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User Manual for BLADE main.py

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ABSTRACT

BLADE (Bolide Light-curve Analysis and Discrimination Explorer) is an automated computational framework for analyzing light curves of bolides, which are high-energy luminous phenomena produced when meteoroids and small asteroids enter Earth's atmosphere. The software systematically processes digitized light-curve data from the Center for Near-Earth Object Studies (CNEOS) Fireball Database. BLADE identifies and classifies fragmentation and energy deposition events using adaptive Savitzky–Golay filtering, prominence-based peak detection, and normalized gradient analysis. The software generates standardized outputs, such as annotated plots and event classifications, and, when trajectory data are available, correlates luminosity with altitude. BLADE is designed to provide efficient and reproducible analysis of large bolide datasets in support of planetary defense and atmospheric science research. This manual provides step-by-step instructions for installation, data preparation, operation, and interpretation of results. For further background, users are referred to the foundational publication:

Silber, E. A., Sawal, V. (2025), "BLADE: An Automated Framework for Classifying Light Curves from the Center for Near-Earth Object Studies Fireball Database," The Astronomical Journal, doi: 10.3847/1538-3881/adeb55.

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ACRONYMS AND TERMS

Acronym/Term	Definition
BLADE	Bolide Light-curve Analysis and Discrimination Explorer
CNEOS	Center for Near-Earth Object Studies
CSV	Comma Separated Values file, a text-based format for storing tabular data
JPL	Jet Propulsion Laboratory
LC	light curve
NASA	National Aeronautics and Space Administration
UTC	Coordinated Universal Time

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1. INTRODUCTION

BLADE is an automated framework for the analysis and classification of bolide (fireball) light curves [1]. Bolides are high-energy luminous phenomena that occur when meteoroids and small asteroids enter Earth's atmosphere at hypersonic speeds [e.g., 2, 3]. These events generate intense luminous emissions as the object interacts with the atmosphere, undergoing heating, ablation, and fragmentation [2]. The resulting changes in brightness over time are captured as light curves by optical sensors and recording instruments [e.g., 4].

This manual is intended to guide researchers and analysts in the use of BLADE, whether for planetary defense, atmospheric science, or broader investigations of natural and artificial high-energy atmospheric phenomena. BLADE is designed for use with digitized light-curve and metadata products from the Center for Near-Earth Object Studies (CNEOS) Fireball Database,[1] hosted by National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL). However, the software is modular and can be adapted for use with other datasets and observational platforms beyond CNEOS.

BLADE's analysis workflow includes adaptive Savitzky–Golay signal smoothing [5], prominence-based peak detection [6], gradient analysis [7], and automated event classification [1]. When trajectory and velocity data are available, the software can also relate light-curve features to changes in altitude, providing additional insight into fragmentation and energy deposition [8].

Please note that BLADE is provided as-is. The software will not receive further updates or maintenance, and there is no designated user support or help contact. Users are responsible for evaluating whether the software meets their requirements and for verifying its application to their specific research or analysis needs. Although the software has been tested for research use, all use is at the discretion and judgment of the user.

The original publication by Silber and Sawal (2025) provides the scientific motivation for BLADE, describes its application in bolide research, and includes detailed interpretation of results with examples. This user manual does not repeat that material. Instead, it focuses on providing step-by-step instructions for software installation and configuration. For detailed scientific context, data interpretation, and practical examples, users should refer to the original publication:

Silber, E. A., Sawal, V. (2025), BLADE: An Automated Framework for Classifying Light Curves from the Center for Near-Earth Object Studies Fireball Database, The Astronomical Journal, doi: 10.3847/1538-3881/adeb55.

If you use BLADE or any results obtained with it in your research, proper attribution to both the software and the original publication is required. For background information and additional scientific context, users are encouraged to consult the published article.

