Photometry with Gated SPAD: Theory and Approach

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ABSTRACT

- Gated single-photon avalanche diode (SPAD) is widely used in satellite laser ranging (SLR). With proper calibration, SPAD is possible to make photon flux measurement simultaneously while performing laser ranging. This presentation models the photon flux response of a gated SPAD while performing laser ranging. Algorithm to analyze range data for input photon flux is introduced.
- Experiment of photon flux measurement is done with Changchun SLR system. Fluxes are measured for dark current, night sky background, day sky background, bright stars and some ILRS targets in typical scenario.
- The method can be widely used in applications involving signal strength of echoes.

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Get Brightness of Echoes

Outline

1. Background and Problem
2. Theory and Algorithm
3. Experiment and Analysis
4. Discussions

1. Background and Problem

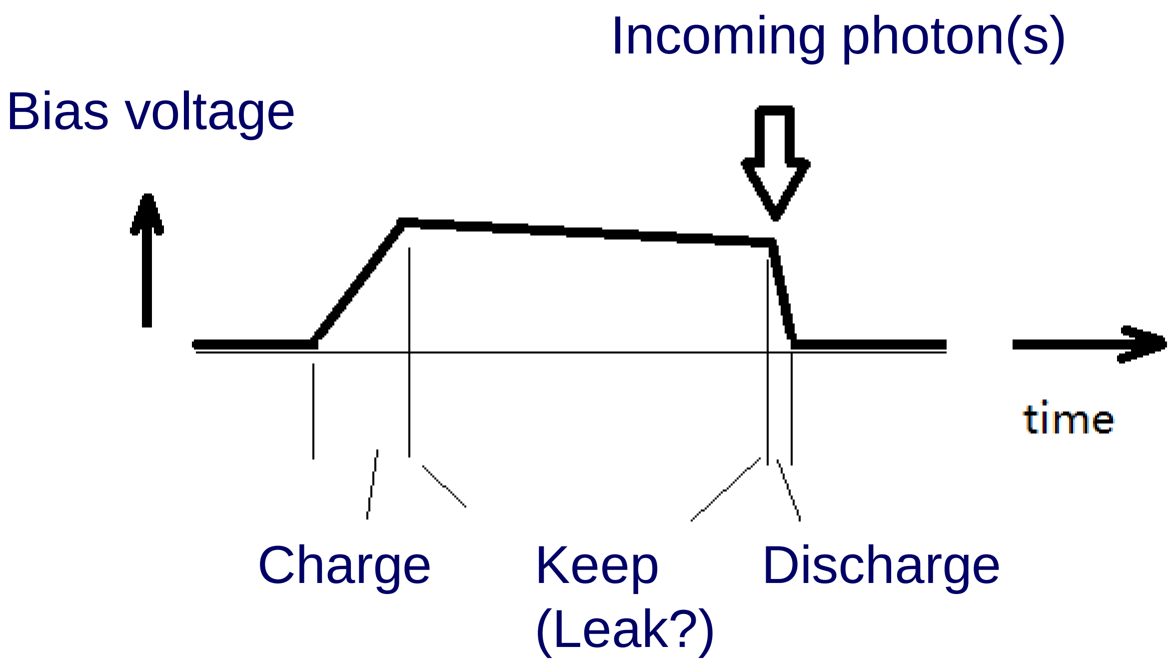
Background

- Avalanche Photon Diode (APD) is used in laser ranging.
- Range precision/biases are hot topics, while luminance is rarely mentioned.
- The existing metric for signal luminance is return rate.

1. Background and Problem

APD work cycle:

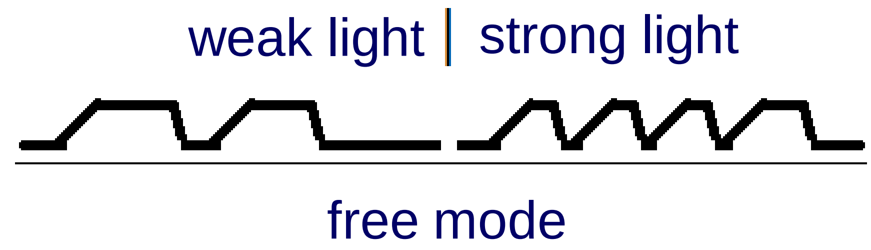
Charge > Keep > Discharge.



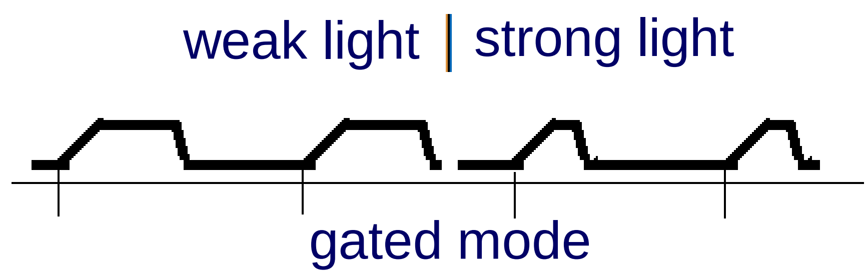
1. Background and Problem

APD Photometry

- Free Mode:
  - APD charges again immediately after avalanche.
  - Used in normal photometry.



- Gated Mode:
  - APD charges only when gate signal allows.
  - Used in SLR.



1. Background and Problem

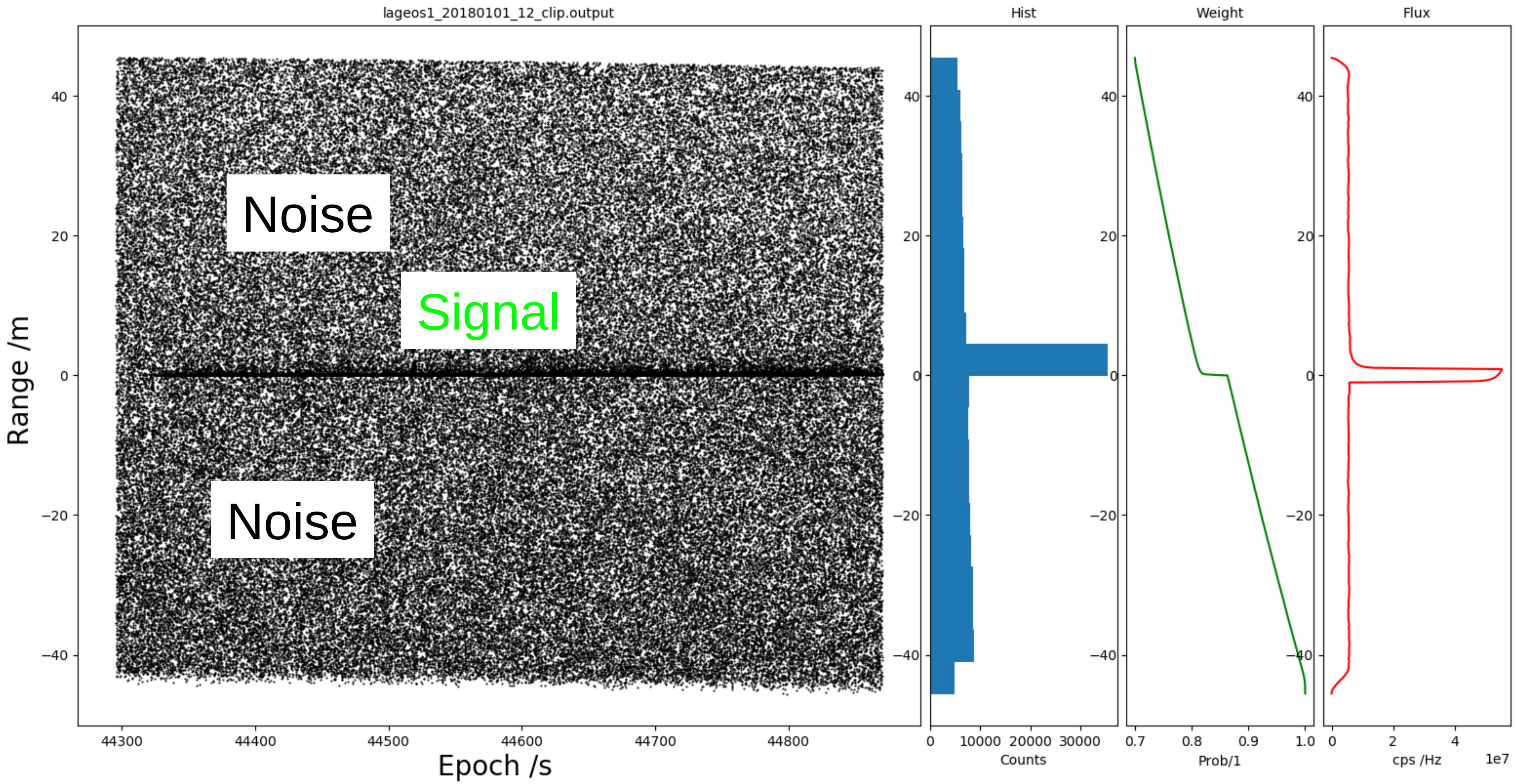
Background

- Avalanche Photon Diode (APD) is used in laser ranging.
- Range precision/biases are hot topics, while luminance is rarely mentioned.
- The existing metric for signal luminance is return rate.

