MPO Canopus v12 Workflow

Complete Guide to Asteroid Lightcurve Analysis

From Raw FITS to Publication-Ready Results

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Abstract

This comprehensive guide provides a step-by-step workflow for asteroid lightcurve photometry using MPO Canopus Version 12. It covers the complete pipeline from image loading and quality assessment through photometric measurement, period analysis, and ALCDEF export. Special emphasis is placed on data quality control, photometric accuracy, and troubleshooting common issues.

Contents

1 Introduction

MPO Canopus v12 is a specialized software package for asteroid photometry and lightcurve analysis. This guide assumes you have:

- Basic familiarity with astronomical imaging and FITS file format
- Calibrated images (bias/dark/flat corrected)
- A basic understanding of differential photometry principles

1.1 Workflow Overview

The complete workflow consists of six main phases:

1. **Prerequisites & Quality Control** — Validate image quality
2. **Setup & Image Loading** — Configure software and import data
3. **Aperture Configuration** — Set photometric parameters
4. **Target & Star Selection** — Identify asteroid and comparison stars
5. **Measurement** — Execute photometry
6. **Analysis & Export** — Determine period and generate outputs

2 Phase 0: Prerequisites & Image Quality Assessment

Poor quality images will produce unreliable lightcurves regardless of analysis technique. Always perform quality checks *before* loading data into Canopus.

2.1 Required Image Preparation

Calibration
All images must be calibrated with appropriate bias/dark and flat frames. While Canopus can perform calibration, the standard v12 workflow assumes pre-calibrated data.

Plate Solving
WCS (World Coordinate System) headers are highly recommended. Plate-solved images enable:

- Automatic catalog star identification
- Accurate coordinate transformations
- Faster processing
- HJD or BJD corrections

File Organization
Store all images for a single observing session in one dedicated folder with consistent naming convention.

2.2 Critical Quality Checks

Examine your images carefully *before* beginning photometry:

Use DS9, MaxIm DL, or similar software to batch-check FWHM and saturation levels before importing to Canopus. This saves time and prevents wasted processing effort.

Check	What to Look For
Star Shape	Stars should be circular. Elongation or trailing indicates tracking errors. *Action:* Remove trailed images.
Saturation	Check histogram and peak pixel values. Target and comparison stars must be below saturation threshold (typically $<$60,000 ADU for 16-bit, $<$4,000 for 12-bit). *Action:* Exclude saturated frames.
FWHM	Full Width Half Maximum should be consistent across the session ($\pm$20%). Large variations suggest focus drift or changing seeing. *Action:* Note FWHM for aperture sizing; consider excluding outliers.
Background	Sky background should be relatively uniform without significant gradients. *Action:* Check flat field quality if gradients present.
Image Count	Minimum 40–50 images recommended for robust period determination. More is better.

3 Phase 1: Setup & Image Loading

3.1 Launching the Asteroid Wizard

1. Launch MPO Canopus v12
2. Navigate to: **Photometry** → **Multi-image Photometry** → **Asteroid Wizard**
3. The wizard interface replaces the older manual photometry workflow used in earlier Canopus versions

3.2 Profile Selection

4. When prompted, select the equipment profile matching your telescope and camera setup
5. If no profile exists: **File** → **Configuration** to create one
6. Profile stores critical parameters:
   - Telescope aperture and focal length
   - Camera pixel size and gain
   - Default aperture settings
   - Observatory location (for HJD corrections)

3.3 Loading Images

7. Click the **Select Images** tab
8. Click **Folder** and navigate to your FITS directory
9. Select all files (Ctrl+A or Cmd+A)

10. Configure display options:
    - **Review:** Set to "No" for faster loading if you've pre-validated images
    - **Scaling:** "Auto" or "Compressed" to visualize faint stars
11. Click **Load**

Canopus will read FITS headers to extract observation time, exposure duration, and coordinates. Verify that times are correctly extracted (check the image list for JD values).

4 Phase 2: Aperture & Photometry Configuration

Aperture sizing is the single most important parameter affecting photometric accuracy. Inappropriate apertures are a leading cause of noisy lightcurves.

4.1 Understanding Aperture Photometry

Canopus uses aperture photometry with three concentric regions:

1. **Measuring Aperture** — Circular region centered on the star, capturing stellar flux
2. **Gap** — Separation zone to avoid contamination
3. **Sky Annulus** — Ring region for background measurement (defined by inner and outer radii)

The instrumental magnitude is calculated as:

$$m_{\text{inst}} = -2.5 \log_{10} \left(\frac{F_{\text{star}} - F_{\text{sky}}}{t_{\text{exp}}} \right) + C$$

where F_{star} is the total flux in the measuring aperture, F_{sky} is the median sky per pixel, t_{exp} is exposure time, and C is an arbitrary constant.

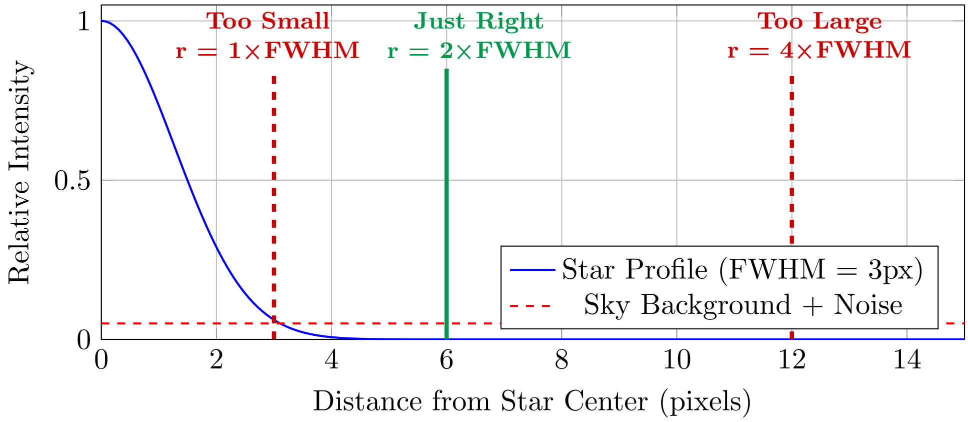
4.2 Setting Aperture Parameters

Access via: **Configuration → Photometry Settings** or directly in the wizard.

