The ACES GNSS Subsystem and its Applications

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ABSTRACT

The ESA mission Atomic Clock Ensemble in Space (ACES) will operate a new generation of atomic clocks on board the International Space Station (ISS) in 2013-2015 timeframe. The ACES payload will be attached externally to the European Columbus module. The ACES clock signal will reach fractional frequency stability and accuracy of 1 part in 10^{-16}. A GNSS receiver will be connected to the ACES clock signal. Primarily, the GNSS receiver will ensure orbit determination of the ACES clocks using GPS, GALILEO/GIOVE, and possibly GLONASS satellite signals in the L1, L2, and L5/E5a bands. Orbit determination is important for the correct evaluation of relativistic corrections in the space-to-ground comparison of clocks. Secondarily, the receiver offers the potential to support additional functionality for remote sensing applications in the field of GNSS radio-occultation and GNSS reflectometry, exploiting opportunities arising from the new GPS and GALILEO/GIOVE signals.

The ACES GNSS instrument consists of a state-of-the-art commercial-of-the-shelf JAVAD GNSS Triumph TRE-G3T receiver board. The receiver is connected to a GNSS antenna which will be directly mounted at the corner of the ACES payload. Antenna boresight is pointing +50° off the ISS flight direction and is tilted 30° toward the zenith direction. This offers ideal conditions to receive coherent reflected GNSS signals and improves radio occultation measurements.

Within the ACES project the receiver will be ruggedized and tested for space environment. Initial tests performed by DLR with the Co-60 source in Euskirchen, Germany, indicate a high tolerance to total ionizing dose. The receiver sensitivity to harmful single event effects of ionizing radiation including single event upset (SEU) and latch-up (LU) has been characterized in SEE testing using the radiation test facility of Groningen, NL. The results will be used to design the protection system counteracting these effects. In addition the receiver will be accommodated in a double redundant architecture. Under simulated low Earth orbit (LEO) conditions the JAVAD Triumph receiver firmware demonstrated fast acquisition of GPS signals and respectable orbit accuracy/ performance. Current status and test results of the ACES GNSS instrument will be presented in this paper.

INTRODUCTION

The Atomic Clock Ensemble in Space (ACES) is a mission in fundamental physics performed by the European Space Agency (ESA). ACES is based on the performances of a new generation of atomic clocks operated in the microgravity environment of the International Space Station (ISS).

The ACES core scientific objectives include:

- A test of a cold atom cesium and hydrogen maser clocks with frequency instability & inaccuracy at the level of 10^{-16},
- Stable and accurate time and frequency transfer space-to-ground and ground-to-ground.
- Performance of Fundamental Physics Tests.

ACES requires accurate orbit determination for it's core objectives to be achieved. ACES mission requirements for Precise Orbit Determination (POD) are 11 m position and 13 mm/s velocity RMS errors. ACES mission aims at exploiting remote sensing applications including Global Navigation Satellite System (GNSS) radio-occultation and reflectometry. To provide this ability independent of other ISS navigation sensors, the ACES payload will be equipped with a dedicated GNSS receiver connected to the onboard timescale. It will provide POD of the ACES clocks and offer the potential for remote sensing from space in the field of radio-occultation [1] and reflectometry [2][3][4] exploring the use of the new GNSS signals.

In the following, the ACES GNSS subsystem and general POD performance of the ACES GNSS receiver under high-signal dynamics in Low Earth Orbit (LEO) is presented. Visibility of GNSS signals for the ACES Payload (P/L) and signal obstruction is shown and status of GNSS subsystem summarized.

