Possible advantages of equipping GNSS satellites with on-board accelerometers

- a way to get profits -

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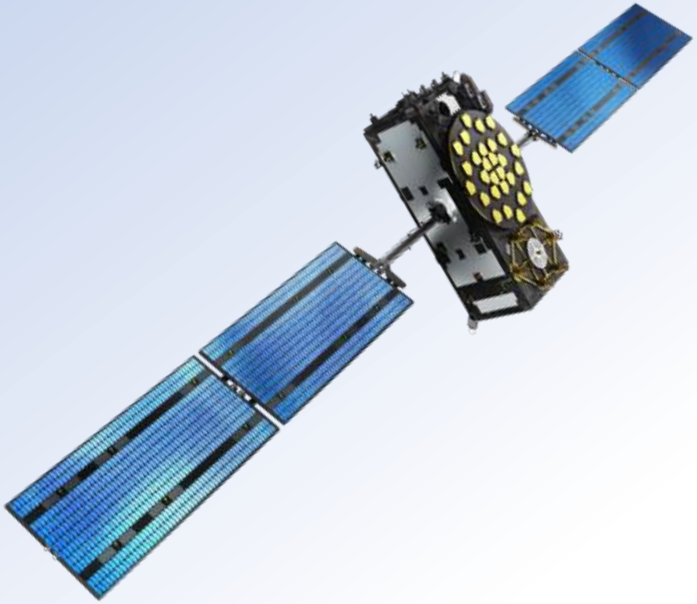


IAG Commission 4 Positioning and Applications Symposium, Wrocław, Poland, September 4-7, 2016

GNSS – evolution

Galileo Science Opportunity Document

secondary payloads, extended satellite features, dedicated test satellites

- Improved clocks and ground-satellite links

  benefit for:

  - global positioning and navigation
  - applications in Earth observation (geodesy, remote sensing)
  - metrology and astronomy (reference frames and time scales)

- **On-board accelerometers**
  - **to monitor the surface forces in real time**
    - **improved models for the orbits**
    - **better control of the effect of the time variations of these forces**

- Inter-satellite links
  - to improve control of the constellation
  - to pave the way to the long term prospect of an autonomous space segment for the GNSS (free it from the current limitations associated with the ground segment)

GNSS – new possible applications

Equipping GPS Satellites with Accelerometers and Satellite-to-Satellite Observables

Proceedings of the 2002 ION National Technical Meeting, San Diego, CA, January 28-30, 2002

Michael E. Ash

ABSTRACT

Millimeter-level accuracy applications of terrestrial Global Positioning System (GPS) phase tracking can be done more robustly with global rather than regional accuracy if the GPS satellites are equipped with (1) accelerometers to measure rather than model nongravitational accelerations, (2) satellite-to-satellite phase tracking as well as ranging cross links to work around inadequately modeled atmospheric propagation effects, and (3) gyroscopes for better satellite attitude control. More complete general relativity modeling is also needed in the orbit fitting and site coordinate estimation process, for which it could be advantageous to employ a combination of Kalman filtering on the orbital motions and maximum likelihood estimation on the site coordinates, accelerometer biases, and other parameters.

INTRODUCTION

Need for New GPS Satellite Instrumentation

The data from geophysics-grade GPS phase tracking receivers are currently used to determine receiving site coordinates with accuracies approaching the millimeter precision of the observables, where the ground observing site coordinates, the GPS orbit initial conditions, and other parameters are simultaneously estimated to best fit the all-in-view phase tracking data.[1]

Among the extra parameters estimated are those in a model of the GPS nongravitational acceleration (~12 nano-g) due to radiation pressure and outgassing. Nongravitational acceleration model inadequacy is a limitation on the site coordinate and orbit fit accuracy obtainable, which problem this paper proposes to circumvent by equipping the GPS satellites with a 3-axis low-g accelerometer (or possibly three single-axis accelerometers), and by the use of satellite-to-satellite phase tracking and ranging observables.

Gyroscopes combined with existing earth and sun sensor data are required to determine the satellite attitude, and hence the position of the transmitting antenna phase center to millimeter accuracy, and to correct for centripetal and angular acceleration effects on the strapdown accelerometers.

Inadequacy of the neutral atmosphere model is another limitation on the site coordinate and orbit fit accuracies obtainable using only ground-based observations. However, use of satellite-to-satellite phase tracking and ranging observables works around this problem. GPS observations from a network of ground sites can then estimate neutral atmosphere characteristics for processing ground-based observations and for input to, e.g., a Navier-Stokes weather prediction model of the atmosphere.

General Relativity Effects

The average earth general relativity effect on GPS clock rate has always been taken into account in the GPS architecture. In addition, the instantaneous earth and sun general relativity effects on GPS clock rate and on orbital motion and radio signal propagation must be taken into account to achieve global millimeter-level orbit and site coordinate determination, and light-time iterations should be done in the solar system barycenter frame, as is done in processing centimeter accuracy lunar laser observations.