[1] https://cneos.jpl.nasa.gov/fireballs/

2. INSTALLATION AND REQUIREMENTS

2.1. Overview and Prerequisites

The `BLADE_main.py` script provides an automated framework to process digitized CNEOS fireball (bolide) light curves. It reads both the raw light-curve data (intensity vs. time) and associated event metadata (UTC date/time, velocity, entry angle, altitude, etc.), performs smoothing and normalization, detects fragmentation peaks via prominence analysis, computes altitude profiles when possible, classifies each event, and saves all outputs (plots and pick summaries).

Prerequisites:

- Python version: 3.7 or higher
- Required Python packages:
  - `numpy`
  - `pandas`
  - `matplotlib`
  - `Scipy`

2.2. Linux/Mac Installation

1. Clone or download the BLADE repository.
2. Create a virtual environment (optional but recommended):
   ```
   $ python -m venv blade_env
   $ source blade_env/bin/activate
   ```
3. Install required packages:
   ```
   (blade_env)$ pip install numpy pandas matplotlib scipy
   ```
4. Ensure the following files/folders are present:
   - `BLADE_main.py` (main script)
   - `LC_processing.csv` (metadata file)
   - `Processed_LC/` (folder containing example digitized light curve CSVs used in the original publication)

2.3. Windows Installation

1. Clone or download the BLADE repository.
2. Create a virtual environment (optional but recommended):

   ```
   C:\> python.exe -m venv blade_env
   ```

3. [Optional] If you encounter a security issue while activating the environment, run the following command:

   ```
   C:\> Set-ExecutionPolicy -ExecutionPolicy RemoteSigned -Scope Process
   C:\> blade_env\Scripts\activate
   ```

4. Install required packages:

   ```
   (blade_env) C:\> pip install numpy pandas matplotlib scipy
   ```

5. Ensure the following files/folders are present:
   - `BLADE_main.py (this script)`
   - `LC_processing.csv (metadata file)`
   - `Processed_LC/ (folder containing digitized light-curve CSVs)`

3. PUT DATA

3.1. Light Curve CSV Files

- Each file must be named `YYYYMMDD_HHMMSS.csv`, where:
  - `YYYY` = 4-digit UTC year.
  - `MM` = 2-digit UTC month.
  - `DD` = 2-digit UTC day.
  - `HHMMSS` = 6-digit UTC time (hour, minute, second).
- Expected columns (header row): `Time [s], Intensity [W/sr]`. Example snippet:

```
Time [s], Intensity [W/sr] 0.000, 2.35
0.014, 3.12
...
```

- Place all digitized CSVs into the Processed LC/ folder.

3.2. Metadata CSV (LC_processing.csv)

- Must contain at least these columns:

```
UTC Year, UTC Month, UTC Day,
UTC Hour, UTC Minute, UTC Second,
Velocity [km/s], Entry Angle [deg], Bolide Altitude [km],
Bolide Latitude [deg], Bolide Longitude [deg], Azimuth [deg],
Total impact energy [kt]
```

- Each row corresponds to a fireball event.
- The script constructs a Python `datetime` from the UTC columns for matching.

4. CONFIGURATION OPTIONS

At the top of `BLADE_main.py`, the following parameters can be adjusted:

- `TIME_TOLERANCE`: # seconds for matching a light curve to metadata (default 5s).
- `FRAG_THRESHOLD`: Minimum sample-index separation between peaks for discrete vs. continuous fragmentation (default 15).
- `PROMINENCE_THRESHOLD, HEIGHT_THRESHOLD, MIN_DISTANCE`: Parameters for peak finding (see SciPy `find_peaks`).
- `ENABLE_PLOTTING (True/False)`: If `False`, no plots are generated or saved; only CSV outputs are produced.