Parameter	Value	Notes
Aperture Radius	1.5–2.5× FWHM	See Figure 1 for optimal sizing *Example: FWHM = 3 px → radius 5–7 px*
Gap	2–5 pixels	Prevents star wings contaminating sky
Sky Inner Radius	r_{ap} + gap	Begin sky annulus outside gap
Sky Outer Radius	r_{inner} + 10–20 px	Sufficient area for robust statistics
Sky Algorithm	Median	Robust against cosmic rays & hot pixels Alternative: Mode for crowded fields

Table 1: Recommended aperture photometry parameters with cross-reference to visualization

The Aperture "Goldilocks Zone"



Aperture Sizing Consequences:

- **Too Small (r < 1.5×FWHM):** Missing flux from star wings → systematic errors, especially in varying seeing
- **Optimal (r = 1.5–2.5×FWHM):** Captures >95% of star flux while minimizing sky noise
- **Too Large (r > 3×FWHM):** Excessive sky noise dominates → poor signal-to-noise ratio

Figure 1: The "Goldilocks Zone" for aperture sizing. The optimal aperture radius balances complete flux capture against sky noise contamination.

How to determine FWHM:

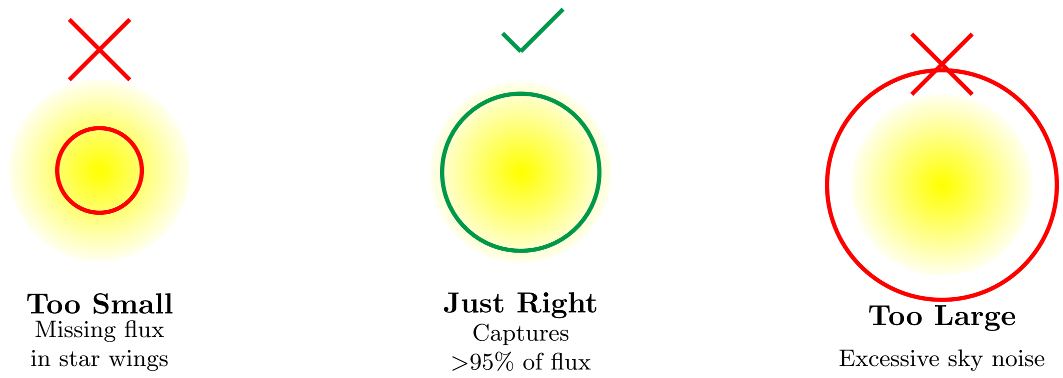
1. Use Canopus's built-in star profile tool on several non-saturated stars
2. Average the FWHM measurements
3. Round up to nearest pixel for aperture calculation
4. If FWHM varies significantly (¿20%), use the median value

4.3 Visual Verification

1. Use the **Aperture Tool** to display apertures overlaid on an image
2. Select a bright (but non-saturated) star
3. Verify:
   - Measuring aperture contains all visible star flux
   - Sky annulus is free from nearby stars
   - Gap prevents star wings from entering sky region
4. Examine the radial profile plot if available

4.3.1 The Goldilocks Zone: Optimal Aperture Sizing

Choosing the correct aperture size is critical. Here's what happens with different choices:



(a) $r < 1.5 \times \mathrm{FWHM}$ (b) $r = 1.5\text{–}2.5 \times \mathrm{FWHM}$ (c) $r > 3 \times \mathrm{FWHM}$

Figure 2: The Goldilocks Zone of aperture sizing. Too small loses flux (left), too large adds noise (right), but the optimal range (center) maximizes signal-to-noise ratio.

5 Phase 3: Target & Comparison Star Selection

5.1 Locating the Asteroid

1. The wizard displays the **first image** in your sequence
2. Locate the asteroid. If difficult to find:
   - Use the **Blink** tool to animate frames
   - The moving object is the asteroid; background stars remain stationary
3. Click on the asteroid — a red circle appears
4. When prompted, locate and click the asteroid in the **last image**
5. Canopus calculates the motion vector and predicts positions for all intermediate frames

If your observing session spans many hours, asteroid motion may be curved (not linear). For sessions >6–8 hours, consider breaking the data into shorter blocks and combining lightcurves later.

5.2 Session Metadata Entry

Accurate metadata is *essential* for ALCDEF export and scientific validity.

Why HJD? Earth's orbital motion introduces timing variations up to ±8 minutes. HJD corrects for this, ensuring accurate period determination when combining data from multiple observing runs.

5.3 Comparison Star Selection

Canopus will automatically identify candidate comparison stars (marked with green or blue circles).

Field	Requirement
Session Name	Descriptive identifier (e.g., "MP1234_20231031")
Object Number/Name	**Must match MPC designation exactly** for catalog lookups
Filter	Accurate filter identification (V, R, I, Clear, etc.) affects magnitude calibration
Observer Code	Your MPC observatory code (if assigned)
Exposure Time	Usually auto-extracted from FITS headers
Time Format	**HJD (Heliocentric Julian Date) recommended** Canopus can convert JD → HJD if object coordinates are known

5.3.1 Selection Criteria

Choose 3–5 comparison stars based on:

1. **Brightness Match:**
   - Similar magnitude to the asteroid (within ±2 mag ideally)
   - Ensures comparable signal-to-noise ratio
2. **Non-Saturation:**
   - Inspect star profiles — reject any with flat-topped peaks
   - Check pixel values if uncertain
3. **Stability (Variable Star Check):**
   - Cross-check against VSX (Variable Star Index) database
   - Canopus can perform this check if catalog access is configured
   - *Avoid known variables at all costs*
4. **Spatial Distribution:**
   - Spread stars across the field of view
   - Don't cluster all comparisons in one corner
   - Helps average out field-dependent systematics (vignetting, etc.)
5. **Color Match (Advanced):**
   - Ideally, select stars with similar spectral type to the asteroid
   - Reduces differential extinction and filter transformation errors
   - Often impractical; use similar brightness as primary criterion
6. **Path Avoidance:**
   - Ensure comparison stars don't lie in the asteroid's predicted path
   - Check motion vector overlay

Check Star Technique: Designate one comparison star as a "check star" and monitor its constancy relative to other comparisons during analysis. A stable check star validates your comparison ensemble.

