Manoeuvre detection methods for satellites in Low Earth Orbit based on Two-Line Elements and Applications

Steps Towards Environment Control

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Manoeuvre detection

1) Problem statement: the detection of events in time series derived from orbital parameters
   - In near real-time (e.g. SSA)
   - Historical (e.g. analysis)

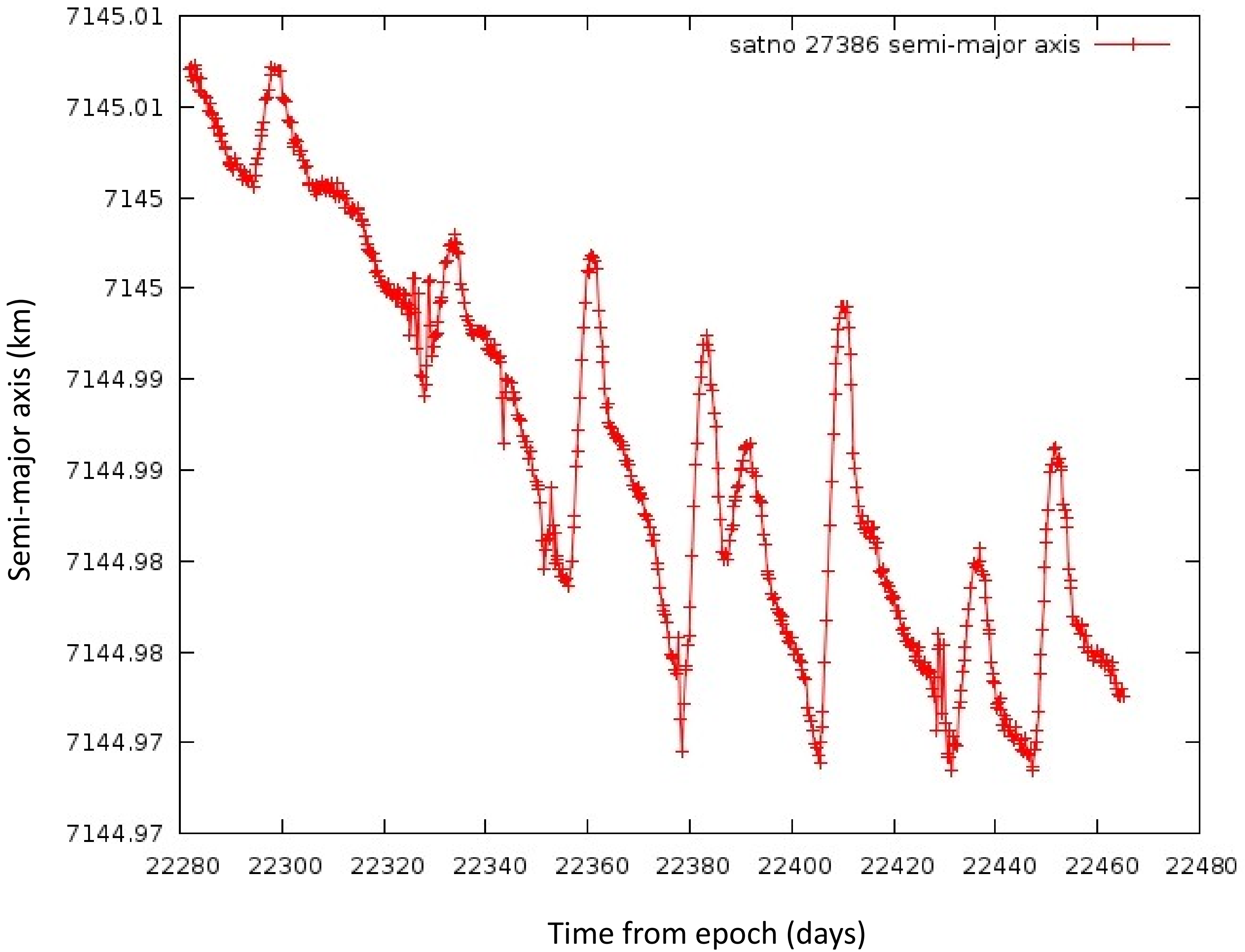
2) Event detection methods:
   - Algorithms aimed towards detection of manoeuvres
   - Automated processing of entire LEO TLE catalogue with consistent Type I and II errors

3) Application: Establish the degree of compliance to the 25-year de-orbit *'rule'* for payloads in LEO

