

Determining, Monitoring and Modelling the Attitude Motion of Potential ADR Targets

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Content

1. Introduction
2. Observation Techniques
3. Observations
and Determination of Attitude States
4. Summary



Introduction

- **Motivation to determine attitude states:**
(spin rate, spin rate evolution, spin axis orientation)
 - **Critical parameter for Active Debris Removal missions**
 - long term attitude evolution monitoring, attitude modeling
 - **Contingency support**
 - **Diagnostics, e.g. satellite functional but not behaving nominally**
 - **Study of specific perturbations, torques on space objects**
 - **Improved orbit determination/propagation**
 - **Validation/refinement/support of other attitude determination techniques, e.g. radar, ISAR, SLR, etc.**



ESA Study Objectives

ESA Debris Attitude Motion Measurements and Modelling Study

- Applications
 - Determination of attitude state of decommissioned intact objects (preparation of ADR missions)
 - Put mechanisms in place for a prompt, full investigation in case of spacecraft contingencies
- Fusion of data from:
 - Ground-based synthetic aperture radar (RCS changes, imaging)
 - Ground-based optical observations (light curves, direct imaging)
 - Ground-based cooperative laser ranging (SLR ranges)
- Development of a 6 degree of freedom simulator (all techniques)
- Collaborative attitude measurements
- Attitude predictions

Team

- **AIUB**
(Astronomical Institute University of Bern, Switzerland)
 - optical measurements, signal level (light curves), direct imaging, SLR spin rates and spin axis directions
- **IWF** 
(Space Research Institute of the Austrian Academy of Sciences, Austria)
 - satellite–laser ranging (SLR) to cooperative and uncooperative targets, spin rates and spin axis directions
- **HTG** 
(Hyperschall Technologie Göttingen GmbH, Germany)
 - simulator development
- **FHR** 
(Fraunhofer Institute for High Frequency Physics and Radar Techniques, Germany)
 - radar for attitude estimation and verification



Ground-Based Observation Techniques

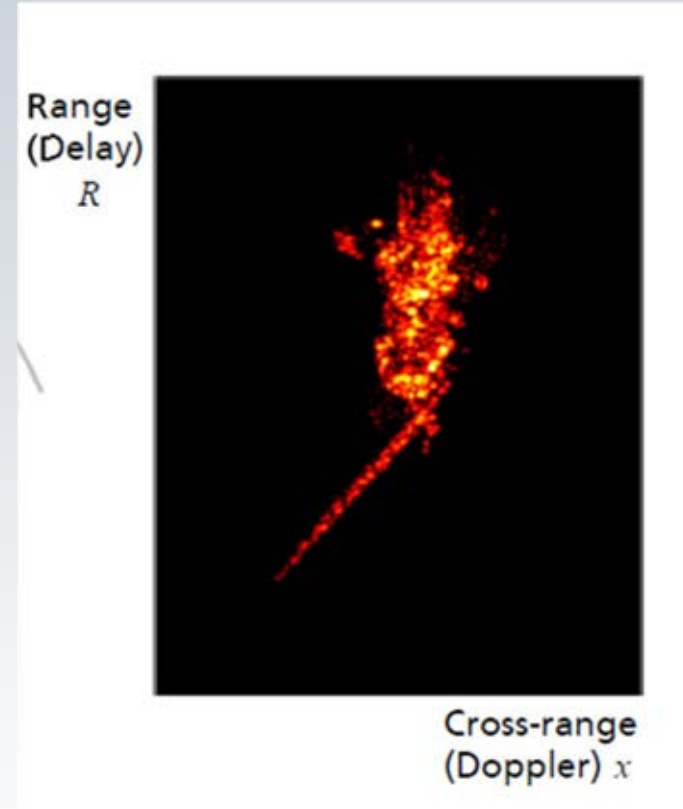
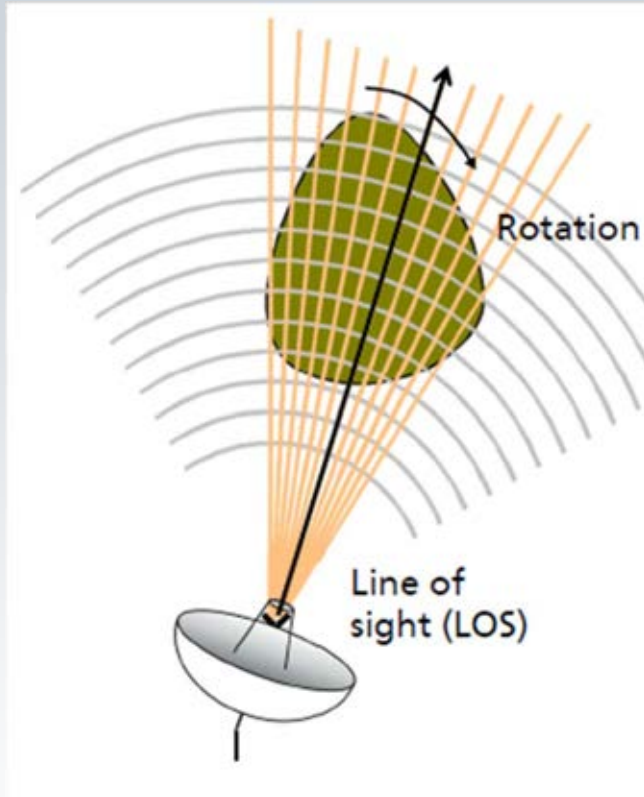
- Radar:
 - Synthetic Aperture Radar Imaging
 - RCS changes (“radar light curves”)
- Passive optical
 - Optical light curves
 - Direct imaging
- Satellite Laser Ranging (SLR)
 - Ranging to space debris carrying a retroreflector array (“cooperative targets”)



Radar

- Disadvantages compared to optical systems
 - Higher system costs
 - Range law $1/R^4$ vs. $1/R^2$
- Attitude determination techniques
 - RCS variations (“radar light curve”)
 - Possibility to image objects in 2D by exploiting the relative motion between radar and objects
- Inverse synthetic aperture radar (ISAR)
 - Resolution is range-independent
 - No disturbance through atmospheric turbulences

ISAR Principle



Curtesy Fraunhofer FHR

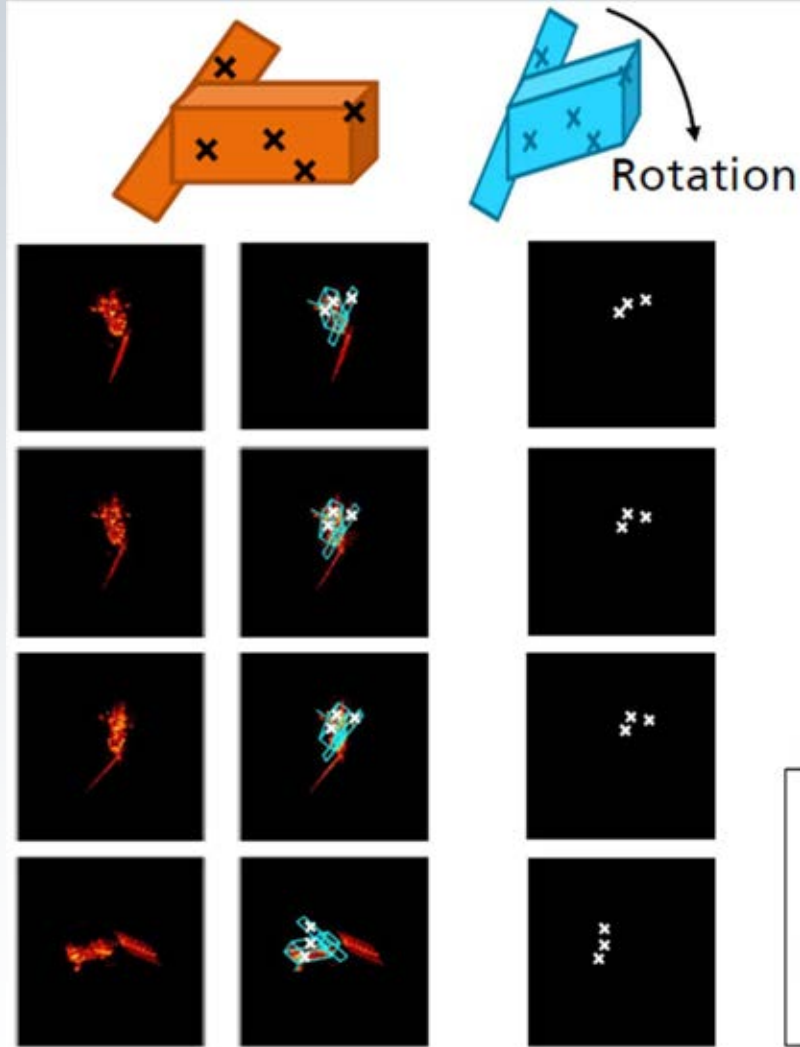




ISAR

- Characteristics and limitations of ISAR imaging
 - Challenge of ISAR is the estimation of the unknown object motion from the radar data
 - Imaging plane results from the relative rotational motion of the object
 - image formation and attitude determination are interlinked
 - Possibility is to match a wire grid model in the ISAR image to estimate the cross-range scaling and the effective rotation vector
 - Cross-check with other techniques highly desirable

ISAR



Curtesy Fraunhofer FHR



Slide 10



Optical Passive

- Different types of Light Curve acquisition Techniques
- Direct Imaging
- Attitude determination:
 - “Direct inversion” (simple shapes only)
 - “Forward modeling”



Light Curve Observation Techniques

- **Method A using CCD camera**
 - ephemeris tracking
 - subframe readout (<0.3 fps)
 - real-time centroiding and photometry
 - active tracking
 - photometric calibration requires full frames
- **Method B using sCMOS camera**
 - ephemeris tracking
 - full frame readout at 5–100fps
 - off-line centroiding and photometry
- **Method C – “streak” photometry**
 - full frames acquired with sidereal tracking
 - reference stars in the frame used for photometric calibration



Observation Techniques

Sensor: ZIMLAT

Tracking: Object, method A,B

FoV: $\sim 0.44 \times 0.44^\circ$

Target: SWISSCUBE (2009-051B)



Sensor: ZimSMART

Tracking: Sidereal, method C

FoV: $\sim 4.1 \times 4.1^\circ$

Target: SL-16 R/B (2000-006B)



COSMOS 1988 (GLONASS)

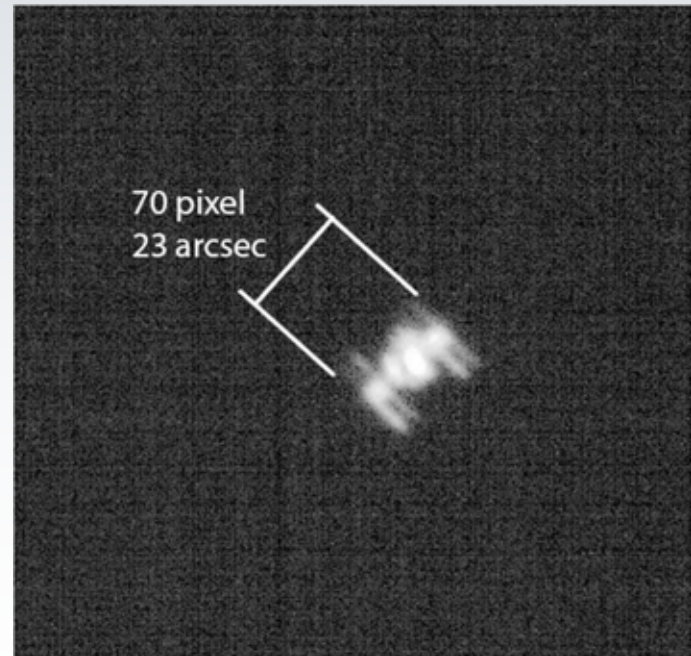
343 pixels

Method C "streak"



Direct Imaging

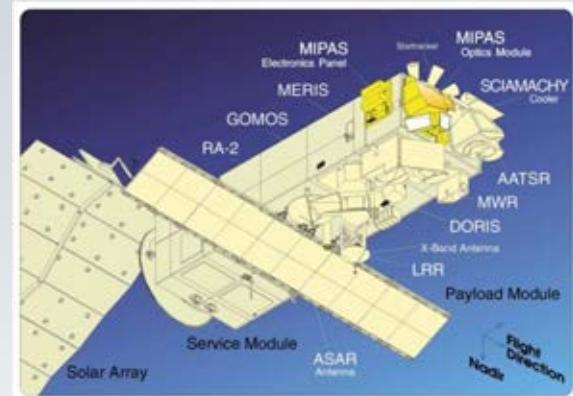
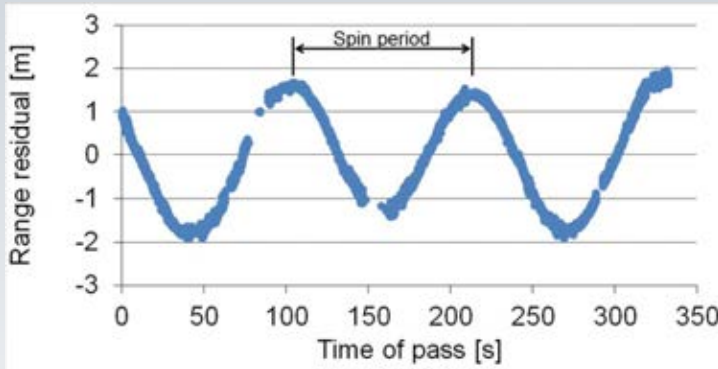
- “Lucky Imaging”
 - High rate imaging (<10 ms exposure)
 - Small aperture telescope (0.3–0.4m)
 - “freeze seeing”
 - Limited to bright targets



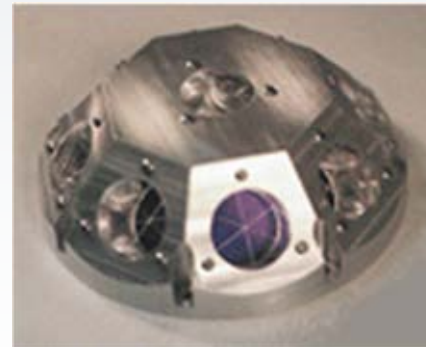
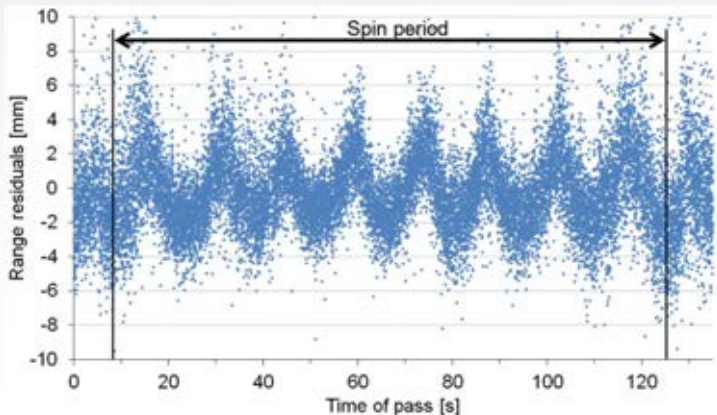


Satellite Laser Ranging

Analysis of meter-scale range oscillation due to offset between retro and spin axis of body. Method is valid for long passes only.



