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Topical Team on Geodesy
Applications of the ACES Mission

ACES and FUTURE GNSS-BASED EARTH OBSERVATION and NAVIGATION

Extended Abstracts

Edited by D. Svehla

IAPG / FESG No. 28
Institut für Astronomische und Physikalische Geodäsie
Forschungseinrichtung Satellitengeodäsie

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ACES and FUTURE GNSS–BASED EARTH OBSERVATION and NAVIGATION

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Preface

"ACES and Future GNSS-based Earth Observation and Navigation" is the ESA workshop held on the 26-27 May 2008 at the Institute of Astronomical and Physical Geodesy, Technische Universitaet München, Germany. The workshop was organized and sponsored by the ESA Topical Team on Geodesy Applications of the ACES Mission.

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Atomic Clock Ensemble in Space (ACES) is an ESA mission based on the performances of a new generation of atomic clocks operated in space, on board the International Space Station in 2013-2015. The ACES clock signal will reach fractional frequency stability and accuracy of 1 part in 10^{-16} opening attractive perspectives for testing Einstein's theory of general relativity. The two-way microwave link developed for the ACES mission will allow frequency comparison of ground microwave and optical clocks at the 10^{-17} level. The ACES frequency reference will be connected to an on-board GPS/(GALILEO) receiver which will ensure precise orbit determination of the ACES clocks and at the same time will allow to develop applications in different areas of research. Besides fundamental physics, the geodesy part of the ACES mission is related to scientific objectives in the field of the LEO orbit determination, combined optical and microwave ranging and time/frequency transfer, determination of gravity potential using ground optical clocks, GNSS radio-occultation and GNSS reflectometry/scaterrometry.

Scope of this workshop was to bring together a wide scientific community and exploit the ACES potential for applications in the fields of geodesy, Earth observation and navigation.

All presentations from the workshop are available on the CD at the end of the proceedings and online
http://www.iapg.bv.tum.de/aces.html

We would like to thank the Technische Universität München for hosting the workshop.

CONFERENCE COMMITTEE

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ACES Mission – Status

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The successful installation of the Columbus laboratory on the International Space Station on February 2008 has represented a major step for Physical Sciences in space. Several new experiments will be performed and in particular in the Fundamental Physics discipline. A pioneering step will take place in 2013, when the Columbus module will receive the Atomic Clock Ensemble in Space (ACES) payload, carrying ultra-stable atomic clocks and a high-precision time transfer system. Using this accurate time reference in space, the ACES mission will perform new tests of general relativity, search for possible minute violations of Einstein's equivalence principle, and develop several applications in Earth observation and geodesy.

The ACES Mission is presently in C/D phase. The engineering models of the on-board clocks and the main ACES subsystems are presently under test. The PHARAO clock reaches a fractional frequency instability of 2.3×10^{-13} at 1 s, well in agreement with the interaction times possible on ground. MWL has recently demonstrated performance levels compatible with mission requirements, confirming the possibility of performing clock comparisons down to the 10^{-17} regime after few days of integration time. After standalone test campaign, the engineering models of ACES clocks and subsystems will be assembled and integrated tests will verify the performances of the complete system releasing the manufacturing of the ACES flight model.

ACES and Applications

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The scientific objectives of the space mission ACES are:
1) Operate a cold atom clock in microgravity, PHARAO, and a space maser
2) Perform a measurement of the Einstein effect at 2 ppm, (x 35 over GPA)
3) Search for Lorentz invariance violation (x 20)
4) Perform space to ground and ground to ground clock frequency comparisons at 10^{-17} level
5) Search for drift of fundamental constants at 10^{-17} per year
6) Demonstrate relativistic geodesy
7) Monitor GPS and Galileo timing signals from Space
8) Earth atmosphere monitoring and ocean water sounding

Topics 1) to 4) have been discussed extensively at the Florence ACES Relativity workshop on May 29-30, 2008 and presentations are available at ftp://cacciapuoti:ln73rn0@ftp.estec.esa.int/
Topics 5) to 8) have been discussed at the Munich workshop and have lead to the conclusion that interesting Science return from the ACES could also be obtained in the geodesy and Earth observation domains if radio-occultation and passive radar reflectometry could be implemented on the ACES platform. On the technical side, all engineering models of the ACES flight payload have been realized (FCDP, MWL, PHARAO, SHM) and all elements have successfully passed performance tests in 2007-2008.

Ground clocks have made rapid progress in the last couple of years, both in the microwave and optical domains. In the microwave domain, cesium and rubidium fountains now routinely reach a frequency stability of 1 E-16 after about 10 days of averaging time. This corresponds to what is expected from the PHARAO clock onboard the ISS. Agreement between the frequency delivered by the 3 SYRTE fountains is at the level of 3-4 E-16, in accordance with their stated accuracy.
In the optical domain, clocks with trapped ions and neutral atoms have made spectacular progress very recently; The NIST Boulder group of J. Bergquist and D. Wineland have published a frequency comparison between two optical clocks with an accuracy of 2 E-17, which represents a one order of magnitude gain over the fountain clocks operating in the microwave range. This accuracy is likely to improve significantly in the near future.
In parallel, optical clocks with neutral atoms trapped in an optical lattice at the magic wavelength have reached a stability and accuracy of 1E-16 surpassing also the microwave clocks and here again there is large potential for improvements in the short term. We anticipate that several groups will operate clocks with 10^{-17} accuracy when the ACES mission flies (2013-2015).

Advances on ground clocks and on the ACES MWL will impact very significantly the scientific return of the ACES mission on the following aspects: (i) search for possible drift of physical fundamental constants (ii) test of the Einstein effect, (iii) relativistic geodesy.