Improved Estimation Procedure

The use of maximum likelihood system identification is advocated in the orbit fitting and parameter estimation process, in which an extended Kalman filter is run on the satellite position and velocity states to take account of noise and unmodeled effects in the dynamics, and a maximum likelihood estimator is run on the orbit initial conditions, site coordinates, atmosphere model parameters, accelerometer biases, clock biases, and other parameters.

Possible applications:

- more accurate, robust, and global ground site coordinate determination
- real-time determination of neutral atmosphere water vapour content,
- very accurate airborne gravimetry,
- millimetre accuracy low-altitude satellite orbit determination using GPS observables,
- length-of-day and earth wobble monitoring at finer detail,
- autonomous GPS satellite operation.

Precise Orbit Determination

NGP – non-gravitational perturbations

Measuring vs. Modelling

NGP

- Solar Radiation Pressure (SRP)
- Earth Radiation (visual and thermal)
- antenna thrust
- thermal re-radiation from S/C surface
- atmospheric drag

Models

- analytical (or physical) models
- semi-analytical SRP models with empirical scaling or augmentation
- empirical models with the estimation of parameters adapting to SRP perturbations (e.g. ECOM)

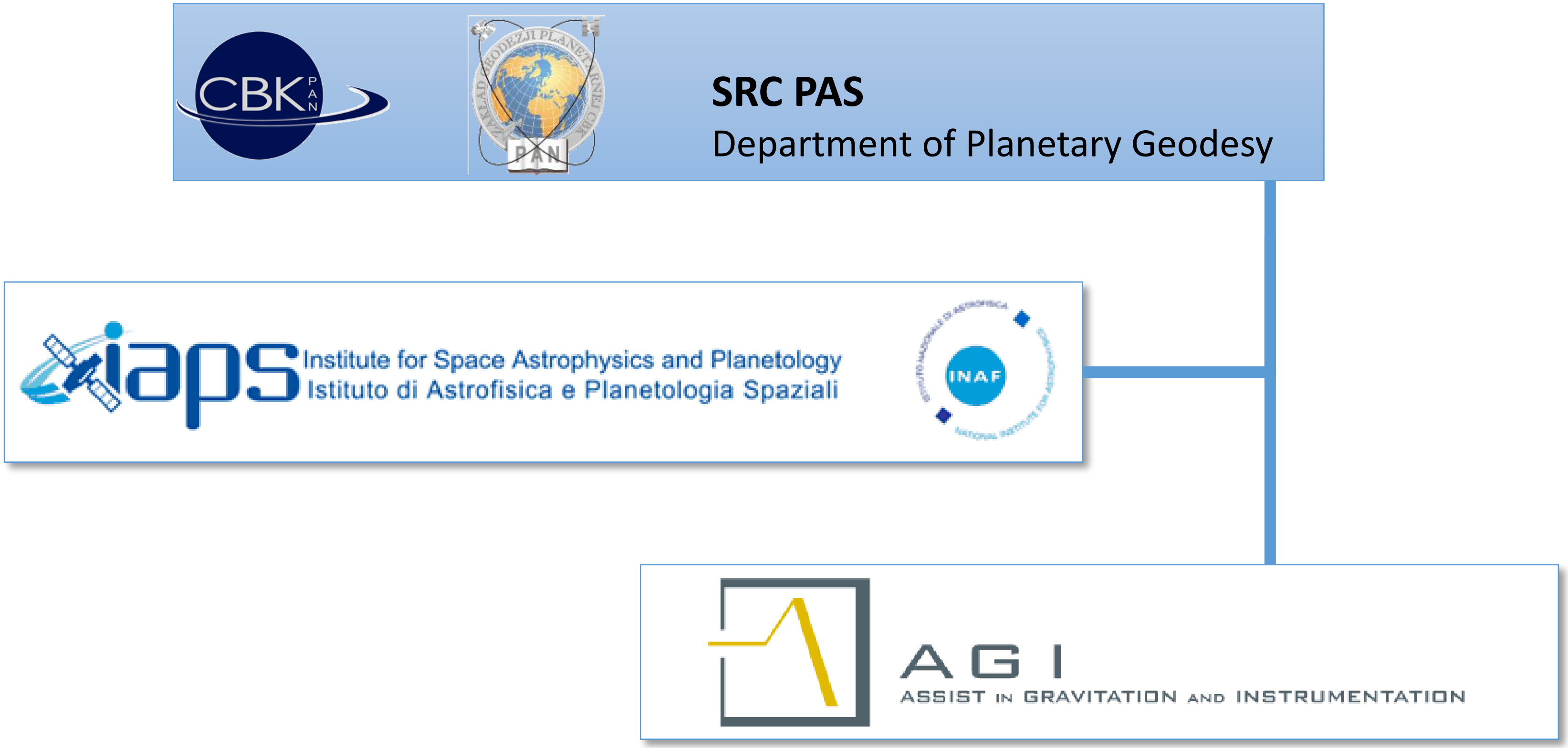
Accelerometer measurements

GalAc – Galileo and Accelerometry

ESA EGEP - The European GNSS Evolution Programme

EGEP ID 89: **GNSS TECHNOLOGY AND SCIENCE** AO

Contractors:



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GalAc – desired outcome

Assessment of the potential on-board accelerometer which can improve Precise Orbit Determination of the Galileo second generation satellites

- **The simulation strategy and data analysis needed to**
  - find the dominant accelerometer error terms
  - perform sensitivity analysis on the order of magnitude of the dominant accelerometer performance metrics
  - provide recommendations for accelerometer performance requirements
  - provide recommendations for Galileo S/C

Accelerometer – generic model

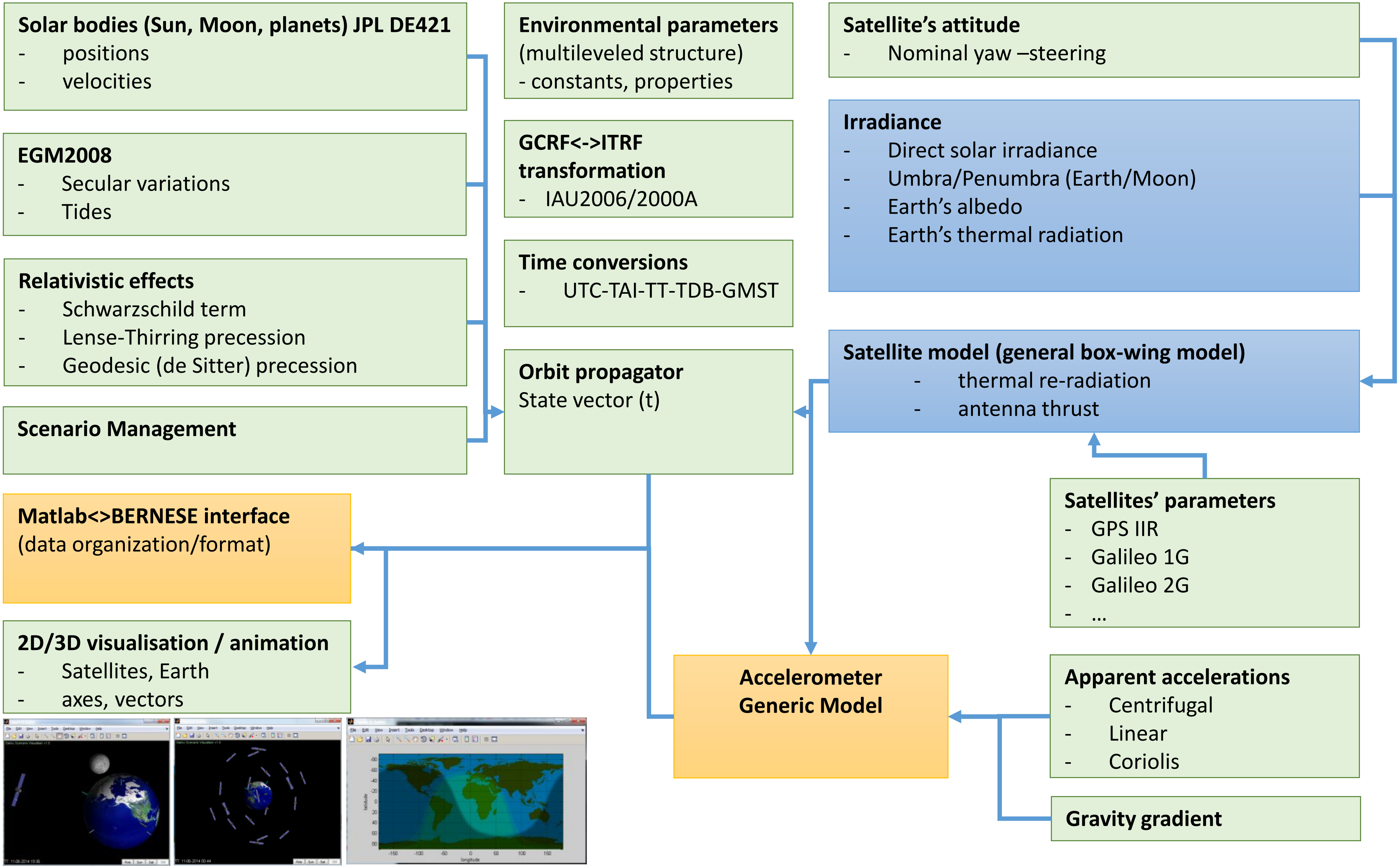
- Velocity Random Walk (VRW)
- Quantization
- Bias Random Walk (BRW)
- Bias instability/flicker noise
- Bias on/off repeatability
- Bias residual over thermal range
- Scale factor error
- Scale factor non-linearity
- Scale factor residual over thermal range
- Misalignment
- Non-orthogonality
- Bandwidth

Accelerations – expected values

Source	Expected acceleration $[nm/s^2]$
direct SRP	**~150**
Earth radiation	~10
gravity gradient	~2 [x]
thermal emission (from S/C surface)	~0.4
antenna thrust effect	~2
nominal rotation	~200 [x]
y-bias	~0.5
- micro-vibrations / fuel sloshing / mass redistribution - thermal effects - effects related to the S/C environment - internal properties of the accelerometer	

expected spectral content of the NGP is within $1 \cdot 10^{-5}$ Hz and $1 \cdot 10^{-2}$ Hz