GNSS SUBSYSTEM

The ACES GNSS instrument is built on the state-of-the-art commercial-off-the-shelf (COTS) JAVAD Triumph TRE-G3TH receiver board [5] providing:

- Reception of GPS, GALILEO/GIOVE, GLONASS, SBAS signals in the L1, L2, and L5/E5a bands with a total of 216 channels
- External frequency input derived from the ACES clocks

Performances of the JAVAD Triumph receiver generation show in signal simulator tests [5] and in a standard LEO orbit test scenario [6]:

- Time To First position solution Fix (TTFF) between 60 ... 90 sec
- 3-D RMS post-facto orbit reconstitution better than 2 cm for an exemplary sun-synchronous, polar orbit with zenith-looking antenna and GPS only

The location of the ACES payload accommodation is driven by the MWL requirement for a nadir field of view. This is unfavourable for zenith GNSS observations. To overcome the drawbacks of field of view and multipath issues in the vicinity of the ACES payload location, the hemispheric GNSS antenna is accommodated on the corner of the ACES Z-panel (see Fig. 1). The antenna boresight is oriented +50° off the ISS flight direction and tilted 30° towards zenith. The ACES GNSS antenna setup has been designed to use the maximum reception capability of the navigation antenna, even taking into account temporary obstruction and multipath effects due to movement of ISS solar and thermal panels.

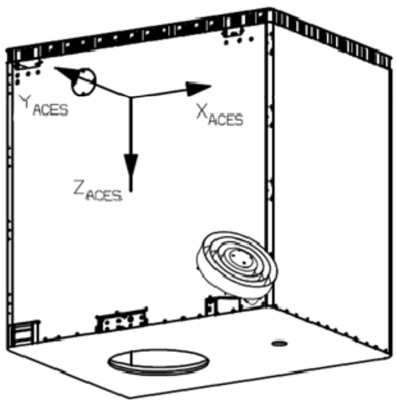


Fig. 1 Schematic drawing of ACES GNSS antenna boresight pointing +50° off ISS flight direction and tilted 30° toward zenith direction

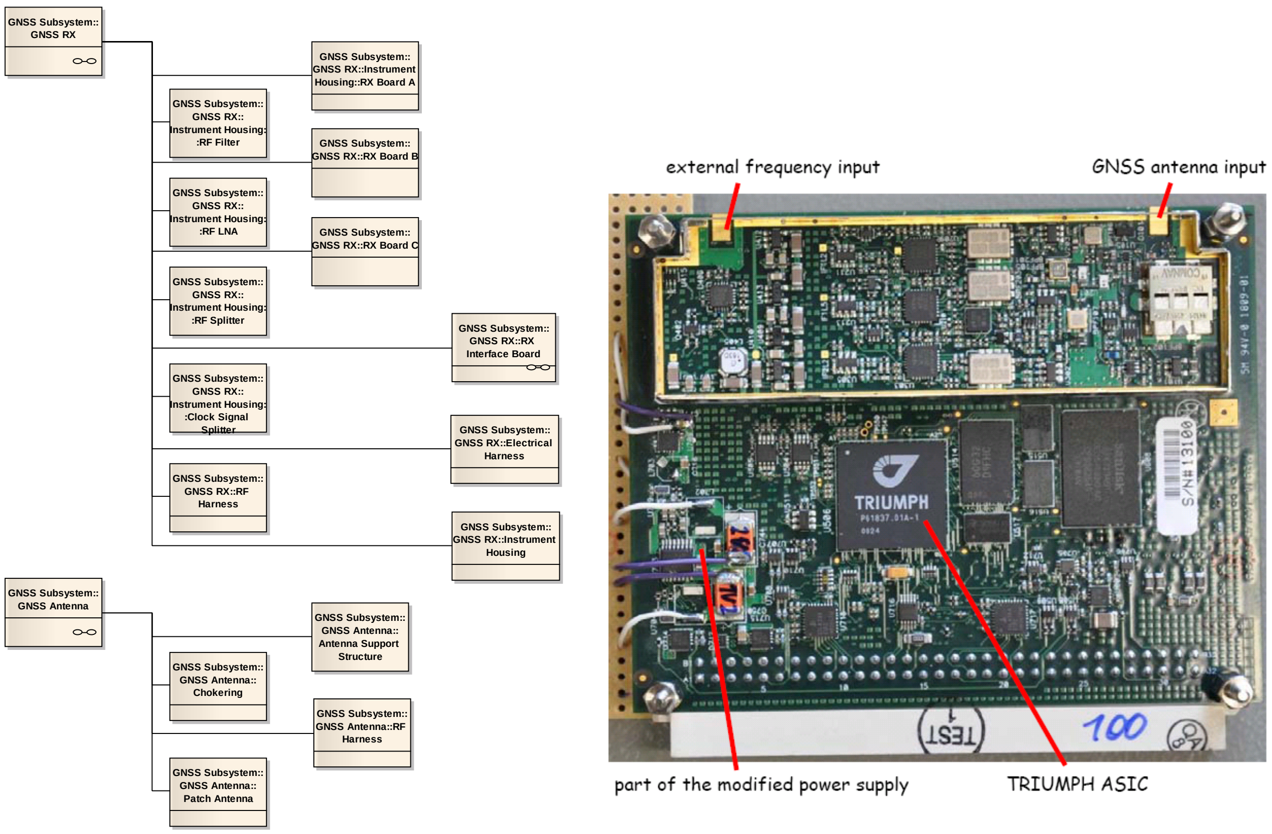
The ACES GNSS subsystem consists of three identical commercial-of-the-shelf (COTS) JAVAD GNSS Triumph TRE-G3TH receiver boards implemented in dual cold-redundancy. Interface boards protect the receiver boards against latch-up effects and manage the Telemetry data streams with the ACES External Payload Computer (XPLC). The ACES Microwave Link Flight Segment (MWL FS) feeds the ACES clock signal to the GNSS subsystem, down converted to 10 MHz. Via one RF splitter each receiver board is connected to the ACES GNSS antenna. The triple-frequency GNSS Dorne-Margolin antenna element will be mounted on an aluminum chokering to minimse multipath effects.. The antenna system includes a Low Noise Amplifier (LNA) with the required bandwidth and appropriate filtering.