(i) The ACES microwave link will be able to compare these distant clocks at the level of 1 E-17 for the relative frequency stability after typically 1 to 3 days of measurements and even better for longer measurement durations. This is clearly beyond the capacity of the GPS carrier phase technique. Because of its worldwide coverage, ACES will thus enable a global test of the stability of fundamental constants by comparing a large set of different clocks in the whole domain of the electromagnetic spectrum. Wether a variation or no variation of constants will be detected will either put new constraints on theoretical models or bring a clear violation of the Einstein Equivalence principle, one of the pillars of modern physics.

(ii) The various ground clocks with 10^{-17} accuracy will bring a negligible contribution to the error budget in the measurement of the Einstein effect (redshift). This budget will then solely depend on the accuracy of the PHARAO clock in space environment and a measurement at the level of 2 ppm on the redshift test is the target of this relativity test.

(iii) The frequency of a clock on the Earth surface depends on the local gravitational potential with a sensitivity coefficient of 1 E-16 per meter. Therefore optical clocks with 1E-17 accuracy can bring an interesting contribution to the geodesy research domain. Indeed the Earth geoid is currently determined by recent space missions with a comparable accuracy (10 cm) and is not easily physically realized on the ground. The consistency between space determinations and levelling methods on the ground is currently at the 23 cm level with some bias removed.

Work in this direction concerning the best locations for optical clocks in connection to the geoid and height reference system is expected.

GALILEO on Board the International Space Station and Combination with the ACES Mission

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We present the project GALILEO-ISS on board the International Space Station. In this project we propose the installation of a geodetic dual-frequency GNSS receiver (GALILEO/GPS) on board the Space Station. The experiment is to demonstrate the potential of the unique combination of the GNSS receiver with the highly stable frequency of the ACES clock ensemble as a sensor for remote sensing and relativistic geodesy. Although large solar panels reduce the field of view and number of tracked GNSS satellites, we show that due to the ISS orbital inclination (52°, almost identical to that of the GNSS satellites) the mean number of GPS satellites visible is considerably larger (by a factor of 1.5) compared to the CHAMP and GRACE satellites in their polar orbits. By installing the GNSS antenna on top of the Columbus module, the near field multipath can be mitigated and the best GNSS tracking secured. We show, in that case, the expected orbit accuracy for the Space Station is about 2-3 cm.

By making use of frequency transfer with an accuracy of about 10^{-17} based on the ACES microwave link (MWL) and the geodetic GPS/GALILEO receiver, we expect to estimate gravitational potential differences between clocks on the ground with accuracy below 10 cm in terms of geoid heights. This will be the first demonstration of the concept of measuring gravitational potential differences in a purely relativistic way by comparing clock frequencies between terrestrial clocks. The GNSS receiver, driven by the ACES clock, can be included into the processing of the global network of GNSS receivers at time laboratories throughout the world, making the ACES time/frequency scale accessible to all those laboratories and any other GNSS stations in view.

GALILEO will provide navigation signals of improved tracking capabilities, and will introduce several new frequencies. In combination with the highly stable ACES frequency we propose a pioneering coherent reflectometry/radio occultation experiment, testing interferometric techniques to derive sea surface heights within or below decimetre level in a large swath. This will allow the demonstration of an altimetry system based on signals from navigation satellites such as GPS and GALILEO. On the other hand, flying this experiment on board the ISS will be a unique opportunity to demonstrate the full potential of GPS/GALILEO-based altimetry as a component of a future global tsunami early warning system. This will be a proof of the concept for designing a future satellite constellation for detecting tsunamis from LEO orbits. The ACES external platform on the Columbus module offers the great opportunity to implement for the first time a scatterometry antenna. Such an arrangement would allow for experiments to derive sea surface characteristics on a global scale using GNSS techniques (e.g., altimetric information, wind speed and direction). Beyond reflectometry applications, the used instrument configuration would also allow for GNSS radio occultation applications with several new scientific aspects compared to the current operational missions. Simulation studies show that due to the lower orbit inclination of the

ISS, the largest number of radio-occultation events will be observed in the tropics and mostly with high antenna gain, providing an ”orthogonal” data set to polar orbiting satellites. It is expected, that this fact would improve the potential of coherent reflectometry in tropical regions in contrast to polar orbiting LEO satellites.

GNSS Receivers for Space Applications

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Over the past two years limited progress in GNSS receiver technology for space applications has been made. Within the European context, spaceborne GNSS receivers are primarily based on the existing AGGA-2 correlator chip, which supports GPS L1 C/A code tracking and semi-codeless P(Y) tracking on L1 and L2. The same chip will also be used for the GNSS receivers to be flown on SWARM and the Sentinel satellites within ESA's Earth observation program. The AGGA-3 development did not proceed as planned and suffers from technical problems and the intermediate revision of the Galielo signal structure. On short term, new signals will only be supported by the Topstar3000G2 receiver. It offers L1 C/A code and L2C code tracking but is limited to six dual-frequency channels, only. A first flight of this receiver is expected for early 2009 onboard the PROBA-2 spacecraft.

In the US, the BlackJack receiver and its commercial variant, IGOR, remain the de-facto standard for numerous national and international science projects. A modified IGOR firmware is reported by JPL to provide experimental L2C occultation measurements onboard one of the COSMIC satellites. Broadreach Engineering is presently working on the design of a next generation receiver (PYXIS) with lower resource requirements, improved radiation hardness and support of new GPS L2/L5 as well as Galileo signals. First engineering models are stated to be available by the end of 2008.

In the field of commercial-off-the-shelf dual-frequency receivers the inflight validation of the PolaRx2 on TET-1 has been delayed until 2010. Preliminary signal simulator test have been conducted with Javad's GeNeSiS receivers but superceded by the new Triumph receivers that should become available by mid 2008. The Triumph receivers will offer an unrivalled number of tracking channels and are designed to support GPS, GLONASS and Galileo signals on the L1, L2 and L5 frequencies. The availability of multiple frontend receivers and the high-rate I/Q vector samples makes the receiver the primary candidate for ACES as regards GNSS based POD and geodesy aspects (i.e., occultation and reflectometry). A detailed performance analysis and environmental qualification will be conducted by GFZ and DLR after delivery of the first test boards. With a final decision on the ACES GNSS receiver required not earlier than one year from now, enough margin is available to thoroughly validate the Triumph receivers for this mission and to coordinate possible software upgrades with the manufacturer.

