Momentum Transfer Events and Other Disturbances in LRI Data

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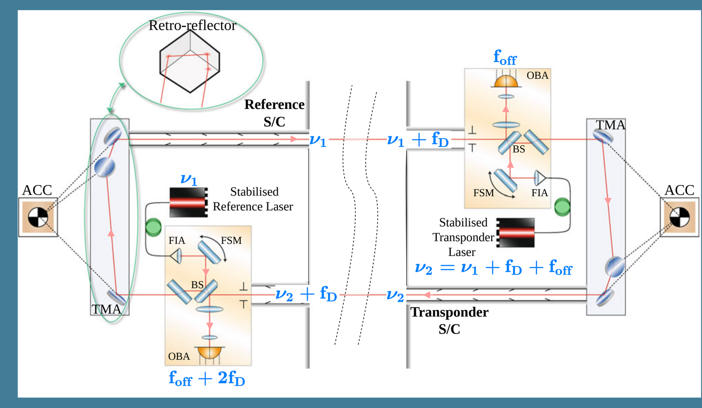
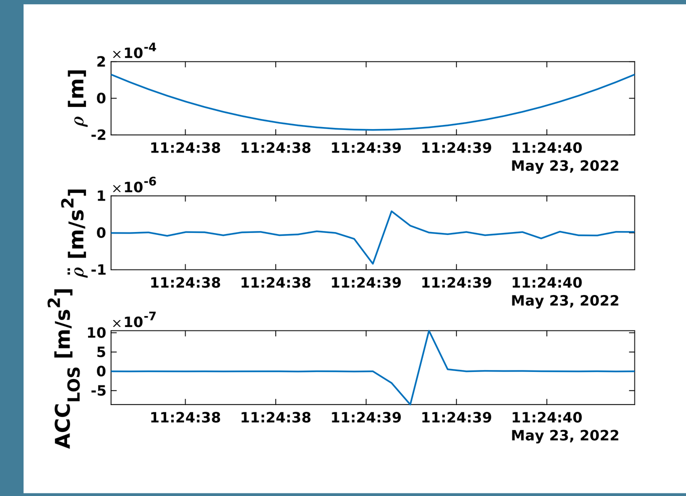
Introduction

Launched in May 2018, GRACE-FO twin satellite mission hosts the technology demonstrator instrument Laser Ranging Interferometer (LRI) to precisely measure the inter-satellite range variations between the two spacecraft, GF1 and GF2. For the past five years, the LRI has resolved this range within a billionth of a meter. The Earth's gravitational pull acts differently on the two spacecraft and thus changes their separation from a reference distance of 220 km These distance variations can be used for mapping the Earth's gravity field.



Courtsey: Sheard et al., 2012

Working Principle of LRI: The spacecraft (S/C) are in Reference or Transponder role. The Reference LRI transmits a near-infrared laser beam ($\nu 1$) from the stabilised laser towards the Transponder S/C along the LOS. The received beam at the Transponder is Doppler shifted due to the relative velocity of the spacecraft. The frequency ($\nu 2$) of the Transponder laser is matched to the received frequency with an offset (f_{off}) of 10 MHz. This beam is transmitted back to the Reference S/C and undergoes another Doppler Shift. The transmitted and received beams at the Reference S/C interfere to produce a beat note containing the Doppler frequency (f_D) from which the range (ρ) can eventually be derived[1].



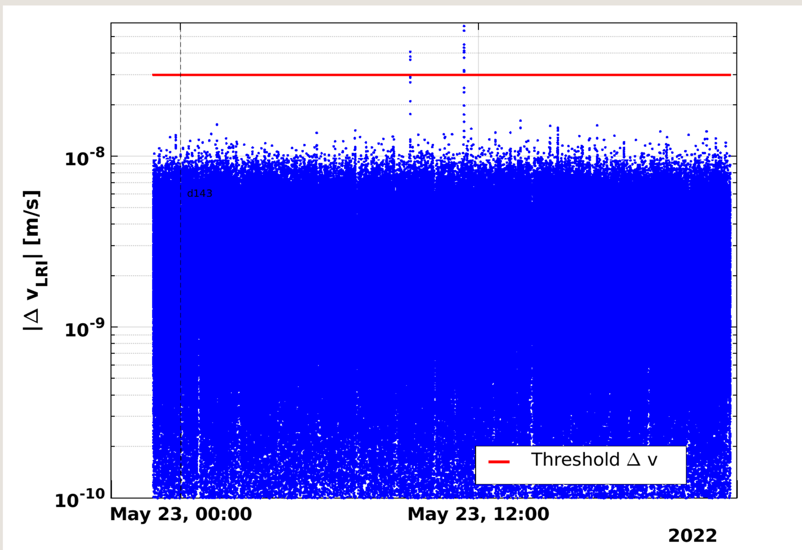
Both LRI and the ACCs measure momentum transfer, and their data is used for the following analysis. The plot shows the respective detrended data in GF1 (Reference) for a typical MTE. mode

