British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Gateway to the Earth

Assessing and enforcing single-photon returns: Poisson filtering

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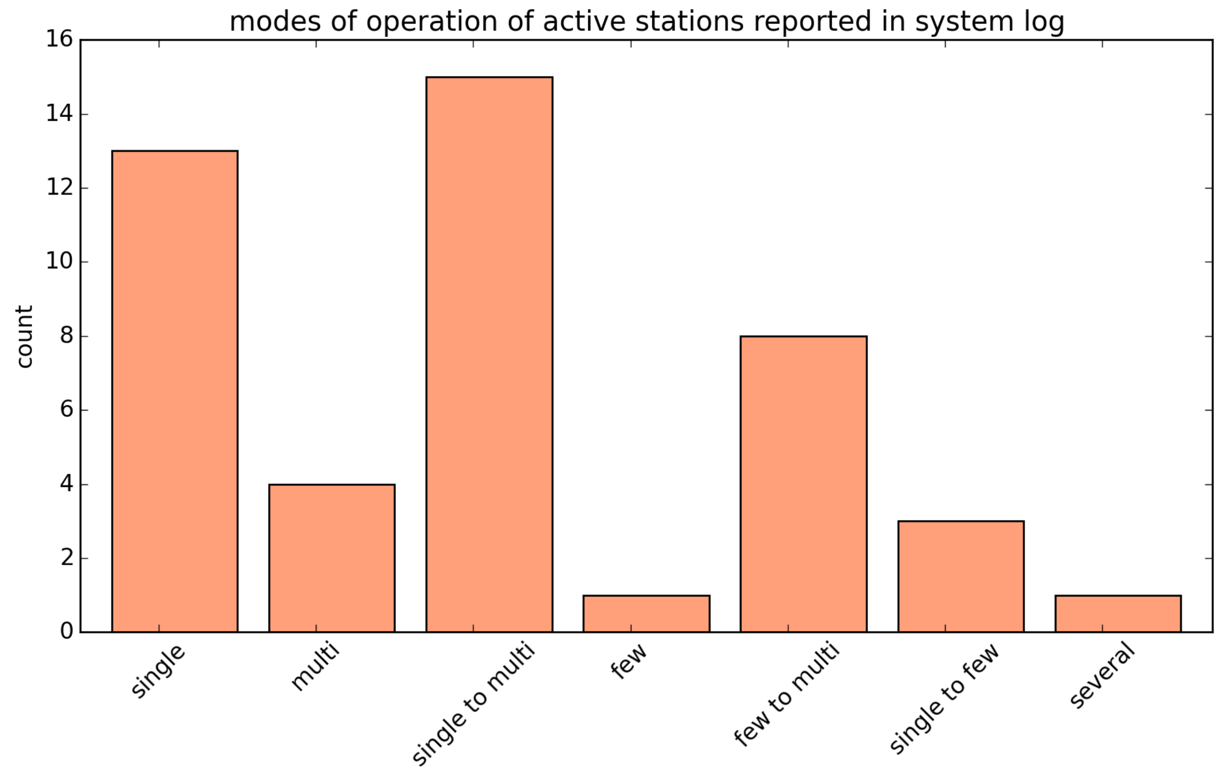
Modes of operation of SLR stations

Mode of operation	**Number of photons in returned pulses**	**Typical reference point**	***Typical* hardware requirements**
Multi-photon	tens	Leading-edge	High energy per shot, reasonable size primary mirror
Few photon	?	?	N/a
Single photon	<1	centroid	Mechanism to control return energy

Different ways to obtain our ranges



(system log retrieved on 11th October 2016)

Why single photon?

- If, statistically speaking, no more than one photon arrives at the detector, it could have been reflected off any point of the laser retroreflector array (LRA) ...
- so the distribution of detections is the convolution of the laser pulse and the satellite response function: possible to compute accurate CoM corrections
- Centroid of distribution of returns from flat arrays (GNSS) theoretically not affected by incidence angle (no elevation dependence)
- Absence of detector time-walk and satellite signature intensity dependent effects
- Single mode of calibration, operation and data reduction, from LEOs to HEOs, independently of LRA cross-section, weather conditions and satellite elevation

Motivation

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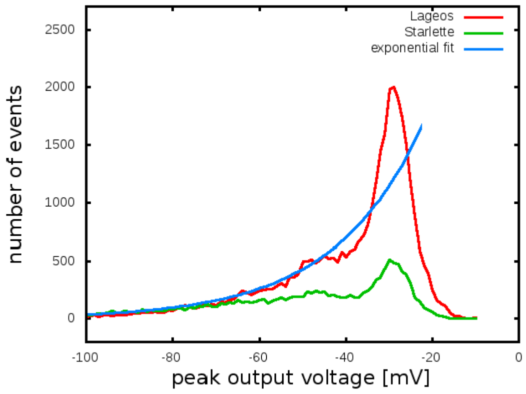
J. J. Eckl and K. U. Schreiber, “Single photon tracking under difficult condition”, *2015 ILRS Technical Workshop, Matera*:



Intensity profile of 4 months of LAGEOS/Starlette data @ 20 Hz WLRS showing presence of multi-photon detections

...“difficult conditions” meaning “anywhere outside the lab”

"Single photon" is a statistical concept

- Photon arrivals follow Poisson statistics (and so does the conversion to photoelectrons process)
- Poisson processes defined by a single parameter, the intensity *r*
- Probability of *k* events at intensity *r* : $P(k, r) = r^k e^{-r} / k!$
- $P(k>1, r) = 1 - P(0, r) - P(1, r)$
- Return rates are normally measured by simply counting, at fixed intervals, events identified as satellite detections
- Counting is the simplest way to estimate the intensity

- Operationally:

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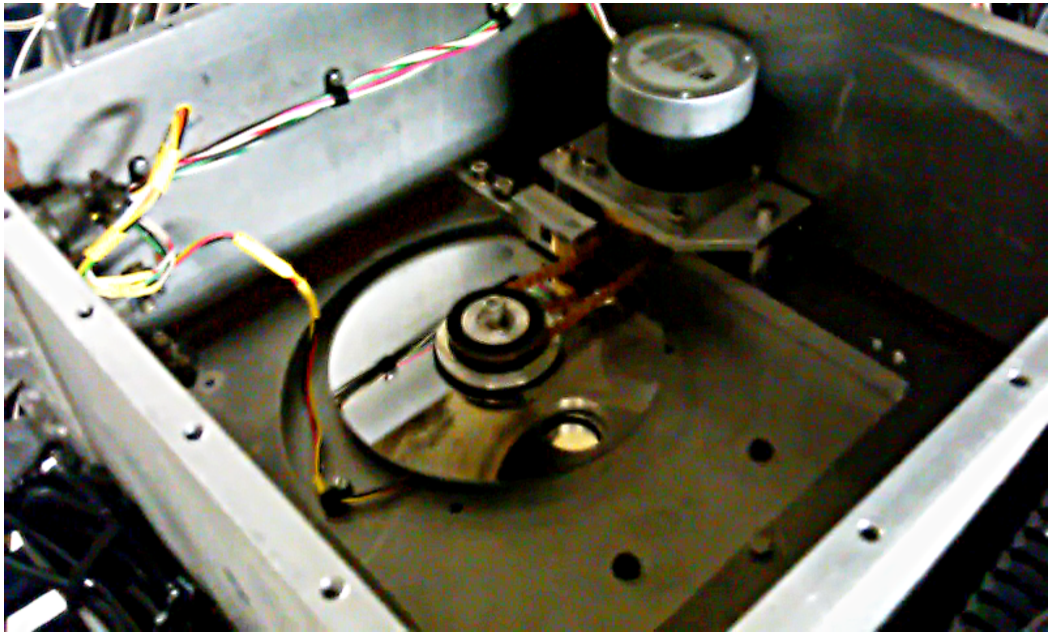
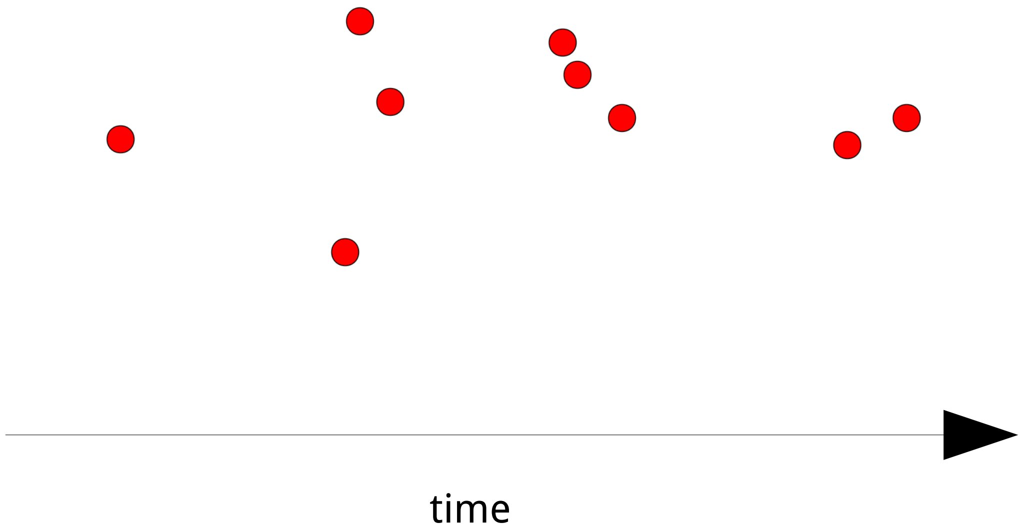
```
while True:
    count()
    if too_many:
        decrease_returns()
```