The ACES GNSS instrument will be designed and tested for operation in the space environment:

- Protection to single-event upset and latch-up effects [5]
- Inherent insensitivity to total ionizing dose
- Thermal, vacuum, launch, vibration, shock

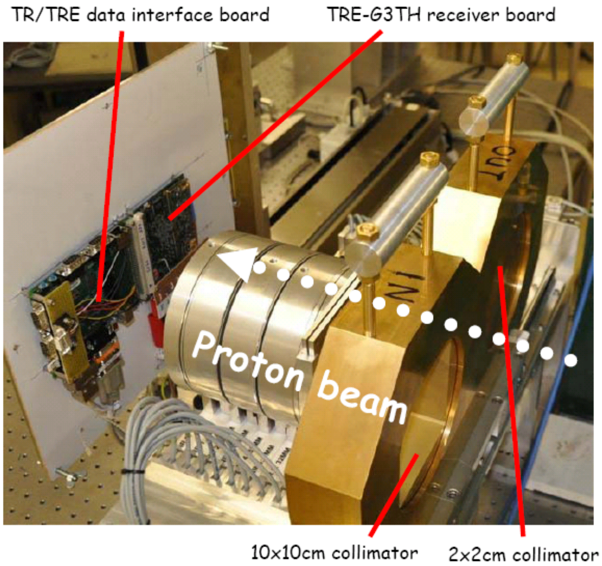
During a first proton radiation test [5] the receiver boards showed high sensitivity to latch-up during irradiation with 184 MeV protons. The Triumph Application Specific Integrated Circuit (ASIC) can clearly be identified as the main component responsible for the SEL behaviour. A latch-up protection was designed and successfully tested to protect the receiver board from destruction by the predicted 1-2 latch-up events per day during ACES mission time.

The antenna was characterized by test; results are used as input for performance modeling using the ESA NAVLAB SW tool.



