Imtrandetect: a new tool/methodology for transient detection

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Goals / Overview

• How can we detect transient candidates to low S/N levels **optimally, reliably and quickly** from large data streams for (possible) follow-up, classification, and to support knowledge discovery?

• Mining deeper => more candidates => increases our chances of discovering rare and new events
  – Must be prepared for a higher rate of false-positives, e.g., instrumental glitches and contamination from a “fog” of uninteresting astrophysical transients. Hence need to work harder at finding those diamonds

• An optimal image-based transient-detection method has been designed and implemented in an automated software tool (*imtrandetect*) that can be run in real-time for a synoptic sky survey
  – optimal method => one that maximizes the S/N of a quantity from a realization of measurements
  – emphasis is on reliability not completeness
  – the methods explored are still very experimental and software is a work in progress
  – will show examples from testing on CRTS and WISE data

• Method is mostly applicable to optical/IR data, but can be extended to harder/softer energies

• Only focus on initial transient detection process, not classification, although latter can drive former
Which are the rare types? Where can we discover new types? 
⇒ Need higher detection statistics for discovery; 
Two approaches: 
(1) probe to lower S/N in current surveys, ensuring reliability 
(2) wait for more sensitive synoptic surveys (LSST)
E.G: Supernovae Type Ia discovery rates (now versus future)

- Will no longer be a rarity with LSST, even to modest S/N levels.
- Multiband photometry will be crucial to ensure reliable detections and classifications.
  => can afford to detect to lower S/N.

Now: $\sim 900$ SNe/year, CRTS + PTF + other

Bernstein et al, 2009, LSST Science Book, ch.11
Popular transient-detection methods

Two methods:

(1) source-catalog matching (e.g., CRTS, Sloan, INTEGRAL ..., Drake et al. 2009; Telezhinsky et al. 2010)
  - generate calibrated, clean source catalogs from deep co-adds of past images (reference catalog)
  - match extractions from new images with reference catalog and search for significant flux changes

(2) image differencing (e.g., PTF, ESSENCE, +many others ..., Alard 2000; Bramich et al. 2008; Law et al. 2009)
  - create a deep template image of a field by co-adding a stack of images
  - given a new observed image, register with template, perform PSF-matching and subtract them
  - search for significant + or – flux changes relative to template
  - powerful, but not suitable for all instruments (e.g., artifacts, residuals from atmospheric refraction)

SN 2009av from PTF
Law et al. 2009
Ingredients for a robust transient-detection tool

- Mask instrumental artifacts: glints, ghosts, glitches, diffraction spikes, saturation bleeds..
- Not affected by PSF variations (temporal + spatially)
- Ability to combine images from different filters, or from contemporaneous observations from different instruments to improve S/N
- Handle data with irregularly spaced observation times, large gaps, varying throughput
- Handle images with non-uniform overlap (hence spatially-varying depth) across epochs
- Optimal use of available data given knowledge of all noise sources
- Relative photometry across image epochs is sufficient, absolute calibration not necessary
- Tunable to detect transients/variability to different S/N thresholds and characteristic timescales
- Optional use of priors to assist in isolating specific candidates (e.g., microlensing light-curves are symmetric and achromatic, while those of Supernovae and many other transients are not)
- Optional constraints to maximize chances that transient is real: e.g., must have at least \( n \) consecutive events above some S/N separated by \(< \Delta t\), and must appear PSF-like (at least)
- Generate light-curves, image cutouts, transient metadata for decision making and QA
- Fully automated; able to process large data streams in real-time reasonably fast!
Processing flow in `imtrandetect` (v1.0)

**INPUTS:**
- $N$ overlapping images (epochs), metadata, bad pixel masks, params

**OPTIONAL:**
- Interpolate images onto common sky pixel-grid, e.g., if data not synoptic (images have different pointing)

