Federal Agency for
Cartography and Geodesy

Single Photon tracking under difficult condition

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What is a difficult condition?

Consider e. g.:

- Telescope pointing in combination with fast moving objects
- The SLR station covered by a lots of small clouds and plane trails
- Low repetition rate SLR systems

Problem:

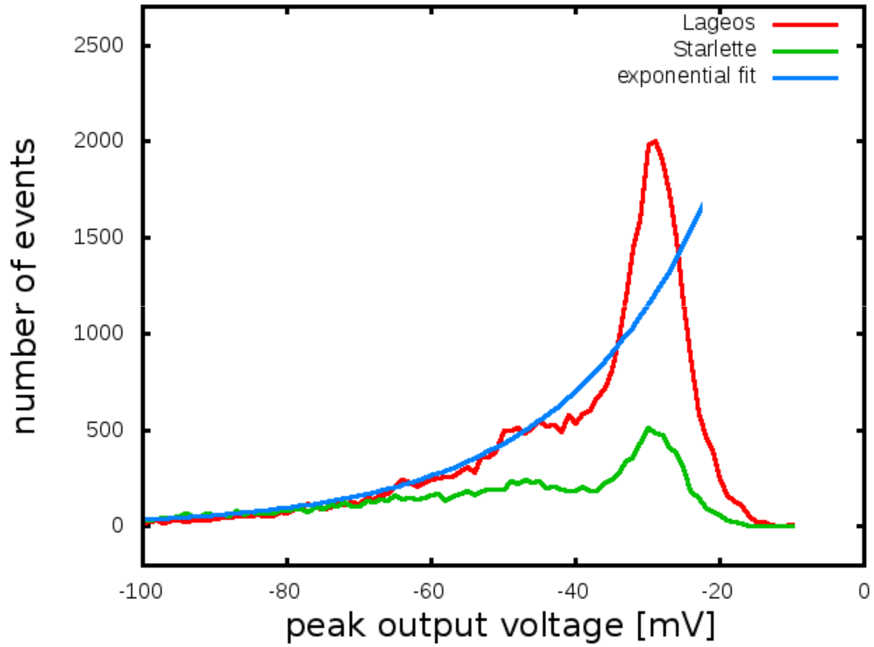
Is single photon really single photon?

WLRS experience

Evaluate 4 month of single photon sensifive MCP data of 20 Hz WLRS (unfiltered),

to get intensity profile.

Distinct single photoelectron peak, washed out multi-photoelectron events (incoherent signal)