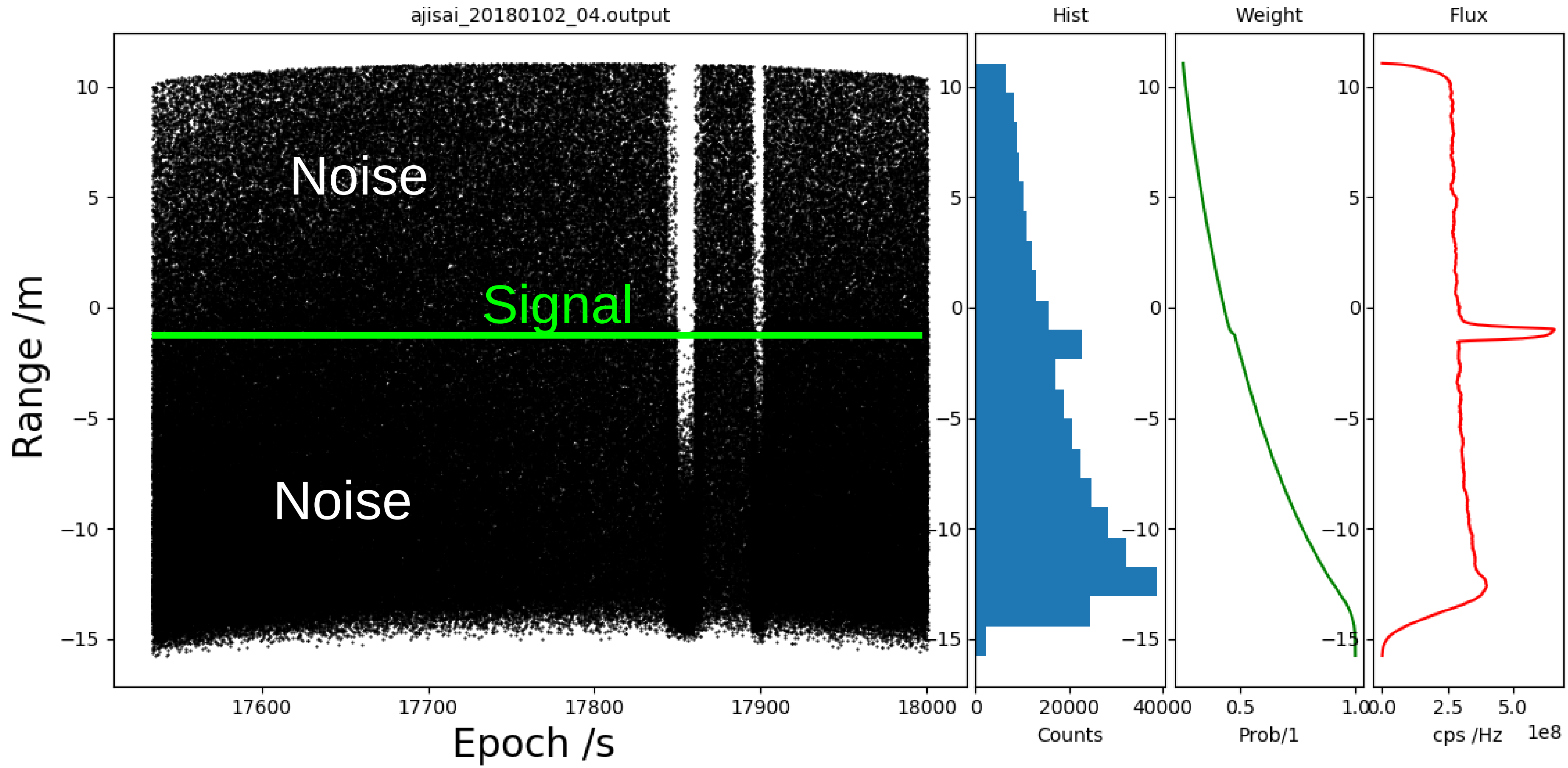
Problem

- Return rate is inaccurate in measuring incoming photon flux.
- Heavy noise may reduce return rate.

Typical O-C Plot (Night Lageos1)



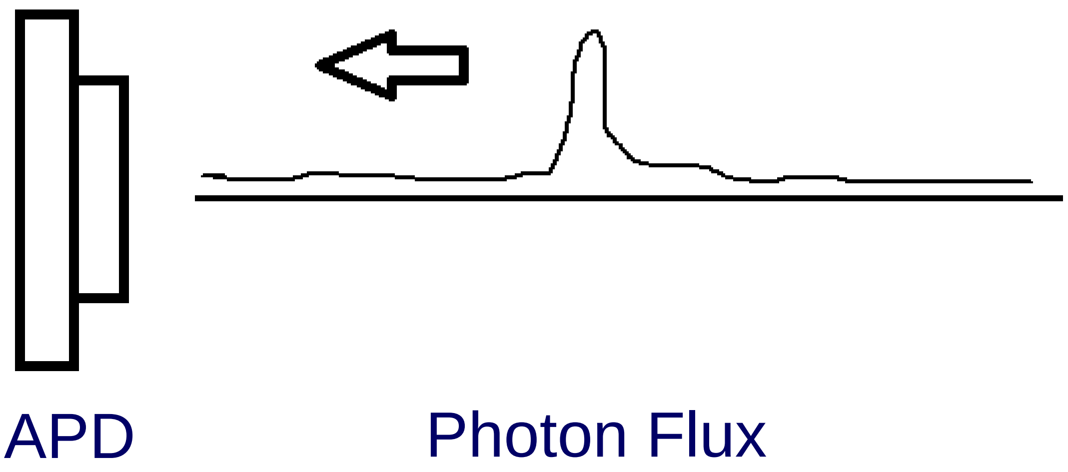
Typical O-C Plot (Daylight Ajisai)



2. Theory and Algorithm

2.1 Assumption

- The photon flux *S(t)* is repeated on every measurement.
- The APD avalanches once on every measurement.



2. Theory and Algorithm

2.2 Mathematical Modeling

- The APD gets charged up before step 1.
- Each step hasΔt time-span.
- P_i – In *i*-th step, the probability that APD is discharged.
  Therefore $P_0 = 0$
- S_i – In *i*-th step, the photon flux (count per second, cps)
- η– Quantum efficiency, number of photoelectrons excited by one photon.
- After a lot of mathematics (See Appendix 1)