Intensity decreased by introducing a variable neutral density filter wheel in the receiver path



Other possibilities: divergence control, pointing offsets (not ideal), laser energy control (not too flexible?), neutral density in the emitter path

We can't measure our return energies directly (no equipment available), but we have many returns as we fire at 1 KHz, so we can play with statistics:



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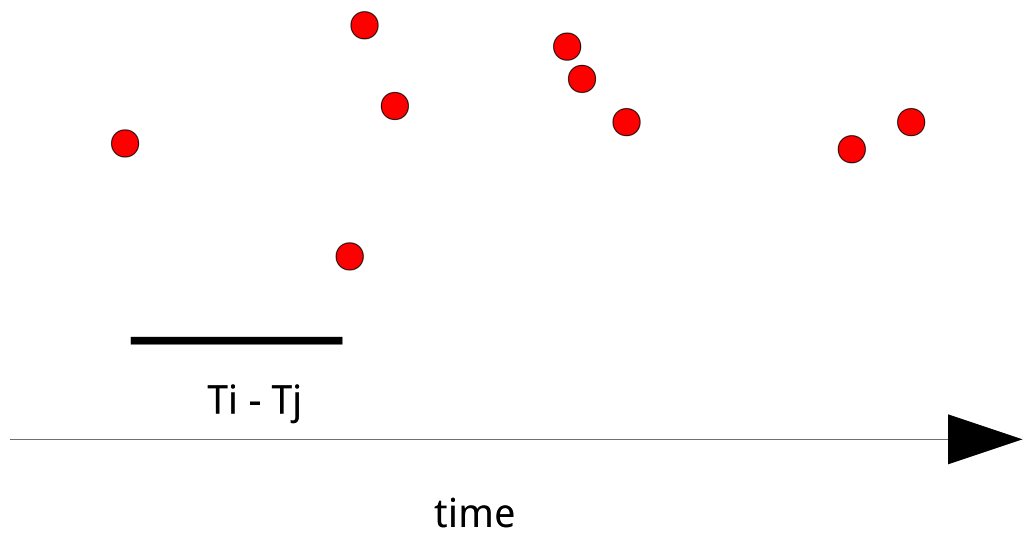
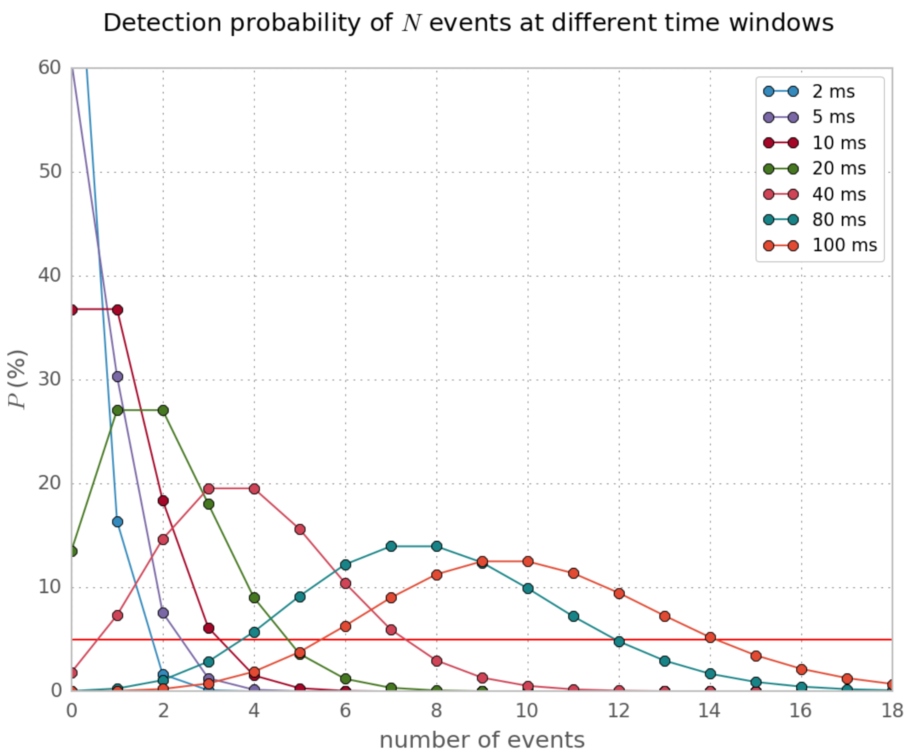
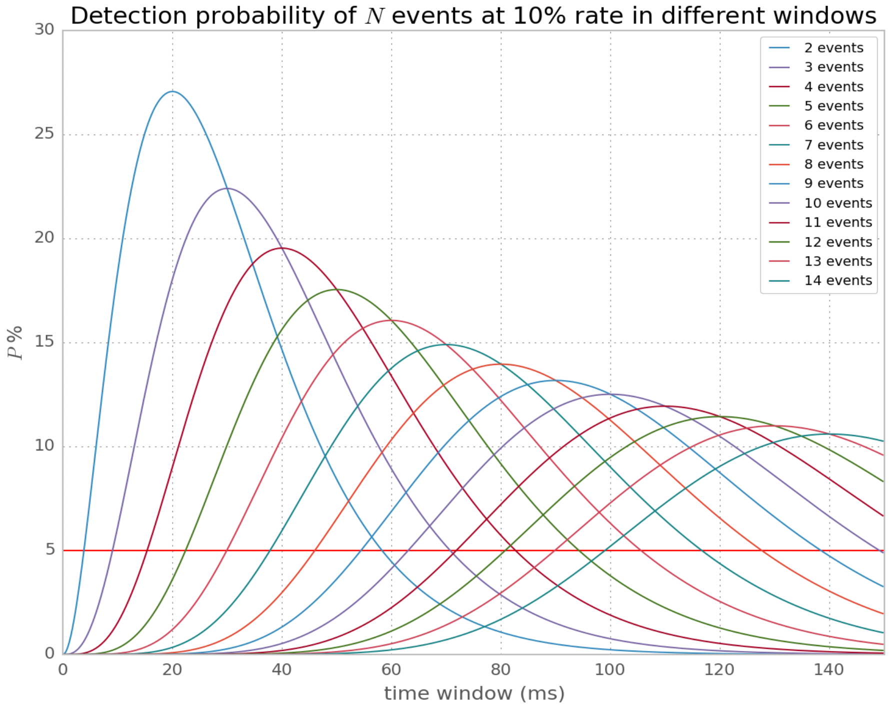


For a given intensity and firing rate, we can compute the probability of groups of K=2, 3,...,*N* events being observed at any given time interval



(1 KHz firing rate, 10% return rate)