(a) (b)

Fig. 2: (a) GNSS subsystem product tree; (b) modified JAVAD GNSS TRE-G3TH receiver board



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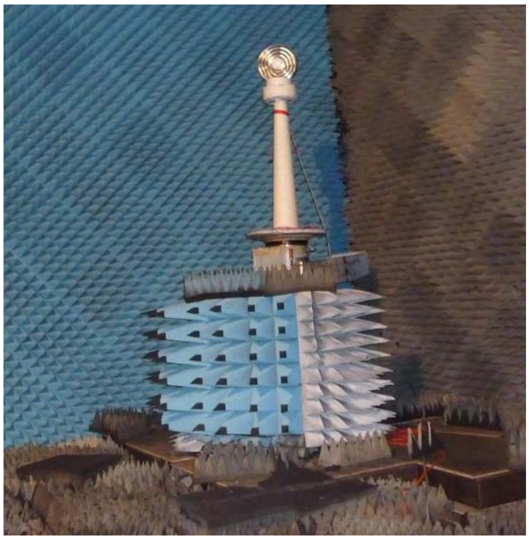


(b)

Fig. 3: (a) Setup of the proton radiation test [5] during June 23, 2009 at KVI cyclotron facility, Groningen, NL; (b) Antenna characterization at Astrium, Friedrichshafen, D.

POD Performance

A prerequisite for using COTS receivers in space is their capability to cope with high signal dynamics in a LEO. Most notably, this includes reliable signal acquisition despite a much wider range of possible Doppler shifts (up to +/-50 kHz) as well accurate tracking despite line-of-sight accelerations of up to 15 m/s² and a pronounced code-carrier divergence.

POD performance was established in signal simulator tests [5] using a standard LEO test scenario [6] and a 30 satellite GPS constellation assuming a zenith-looking antenna. L1 C/A, L1 & L2 P(Y) and L2C code modulation was activated and ionospheric path delay was modelled. Raw code and carrier phase measurements have been processed with state-of-the-art POD software (GHOST, [7]). Resulting measurement accuracy was assessed both through a virtual zero baseline test and a double-differencing of receiver measurements against simulator truth values.

As illustrated in Fig. 4, a 3D RMS accuracy of better than 2 cm was achieved in comparison to the simulated truth orbit. While the result is not necessarily representative for real world applications (for example due to the neglect of GPS ephemeris errors, phase pattern errors or attitude errors), it proves the excellent quality of the JAVAD GNSS Triumph receiver measurements under high signal dynamics.

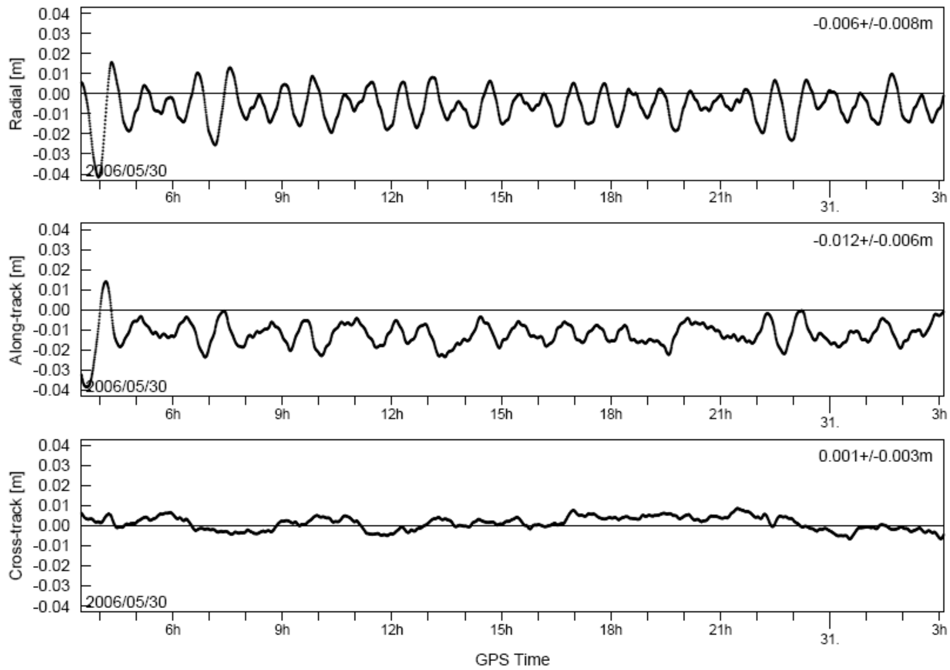
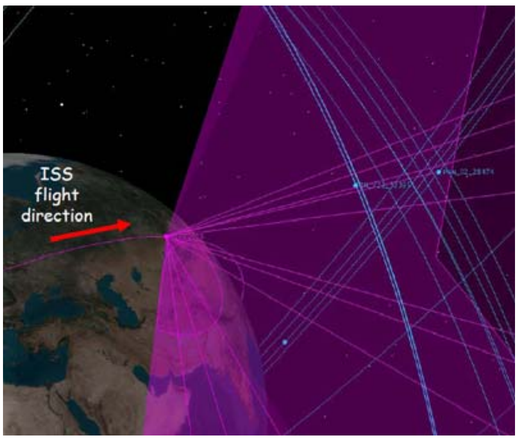