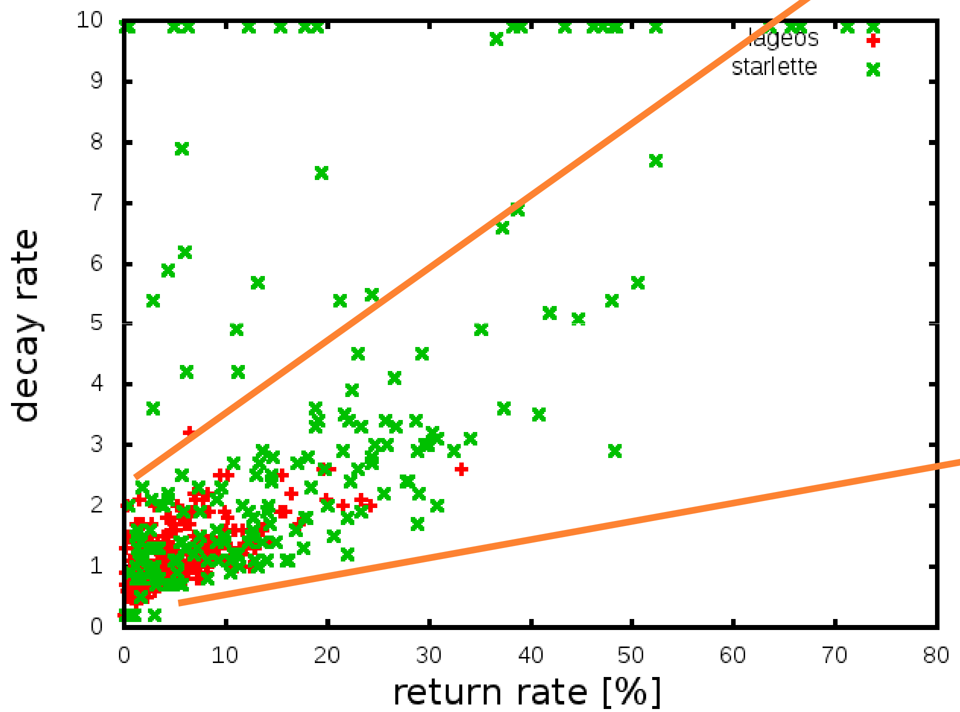


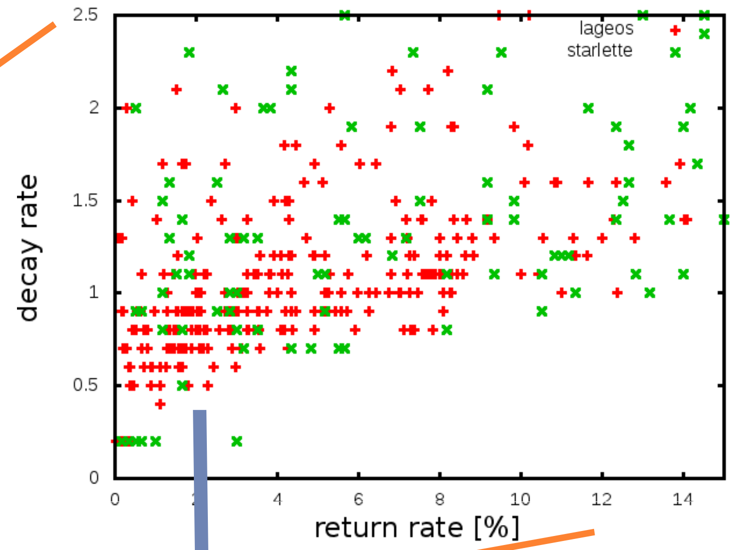
Determination of decay rate possible (gives information about probability of each photoelectron number)

Conclusion: Data is not single photon, consider return rate!

Correlation
return rate – decay rate

Use each NP for Lageos and 3 NPs for Starlette to calculate RR & decay rate





Is there a station dependent lower limit for the decay rate?
What is the range bias for a specific decay rate?

→ Build model to find COM as a function of decay rate

Common model & our idea

Common model:

Tracking of zero signature target to get system noise, convolution with single photon satellite answer (satellite signature)

$$System\ noise\ *\ Satellite\ Signature_{single} = Residual\ Histogram$$

Our idea:

Extend single photon satellite answer for mixed state answer and do convolution with receiver model (receiver signature), **decay rate is the only free parameter (measureable)**

$$Receiver\ Signature_{mixed}\ *\ Satellite\ Signature_{mixed} = Residual\ Histogram$$

Receiver Model
- principle -

SPAD:

Introduced in Fujiyoshida:

$$p(t) = \sum_{n} exp^{(n \cdot f)} \cdot exp^{\left(\frac{(t+e \cdot log(n))^2}{-2 \cdot b^2}\right)}$$

n: different photon numbers, evaluation from 1 to 5 suffizient for decay rate up to ~ 1.5

