locations in the solar system. As the clock instability is reduced the requirement for precise time transfer between space and ground will become more critical. The extreme sensitivity of such clocks to their gravitational environment will make them the instruments of choice for gravimetry to study the Earth in increasing detail and on increasingly short timescales.

A key organisational challenge for the agency will be the structuring of technology development for the lasers needed for cold atom payloads, each of which may require five or six different laser frequencies but derived from similar basic technology. The separate qualification of each laser frequency source creates very large technical workloads and long delays in programme approval. The development of a generic qualification philosophy would speed ESA's ability to make use of this new technology.

The development to flight status of extremely sensitive accelerometers like those for LISA Pathfinder will enable profound improvements in the science return from planetary missions. Studies of internal planetary dynamics and tests of general relativity will both be substantially enhanced by being able to remove the effects of spurious non gravitational accelerations. In addition, the ability to stabilise payload elements to high precision within an inertial frame may be of value in deploying large items of space infrastructure.

The high technology readiness levels generated by the agency for the interferometry in the LISA programme will find direct application in Earth Observation missions for inter-satellite ranging at high precision.

Conclusions

At the end of the meeting and in subsequent discussions the following recommendations were agreed by the participants:

1. The wide ranging discussions during the meeting demonstrated that there are large benefits to be gained by detailed transfer of technical information between the different areas of science within ESA. The technical issues concerning gravity could include accelerometry, inertial sensors, atomic interferometers, atomic clocks and navigation/clock comparison methods. Novel analysis techniques and software developments are not to be excluded from such activity. Mechanisms should be sought for this transfer of information and actively pursued as a means of maintaining an efficient programme of science delivery.
2. The opportunities for cross fertilisation of technical progress between science areas as diverse as Fundamental Physics and Earth Observation presents a major opportunity for ESA. In particular the techniques of interferometry, either using lasers or cold atom sources, may contribute substantially to new levels of performance in the study of the Earth via gravimetry.
3. The many extremely novel aspects of instrumentation for fundamental physics require considerable care in allocating hardware development tasks between industry and academic institutes. At present the administrative processes for space mission management favour technical developments in industry where high risk development programmes are expensive and time consuming. The allocation of early stage development work needs to be made by analysing where the risks and costs are best managed.
4. Whenever possible ESA should make available opportunities for small secondary payloads to maximise the science outcomes from missions. These might be fundamental physics experiments benefiting from deep space orbits in planetary missions or small payloads on Galileo platforms where multi-point measurements could be effective.

5. An active watch should be maintained for synergy between other fast growing technical sectors (such as telecoms, for example) in which ESA could benefit from developments leading towards flight hardware of value to the science programme.
6. ESA may wish to build upon the ISSI meeting reported in this note by organising further workshops on the detailed transfer of single items of technology between different programmes within the agency. Some suggestions for workshop topics are made below.
7. The role of scientists in ESA is crucial to the success of all science missions. These scientists must maintain their knowledge base and community contacts by having formally allocated time for their own research in order to carry out their agency function effectively and act as a channel of communication between ESA and the scientific community. It has been proposed that the ESA Director General establish an inter-directorate scientific structure within which ESA scientists from all program areas could meet and foster scientific synergy across the Agency.

Suggested Workshops/Working Groups

A. High Performance Clocks in Geodesy and Geophysics

Objective: Bring together scientists from the time/frequency community and from the geodesy/geophysics community in order to study by extensive numerical simulation possible improvements in geodesy/geophysics applications when including local clock measurements at 1e-18 (1 cm level in geopotential height difference). The outcome would be the determination of the possible improvements (if any) in global and regional geopotential models and specific geophysics applications when using a combination of satellite data (GOCE, GRACE, etc…), ground gravimetry and levelling, and clock measurements.

B. Quantum Tests of the Einstein Principle of Equivalence

Objective: The group should be a plenum for discussing the peculiarities of tests of the Einstein principle of equivalence with atom interferometers and clocks. Other related topics are the complementarity of quantum tests and tests based on classical objects with respect to different models (e.g. the standard model extension), tests of Schiffs conjecture or generally the connection between redshift measurements and free fall experiments in atom interferometers and tests of the foundation of quantum mechanics.

C. Synergies and Limitations of Space Gravity Sensors for Earth Observation and Fundamental Physics

Objective: Identify to what extent techniques from the fundamental physics area can be applied to measure the Earth's gravity field. What in addition would be required to achieve the science goals of Earth science in the hazardous environment of Low Earth Orbit? What is the technical readiness of such sensors?

D. Planetary Metrology with New Technology

Objective: What science results from Venus and Mars might be derived from using essentially the GRACE or GOCE platforms in suitable orbits?

ANNEX

Participants
HISPAC / ISSI Forum on "Understanding Gravity"
December 3/4, 2013

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ISSI/HISPAC Forum on "Understanding Gravity"

Tuesday, 3 December 2013

Introduction

9:00-9:15 Welcome and Introduction: What we hope to accomplish (**R. Rodrigo**)

Block I: Probing the Fundamentals

9:15-9:45 Gravitation and Quantum Theory: Stating the Issues with Gravitation (**C. Laemmerzahl**)

9:45-10:15 Black Holes, Gravitation and General Relativity (**P. Amaro-Seoane**)

10:15-10:45 Gravitational Wave Detection: Earth- and Space-based Approaches (**K. Danzmann**)

10:45-11:15 Coffee Break

11:15-11:45 Dark Matter, Dark Energy and Alternative Gravitation Theories (**B. Sathayaprakash**)

11:45-12:15 High Precision Time Measurement in Space (**P. Wolf**)

12:15-12:30 General Discussion

12:30-13:30 Lunch break

13:30-14:00 Testing General Relativity and Quantum Mechanics in Space (**E. Rasel**)

14:00-14:30 Fundamental Physics Experiments in a Zero-Gravity Environment (**A.M. Cruise**)

14:30-15:00 General Discussion

15:00-15:30 Coffee Break

Block II: Related Observational Areas

15:30-16:00 Observing the Environment of Collapsed Objects (**L. Stella**)

16:00-16:30 Measurement of the Time-variable Earth Mass Distribution (**A. Cazenave**)

16:30-17:00 Ice Sheet Mass Loss inferred from Space Observations (**F. Flechtner**)

17:00-17:30 General Discussion

Conclusion of Day 1

20:00 ***Dinner***

Wednesday, 4 December 2013

Block III: Related Observational Areas (continued)

9:00-9:30 Gravity Measurement and the Study of Solar System Planets (**P. Tortora**)

9:30-10:00 Future High Precision Measurement of Earth and Planetary Mass Distributions (**O. Carraz**)

10:00-10:30 Time Measurement and its Importance for Navigation (**T.J. Martin-Mur**)

10:30-11:00 ***General Discussion***

11:00-11:30 ***Coffee Break***

Block IV: Overall Discussion (How our Forum can assist the HISPAC aim of advancing long-term science and technology developments across ESA)

Introduced and chaired by M. Longair/M. Heppener

12:30-13:30 ***Lunch at ISSI***

13:30-15:00 Outline of Forum Report, Discussion (**A.M. Cruise, A. Cazenave, L. Culhane**)

Possible ISSI Workshops, Discussion (**A. Cazenave**)

15:00 ***Coffee Break***

Adjourn