The Phoenix GPS Receiver - A Practical Example of the Successful Application of a COTS-Based Navigation Sensor in Different Space Missions

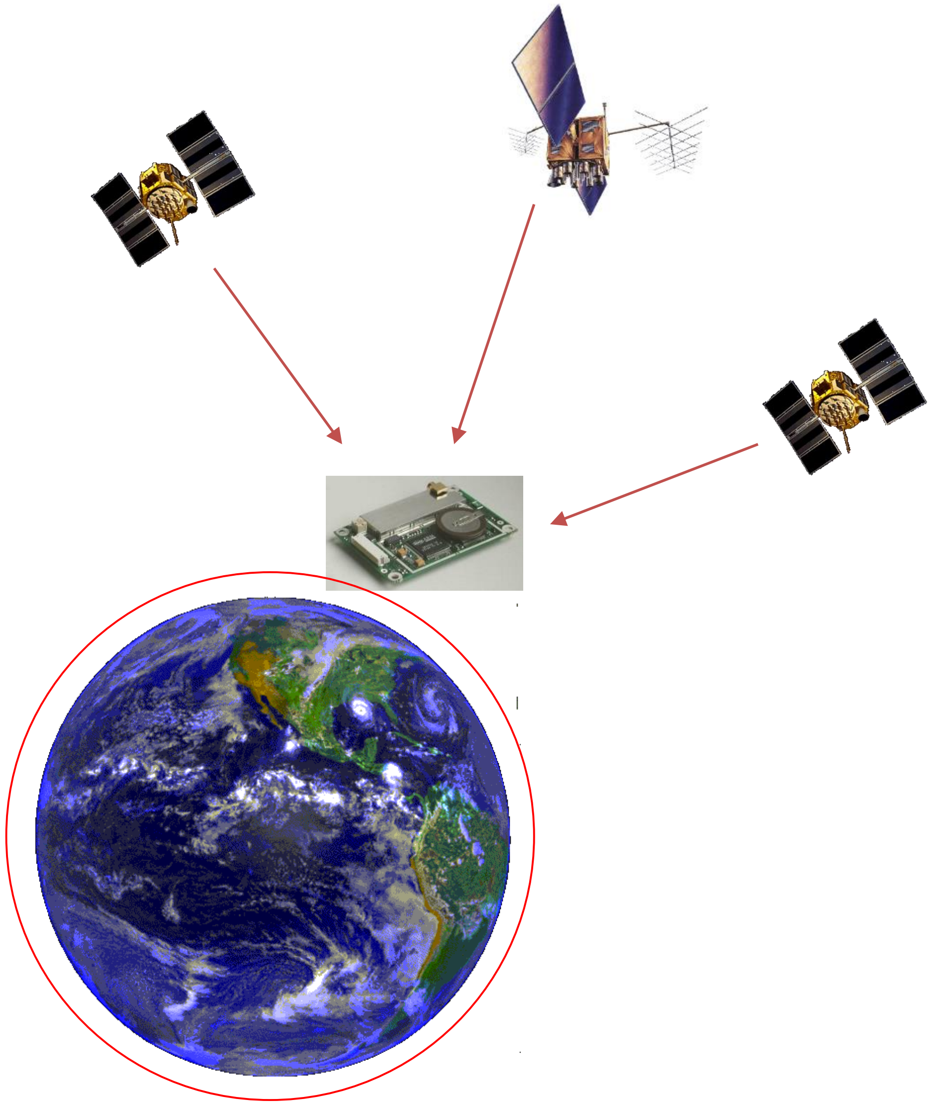
M. Markgraf (markus.markgraf@dlr.de)

DLR/GSOC, Oberpfaffenhofen, D-82230 Wessling, Germany

DLR

Content

- Background and Motivation
- Phoenix GPS Receiver
- Qualification and Test Program
  - Environmental Testing
    - Vibration & Shock
    - Thermal-Vacuum
    - Radiation
  - Performance Testing
- Flight Heritage
- Proba-2 Mission
  - Overview and GPS System Architecture
  - Flight Result
  - Radiation Effects
- Summary and Conclusions



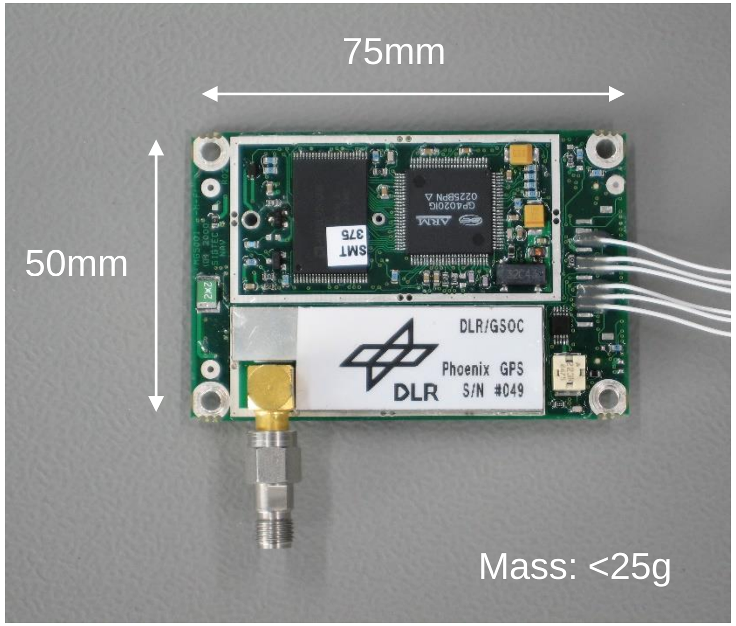
Background and Motivation

- GPS has become a „standard“ sensor in almost every space mission over the last two decades
- Fully space-qualified GNSS receivers are expansive (>1M€) - unaffordable for many projects due to limited budgets
- COTS-based GPS receivers are typically the only alternative for such missions
- However, use of COTS-based technology requires thorough testing and good understanding of reliability and failure mechanisms

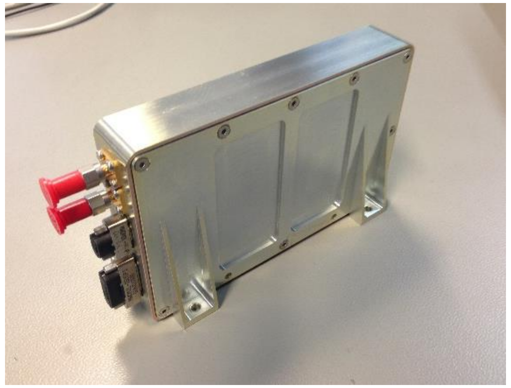
- DLR designs, builds and operates satellites and sounding rockets
- Strong in-house need for affordable GPS/GNSS technology
- DLR’s Space Flight Technology group commenced to explore, develop, and test COTS-based GPS receiver in the late 1990s.
- Phoenix GPS receiver for space missions as an outcome of these works

Phoenix GPS Receiver - Hardware

- 12 channel L1 single-frequency receiver for high-dynamics applications
- Entirely based on COTS technology
- Commercial H/W platform (SigTec MG5001)
- Ca. 70 x 47 x 11 mm^3
- Mass < 25 g
- Power Consumption 0.7-0.9 W
- Only minor modifications required for use onboard rockets and satellites (battery, connectors)
- Additional I/F electronic requires (Power and signal conditioning, latch-up protection, etc.)



