

# Solar radiation pressure modeling for a Gravitational Redshift Test with Galileo 5 + 6

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Jul. 11, 2016

**GR conference, New York**



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# Overview

## Introduction

- ▶ Galileo 5+6 redshift test

## Redshift evaluation

- ▶ redshift parameter  $\alpha$
- ▶ clock residuals

## Models

- ▶ Solar radiation pressure
- ▶ Galileo FE model

## First results

- ▶ SRP parametric analysis
- ▶ SRP influence on redshift

## Conclusion and Outlook

# Galileo system

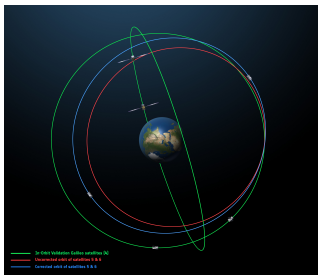
- ▶ European Positioning System (Joint EU/ESA project and several non-EU states),
- ▶ Project Start 2003,
- ▶ A total of 30 Satellites in circular orbits at 23260 km,
- ▶ Walker-constellation ( $56^{\circ}:27/3/1$ ),
- ▶ IOV Satellites manufactured by Airbus, FOC Satellites manufactured by OHB,
- ▶ Currently 14 FOC in orbit, completion planned in 2018.



Galileo FOC geometry, Source:ESA



# Galileo launch anomaly



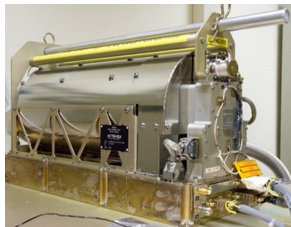
Galileo 5+6 Orbits, Source:ESA

	GSAT-5	GSAT-6
$a$	27978 km	27978 km
$e$	0.15601	0.15167
$i$	$49.775^\circ$	$49.874^\circ$
$h_a$	25818 km	25848 km
$h_p$	17240 km	17220 km
$T$	12.9367 h	12.9366 h

- ▶ Launch anomaly during Galileo 5+6 launch,
- ▶ Valve failure in Fregat upper stage,
- ▶ Consequence: Non-nominal elliptic orbit,
- ▶ Satellites flying through van-Allen belts,
- ▶ Available fuel used to reduce eccentricity and to increase orbit altitude.
- ▶ But: final orbits of both satellites are still elliptic!

# High precision clock in space

- ▶ Satellite bus is equipped with PHM and RAFS clocks,
- ▶ Stability w.r.t. orbital period:  
 $\sigma_{y,PHM} = 3 \cdot 10^{-15}, \sigma_{y,RAFS} = 2 \cdot 10^{-14}$
- ▶ Orbits are still elliptic  $\rightarrow$  high precision clocks in a changing gravitational potential!
- ▶ Perfect conditions for a test of the gravitational redshift!



Passive hydrogen maser, Source:ESA



Rubidium atomic frequency standard clock, Source:ESA

## Redshift parameter $\alpha$

A clock's ticking rate slows down if brought closer to a massive object. The resulting redshift can be tested with test parameter  $\alpha$ :

$$\frac{\Delta\nu}{\nu} = -(1 - \alpha) \frac{\Delta U}{c^2} .$$

The most accurate test of  $\alpha$  has been conducted with GPA (hydrogen maser on a sounding rocket) :  $\alpha < 1.4 \cdot 10^{-4}$ ,

Vessot et al., Phys. Rev. Lett. 45 (1980)

## Redshift model in time domain

Leading order relativistic effect:

$$\Delta t = \int \left( 1 - \underbrace{\frac{(V - \Phi_0)}{c^2}}_{\text{Grav. Redshift}} + \underbrace{\frac{v^2}{2c^2}}_{\text{Quadr. Doppler}} \right) d\tau .$$