Analysis of the millimeter scale oscillations of the SLR range residuals; only for kHz SLR data



Curtesy IWF/ÖAW
GRAZ





AIUB Light Curve Observations

- ZIMLAT

- 1-m ZIMLAT
- 2kx2k thinned CCD
- high speed CMOS camera (up to 100fps)
- FoV~0.44°x0.44°

- Shared telescope time

- quasi simultaneous SLR observations
- semi automated observations



1-m ZIMLAT
Switzerland



AIUB Observations of LEO Upper Stages

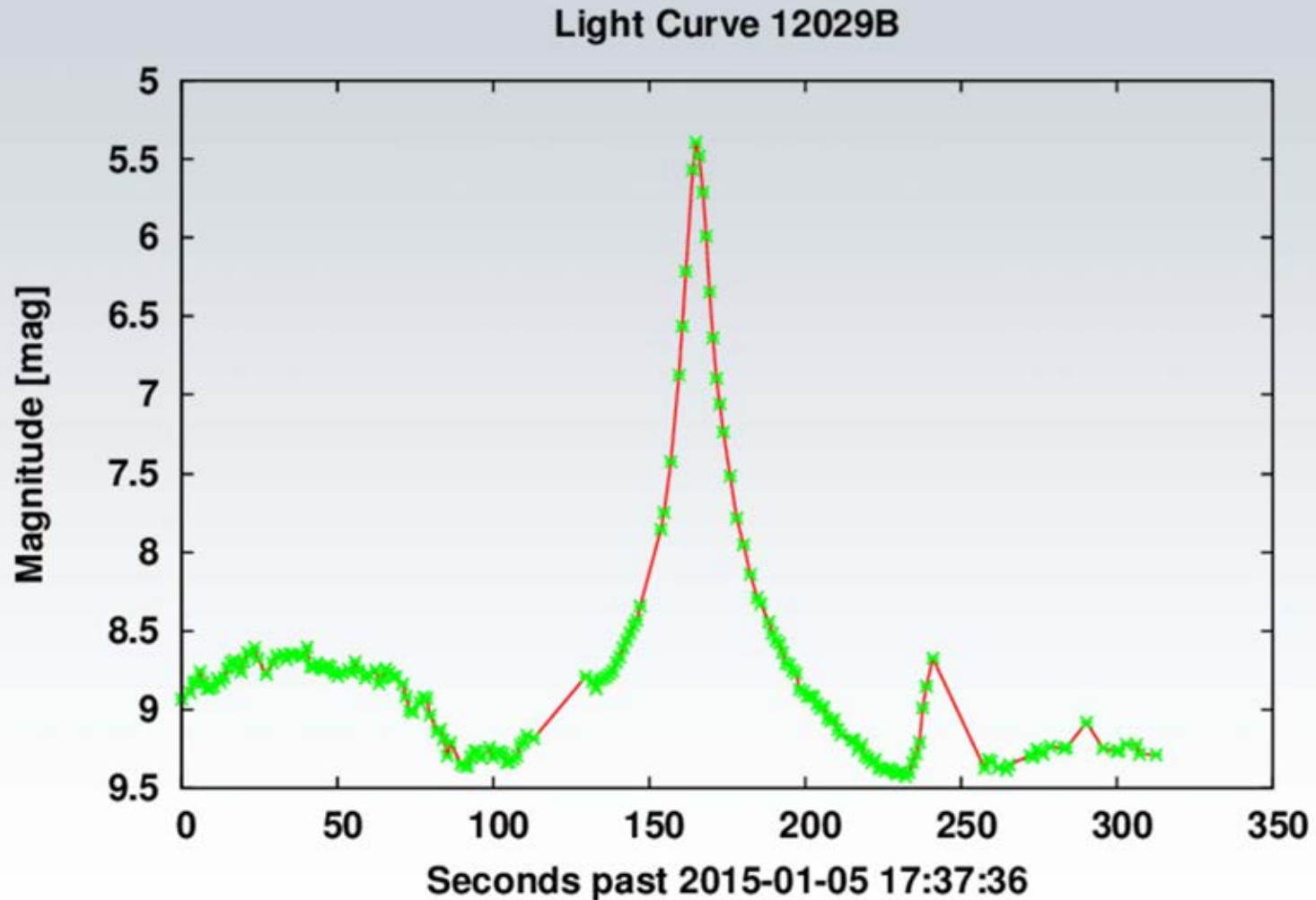
- **Objective**
determination of spin rate (potential ADR targets)
- **> 120 objects observed**
- **Taxonomy (objects)**
 - structure 58%
 - period lower limit estimated 36%
 - Period 3%

Period can only be determined if period < length of pass

**For period > length of pass (typ. few minutes):
Phase function unknown → cannot be reduced; phase
(viewing geometry) effects may mimic attitude motion**

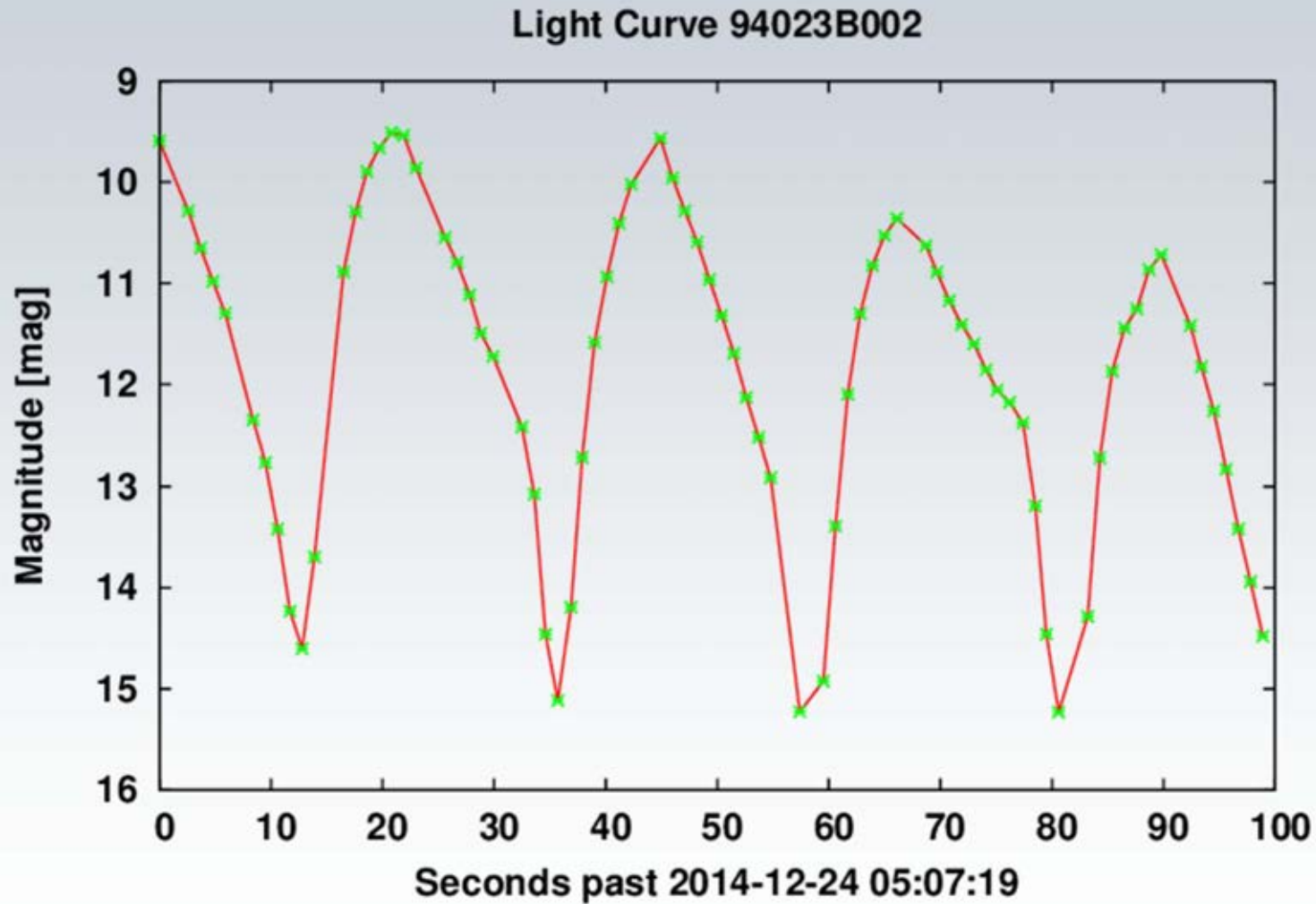


Exemplary Light Curves “structured”





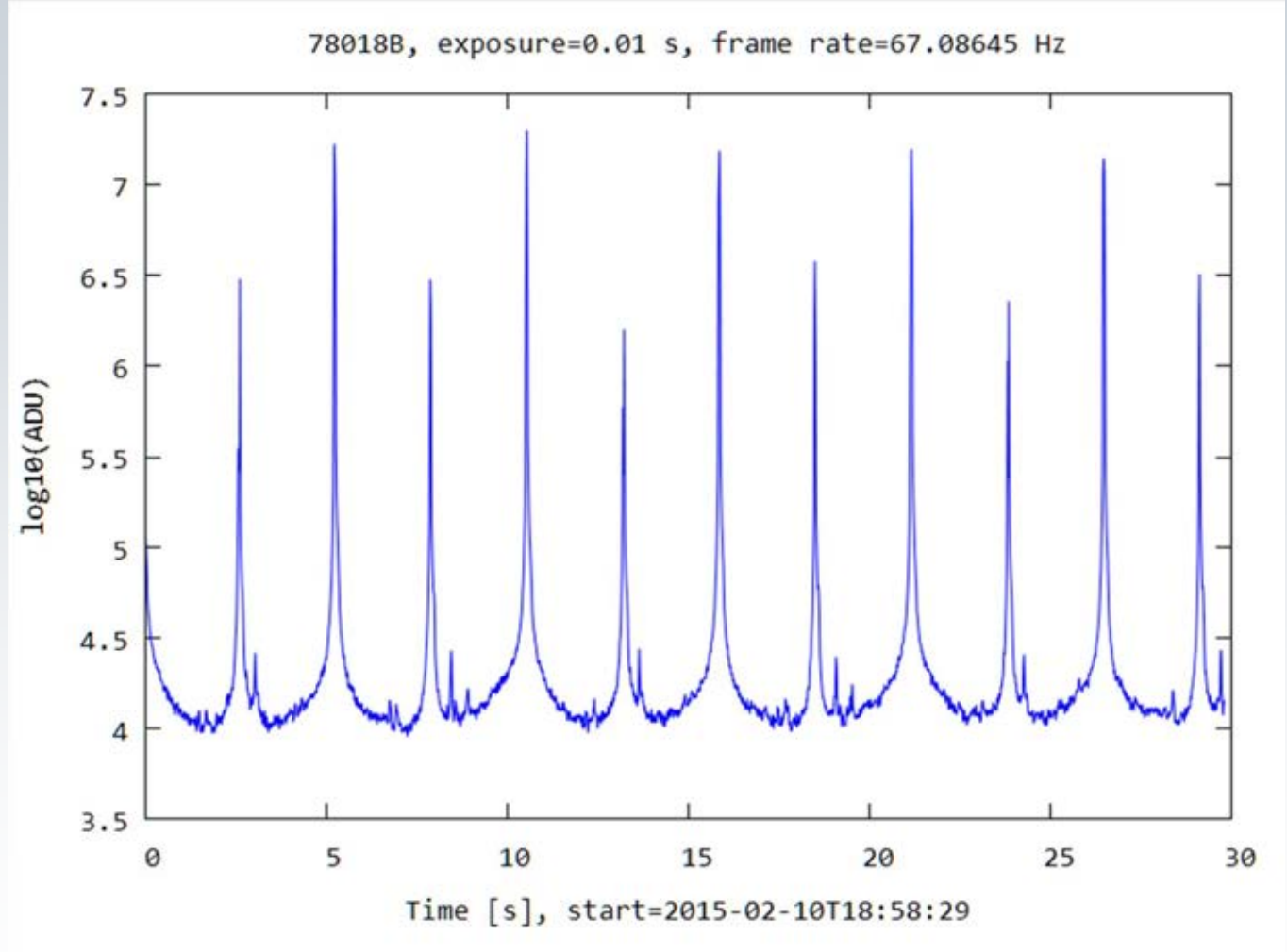
Exemplary Light Curves “periodic”