Top side of the Phoenix GPS receiver board



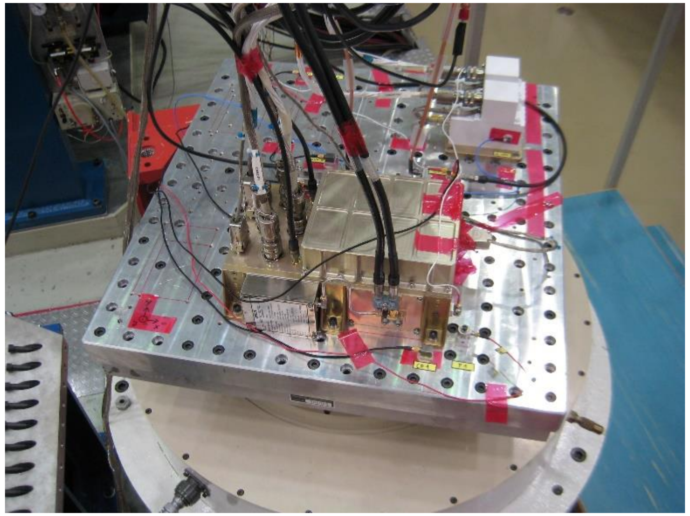
Self-contained GPS unit developed for Eu:CROPIS satellite mission

Phoenix GPS Receiver - Firmware

- Originates from sample source code of an earlier available GPS development kit
- Received extensive revision and enhancements
- Added Carrier tracking
    - Carrier phase smoothing (reduced position noise)
    - Range-rate from carrier phase (accurate velocity)
- Advanced tracking loops for robust tracking under high signal dynamics
- Flexible TM/TC interface
- Integer second synchronization and 1PPS signal
- Hot start capability (30s)
    - Non-volatile memory and real-time clock
    - Aiding with twoline elements
- Available in two versions:
    - Phoenix-HD for high dynamic applications (launchers and rockets)
    - Phoenix-S for LEO satellites

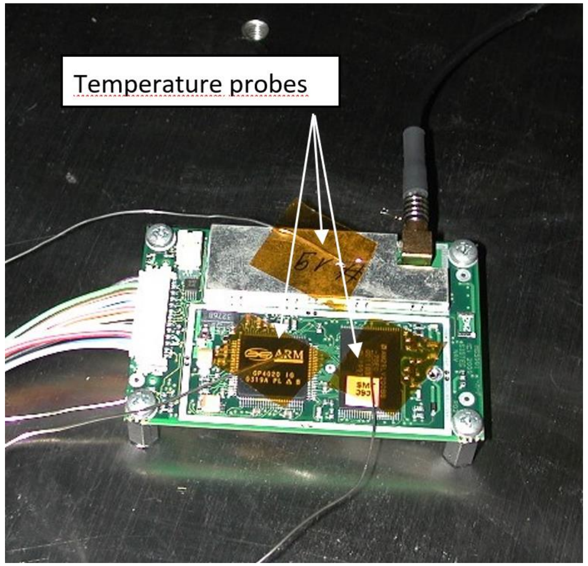
Environmental Testing – Vibration & Shock

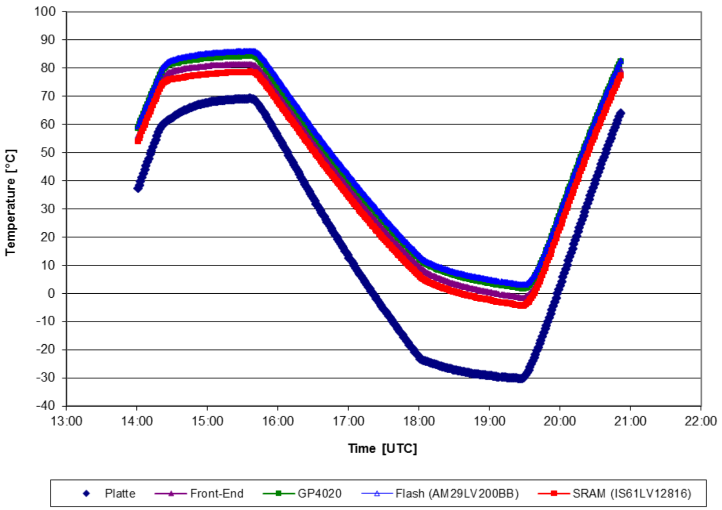
- Tests conducted for wide range of load profiles (Soyuz, Ariane-5, Vega…)
- On Sub-system or system level
- Operational mode
- Stimulation of receiver with signals from a GNSS signal simulator
- Study of impact of vibration onto tracking and navigation behavior