We, at the AEI, analyse the LRI data to find disturbances like phase jumps[2] and Single Events Effects (SEU)[3], and remove them to obtain low noise range measurements. Momentum Transfer Events (MTEs), as the one on the right, are also a non-gravitational disturbance, but they are not removed from the data because they are true changes in range.

Detection of MTEs

1. Firstly, the range ρ is calculated from the ranging phase φLRI. From this range, the spacecraft momentum change Δv_{LRI} is determined. This is done using a unique detrending method[4] that removes the background signal and isolates impulse like events to provide an accurate estimate of the Δv_{LRI}. Stretches of the Δv_{LRI} above a certain threshold are considered an MTE candidate.

2. The ACC measures accelerations along 3 axes. The ACC time-series along the axis which is roughly aligned with the line-of-sight (LOS) axis of the LRI, is correlated with the LRI range acceleration $\ddot{\rho}$ for each MTE candidate.



3. MTE candidates where the cross-correlation between ACC and LRI accelerations is larger than 0.1 are marked as MTE.

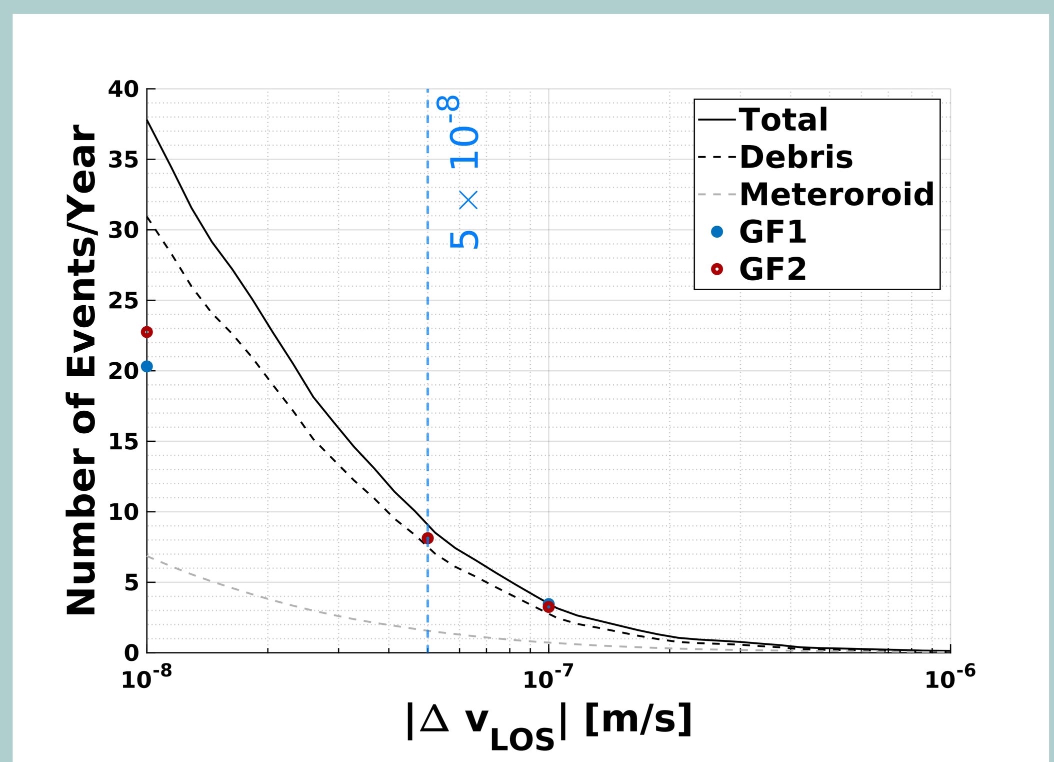
4. Since MTEs are only detected in the LRI Reference S/C data, the ACC data is used to identify the S/C on which they have occurred. The cross-correlation is computed with ACC data from both S/C. This helps define on which satellite the MTE occurred.

