GALILEO ATTITUDE DETERMINATION

Attitude determination of Galileo spacecraft using high resolution kHz SLR

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ESAs project within Alcantara Initiative:
Verification of mm SLR measurements to Galileo satellites by variation of laser beam polarization plane orientation

Outline / project goals:
• mm SLR measurements to Galileo varying the laser beam polarization
• Ground based range measurements to ESA IOV spare retroreflector panel
• Transfer of know how Austria -> Argentina: build-up of AGGO SLR station
LASER BEAM POLARIZATION

- Laser beam: fixed linear polarization at laser table
- Polarization varied according to orbit
  - along satellite track
  - across satellite track
  - circular polarization
- Principle behind
  - $\lambda/2$ wave plate (rotatable): set arbitrary linear polarization plane
  - $\lambda/4$ wave plate (switched in and out): linear -> circular

$\lambda/2$ wave plate rotator

$\lambda/4$ wave plate switch
Certain Glonass satellites (e.g. Glonass 115 (NORAD 33467 / 2008-067B))
- Differences of up to 9 mm between two polarization states (along, across)

Project goals -> Galileo satellites:
- Determine laser polarization induced offset / influence of clocking quality of Galileo panels
- Statistical evaluation of a large data set with different pass geometries

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**PRE-Alcantara Results**

green ... polarization along satellite track
red ... polarization across satellite track
x–axis ... elevation [°]
y–axis ... Observed–Minus–Calculated [mm]
Results: polarization plane switching

- Full rate data of Galileo103: x-axis: Elvation [°], y-axis: O-minus-C residuals [mm]
- Polarization: Red: linear along track, green: linear across track, cyan: circular)

Offsets between normal points: < 2 mm (close to SLR accuracy)

Low elevations: tilt of panel --> increased jitter between photons from front and back of panel

9 cm @ 21.6° elevation
4 cm @ 74.1° elevation

Maximum jitter: 10 cm @ 12.4° tilt: (panel width: 46.8 cm)
13 Galileo satellites / 27 hours observations
1600 1-minute normal points

Y-axis: Range difference of normal points at different polarization states (across-along, across-circ)

- **No trend visible** -> averages to zero -> **good quality of ESA panels**
- Jitter of normal point difference dependent on elevation (incidence angle on panel)
- Jitter increases from ±1 mm (large elevations) to ±4 mm (low elevations)
  - Possible explanation: far field diffraction patterns of CCR separate further the larger the incident angle
  - Different linear polarizations rotate the whole field diffraction pattern
  - Different position within far field diffraction pattern --> retros with a certain clocking contribute more
    --> slightly different reflection point --> offset / jitter between normal points

Polarization and far-field diffraction patterns of total internal reflection corner cubes; Murphy, Goodrow; Appl Opt 53 (2); 2013
• ESA provided a spare IOV panel to perform ground based measurements
• Panel was mounted on an astronomical tripod
• Panel rotatable between -18° and +18° (around azimuth axis) / 0.1° steps
• Panel first time out of a clean room -> we asked ESA first :-) 
• Remote location 32 km outside of Graz (Absetzwirt)
Range measurements to Absetzwirt (analyze full rate data): y-axis: range [m], x-axis [seconds of day]

- Panel: 0° laser beam incident angle alignment of: using four 45° mirrors, 4 orthogonal screens
- Panel tilt angle around azimuth axis: increased from 0.0° to 18° (laser beam incident angle)
- Range jitter increases (photon statistically from front or back of tilted panel)
- True 0° incident angle (minimum jitter) 0.3° / 1.3° after mechanical 0° alignment (alignment errors)
- 11 clearly distinguishable tracks which separate from each other -> 11 retroreflector columns
Histogram analysis

- Histogram through range data (at incident angles above 10°)
- Number of photons / 500 µm bin at different ranges; Fitted with a smoothing function (red)
- Peak distance calculated (autocorrelation)
- Incident angle calculated from peak distances (42 mm CCR distance)

Compared to mechanical (red, dashed) incident angle alignment offset:
- 0.3° (green dotted, measurement day 1)
- 1.3° (blue dotted, measurement day 2)
Comparison: Absetzwirt vs. Galileo 103

Comparison to space-based measurement to Galileo 103

- SLR station Graz seen from Gal. ref. frame: 11.37° elevation / 90° azimuth (Yaw steering)
- From histogram: CCR column distances -> incident angle re-calculated: 11.38°
- Very good agreement: Unique method to verify the attitude of CCR panels

Peak heights: Galileo vs. spare panel -> clocking orientation contributing more to measurement
Laser beam polarization switching
1600 1-minute normal points to 13 different Galileo satellites
Very good clocking quality of Galileo panels
Maximal offsets between polarizations of 4 mm
Spare ESA retroreflector panel mounted at 32 km distance
Different columns of retroreflectors clearly visible
From distance offsets tilt angles calculated
Method to verify attitude of Galileo satellites < 0.1°
Satellite laser ranging (SLR) on astronomy telescope.

Quantum cryptography.

SLR station Graz.

Alcantara.

Andromeda galaxy (not a target yet ...)

Satellite laser ranging on astronomy telescope.

Thank You!!!