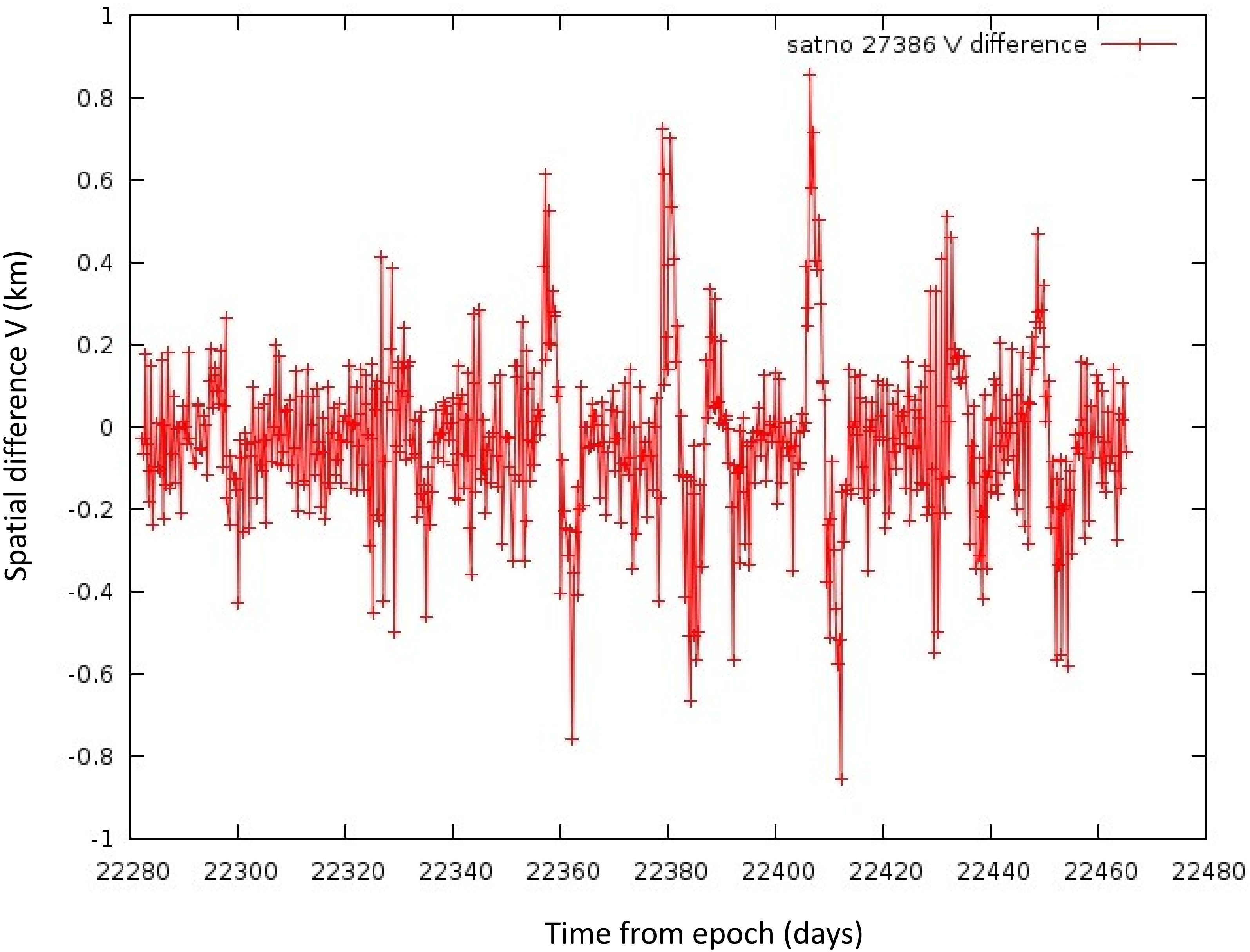
TLE Consistency Check

1) Algorithm working principle: for an object free from any non-natural disturbance, propagating TLEs to a consecutive state should be consistent.
    - Most important natural orbit disturbances are incorporated in the SGP4/SDP4 model
    - Inconsistencies are measurable as differences in the spatial inertial coordinate system associated with the propagated TLE state.

TLE Consistency Check



TLE Consistency Check



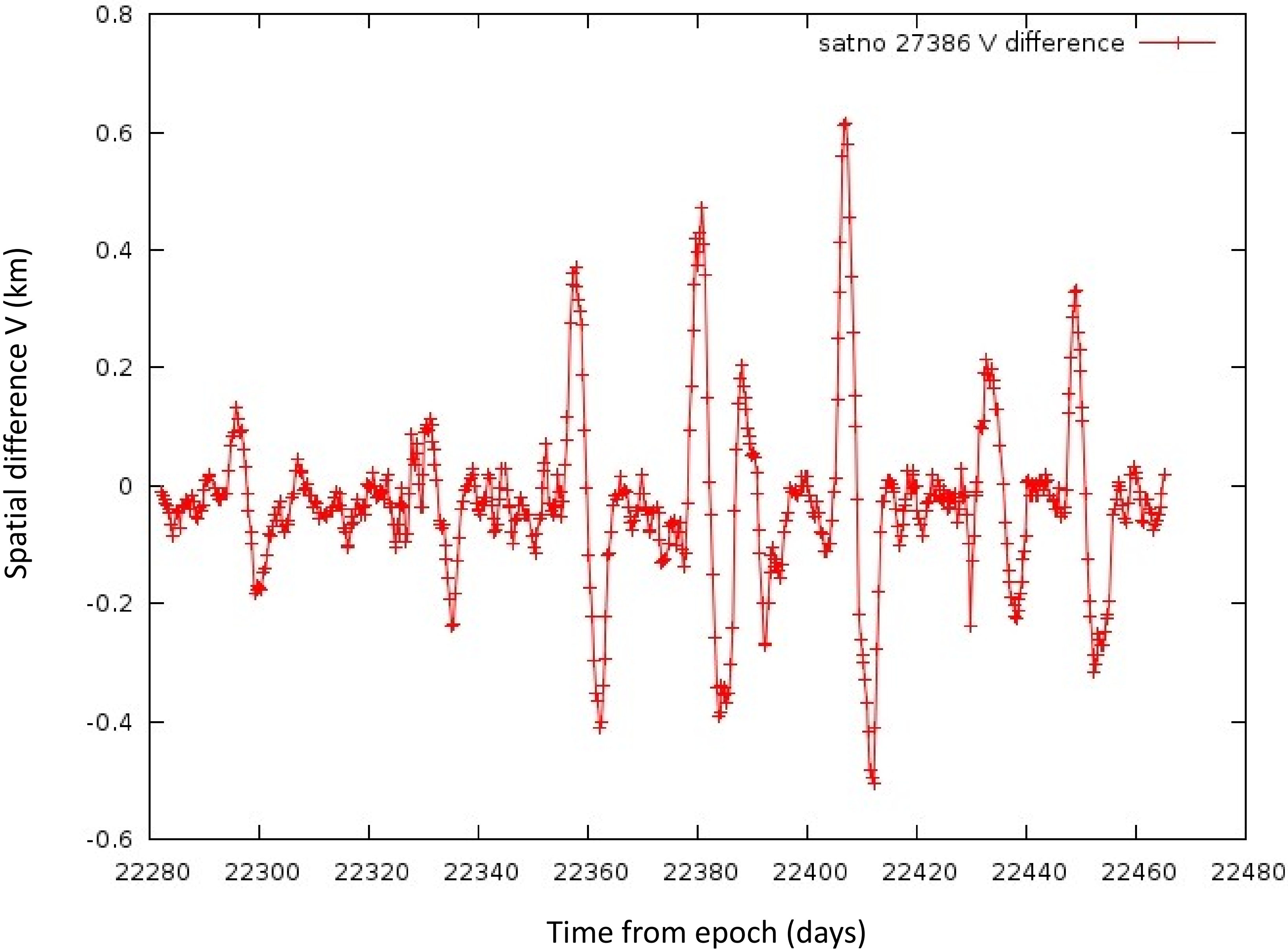
TLE Consistency Check

1) Effects defining the spatial difference time series:
   - Non-natural events, possible with a time lag and convergence period
   - Systematic errors due to SGP4/SDP4 model: Propagation errors and unmodelled effects
   - Biases and random errors in the orbit- and TLE-generation process

TLE Consistency Check

1) Filter the difference time series with the following process:
   - Locally weighted regression (LOWESS)
   - The expected variance due to propagation time is estimated from the sample via the same difference time series with multiple propagation steps (Weighted regression)
   - Local weights (LOWESS) are given to the data points based on their difference/time distance from the estimated point.