**PROCESSING:**
1. Subtract slowly varying local background from each image (median block filter with smoothing). Ensures "stationary" pixel signal baselines vs time.
2. Subtract slowly varying local background from each image (median block filter with smoothing). Ensures "stationary" pixel signal baselines vs time.
3. Threshold ‘robust’ SNR image to create mask of ~static bright sources to avoid; reduces impact of detector artifacts. Optional masking expansion to reduce impact of noisy PSF wings, diffraction spikes etc..
4. Regularize/stabilize global $\sigma_j$ image in unmasked regions to avoid inflation by residual artifacts and actual real transients. Uses winsorized clipping about the mode of the spatial $\sigma_j$ distribution.
5. Compute median SNR = $\sqrt{N(m_j/\sigma_j)}$ per pixel for use in "static-signal” masking. “Static” => signals which persist for $\geq 50\%$ in stack.

**OUTPUTS:**
- For each candidate:
  - light curve
  - image cutouts
  - metadata/statistics

**REPEAT:**
- Repeat for all windows along image sequence

**FORMULAS:**
- Normalize bckgnd-subtracted imgs at times $t$ against long run ‘robust’ pixel baselines/sigmas: $z_{jt} = \frac{p_{jt} - m_j}{\sigma_j}$
- Combine consecutive images $z_{jt}$ in a moving block window of length $N_w$ using 4 different metrics. $\Rightarrow$ 4 metric images per win
- Threshold on extended (PSF-like) regions in metric images; combine (&) results from all imgs $\Rightarrow$ transient candidates!
Optimal image-combination metrics for transient detection

- Considered four image-combination metrics per window $w_i$ (see below).
- An extension of single-image differencing method but more optimal since S/N is increased by combining multiple epochs where transient may be “active”.

**Reason for windowing:** reduce dilution to metric S/N from baseline noise (see pg. 9)

- In practice, set window length $N_{wi}$ to *smallest* possible such that metric S/N is high enough to detect *shortest* transient timescale of interest. For long-term variability, set length to entire data span.

\[
\begin{align*}
z_{j,\text{max}} &= \max \{ z_{jt} \ \forall \ t = 1,2,3 \ldots N_{wi} \} \quad \Rightarrow \text{image of maxima} \\
R_j &= \frac{\text{Frac}(z_{jt} \geq z_{\text{thres}})}{\text{FracGaussian}(\geq z_{\text{thres}})} \quad \Rightarrow \text{image of frac. excesses above some threshold} \\
\chi^2_j &= \frac{1}{N_{wi} - 1} \sum_{t=1}^{N_{wi}} z_{jt}^2 \quad \Rightarrow \text{image of reduced chi-squares} \\
S_j &= \sqrt{\frac{N_{wi}(N_{wi}-1)}{N_{wi}(N_{wi}-2)}} \sum_{t=1}^{N_{wi}} z_{jt}^3 \quad \Rightarrow \text{image of skewnesses}
\end{align*}
\]

cf. to Babu et al. 2006, astro-ph/0612707:

\[
\chi^2_j \equiv (p_j - m_j)^T \Omega_{Nw}^{-1} (p_j - m_j)
\]
we assume cov. matrix $\Omega$ is diagonal.

\[
\begin{align*}
z_{jt} &= \frac{p_{jt} - m_j}{\sigma_j} \\
w_i &= w_1 \quad w_2 \quad w_3 \ldots
\end{align*}
\]
Sensitivity of image-combination metrics to transients

- Monte-Carlo simulation to test metric strength and dilution by uncorrelated Gaussian noise in a window of length = 50 images
- Assumed simple transient with flux ~ constant and single image S/N = \( n \) lasting for \( N \) images
- \(<z^3>\) is most sensitive overall, e.g., has S/N > 10 for single-image \( n \geq 3 \) occurring \( N \geq 8 \) times
Testing on image data from the Catalina Real-Time Transient Survey (CRTS)

- Ran `imtrandetect` on ~ 0.5° × 0.5° fields containing CRTS-discovered transients (mostly Supernovae, no personal bias!) and searched for new transients.
- Below: products from a field containing SN 2011cw (Type IIn), discovered 5/1/2011. Used a running window of 15 images.
Some new(?) CRTS transient candidates

Pushed to S/N = 3, found spurious transient rate of ~8% (glitches, glints, CRs) and tons of faint asteroids!

