New tools for improved UVOT photometry

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We are developing tools to improve the reliability and usability of UVOT data

- Improved characterization of small-scale sensitivity (SSS) variations across the detector
  - Quantitative characterization will enable flux corrections
  - Data previously masked will become usable, enabling the recovery of >10% of archival data, effectively adding >45 Msec of usable data to the archive
- Tools to remediate – or even eliminate – the impact of telescope pointing instabilities
  - Can eliminate impact of jitter upon UVOT event mode data
  - Will greatly improve quality of photometry from UVOT image mode data affected by jitter
  - Will restore utility of data taken during 2023-2024 period of degraded pointing stability, as well as scattered problematic observations at other times, causing more than 14 Msec of UVOT data to become usable for all areas of Swift science

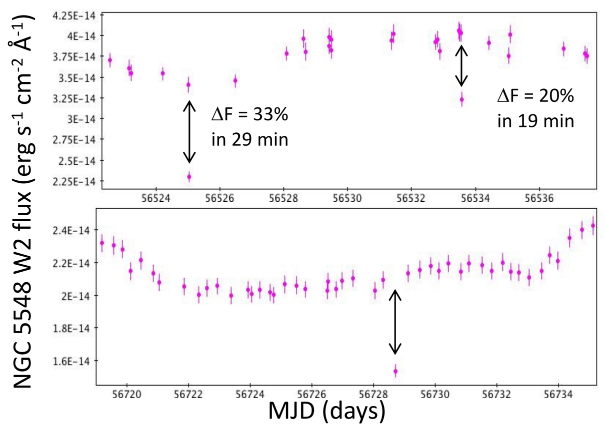
These tools will benefit all users of UVOT data

- Flux corrections will improve the precision of UVOT photometry, increasing Swift's sensitivity to such phenomena as exoplanet transits and providing greater uniformity for surveys
- The restoration of measurements is essential for time critical targets such as transient sources (e.g., tidal disruption events, gamma ray bursts), prompt responses to multimessenger triggers (gravity wave or neutrino events), coordinated observations and any experiment that cannot be repeated
- The data restored by these tools will be a boon for time domain studies, improving the density and consistency of temporal sampling for monitoring programs such as AGN reverberation mapping

Characterizing SSS variations

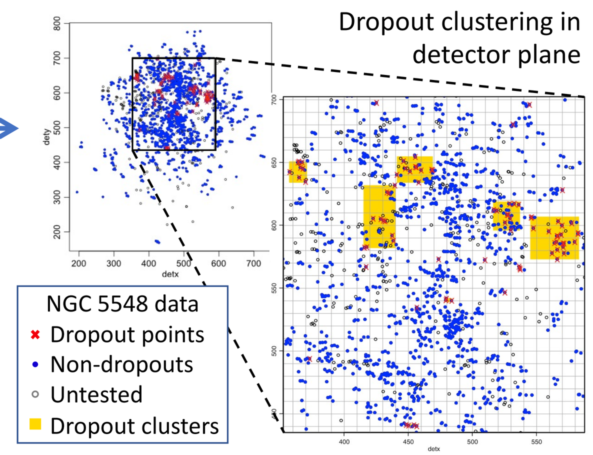
1. Dropouts:

- UVOT light curves exhibit occasional data points with sharply lower fluxes
  - Can affect all filters when data are taken together
- Intensive monitoring of the AGN NGC 5548 showed dropouts occurring and then reversing within hours, or even minutes
  - Too rapid for such large changes to be intrinsic to AGN



2. Evidence of spatially-varying detector sensitivity:

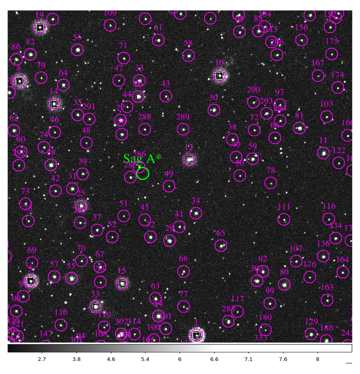
- When mapped to detector plane, dropouts found to lie in clusters
- Not detected in flat field exposures
- Impact correlates with wavelength
  - Dropouts most extreme, most apparent in UV
  - Largest flux deficits seen approach 40% in W2, 30% in M2, 15% in W1 & U, 10% in B & V