TLE Consistency Check



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2) Primary outlier detection with a moving window and threshold determined by the sample statistics

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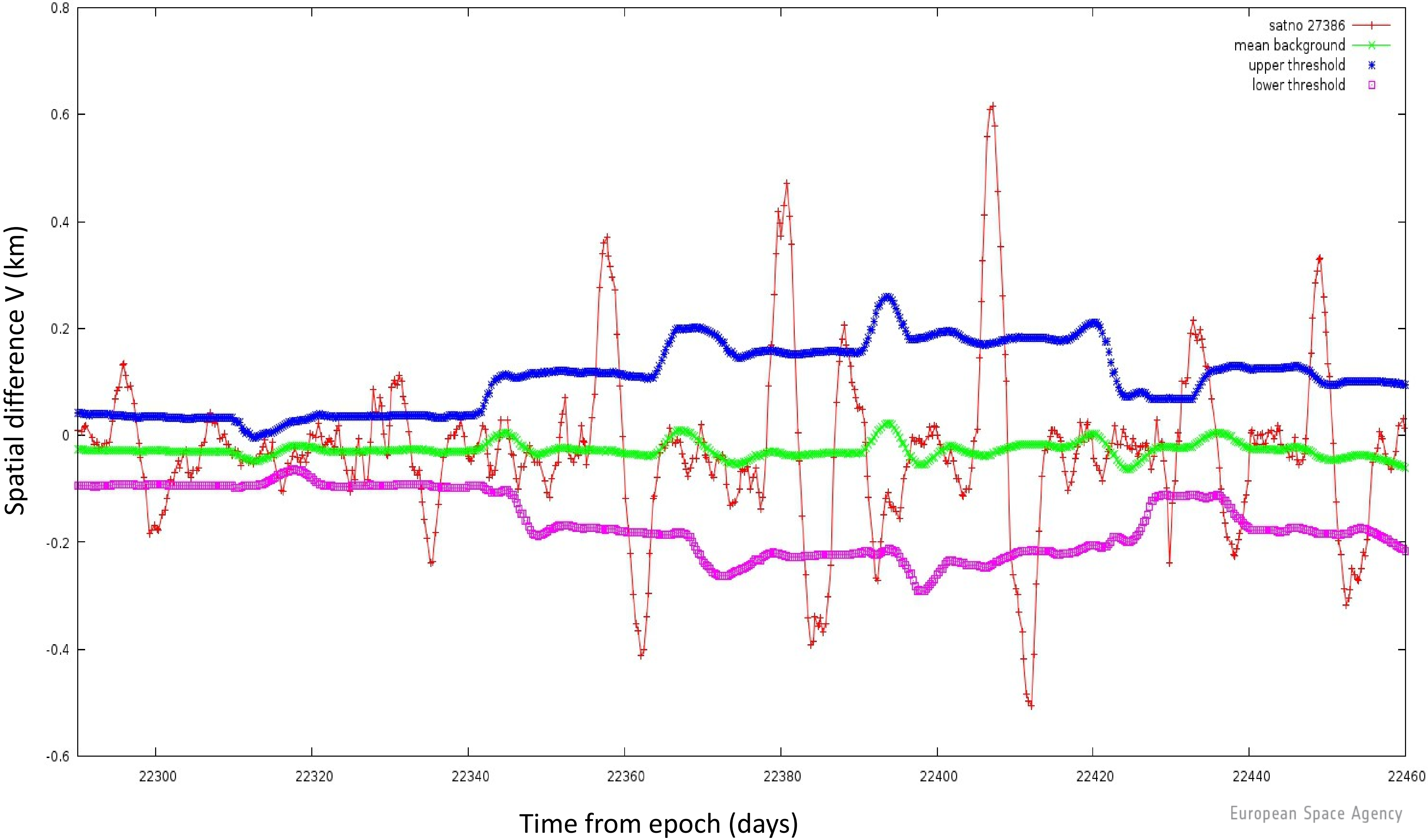

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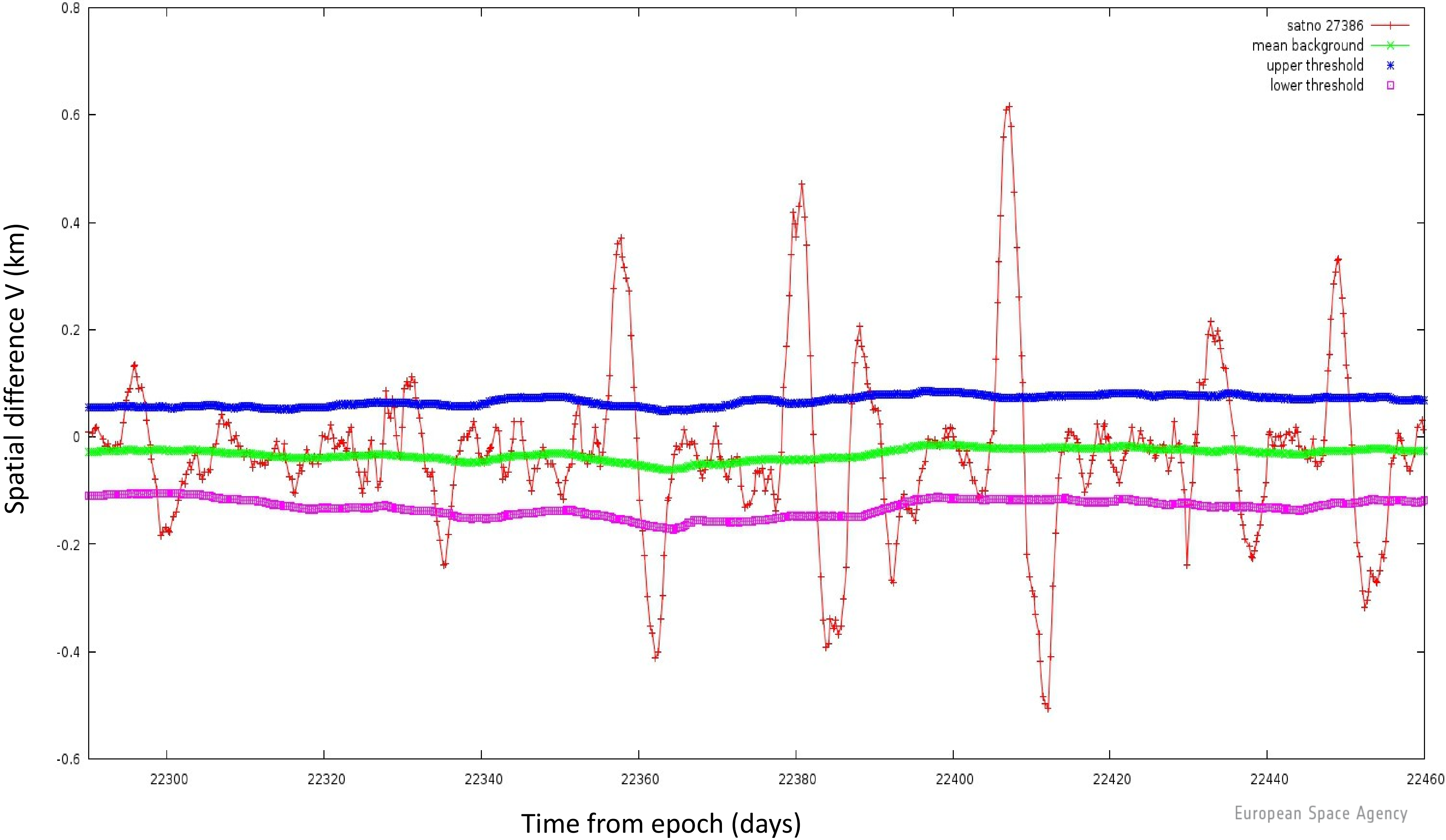
2) Primary outlier detection with a moving window and threshold determined by the sample statistics
3) Refined outlier detection by fitting a Gaussian to the outlying region (limits application to LEO).