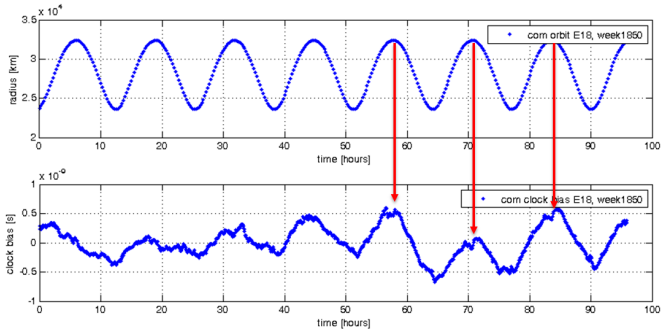
Influence of eccentricity:

$$\Delta t = \int \left( \frac{3GM_E}{2ac^2} + \frac{\Phi_0}{c^2} - \underbrace{\frac{2GM_E}{c^2} \left( \frac{1}{a} - \frac{1}{r} \right)}_{\Delta t_r = \frac{2\sqrt{GM_E a}}{c^2} e \sin E + \text{const.}} \right) d\tau .$$

Practical implementation:

$$\Delta t_r = \frac{\vec{v} \vec{r}}{c^2} .$$

# Clock residuals



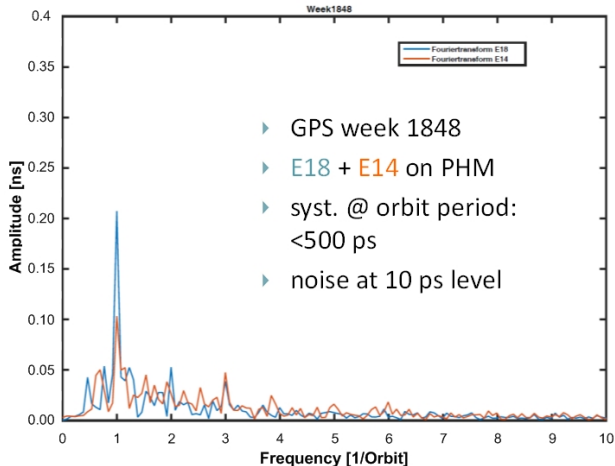
Orbit and CODE (TUM) clock bias for GPS week 1850

Possible cause of systematic effects:

- ▶ Direct systematics on satellite clock: Temperature effects / Magnetic fields,
- ▶ Indirect systematics on orbit/clock solution: **SRP mismodelling** / Attitude effects,
- ▶ Systematics on ground clocks ?



# Clock residuals



- ▶ GPS week 1848,
- ▶ E18 + E14 on PHM,
- ▶ syst. @ orbit period: <500 ps,
- ▶ noise at 10 ps level.

# Solar radiation pressure model

Photon momentum:

$$E = \sqrt{(m_0 c^2)^2 + (|\vec{p}_{\text{Ph}}| c)^2}$$

$$\rightarrow E_{\text{Ph}} = |\vec{p}_{\text{Ph}}| c \text{ mit } E_{\text{Ph}} = h \nu_{\text{Ph}} .$$

Momentum exchange when absorbing photons:

$$\frac{d|\vec{p}|}{dt} = \frac{h \nu_{\text{Ph}} dN}{c dt} = |\vec{F}_{\text{TRP}}| = \frac{P}{c} .$$

Received Solar Power:

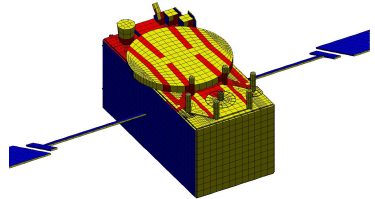
$$P_{\text{Sat}}(r) = \frac{P_{\odot, 1 \text{ AU}}}{r^2} \alpha A_{\text{Sat}} .$$

Resulting SRP force per surface element:

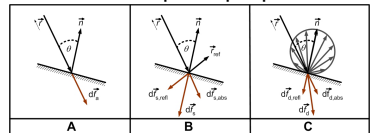
$$d\vec{f}_{\text{res}} = d\vec{f}_a + d\vec{f}_s + d\vec{f}_d$$

$$= \frac{-P_{\text{inc}} \cos \theta dA}{c} \left[ (1 - \gamma_s) \vec{r} + 2(\gamma_s \cos \theta + \frac{1}{3} \gamma_d) \vec{n} \right] .$$

Implementation of shadowing:

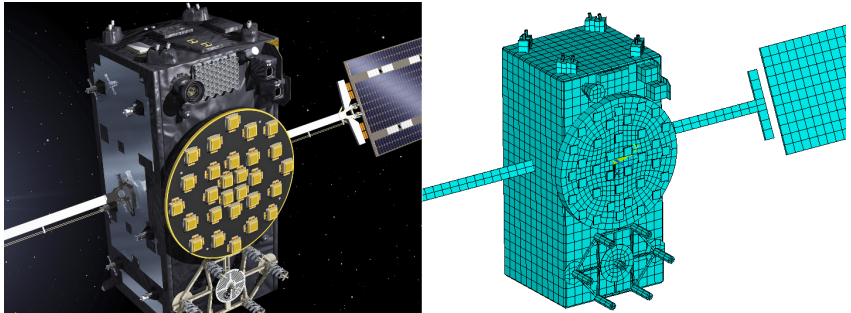


Treatment of optical properties:



A: Absorption, B: Spec. Reflection, C: Diff. Reflection

# Galileo FE model

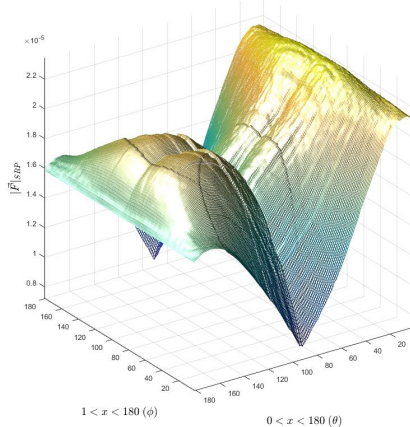


Comparison between real satellite and FE model

- ▶ Different optical properties for each surface cell,
- ▶ Orbital state and attitude from numerical orbit/attitude simulation.

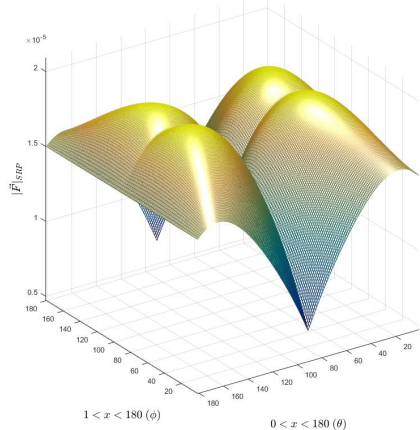
# Parametric analysis: Solar incidence angle