Light Curves “periodic” – High Resolution

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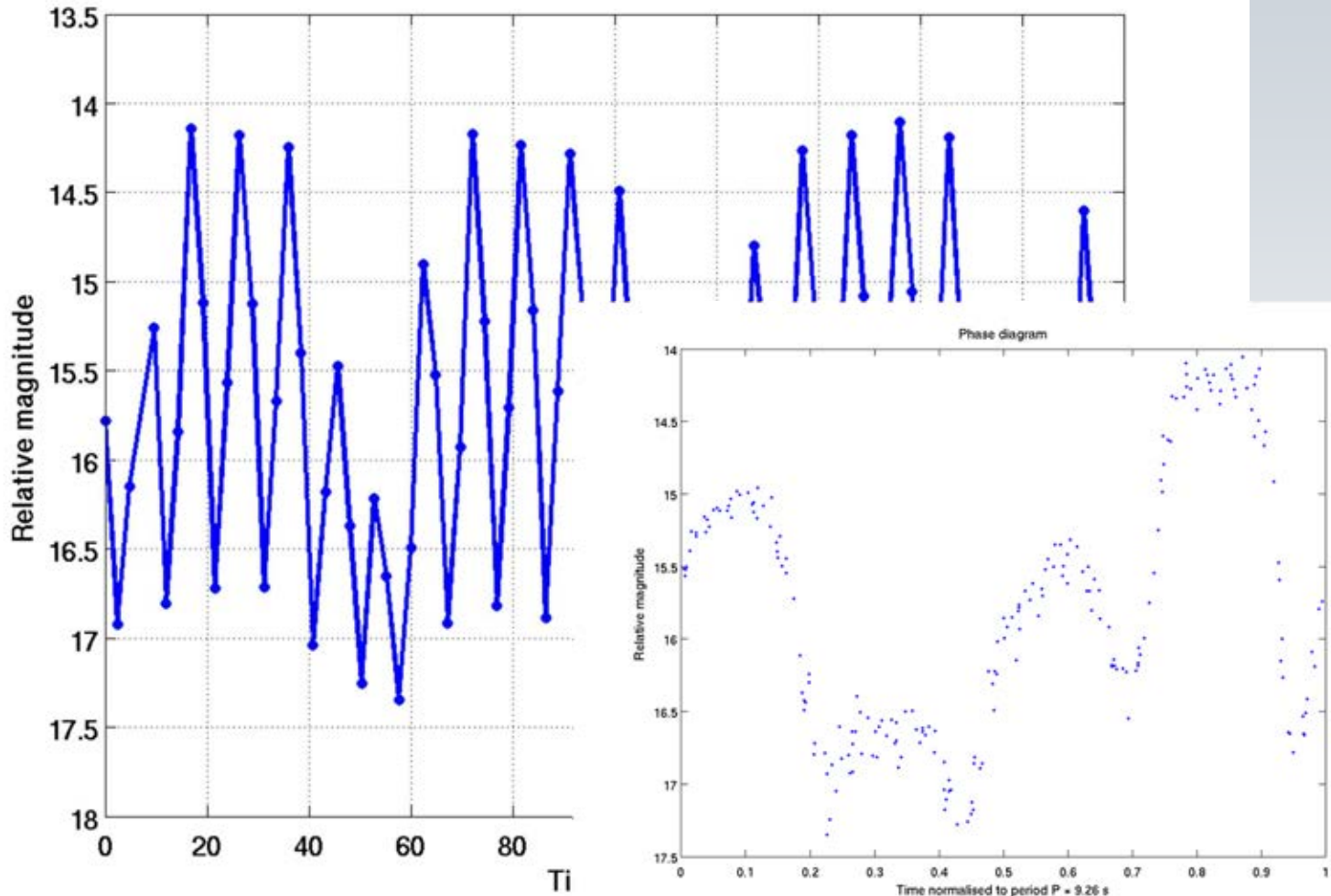


High resolution light curve of N-1 R/B (1978-018B), LEO orbit.



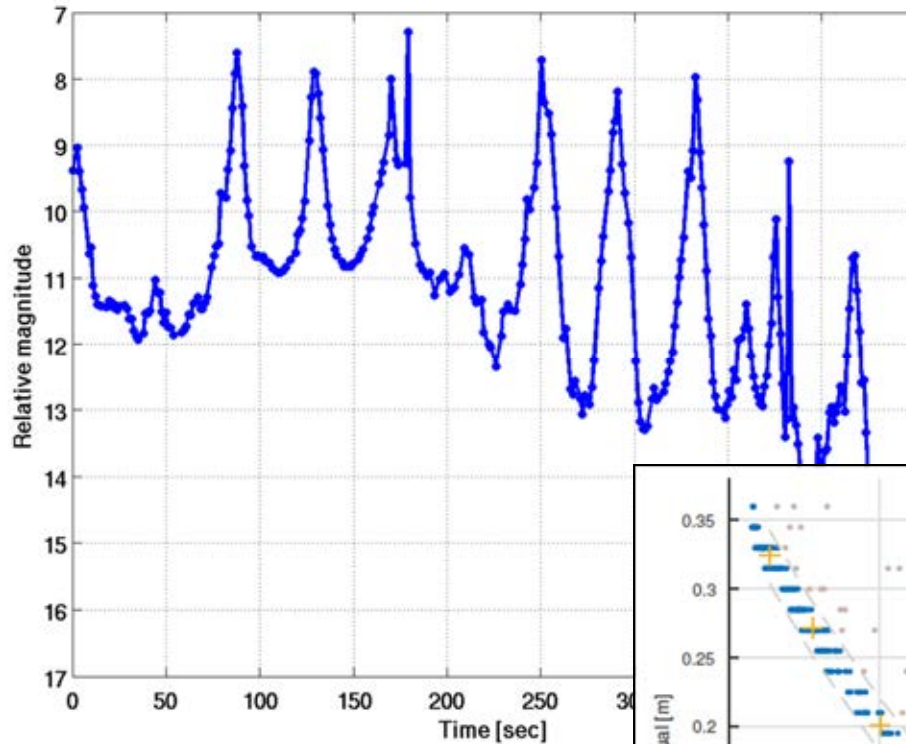
COSMOS 1988 (GLONASS)

aliasing





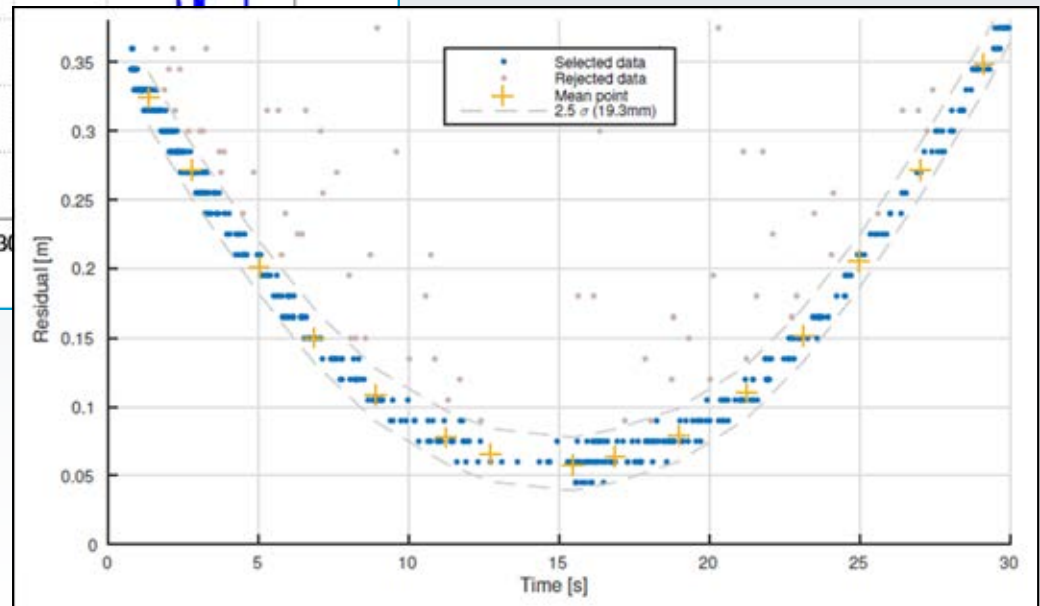
Envisat Photometry & SLR



Optical Light Curve
 $P=123s$

apparent period
changing within
light curve
(changing
geoemetry)!

SLR Residuals

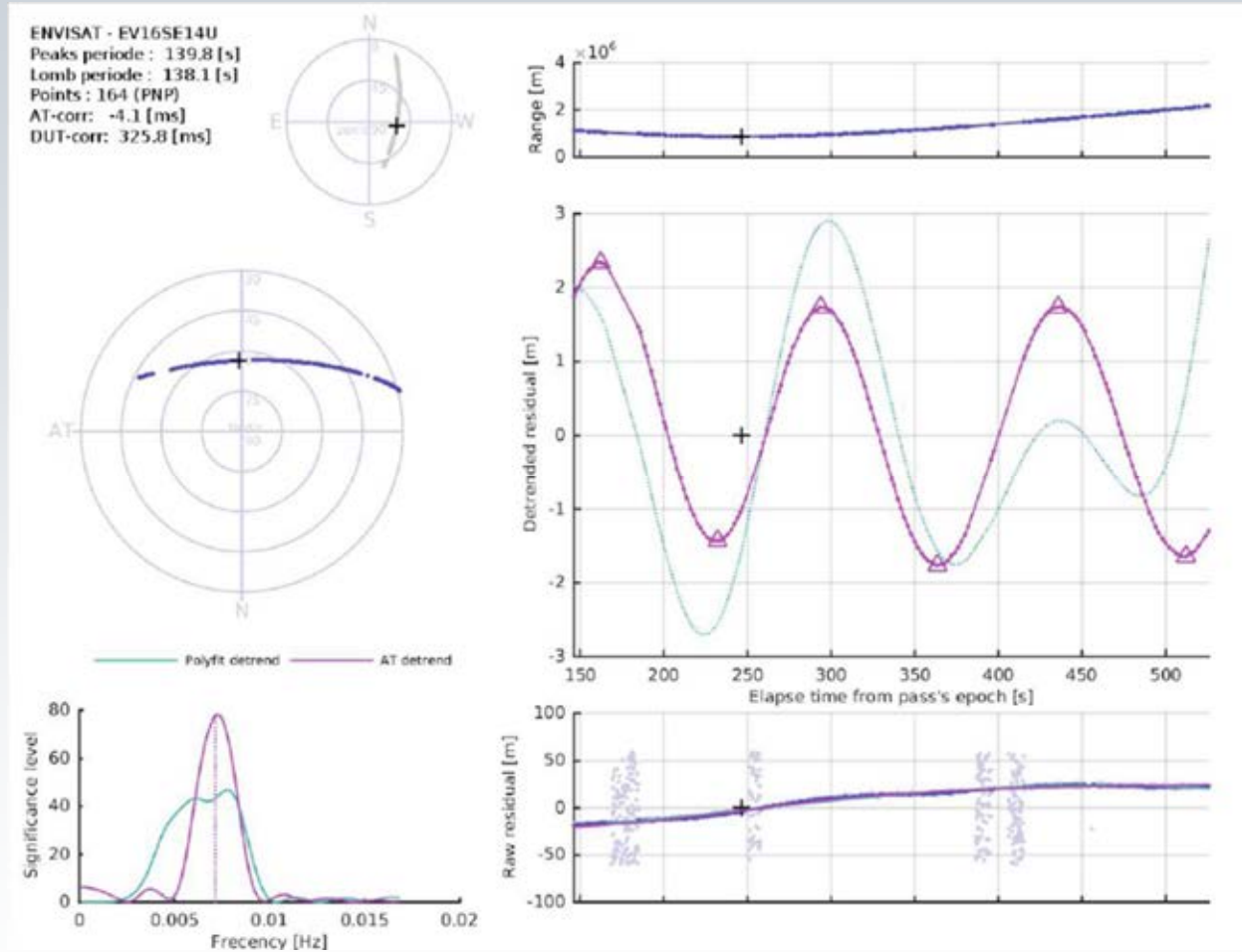




Envisat: Detrending SLR Residuals

Detrending

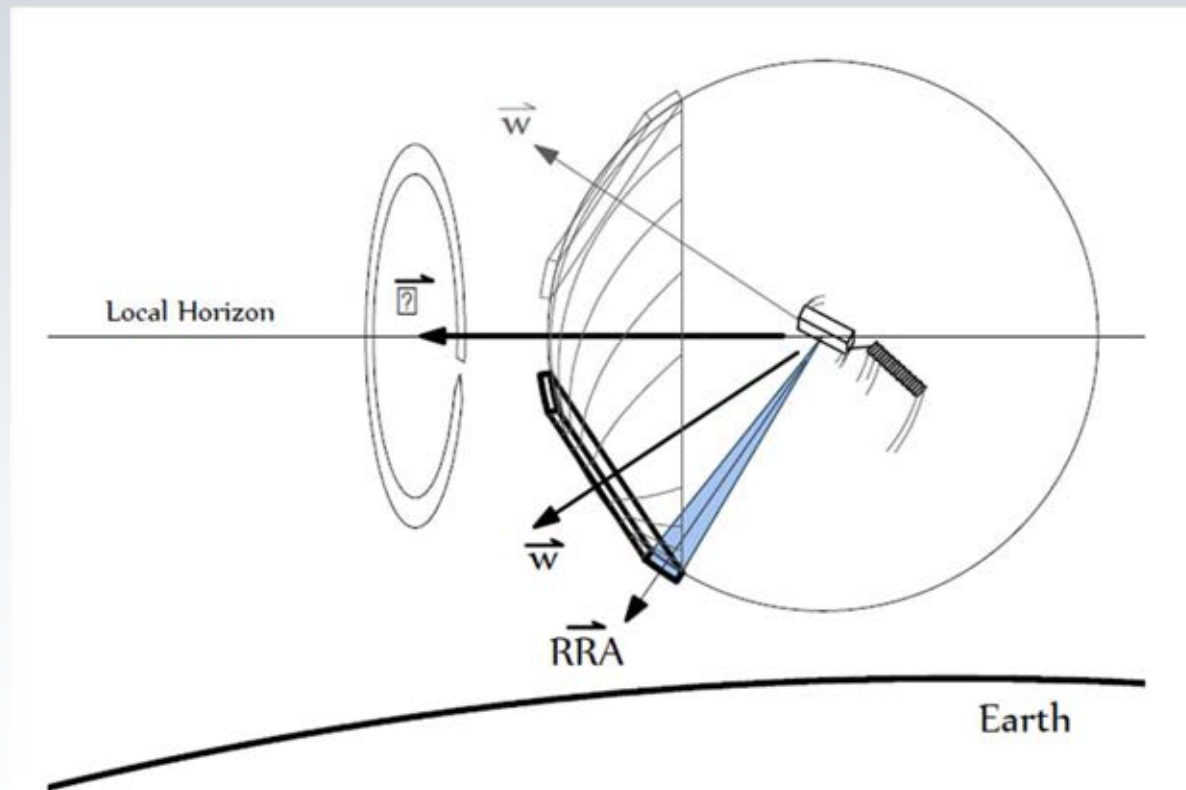
- Estimate along-track error (physical model)
- removes trend
- Period estimation
- Less susceptible to missing data than polynomial fits!