5.4 Understanding Differential vs. Calibrated Photometry

5.4.1 Differential Photometry (Default)

Canopus measures the asteroid's brightness *relative* to comparison stars:

$$\Delta m = m_{\text{target}} - m_{\text{comp}}$$

This produces:

- Instrumental magnitudes (arbitrary zero-point)
- Excellent for period determination (only relative changes matter)
- **Cannot** be directly compared to catalog values

5.4.2 Calibrated Photometry (Optional)

For standard magnitudes:

1. Obtain catalog magnitudes for your comparison stars from:
   - AAVSO Photometric All-Sky Survey (APASS)
   - Gaia DR3
   - 2MASS (for infrared)
   - Pan-STARRS
2. Enter catalog magnitudes in: **Session Manager → Comparison Stars**
3. Canopus will calculate calibrated target magnitudes
4. Results can be compared to predicted asteroid magnitudes

For most lightcurve work, differential photometry is sufficient. Calibration is necessary when reporting absolute magnitudes or combining data from different observatories.

6 Phase 4: Photometric Measurement

6.1 Executing the Measurement

1. Verify all settings (apertures, comp stars, metadata)
2. Click the **Measure** button
3. Canopus will iterate through all FITS files, measuring:
   - Target asteroid at predicted positions
   - All comparison stars at fixed positions
   - Sky background in annuli

6.2 Monitoring the Process

Critical: Watch the measurement progress carefully. The red target aperture must accurately track the asteroid across all frames.

What to monitor:

- Red aperture stays centered on the asteroid
- No aperture overlaps (target and comp stars)
- Progress bar advances smoothly
- No error messages about saturated or failed measurements

If tracking fails:

1. Stop the measurement immediately (Escape or Stop button)
2. Return to target selection
3. Re-click asteroid in first/last frames more precisely
4. For long sessions, consider breaking into shorter blocks

Handling Non-Linear (Curved) Motion

For sessions exceeding 6–8 hours, asteroid motion often becomes non-linear, causing the fixed-path tracking to fail.

1. **Data Segmentation:** Break the session into 3–4 hour "blocks."
2. **Measurement:** Run the measurement wizard for the first block. Once complete, do *not* clear the session.
3. **Stitching:** Load the next block of images. MPO Canopus will treat these as a continuation. Re-center the target on the first frame of the new block; the software will calculate a new motion vector while preserving the photometric zero-point from the previous stars.

6.3 Automatic Session Saving

Upon completion, Canopus automatically saves:

- Photometric data to the MPO database (.MDB file)
- Session parameters and metadata
- Comparison star information

Session name can be found in: **Lightcurve Analysis → Sessions**

7 Phase 5: Period Analysis with FALC

7.1 Loading Data into Analysis Mode

1. Close the Photometry Wizard (if still open)
2. Navigate to: **Lightcurve Analysis** (toolbar icon or Analysis menu)
3. In the Analysis window:
   - Click **Sessions** (top-left panel)
   - Check the box next to your session name
   - Click **Load**
4. Raw data points appear in the main graph (unphased, time-series plot)

7.2 Understanding FALC

FALC (Fourier Analysis of Light Curves) determines the rotation period by:

1. Testing a range of trial periods
2. For each period, folding the lightcurve (wrapping time onto phase 0.0–1.0)
3. Fitting a Fourier series to the phased data
4. Computing the RMS (Root Mean Square) residual
5. Identifying the period with minimum RMS as the best-fit rotation period

The Fourier series used is:

$$m(\phi) = A_0 + \sum_{k=1}^{N} [A_k \cos(2\pi k\phi) + B_k \sin(2\pi k\phi)]$$

where ϕ is the rotation phase, N is the order (number of harmonics), and A_k, B_k are Fourier coefficients.

7.3 Period Search Strategy

The following flowchart illustrates the iterative strategy for determining rotation periods within the MPO Canopus v12 environment:

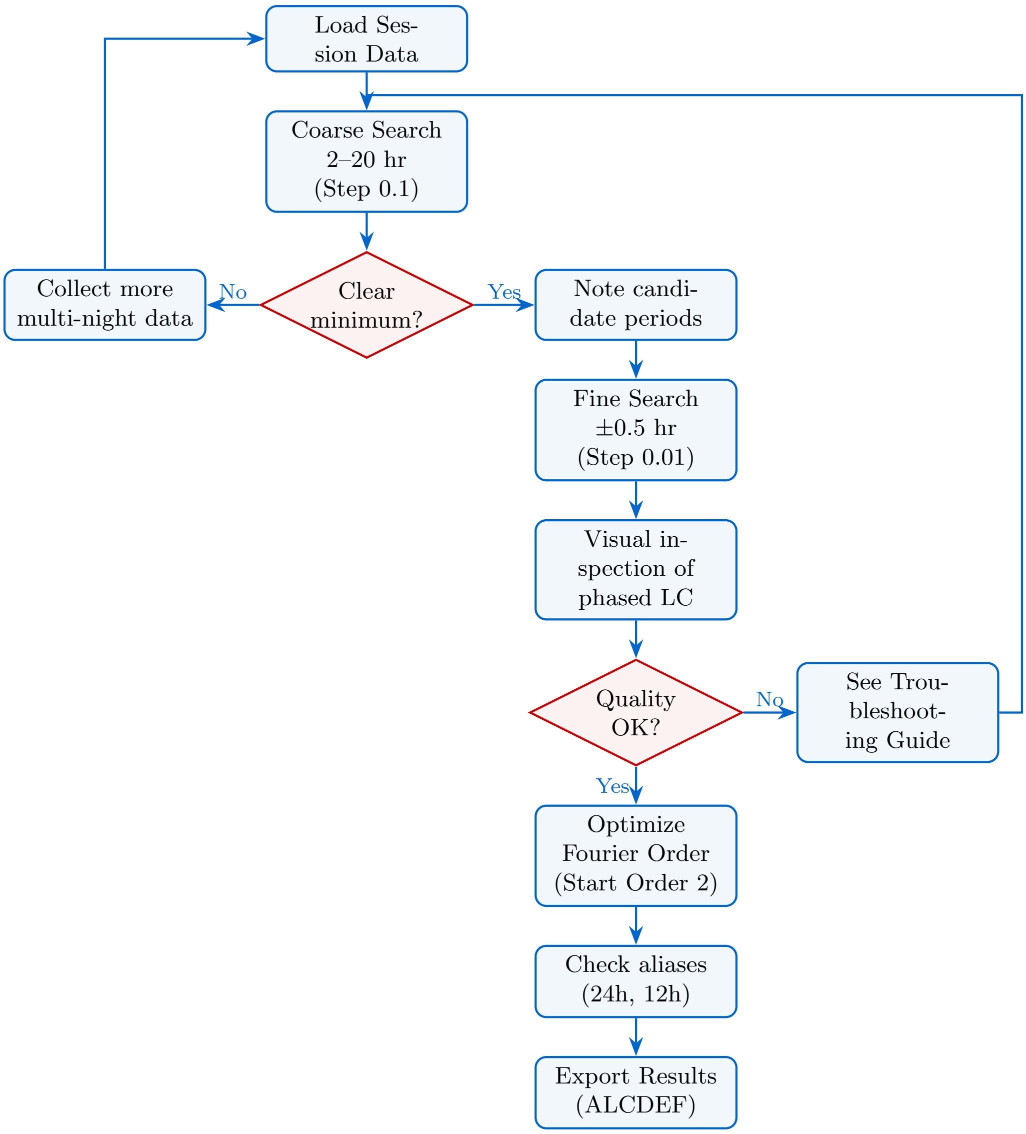


Figure 3: Period search workflow in MPO Canopus. The process is iterative: clear minima in the coarse search lead to fine tuning, while ambiguity requires more data or troubleshooting.

7.3.1 Step 1: Coarse Search

1. Locate the **FALC** panel (typically right side of Analysis window)
2. Set search parameters:
   - **Start:** Lower period bound (e.g., 2.0 hours)
   - **Stop:** Upper period bound (e.g., 20.0 hours)
   - **Step:** Coarse step size (e.g., 0.1 hours)
   - **Order:** Start with 2 or 3
3. Click **Find Period** or **Search**
4. Examine the **Period Spectrum** (periodogram) that appears

Choosing the search range:

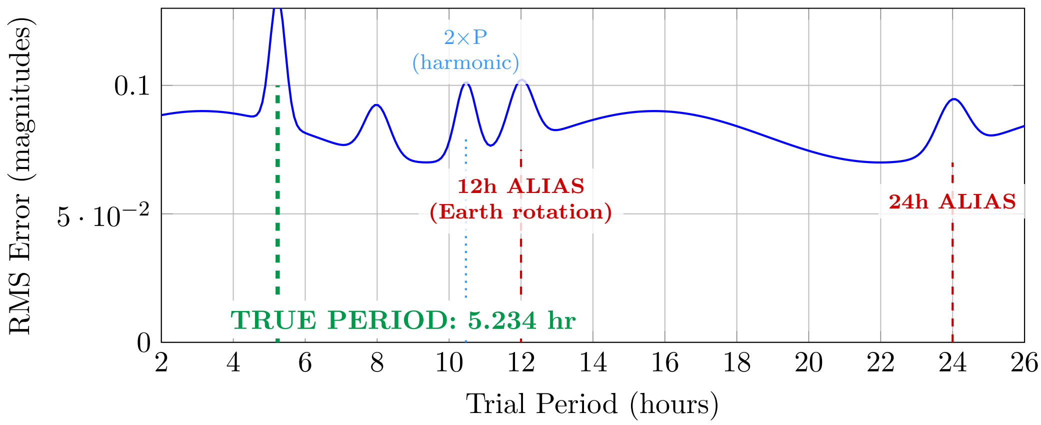
- Main-belt asteroids: typically 4–12 hours
- Near-Earth asteroids: can be 2–30+ hours
- If unsure, search 2–24 hours initially
- Very slow rotators (>24 hr) may require multi-night data

7.3.2 Step 2: Identifying Candidate Periods

The period spectrum shows RMS error vs. trial period:

- **Deep minima** (low RMS) indicate good period candidates
- Multiple minima are common — requires further investigation
- **Lowest global minimum** is the primary candidate

Example Periodogram: Identifying the True Period vs. Aliases



How to Distinguish True Periods from Aliases:

1. **True period**: Deepest RMS minimum, produces clean double-peaked lightcurve
2. **Daily aliases (12h, 24h)**: Artifacts of observing cadence. Test by:
   - Adding data from different nights (breaks the 24h pattern)
   - Checking if lightcurve morphology makes physical sense
3. **Harmonics (2×P, 3×P)**: Integer multiples of true period. Usually shallower minima.

Figure 4: Example periodogram showing the distinction between a true rotation period and common aliases. The true period (5.234 hr) produces the deepest minimum, while 12h and 24h aliases are artifacts of Earth's rotation.

7.3.3 Step 3: Fine Search

1. Note the period(s) with lowest RMS from coarse search
2. Set a narrow search range around the best candidate:

- **Start:** Best period −0.5 hours
- **Stop:** Best period +0.5 hours
- **Step:** Fine step (0.01 or 0.001 hours)

3. Re-run FALC

4. The refined minimum gives your final period estimate

7.3.4 Step 4: Optimizing Fourier Order

1. With the best period selected, experiment with Fourier order:
   - **Order = 2:** Double-peaked, sinusoidal lightcurve
   - **Order = 3–4:** Asymmetric or complex shapes
   - **Order = 5+:** May overfit noise (use cautiously)

2. Choose the *minimum* order that adequately represents the lightcurve shape

3. Higher orders reduce RMS but risk fitting noise rather than signal

Order	When to Use	Physical Interpretation
2	**Default for most asteroids** • Clean double-peaked lightcurve • RMS not improved by higher orders	Symmetrical ellipsoidal shape Two identical maxima/minima per rotation Uniform surface albedo
3	Moderate asymmetry • One peak higher than the other • Noticeable RMS improvement over Order 2	Slight shape irregularity or albedo variation between hemispheres
4	Significant asymmetry • Complex multi-peaked structure • Flat-bottomed minima • Sharp peaks or shoulders	Highly irregular shape (contact binary, elongated tumbler) OR mutual events in binary asteroid systems
5–6	**Rarely justified** Use only if: • Very high SNR data (>100 points) • Obvious complex structure • Order 4 clearly inadequate	Risk of overfitting! May indicate: • Binary with partial eclipses • Tumbling (non-principal axis rotation) • Insufficient data coverage
7+	**Almost never** Consult with experienced observers	Likely fitting noise rather than signal Requires expert interpretation

Table 2: FALC Decision Matrix: Choosing the appropriate Fourier order based on lightcurve morphology

Order Selection Strategy:

1. Start with Order 2
2. Increase to Order 3, check if RMS improves by >10%
3. If yes, try Order 4
4. Stop when RMS improvement becomes marginal (<5%)
5. Visually inspect: does higher order actually fit structure, or just noise?