5. RUNNING THE SCRIPT

From the command line (in the directory containing `BLADE_main.py`):

- Linux/Mac: `python BLADE_main.py`
- Windows: `python.exe BLADE_main.py`

The script will:

1. Scan `Processed_LC/` for all `*.csv` files.
2. Skip any files already recorded in `processing_progress.txt`.
3. For each new file:
   (a) Parse UTC event time from filename.
   (b) Match to metadata row within `TIME_TOLERANCE`.
   (c) Read `Time [s]` and `Intensity [W/sr]`.
   (d) Optionally generate and save:
      - Raw intensity vs. time (`raw_intensity.png`)
      - Smoothed + Normalized intensity vs. time (`normalized_intensity.png`)
   (e) Compute adaptive smoothing (Savitzky–Golay), normalization, numerical gradient.
   (f) Detect peaks via prominence-based method; record pick times, intensities, prominence.
   (g) Classify event as:
      - *No Significant Peaks*
      - *Continuous Fragmentation*
      - *Discrete Fragmentation*
      - *Airburst*
      - *Single Peak*
   (h) Save picks CSV in the following folders:
      - The event's output folder (e.g. `Output_LC_BLADE/YYYYDDMM_HHMMSS/YYYYDDMM_HHMMSS_picks.csv`)
      - The central `automated_picks/` folder (`automated_picks/YYYYDDMM_HHMMSS_picks.csv`).
   (i) Append to `summary.csv: FileName, Classification`.
   (j) Mark file as processed in `processing_progress.txt`.
4. Upon completion, report counts of processed and skipped files.

6. DESCRIPTION OF OUTPUTS

6.1. Directory Structure

```
Output_LC_BLADE/
  automated_picks/
    YYYYDDMM_HHMMSS_picks.csv
    ...
  YYYYDDMM_HHMMSS/                               % One folder per event
    YYYYDDMM_HHMMSS_raw_intensity.png
    YYYYDDMM_HHMMSS_normalized_intensity.png
    YYYYDDMM_HHMMSS_lc_prominence.png
    YYYYDDMM_HHMMSS_auto_picks.png
    YYYYDDMM_HHMMSS_alt_vs_intensity_yx.png       % if altitude available
    YYYYDDMM_HHMMSS_intensity_vs_alt_xy.pn        % if altitude available
    YYYYDDMM_HHMMSS_picks.csv
    ...
  processing_progress.txt             % List of already processed filenames
  summary.csv                         % List of FileName, Classification
```

6.2. Picks CSV Columns

Each `*_picks.csv` contains:

```
Peak Time [s], Original Intensity, Normalized Intensity, Peak Altitude [km],
Prominence
```

Example line:

```
0.650000, 1234.567000, 0.876543, 45.123000, 0.234567
```

6.3. Classification Categories

- **No Significant Peaks:** No peaks found above thresholds.
- **Continuous Fragmentation:** Multiple peaks with some adjacent peaks closer than FRAG_THRESHOLD samples.
- **Discrete Fragmentation:** Multiple peaks all separated by at least FRAG_THRESHOLD samples.
- **Airburst:** Single peak with a short rise relative to fall time (rise < 0.5 fall) and large maximum gradient (> 0.5).
- **Single Peak:** Exactly one peak not meeting airburst criteria.

7. CODE WORKFLOW SUMMARY

1. **Read Metadata:** Load `LC_processing.csv`, drop incomplete rows, build a `datetime` column.
2. **Loop Over Light Curves:** For each `YYYYMMDD_HHMMSS.csv` in `Processed_LC/`:
   (a) Parse the event UTC time from the filename.
   (b) Match with metadata row within `TIME_TOLERANCE`.
   (c) Read `Time[s]` and `Intensity[W/sr]` into `numpy` arrays.
   (d) Optionally plot and save:
      - Raw intensity.
      - Smoothed + normalized intensity.

   (e) Compute numerical gradient of normalized intensity.
   (f) Detect peaks via SciPy `find_peaks` with configured thresholds.
   (g) Optionally plot:
      - 2×1: normalized (top) + prominence bar plot (bottom).
      - Overlay: gradient + normalized + picks.

   (h) Classify event by peak count, spacing, and gradient.
   (i) If metadata has altitude, velocity, entry angle:
      - Compute altitude vs. time (km).
      - Optionally plot altitude vs. intensity (Y–X) and intensity vs. altitude (X–Y inverted).

   (j) Save a picks CSV in the event's folder and `automated_picks/`.
   (k) Update `summary.csv` and `processing_progress.txt`.
3. Finish: Report total processed and skipped.