GSTE – General Simulation Tool for Earth-Orbiting Objects



Solar bodies (Sun, Moon, planets) JPL DE421
- positions
- velocities

EGM2008
- Secular variations
- Tides

Relativistic effects
- Schwarzschild term
- Lense-Thirring precession
- Geodesic (de Sitter) precession

Scenario Management

Environmental parameters
(multileveled structure)
- constants, properties

GCRF<->ITRF transformation
- IAU2006/2000A

Time conversions
- UTC-TAI-TT-TDB-GMST

Orbit propagator
State vector (t)

Satellite's attitude
- Nominal yaw –steering

Irradiance
- Direct solar irradiance
- Umbra/Penumbra (Earth/Moon)
- Earth's albedo
- Earth's thermal radiation

Satellite model (general box-wing model)
- thermal re-radiation
- antenna thrust

Satellites' parameters
- GPS IIR
- Galileo 1G
- Galileo 2G
- …

Matlab<>BERNESE interface
(data organization/format)

2D/3D visualisation / animation
- Satellites, Earth
- axes, vectors

Accelerometer Generic Model

Apparent accelerations
- Centrifugal
- Linear
- Coriolis

Gravity gradient

NGP – simulation

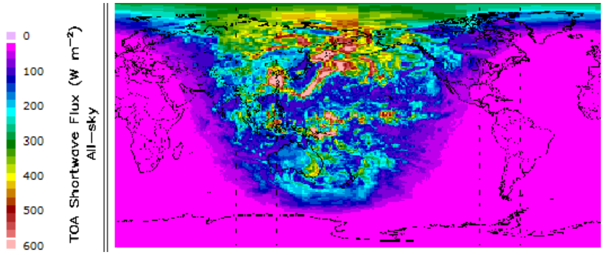
- Direct Solar Radiation Pressure

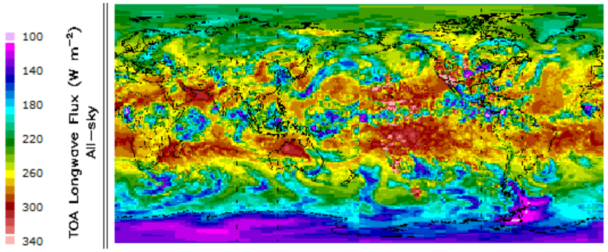
  Total Solar Irradiance Data from **SORCE – Solar Radiation & Climate Experiment**

- Eclipses - umbra/penumbra

- Earth Radiation (visual and thermal)
  - analytical model
  - observed fluxes from **CERES – Clouds and the Earth's Radiant Energy System**

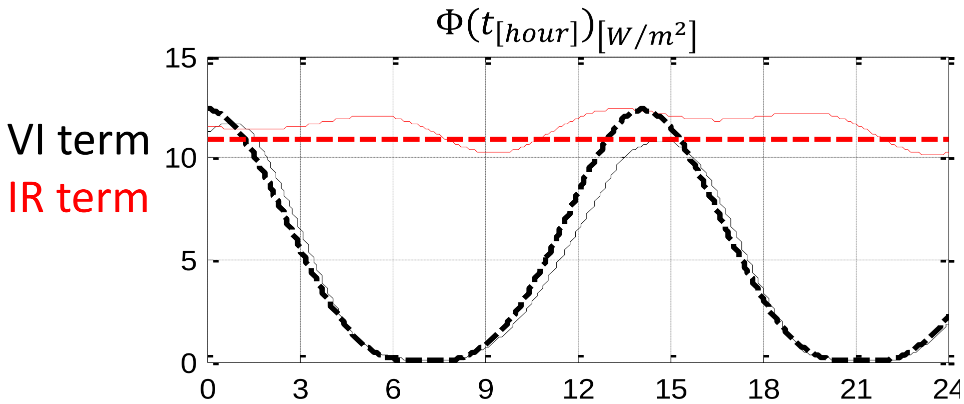
    (observed 3-hourly CERES all-sky energy fluxes with spatial resolution of $1^0 \div 1^0$)





Flux due to Earth Radiation

Galileo orbit (observed vs. modelled)