Overfitting Danger: High Fourier orders can fit random noise, producing artificially low RMS values. Always visually inspect whether higher orders genuinely improve the fit or just follow data scatter. A good test: if Order 6 looks significantly better than Order 4, you may have a genuine complex shape. If it only marginally reduces RMS, stick with the lower order.

7.4 Validation and Quality Checks

If your period search yields noisy or ambiguous results, revisit the image quality checks in Section 2 to ensure your input data meets photometric standards.

7.4.1 Aliasing Detection

Common Aliases: Periods near 24h, 12h, 8h, 6h may be artifacts of Earth's rotation (daily observing cadence). Be skeptical of these results.

How to check:

- If your best period $P \approx 24$ hours, test $P/2$ and $2P$
- Compare RMS and visual appearance of phased lightcurves
- Multi-night observations break daily aliases

Breaking Aliases: The most reliable way to eliminate aliases is multi-night coverage with varying observing windows. If you observe from 20:00–02:00 on Night 1 and 23:00–05:00 on Night 2, a 24-hour alias will phase incorrectly, while the true period will phase all data coherently.

7.4.2 Lightcurve Morphology

After phasing with the best period, assess the lightcurve:

Single-peaked lightcurves: Uncommon but possible for pole-on viewing geometries or spherical objects with surface albedo variations. Verify period by testing $P/2$.

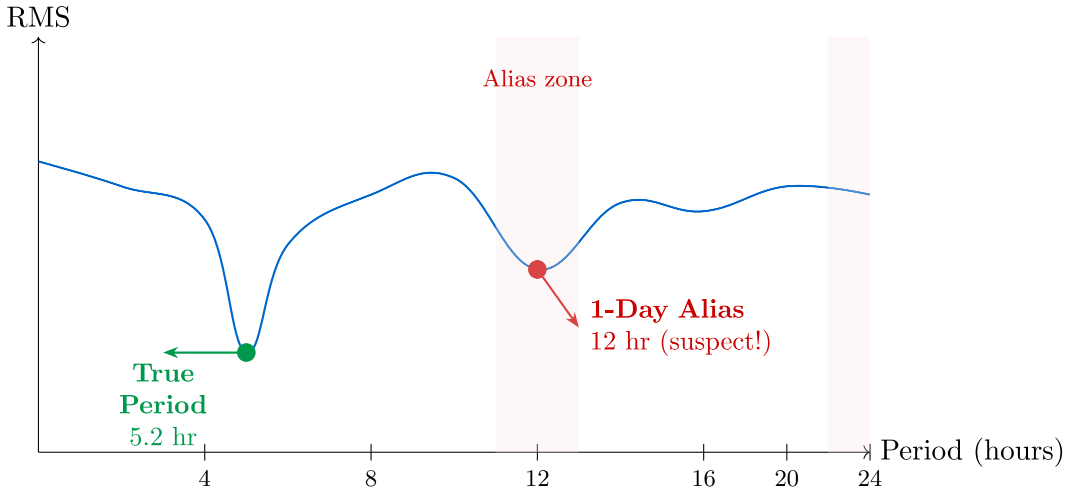


Figure 5: Example periodogram showing a true rotation period at 5.2 hours (green) vs. a 1-day alias at 12 hours (red). The alias appears as a local minimum but with higher RMS. Always test both solutions by visual inspection of the phased lightcurve.

7.4.3 Statistical Indicators

- **RMS (Root Mean Square):** Measure of fit quality. Lower is better, but compare only within the same dataset.
- **Reduced χ^2:** If available, values near 1.0 indicate good fit. $\chi^2 \gg 1$ suggests underestimated errors or poor fit.
- **Error bars:** Display measurement uncertainties. Scatter should be consistent with error bars.

7.5 Period Uncertainty

Canopus may report formal period uncertainty, but consider:

- **Statistical uncertainty:** From the curvature of the RMS minimum
- **Systematic uncertainty:** From observing baseline
- Longer time baseline $\rightarrow$ better period precision
- Rule of thumb: $\sigma_P \approx P^2/T$ where T is observing baseline

Reporting periods: Use appropriate significant figures based on uncertainty. For example:

- If $P = 5.2347$ hr with $\sigma = 0.015$ hr, report: $P = 5.235 \pm 0.015$ hr
- Don't over-report precision (e.g., 8 decimal places with 2-hour baseline)

Feature	Expected / Quality Indicator
Symmetry	Most asteroids show **double-peaked** lightcurves (two maxima and two minima per rotation) due to elongated shape
Amplitude	Typical range: 0.1–1.0 magnitudes. Amplitude relates to axial ratio. Spherical asteroids: <0.1 mag. Highly elongated: >0.5 mag.
Scatter	Points should cluster tightly around the fitted curve. Large scatter indicates: • Poor comp star selection • Incorrect period • Weather variability
Phase Coverage	Ideally, data spans all phases (0.0–1.0). Gaps are acceptable but reduce confidence

8 Phase 6: Data Export & Reporting

8.1 Exporting the Lightcurve

Canopus provides several export options:

Lightcurve Plot Use **Print/Export** to save the phased lightcurve as:

- Image file (PNG, JPEG) for publications
- PDF for reports

Data Tables Export raw photometry as:

- CSV or TXT for custom analysis
- Includes: time (JD/HJD), magnitude, error, phase

Period Spectrum Save the RMS vs. period plot to document your period search

8.2 ALCDEF Format

8.2.1 What is ALCDEF?

ALCDEF (Asteroid Lightcurve Data Exchange Format) is the international standard for reporting asteroid photometry to the Minor Planet Center. It ensures:

- Consistent data format across observers
- Machine-readable for database ingestion
- Metadata completeness for scientific utility

8.2.2 Generating ALCDEF Files

1. In the Lightcurve Analysis window: **File → Export → ALCDEF**
2. Canopus auto-populates most fields from session metadata:
   - Object designation
   - Observer information
   - Filter
   - Comparison star details
   - Photometry parameters
   - Observation dates/times
3. Verify all required fields are complete
4. Save the .txt file

Critical ALCDEF Fields:

- **FILTER**: Must be standard notation: V, R, I, B, Clear, etc. (NOT "red filter" or "Johnson R")
- **STANDARD**: Photometric system—Johnson, Cousins, SDSS, etc.
- **REDUCEDMAGS**: Set to CALIBRATED if you entered catalog magnitudes for comp stars, otherwise DIFFERENTIAL
- **COMPNAME**: Use catalog designations (TYC, UCAC4, Gaia DR3) separated by pipes (—)
- **MPCDESIG**: Must exactly match MPC format (e.g., "2023 AB" not "2023AB")