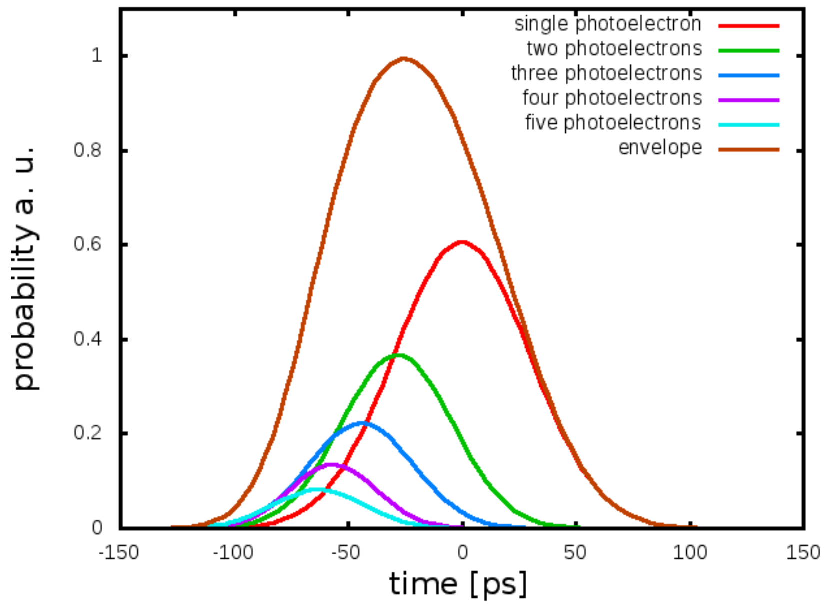
MCP:

Empirical model behaviour of Discriminator hard to describe by theory, build by filtering different peak voltage intervals in laboratory measurement.

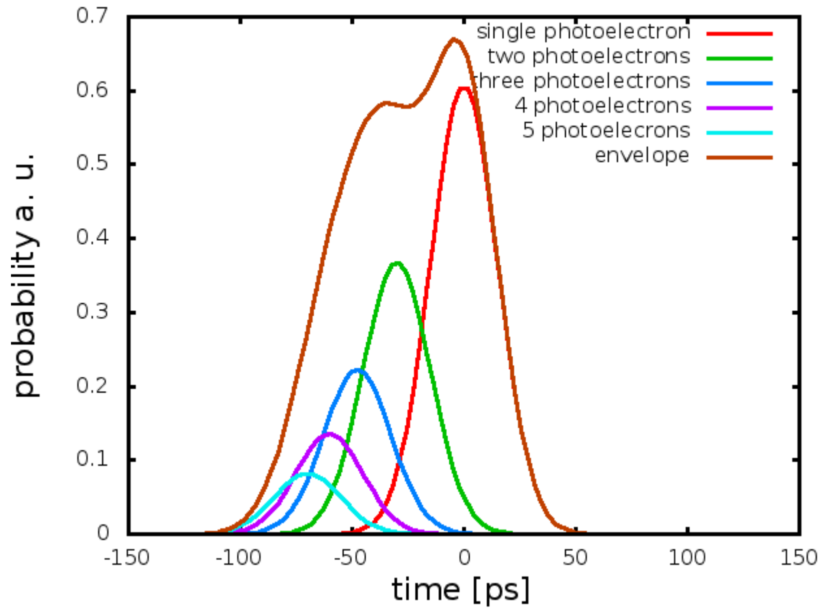
Receiver Model
- plots -

Combine single and multiple photoelectron multiplication together with decay rate to receiver signature e. g. for:

MCP, decay rate 2



SPAD, decay rate 2

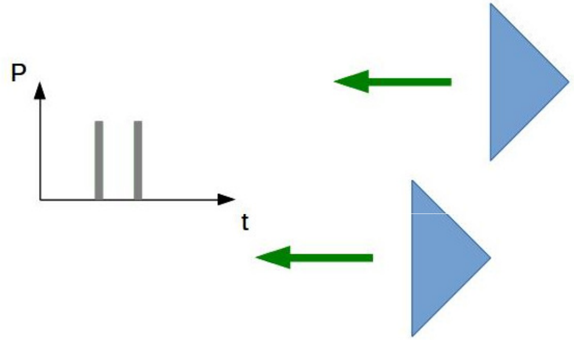


Satellite Model
- principle -

Need to find multiple photon satellite answer, principle:

Consider 2 identical CCR with Single Photon Detector (first photon counts)

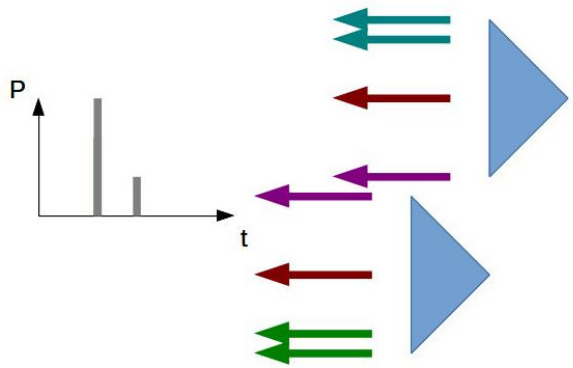
Two peaks for single photon returns, with same Probability



Now: two returning photons

Apply methods of Combinatorics

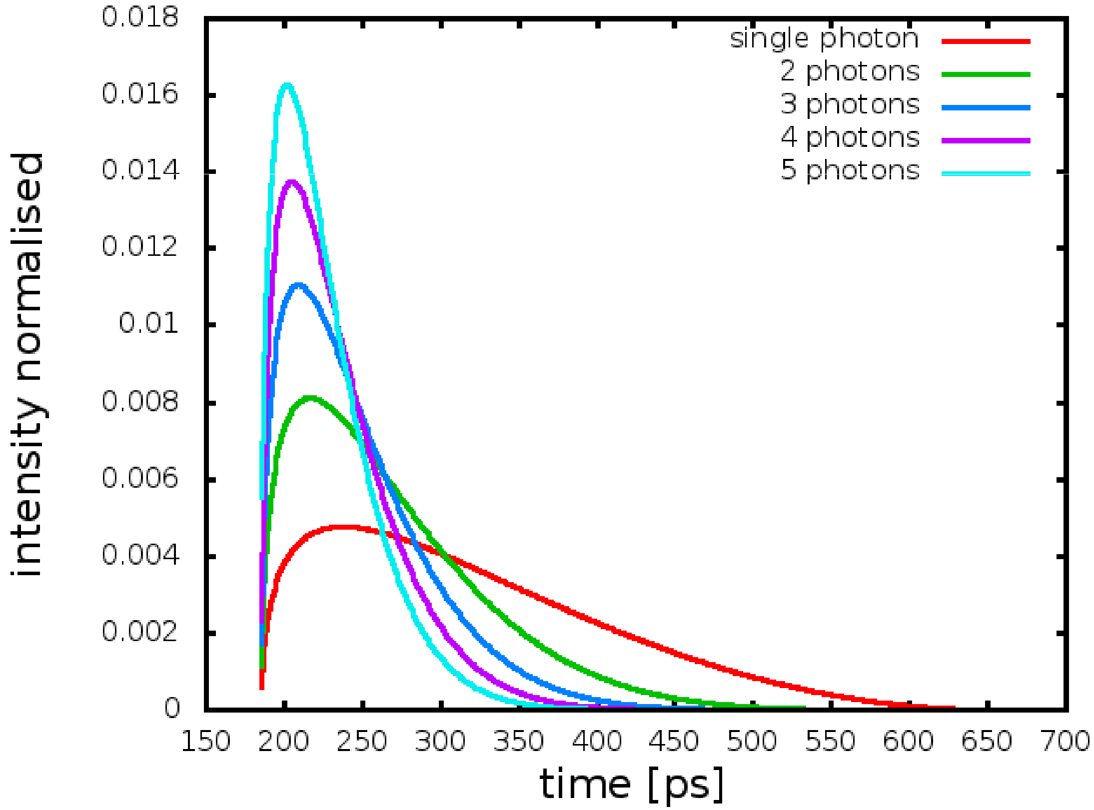
$\rightarrow \; P(CCR1) = 3 \cdot P(CCR2)$