observed - solid, analytical - dashed

Satellite properties – box-wing model

Assumed parameters of the satellites

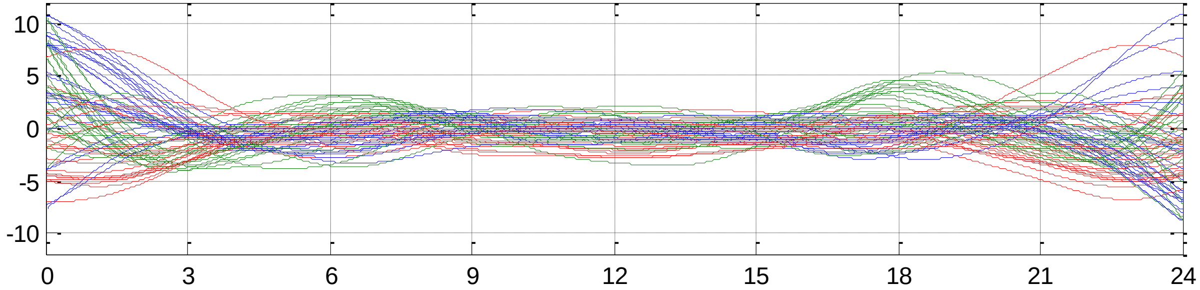
			Satellite parameters		
Parameter			**GPS IIR**	**Galileo 1G**	**Galileo 2G**
mass		[kg]	1125	733	1528
bus dimensions		[m]	1.57, 1.96, 2.21	2.5, 1.2, 1.1	3.5, 1.15, 1.2
area of solar panels		[m^2]	13.5	14.7	44.0
solar panel	front	ρ, δ	0.25, 0.044	0.25, 0.044	0.25, 0.044
	back	ρ, δ	0.055, 0.055	0.055, 0.055	0.055, 0.055
		ρ_{IR}, δ_{IR}	0.1, 0.1	0.1, 0.1	0.1, 0.1
bus		ρ, δ	0, 0.06	0, 0.06	0, 0.06
		ρ_{IR}, δ_{IR}	0.1, 0.1	0.1, 0.1	0.1, 0.1
ρ - fraction of reflected photons δ - fraction of diffusely scattered photons					

GalAc – POD with accelerometer measurements

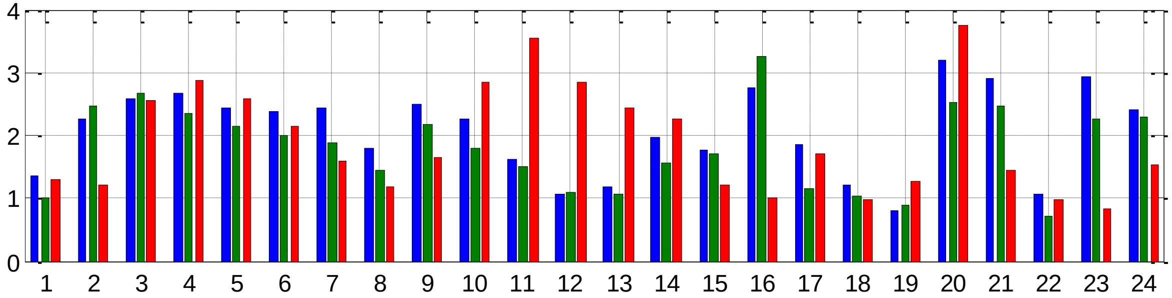
based on simulation of Galileo-like satellite

POD residuals: $RES_{ACC}(t_{[hour]})_{[cm]}$

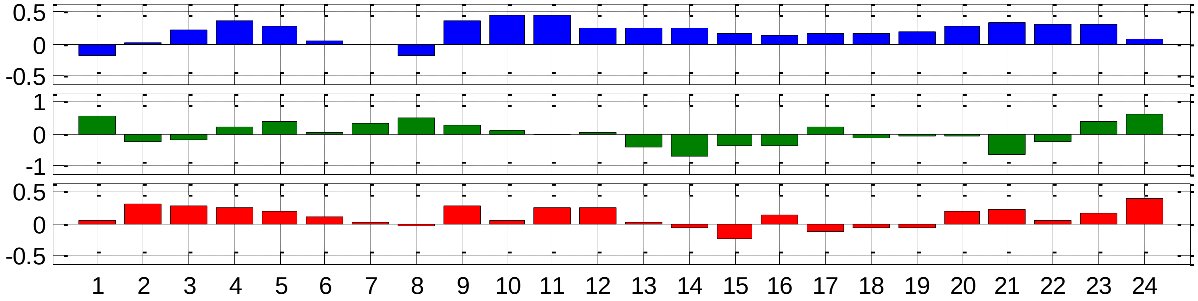
R-blue, S-green, W-red



POD residuals: $RMS_{ACC}(Sat\#)_{[cm]}$



Accelerometer bias estimation error: $Bias_{err}(Sat\#)_{[nm/s^2]}$



Assumed acc. errors:

- intrinsic noise:

  $$0.2 = \frac{nm}{s^2}/\sqrt{Hz}$$

- bias

  $$< 10 \div 200 > \frac{nm}{s^2}$$

- thermal error

  $$2.5\sin(\omega t + \varphi)\frac{nm}{s^2}$$

- in-band vibrations

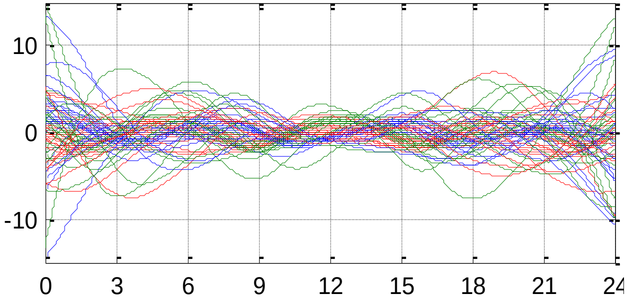
  $$1.5\sin(\omega_1 t + \varphi_1)\frac{nm}{s^2}$$