TLE Consistency Check

1) The detection threshold can be made more accurate by the use of a reference population

TLE Consistency Check

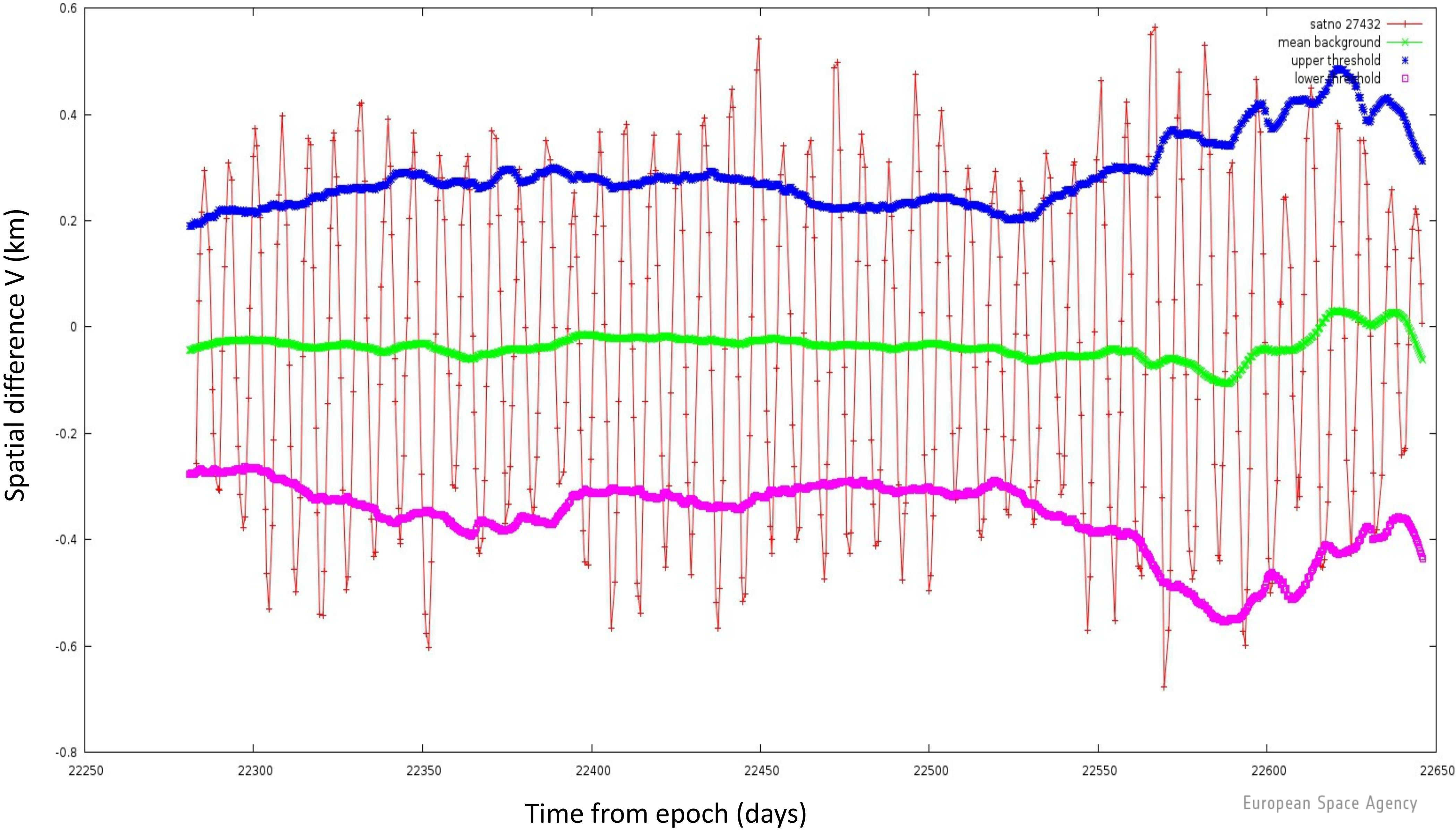


TLE Consistency Check

1) The detection threshold can be made more accurate by the use of a reference population

2) Unmodelled perturbations or periodic effects are detected with periodogram analysis