Satellite Model
- Plots -

Use single photon satellite response from John Degnan [Millimeter Accuracy SLR] for single photon data and compute multi photon distributions, e. g. Lageos:

Apply decay rate & convolute with receiver signature



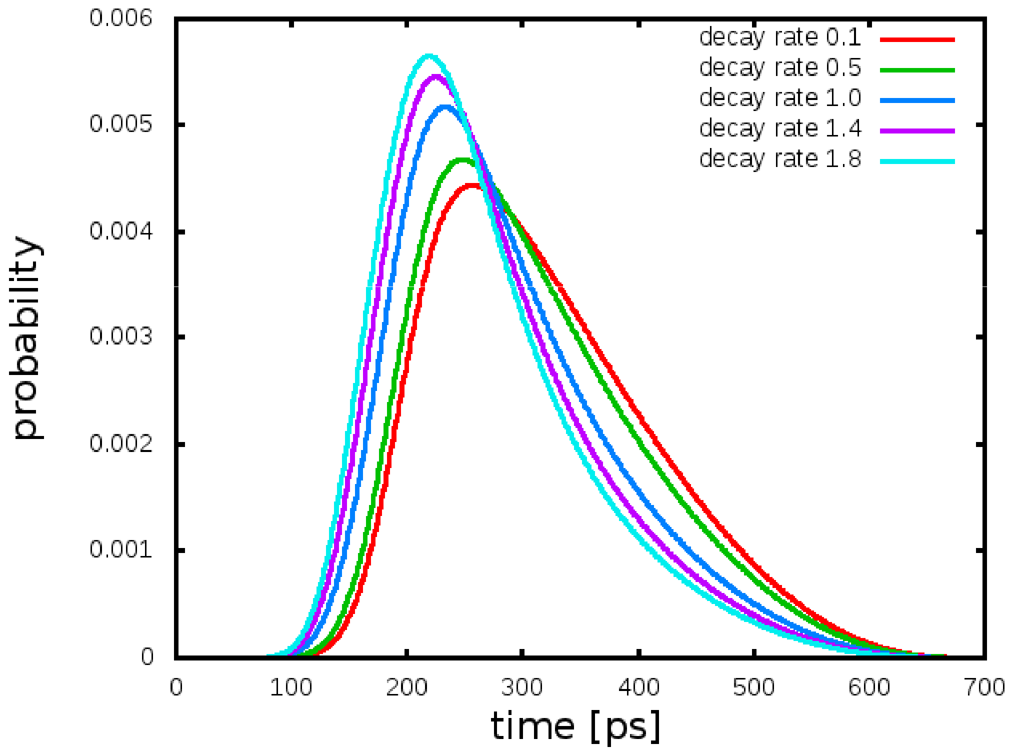
Convolution

For Lageos tracked with MCP and different decay rates