  $$3.5\sin(\omega_2 t + \varphi_2)\frac{nm}{s^2}$$

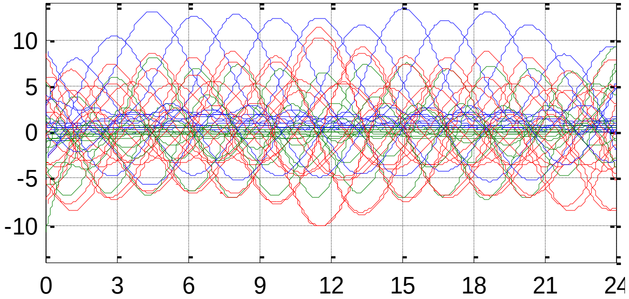
GalAc – Accelerometer measurements vs. ECOM

POD residuals = $RES(t_{[hour]})_{[cm]}$

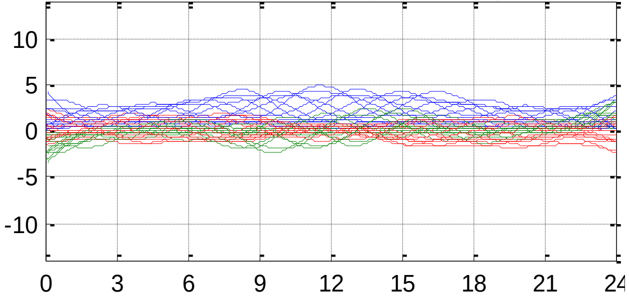
Acc. measurements



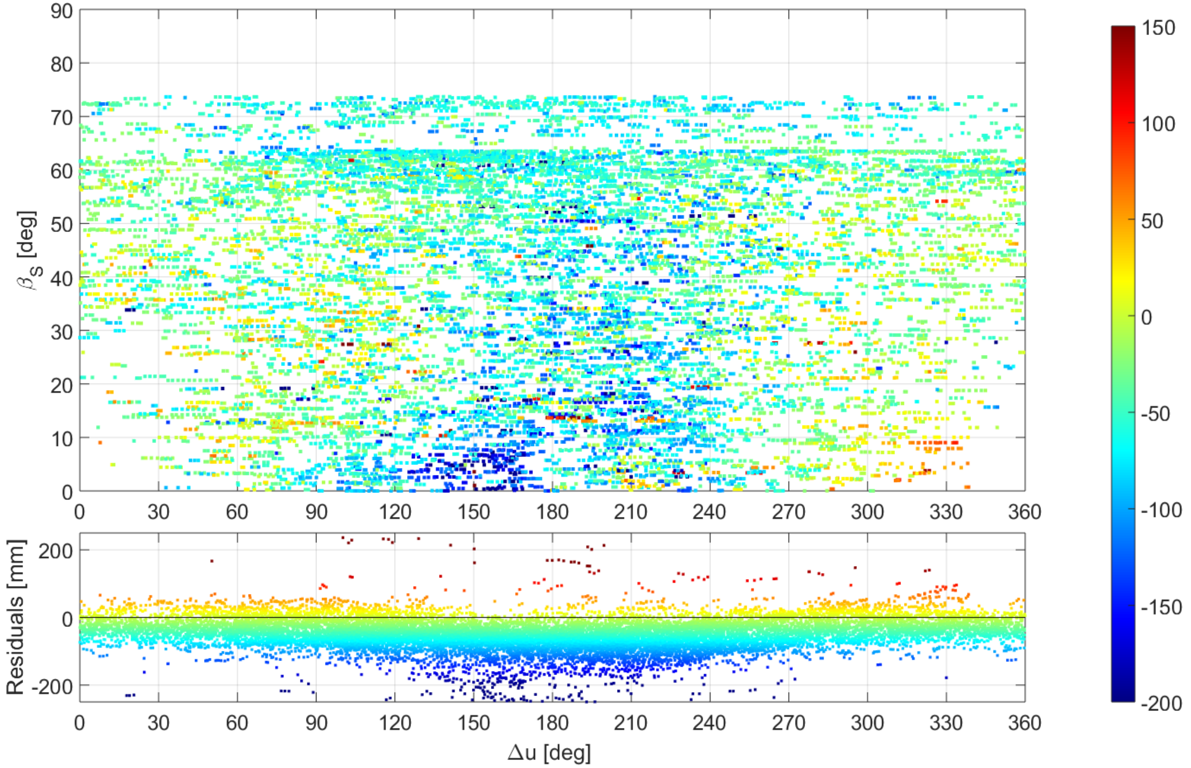
ECOM classical p5



ECOM new (D2, D4)