TLE Consistency Check



European Space Agency

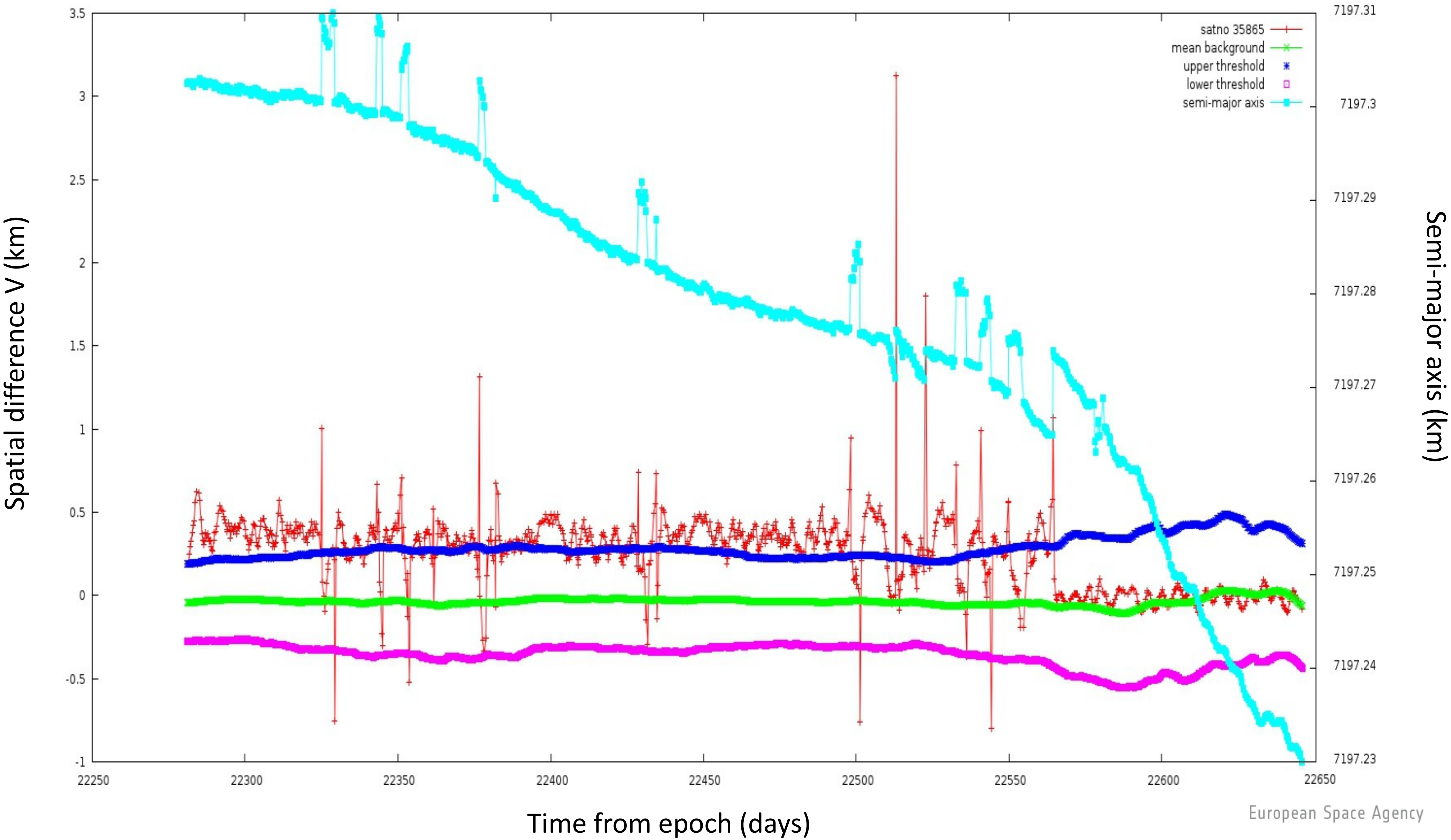
TLE Consistency Check

1) The detection threshold can be made more accurate by the use of a reference population

2) Unmodelled perturbations or periodic effects are detected with periodogram analysis