Remote Clock and Timescale Comparisons: a Status Report

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Satellite based time and frequency transfer is routinely performed in many institutes worldwide, last-not-least for contributing to the realization of International Atomic Time TAI. The routine operations allows remote clock comparisons with an uncertainty of about 10^{-15} (1 day averaging time) for frequency which is perfect for the current quality of national timescales, acceptable for fountain comparisons, but still insufficient to compare optical frequency standards in a meaningful way. Two different methods exist: GPS based techniques and two-way satellite time and frequency transfer (TWSTFT). While both methods allow comparisons with the low uncertainty in frequency, only TWSTFT has been proven to allow time transfer with one nanosecond uncertainty.

In this contribution, the current status of satellite based time and frequency transfer techniques as it is in routine operation is described and limiting factors as well as the potential for improvements are discussed.

ACES Microwave Link (MWL), as an Universal Tool for Time Transfer and Ranging from Low Earth Orbit to Deep Space Applications

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The time scale generated by the ACES clocks on-board the ISS is delivered to Earth through a high-performance microwave two-way time and frequency transfer link (MWL). Its primary operational mode is for space-to-ground clock comparison. Additionally, it supports high-performance ground-to-ground comparisons of atomic frequency standards. Suitable ground terminals, which are presently being designed and manufactured, will be located directly at sites and laboratories equipped with high performance frequency and time standards.

The MWL design uses a bi-directional dual frequency PN-coded spread spectrum signal with simultaneous operation in both directions. It is designed to remove the first-order Doppler effect due to the relative motion between the ACES clocks and the ground observers. The instrument architecture and the choice of measurements have been carefully designed to reduce signal-path induced effects, such as tropospheric delays, dispersion from ionosphere and multi-path effects, to a minimum.

The MWL engineering model has been manufactured, tested and calibrated to demonstrate its compliance to ACES specifications and in particular to maintain a link delay stability ranging from below 230 fs within one pass of 330s up to 15ps after 10 days.

The design combines traditional two-way ranging techniques used for satellite navigation from low-earth orbit up to deep-space together with the well-established two-way time- and frequency transfer techniques for metrology grade comparison of primary reference clocks. An integral data transfer capability is included for system operation and for the exchange of measurement data between the two sides of the link.

The spread spectrum and coding techniques are ideally suited to perform simultaneous and uninterrupted measurements of

- Ranging, round-trip or one-way
- Range-rate based on code- and/or carrier phase
- Time- and Frequency transfer, between ground and space or between S/C
- Tele-command and telemetry data transmission

Although the MWL instrument has been designed specifically to meet the ACES mission objectives, it can be easily adapted with only minor modifications to a variety of applications and orbits, ranging from earth to deep space in support of satellite operations as well as scientific objectives, including such missions, in which the clock under observation becomes the sensor itself for sensing the local gravitational potential.

Interesting new applications and capabilities arise from the advent of advanced, high speed laser ranging and communication links. These might be combined in novel ways with the well-established microwave-based technologies, for to enhance capabilities, to reduce instrumental or link-induced errors and in general to enhance operations and the scientific outcome in the in the field of high performance ranging and time-transfer. Further applications include

- comparison and harmonisation of optical and microwave based techniques
- comparison and alignment of reference systems
- one-way laser ranging and time transfer out to deep-space distances
- monitoring of satellite-based reference clocks and time-scales

- radio science en route and to orbiting probes
- support of positioning, navigation and timing (PNT) within the solar system.

It is recommended to demonstrate these capabilities during the conduction of the ACES mission as part of the secondary mission objectives. It is further recommended to consider these readily available techniques to support and enhance European ground- and space-based PNT capabilties and to establish a sustained metrology-grade time-reference in space.

Considerations for an Optical Link for the ACES Mission

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Satellite Laser Ranging (SLR) provides a technology, which is most suitable for time transfer. While other optical timescale adjustment approaches usually perform frequency comparisons and make use of data averaging, SLR directly links the epochs of the respective timescales with high accuracy on a shot by shot basis. However technologically one has to overcome a few obstacles, because the timing of optical laser pulses still requires the transition from the optical regime into the electronic regime. Systematic effects in the signal conversion cause extra time delays and this may result in an unwanted timescale offset if not properly accounted for. Additional difficulties are coming from the measurement requirement of a very wide receiver field of view (1 rad or more) and the corresponding high level of background light. Therefore the proper choice of the applied optical detector in the most stable operation regime makes up an important part of the proposed laser ranging clock comparison on the ACES mission. The K14 Single Photon Avalanche Diode (SPAD) fulfills these requirements. Operated in the coherent Geiger mode the calculations show, that a sufficient signal to noise ratio can be achieved even when the entire receiver footprint on the Earth is illuminated by the sun.

Ultra Stable Frequency Transfer Using Laser Optical Phase on a Fiber Telecom Network

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Transfer of ultra-stable frequencies between distant laboratories has found many applications in time and frequency metrology, fundamental physics, particle accelerators and astrophysics. Clock comparisons are currently performed using satellites, directly by Two-Way Satellite Time and Frequency Transfer, or indirectly through the Global Positioning System carrier phase. However, both methods are limited by instability at one day of 10^{-15} and are consequently insufficient to transfer modern cold atom microwave frequency standards having demonstrated frequency stability Allan standard deviation of a few 10^{-16} @ 1 day. Moreover, cold atom optical clocks are expected to reach instability level of 10^{-17} @ 1 day or better and will consequently require still more stable transfer system.