8.2.3 Sample ALCDEF Header

Below is an annotated example of a correctly formatted ALCDEF header:

Sample ALCDEF Header (Correctly Formatted)

```
# ALCDEF FORMAT VERSION 2023
STARTMETADATA
OBJECTNUMBER=1234
OBJECTNAME=2023 AB
OBSERVERS=J.Smith
OBSCODE=G52
CONTACTNAME=John Smith
CONTACTINFO=jsmith@example.edu

FILTER=R
MAGBAND=R
STANDARD=Cousins
REDUCEDMAGS=CALIBRATED

LTCTYPE=DIFF
LTCDAYS=0.218
LTCAPP=5.234
PAAO=60.0
PHASE=12.5

TELESCOPE=0.35-m SCT
CAMERA=SBIG ST-8XE
PIXELSCALE=1.2

COMPNAME=TYC 1234-5678-1|TYC 1234-5679-1
COMPMAG=12.34|12.56

CICORRECTION=SKY
CIBAND=R

SESSIONDATE=2023-10-12
SESSIONTIME=22:30:00
OBSLATITUDE=+35.123
OBSLONGITUDE=-106.456

ENDMETADATA

DATA=JD|MAG|MAGERR
2460233.45678|13.456|0.012
2460233.45834|13.489|0.011
2460233.46012|13.512|0.013
# ... (additional data points)
ENDDATA
```

Figure 6: Example of a properly formatted ALCDEF file. Key fields include filter designation (R), standard system (Cousins), and whether magnitudes are calibrated or differential.

Example ALCDEF Header

```
# ALCDEF FORMAT VERSION 2023
STARTMETADATA

OBJECTNUMBER=1234
OBJECTNAME=Smith
# The object designation MUST match MPC database exactly

OBSERVERS=J.Doe,M.Smith
# First initial + last name, comma-separated

OBSCODE=G52
# Your MPC observatory code (if assigned)

MPCDESIG=2023 AB1
# Provisional designation (if not yet numbered)

CONTACTNAME=Jane Doe
CONTACTINFO=jdoe@example.edu

FILTER=R
# Standard filter: U, B, V, R, I, Clear, CV, CR, etc.

MAGBAND=R
# Photometric band (usually same as FILTER)

STANDARD=COUSINS
# Photometric system: COUSINS, JOHNSON, SLOAN, MAGS (instrumental)

REDUCEDMAGS=DIFF
# DIFF (differential), CALIBRATED, NORMALIZED, or COMP

DIFFERMAGS=
# Leave blank for DIFF photometry

LTCTYPE=NONE
# Light-time correction: NONE, HELIO, or both

LTCDAYS=
# Leave blank if LTCTYPE=NONE

PHASE=
# Phase angle (optional; auto-calculated if RA/DEC provided)

PERIOD=5.2347
PERIODERR=0.0015
# Rotation period in hours with uncertainty

AMPLITUDE=0.35
AMPLITUDEERR=0.02
# Lightcurve amplitude in magnitudes

DELIMITER=PIPE
# Data separator: COMMA, PIPE, or TAB

DATA=JD|MAG|MAGERR|
# Column definitions for data section

ENDMETADATA
# Below this line: actual photometric data points
2460234.567890|14.23|0.02|
2460234.578901|14.31|0.02|
2460234.589912|14.28|0.02|
...
```

Field	Example	Notes
FILTER	`R`, `V`, `Clear`	Use standard notation
STANDARD	`COUSINS`, `JOHNSON`	Photometric system
	`MAGS`	Use MAGS for instrumental magnitudes
REDUCEDMAGS	`DIFF`	Differential photometry (most common)
	`CALIBRATED`	Calibrated to catalog standards
LTCTYPE	`NONE`	No light-time correction
	`HELIO`	Heliocentric correction applied

Table 3: Common ALCDEF field values and their meanings

8.2.4 Required ALCDEF Metadata

Ensure these are correctly entered:

- **Object:** Proper MPC designation
- **Observers:** Names (first initial + last name)
- **Filter:** Must use standard notation (V, R, I, Clear, etc.)
- **Magband:** Photometric system (usually same as filter)
- **Observatory:** MPC code (if assigned) or coordinates
- **Comparison stars:** RA/Dec and catalog magnitudes
- **Exposure time**
- **Cycle time:** Total time including readout

ALCDEF submission: Submit files to the Minor Planet Center's Asteroid Lightcurve Database (LCDB) via the online portal. Include contact information for follow-up questions.

8.3 Publication Checklist

When reporting lightcurve results (journal article, CBET, etc.), include:

1. **Rotation Period:** $P = X.XXX \pm 0.XXX$ hours
2. **Amplitude:** $A = X.XX \pm 0.XX$ magnitudes
3. **Observing Dates:** JD or calendar dates of observations
4. **Phase Coverage:** Fraction of rotation period observed
5. **Photometric System:** Filter and comparison methodology
6. **Instrumentation:** Telescope aperture, camera model
7. **Phased Lightcurve Plot**

8. **Period Spectrum:** Demonstrates uniqueness of solution
9. **Data Quality:** RMS scatter, number of images, exposure times

9 Troubleshooting Common Issues

9.1 Noisy or Scattered Lightcurve

Symptom Data points widely scattered around fitted curve; high RMS

Possible Causes & Solutions

1. **Variable comparison star:**
   - Plot comp stars against each other (Canopus has this feature)
   - If one deviates, remove it from the ensemble
   - Re-measure with revised comp star set
2. **Aperture too large:**
   - Captures excessive sky noise
   - Reduce aperture to 1.5× FWHM
   - See Figure 1 for optimal sizing
3. **Aperture too small:**
   - Loses flux, especially in varying seeing
   - Increase to 2.5× FWHM
   - Review Section 4 for parameter guidance
4. **Poor calibration:**
   - Check dark/flat frame quality
   - Ensure flats are recent and match filter
   - Revisit Section 2 for calibration validation
5. **Atmospheric variations:**
   - Thin clouds, variable seeing
   - May be unavoidable; increase observing time
6. **Image quality issues not caught during preprocessing:**
   - Return to Section 2 and re-examine:
     - FWHM consistency (should vary <20%)
     - Saturation levels
     - Star trailing
   - Remove problematic frames and re-measure