3) Pathologies continue to exist

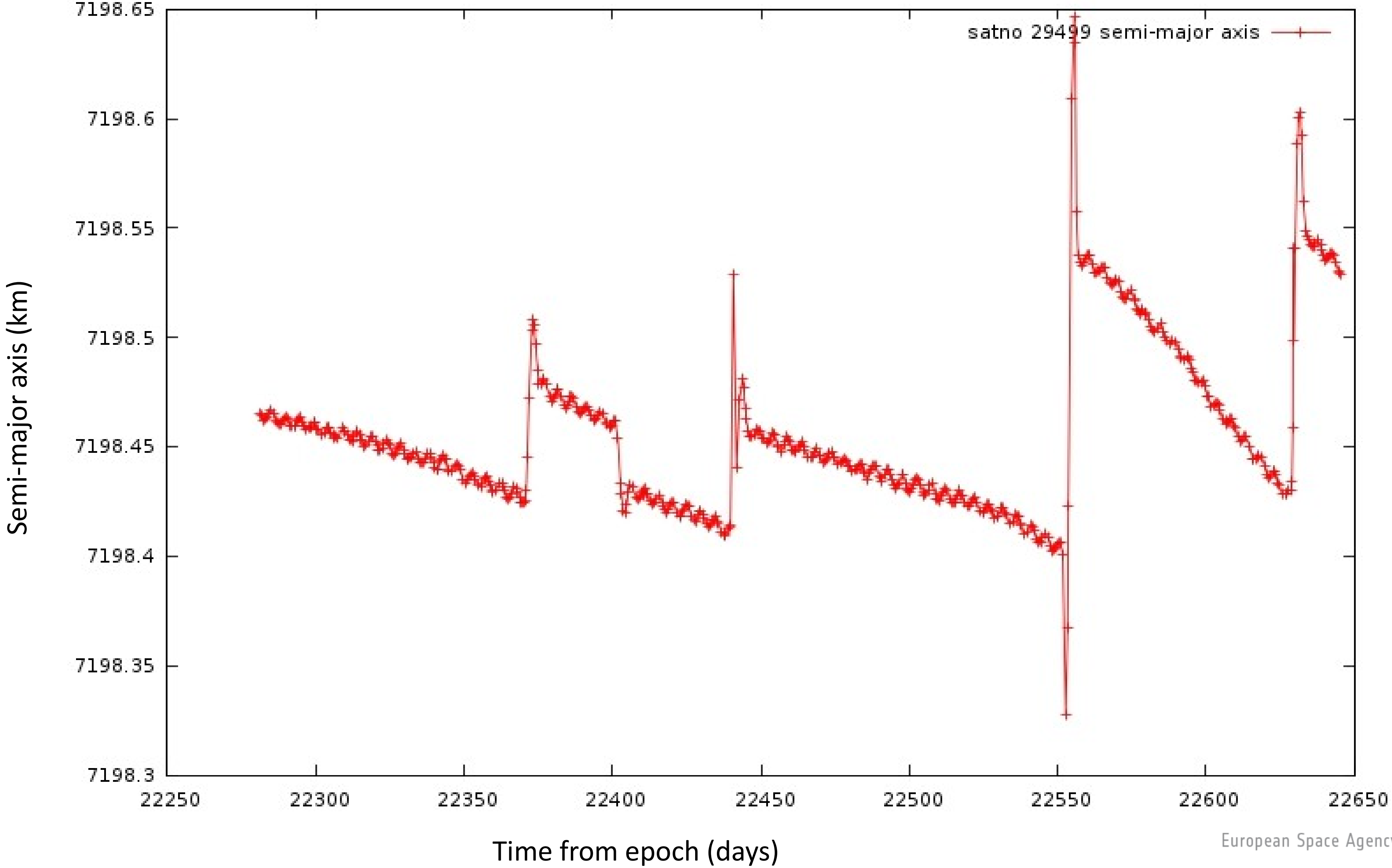
TLE Consistency Check



TLE Time Series analysis

1) Algorithm working principle: Detect outlying, compared to an earlier reference, regions of a time series based on robust statistics
   - Any orbital parameter, or quantity derived thereof, can be used to find events
   - Data points in a moving window are used to extrapolate values for data points consecutive to the window
   - Implementable as a continuous process

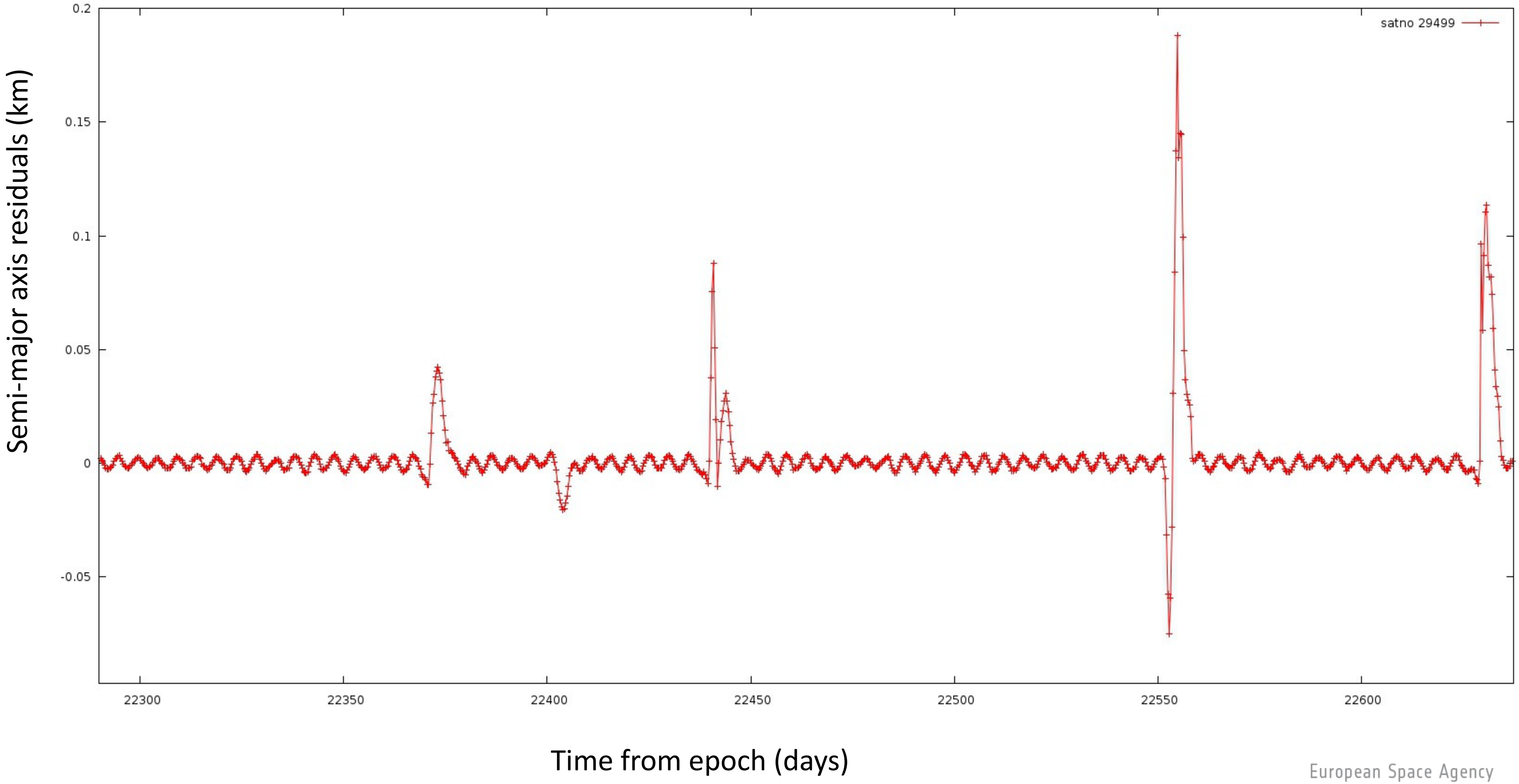
TLE Time Series analysis



TLE Time Series analysis

1) Biases are removed from the time series by subtracting within a moving window a line fitted with the Theil-Sen-Siegel estimator
   - Estimator breakdown point: 50%