To overcome satellite based link limitations and allow direct optical frequency domain transfer, transmission of frequency standards over optical fiber has been experimented for several years. This technique takes advantage of the fiber low attenuation, high reliability and phase noise cancellation achievability. Microwave frequency transmission using amplitude modulation of an optical carrier has demonstrated instability as low as $2x10^{-18}$ over 86-km [1]. Direct optical frequency transfer can provide even better stability and be extendable to greater distance [2] [3] [4] thanks to the direct electromagnetic field sensitivity.

Two experiments of optical frequency transfer have been performed in 2007 over more than 200-km long fiber link by using fiber spool extension of an urban link [3] [4]. Both of them have demonstrated the feasibility of a full optical link with stability in the 10^{-18} range. We report here the results of the transmission of a sub-Hz line-width optical frequency on fully urban network 86-km and 172-km long links.

Our frequency transfer link is comprised of two cascaded 43-km fibres, part of an urban telecommunication network connecting two French laboratories, LNE-SYRTE and LPL in Paris area. It is fed with a 1542-nm fibre laser having a sub Hz line-width. We present our first results on an 86-km link and on a 172-km link obtained using recirculation through the installed fibre. The phase fluctuations due to the variation of the propagation delay are measured with an all-fibre-based interferometer. The compensated 172-km link shows an Allan deviation of a few 10^{-16} @ 1 s and a few 10^{-19} @ 10,000 seconds.

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GNSS Atmospheric Remote Sensing: An opportunity for ACES

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Since the proof-of-concept GPS/Meteorology mission in 1995 space-based radio occultation (RO) has matured to become a well established atmospheric remote sensing technique. Currently several operational RO missions are in orbit, e.g. CHAMP (launched in 2000), GRACE (launched in 2002), FORMOSAT-3/COSMIC (launched in 2006) and MetOp (launched in 2006).

In an occultation measurement a space-based receiver observes signals transmitted by GNSS satellites as they disappear (or appear) at the horizon. The basic observable is carrier excess phase path which quantifies the accumulated influence on the signal propagation through the iono-, strato- and troposphere. From excess phase paths vertical profiles of bending angle are obtained which in turn are inverted to yield atmospheric refractivity, (dry) temperature and pressure. If auxiliary information on the dry part of refractivity is available, e.g. from meteorological analysis fields, humidity profiles can be derived as well. An occultation measurement is in essence a time measurement and therefore inherently bias-free. With GPS wavelengths of 19.0 and 24.4 cm, corresponding to carrier frequencies of 1575.42 MHz (L1) and 1227.60 MHz (L2), RO is insensitive to clouds, preciptation and aerosols.

Validation studies show good agreement with meteorological analysis data. The agreement between CHAMP, FORMOSAT-3/COSMIC and ECMWF in terms of fractional refractivity is below 0.5% with standard deviations of about 1%. Significant differences between CHAMP and FORMOSAT-3/COSMIC are found regarding the penetration altitude in the lower troposphere, i.e. the altitude at which loss of signal occurs. These differences are caused by an open-loop tracking algorithm which is implemented in the more advanced FORMOSAT-3/COSMIC receivers, but not available for CHAMP.

For ACES aboard the ISS we propose a forward-looking occultation experiment. In support of the proposal a simulation study was performed based on CHAMP-like instrumental parameters. In contrast to CHAMP the ACES occultation receiver will be supplied with precise timing information allowing signal acquisition using zero differencing as opposed to single or double differencing employed by CHAMP. With 51.6 degrees the ISS's orbit inclination is similar to the GPS satellites' inclination of about 54.9 to 55.5 degrees and the geographical distribution of ACES RO events is therefore restricted to low and mid latitudes. On the other hand, most low latitude events are observed by ACES at off-boresight angles close to zero degrees improving the signal-to-noise ratio and reducing the probability of early signal loss. Polar orbiting platforms such as GRACE or CHAMP suffer from a lack of occultation events for off-boresight angles below 30 degrees at tropical latitudes. In this respect the proposed RO experiment for ACES operates at a complementary occultation geometry in comparison to existing RO missions.

GNSS Reflectometry at IEEC

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The transmitted L-Band Global Navigation Satellite Systems (GNSS) signals after its reflection on the sea surface could be collected by suitable receivers placed on different platforms (on ground, aircrafts, balloons or satellites). The GNSS reflected signals are further processed to extract the *waveforms*: cross correlation functions of the reflected signals with parametrized models of them. This is similar to the correlation processes implemented in the traditional GNSS receivers. The main difference is the need of a larger number of correlator because the departure of the reflected *waveforms* from the triangular shape requires additional information. These GNSS-R *waveforms* are considered the primary observables for the analysis: the GNSS Reflectometry (GNSS-R) uses the obtained *waveforms* to infer properties of the Earth surface (sea state and sea altimetry, soil moisture, ice properties, etc). The concept was proposed initially by ESA under the term PARIS (Passive Reflectometry and Interferometry System).

In the demonstration phase of the concept, the GNSS-R research was based on the use of recording devices (magnetic tapes or hard disk drives) like in other microwave interferometric techniques (i.e. VLBI) to sample the signals at rates on the order of Msamples/second and to perform the correlations off line. The advent of large capacity Field Programmable Gate Arrays (FPGAs) allowed to avoid the need of off line computations.

This presentation deals with the work done by the GNSS-R IEEC, which ranges from instrument design and fabrication to the scientific applications of the concept and demonstration campaigns. In addition we will provide some details of the Altimetric and Scatterometric Applications of the PARIS Concept (ASAP), project part of the Spanish Space Program, which IEEC is carrying out in cooperation with the Spanish Instituto Espacial de Técnica Aeroespacial (INTA) and the Spanish space industry TTI Norte.