9.2 Asteroid Not Tracking Properly

Symptom Red aperture drifts off asteroid during measurement

Solutions

1. **Re-select endpoints:**
   - Return to target selection
   - Click asteroid more precisely in first/last images
   - Use zoom feature for accuracy
2. **Non-linear motion:**
   - Long sessions (>6–8 hrs) may show curved paths
   - Break into 2–3 hour blocks
   - Measure separately, then combine lightcurves
3. **Images out of time order:**
   - Verify FITS headers have correct timestamps
   - Check file loading order in image list

9.3 No Clear Period Found

Symptom Period spectrum shows no distinct minimum, or all RMS values similar

Possible Causes

1. **Insufficient data:**
   - Need more images or longer time baseline
   - Aim for >1 complete rotation
2. **Very slow rotator:**
   - Period >24 hours requires multi-night observations
   - Extend search range to 48+ hours
3. **Very fast rotator:**
   - Period <2 hours (rare but possible for small asteroids)
   - Ensure time resolution is adequate
   - May require shorter exposures
4. **Low amplitude:**
   - Nearly spherical asteroids ($A < 0.05$ mag)
   - Signal buried in noise
   - Need higher photometric precision
5. **Pole-on view:**
   - Viewing asteroid down its rotation axis
   - Little to no brightness variation
   - Consider observing at different apparition

9.4 Comparison Stars Showing Variability

Symptom When plotting comp stars against each other, one or more show trends or variations

Solutions

1. Identify the variable star(s)
2. Remove from comparison ensemble
3. If possible, add new comparison stars to replace
4. Re-measure the session
5. Cross-check remaining comp stars against VSX catalog

9.5 Saturated Stars

Symptom Canopus reports saturation warnings, or stars show flat-topped profiles

Solutions

1. If asteroid is saturated:
   - Cannot be salvaged — must re-observe with shorter exposures
2. If only comp stars are saturated:
   - Select fainter comparison stars
   - Re-measure with new comp set
3. Prevention:
   - Pre-check saturation before long observing runs
   - Keep peak counts <60% of sensor full well

10 Advanced Topics

10.1 Multi-Night Observations

Combining data from multiple nights improves:

- Period precision (longer time baseline)
- Phase coverage
- Alias rejection (breaks daily cadence)

Procedure:

1. Create separate sessions for each night
2. Use *identical* comparison stars across nights (if possible)
3. In Lightcurve Analysis, load multiple sessions simultaneously
4. FALC will analyze combined dataset

For multi-night data, differential photometry is essential. Absolute calibration variations between nights will introduce offsets.

10.1.1 Zero Point Shift Tool: Aligning Multi-Night Data

When combining observations from different nights, atmospheric conditions, instrument configuration, or comparison star availability may cause systematic magnitude offsets between datasets.

When Zero Point Shifts Are Needed:

- Different atmospheric transparency between nights
- Changed comparison star ensemble
- Different telescope or camera used
- Filter swapped or cleaned between sessions

These produce *vertical offsets* in the lightcurve that don't affect the period but reduce overall fit quality.

Using the Zero Point Shift Tool in Canopus:

1. Load multiple sessions into Lightcurve Analysis
2. Phase the data with your best-fit period
3. Navigate to: **Analysis → Zero Point Adjustment** (or similar menu item)
4. Canopus will display each session's data in different colors
5. Options for alignment:

- **Automatic:** Canopus minimizes RMS by shifting each session vertically
- **Manual:** You specify the offset for each session (in magnitudes)
- **Reference Session:** Choose one session as the reference (zero shift); others are adjusted relative to it

6. Click **Apply Shifts**

7. Re-run FALC to generate combined fit

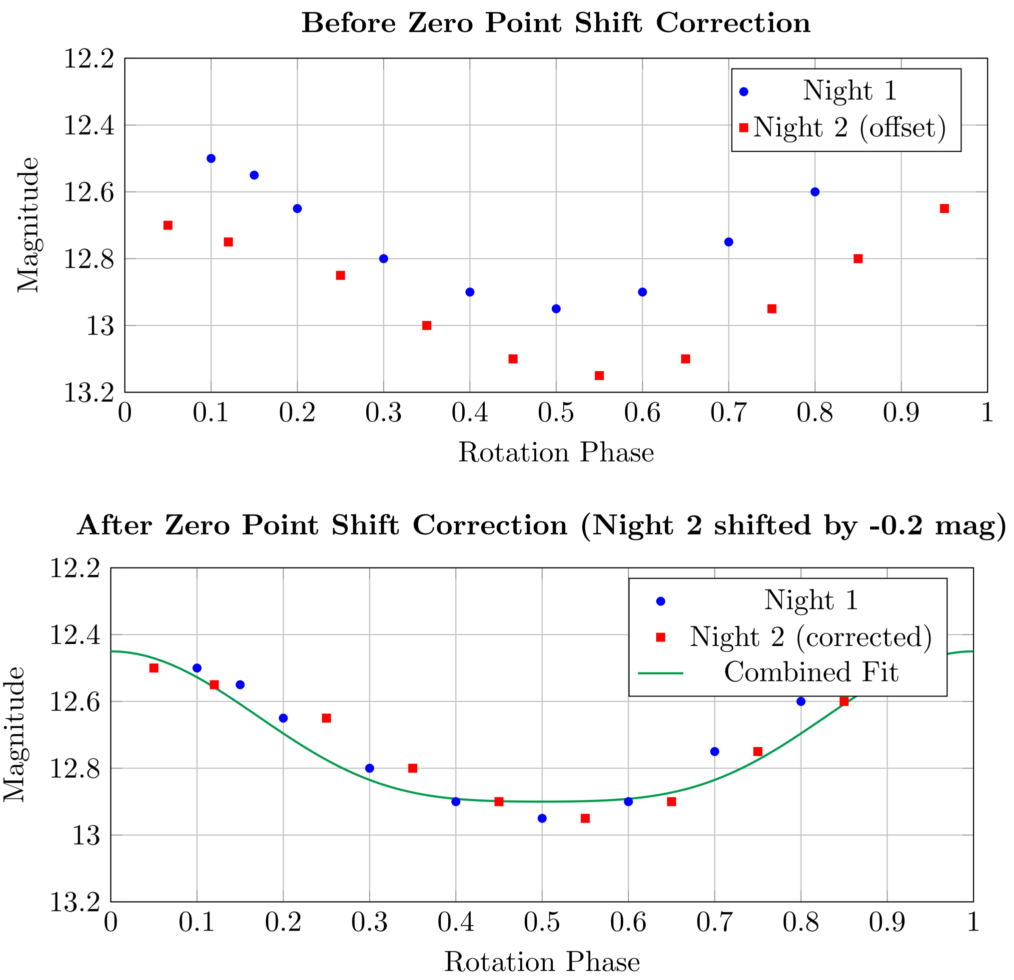


Figure 7: Zero point shift correction aligns multi-night data by removing systematic magnitude offsets. Top: Raw data shows Night 2 offset by +0.2 mag. Bottom: After correction, data from both nights align, enabling a unified period fit.