Fig. 4: Accuracy of a 24h POD solution based on raw code and carrier phase measurements collected with the JAVAD GNSS Triumph receiver in a signal simulator test.

ACES GNSS Visibility

A 24-hr simulation using Satellite Tool Kit SW and based on actual orbit information (Two-Line Elements) of ISS, GPS, GLONASS and Giove satellites has been performed with the ACES GNSS antenna setup. ISS structure/Columbus obstruction has been taken into account by limiting the 80° visibility conus of the GNSS antenna to an area of -30° to 130° in azimuth and -10° and 90° in elevation.

Typically more than 5 GPS satellites are visible. The number dropping only from time to time to 4 GPS satellites.. Taking GLONASS (and Giove) satellites additionally into account, we expect more than 7 GNSS satellites to be visible.



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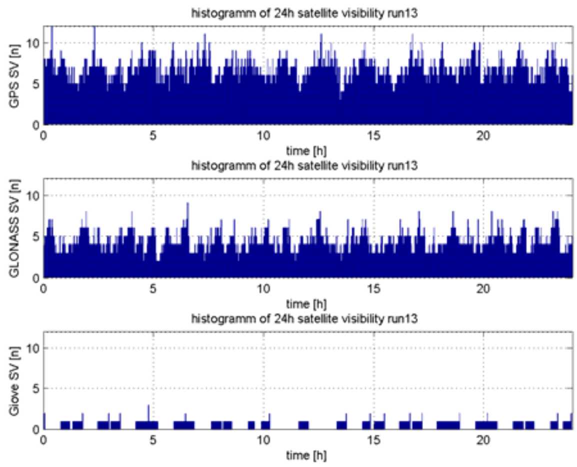


(b)

Fig. 5 A 24h simulation using STK SW and todays orbits of ISS, GPS, GLONASS and Giove satellites