A more detailed description of part of the work done could be found in the references:

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GNSS Reflectometry at GFZ

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During the last years several studies and experiments have been conducted at GFZ related to GNSS reflectometry. A first milestone was the detection of coherent GPS reflections onboard CHAMP from low Earth orbit (LEO), using the GPS radio occultation measurements (50 Hz amplitude and phase data) of the Blackjack receiver with the aft-looking radio-occultation antenna. Since 2000 CHAMP is successfully in Earth orbit. The additional nadir-looking LHCP antenna onboard CHAMP, dedicated for GPS altimetry and scatterometry measurements, has not been switched on and a necessary firmware modification of the GPS Blackjack receiver has not been performed mainly due to the priority of the main scientific gravimetric, magnetic and radio-occultation experiments. Own receiver developments have been initiated at GFZ starting with the COMNAV receiver, a raw GPS L1 bitgrabber with two radio frequency (RF) antenna frontends. A flight campaign at Lake Constance approved the feasibility to use GPS code altimetry to determine the flight height above waer within meter accuracy. Receiver developments based on the well documented Zarlink correlator chipset were continued with the OpenGPS receiver. The OpenGPS receiver allows direct communication with the Zarlink correlator chip. Hence, open-loop tracking could be implemented and the receiver can record 50 Hz in-phase and quad-phase data of up to 4 reflected GPS signals in parallel. Additionally, the reflected signal waveform of one GPS satellite can be sampled with up to 22 correlator arms. Since 2003 several ground□based experiments demonstrated that the OpenGPS receiver can record coherent GPS reflections which allow for carrier-phase based height observations and relative altitude accuracies within cm-level. Receiver developments are extended by the Namuru receiver which is based on a field-programmable gate array (FPGA) implementation of the Zarlink correlator design.

Within the German Indonesian tsunami early warning system (GITEWS) project, concept studies for space based warning systems were initiated and related activities to develop new technologies like space-based GNSS reflectometry and scatterometry were started in 2006. The general idea is that with multi-frequency GNSS receivers, as add-on payload of independently planned Earth observation missions, densely spaced grids of sea surface heights with decimeter precision could be established fairly rapidly. Simulation studies within GITEWS analyze statistically various scenarios of Walker orbit constellations with different numbers of LEO orbit planes and satellites at different inclination angles and heights with respect to tsunami detection time and spatial coverage assuming the Sumatra tsunami event represented by a tsunami wave propagation model. These studies indicate that only a large number (18 or even more) LEO satellites can monitor the ocean with the required high resolution in space and time in order to detect a tsunami wave sigature. Such a dedicated constellation can be realized by a set of small and affordable satellites which are equipped with a GNSS instrumentation based on commercial off-the-shelf (COTS) receivers rather than dedicated expensive space receivers. GFZ has set up and leads a team complemented by the German Aerospace Center (DLR) and JAVAD GNSS to adapt and extend the new generation JAVAD GNSS receivers for advanced scientific space applications on small LEO satellites. The GNSS occultation, reflectometry and scatterometry (GORS) space receiver prototype consists of a COTS JAVAD GNSS GeNeSiS-112 72 channel receiver board. As major step forward compared to current space receivers the new GORS receiver prototype supports tracking of the civil L2C signal emitted from modernized GPS satellites (GPS-M). Signal simulator tests show that this prototype provides proper GPS measurements for orbit determination and scientific applications under the signal dynamics of a simulated LEO satellite. The receiver firmware is modified to allow for two-frequency 200 Hz in-phase and quad-phase data output and open-loop tracking of reflected GPS signals. Ground-based water level observations with the GORS instrument show the possibility to remotely derive height profiles of a reflecting water surface within cm-level accuracy from GPS L1C/A and GPS L2C signals, respectively. These results show good agreement with water level observations from a conventional tide gauge sensor. Furthermore, it is possible to record the reflected signal waveform in order to derive surface roughness, wave height and wind speed information.

The current activities are focused on the next generation GORS2 receiver prototype which is based on the JAVAD GNSS TRIUMPH COT receiver platform. The TRIUMPH chip has 216 channels for tracking all types of GNSS signals including GPS, GLONASS, Galileo, QZSS, WAAS, EGNOS, and Compass/Beidou. Beside of the high number of available channels and GNSS signals the TRIUMPH receiver family can provide 1-4 RF antenna frontends and external frequency in/output. Within GITEWS, until the final decision on the ACES GNSS receiver has to be made, signal simulation, performance analyses and environmental tests will be conducted with a set of 1-RF TRIUMPH TR-G3T boards in summer 2008. Additionally, further receiver software modifications will be made together with the manufacturer and ground-based and airborne campaigns are planned with a multi-frontend GORS2 prototype until November 2008.

For ACES we propose a 4 RF frontend GORS2 prototype as a candidate scientific COTS based space receiver which would represent a demonstrator mission instrument covering new scientific aspects for reflectometry and occultation. We propose a zenith-looking RHCP antenna for precise orbit determination (POD), a nadir-looking LHCP antenna for scatterometry and altimetry based on incoherent GNSS reflections and a forward-looking RHCP antenna for altimetry used for coherent GNSS reflection and radio-occultation observations.

On the combination of gravity and altimetry - possible applications of ACES

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Extended geodetic levelling networks suffer from measurement errors accumulating along the levelling path and missing or unreliable gravity observations along this path, required to derive potential differences. The Brazilian levelling network is an example. It exhibits discrepancies between the physical heights and the mean sea level, summing up to more than 80 cm along a levelling path at the Atlantic coast from Imbituba in the South East to Belem, located at the Amazonas delta. Potential differences between the end points of this path could be used as a constraint in the adjustment of the network. In principle, the ACES project provides all necessary components to derive potential differences: the two atomic clocks on the ISS, the microwave link for transmitting the time signal to ground, the ground terminals and atomic clocks on the ground. More general, as the frequency shift of atomic clocks operated at different levels of the Earth gravity field is proportional to the potential differences, the ACES project could be applied for a straightforward solution to the world wide unification of height systems. Traditionally national height systems are related to coastal tide gauge stations using a long term realisation of the mean sea level. The sea level however is neither an equipotential surface of the Earth gravity field nor a stationary surface in space. This causes inconsistencies between the heights systems of neighbouring countries. The current efforts to unify height systems focuses on a rather complex combination of different techniques (levelling, gravity measurement, GPS, satellite altimetry) at the tide gauges. Thus, the application of the ACES project for stabilizing and unifying the world wide height systems would be a great challenge.