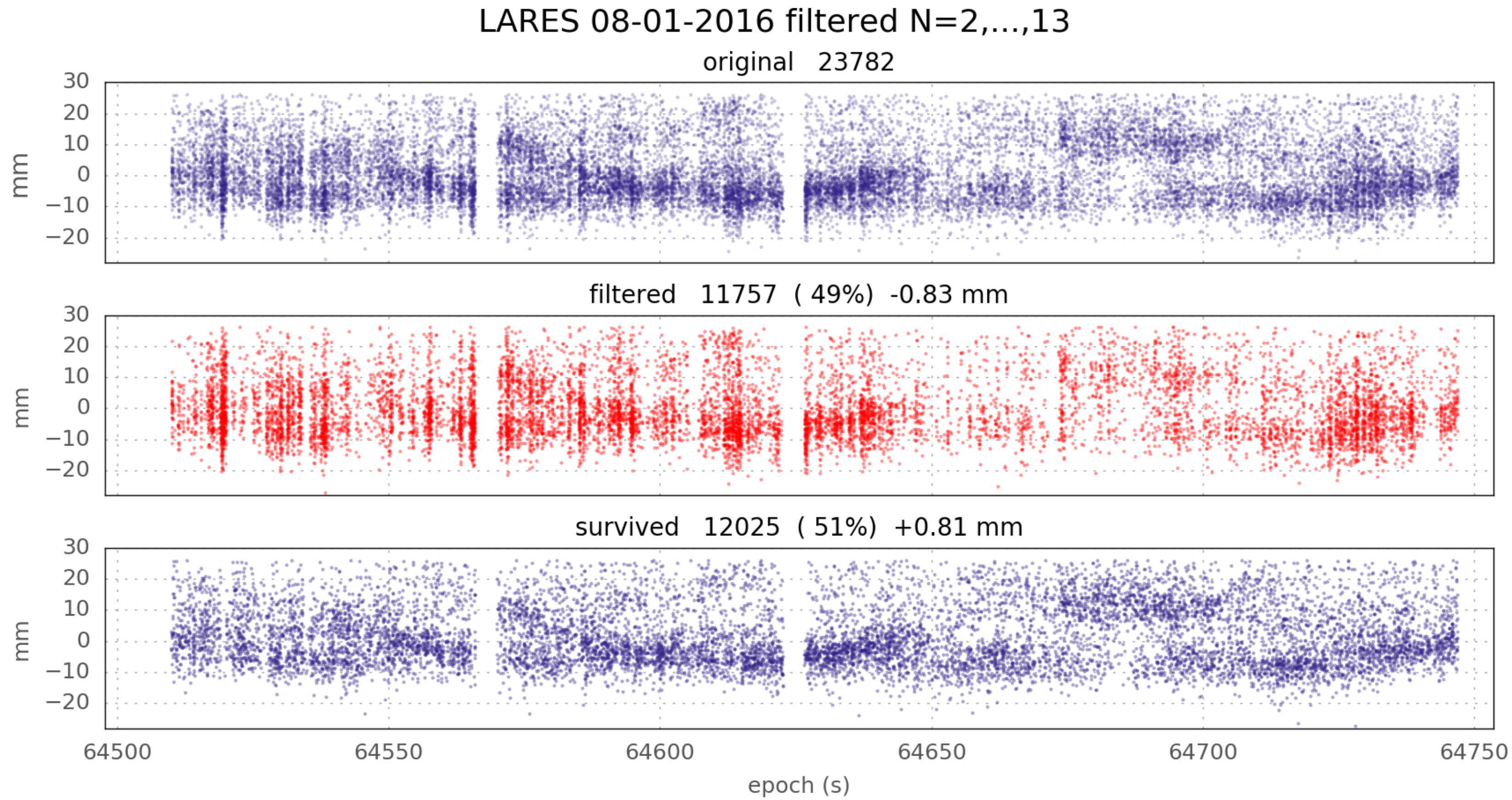
(1 KHz firing rate, 10% return rate)

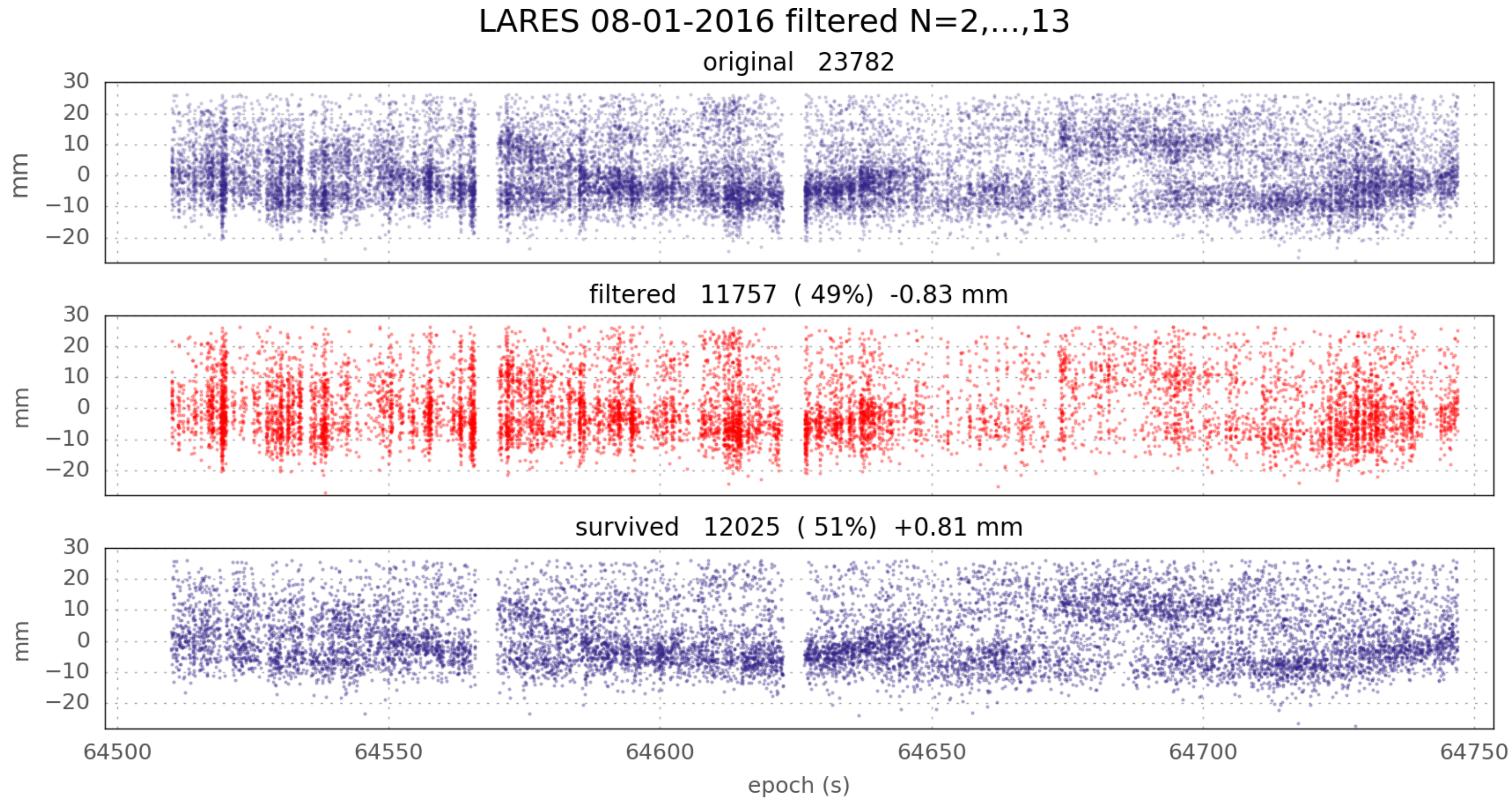
- For a target return rate, compute minimum time windows at which $k = 2, 3, \ldots, N$ events can be observed with a probability higher than some arbitrary minimum threshold (e.g. 2%)

- Go through all detections rejecting all groups of $k = 2, 3, \ldots, N$ events observed in shorter time windows than the precomputed ones