Envisat: SLR Spin and Visibility Model

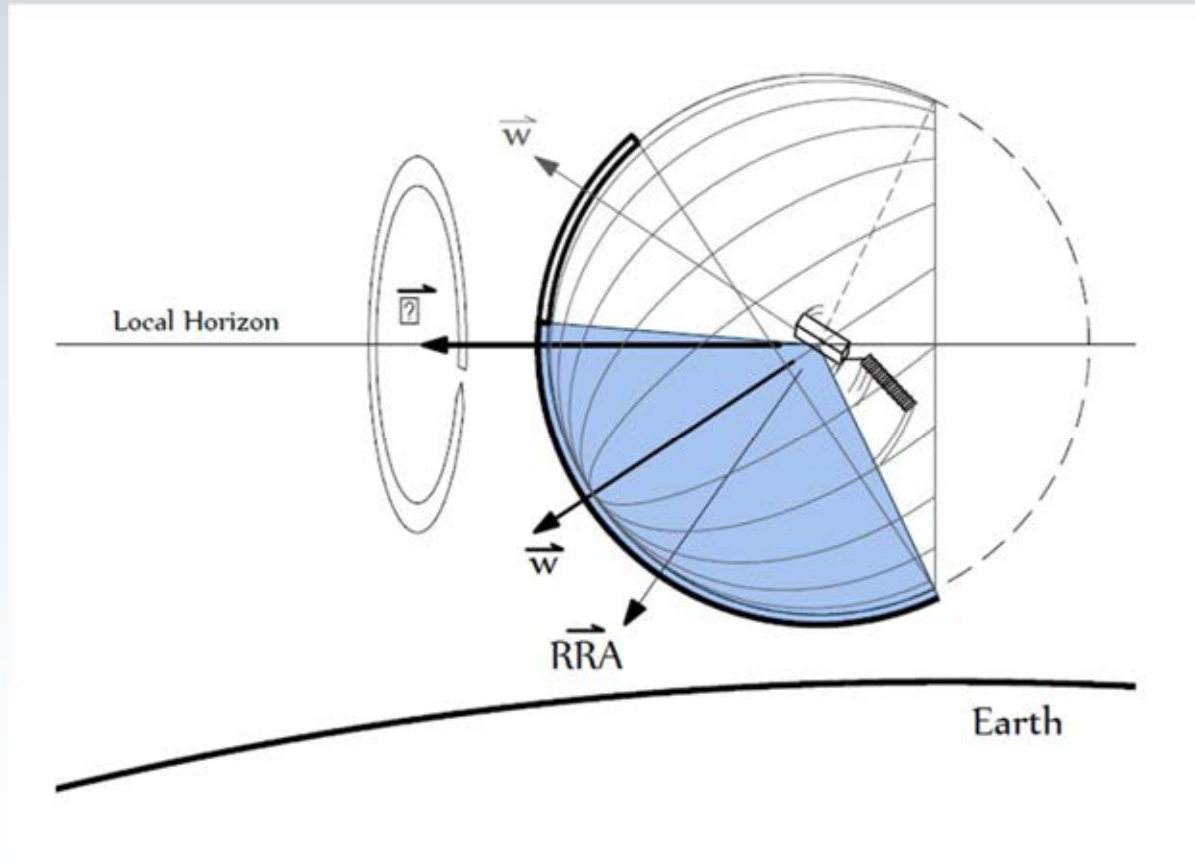
- New approach, free of assumptions on spin axis orientation (e.g. fixed in RSW system)





Envisat: SLR Spin and Visibility Model

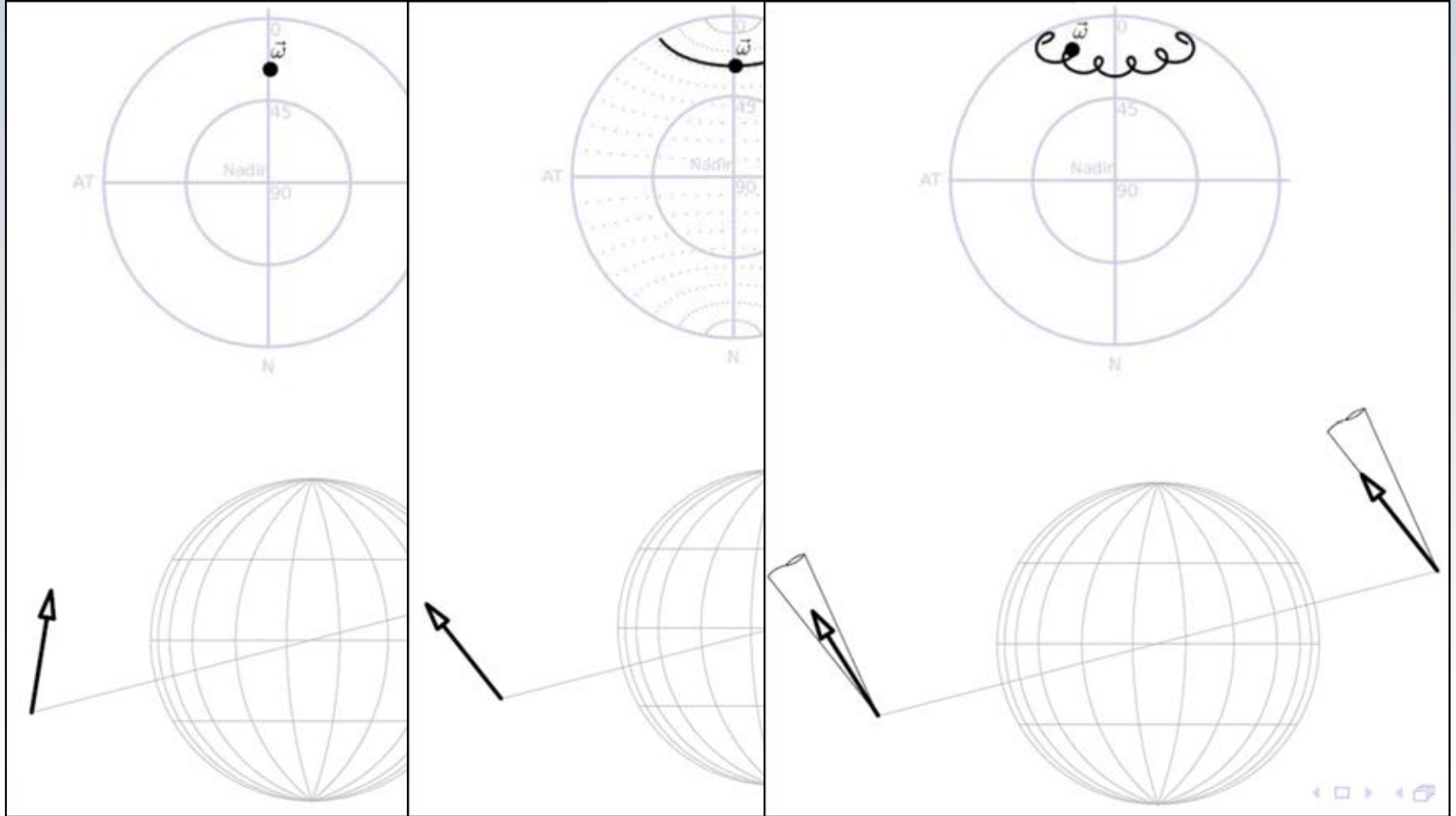
- New approach, free of assumptions on spin axis orientation (e.g. fixed in RSW system)





Envisat: SLR Spin and Visibility Model

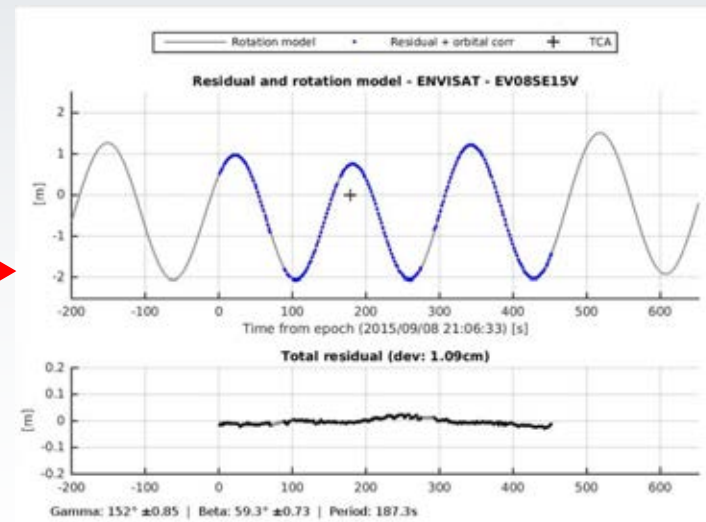
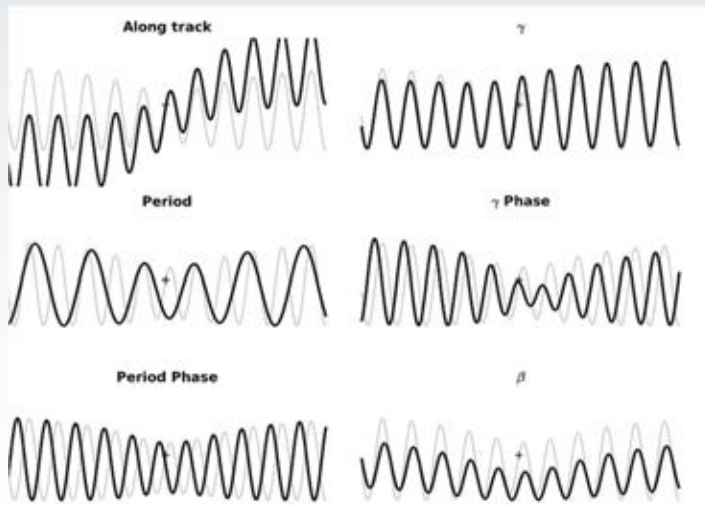
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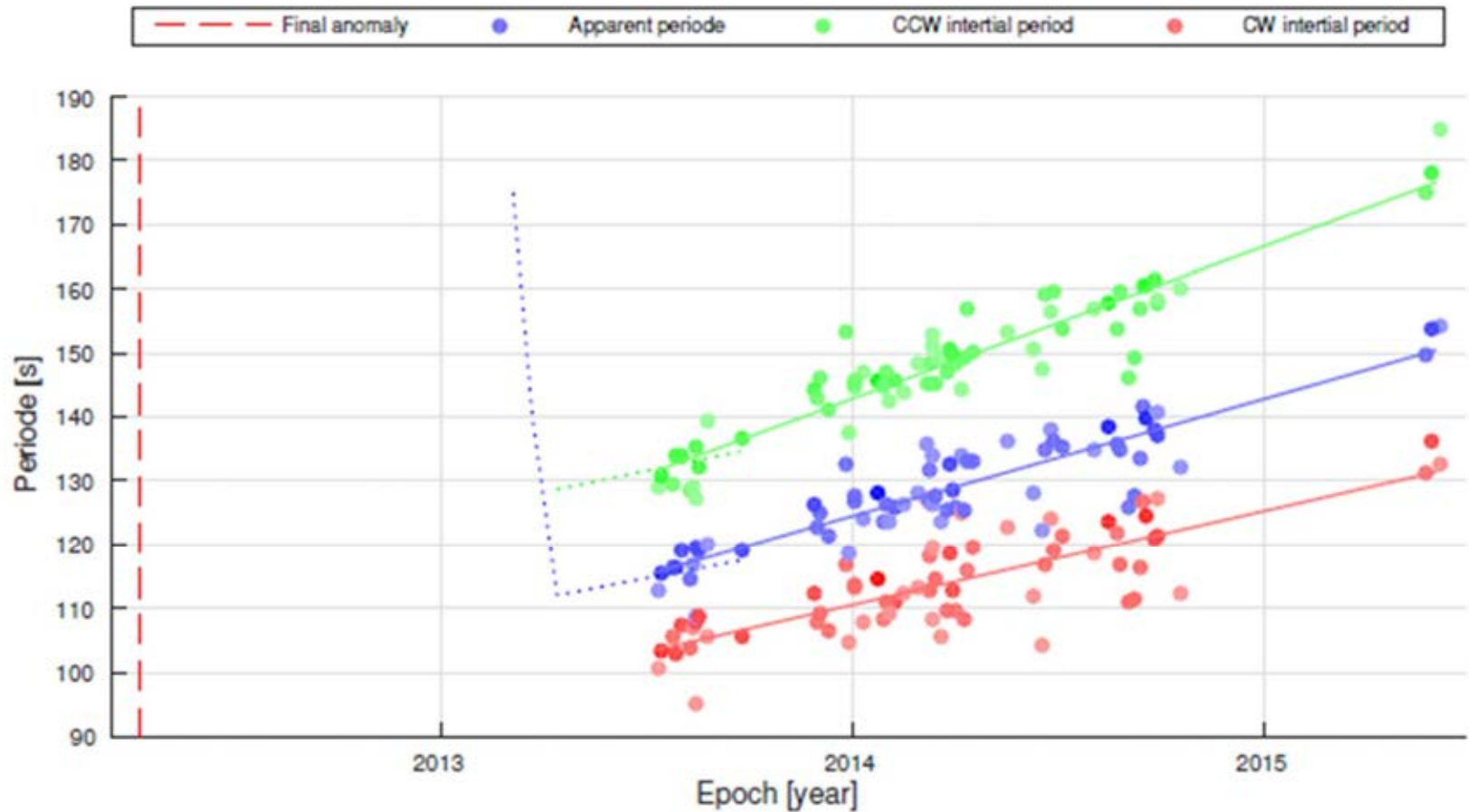
Envisat: Attitude State (Modeling)