Environmental Testing – Thermal-Vacuum

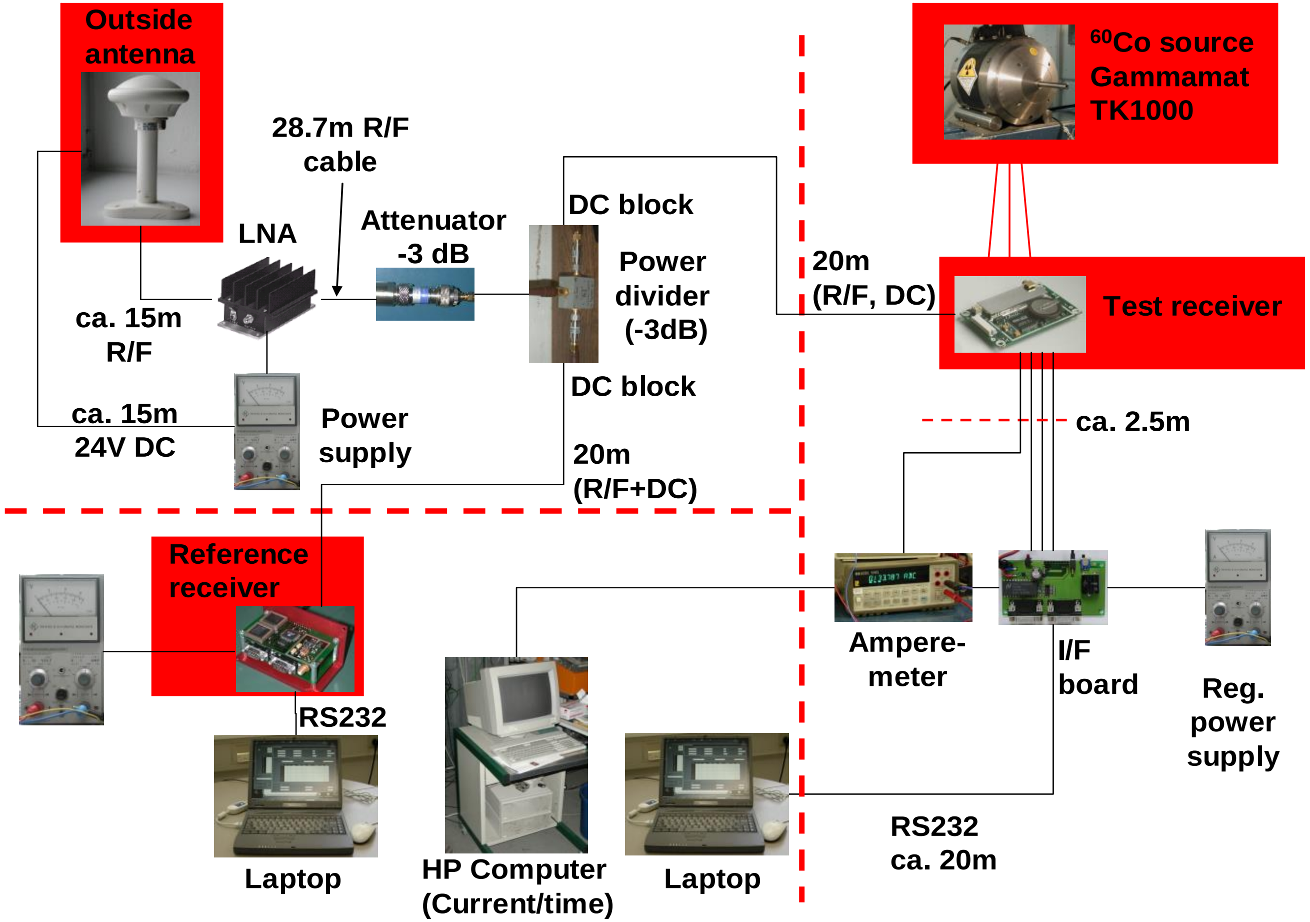
- Test conducted at DLR's own test facilities at Oberpfaffenhofen in close accord with ECSS testing standards
- Atmospheric pressure as well as vacuum conditions
- Thermal cycling in operational and passive mode
- Temperature range:
  - -30° to +70° operational
  - -40° and +80° non-operational (storage)
- Increase of power consumption at higher temperatures (ca. +8%/100K)
- No impact on navigation performance





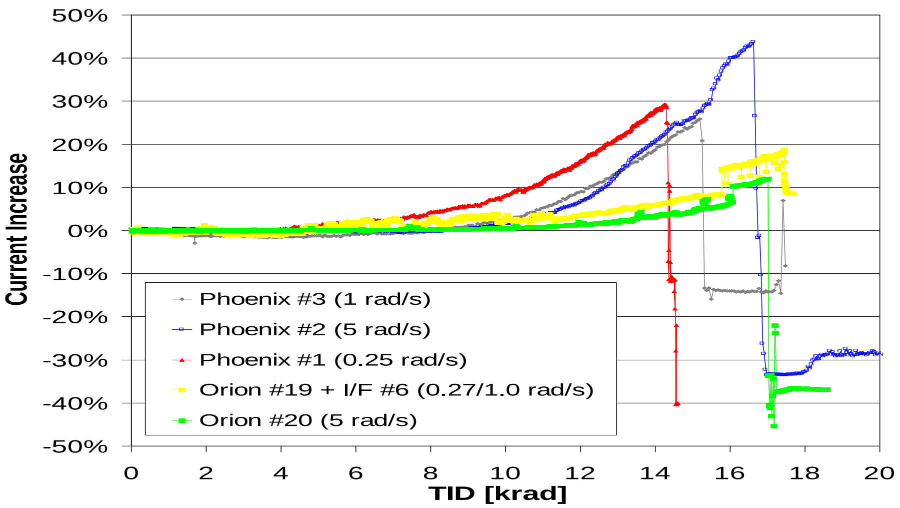
Radiation Tests – TID (I)

- Total Ionizing Dose (TID) test using Co-60 source
- Conducted at Fraunhofer Institute for Technological Trend Analysis (FhG/INT) at Euskirchen, Germany
- Hardware-in-the-loop test setup
- Live GPS signals via roof-top antenna
- Reference receiver operated outside test chamber
- Direct comparison of navigation solution and raw data