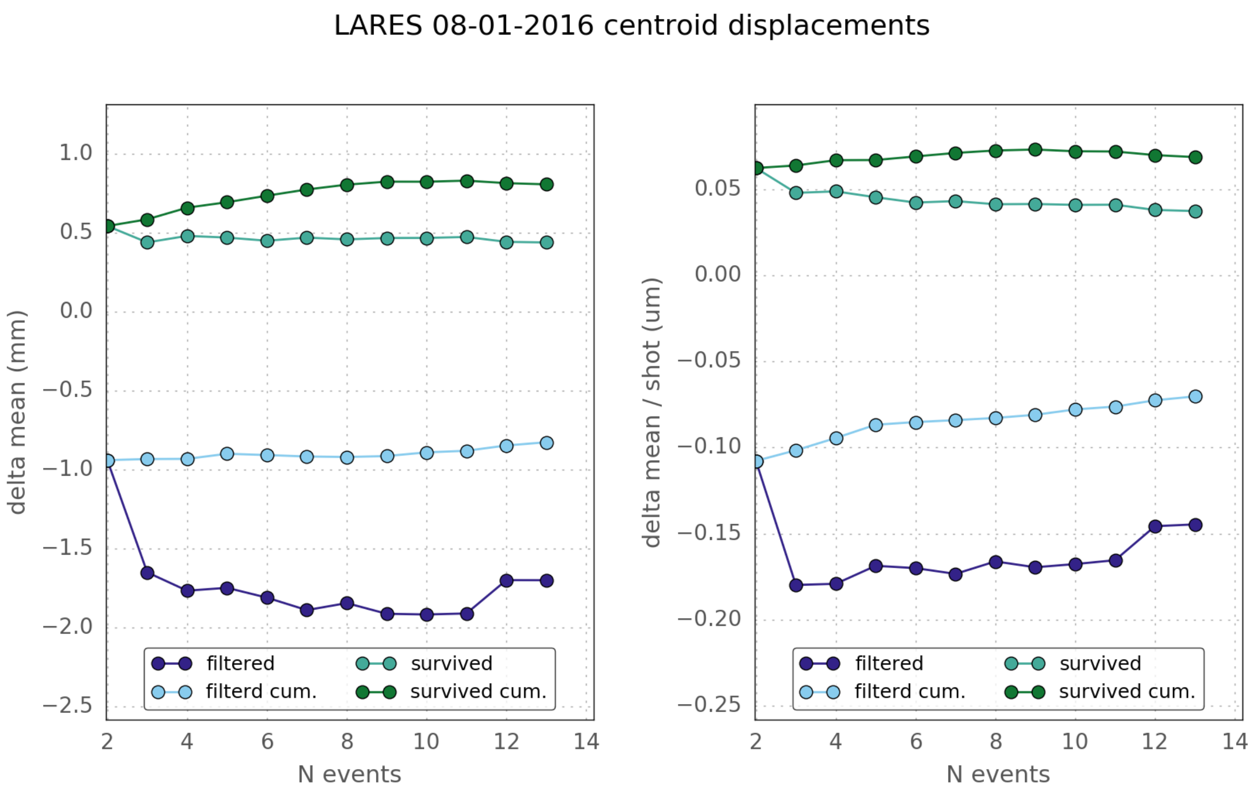
- Rejections are not necessarily multi-photon detections (in fact, most of them will not be), but will contain multi-photon events with a higher probability than that implied from the average intensity rate, and therefore may cause a displacement in the centroid

- This strategy offers the highest possible granularity (event-by-event discrimination)

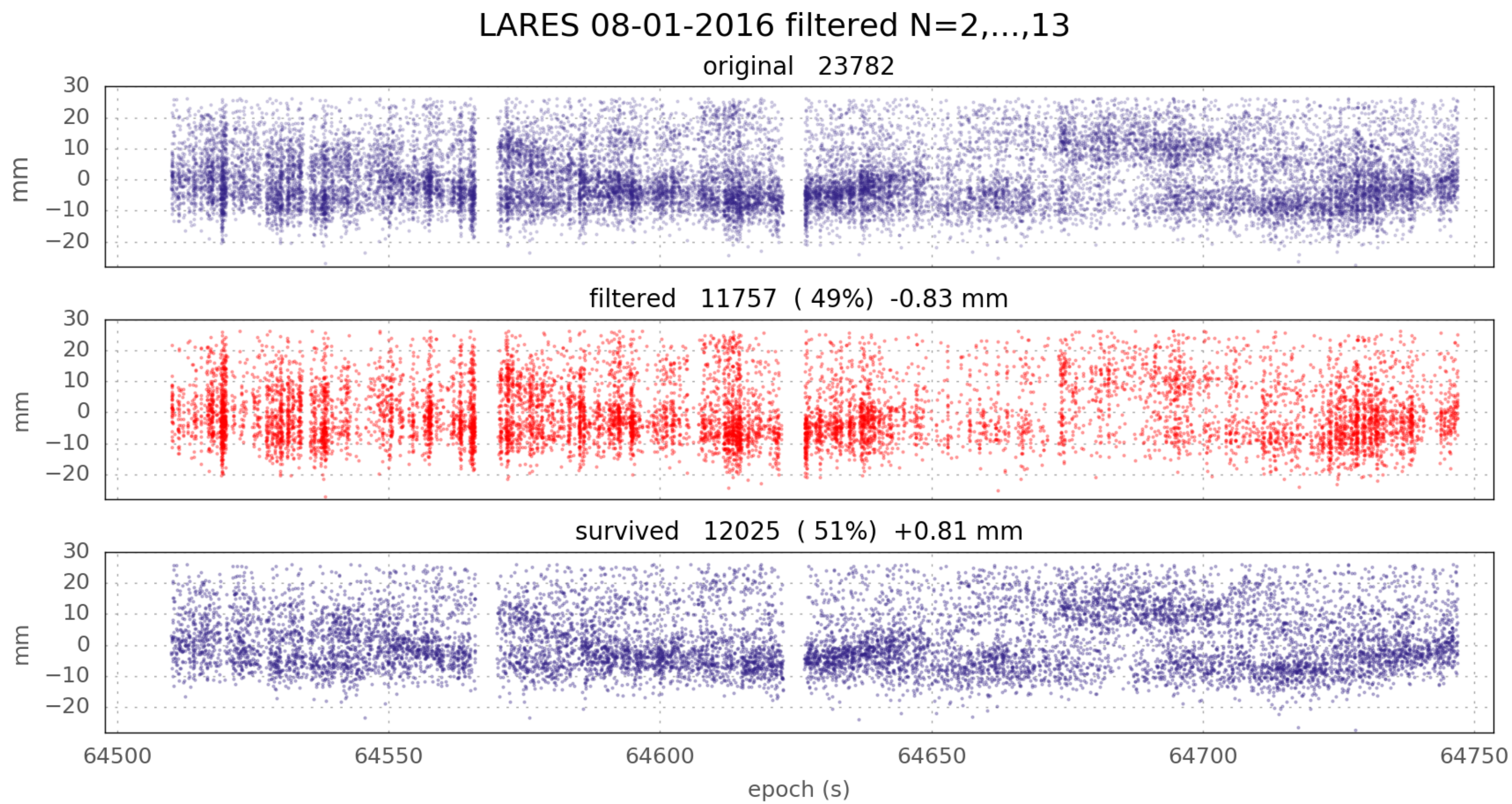

LARES 08-01-2016 filtered N=2,...,13
original 23782
filtered 11757 (49%) -0.83 mm
survived 12025 (51%) +0.81 mm
mm
epoch (s)
30
20
10
0
−10
−20
64500
64550
64600
64650
64700
64750