- AIUB attitude description
 - Method based on fitting synthetic measurements with the real measurements
 - Attitude defined for given time by 6 main parameters
 - spin axis in the orbital reference frame
 - spin axis in the satellite fixed reference frame
 - Inertial spin period [s] and phase [deg]



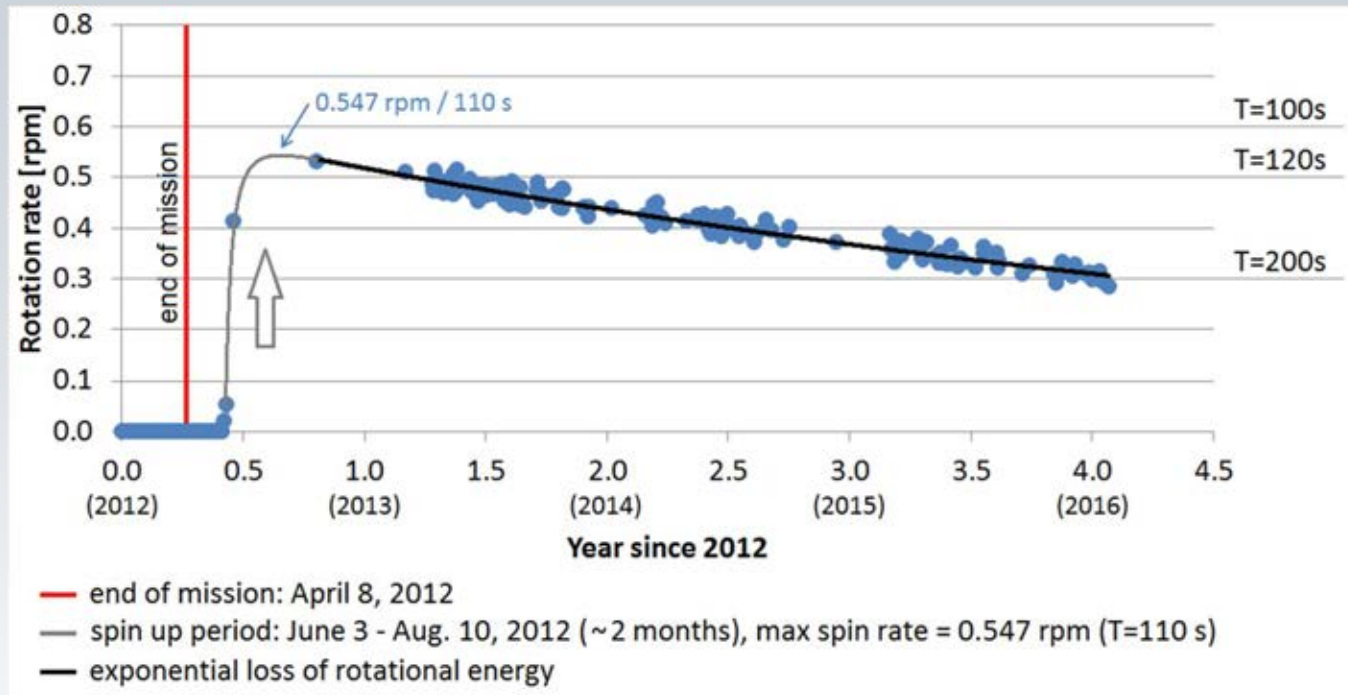


AIUB Envisat Period Evolution





ENVISAT: Inertial spin, measured by SLR



Curtesy
IWF/ÖAW GRAZ



- Only 4 SLR passes (Graz and San Fernando on) measured around the spin up period are good enough for the spin analysis :
- The mm-precision SLR passes measured by Graz from March 3, 2013 until January 26, 2016 give 151 accurate spin period estimations from the analysis of the mm-scale range residual oscillations.



Data Fusion Examples and Modelling

- Target data acquired for two purposes:
 - Attitude state monitoring, e.g. through collaborative measurements
 - Attitude and observations modeling by iOTA
- Currently five different sources of data:
 - AIUB light curves
 - AIUB SLR ranges
 - AIUB specular reflection
 - IWF SLR ranges
 - IWF single photon light curves



Target List – Stable Objects

- The light curves of these targets show no signals except for the phase and aspect angle changes

Object ID	Name	NORAD		Orbit	STATUS LC	DATE	STATUS SLR	DATE
1990-005H	ARIANE 40 R/B	20443	1 (60d)	LEO	Stable	20151104		
1991-050F	ARIANE 40 R/B	21610	1 (60d)	LEO	Stable	20150920		
1993-061H	ARIANE 40 R/B	22830	1 (60d)	LEO	Stable	20150924		
1995-021B	ARIANE 40+ R/B	23561	1 (60d)	LEO	Stable	20150820		
1995-033D	ARIANE 40+3 R/B	23608	1 (60d)	LEO	Stable	20150603		
1998-017B	ARIANE 40 R/B	25261	1 (60d)	LEO	Stable	20150711		
2002-009B	ARIANE 5 R/B	27387	1 (60d)	LEO	Stable	20150711		
2004-049H	ARIANE 5 R/B	28499	1 (60d)	LEO	Stable	20150611		
2013-021D	AVUM DEB (ADAPT)	39162	1 (60d)	LEO	Stable	20150604		
1986-019Y	ARIANE 1 DEB	17129	1 (60d)	LEO	Stable	20150708		



Stable Objects – Example

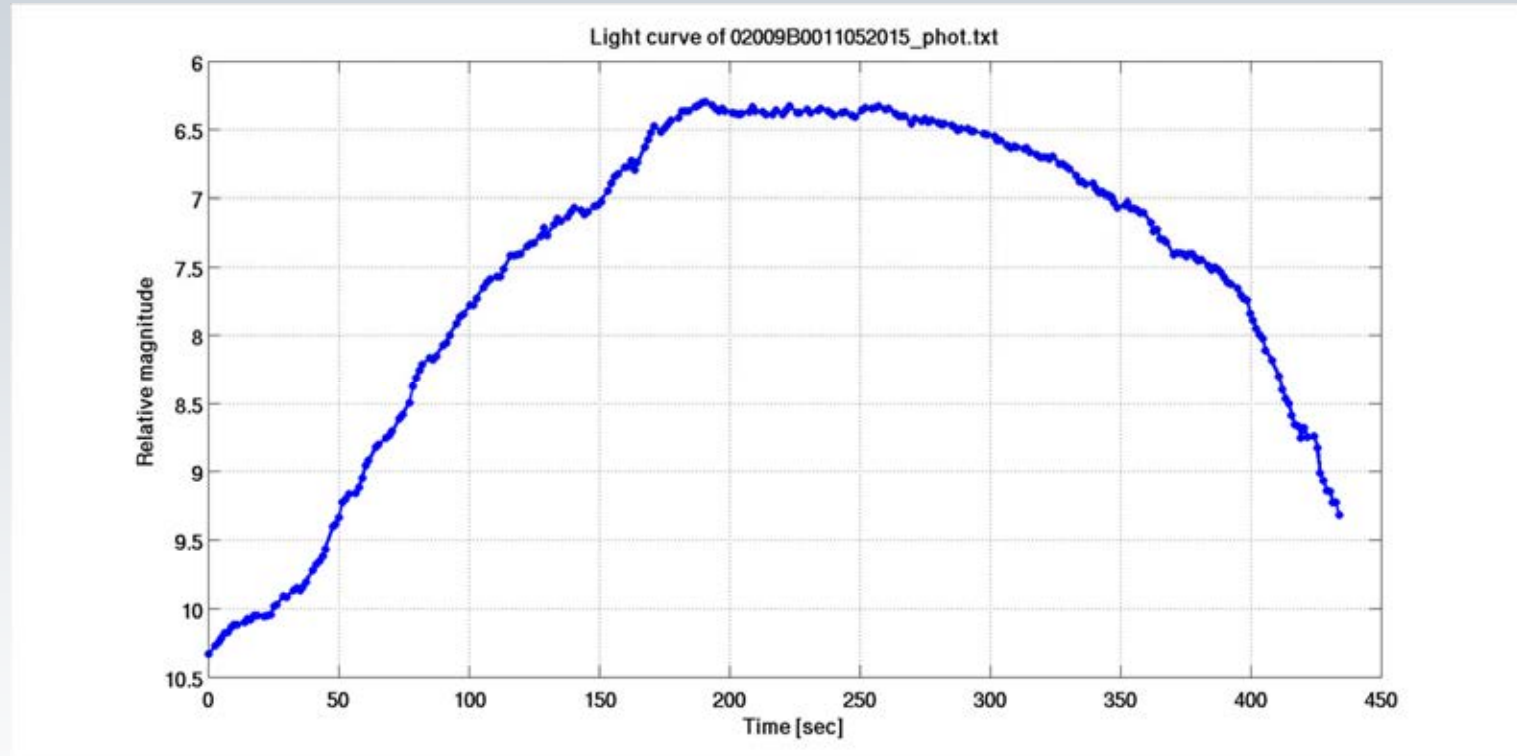


Figure – Ariane 5 R/B light curve acquired by Zimmerwald observatory in June 2015.



Target List – Slow Tumblers

- The light curves of these targets show signals, but the time series are too short to extract the apparent period

Object ID	Name	NORAD		Orbit	STATUS LC	DATE	STATUS SLR	DATE
1986-019C	ARIANE 1 R/B	16615	1 (60d)	LEO	>178 s	20150820		
1988-018C	ARIANE 3 R/B	18953	1 (30d)	GTO	>1200 s	20151206		
1991-050A	ERS 1	21574	2	LEO	>229.0 s	20150920		
1992-052D	ARIANE 42P R/B	22079	1 (60d)	LEO	>457 s	20150711		
1996-046A	ADEOS	24277	1 (30d)	LEO	>210 s	20150604		
1997-051E	IRIDIUM 28	24948	1 (30d)	LEO	>447 s	20150820		
1999-064C	ARIANE 40 R/B	25979	1 (60d)	LEO	>293 s	20151228		
2001-055A	JASON	26997	1 (60d)	LEO	>448? S	20150527		
2005-031A	OICETS	28809	2	LEO	>179.5 s	20150921		
2005-051A	GIOVE-A	28922	1 (30d)	GNSS	>499.9 s	20151228		
2006-002A	ALOS	28931	1 (30d)	LEO	>337.6 s	20150828		



Slow Tumblers – Example

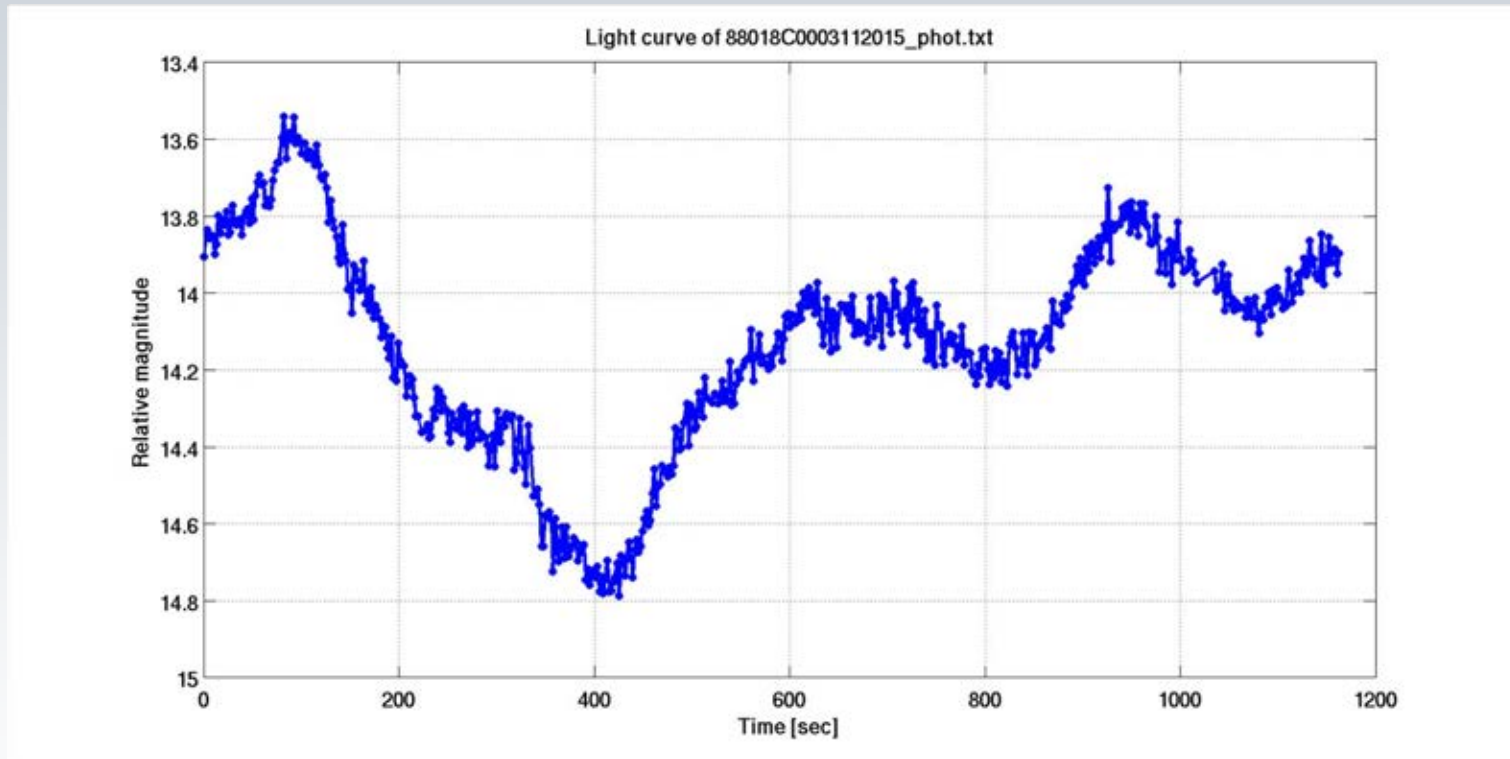


Figure – Ariane 3 R/B light curve acquired by Zimmerwald observatory in June 2015.