Force distribution wrt theta and phi



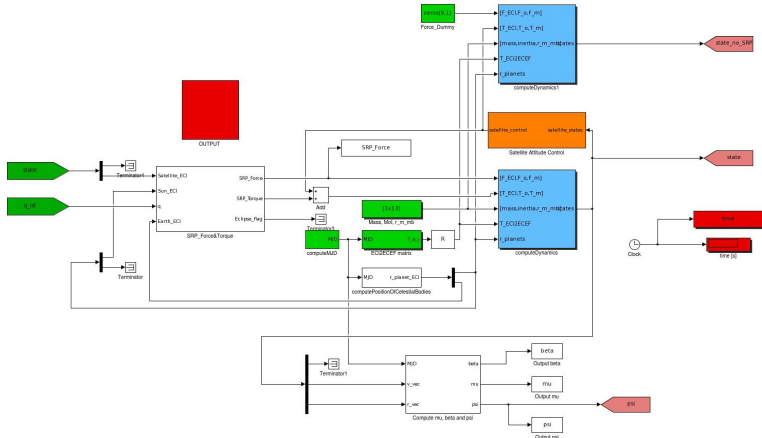
Galileo FE model

SRP force distribution wrt theta and phi

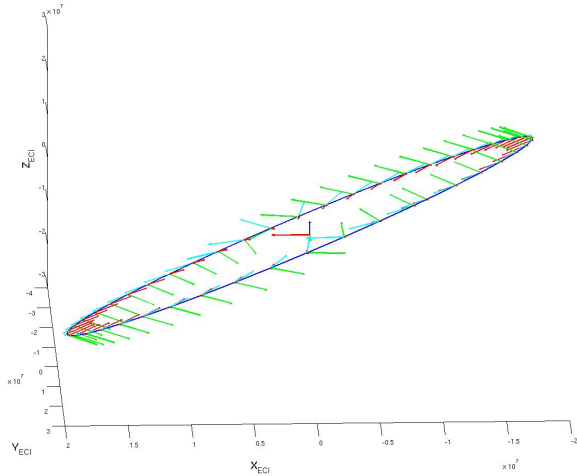


Box model

# Orbit model

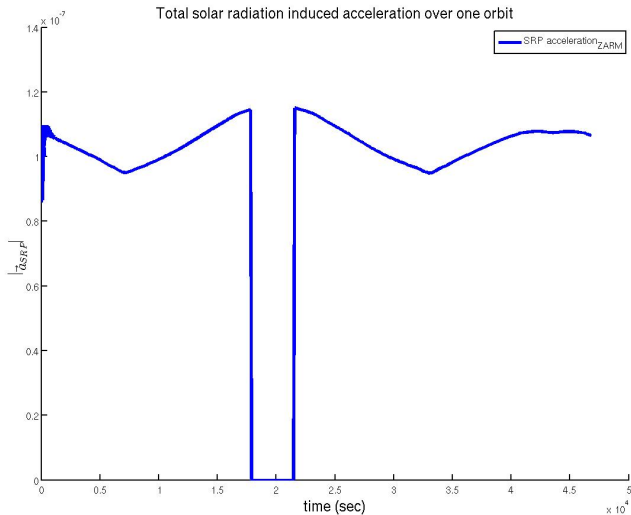


# Orbit model

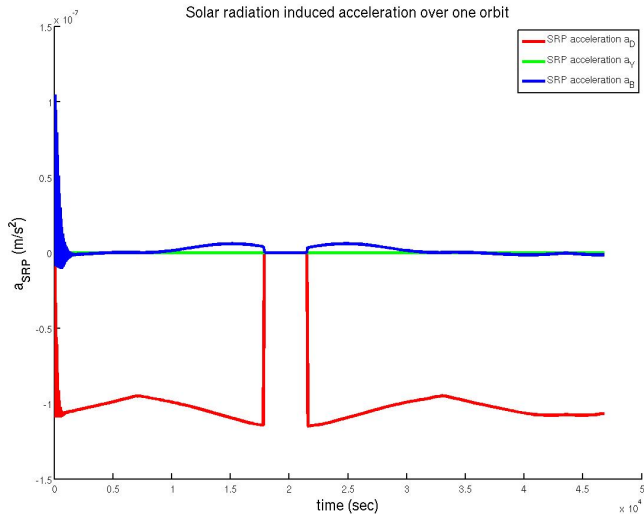


Simulated satellite attitude (yaw-steering) and trajectory

# First SRP results

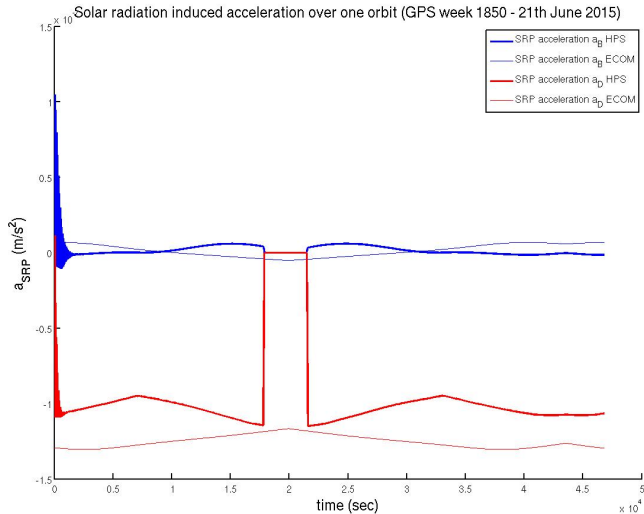


# First SRP results

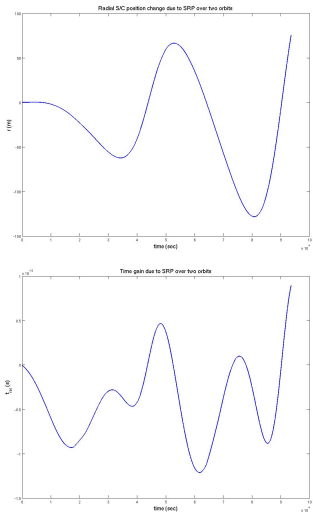




# First SRP results



# Predicted Redshift due to SRP

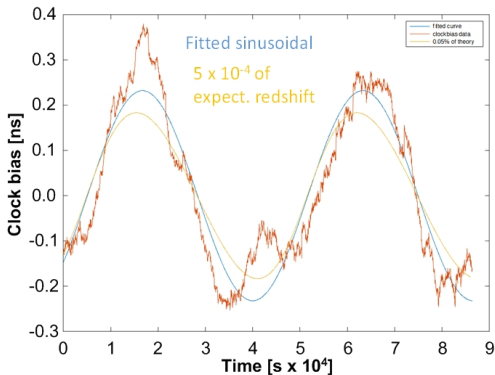


- ▶ Radial Position change growing with each orbit,
- ▶ Observed residuals correspond to about 100 orbits with SRP,
- ▶ Leads to modulation of clock residuals at orbit frequency,
- ▶ Causes secondary frequencies at satellite rate and 1 year.

# Conclusion

- ▶ A priori model for Solar radiation pressure,
- ▶ Input: Satellite geometry, materials, trajectory, attitude,