R-blue, S-green, W-red

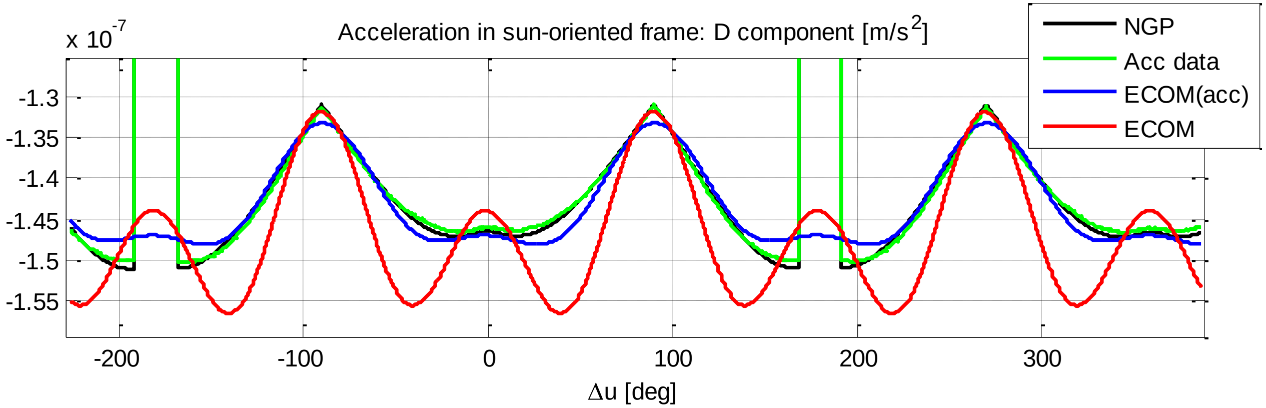


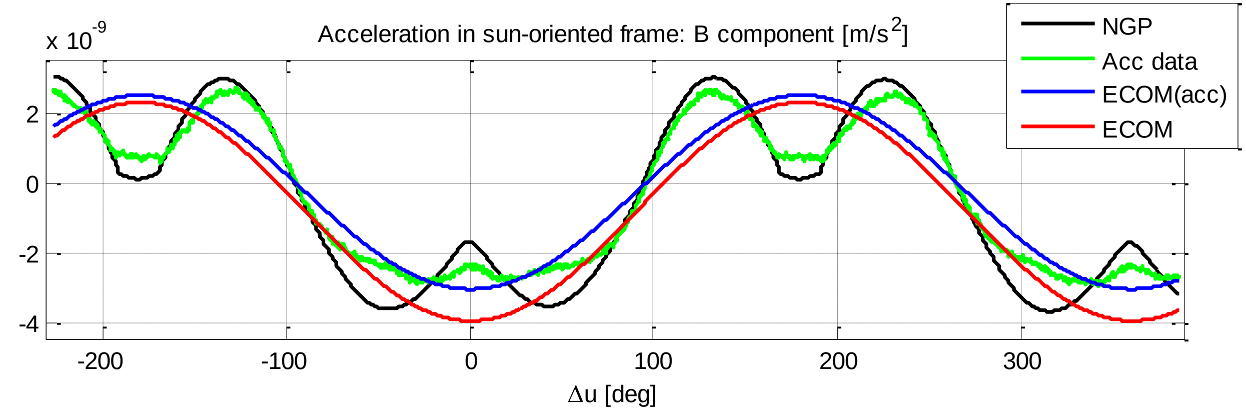
performance of new ECOM w.r.t SLR residuals (example for Galileo satellites)

GalAc – Improvement of the ECOM

Improvement of the NGP models based on accelerometer data

- estimation of accelerometer bias in POD
- application of the estimated bias to the accelerometer data (measurements)
- transformation to DYB (Sun-oriented) frame
- least squares fit of the new ECOM