Simulating MTEs annual rate using ESA MASTER v8.0.3

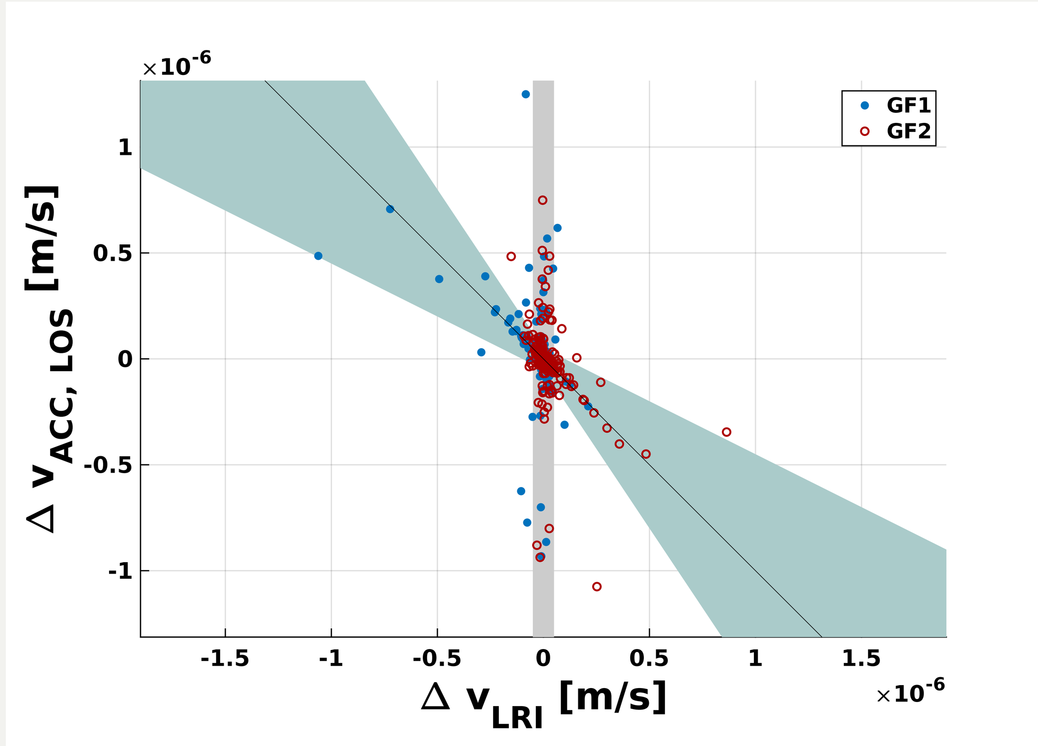
The software simulates the 3D impact flux of orbital debris and meteoroids on the S/C based on the GRACE-FO's orbit and S/C dimensions. The cummulative histogram shows simulated and observed distribution of events per year for the obsereved Δv_{LOS} range.

1. For both S/C, the observation adequately matches the simulation for total number of events anually, for $|\Delta v_{LOS}|$ above 5×10^{-8} m/s.

2. The observation values fall below the model for smaller $|\Delta v_{LOS}|$, because such small events can not be properly detected in the noise .



Results of Detection



Observations:

1. Number of MTEs detected in GF1 are 140 and in GF2 are 152 for the period between launch of GRACE-FO to July 2023.

2. The Δv estimate of LRI and ACC is either :

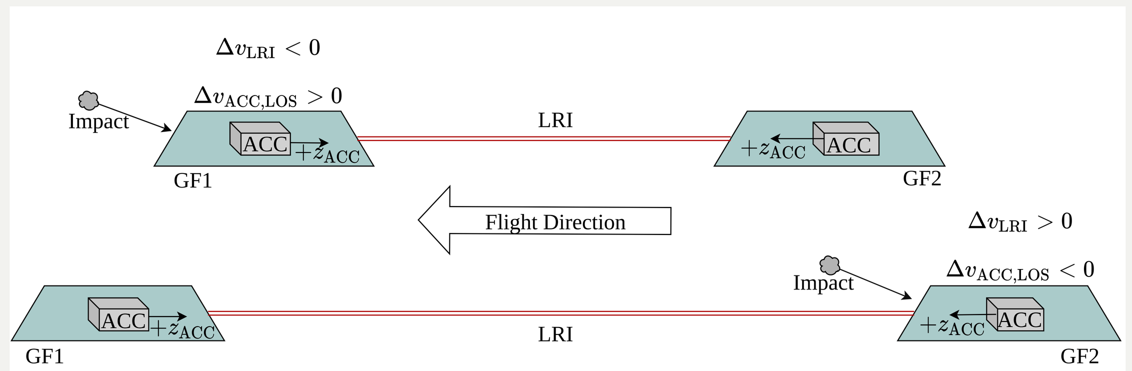
A well correlated

B high $\Delta v_{ACC,\ LOS}$

3. Corellation plot between $\Delta v_{ACC,\ LOS}$ and Δv_{LRI} , show that GF1 and GF2 events occupy different areas along the correlation line. Explained below.

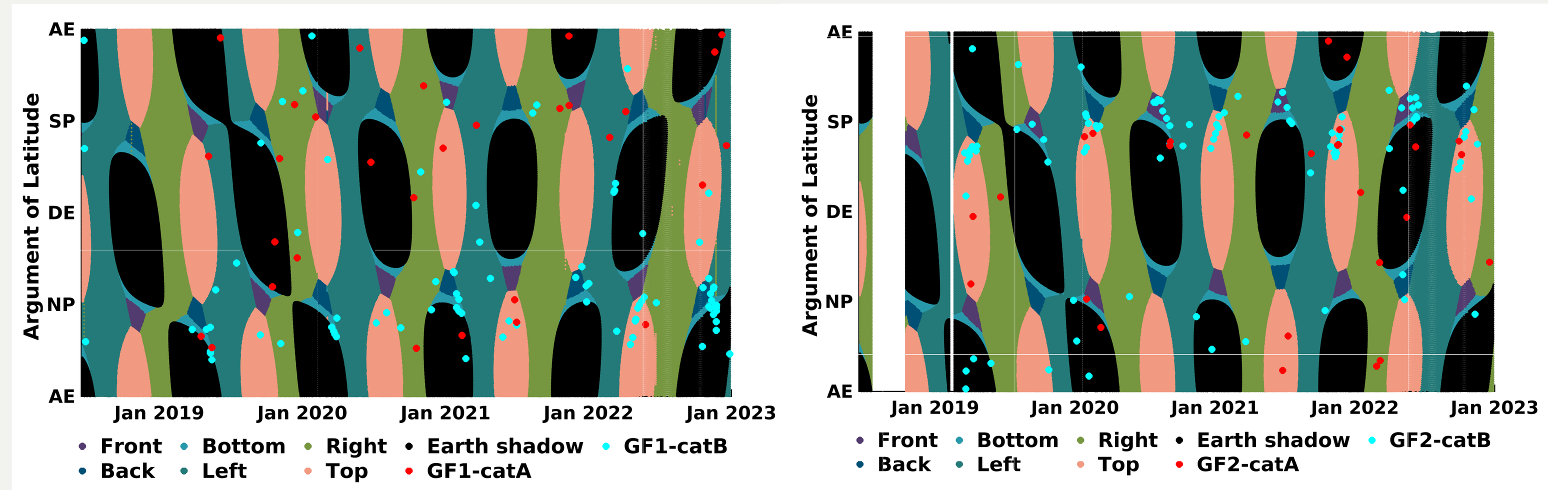
Debris and meteoroids predominantly impact both spacecraft from the direction of flight:

- Impacts on GF1 decrease the intersatellite distance and those on GF2 increase the distance, thereby producing a negative and positve Δv_{LRI}, respectively.
- The SRF +z axis for the ACC is the LOS direction, so impacts on GF1 are along this direction and those on GF2 are against.