- ▶ Better accuracy with respect to Box-and-Wing, Cannonball, ECOM,
- ▶ Self-Shadowing and Reflection included,
- ▶ Clock residuals at orbit frequency strongly suggests SRP influence on redshift,
- ▶ Total improvement may lead to a better  $\alpha$  compared to GPA.

# Outlook



- Reduction of residuals by improved SRP model,
- Improvement of orbit determination by SLR campaign,

# Acknowledgements

- ▶ Javier Ventura-Traveset (ESAC)
- ▶ Roberto Prieto Cerdeira (ESAC)
- ▶ Erik Schöнемann (ESOC)
- ▶ Claus Lämmerzahl (ZARM)
- ▶ Dirk Pützfeld (ZARM)
- ▶ Volker Perlick (ZARM)
- ▶ Eva Hackmann (ZARM)
- ▶ Christoph Günther (TUM)
- ▶ Gabriele Giorgi (TUM)
- ▶ Martin LülF (TUM)
- ▶ Hansjörg Dittus (DLR)
- ▶ Fritz Merkle (OHB)

We gratefully acknowledge support for the GREAT project by the European Space Agency ESA



We also acknowledge support from DLR for the RELAGAL project under FKZ: 50WM1555



Gefördert durch:



aufgrund eines Beschlusses  
des Deutschen Bundestages