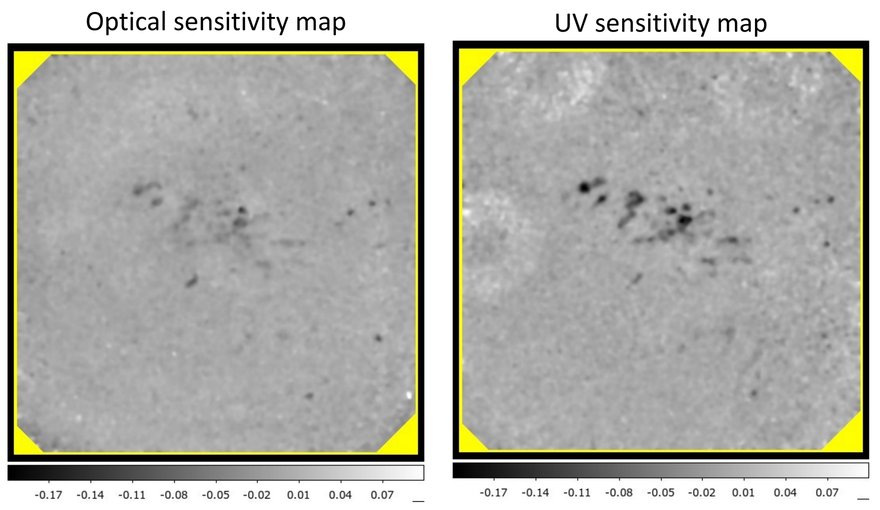


3. The current SSS maps and masks:

- Detector sensitivity variations mapped using light curves of stars in field of Sag A*
  - Most ersistently monitored field with high stellar density
  - Tracked hundreds of stars in 3200 obs through April 2018

Part of Sag A* field in U, with tracked stars marked

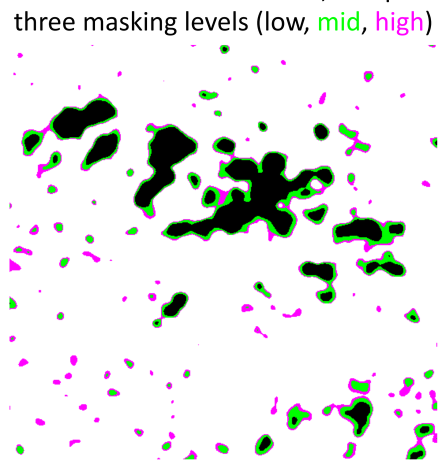




- Light curve deviations mapped to detector plane to identify sensitivity variations

- Thresholds applied to maps to define masks for screening
- Masks are available through CALDB, implemented in FTOOLS
- Three sets of masks are offered, differing by aggressiveness of screening: Low, Mid, High
  - Masking typically affects 10-20% of UV measurements, but in some monitoring campaigns >30% of data are lost with the Mid masks.

Central 8.5′×8.5′ of W2 mask, comparing three masking levels (low, mid, high)



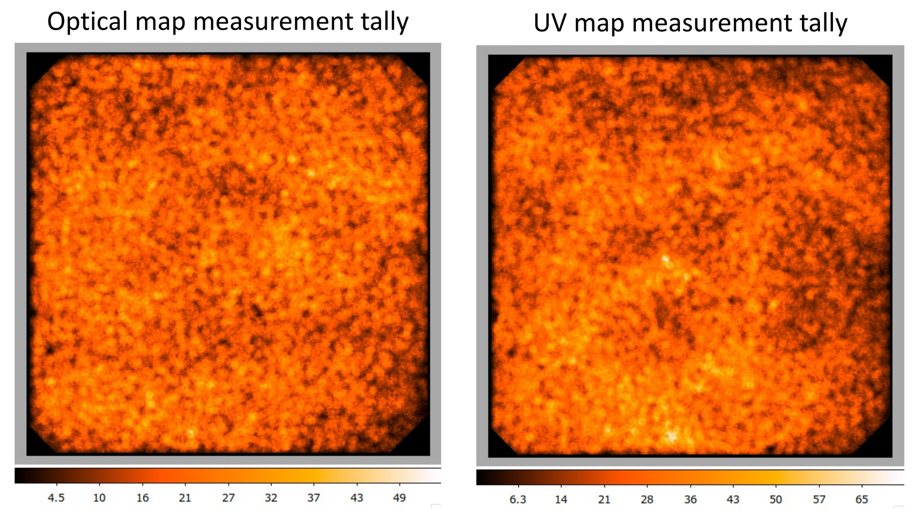
Percentage of area within 4.5′ of center of UVOT field that is screened out by each mask in each filter.