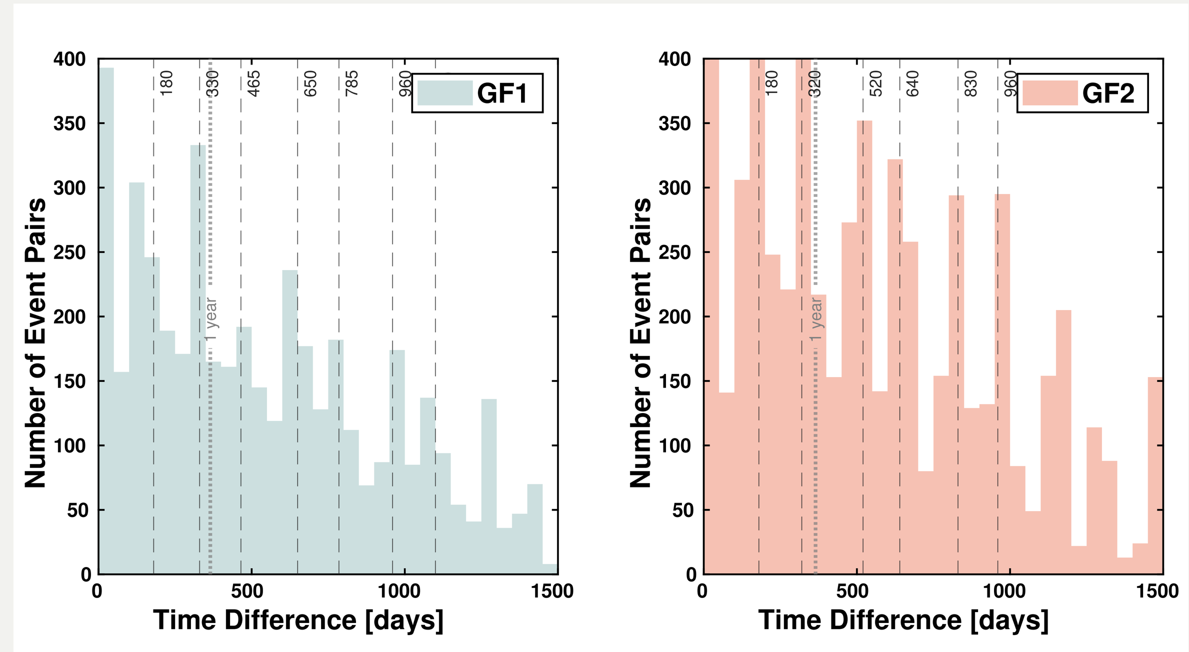


Argument of Latitude and Periodicity

Events from the two categories over the argument of latitude and time, alongside the different surfaces of the S/C illuminated by the sun:



Events from category A are randomly distributed over the argument of latitude and time, however, those of category B appear in clusters when the surface illumination changes. The periodicty of category B shows its relationship with the beta-angle of the sun.



Plot to the left is a histogram of pair -wise time separation between all events.

1. The beta angle repeats every 160 days.

2. Clusters in GF2 are when the beta angle is at 0.

Conclusion

- Successful detection of 292 MTEs using the LRI data in the five years of its operation.
- The events can be categorised depending on the correlation: The category with high $\Delta v_{ACC,LOS}$ shows grouping around the argument of latitude where the S/C enters or exits sun shadow. The periodicity of these events can be correlated with the beta-angle of the sun.
- Simulation of MTEs rates using the ESA MASTER software matches observation in the number of events anually for $|v_{LRI}| \geq 5 \times 10^{-8}$ m/s.
- As MTEs are actual changes in momentum, these events are not removed from LRI data.

References

[1] **Sheard, B. S. et al.**, "Intersatellite laser ranging instrument for the GRACE follow-on mission". *Journal of Geodesy* 2012

[2] **Abich, Klaus et al.**, "In-Orbit Performace of the GRACE Follow -on Laser Ranging Interferometer". *Physical Review Letters* 2019

[3] **Misfeldt, Malte; Bekal, Pallavi et al.**, "Disturbances from single event upsets in the GRACE follow-on laser ranging interferometer" . *Advances in Space Research* 2023

[4] **Bähre, Simon J.**, "Modelling and Removal of Thruster Signatures in GRACE Follow-On Laser Ranging Interferometer Data". *Bachelor Thesis* 2023

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