8. EXAMPLE: DISCRETE FRAGMENTATION

This example provides data on the event recorded on October 14, 2006 at 18:10:49 UTC exhibits distinct characteristics of discrete fragmentation, as identified by the BLADE framework.

8.1. Directory Structure

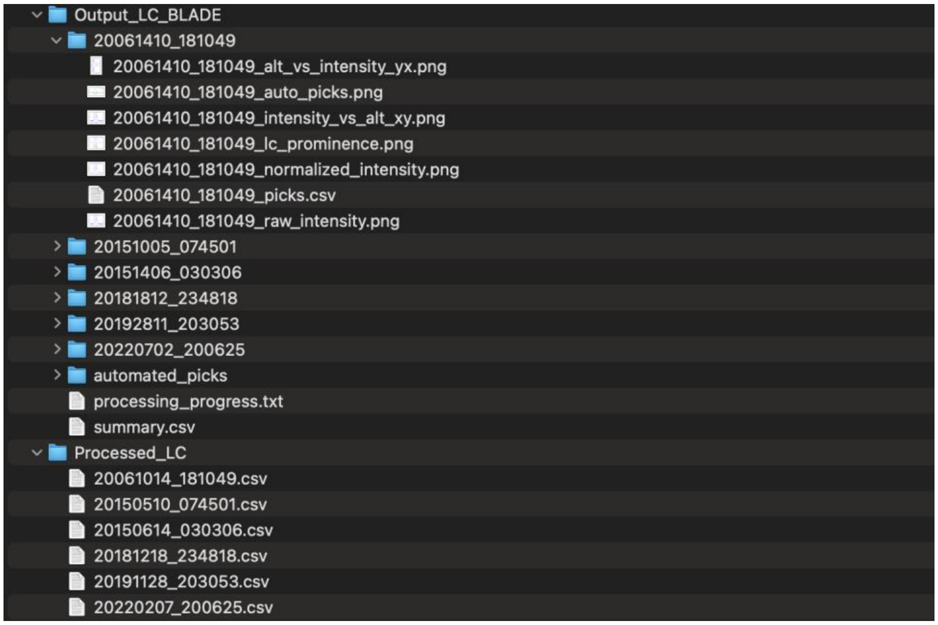

Figure 1. Directory Structure

8.2. Output Plots

This is the description of the output plots

(a) Intensity-vs-time plot showing two dominant peaks corresponding to distinct fragmentation events.

(b) Intensity-vs-altitude plot indicating that the primary peaks occurred at altitudes of~47 and 44 km, with additional fluctuations suggesting possible secondary fragmentation.

(c) Normalized light curve.

(d) Gradient analysis and peak detection plot, where the green dashed line represents the gradient, the blue line indicates the normalized light curve, and red dots mark the detected peaks.