TLE Time Series analysis



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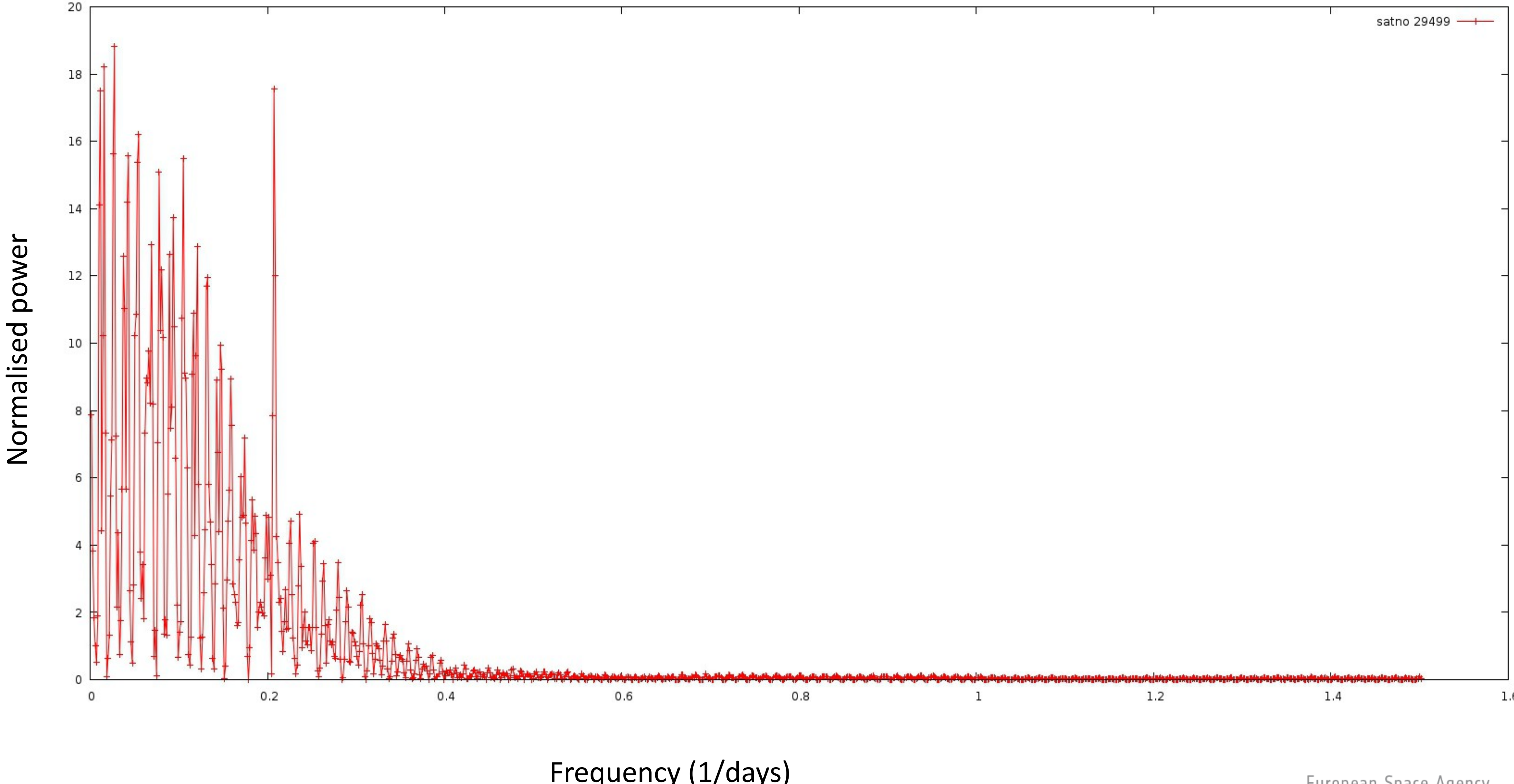

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2) Clear periodic signals are identified via a Lomb periodogram of the data and subtracted from the time series

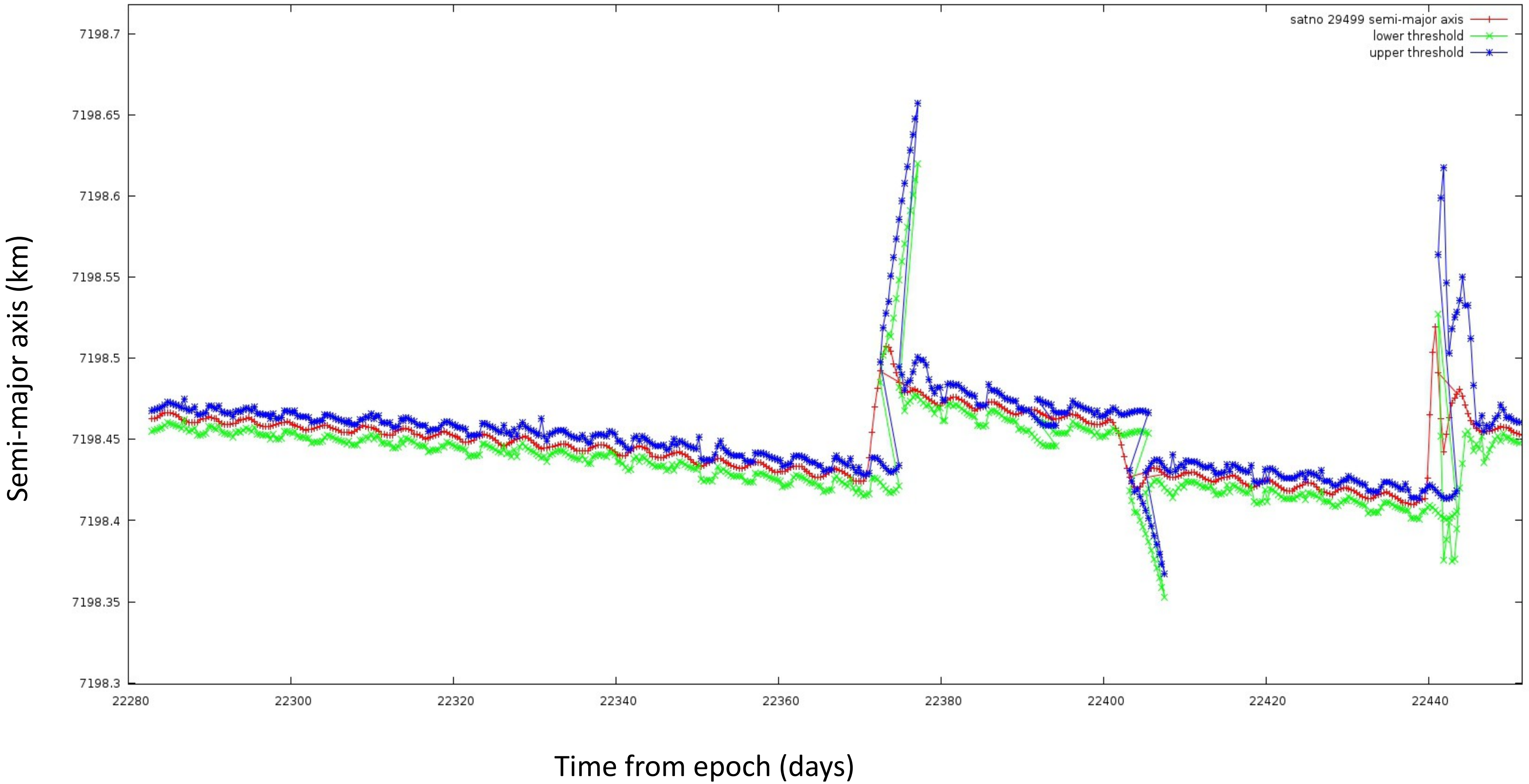
3) The interquartile range of the remaining time series is computed and defines the minimum detection threshold of the series
   - Estimator breakdown point: 25%

TLE Time Series analysis

1) A moving window runs over the data, repeats the line and harmonic removal process and computes a local threshold as the maximum of the local IQR and minimum threshold

2) The time series inside the moving window is extrapolated to the consecutive TLEs and the corresponding time series elements check against the local threshold for outliers.