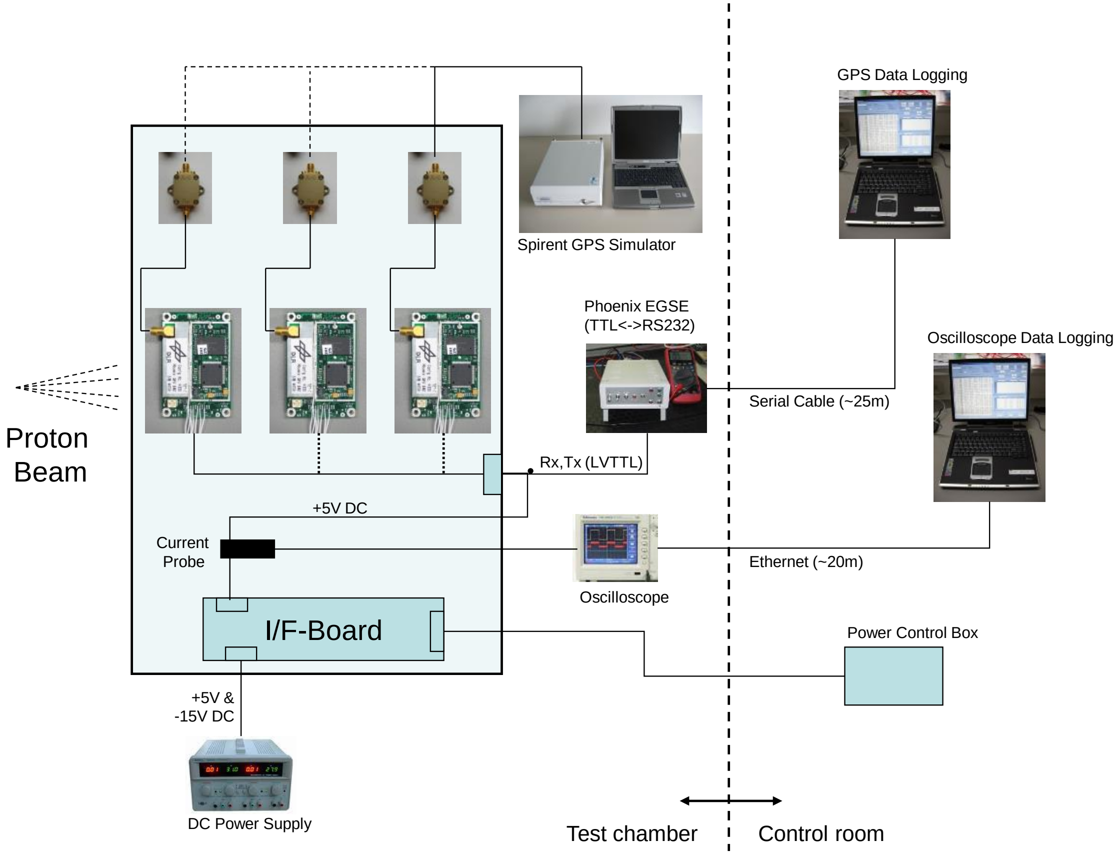
Radiation Tests – TID (II)

- Dose rate 0.25 – 5 rad/s
- Gradual current increase (25-40%)
- Break-down at 14-17 krad
- Osc. frequency shift -1.1ppm/krad
- Increased risk of cycle slips (oscillator?)
    - Dose rate dependent
- Self-healing after end of exposure



Radiation Tests - Single Event Effect (I)

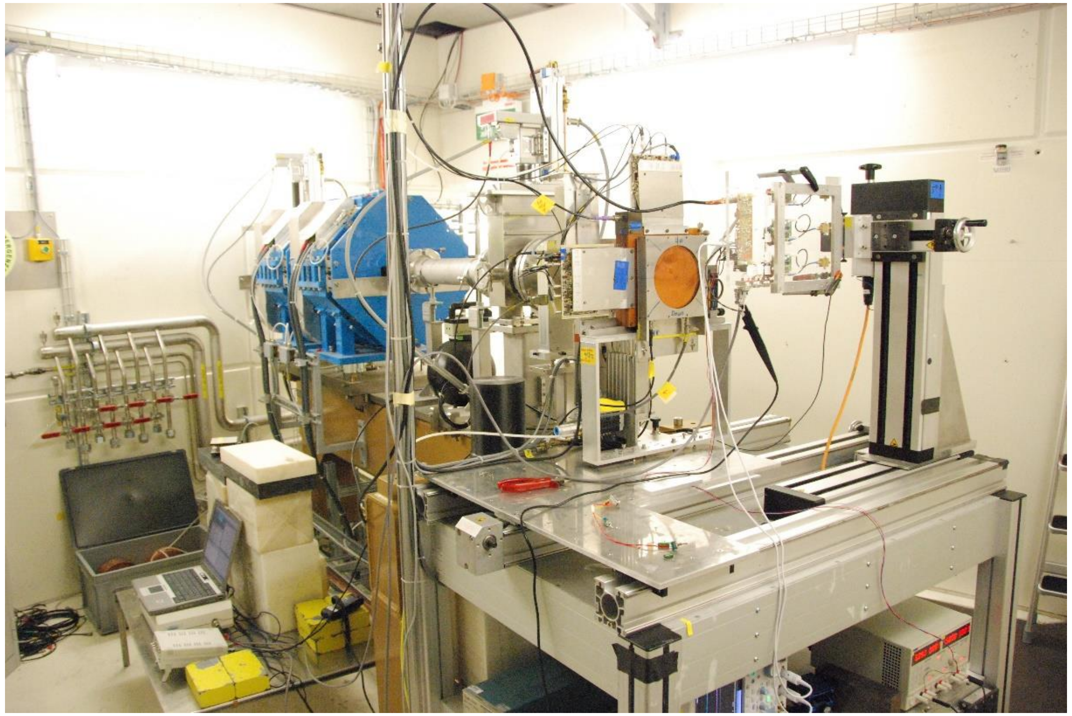
- SEE Proton characterization performed:
  - at the JULIC proton cyclotron of the Research Center Jülich, Germany (together with Fraunhofer-INT)
  - at the Paul Scherrer Institute (PSI) in Villigen, Switzerland (together with ESA/ESTEC)
- Key objectives of the test campaign were:
  - Verify anomalies observed in previous satellite missions
  - Identify sensitive component(s)
  - Characterize nature of the anomalies and assess usability of the receiver for future space missions
- All tests performed on board level.
- Test boards connected to GPS signal simulator



Test setup used for the proton radiation tests conducted with the Phoenix GPS receiver

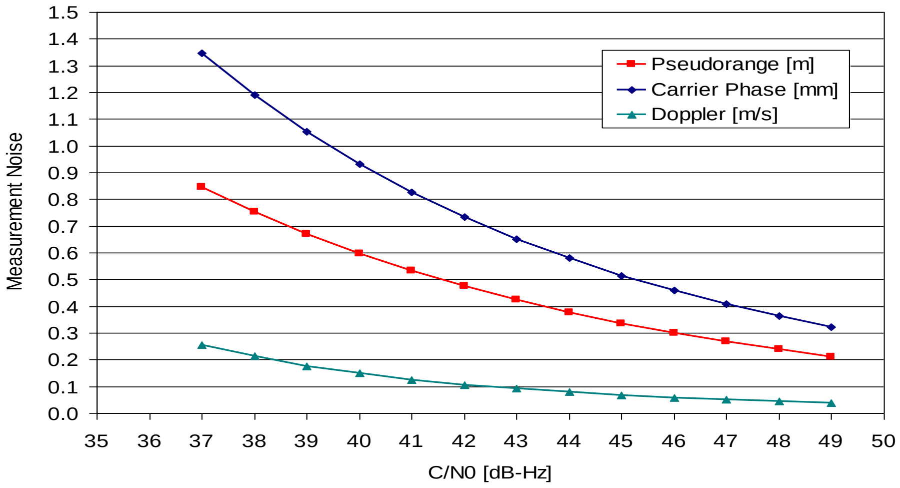
Radiation Tests - Single Event Effect (II)