Synergy of the ASIM and ACES Radio-Occultation

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This presentation served two purposes: To describe the ASIM payload, its hardware and its scientific goals, and to give a preliminary indication of common scientific interests between ASIM and ACES.

The ASIM payload consists of 6 cameras and 6 photometers covering a selection of wavelength bands and an x-ray detector. 4 cameras and 4 photometers are looking at the limb in the ram direction. The rest of the instruments are looking towards nadir. The overall objective of the payload is to study thunderstorms and their relation to atmospheric processes and a changing climate. ASIM will study the atmosphere above thunderstorms to investigate electrical discharges (Sprites, Elves, Halos, Jets and X-rays) and the connection between the storms and the ionosphere. Further studies involve clouds and water vapor, gravity waves and atmospheric chemistry.

One area of interest is the study of cloud turrets. In order to access the role of thunderstorms in the circulation of water vapor in the troposphere and the lower stratosphere ASIM will determine the role of tropical thunderstorms in the deep convection in the tropical tropopause. This will be done by observing high altitude clouds on the limb. Here the ACES experiment can play a useful role. By measuring the radio transmission from GNSS through these regions an estimate of the water content in the areas above the thunderstorms can be obtained. The ACES experiment needs to determine the water content in order to correct the atmospheric transmission times.

It thus appears that the two experiments ACES and ASIM have overlapping scientific interests in this area.

GNSS Reflectometry and Passive Radar at DLR

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The presentation mainly summarises a planned GNSS reflectometry satellite mission that has been proposed by the Microwaves and Radar Institute to the DLR programme board in close cooperation with the GFZ Potsdam. The proposal was driven by the possible opportunity to use the DLR TET-1/-2 (Technologie Erprobungs Träger, very similar to the BIRD satellite bus) platform for a mission based on GNSS technology. The main instruments comprise Javad GNSS receivers (1- and multi-frequency), GNSS antennas plus a phased array beam-steerable reflectometer antenna (passive radar), an SLR retro reflector and a VLBI. The goals of the mission are

- GNSS-based remote sensing for atmosphere, ionosphere, oceans, ice, soil (moisture), etc. using radio occultation and reflectometry
- Precise orbit determination (POD) and co-location of geodetic methods from space (reference systems, gravity field, etc.)
- Development of technologies and know-how for future micro satellite constellations (formation flights) using GNSS
- Passive radar for altimetry and scatterometry using a beam-steerable antenna
- Antenna development for passive radar, including space qualification

A number of possible applications and experiments have been identified, particularly in the oceanographic field, i.e. sea level estimation (altimetry), determination of ocean wave spectra (2D), sea roughness and swells (scatterometry), retrieval of wind speeds, sea ice parameters and the estimation of ocean wave orbital velocities. Finally also the possibility of using a large constellation of such satellites for Tsunami detection is taken into account. Additional applications could be soil moisture extraction, ionospheric and atmospheric effects and land mapping (clutter).
It is not yet decided whether the mission concept will be considered for TET-2 or not. However, it should be clearly pointed out that such an instrument would be the first complete demonstration of ESAs PARIS concept [Martin-Neira et al. 1993] from space and could thus serve the scientific community with very valuable information for future developments in this area.

A Novel Design for the Navigation System and Proposal to Unify The Timing and The Positioning System Using GIOVE Follow-on

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Firstly, we present a novel design of the global navigation system based on two-way links and master clock(s) in the GEO orbit. The idea is to place at least one or several master clocks in the GEO orbit and to use two-way links to transfer their stable frequency to the navigation satellites in the MEO orbit equipped with simple clocks (e.g. ultra-stable oscillators - USO). The advantage of the two-way links is the cancellation of the first order Doppler effect and hence the real-time frequency dissemination. We will make a comparison between an option based on two-way microwave links with USO, and an optical carrier with the frequency comb. With this concept, the use of H-masers and Cs- or Rb-clocks in the GNSS satellites can be reduced to the clock of higher quality. In order to introduce redundancy in such a system, at least two or three master clocks would be required in the GEO orbit. However, considering geometry and performance of the USO clock, only one GEO satellite is sufficient to have an operational frequency dissemination system. In addition, to steer the frequency of the several GEO satellites using master clocks on the ground is an alternative and will be discussed here as well. Compared to pseudo-range and carrier-phase observables from the GPS or GALILEO system, two-way links provide range in the real-time that does not require estimation of the clock/ambiguity parameters in the orbit determination. This is the reason why simulations show that, based on the two-way range, the orbits of the GEO and MEO satellites can be determined with an accuracy of several centimeters in the real-time. The concept of such a navigation system based on the dual constellation between “fast moving” GNSS satellites in the MEO and “stable” GEO satellites enables very accurate real-time orbit and frequency dissemination and considerably reduces the need for dense real-time network on the ground. Such a navigation system can be extended to other orbit altitudes between LEO and GEO, e.g satellites like ASTRA and IRIDIUM. However, the use of a LEO orbit in such a navigation system considerably limits the tracking time for a ground station to only a few minutes. Using simulated data we show all the advantages of the navigation system based on master clocks and two-way links in space. The first optical clock reached stability down to one part in 10^{-17} over a few hours of averaging and the first cesium clock for space have been under development for the ACES mission on board the Space Station with the accuracy of 10^{-16}. The microwave two-way link developed for the ACES mission follows these orders of accuracy.