Target List – Fast Tumblers

- For these targets the apparent period extracted and the phase was reconstructed from the light curves

Object ID	Name	NORAD		Orbit	STATUS LC	DATE	STATUS SLR	DATE
1991-084C	ARIANE 44L R/B	21815	1 (30d)	GTO	207.4 s	20151223		
1992-052A	TOPEX/POSEIDON	22076	1 (15d)	LEO	11.215 s	20151202		
1995-021A	ERS 2	23560	2	LEO	>168.5 s	20150713		
2000-016C	ARIANE 5 DEB (SYLDA)	26109	1 (30d)	GTO	89.6 s	20151206		
2000-016D	ARIANE 5 R/B	26110	1 (30d)	GTO	23.2 s (*2)	20151218		
2001-038B	H-2A R/B	26899	1 (15d)	GTO	44.65 s	20151214		
2002-009A	ENVISAT	27386	2	LEO	164.5 s	20150611		
2002-056A	ADEOS 2	27597	1 (30d)	LEO	77.8 s	20151224		
2008-020A	GIOVE-B	32781	1 (30d)	GNSS	~202 s	20151012		
2009-017B	ATLAS 5 CENTAUR R/B	34714	0	GTO	56.7 s	20151224		
2009-067B	BLOCK DM-SL R/B	36107	4	GTO	32.2 s	20151222		

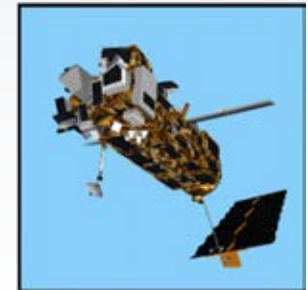
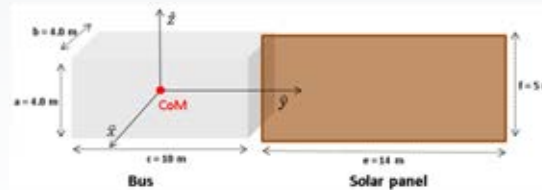
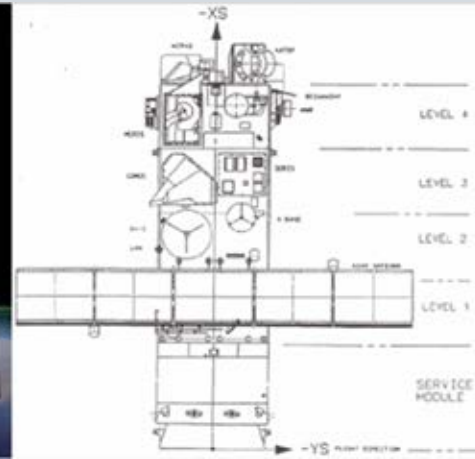


Fast Tumblers - ENVISAT, 2002-009A, no.27386

- ESA mission, “lost” since April 2012
- LEO orbit, $i = 98.4\text{deg}$, $h \sim 766\text{km}$

- **Data availability:**

- 1. Observation data - **YES**
 - light curves - **YES**
 - SLR - **YES**
 - Specular reflection - **YES**
 - Direct images - **NO** (AIUB), YES (Pleiades)
 - SAR - **NO**, archive YES
 - Monitoring - **YES**, light curves and SLR
- 2. Attitude model - **YES**
 - IWF from SLR
 - AIUB from SLR
- 3. Physical model - **YES:**
 - CoM - YES (ESA, ILRS)
 - MOI - YES (ESA, AIUB Mol 3D model)
 - 3D model - YES



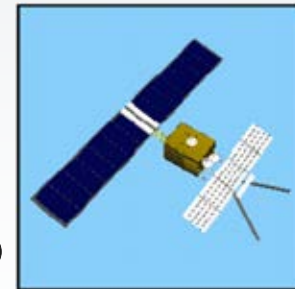
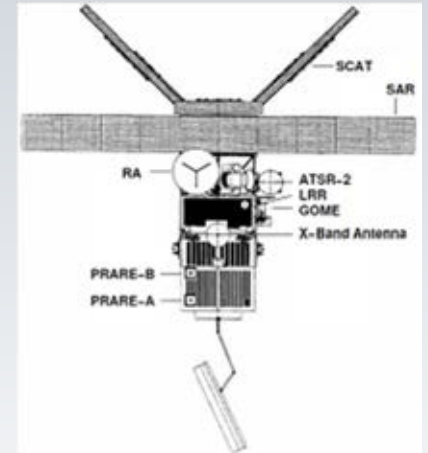


Fast Tumblers - ERS-2, 1995-021A, no.23560

- ESA mission, mission decommissioned in September 2010
- LEO orbit, $i = 98.6\text{deg}$, $h \sim 534\text{km}$

- Data availability:

- 1. Observation data - **YES**
 - light curves - **YES**
 - SLR - **YES**
 - Specular reflection - **NO**
 - Direct images - **NO**
 - SAR - **NO**
 - Monitoring - **YES**, light curves and SLR
- 2. Attitude model - **YES**
 - IWF from SLR
 - *AIUB from SLR (TBC)*
- 3. Physical model - **YES**:
 - CoM - **YES** (ILRS)
 - MOI - **YES** (ESA documentation, AIUB Mol can be constructed)
 - 3D model - **YES**





Fast Tumblers - ERS-2, 1995-021A, no.23560

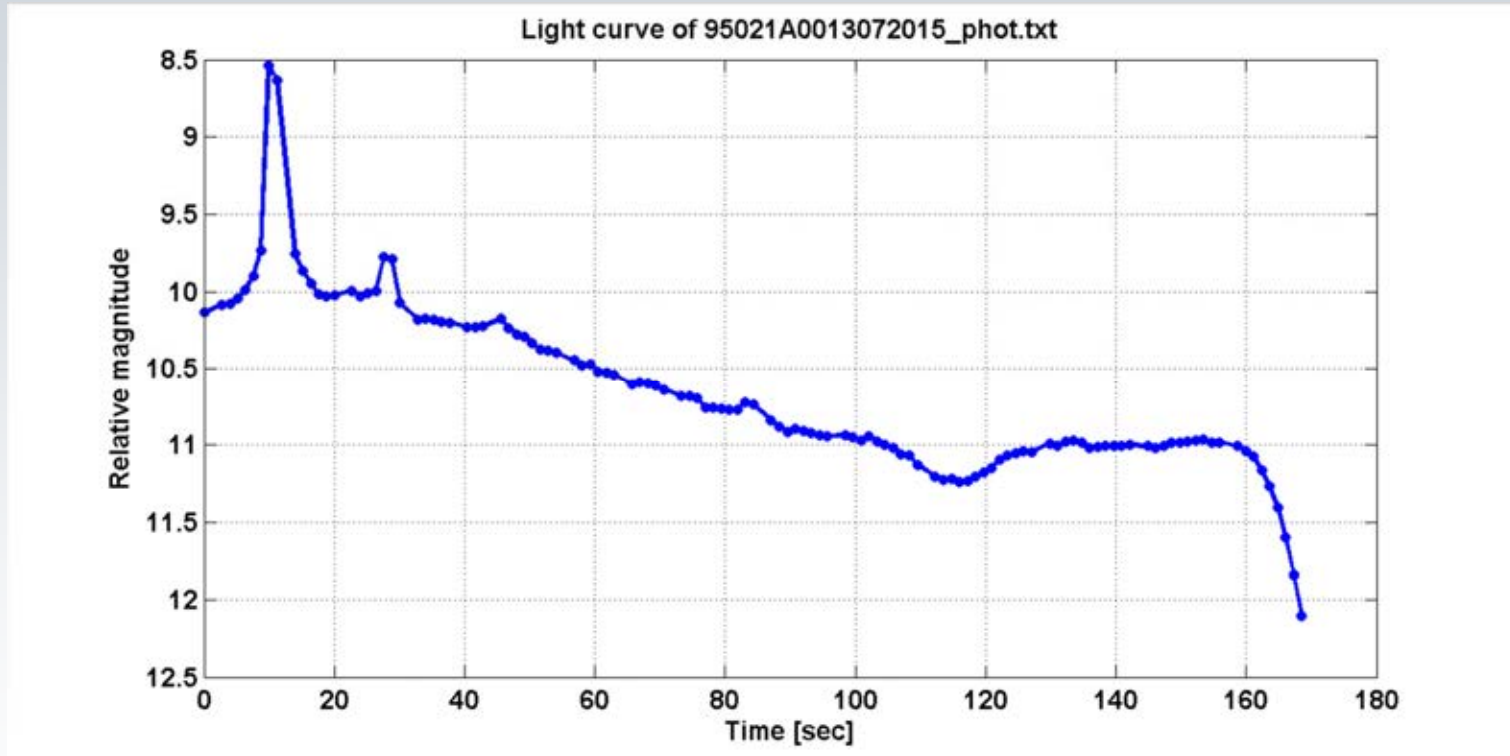


Figure - ERS-2 light curve acquired by Zimmerwald observatory in July 2015.

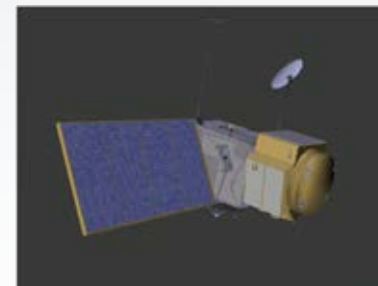
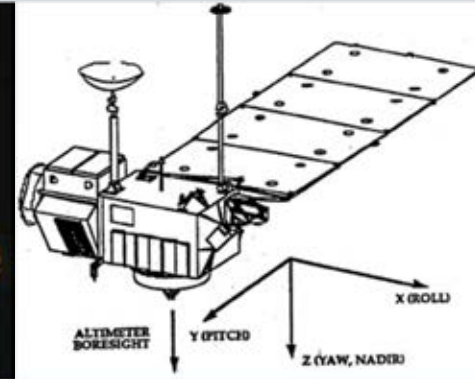


Fast Tumblers - TOPEX/Poseidon, 1992-052A, no.22076

- CNES/NASA mission, inactive since Jan 2006
- LEO orbit, $i = 66.0\text{deg}$, $h \sim 1,337\text{km}$

- **Data availability:**

- 1. Observation data - **YES**
 - light curves - **YES**
 - SLR - **YES**
 - Specular reflection - **YES**
 - Direct images - **NO**
 - SAR - **NO**
 - Monitoring - **YES**, light curves and SLR
- 2. Attitude model - **YES**
 - IWF from SLR
 - AIUB from SLR
- 3. Physical model - **YES**:
 - CoM - **YES** (ILRS)
 - MOI - **NO**, but AIUB Mol can be constructed
 - 3D model - **NO**, only from NASA LWO model





Fast Tumblers - TOPEX/Poseidon, 1992-052A, no.22076

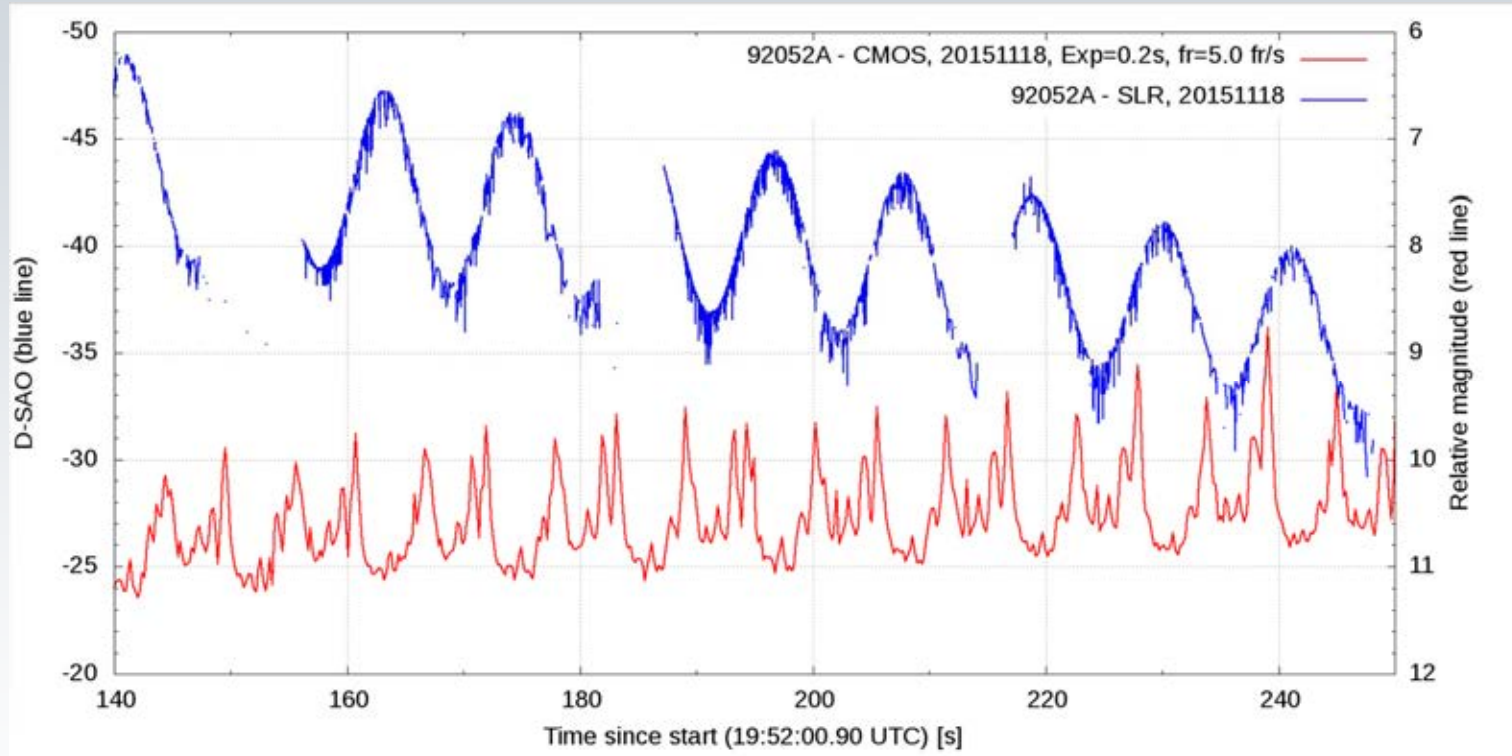


Figure - TOPEX/Poseidon light curve and SLR ranges simultaneously acquired by ZIMLAT November 2015.