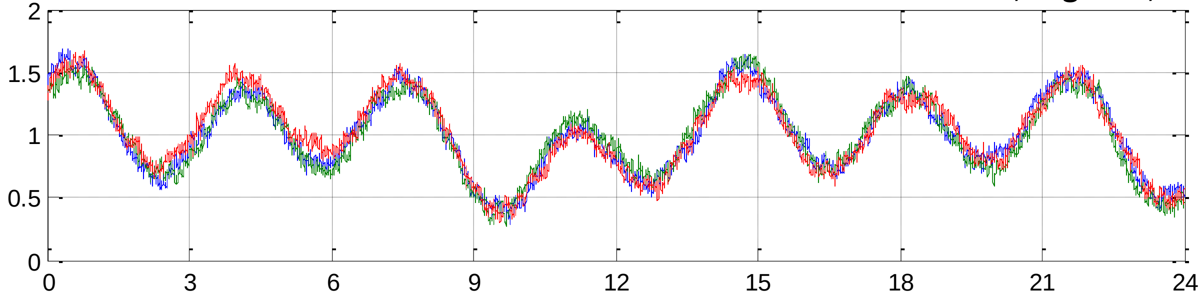




Accelerometer error – impact on POD

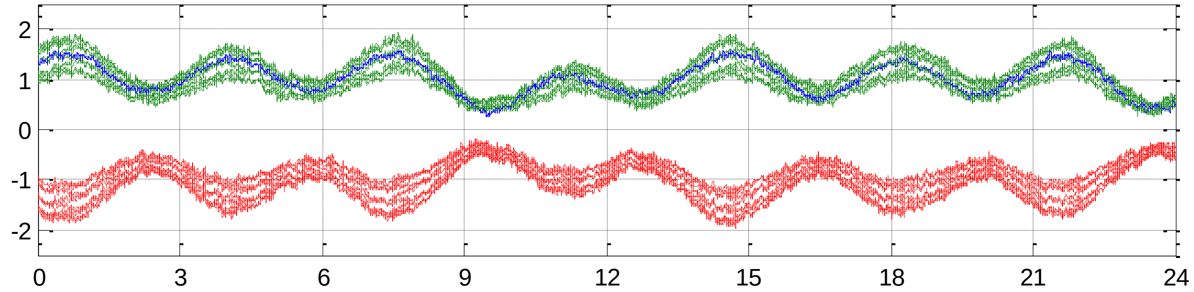
$Acc_{ERR}(t_{[hour]})_{[nm/s^2]}$ in body frame

X-blue, Y-green, Z-red



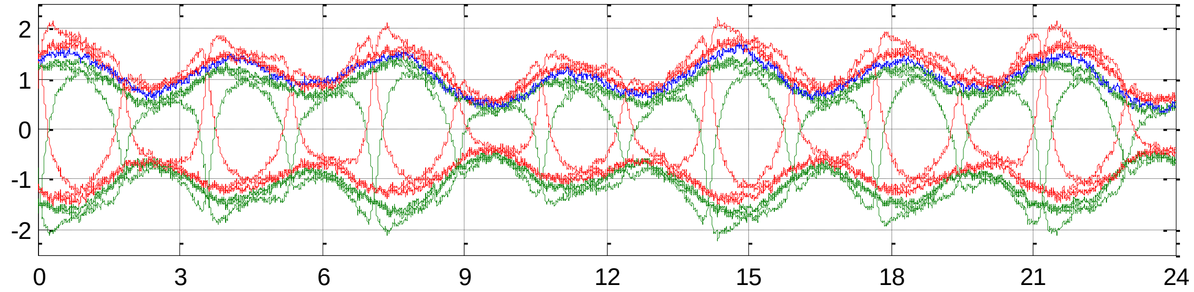
$Acc_{ERR}(t_{[hour]})_{[nm/s^2]}$ for HIGH beta

R-blue, S-green, W-red

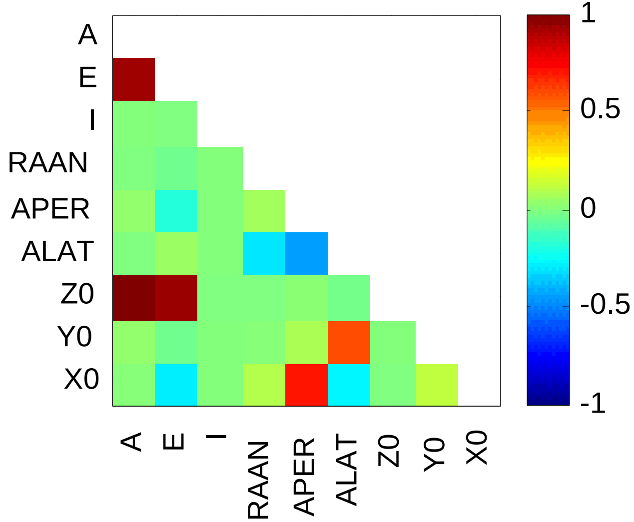


$Acc_{ERR}(t_{[hour]})_{[nm/s^2]}$ for LOW beta

R-blue, S-green, W-red



correlation matrix



Conclusions

Unmodelled terms of NGP shall be seen by accelerometer

- difference between observed and analytical Earth Radiation Model results in the acceleration at the level of $0.2 \div 0.3\ nm/s^2$
- y-bias

Initial set of accelerometer requirements

- **dynamics** - expected NGP amplitude: lower than $200\ nm/s^2$
- **bandwidth** - expected NGP spectral content: $1 \cdot 10^{-5}$ Hz ÷ $1 \cdot 10^{-2}$ Hz
- **accuracy** - at least $1 nm/s^2$ (to be averaged in time)

- accelerometer bias can be effectively recovered by POD

Possible prospects

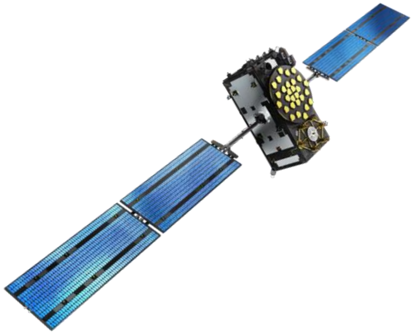
GSTE

General improvement

- atmospheric drag
- more sat. models (database)
- user interface
- …

Towards Galileo second generation

- more detailed analysis of the on-board accelerometer
- advanced data fusion algorithms (GNSS, accelerometers, ISL, …)
- algorithms for real-time data processing
- simulation of quasi-geostationary orbits
- alternative constellations
- …



Thank you for your attention

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