decay rate increasing

=>

Distribution becomes peaky and (of course) shifts towards satellite front

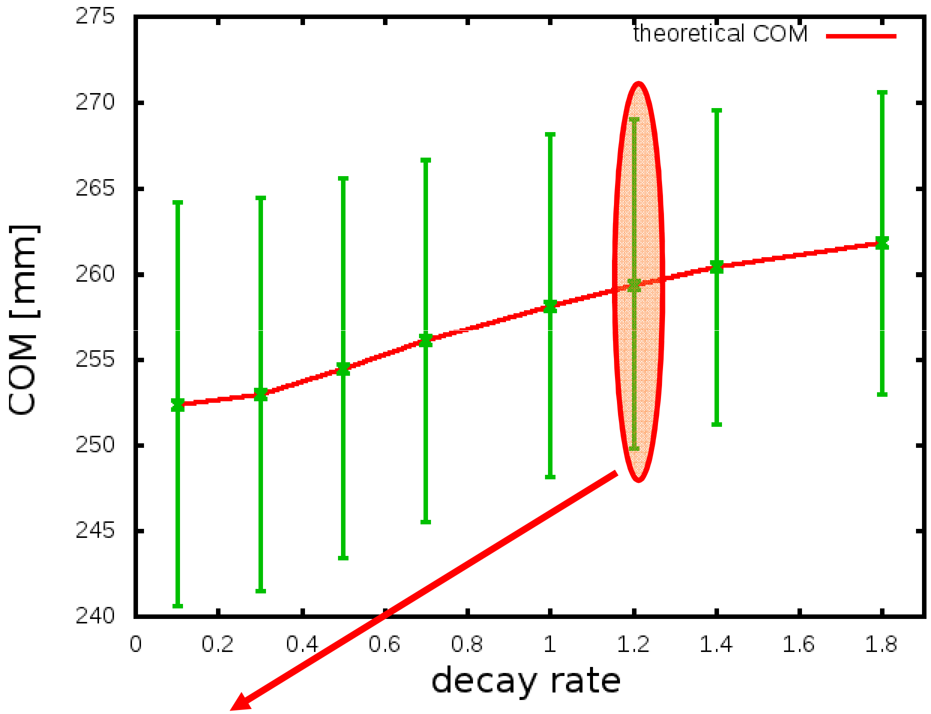


Calculate mean to get COM (decay rate)

Theoretical COM correction

COM and SDEV (Lageos, MCP)

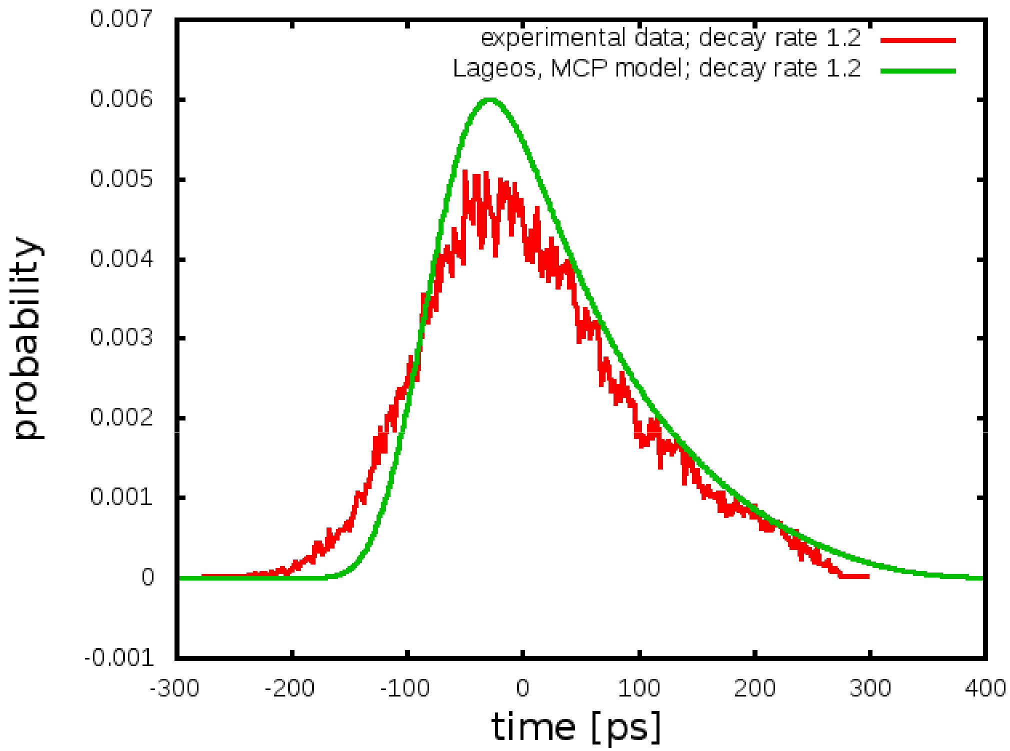
Range Bias > 1mm
for decay rate > 0.4



Mean Decay Rate WLRS 1.2 => Range Bias ~ 7 mm !