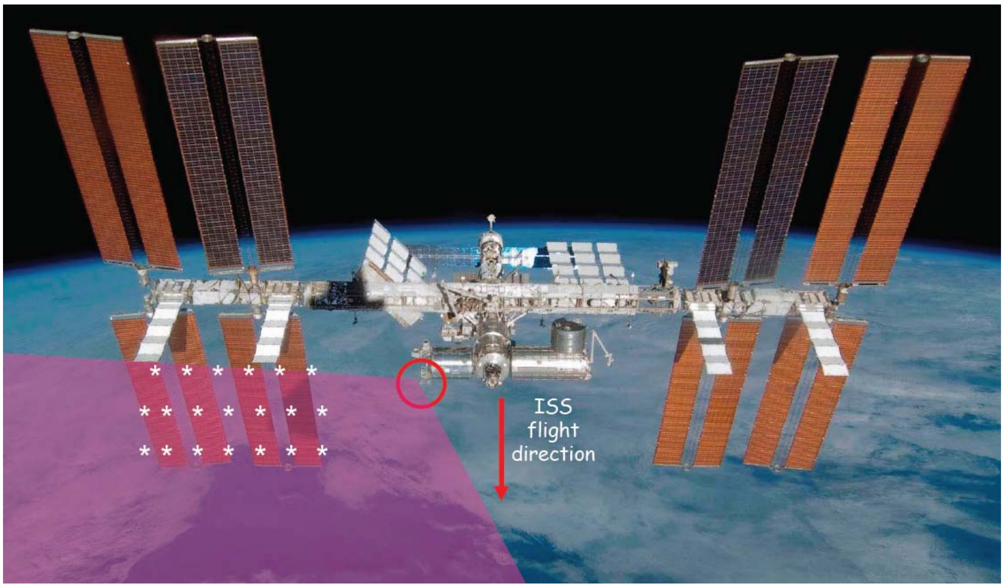


Fig. 6 ISS structures, e.g., moving solar panels, limit the field of view of ACES GNSS antenna

ACES GNSS Obstruction

ISS structures, e.g., moving solar and thermal panels, limit the field of view of ACES GNSS antenna. Obstruction from ISS structure and Columbus has been simulated using ISS/ACES 3-D model (Fig. 7 (a)) and calculating a visibility matrix (Fig. 7 (b)) with ESA's MVL SW tool. A 24-hr simulation using ESA's NAVLAB SW tool and orbit information of ISS and GPS satellites has been performed. Minimum elevation was set to -20°. 4 or more GPS satellites are expected to be visible most of the time (Fig. 7 (c)).