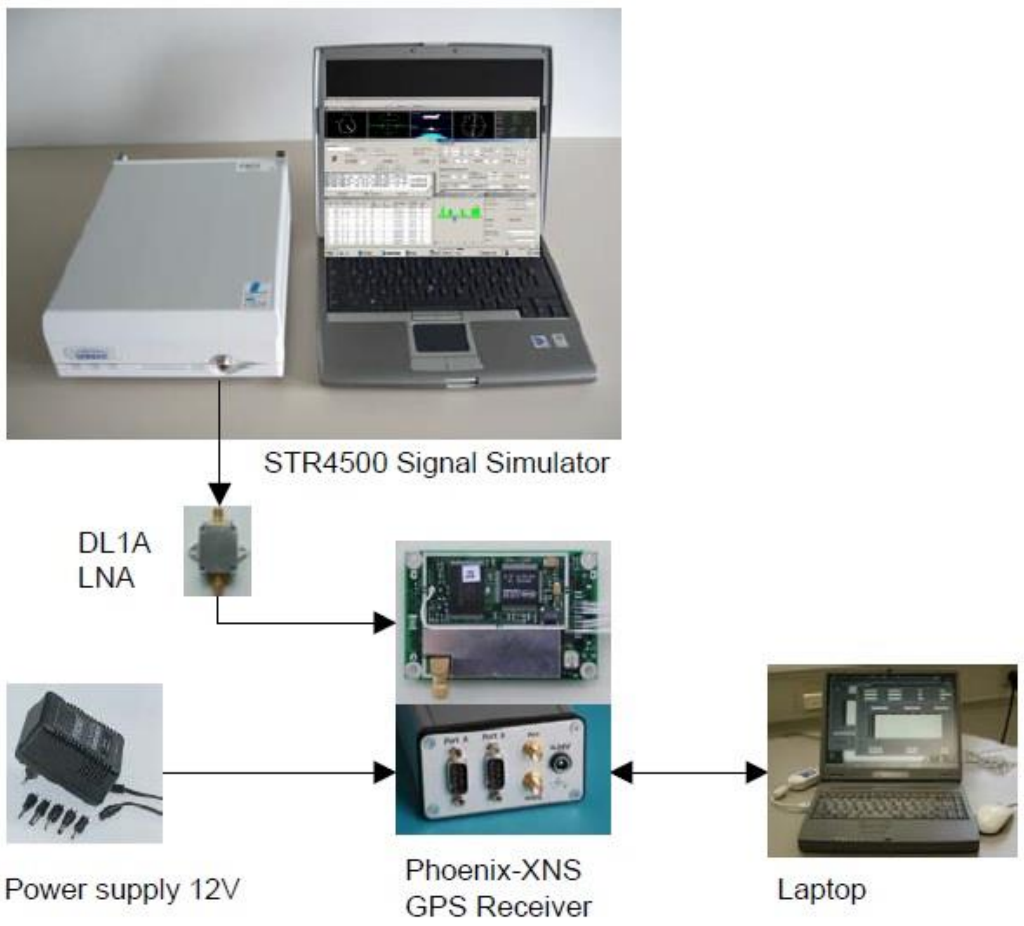
- Two different versions of Phoenix boards tested
  - Only difference in size of SRAM chip
- Broad beam irradiation of entire board
- Narrow beam irradiation of different regions
- Receiver generally sensitive to SELs
- Latch-ups were found to be non-destructive
- SRAM chip identified as radiation-critical component
- SEL rate estimation performed for Proba-2 orbit (near-circular, sun-synchronous, 725 km altitude)
  - 0.01 /device/day for “standard” SRAM
  - 0.1 /device/day for extended SRAM
- No SEUs observed (probably due to “masking” by SELs)



Performance Assessment

- Hardware-in-the-loop test bed
- Use of a GNSS signal simulator (constellation simulator)
- Simulation of the R/F signals as seen by a receiver onboard a space vehicle
- Assessment of:
  - Acquisition and tracking performance
  - Navigation accuracy
  - Raw data accuracy

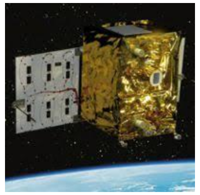


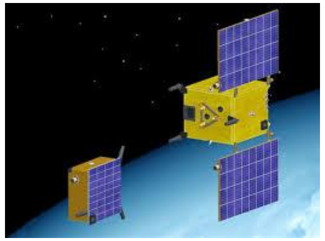


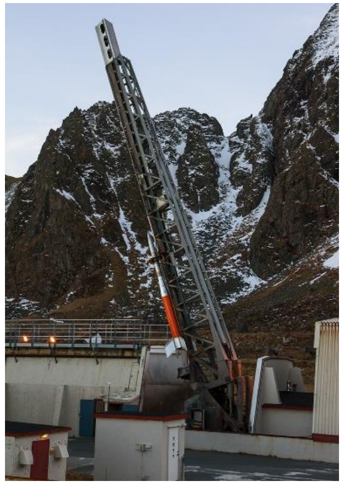
Phoenix GPS – Flight Heritage

Non-exhaustive list of missions and projects using Phoenix GPS receiver

LEO Satellites		
Mission/Project	Launch Date	Purpose
Proba-2 (ESA)	11/2009 - today	orbit determination, flight dynamic services, time synchronization
Proba-V (ESA)	5/2013 - today	orbit determination, flight dynamic services, time synchronization
Prisma (SSC)	06/2010 – (status unknown)	orbit determination, time synchronization, autonomous orbit and formation control
TET-1 (DLR)	07/2012 - 2019	orbit determination, flight dynamic services, time synchronization
BIROS/BEESAT-4 (DLR & TU Berlin)	06/2016 - 2019	orbit determination, flight dynamic services, time synchronization, formation flying
EuCROPIS (DLR)	12/2018 - 2020	orbit determination, flight dynamic services, time synchronization