Fast Tumblers - TOPEX/Poseidon, 1992-052A, no.22076

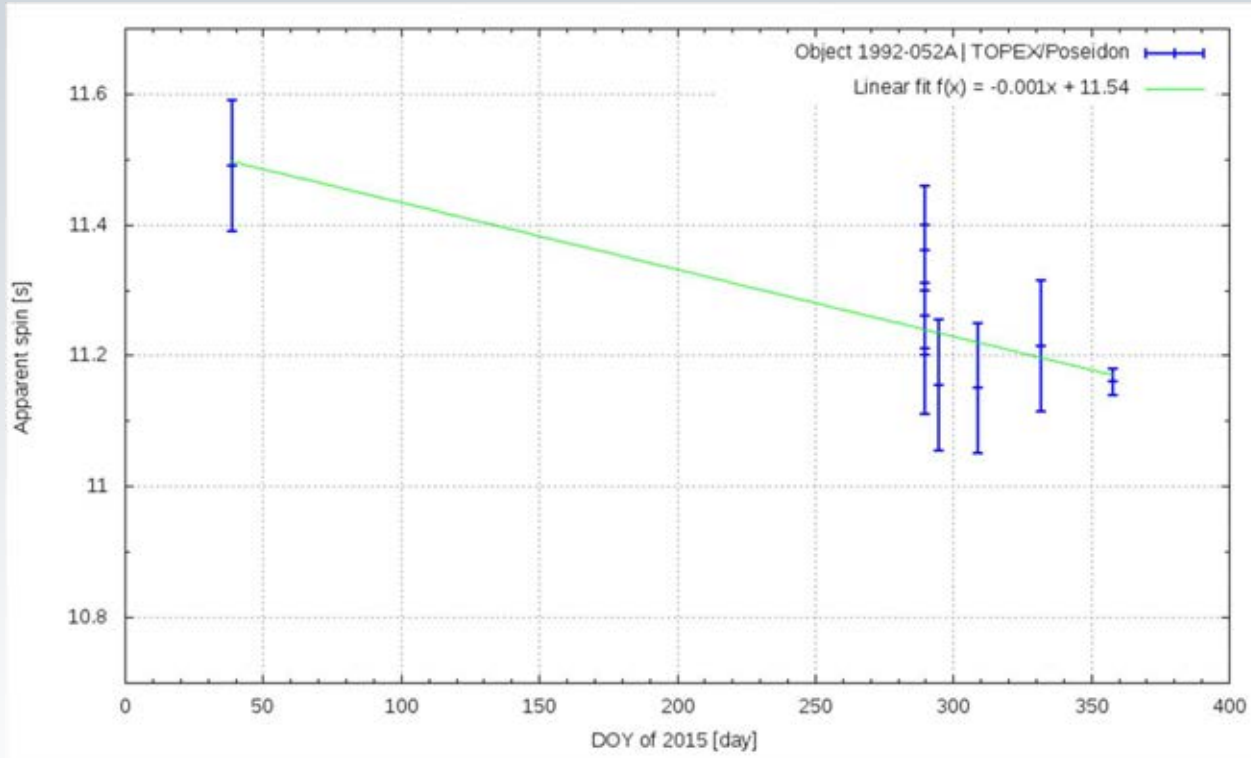


Figure - TOPEX/Poseidon apparent spin period evolution extracted from AIUB's light curves.

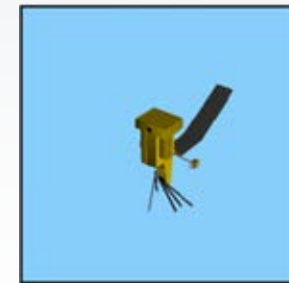
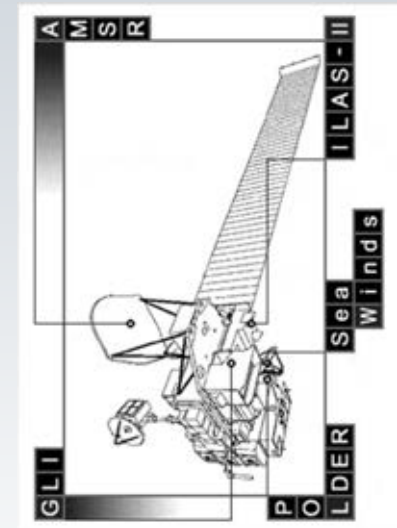


Fast Tumblers – ADEOS 2, 2002-056A, 27597

- JAXA/NASA/JPL mission, failure in Oct 2003
- LEO/SSO orbit, $i = 98.3\text{deg}$, $h \sim 802\text{km}$
- Object rapidly accelerated rotation in last 12 months
- $P \sim 77.8\text{s}$ (20151224)

● Data status:

- 1. Observation data – YES
 - light curves – YES
 - SLR – YES
 - Specular reflection – NO
 - Direct images – NO
 - SAR – NO
 - Monitoring – YES, light curves and SLR
- 2. Attitude model – YES
 - IWF from SLR
 - AIUB from SLR
- 3. Physical model – YES:
 - CoM – YES (ILRS)
 - MOI – NO, but AIUB Mol can be constructed
 - 3D model – YES





Fast Tumblers – ADEOS 2, 2002-056A, 27597

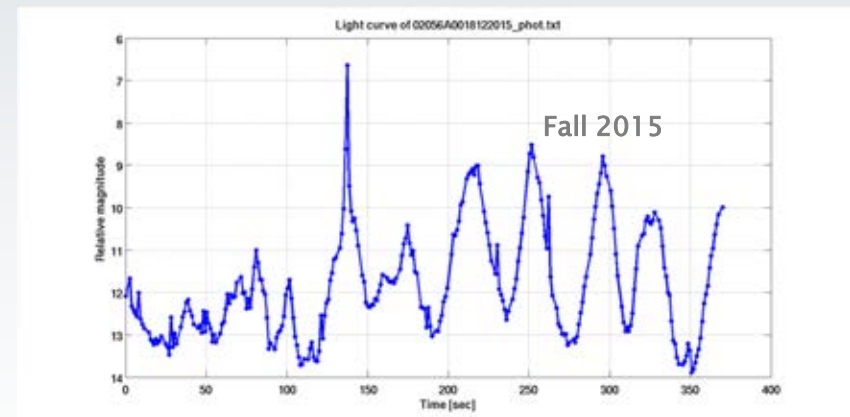
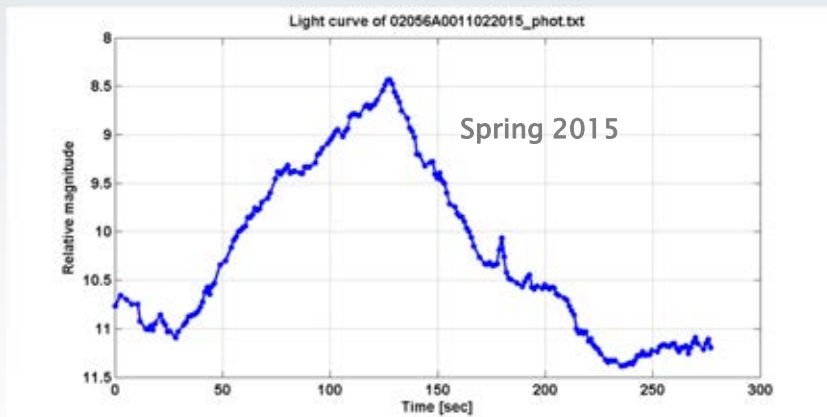
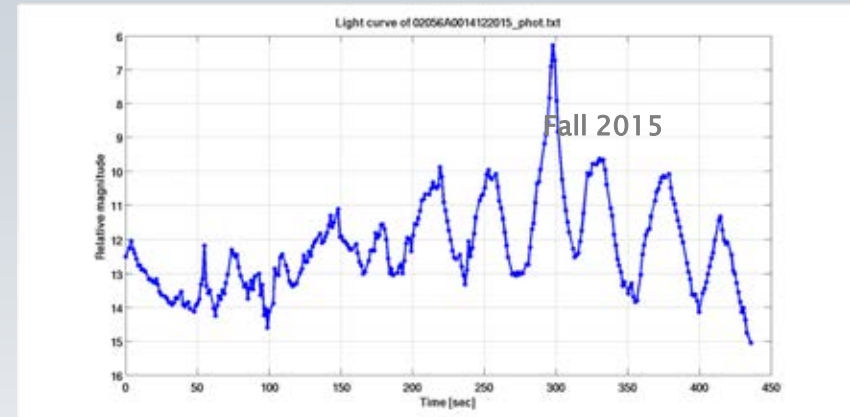
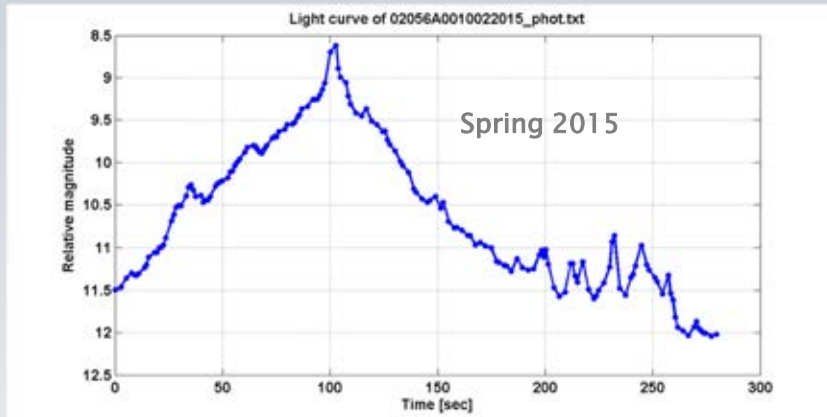


Figure – ADEOS 2 light curves acquired by ZIMLAT during slow tumbling period (left panels) and fast tumbling period (right panels).



Fast Tumblers - Giove-B, 2008-020A, 32781

- ESA mission, decommissioned in July 2012
- GNSS orbit, $i = 57.1$ deg, $h \sim 23,820$ km
- Object light curve complex, currently no acceleration observed
- $P \sim 203$ s (20151009)
- Data status:
 - 1. Observation data - **YES**
 - light curves - **YES**
 - SLR - **NO**
 - Specular reflection - **NO**
 - Direct images - **NO** (AIUB)
 - SAR/RCS - **NO**, YES in the past
 - Monitoring - **YES**, light curves
 - 2. Attitude model - **NO**
 - TBD AIUB diffuse reflection
 - 3. Physical model - **NO**:
 - CoM - **NO**
 - MOI - **NO**
 - 3D model - **NO**



Courtesy: ESA



Fast Tumblers - Giove-B, 2008-020A, 32781

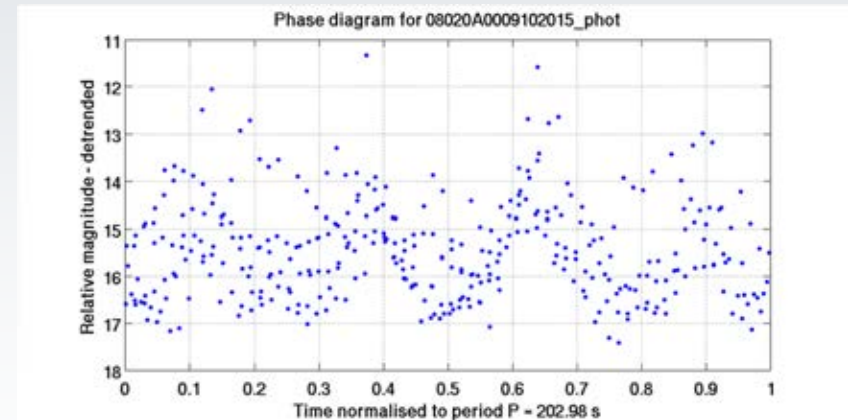
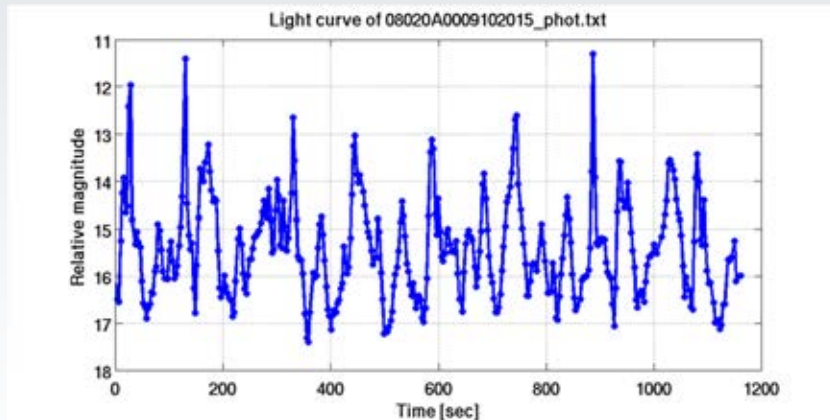
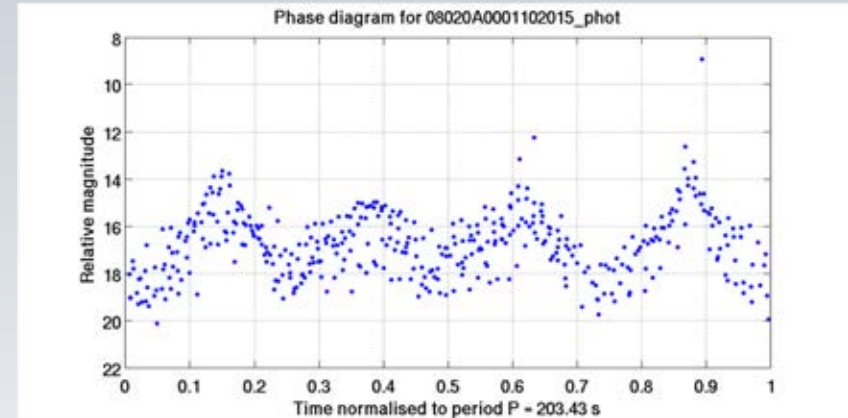
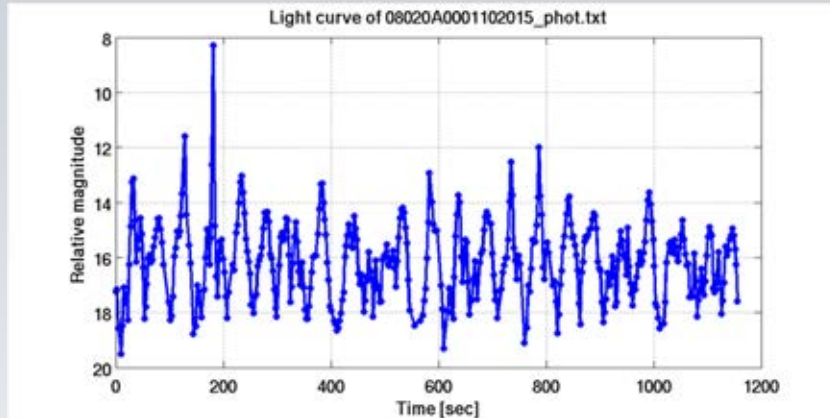