Filter:	W2	M2	W1	U	B	V
Low Mask	8.3%	10.6%	9.3%	5.0%	1.7%	1.9%
Mid Mask	12.9%	17.1%	17.8%	13.8%	5.0%	4.2%
High Mask	16.3%	19.3%	24.9%	19.4%	6.6%	6.0%

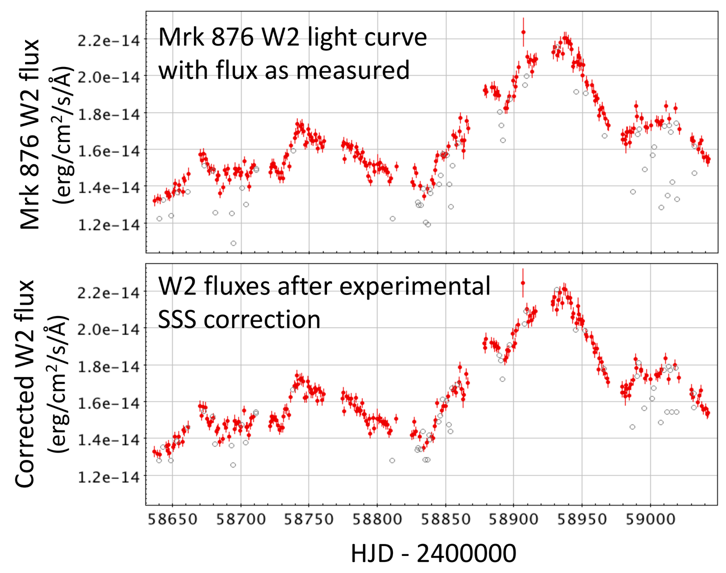
These percentages are indicative of the fraction of target measurements that may be discarded by masking, but larger fractions are eliminated from some LCs because where source falls on detector tends to be correlated from day to day. For example, in the case of Mrk 876 (next section) nearly 20% of W2 data are lost when applying the mid mask.

4. Limitations of the current SSS tools:

- Sag A* monitoring only used four UVOT filters
  - No light curves in B, V, White filters
- SSS characterization limited by statistics
  - Quality-screened measurements sample detector plane sparsely
    - Tally of surviving measurements range from 14,700 (in M2) to 59,300 (U)
    - Ratio of (detector area) / (nominal PSF FWHM area) is > 200,000
  - Remedies:
    - Defined a single UV sensitivity map combining 77,400 meas from 3 filters
    - U-filter data used to define sensitivity for all optical filters
    - Smoothing (5″ Gaussian kernel) applied to ensure that multiple measurements contribute to sensitivity value at all pixels



Maps showing number of measurements within 10″ of each pixel (i.e., within Gaussian smoothing kernel 2σ radius) available to define values for the optical and UV sensitivity maps. Gaussian kernels <5″ leave gaps in coverage.



- Smoothing and blending of filters limits accuracy of sensitivity estimates of each pixel in each filter
  - Limits ability to quantify impact, define flux corrections
  - Case study: attempting flux corrections for Mrk 876
    - W2 Mid mask screens out 19.3% of observations (the source tended to land on bad areas of the detector)
    - Most masked points (open circles) are clear dropouts, falling below light curve
    - Attempted flux correction based upon existing sensitivity maps provides some improvement, but many dropouts remain

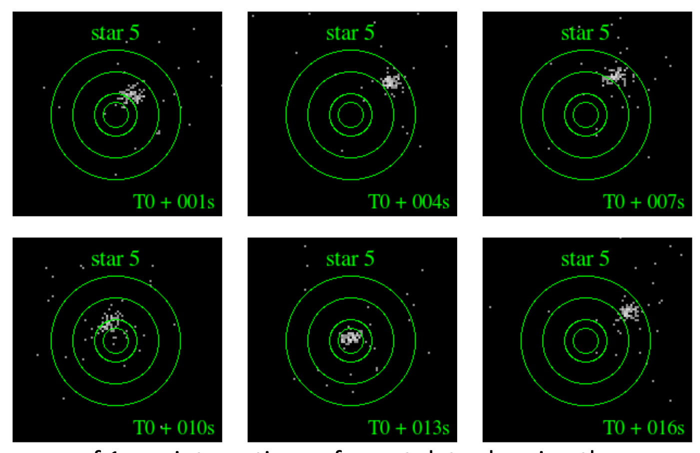
5. The next generation of SSS tools:

- We're starting a program to measure UVOT sensitivity variations in unprecedented detail
  - An order of magnitude more measurements
    - 50% more Sag A* data, plus many additional fields available
  - Will map variations for each filter separately, including B, V, White
    - Will secure more measurements in each filter than used in either current sensitivity map
- More accurate sensitivity characterization will enable flux corrections
  - Data previously discarded will become usable
    - Will recover ~2 years' worth of data from archive
  - Reduces a source of noise in *all* flux measurements, even ones that previously were not masked
    - Improved photometric sensitivity for programs such as monitoring exoplanet transits