$$S_i = \frac{1}{\eta \Delta t} \ln\left(\frac{1-P_i}{1-P_{i+1}}\right)$$

3. Experiment and Analysis

3.1 Photometry of Dark Noise and Sky Noise

3.2 Photometry of Stars

- 3.2.1 Stellar Magnitudes
- 3.2.2 Measurement Data Display

3.3 Photometry of Satellites

- 3.3.1 Avalanche Rate Measurement
- 3.3.2 Avalanche Rate to Magnitude

3. Experiment and Analysis

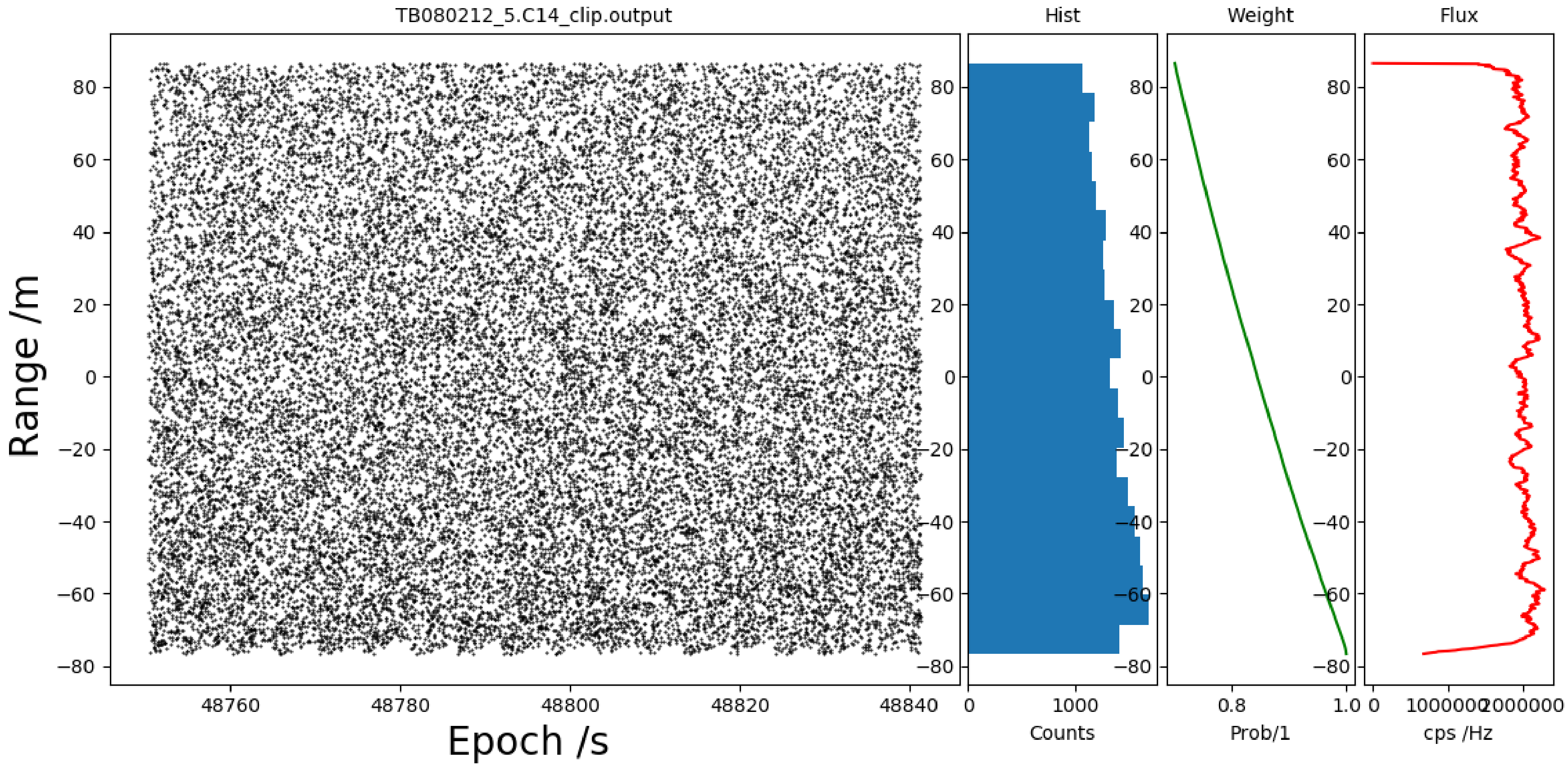
3.1 Photometry of Dark Noise and Sky Noise

- Measure Dark Noise
  - Block transmission beam.
  - Plug receive hole. (?)
  - Do laser ranging.

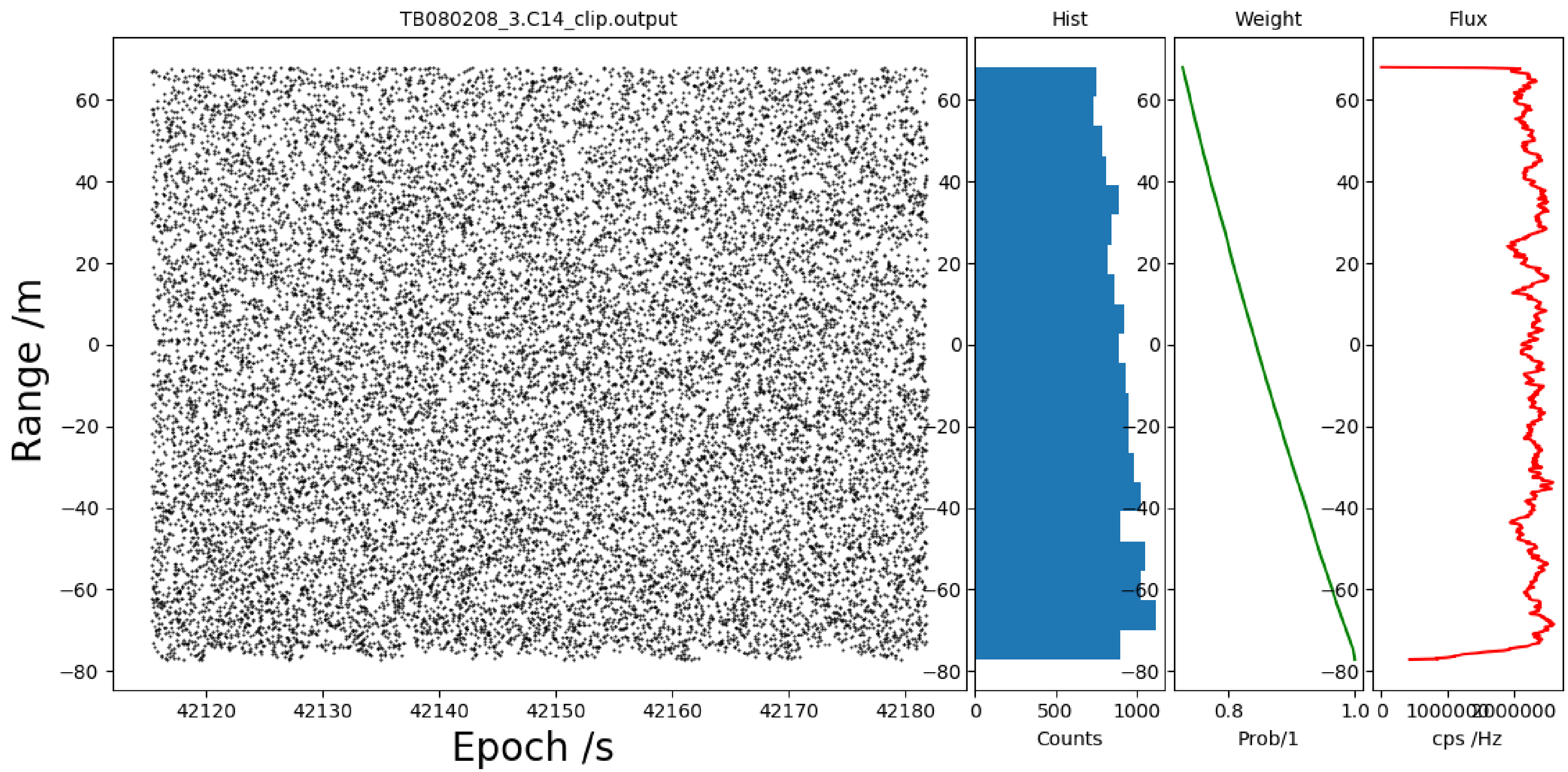
- Measure Sky Noise
  - Block transmission beam.
  - Aim at sky.
  - Narrow down the FOV iris.
  - Do laser ranging.

Cork Plugs

Dark Noise (Plug)