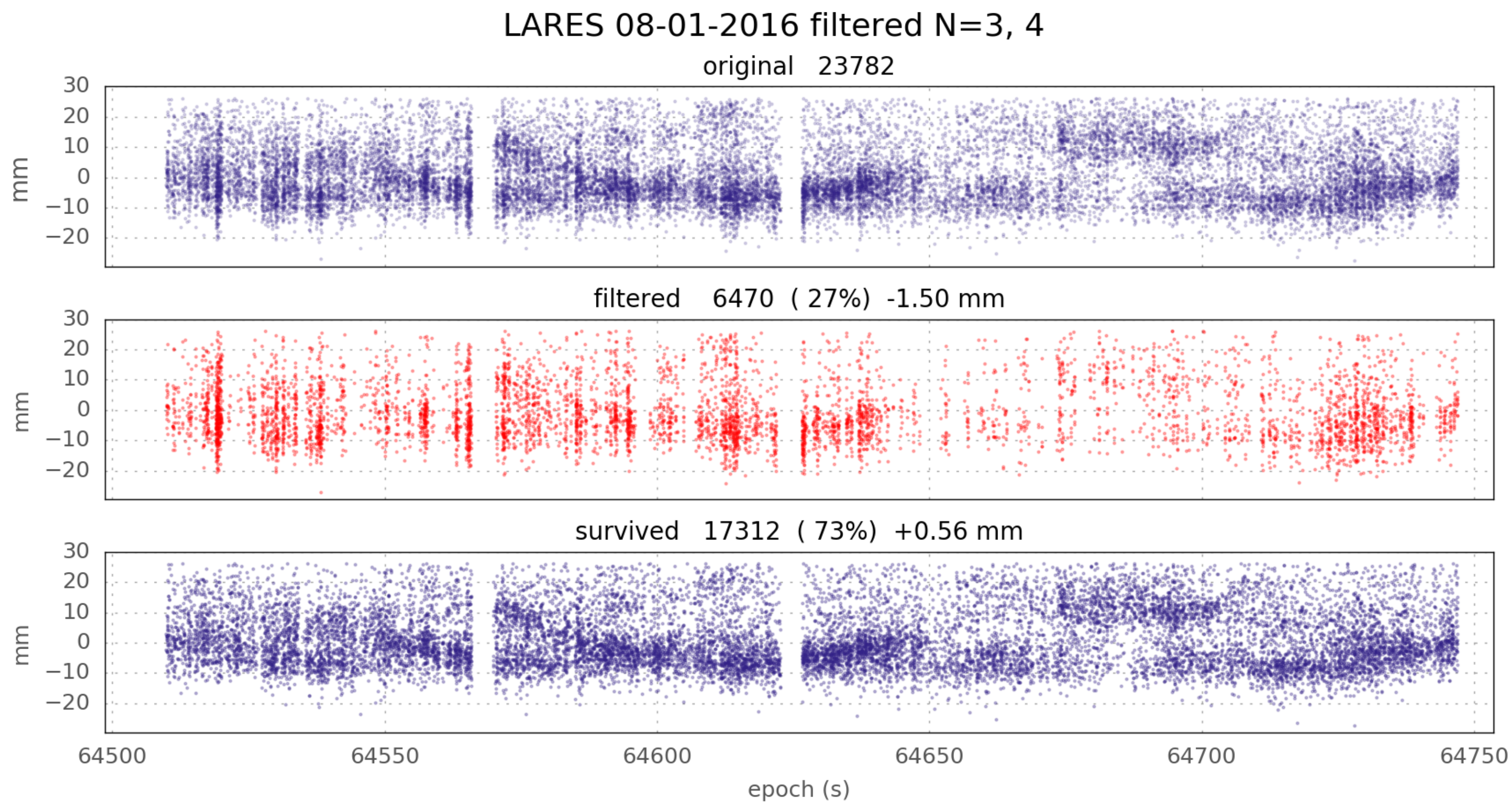
Filter too greedy!



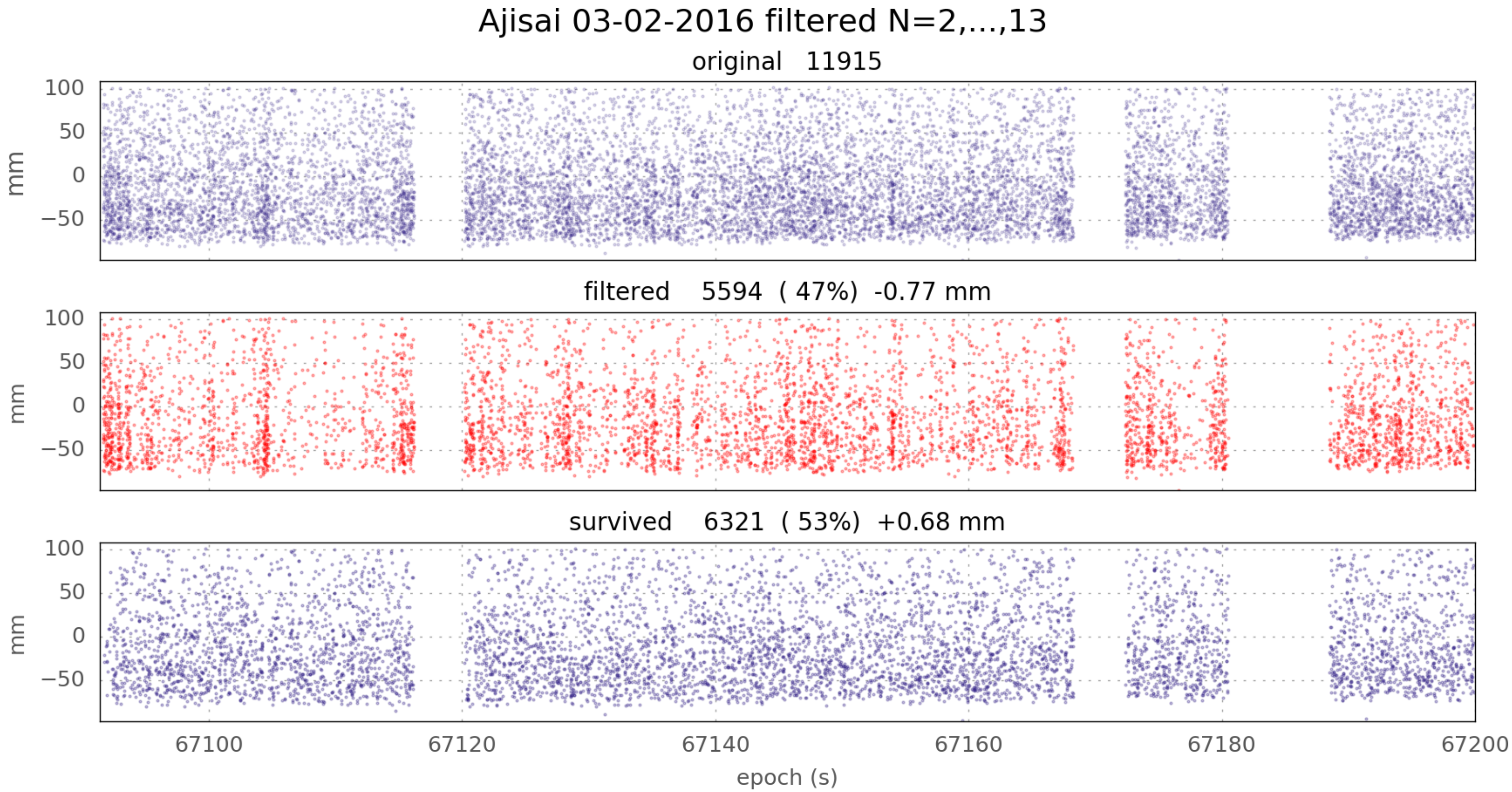
- Look at what subset of filtered events present the greatest centroid displacement
- or better: centroid displacement / shots (more efficient)