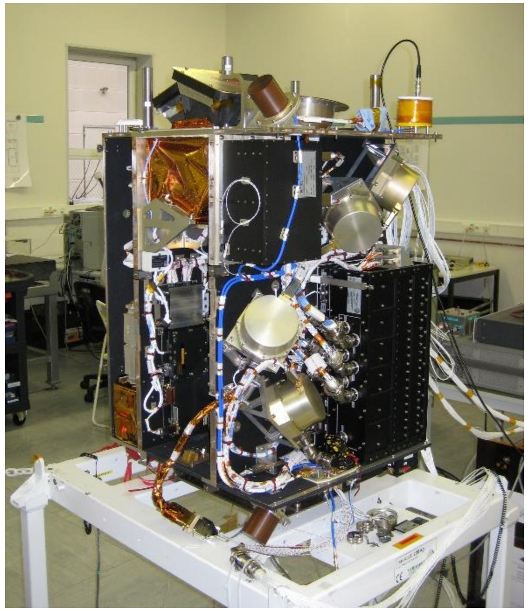




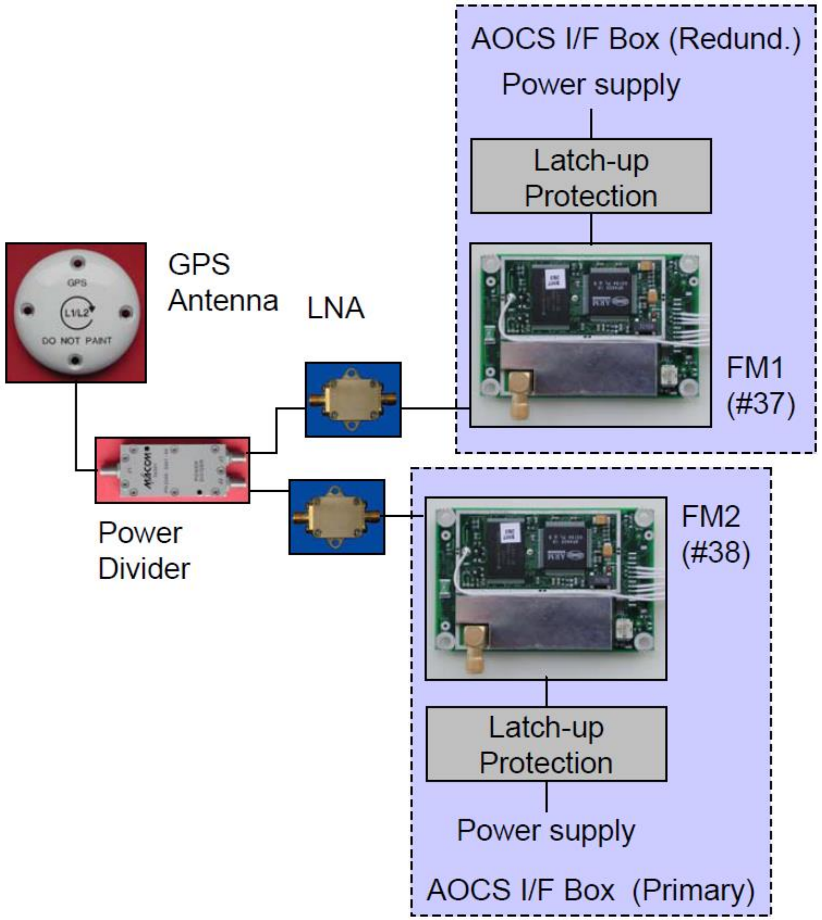
Sounding Rockets		
Mission/Project	Launch Date	Purpose
Texus 39 – 56 (ESA/DLR)	2001 - today	Flight safety, recovery, trajectory determination, time-synchronization
Maxus 4 – 9 (ESA)	2001 - 2017	Flight safety, recovery, trajectory determination, time-synchronization, GNC
Rexus 4 – 26 (DLR/SSC)	2008 - today	Flight safety, recovery, trajectory determination, time-synchronization
Shefex-I & -II (DLR)	2005 & 2012	Flight safety, recovery, trajectory determination, time-synchronization, GNC
WADIS 1 & 2 (DLR)	2013 & 2015	Flight safety, recovery, trajectory determination, time-synchronization, experiment support
MaxiDusty 1 & 2 (DLR/ASC)	2016	Flight safety, recovery, trajectory determination, time-synchronization (flight validation of a new rocket motor)
Launch Vehicles		
Ariane-V (VA 219) (ESA & OHB)	2014	Technology demonstration, Flight experiment, trajectory determination

Proba-2 Mission

- Second spacecraft in ESA's **PR**oject for **O**n**B**oard **A**utonomy
- Micro-satellite platform for technology demonstration and science:
  - Scientific goals: Sun observation and study of space environment
  - Novel technology components: Sun and star sensors, two GPS receivers, propulsion and power system components, data handling system, etc…
- Built by QinetiQ Space Technology
- Launched 2nd Nov. 2009 01:50 UTC from Plesetsk onboard Rockot
- Sun-synchronous dusk-dawn orbit at approx. 725 km altitude



Proba-2 - GPS System Architecture

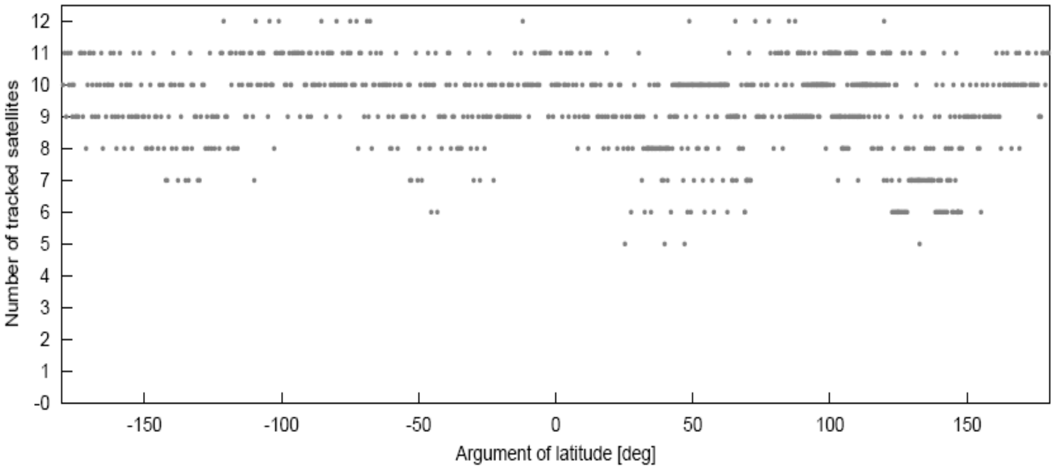


- Cold redundant system
- Phoenix receivers integrated in AOCS Interface boxes
  - Power conditioning
  - Line drivers
  - Latch-up protection
- Common antenna, but independent LNAs
- Independent measurements from prototype Topstar3000G2 receiver (by Alcatel)
- Laser Retro Reflector