- Moving => asteroid ~15 asec / hr
- Moving => asteroid ~10 asec / hr
- Moving => asteroid too?
- Moving => asteroid ~9 asec / hr
Wide-field Infrared Survey Explorer
Core of LMC (3.4μm)

- **Not a synoptic survey**, but have multiple irregularly spaced epochs of non-uniform depth over sky
- Performed a blind search for variable stars at 3.4 μm in the core of the LMC using *imrandetect*

![Intensity map (co-add)](image1)

![Image-depth map (#epochs)](image2)

~1.1°

~60 deep

~125 deep

⇒ **sample baselines of ~ 15 – 20 days**
Example light-curves of variable candidates in LMC (3.4µm)

New RR-Lyrae? Period ~1.58 days
Red curve => to guide the eye

Classified as a short period Cepheid in optical by OGLE
Example light-curves of variable candidates in LMC (3.4µm)

Some “uncertain unknowns”. Main limitation for IDs are short noisy baselines.
Summary, closing thoughts..

- Described some optimal metrics for detecting transients, implemented in a new standalone tool: `imtrandetect` (work in progress; plan to make publically available)

- **Goal:** probe down to low S/N levels to maximize chances of discovering rare/new events
  \[ \Rightarrow \] place more emphasis on reliability than completeness, e.g., through static-source filtering to reduce detector and bright-source artifacts, varying PSF, …

- Optimization methods are easy to apply for classical noise-distributions, and the CLT usually saves us. But to apply the *most optimal* method, need to understand how all *your* noise sources are distributed, especially systematics. These control the degree of reliability.
  \[ \Rightarrow \] future panchromatic surveys will vastly improve reliability against artifacts and uninteresting transient “fog”

- **Dilemma still remains:** how and which candidates do we follow-up for classification from the deluge of detections to low S/N (which is still a problem today at high S/N)?
  - is rigorous, exhaustive follow-up always needed? Statistical studies on archives of reliable light-curves using contextual info, classification templates, models, matched filters… will still be very powerful
  - still strive to make unsupervised, real-time classification an integral component of synoptic surveys
Backup Slides
Sensitivity of $\chi^2$ metric to transients

- Different representation for the $\chi^2$ image metric: probability that observed flux sequence will occur by chance under H0 of no transient in the presence of pure Gaussian noise (see page 9)

- Distribution for a $\chi^2$ random variable is well known, but not for skew

- In general, the lower the single image epoch S/N, the longer the transient must persist at $\geq$ S/N for it to be detected using these image-combination metrics

- These results assume one can robustly measure a long-run baseline level per pixel (stationary background; e.g., a stacked median) and a robust $\sigma_{\text{noise}}$ with no contamination from actual transient

$S/N = n = 1, 3, 5, 7, 9, 11, 13$
Testing on WISE image data

• The Wide-field Infrared Survey Explorer:
  o Performed an all-sky survey in 2010 in four IR bands: \( \sim 3.4, 4.6, 12, 22 \, \mu m \)
  o Not a synoptic survey, but have multiple epochs of non-uniform depth over sky
  o Sun-synchronous Earth-polar orbit
    => image-depth (#epochs) increases towards ecliptic poles
    => Large Magellanic Cloud (LMC) fits the bill
  o Observation times irregularly spaced, \( \Delta t >\sim 95 \) minutes
  o Baselines sampled: \( \sim 2 \) days to \( > 6 \) months over sky

• Performed a blind search for variable stars at 3.4 \( \mu m \) in the core of the LMC using \textit{imtrandetect}. Postdoc Doug Hoffman is assisting with classifications

• \textit{imtrandetect} is most optimal for detecting transients but can be tuned to detect variables or anything with a flux variance in excess of that expected for a static source of similar flux

• Have multi-band information to improve reliability of transient/variable-source detections
WISE photometric repeatability (3.4µm)