However: verification of model still pending

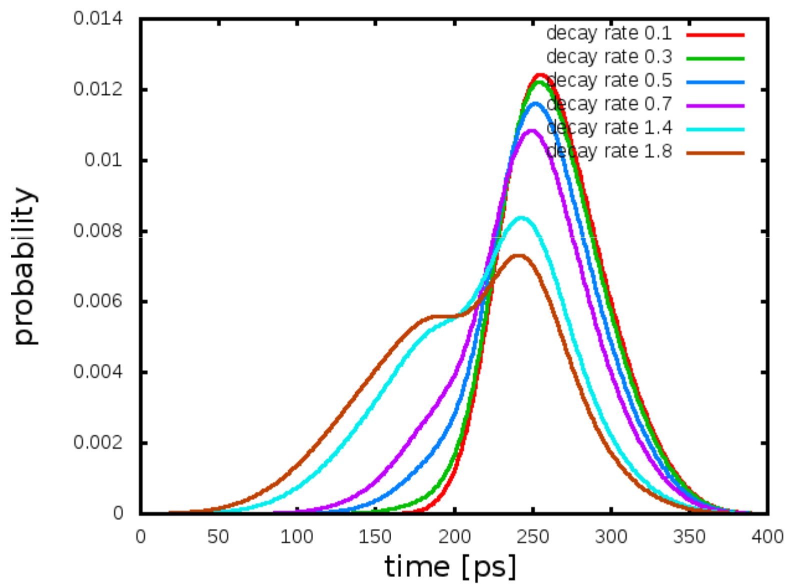
Residual Histogram
- 20 Hz data -

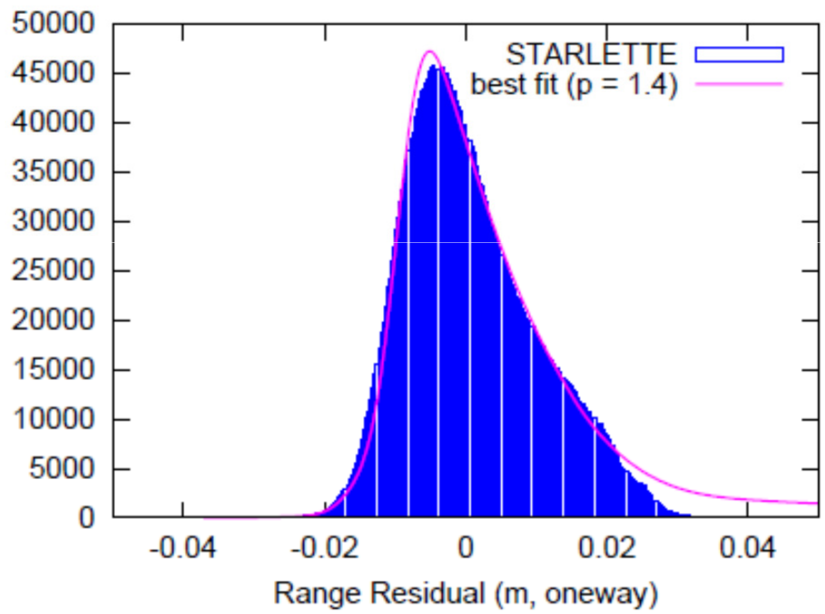


Agreement not perfect, accumulation of different passages.
Find agreement during 1 passage → kHz data neccessary

Residual Histogram
- kHz data -

Considering data published by Toshi [Annapolis, 2014]
And our model for Starlette & K14 SPAD





Our model might be able to explain behaviour of rising edge

Trailing edge is more complex, SPAD diffusion tail not modelled, yet

Conclusion

- Unfortunately model verification still pending
- Introduced receiver signature
- Chance to identify constant (SCALE, lower limit of decay rate) and varying range biases (NP RMS)
- We have developed a model that is able to handle mixed states, which may arise in difficult tracking conditions with all of the parameters measureable