All groups of events filtered



Two groups of events filtered



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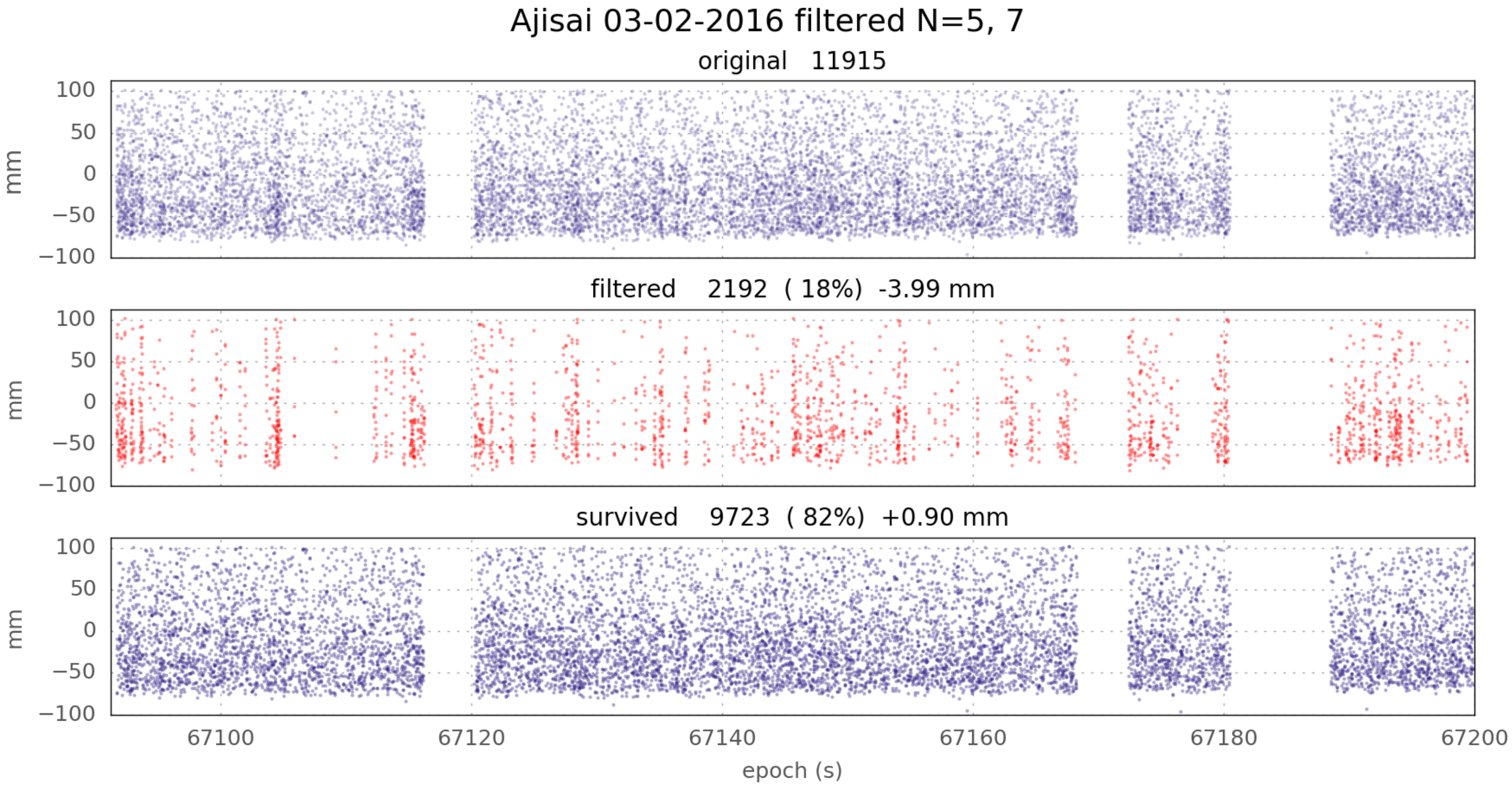
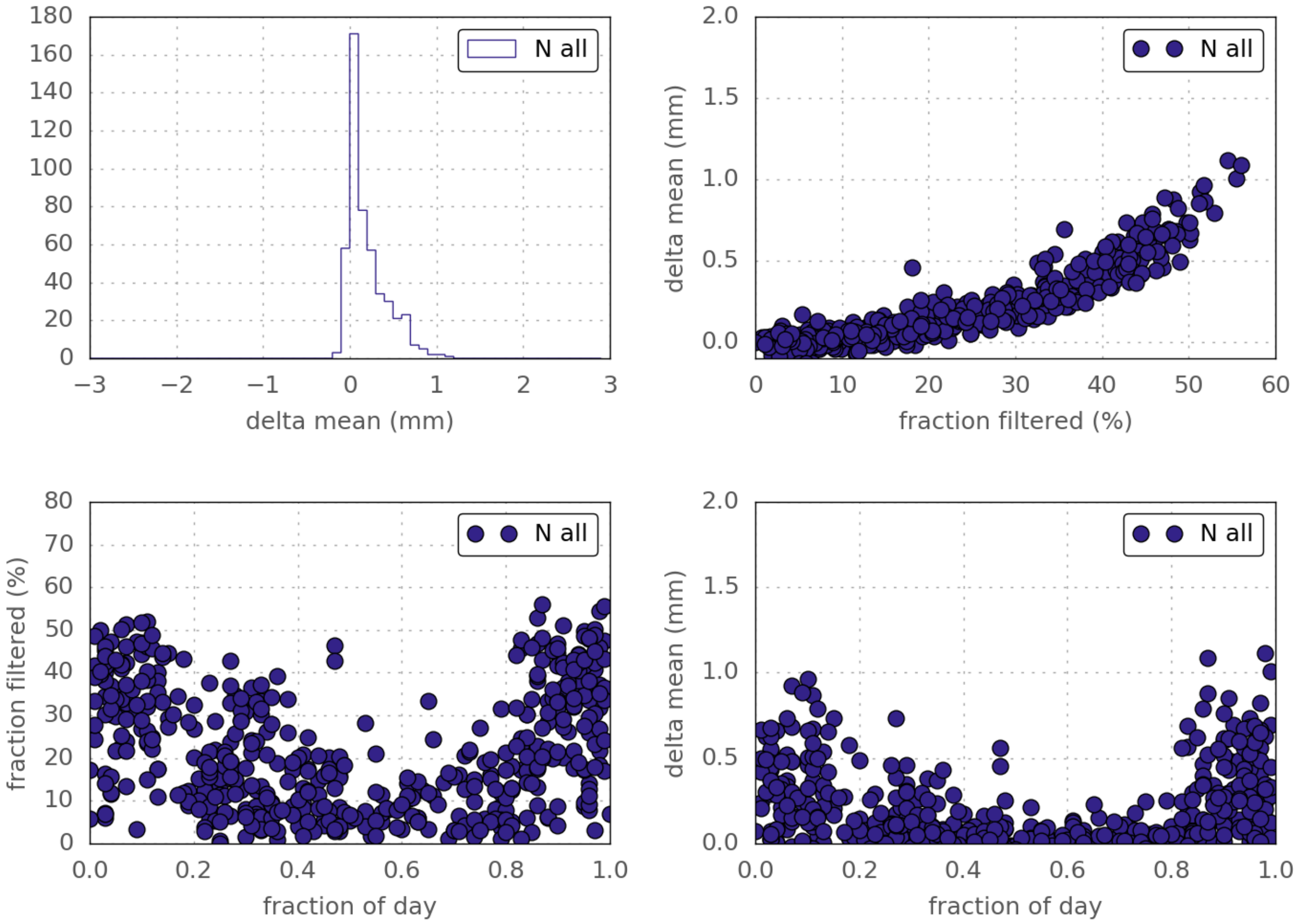