Proba-2 – Flight Results

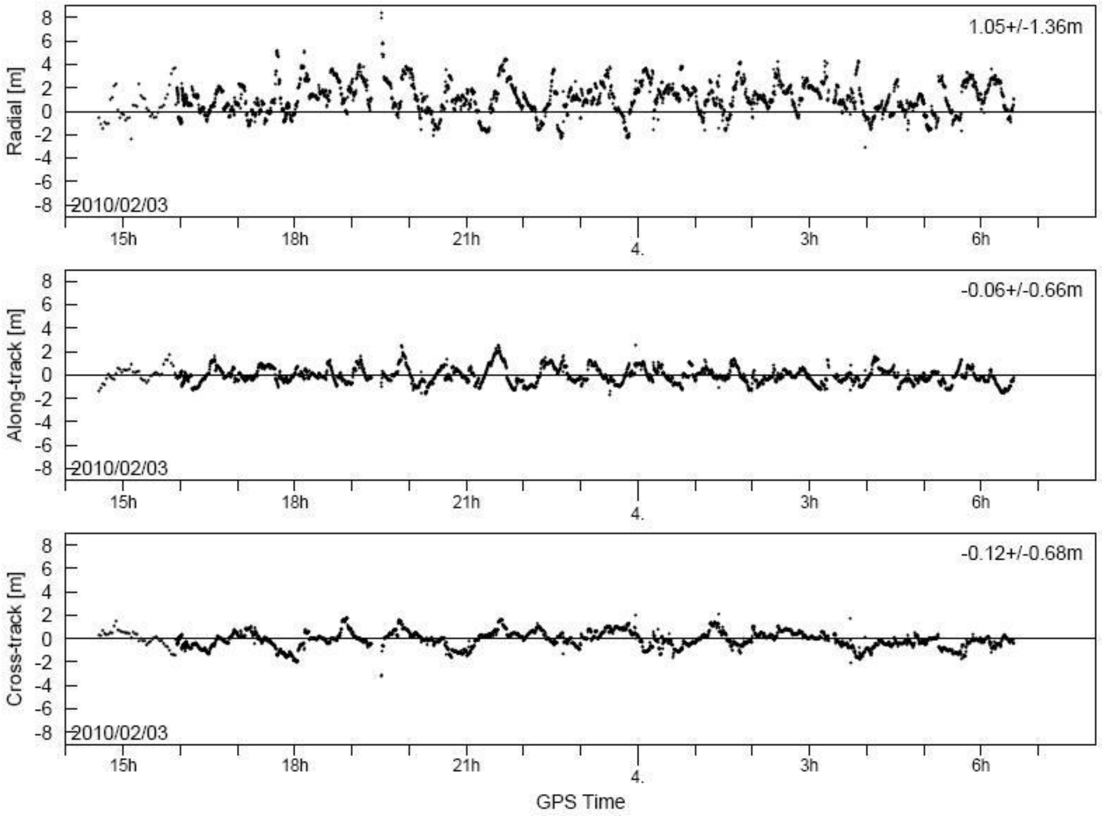
Acquisition and Tracking

- Typical Times-To-First-Fix in standard Sun pointing attitude mode :
    - Cold-start: 5..15 min
    - Assisted boot: < 2 min
- On average 9 GPS satellites tracked
- 3D rms position accuracy of ~2 m (with peak errors up to 10m)