Figure - Giove-B light curves (left panels) acquired by ZIMLAT in October and November 2015 and their reconstructed phases (right panels).



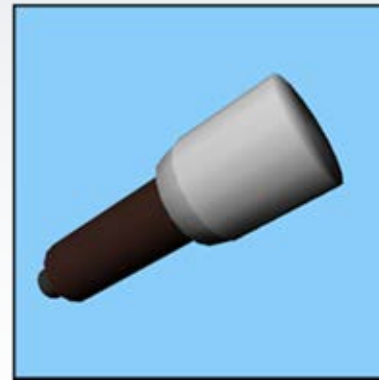
Fast Tumblers - ARIANE 44L R/B, 1991-084C, 21815

- ESA upper stage of Ariane 44L H10 launcher, launched in Dec 1991
- GTO orbit, $i = 3.9\text{deg}$, $h_a \sim 35120\text{km}$, $h_p \sim 383\text{km}$
- Object light curve sinusoidal shape, currently no acceleration observed
- $P \sim 207.4\text{s}$ (20151223)

- **Data status:**

- **1. Observation data - YES**
 - light curves - YES
 - SLR - NO
 - Specular reflection - NO
 - Direct images - NO (AIUB)
 - SAR/RCS - NO, YES in the past
 - Monitoring - YES, light curves
- **2. Attitude model - NO**
 - TBD AIUB diffuse reflection
- **3. Physical model - NO:**
 - CoM - NO
 - MOI - NO
 - 3D model - YES

Courtesy: space.skyrocket.de





Fast Tumblers - ARIANE 44L R/B, 1991-084C, 21815

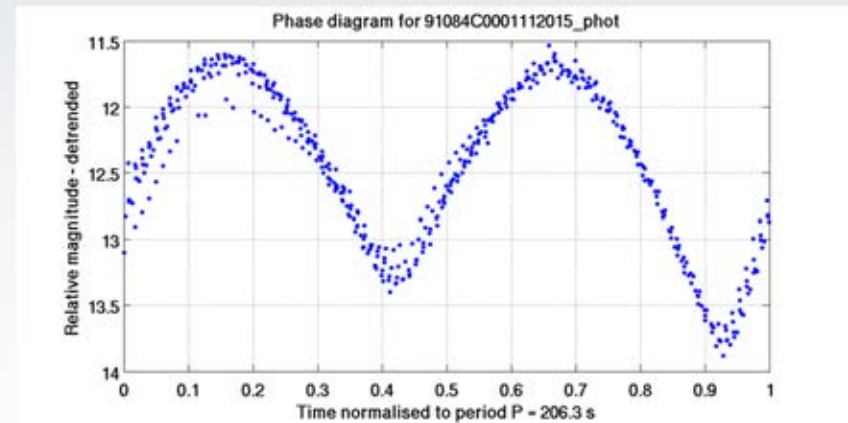
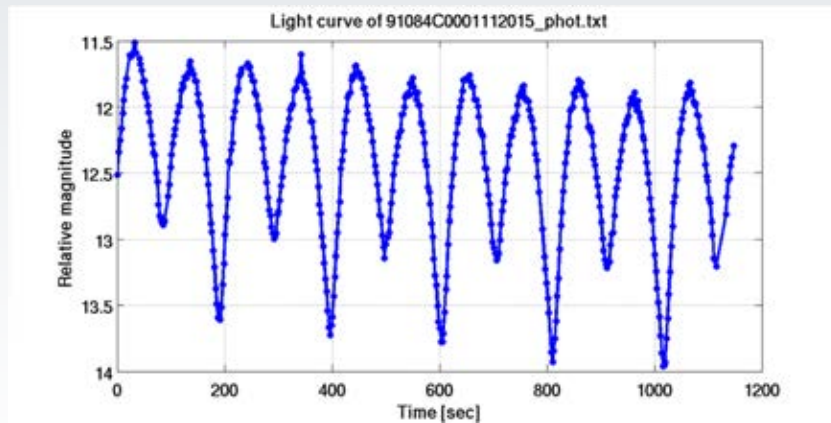
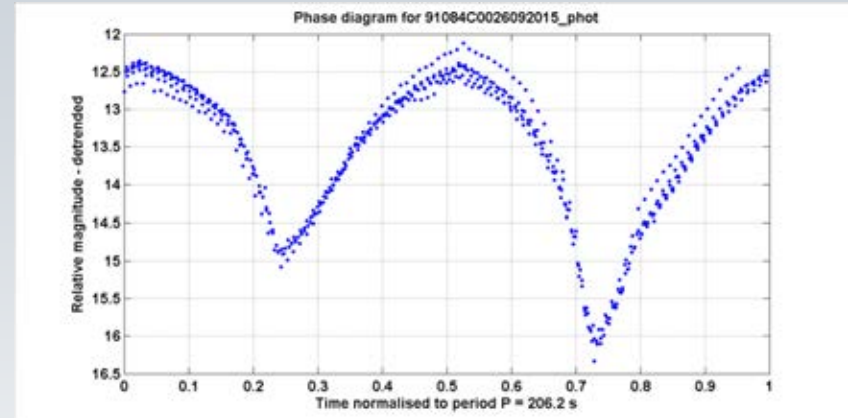
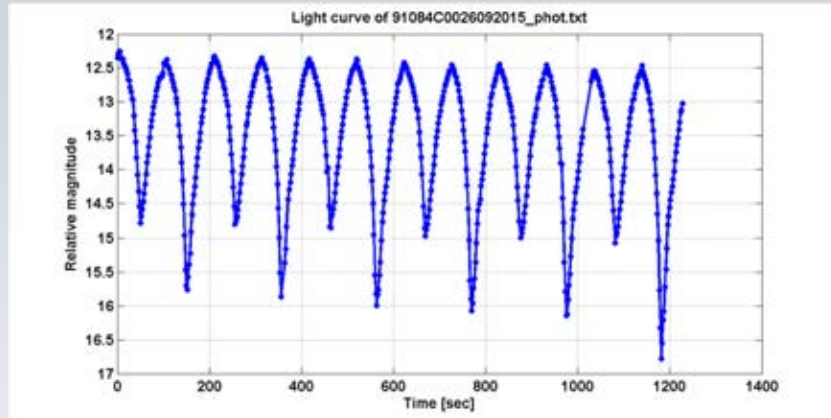


Figure - Ariane 44L R/B light curves (left panels) acquired by ZIMLAT in Sep and Nov 2015 and their reconstructed phases (right panels).



Fast Tumblers - ARIANE 44L R/B, 1991-084C, 21815

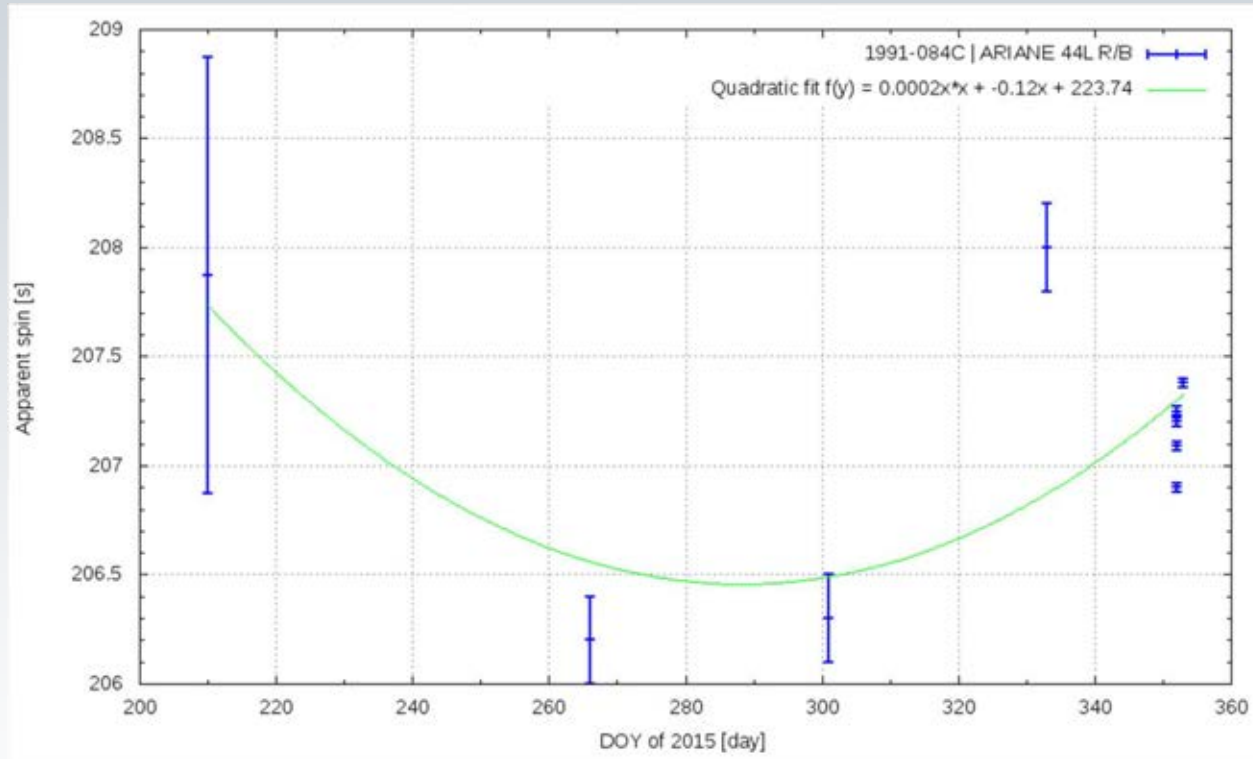
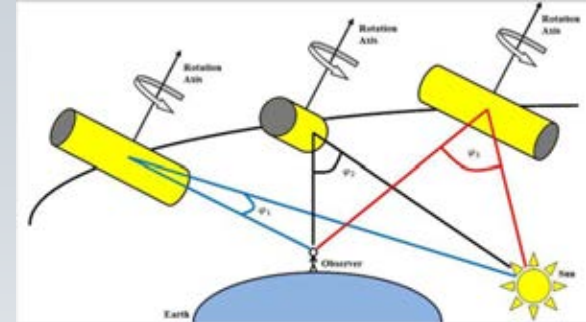


Figure - Ariane 44L R/B apparent spin period evolution extracted from AIUB's light curves.



IoT Forward Modelling Tool

- Simulation modules
 - 3rd-B – Third-body force module
 - Aero – Aerodynamics module
 - Eddy – Eddy current module
 - Grav – Gravitational force module
 - MoveP – Moving parts module
 - MTQ – AOCS: Magnetic torquer module
 - Outlm – Outgassing and impact module
 - RWL – AOCS: Reaction wheel module
 - SolRad – Solar radiation pressure module
 - Thrust – AOCS: Thruster module
- Post-processing modules
 - History – History module
 - SimLC – Simulated measurements module: light curves
 - SimOpt – Simulated measurements module: optical image
 - SimRad – Simulated measurements module: radar image and RCS
 - SimSLR – Simulated measurements module: satellite laser ranges





Summary

- **Light curves**
 - for >120 LEO objects
 - >1000 light curves from high-altitude r/b, s/c and fragments including objects with SLR retroreflectors
- **SLR observations** of a series of cooperative LEO/MEO targets
- **Light curve attitude state determination** for simple-shaped LEO r/b
 - direct inversion
- **SLR attitude state determination** for Envisat, (Topex, ERS-2, ADEOS-2, more to come)
 - physical model for «detrending»
 - fusion of SLR and optical data (attitude state and orbit)
 - forward modeling



Summary (cont.)

- **Validation/refinement of other attitude determination techniques**, e.g. radar, ISAR, and optical to be used for non-cooperative targets
- Unexplained spin-up/spin-down of debris objects
→ **continuous monitoring of spin state of potential ADR targets required!**
- **Fast tumblers ($P < 100s$)**
 - some of the massive payloads
 - census for LEO r/b shows few fast tumblers

Thank you for your attention