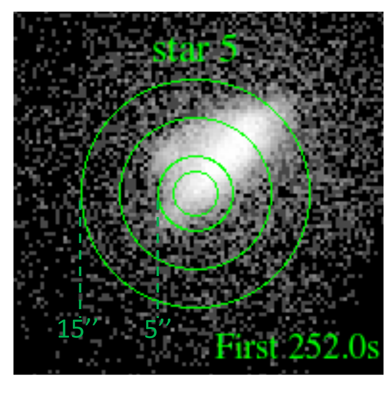
Tools for mitigating jitter

1. Swift pointing issues:

- Recent Swift attitude control system anomaly detail
  - 7 months of unstable pointing with what turned out to be a failing gyro
    - All data from 2023-08-08 through 2024-03-15 affected
  - Oscillations in telescope pointing direction smear point sources
    - Shape and size of distorted PSF differs observation to observation
    - Typical motion is ~20 arcsec amplitude, ~10 sec period
  - Scale of movement a serious problem for UVOT, not for XRT or BAT
    - Standard UVOT measurement aperture is 5″ radius
- Tools to address this anomaly may also benefit other data impaired by sub-nominal pointing control



Sequence of 1-sec integrations of event data showing the movement of a field star to illustrate jitter behavior through 16 seconds.

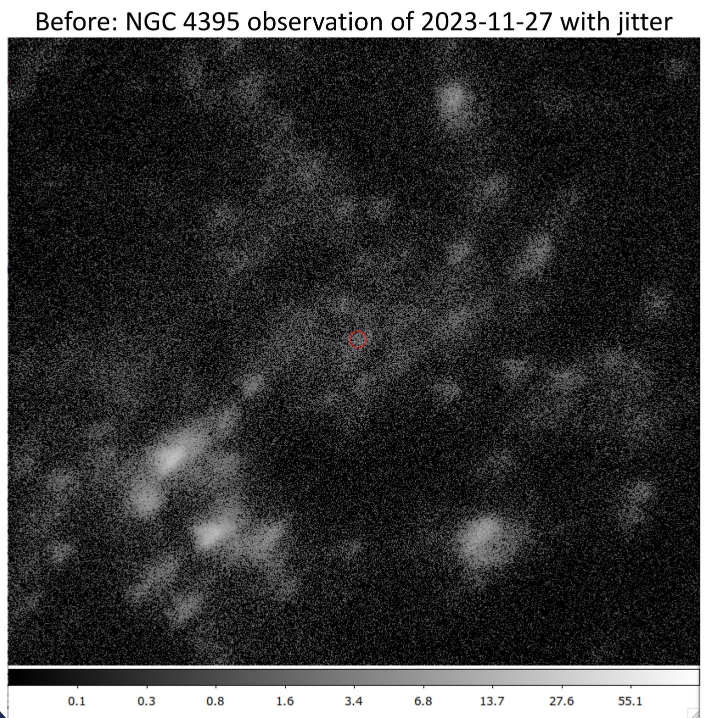


Smeared PSF resulting when the same data is integrated through 252 sec.

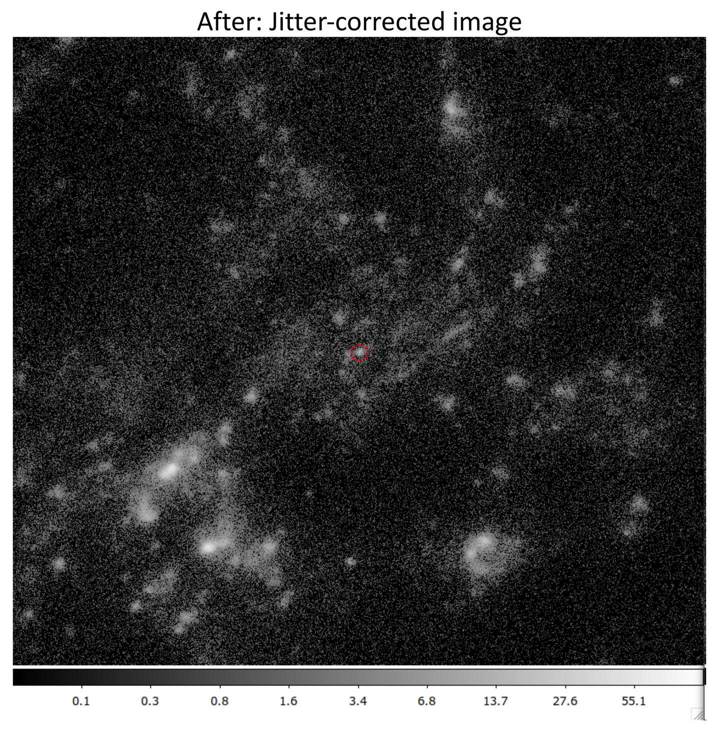
2. Eliminating jitter from UVOT event mode data:

- Time resolution of event mode data makes it possible to correct astrometry
  - Event mode time-tags each detected photon with 11 ms precision
  - Can determine pointing offsets as functions of time
  - Apply this to make time-dependent refinement of photon coordinates
  - Resulting image is at least as sharp as data unaffected by jitter

Before: NGC 4395 observation of 2023-11-27 with jitter

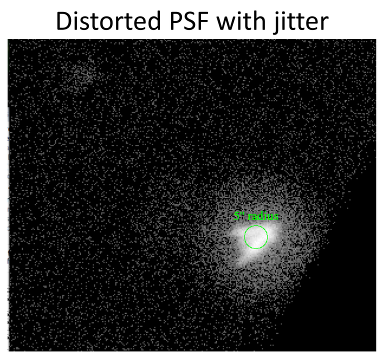


After: Jitter-corrected image



Field stars in the 2023-11-27 data

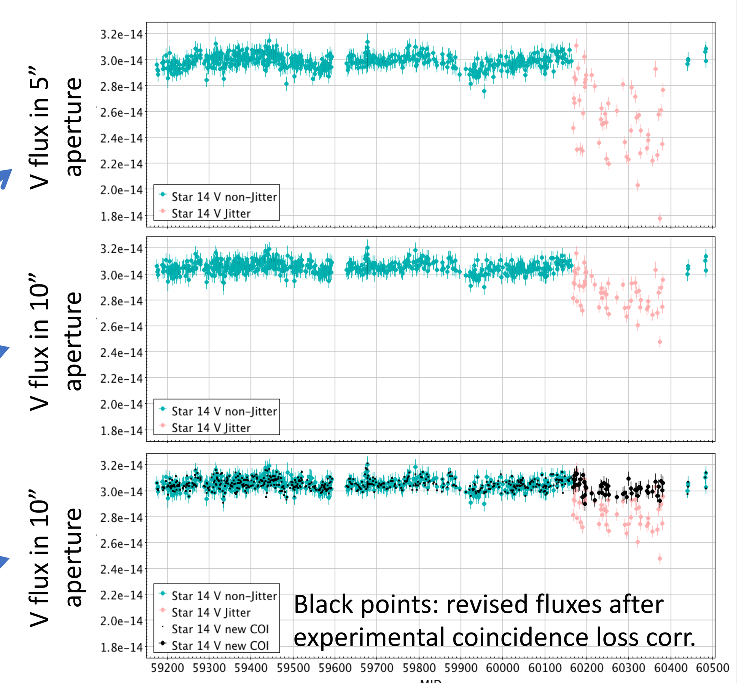
Distorted PSF with jitter



Restored image after correction

3. Mitigating jitter in UVOT image mode data:

- All data is time-integrated
  - Can't back out telescope motion
  - Need larger extraction regions to avoid aperture losses
- Case study: light curve of an isolated field star
  - Pink markers during jitter, cyan at other times
  - Large aperture losses during jitter epoch when standard 5″ measurement apertures are used
  - Aperture losses mitigated with 10″ aperture; jitter epoch still problematic
  - No further improvement with larger apertures
  - Residual trouble dominated by coincidence losses (i.e., pileup)
  - Preliminary attempt to redefine coincidence loss correction makes large improvement (black points)



Annotated references:

- Gelbord, Gronwall, Grupe, Vanden Berk & Wu 2014, in Swift: 10 Years of Discoveries (arXiv:1505.05248) – First report of dropouts
- Edelson, Gelbord, Horne, McHardy, et al. 2015, ApJ 806, 129 – First SSS maps
- Edelson, Gelbord, Cackett, Peterson, et al. 2019, ApJ 870, 123 – Refined SSS maps
- Hernandez-Santisteben, Edelson, Horne, Gelbord, et al. 2020, MNRAS 498, 5399 – Current SSS maps
- Breeveld, Gelbord & Edelson 2022, CALDB Release Note SWIFT-UVOT-CALDB-17-02 – Documentation for current SSS procedure (https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/docs/uvot/uvotcaldb_sss_02b.pdf)

Questions? Feedback? Email me at jgelbord [at] gmail.com