One Trillion
Time-Tagged Photons

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What Is a “Photon Counting” Detector?

(aka “Single Photon” Detector)
The rods in your eye...

...and eye of toad

Rieke & Baylor (1998)
The GALEX Mission uses a Microchannel Plate Detector

Photon impinges on microchannel plate pores

Microchannel plate preserves position information across the gain stage

Photon Counting

\[ X = v_x(t_{x\text{ stop}} - t_{x\text{ start}}) \]

\[ Y = v_y(t_{y\text{ stop}} - t_{y\text{ start}}) \]
Ideally single photons are detected unambiguously with no noise.
In practice noise is always present:

- Internal detector backgrounds (e.g. radioactivity, thermionic emission)
- “Local” backgrounds (e.g. space weather due to solar activity, thermal instrument)
- Astronomical background (e.g. night sky, zodiacal light)

Photon-counting devices are favored in applications where backgrounds are low (e.g. X-ray, gamma ray) or sources are bright but integration times are short.
GALEX operates in regime between X-ray and optical: Low/moderate sky background w/ many bright sources

GALEX has collected \(~1,000,000,000,000\) photons in two ultraviolet bands
Photon Counting

**Aspect Solution**

\[ p_i(\alpha, \delta, t) = A(\alpha, \delta | x_{FP}, y_{FP}, t) \times T(x_{FP}, y_{FP} | x_{Det}, y_{Det}, q, xa, t) \times \]

\[ \times R(x_{Det}, y_{Det}, q, xa, t | \text{photon word}_i) \]

**Distortion/Offset/”Walk”**

**Delay Line Timing**

\[ \text{phot}_i(\alpha, \delta, t) = A \times T \times R \ (\text{photon word}_i) \]

Photon sky position

Digitized photon word

Transformations can be determined ex post facto
Time-tagged photon data

- Time-tagged photon data can be collected while moving (relax attitude control requirements)

- Many aspects of calibration including aspect solution can be refined ex post facto. (Optimal aspect reconstruction)

\[
\bar{J}_{ML} = \arg \max_{\bar{J}} \left\{ \sum_p \sum_i s_p(i + j_p) \ln[r_{ML}(i, \bar{J})] - r_{ML}(i, \bar{J}) - \ln[s_p(i + j_p)!] \right\}
\]

- Provides excellent compression for sparse images

- Allows time-series analysis on millisecond-second timescales (for astronomical sources and other transient/artifacts)
GALEX collects data while moving (dither pattern)

Ideal

Uncorrected

Corrected
Photon Counting

FUV

NUV

Detector Frame
Photon Counting

CW Leo
Satellite Transit ~ 10 min
Photon Counting

Multiple Satellite Transit ~ 10 min
M-Dwarf Flare Star ~ 20 min  (Welsh et al 2005)
Supermassive Black Hole - Tidal Capture Flares in the UV (Gezari et al 2008)
SN Type IIp - Shock Break Out Events
Rising edge of 2 SN detected ex-post facto in GALEX imaging (Gezari et al 2008, Schawinski et al 2008)
1,000,000,000,000 Photons (6 TB)

GALEX has provided to community in the form of images and catalogs.

For good reason, raw photon data are considered a lower priority data set.
How best to store/serve photon data?

How to let users `calibrate’ photons for time series analysis?

Timing accuracy over long durations

Time domain (10 ms-100s) remains relatively unexplored

Open issues:

1,000,000,000,000 Photons
(6 TB)