In the second part we show the benefits if only one GALILEO satellite is equipped with the two-way link, like the one developed for the ACES mission. The two-way link on only one GALILEO satellite will allow, for the first time, unification of the timing and positioning system and calibration of the GALILEO signal. Currently, there is no operational system available to compare the best ground optical clocks that have already demonstrated an accuracy of few parts in 10^{-17}. In the very near future, there will be a gap in performance between the TAI clocks and the satellite based time/frequency comparison systems. The two way link developed for the ACES mission allows frequency comparison down to 10^{-17} and this is almost two orders of magnitude better compared to the best TWSTFT, or one-way systems like GPS and GALILEO. With the two-way link on only one satellite, like GIOVE follow-on, GALILEO will serve in establishing the reference frame for time (TAI), and open doors for operational relativistic geodesy. One part in 10^{-17} of the clock frequency corresponds to about 10 cm in the variation of the gravitational potential in terms of the geoid heights. Therefore, already now it is feasible to measure “physical heights” or so-called dynamic height using terrestrial clocks, but there is no satellite system available to compare frequencies of the terrestrial clocks with sufficient accuracy. In this way, GALILEO will unify geometrical and gravitational positioning (potential). On the other hand, GALILEO orbit is high enough and the two-way MW-downlink signal can be tracked by the VLBI antenna (S/Ku band). This opens new possibilities in combining the GNSS based reference frame and, at the moment, fully independent VLBI inertial reference frame based on quasars. Compared to the two-way link, with the one-way systems like GPS and GALILEO it is impossible, in the absolute sense, to separate the receiver/satellite clock, the phase ambiguity, the ionosphere/troposphere delay and the differential code biases (DCBs). This will be the case even if three or four GALILEO frequencies are available and two-way links is only alternative. Therefore, two-way links on only one GALILEO satellite in combination with the one-way GALILEO signal will play a major role in the calibration of the GALILEO measurements and ambiguity resolution.

Optical Clocks – Latest Developments and Future Trends

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Recent progress in the field of optical clocks has been spectacular, with two different optical clocks having reached an accuracy at the level of 2 parts in 10^{-17}. It is believed that a further improvement by one order will be possible, since the systematic effects limiting the current performance are well understood.

Worldwide there is a large effort on optical clocks, both in the national metrology labs as well as at research centers and universities. The development is helped by activities in related fields, in particular theoretical atomic physics, quantum optics and quantum information.

Space agencies ESA, DLR, ASI, CNES, have started funding both studies as well as experimental projects. ESA/DLR are funding a 3-year project "Space Optical Clocks" performed at LENS Firenze, SYRTE Paris, PTB Braunschweig, ENS Paris and Heinrich-Heine-Universität Düsseldorf.

The main goal is to demonstrate lattice optical clocks with performance beyond the best cold atom microwave clocks (inaccuracy at or below 1×10^{-16} level). Two atom species are studied, Strontium and Ytterbium. One important aspect is to develop and characterize transportable subsystems, culminating in the demonstration of a transportable cold Sr system with clock transition interrogation.

Next generation atomic clocks have the potential to reach 10^{-18} accuracy and instability and with an appropriate effort could likely be reasonably compact and power-efficient. With such specifications a number of applications will become possible.

Examples are: precision navigation in space, e.g. - formation flying; - space-VLBI; - fundamental physics (ultraprecise tests of General Relativity effects or foundations, such as Shapiro delay, Gravitational clock shift, Local Position Invariance, Local Lorentz Invariance and search for deviations (Pioneer anomaly etc.)), with appropriate satellite missions

A very promising application is relativistic geodesy. One implementation are differential measurements of the terrestrial gravity potential. Here optical clocks a different locations are compared with each other. The comparison link must have a performance compatible with the clock instability and accuracy, in order to obtain a precise comparison is a sufficiently short time. Such comparisons could be used not only to obtain information about the geoid, but also to study variations of local gravitational potential due to local climatic effects, e.g. the water table in a river basin and its weekly to yearly changes. The comparison of the clocks could be via free-space, via optical fiber, or via a space transponder. The latter could be a stratospheric plane or airship (see this workshop), or a satellite.

The satellite transponder would be based on a two-way link. An upgraded ACES-MWL could be a solution. An attractive aspect is that the transponder would not necessarily require a full optical clock, but only a stable local oscillator from which a stable microwave signal is deduced (of higher performance than an USO). The gravitational potential difference of two distant clock on earth also possesses a contribution from the sun. As the earth rotates, this contribution is modulated in time. A precise measurement of this effect over many years could yield a very precise test of the gravitational redshift of the sun. Such a test is interesting because the sun's matter constitution differs from that of the earth and has not been previously tested with high accuracy.

One step further is the operation of optical clocks in reference locations where the gravitational potential is sufficiently well known that the corresponding uncertainty is significantly less than the clock inaccuracy. This implies operation in space, in particular in high orbits (e.g. geostationary).

A comparison between such a "master clock" and terrestrial clocks then allows an absolute determination of the gravitational potential at the earth clock location.

A satellite mission comprising these aspects (but a lower resolution than 10^{-18}), is the proposal "Einstein Gravity Explorer" submitted to ESA in 2007 with the Cosmic Vision call for proposals.

We can envision a large network of compact, remotely operated optical clocks distributed over the globe and interoperated at desired intervals, for continuous monitoring of the earth gravitational potential.

Optical clocks represent a rapidly evolving field of quantum sensors, where it is likely that other atoms, and methods beside those used so far will contribute significantly.

A possible near-future technology are chip traps, which could allow to operate multiple miniature clocks in parallel, thus improving the stability. For example, an array of ~100 chip single-ion clocks with a concomitant improvement by a factor 10 seems a realistic option.

Certainly, there is a need for a concerted effort towards optical clock technology demonstrators.

If the scientific community calls for a space based clock comparison satellite for comparisons at the 10^{-18} level, this would strongly stimulate the development of reliable, remotely controlled clocks of similar inaccuracy. A large number of those could be produced and usefully employed for geophysics studies. This would generate a knowledge base that could be used to implement space clocks of similar performance and having moderate volume, weight and power consumption (150 kg, 200 W).