TLE Time Series analysis



Methods summary

1) TLE Consistency Check
   - Detection based on propagation inconsistencies
   - Most accurate use limited to LEO with reference objects
   - Global threshold has to be set

2) TLE Time Series Analysis
   - Detection based on comparison with data extrapolation
   - Any orbital regime
   - Window sizes depend on the update frequency

LEO de-orbit compliance

1) ESA's GEO report to reflect re-orbit compliance in GEO
2) IADC guideline: limit the orbital lifetime of an object to a period not longer than 25 years after the end of mission
    - Compliance is easily checked for rocket bodies
    - Detecting end of mission for payloads is harder
    - Estimate global compliance to raise awareness and reflect the acceptance of such rules

3) Define end of mission of a payload in year *i* as manoeuvring in year *i-1* but not in year *i*.
    - Cubesats ($m < 50$kg) are excluded
    - The estimate will be a lower limit

LEO de-orbit compliance

1) Payloads launched between 1990 and before 2010 with perigee altitude below 2000km, still in orbit on the 1st of January 2012 and having continuous TLE history were checked for manoeuvres in 2010 and 2011 with TTSA on the semi-major axis time series

Orbital regime	Tot. Pay.	Man. Pay. 2010	Man. Pay. 2011	Pay. EOL
$0 \le e < 0.1,\ 0 < r_p \le 1000$	425	194	186	9
$0 \le e < 0.1,\ 1000 < r_p \le 2000$	174	52	37	13
$0.1 \le e < 1,\ 0 < r_p \le 1000$	53	2	2	0
$0.1 \le e < 1,\ 1000 < r_p \le 2000$	35	3	3	0
$0 \le e < 1,\ 0 < r_p \le 2000$	687	251	228	22

2) Only one payload abides to the guideline

3) Three extra payloads already decayed

4) 42 rocket bodies out of 53 injected into LEO in 2011 comply.

Questions

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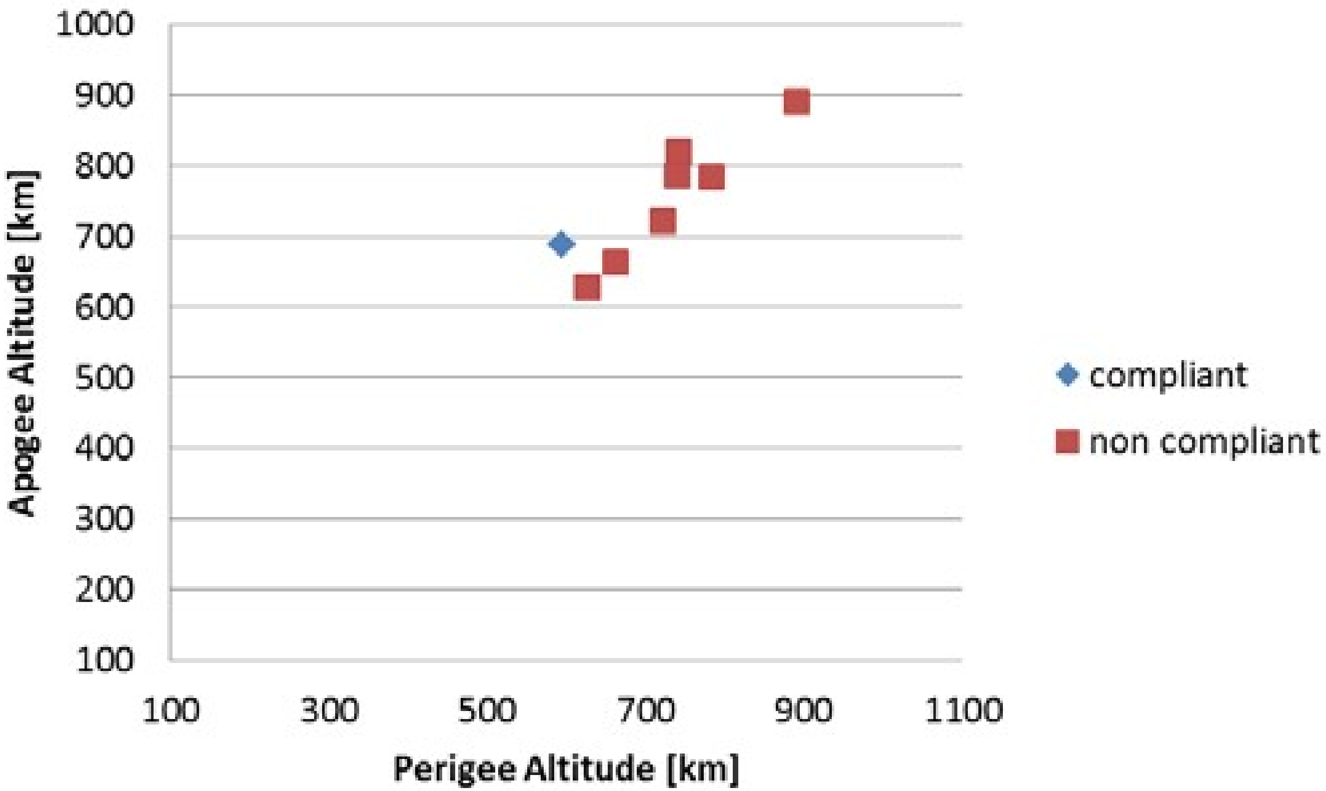

1000
900
800
700
600
500
400
300
200
100
Apogee Altitude [km]
100
300
500
700
900
1100
Perigee Altitude [km]
compliant
non compliant