Sky Background Noise



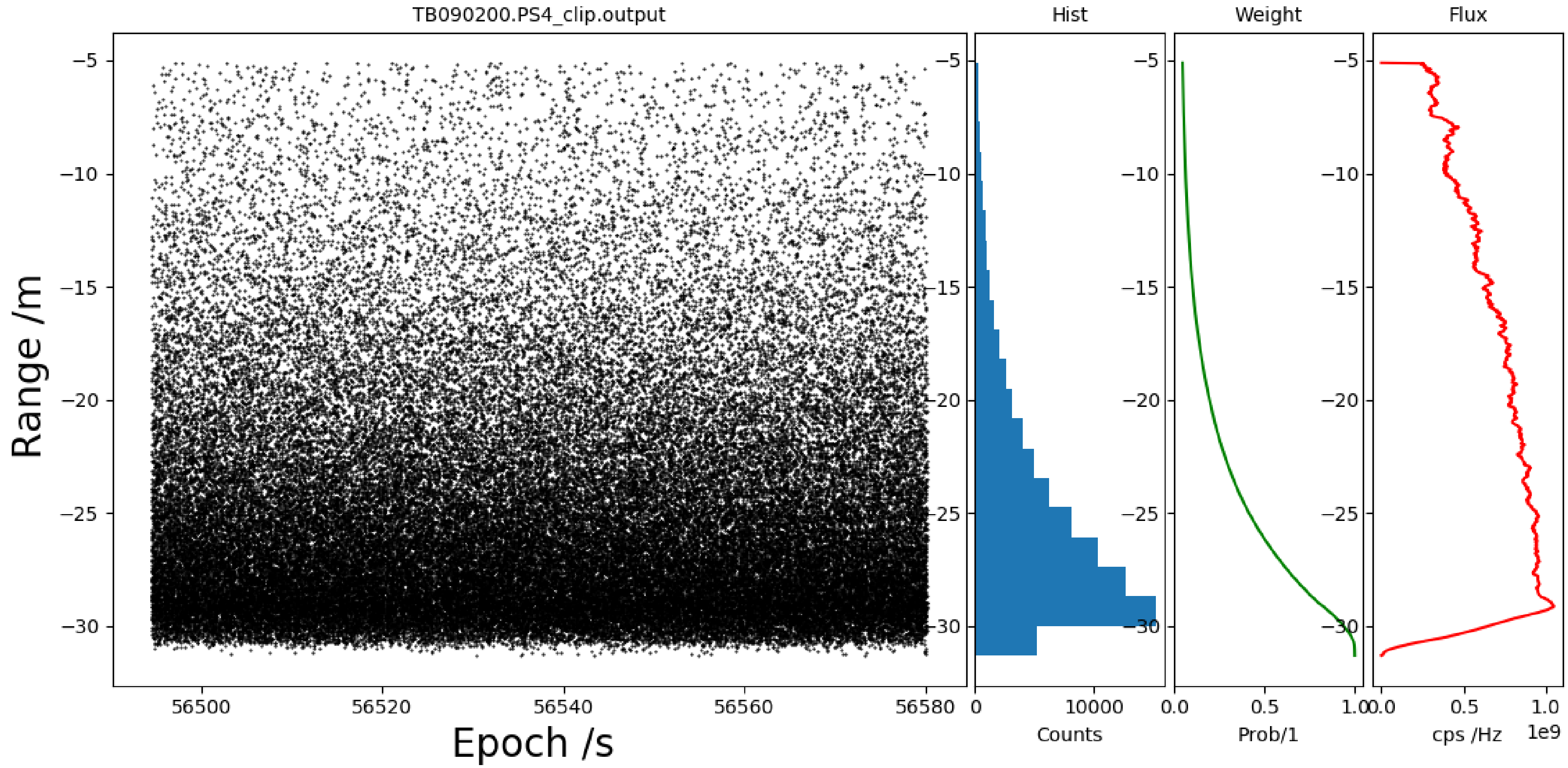
3. Experiment and Analysis

3.2 Photometry of Stars

- Arbitrarily choose bright stars around current zenith.
- Get star information from SIMBAD database.
- For 532nm wavelength, choose V magnitude among UBVRIJHK fluxes. (For 1064nm choose I.)

Catalog No.	Star Name	Vmag
HD8890	Polaris	V 2.02
HD432	bet Cas	V 2.27
HD3712	alf Cas	V 2.23
HD8538	del Cas	V 2.680
HD11415	eps Cas	V 3.37
HD20902	alf Per	V 1.79
HD137422	gam UMi	V 3.002
HD142105	zet UMi	V 4.274

Photometry for Polaris (Vmag 2.02)



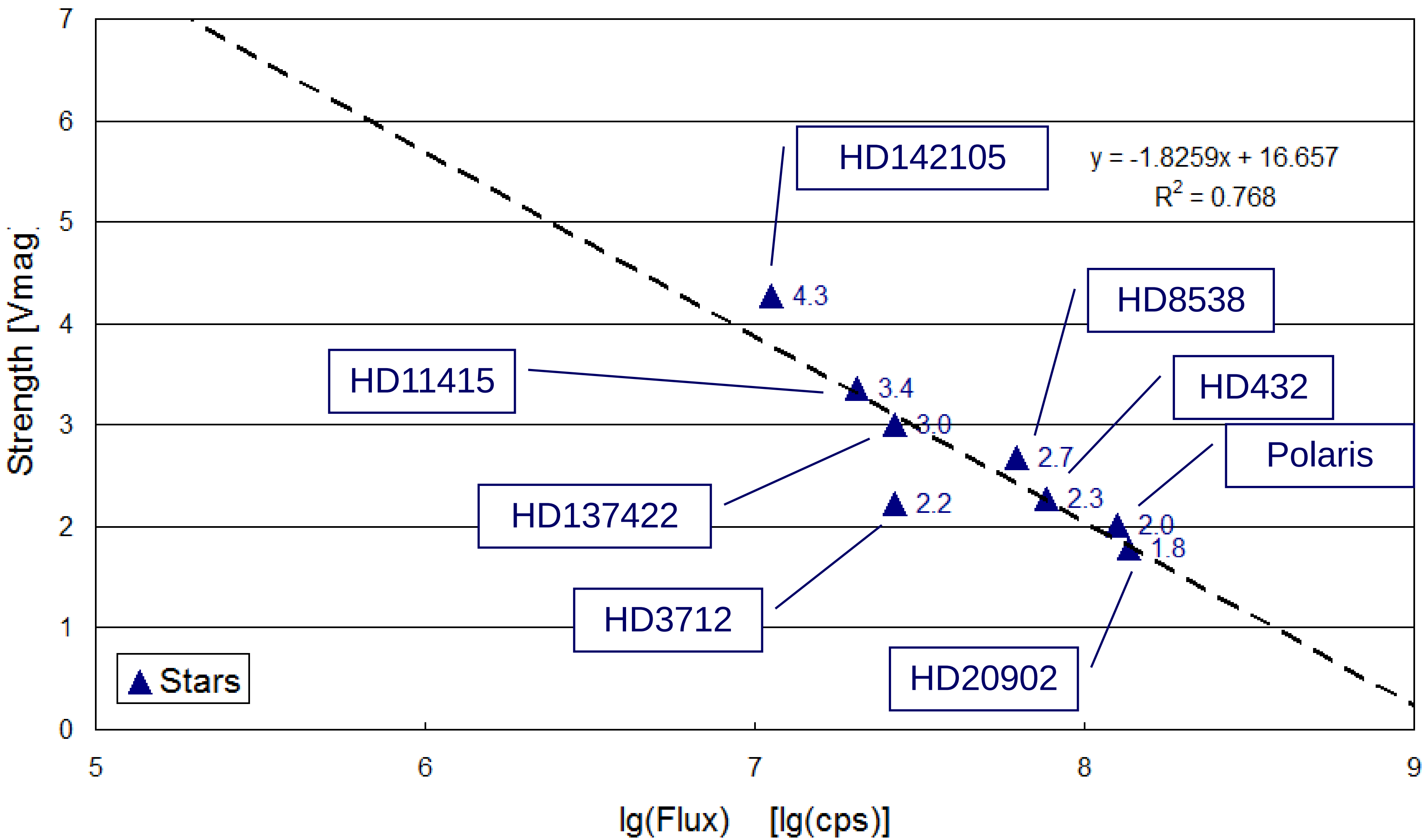
3. Experiment and Analysis

3.2 Photometry of Stars

- Steps:
  - Track a star.
  - Block transmission beam.
  - Do laser ranging.

- Remove dark noise flux from star flux measurements.

- Fit nominal Vmag to lg(flux) with linear regression.