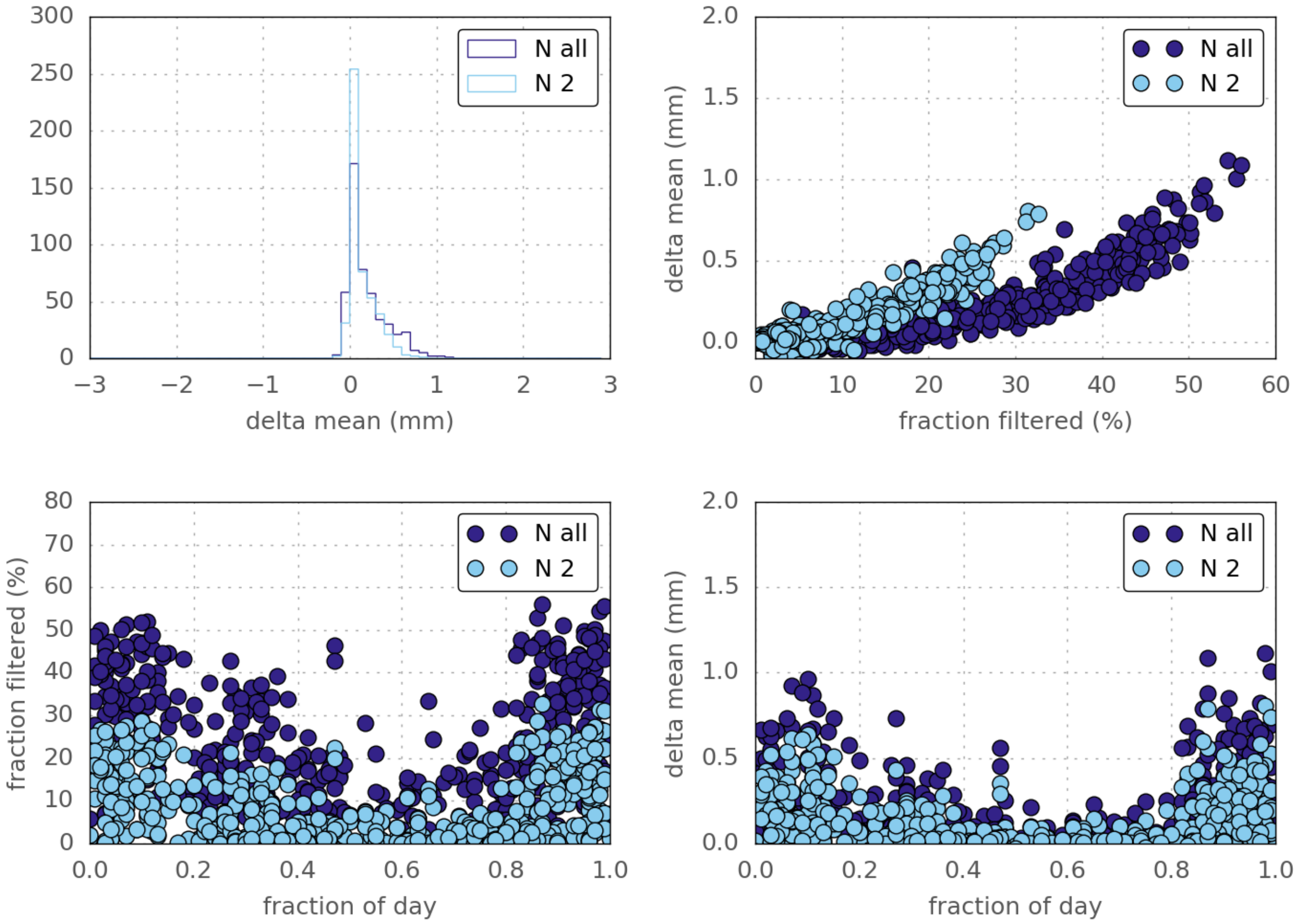
Two groups of events filtered

LAGEOS 2016

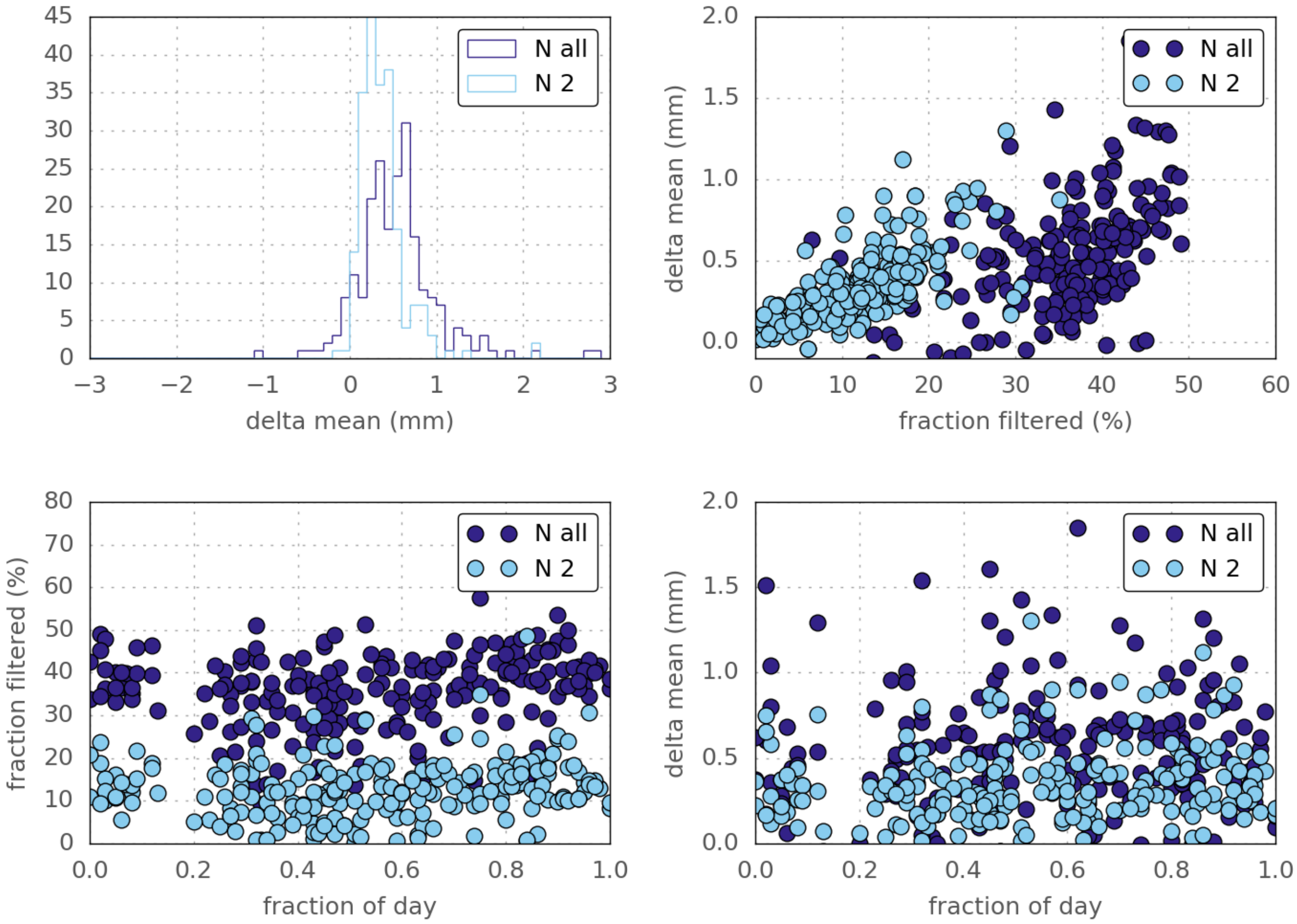


N all
delta mean (mm)
delta mean (mm)
fraction filtered (%)
N all
fraction filtered (%)
fraction of day
N all
delta mean (mm)
fraction of day
N all

LAGEOS 2016



AJISAI 2016



- Why are there bursts of data?