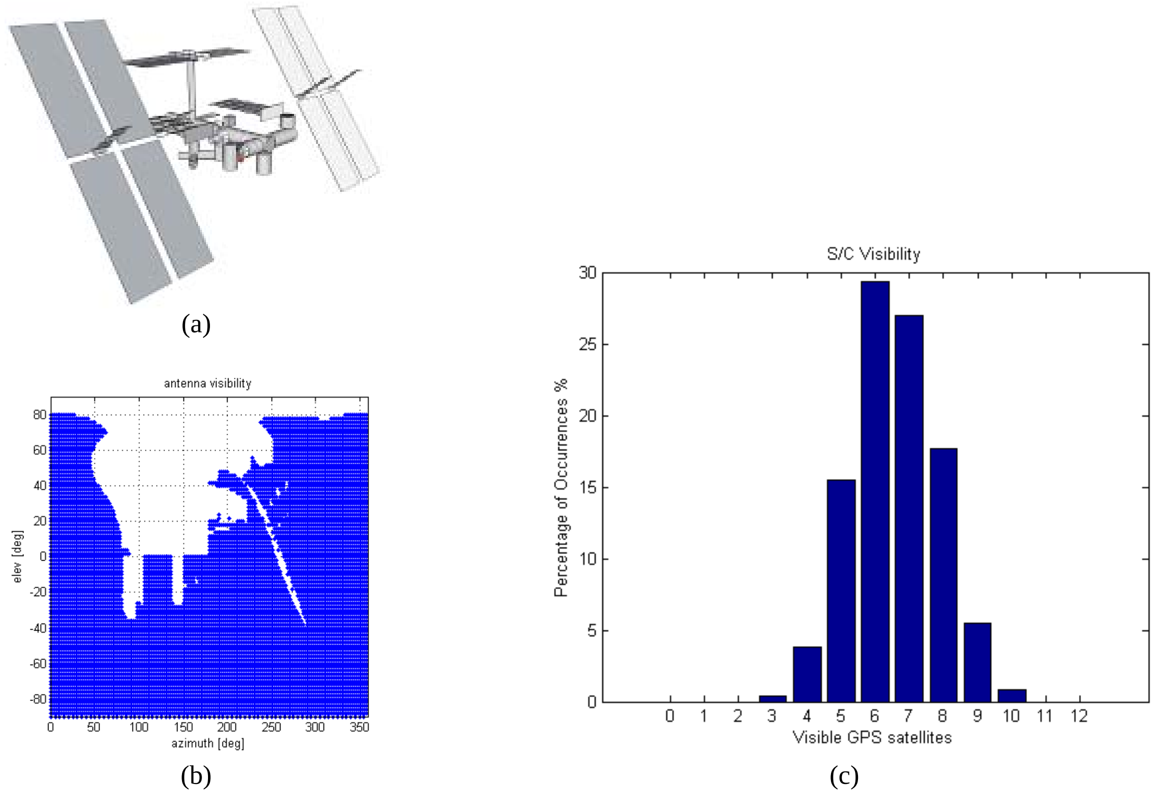


Fig. 7 A 24h simulation using ESA's NAVLAB SW tool and orbit information of ISS and GPS satellites

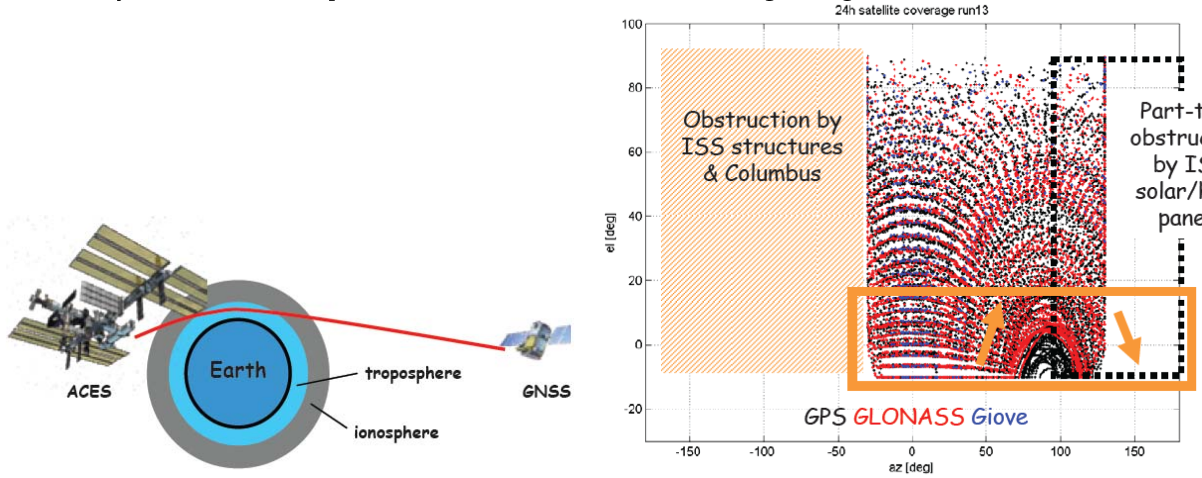
GNSS REMOTE SENSING

The ACES GNSS subsystem supports remote sensing applications from space in the field of GNSS radio-occultation and GNSS reflectometry, exploring the possibilities of the new GPS and GALILEO/GIOVE signals. The forward looking ACES GNSS antenna together with the 51.6° ISS orbit inclination, compared to the GPS satellites' inclination of about 54.9° to 55.5°, provides an excellent opportunity for these measurements.

GNSS Radio-Occultation

In an occultation measurement a space-based receiver observes signals transmitted by GNSS satellites as they disappear or appear at the Earth horizon. The basic observable is carrier excess phase path which quantifies the accumulated influence on the signal propagation path through the iono-, strato-, and troposphere. The ISS orbit allows measurements complementary to existing satellite missions with significantly higher number of occultation events in tropical regions. Furthermore, the provision of the precise ACES clock signal to the receiver potentially allows exploiting zero differencing signal acquisition techniques [1] as opposed to single or double differencing techniques.