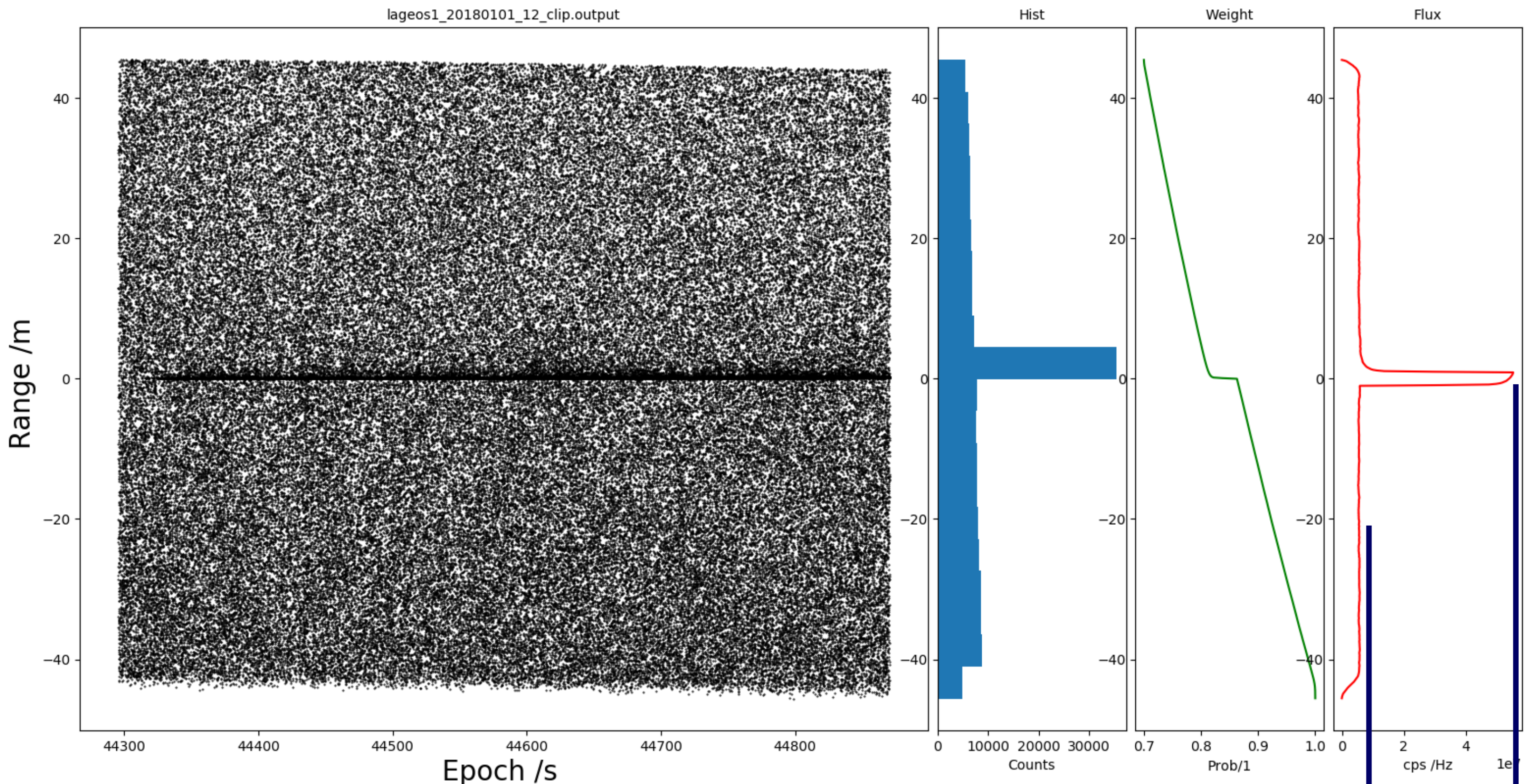

HD142105
y = -1.8259x + 16.657
R2 = 0.768
HD8538
HD11415
HD432
Polaris
HD137422
HD3712
HD20902
4.3
3.4
3.0
2.7
2.3
2.2
2.0
1.8
Stars
Strength [Vmag]
lg(Flux) [lg(cps)]
0
1
2
3
4
5
6
7
5
6
7
8
9

3. Experiment and Analysis

3.3 Photometry of Satellites

- Avalanche rate measurement:
  - Lageos-1 at night.
  - Starlette at night.
  - Ajisai in daylight with narrowband filter(0.15nm@532.08nm).
- The echo pulse contains dark noise + retroreflection.
- The background noise contains dark noise + sky background noise + satellite surface reflection.

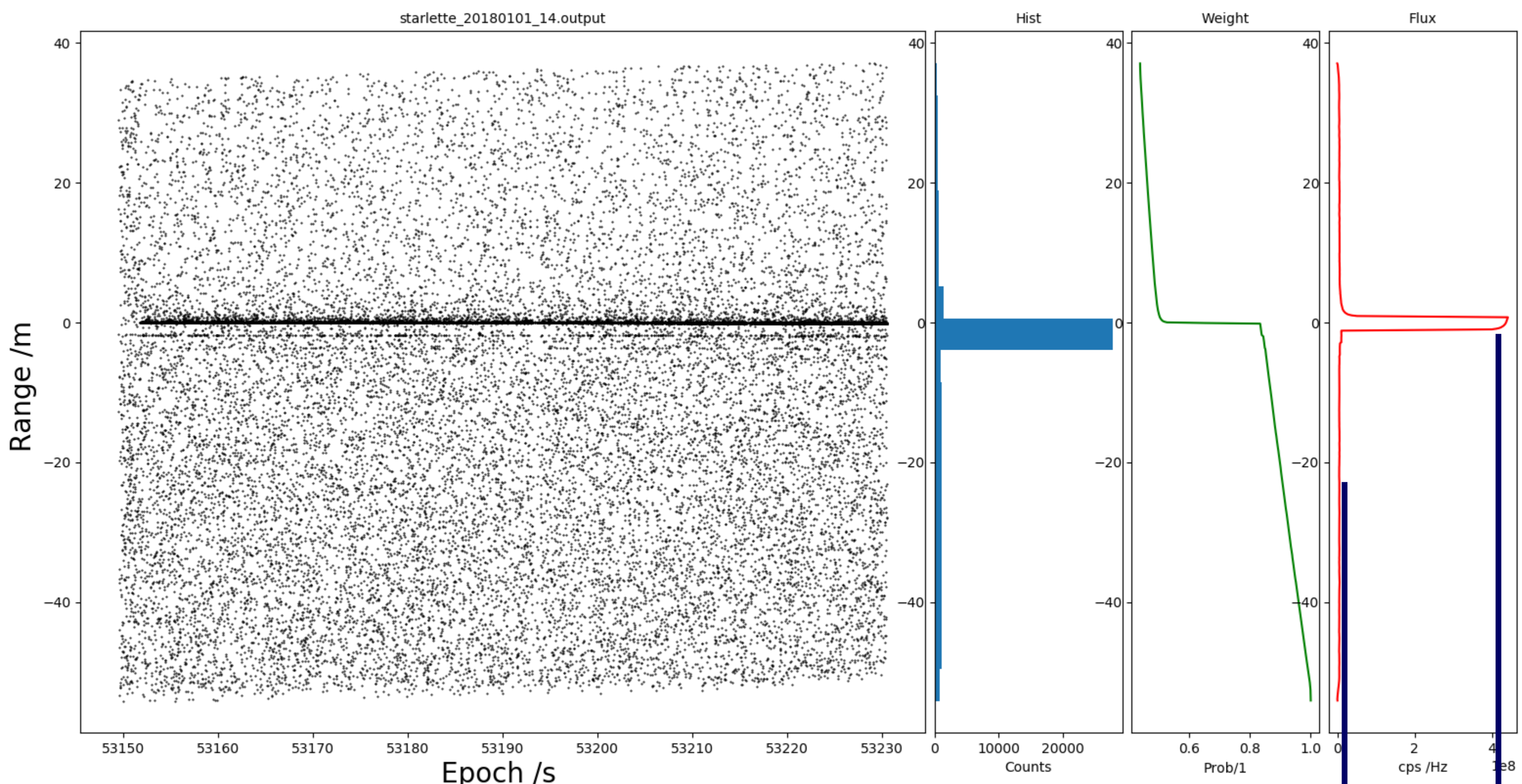
Lageos-1 (Night)