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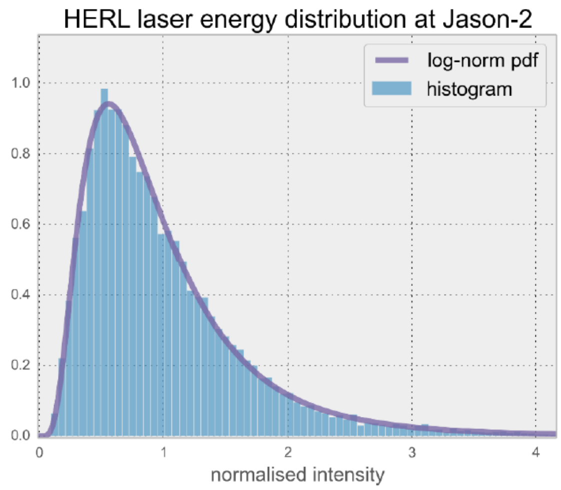
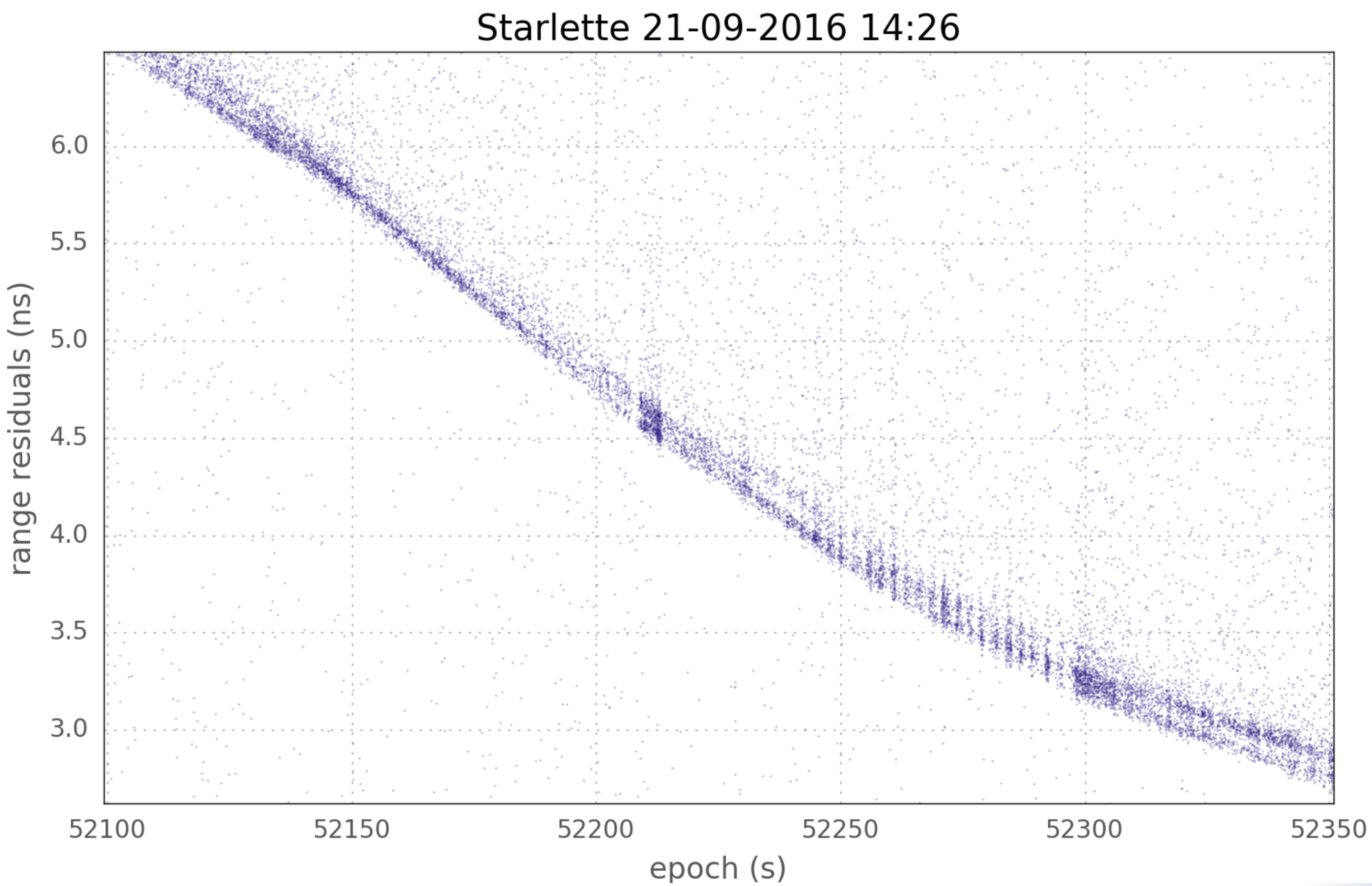
- Turbulence-induced scintillation?



M. Wilkinson, J. Rodriguez, SLR energy density estimations and measurements for the Herstmonceux station; *18th ILWSR, Fujiyoshida, 2013*

- Mostly pointing/tracking when ranging with low laser divergence:



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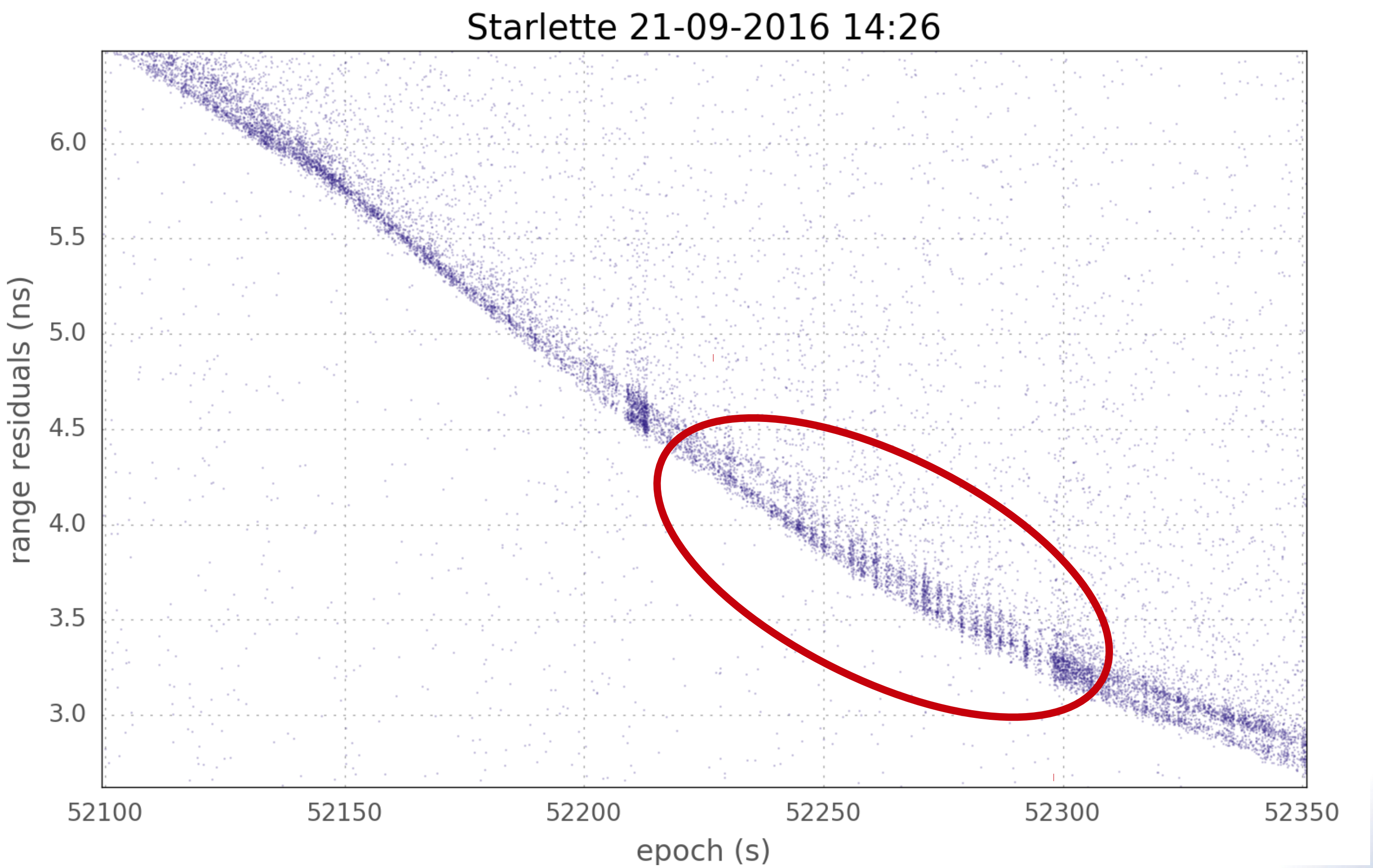

Conclusions

- Using Poisson statistics and counting/timing groups of events we confirm that there are multi-photon detections even at controlled rates

- The impact on *our* data is bounded to a maximum of ~1 mm for LARES/LAGEOS and ~1.5 mm for Ajisai, but most of the time much less than that

- This filtering strategy can be used for simple diagnosis and/or to reject data with higher probability of containing multi-photon events

- The temporal characteristics of the flagged data indicate pointing as the main cause for the short bursts of higher intensity. Easy solution: increase beam divergence to a level where less neutral density is required

- For single photon at KHz rates, the combination of real-time return rate control, generous beam divergence, and use of post-processing Poisson filtering, the contribution to the total error budget attributable to the observing policy is a few tenths of a mm at maximum

Thank you