A subset of visible GNSS satellites can be used for radio-occultation. The subset is limited to satellites at lower elevations when the GNSS signal link enters the Earth's troposphere until the Earth's horizon blocks the signal. Bending effects caused by the atmosphere extend signal reception below the geometrical shadowing limit of the Earth's horizon. ACES radio-occultation measurements are not limited to rising occultation events. As antenna boresight is pointing +50° off ISS flight direction, signal reception of a number of setting occultation events is also expected. Part-time obstruction by ISS solar/thermal panels has to be taken into account during setting occultation events.



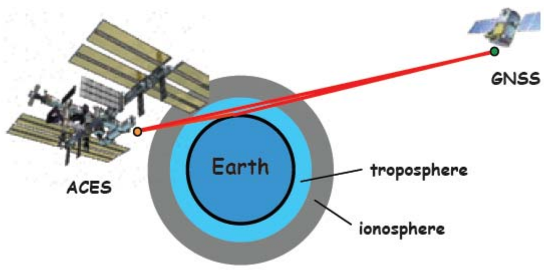
(a) (b)

Fig. 1. Looking in ISS flight direction: Daily target GNSS satellites in view for rising and setting radio-occultation events.

GNSS Reflectometry

Water, ice and snow covered areas show a high reflectivity for GNSS signals in the L-band frequency range. The reflected signals can be used to determine height and surface properties, e.g., roughness, of the reflecting surface. Within the German Indonesian Tsunami Early Warning System (GITEWS), GFZ Potsdam implemented such tracking techniques successfully in a modified JAVAD GNSS GeNeSiS-112 receiver [4] which is the predecessor of the current JAVAD GNSS Triumph receiver generation.

A subset of visible GNSS satellites can be used for coherent reflectometry. ACES GNSS antenna boresight is optimal for coherent reflectometry observations. The subset is limited to satellite elevations below 5°. At elevations below 5° a coherent reflected GNSS signal is expected to be scattered from water, ice or snow surfaces of the Earth. At higher elevation angles the effective surface roughness increases and the signal no longer shows coherency with respect to the carrier phase of the used GNSS signal. At grazing elevation angles a large fraction of the received reflected signal is Right Handed Circular Polarized (RHCP) and can be received with the ACES RHCP GNSS antenna.



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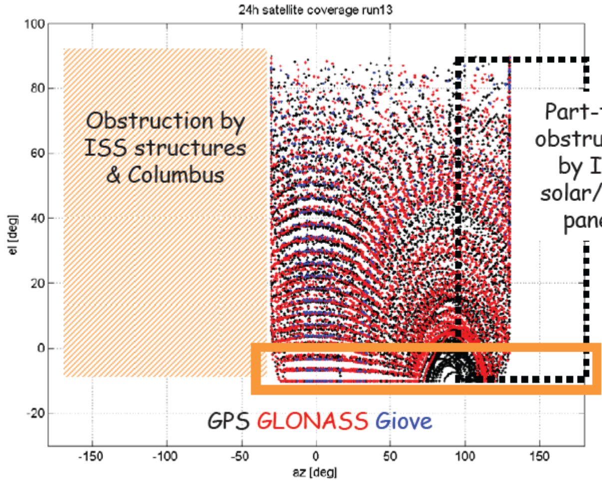

(b)

Fig. 8 Looking in ISS flight direction: Daily target GNSS satellite in view for coherent reflection events.

SUMMARY

The ACES GNSS subsystem fulfills ACES mission requirements for POD. The excellent quality of receiver measurements under high signal dynamics and short signal acquisition times of the JAVAD Triumph receiver of about 60-90 sec compensate for drawbacks due to limited field of view of the ACES antenna. The antenna setup offers ideal conditions for reception of coherently reflected GNSS signals. The ISS orbit and ACES antenna positioning permits rising and setting radio-occultation observations with a focal point on tropical regions complementary to existing satellite missions. The performed radiation tests and implemented design mitigation illustrate that the ACES GNSS subsystem can withstand the radiation environment expected during ACES mission life time.

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