Background Noise: 4.6 mag

Lageos1 Echo: 2.6 mag

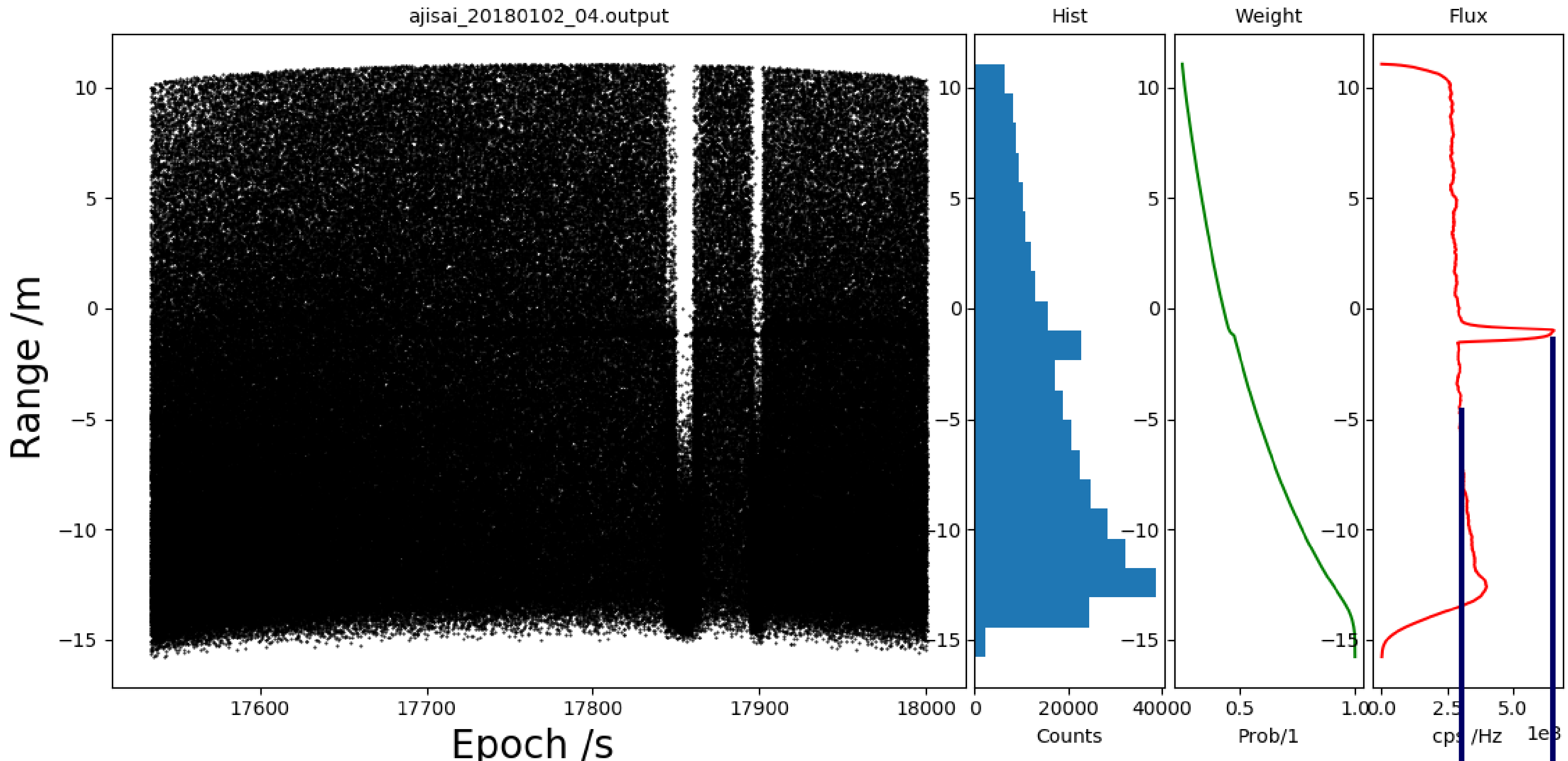
Starlette (Night)



Night noise: 3.7 mag

Starlette Echo: 0.9 mag

Ajisai (Day & NBF)



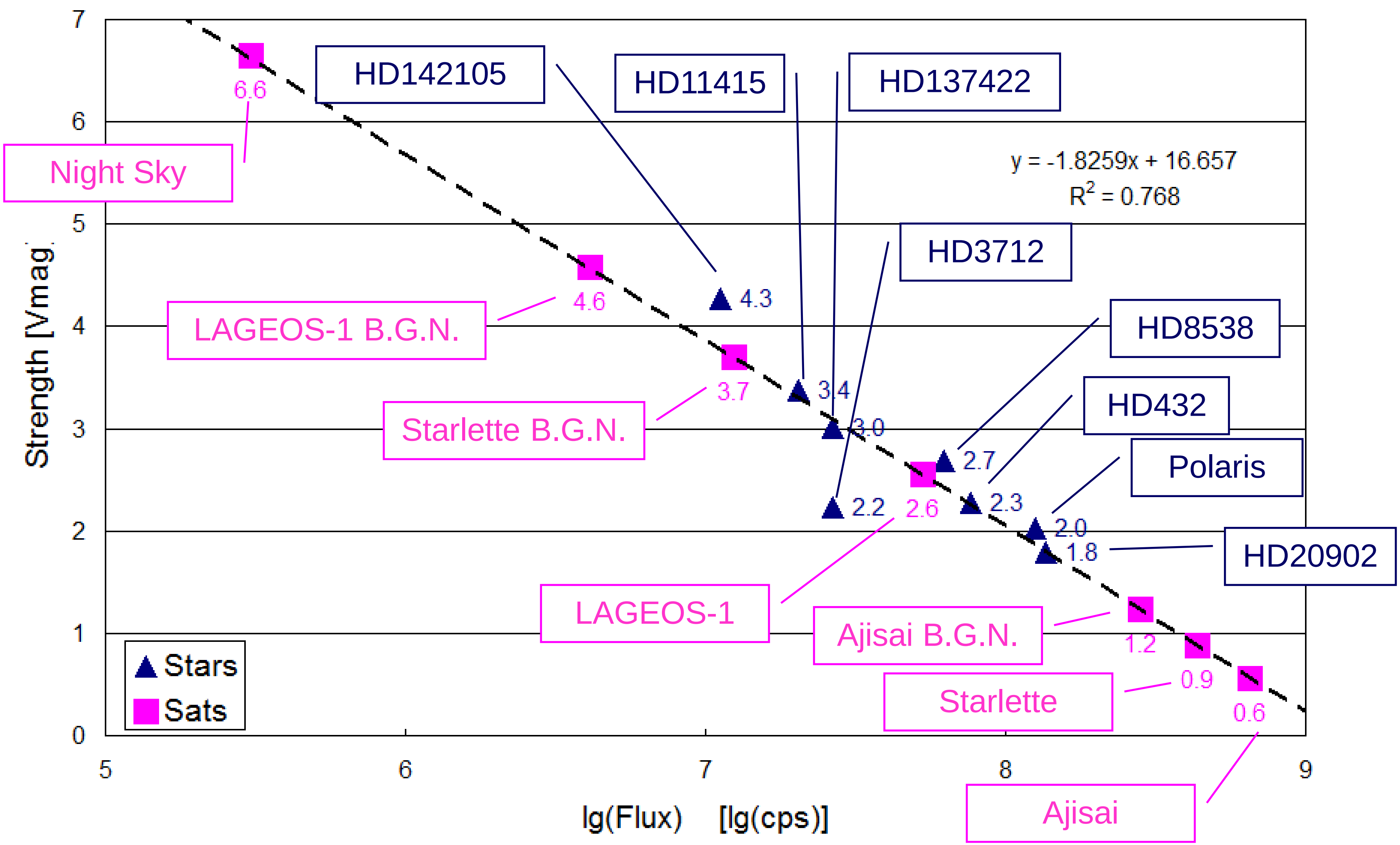
Daylight noise (filtered): 1.2 mag

Ajisai Echo: 0.6 mag

3. Experiment and Analysis

3.3 Photometry of Satellites

- Avalanche Rate to Magnitude
  - Remove dark noise flux from measurements.
  - Find corresponding lg(flux)
  - Find equivalent Vmag from the star-fit correlation.