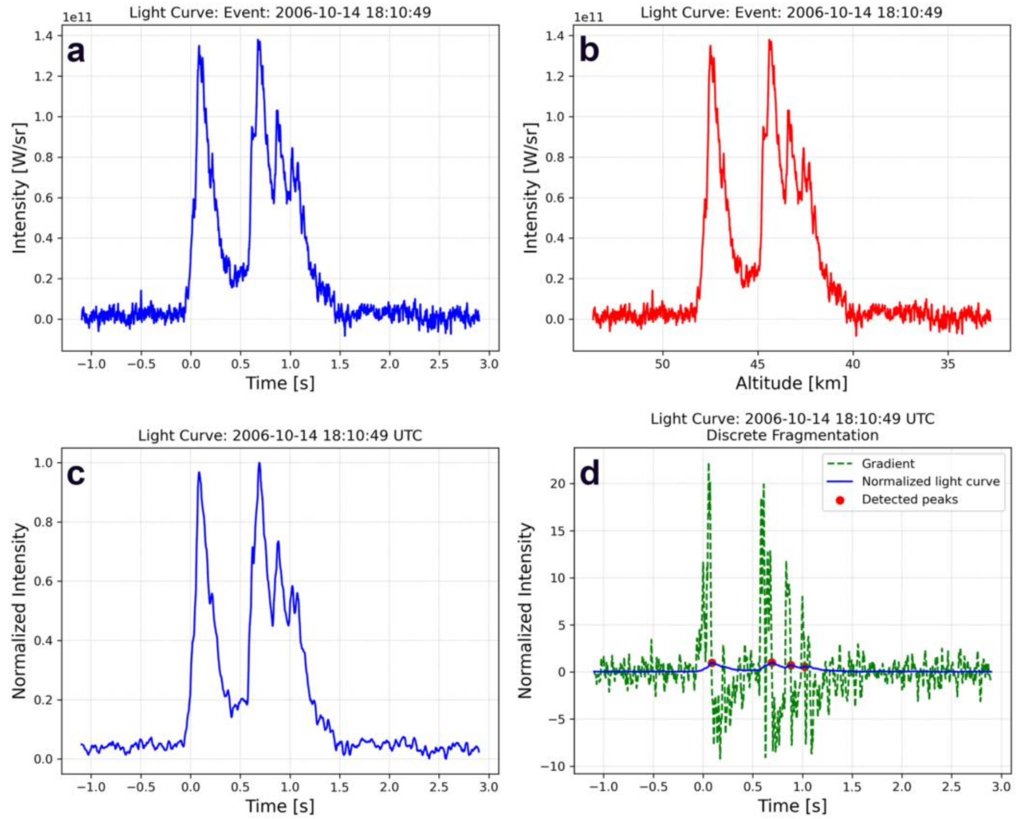

Figure 2. Light curve analysis of the event that occurred on October 14, 2006 at 18:10:49 UTC (this is Figure 3 in Silber & Sawal (2025), published under Creative Commons license)

8.3. Picks file

Output_LC_BLADE > 20061410_181049 > 20061410_181049_picks.csv > data

```
Peak Time [s], Original Intensity , Normalized Intensity, Peak Altitude [km], Prominence
      0.086001, 131998553519.783615,            0.961712,  47.54142754117325,   0.822710
      0.687135, 133144165863.069061,            1.000000,  44.4             ,   0.985976
      0.875953, 100148987463.862457,            0.727001,  43.41326955437507,   0.272842
      1.022383,  84246287367.407318,            0.580116,  42.64805002511492,   0.129019
```

Figure 3. Contents of 20061410_181049_picks.csv

9. SUMMARY, DISCLAIMER, AND ATTRIBUTION

9.1. Summary

This user manual provides step-by-step instructions for installing, configuring, and operating BLADE with supported datasets. Scientific context, interpretation of results, background information, and practical examples are not repeated here and can be found in the original publication [1]. Users are strongly encouraged to consult the published article for methodological details, scientific motivation, and comprehensive discussion of BLADE's applications and limitations.

For further clarification, examples of data analysis, or interpretation of scientific results, please refer to the original peer-reviewed publication. This manual is intended as a practical resource for software setup and usage, while all scientific interpretation is documented in the foundational article.

9.2. Disclaimer

If you use, adapt, modify, build upon, or incorporate any elements of BLADE, whether in whole or in part, the software is provided as-is without any warranty, support, or guarantee of accuracy or suitability for any particular application. The authors and developers assume no responsibility or liability for any outcomes resulting from the use or adaptation of BLADE or any of its components. All users are solely responsible for verifying the fitness and correctness of the software or its components for their intended research or operational needs. All use is at the discretion and judgment of the user.

9.3. Attribution

If you use BLADE, adapt its code, utilize its methods, or generate results based on its workflow in your research, publications, or presentations, you must provide proper attribution to both the software and the original peer-reviewed publication. Appropriate citation is required as follows:

Silber, E. A., Sawal, V. (2025), BLADE: An Automated Framework for Classifying Light Curves from the Center for Near-Earth Object Studies Fireball Database, The Astronomical Journal, doi: 10.3847/1538-3881/adeb55.

Any derivative works, modifications, or applications based on BLADE must also acknowledge the original software and publication.

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