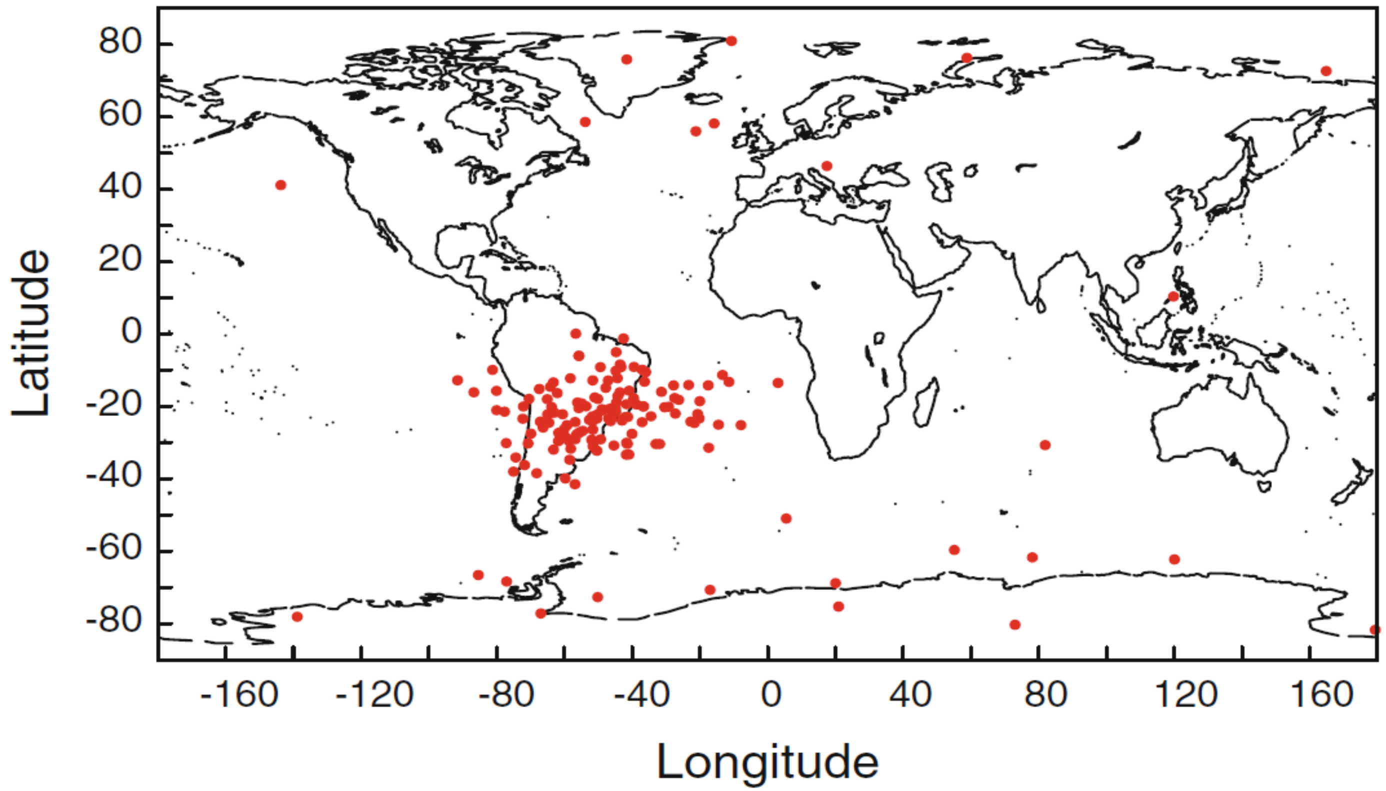
Navigation Accuracy

- 3D rms navigation accuracy of about
    - 2 m pos
    - 5 cm/s vel
- Peak errors up to 10m



Proba-2 – Radiation Effects (I)

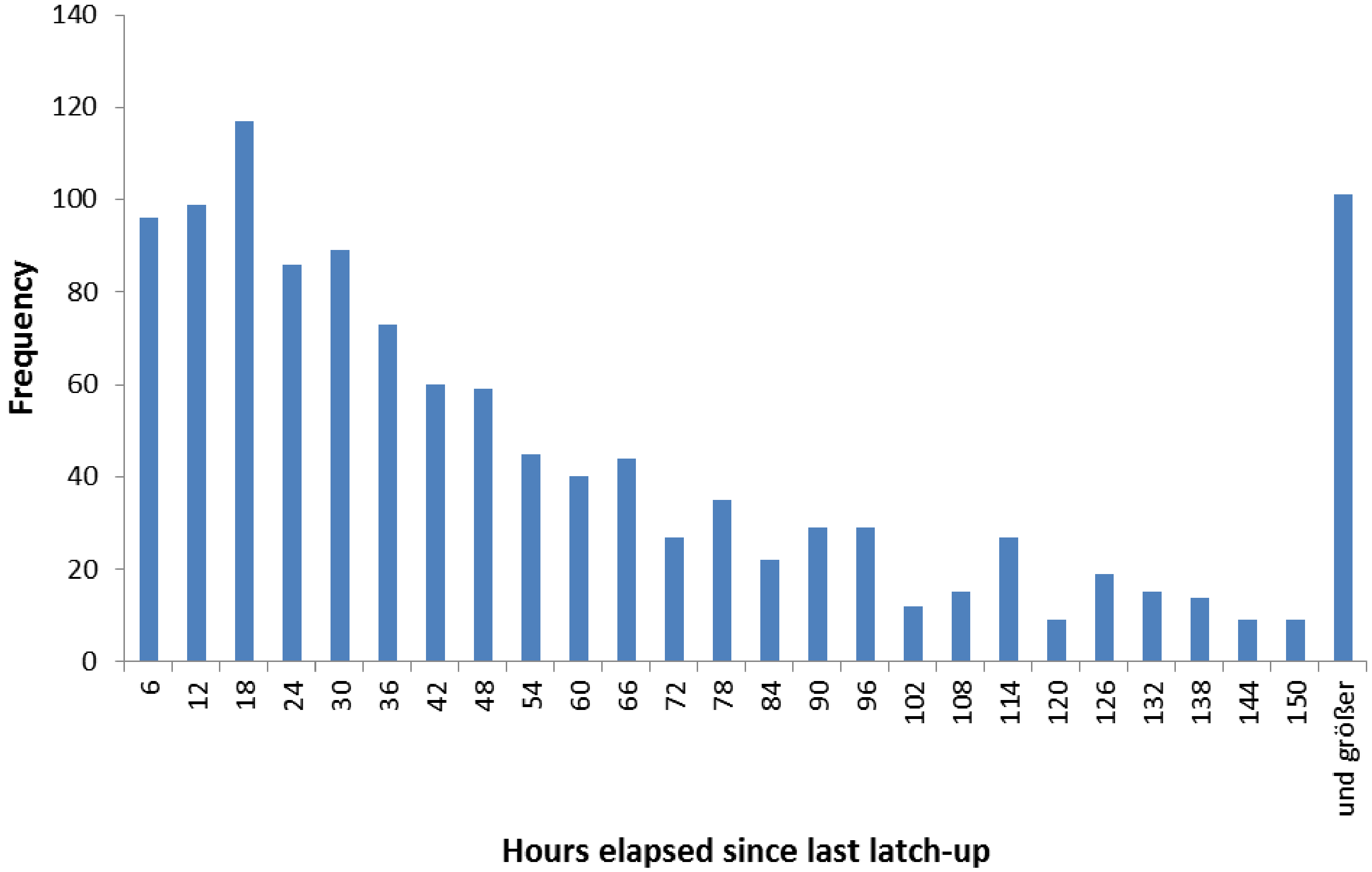
- Numerous SELs in almost regular intervals from beginning of operation
- In average one to two latch-up events every 48 hours
- Majority of latch-ups can be associated with the South Atlantic Anomaly
- Remaining events occurred at high latitudes in the North and South Pole region
- Also SEUs observed but less frequent
- Both receivers onboard Proba-2 still performing nominal (almost 11 years in orbit!!)



Geographic distribution of Phoenix-XNS latch-up events on PROBA-2 (September 2010–August 2011)

Proba-2 – Radiation Effects (II)

Statistical analysis of the times between two subsequent latch-up events (2009-2019).



Summary and Conclusions

- The Phoenix GPS receiver has been developed as an affordable alternative to fully space qualified GPS/GNSS receivers.
- A test and qualification program has been conducted with the receiver to ensure a proper operation in space.
- During these tests a relatively high sensitivity to space radiation has been detected (mainly SEL).
- Latch-ups were found to be non-destructive.
- Receiver successfully flying in orbit onboard numerous LEO satellite (11 years abord PROBA-2!!)

- This example demonstrates that COTS electronics can be an alternative to expensive space-qualified hardware.
- However, environmental testing is essential!
- One should not underestimate the costs and effort associated with the qualification of a COTS system for space use.