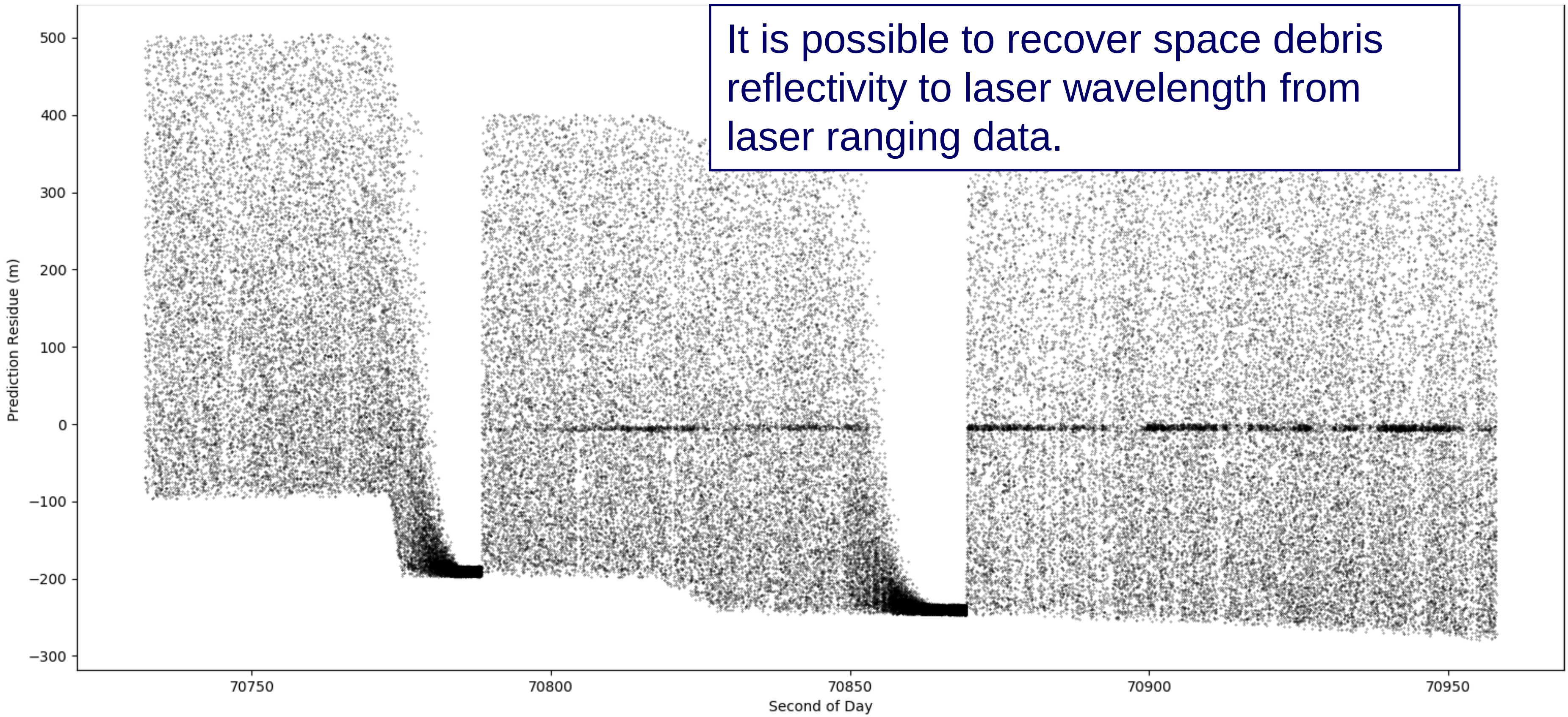

HD142105
HD11415
HD137422
HD3712
HD8538
HD432
Polaris
HD20902
Night Sky
LAGEOS-1 B.G.N.
Starlette B.G.N.
LAGEOS-1
Ajisai B.G.N.
Starlette
Ajisai
y = -1.8259x + 16.657
R^2 = 0.768
6.6
4.6
4.3
3.7
3.4
3.0
2.7
2.6
2.3
2.2
2.0
1.8
1.2
0.9
0.6
Stars
Sats
Strength [Vmag]
lg(Flux) [lg(cps)]
0
1
2
3
4
5
6
7
5
6
7
8
9

3. Discussions

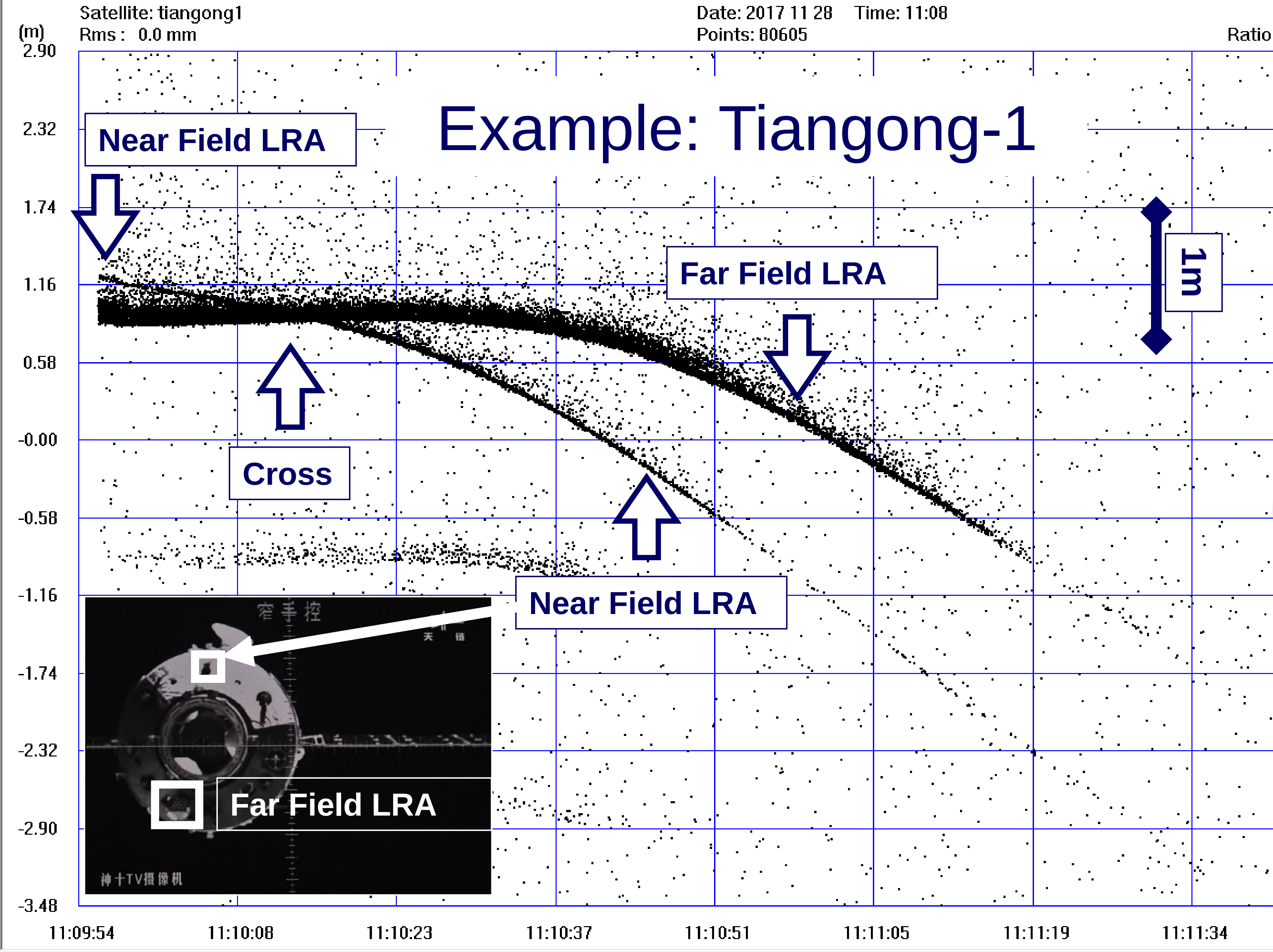
- Possible Applications:
  1. Applicable to ALL gated single photon detectors.
  2. SD monochrome reflectivity from LR data.
  3. Multiple reflector strengths: SNETs, Technosat, Tiangongs
  4. Rapid diagnosis of LR system.

- Possible Improvements:
  1. Photometry on more & stable stars. (Now variable stars)
  2. Adapt for inclined echoes. (Now horizontal)
  3. Uncertainty assessment. (Now none)
  4. Incorporate APD hardware tests: QE(t) (Now constant QE)
  5. Investigate sunlit vs. shadowed targets. (Now none)
  6. LAMOST 532nm spectral flux of stars. (Now none)