Such clocks could then serve as master clocks in space or for extremely powerful fundamental physics missions.

Focus on ASI activities in the field of atomic clocks: ORA and POP projects

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In this paper an overview of the activities that are being undertaken in the frame of the feasibility phase of the atomic clock projects is presented. Italy, through the Italian Space Agency (ASI), has financed two projects; POP (atomic clock using the Pulsed Optical Pumping technique) and ORA (Optical Atomic Clock based on *neutral Strontium* (87Sr)).
In the year 2004 ASI funded phase A (feasibility study) of the WAVE project for the design and development of a W band geostationary payload with the aim to perform experimental studies of the W band channel and to evaluate its possible utilisation in satellite data communications and data-relay services.
ASI funded phase A (feasibility study) of the atomic clock projects considering the following Mission Statements, in order of priority:

- Primary Objective: Reference clock on navigation satellites, in substitution of the present clocks, in particular of the hydrogen maser PHM, for Galileo 2nd generation;
- Secondary Objectives: Technology evaluation/validation unit on board the ISS, as part of an internal or external payload; Technology evaluation/validation unit for an experimental mission on board a GEO data-relay satellite.

Both the projects, POP and ORA, respond to all the above missions objectives with some differences:

- POP (atomic clock using the Pulsed Optical Pumping technique), offers a stability close to that of the passive hydrogen maser (PHM) of Galileo constellation, but with less operational constraints and lower mass, size and power consumption;
- ORA (Optical Atomic Clock based on *neutral Strontium* (87Sr)) explores the possibility to develop a clock whose performances exceed the values foreseen for PHM, and characterized by very high long term stability.

Additionally, there is a strong interest toward the Optical Atomic Clock, motivated by the high number of possible application; besides GALILEO:

- Deep space tracking of spacecrafts
- Radioscience research
- Fundamental physics
- Geophysics
- Relativity tests
- Planet ranging

This phase of the study has been carried out by: Kayser Italia and the European Laboratory for Non-linear Spectroscopy (LENS-Firenze) for the Optical Atomic Clock; Galileo Avionica and INRIM for the Pulsed Optical Pumping Clock.

The POP project activities have been, mainly, addressed to the the feasibility study of a Rubidium Atomic Clock adopting the Pulsed Optical Pumping (POP) Technique. This is based on the

separation in time of the three phases of pumping, interrogation and detection, which is made possible by adopting the novel technique introduced by the studies carried out in the recent years at INRIM.
A demonstrator of the POP clock has been manufactured and tested, in order to assess the capabilities of this new technique and to verify the feasibility of the requirements.
This demonstrator includes a prototype of the Physic Package (RF cavity containing the 87Rb vapour cell), interfaced to a devoted test setup simulating the remaining parts of the clock (electronic package and optic package)

The purpose of ORA study has been to give an overview of the possible architectures and technologies candidate to be used as time reference provider on board the next generation of the Galileo GNSS and to select the more promising one in term of final performances of the atomic clock.
The three sub-systems composing the Optical Atomic Clock (Local Oscillator (LO), Quantum Frequency Reference (QFR) and Optical Frequency Comb (OFC)) have been carefully analyzed during the feasibility study for both neutral atoms and single ion technology.
In particular, experimental activity, carried out at LENS laboratories, has been mainly addressed to the measurement of the LO stability. The measurements have been based on a high-finesse cavity made of Ultra Low Expansion quartz mounted in thermally stabilized environment. The Allan variance of 10^{-15} over (1-100) sec temporal range has been measured.

The experimental activity performed so far for the LO sub-system represents the starting point for further developments in the fields of OAC that ASI intends to pursue with a Phase B activity expected to be started by the end of year 2008. In particular, for the development of a self-consistent LO sub-system that in combination with an OFC, shall be able to produce a frequency standard characterised by very high short term stability in the 1-100 sec range.
Indeed, the LO coupled with a space qualified OFC shall represent a "*simplified*" version of a clock; in this case there will be not atomic sample interrogation, and t40he system shall generate a frequency standard characterized but very good short-term stability. This would represent the first validation of an engineered version of the optical clock technology
Furthermore, LO is a "*transversal*" sub-system common to several clock architectures: as an example, the space validation of the LO sub-system shall represent an important step toward the development of clocks based on cryogenic resonator (a high-quality oscillator at cryogenic temperatures) in space.

Inertial Atomic Quantum Sensors

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Atom interferometers are more and more developing from laboratory prototypes towards inertial sensors with multi disciplinary applications on ground and in space. They represent a method for realizing nearly ideal free falling inertial reference systems to measure inertial and gravitational forces with highest sensitivity and in particular with *highest accuracy*. On ground current state of the art inertial sensors, either of atomic or photonic nature, measure gravity with an accuracy of a few parts in 10^{-9}. The demonstrated long term stabilities (at timescales of 10^3 to 10^4 s) for cold atom gyroscopes are 10^{-8}rad/s.

The ultimate limitations of these devices are still not known, new techniques and concepts are still emerging. Examples are atom lasers and other sources of degenerate quantum gases, where the potential for applications in high precision measurement is yet to be explored and are unanswered. High accuracy and long term stability are the most important features of these sensors and makes them interesting for space navigation and long-term geodesy. Inertial atomic sensor combined with ultra stable clocks show a high potential to improve the current knowledge of the geoid by combining high accuracy gravitational red-shift measurements, position measurements and local gravity measurements.

In the excellent, perturbation-free conditions of microgravity environment and during the extended free fall the sensors can fully exploit the low temperatures of the atoms as their sensitivity increases by two orders of magnitude.

Several activities sponsored by the national space agencies and by ESA are on the way to explore the achievable accuracy in microgravity. A European collaborative research project is currently investigating the ultimate potential of inertial atomic and photonic quantum standards and their applications in earth observation and fundamental physics. Within the consortium scientists working on atomic and photonic quantum sensors will collaborate with experts in earth observation in an international frame:

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