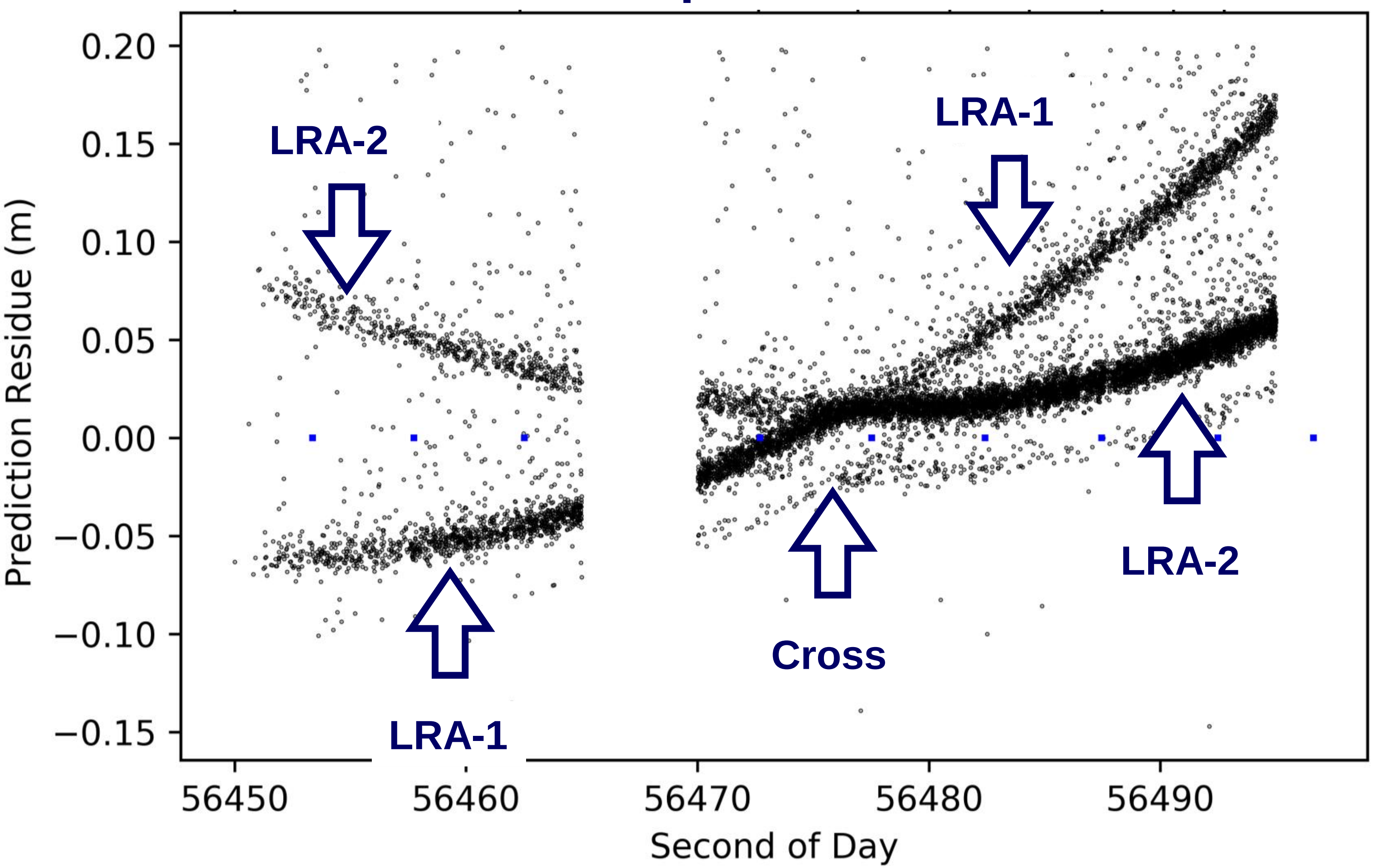
Example: Space Debris



It is possible to recover space debris reflectivity to laser wavelength from laser ranging data.


Satellite: tiangong1
Rms : 0.0 mm
Date: 2017 11 28
Time: 11:08
Points: 80605
Ratio
(m)
2.90
2.32
1.74
1.16
0.58
-0.00
-0.58
-1.16
-1.74
-2.32
-2.90
-3.48
11:09:54
11:10:08
11:10:23
11:10:37
11:10:51
11:11:05
11:11:19
11:11:34
Example: Tiangong-1
Near Field LRA
Far Field LRA
1m
Cross
Near Field LRA
Far Field LRA
神十TV摄像机

Example: SNET



Thank you!

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Changchun SLR

Appendix A

- APD Temporal Response Mathematical Model
- A1: Continuum Problem
- A2: Discrete Problem
  - Discretization of the continuum problem
  - Algorithm to solve flux rate

A1. Continuum Problem

Definitions

- The APD gets charged up at epoch $t_0=0$
- P(t) – At epoch t, the probability that APD is discharged (avalanched).
- F(t) – At epoch t, the probability that APD remains charged.
- S(t) – At epoch t, the photon flux rate (count per second, cps)
- η – Time invariant quantum efficiency, i.e. number of photoelectrons excited by each photon.

A2. Discrete Problem

- Choose *Δt* sufficiently small, so that:
  - All photons within *Δt* participate in the avalanche as a whole.
  - i.e., later photons are not wasted.
  - Note that *Δt* is hardware related.

- Let: $i = 0, 1, 2, ..., N \qquad t_0 = 0 \qquad t_i = i \cdot \Delta t$

$$P_i = P(t_i)$$

$$F_i = F(t_i)$$

$$S_i = \frac{1}{\Delta t} \int_{t_{i-1}}^{t_i} S(\tau) d\tau$$

Discretization of the continuum problem

A2. Discrete Problem

- Given a charged APD, the probability to avalanche:

$$A_i = 1 - e^{-\eta S_i \Delta t}$$

- Therefore, *P* increases only when:
  - APD remains charged
  - Avalanche happens

$$P_{i+1} - P_i = F_i A_i$$

- Note that

$$F_i = 1 - P_i$$

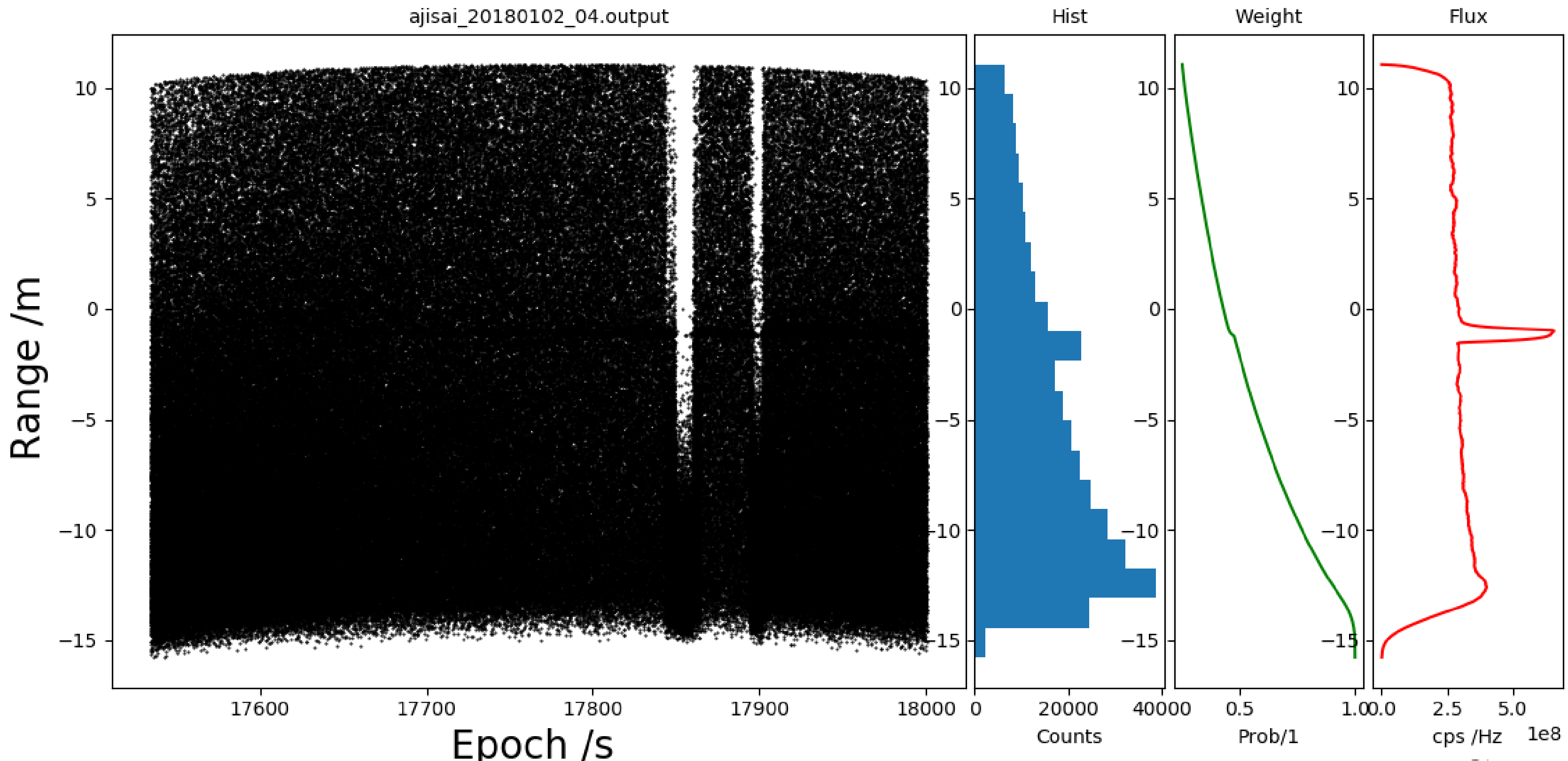
- Solve flux as

$$S_i = \frac{1}{\eta \Delta t} \ln\left(\frac{1 - P_i}{1 - P_{i+1}}\right)$$

A2. Discrete Problem

- Explanation of the discrete variables:
- P_i – In *i*-th step, the probability that APD is discharged.
  Therefore $P_0 = 0$
- S_i – In *i*-th step, the photon flux (count per second, cps)
- η– Quantum efficiency, number of photoelectrons excited by one photon.

- P_i can be estimated by partial sum of range histogram.


ajisai_20180102_04.output
Hist
Weight
Flux
Range /m
Epoch /s
Counts
Prob/1
cps /Hz
1e8

$P_i - P_{i-1}$ F_i S_i