Best Practices for Multi-Night Photometry:

- Always use the same comparison star ensemble across nights if possible
- If comp stars must change, ensure at least 1–2 stars overlap between nights
- Document any changes in observing setup (filters, cameras, etc.)
- The zero point shift should be <0.3 mag for good differential photometry
- If shifts are >0.5 mag, investigate: possible star misidentification or bad calibration

10.1.2 Handling Zero-Point Shifts Between Nights

When atmospheric conditions differ significantly between nights (transparency, airmass variations), your comparison star ensemble may show systematic offsets. Canopus provides tools to correct these:

1. **Identify the shift:** After loading multi-night sessions, examine the raw lightcurve. Look for vertical offsets between different nights' data.
2. **Access the Zero-Point Tool:**
   - In Lightcurve Analysis mode: **Analysis → Adjust Zero Points**
   - Or right-click on the data plot and select **Zero Point Corrections**
3. **Apply corrections:**
   - Canopus will display each session separately
   - Select a reference session (usually the one with best seeing/most data)
   - For other sessions, enter magnitude offsets to align with reference
   - Alternatively, use the **Auto-Align** feature which minimizes RMS between overlapping phases
4. **Verify alignment:**
   - Re-run FALC on the corrected data
   - Check that data from all nights now phase coherently
   - Scatter should be consistent across all nights

Cause of Offset	**Solution**
Different airmass	Zero-point correction (typical offset: 0.1–0.3 mag)
Thin clouds on one night	Zero-point correction + increase uncertainties for cloudy night
Different comp star sets	Re-reduce with identical comp stars, or apply differential corrections
Instrumental changes	Check flat fields; may require recalibration

Table 4: Common causes of zero-point shifts in multi-night data

Best Practice: Always use the same comparison stars across multiple nights. If your field of view changes, select stars that appear in *all* nights' images. This minimizes zero-point issues.

10.2 Composite Lightcurves

Combining data from different observers/telescopes:

- Each dataset must be internally consistent (same comp stars per dataset)
- Import data into Canopus as separate sessions
- Phase all data to common period
- May require magnitude offsets between datasets

10.3 Fast Rotators (Period < 2 hours)

Special considerations:

- Exposure time must be short (< 5% of period) to avoid rotational smearing
- Need many images per rotation (20+ recommended)
- Timing accuracy becomes critical
- Verify FITS timestamp precision (sub-second accuracy needed)

10.4 Sparse Data and Incomplete Coverage

If phase coverage is poor:

- Period determination becomes less certain
- May have multiple equally good solutions
- Amplitude measurement is unreliable
- Additional observations recommended before publication

10.5 Shape and Pole Modeling

High-quality lightcurves from multiple apparitions enable:

- 3D shape reconstruction (convex inversion methods)
- Spin pole determination
- This is beyond Canopus scope — requires specialized software
- Examples: KOALA, DAMIT database

For these studies, maximize:

- Number of apparitions (different viewing geometries)
- Phase coverage per apparition
- Photometric precision (<0.02 mag RMS)

11 Glossary

ADU Analog-to-Digital Unit. The raw count value from a CCD/CMOS sensor. Related to photon flux by the camera gain.

Aperture Photometry Technique of measuring stellar brightness by summing pixel values within a defined circular region (aperture).

ALCDEF Asteroid Lightcurve Data Exchange Format. Standard format for submitting asteroid photometry to the Minor Planet Center.

Differential Photometry Measuring an object's brightness relative to comparison stars rather than to an absolute calibration standard.

FALC Fourier Analysis of Light Curves. Algorithm used by Canopus to determine rotation periods via Fourier fitting.

FWHM Full Width at Half Maximum. Measure of star image size (in pixels). Equal to the diameter of the star profile at 50% of peak intensity. Used to determine appropriate aperture size.

HJD Heliocentric Julian Date. Julian Date corrected for light-travel time to the Sun's center, removing Earth's orbital motion effects.

JD Julian Date. Continuous day count since January 1, 4713 BCE (astronomical timekeeping standard).

Lightcurve Plot of an object's brightness vs. time (or rotation phase). Reveals rotation period and shape information.

MPC Minor Planet Center. International clearinghouse for asteroid and comet observations.

RMS Root Mean Square. Statistical measure of scatter around a fitted curve. Lower RMS indicates better fit quality.

SNR Signal-to-Noise Ratio. Ratio of detected signal to background noise. Higher SNR yields more precise photometry.

WCS World Coordinate System. FITS header information linking pixel coordinates to sky coordinates (RA/Dec).

VSX Variable Star Index. Online database of known variable stars maintained by AAVSO.

12 Quick Reference Checklist

Use this checklist to ensure you've completed all critical steps:

12.1 Pre-Processing Phase

☐ Images calibrated (bias/dark/flat applied)

☐ FWHM measured (all images within 20%)

☐ Saturation checked (target and comp stars <60k ADU)

☐ Trailed or defective images removed

☐ Minimum 40–50 images available

☐ Files organized in dedicated folder

12.2 Software Setup Phase

☐ Correct equipment profile selected

☐ Images loaded successfully

☐ Aperture radius set to 2× FWHM

☐ Sky annulus parameters configured

☐ Aperture visually verified on test star

12.3 Target Selection Phase

☐ Asteroid identified and clicked in first image

☐ Asteroid identified and clicked in last image

☐ Motion vector appears reasonable

☐ Session name entered (descriptive)

☐ Object number/name matches MPC database

☐ Filter correctly specified

☐ Observer code entered (if applicable)

☐ HJD time format selected

12.4 Comparison Star Phase

☐ 3–5 comp stars selected

☐ All comp stars non-saturated

☐ Comp stars similar brightness to asteroid

☐ Comp stars checked against VSX (no known variables)

☐ Comp stars spatially distributed

☐ Comp stars not in asteroid's path

☐ Catalog magnitudes entered (if calibrated photometry desired)

12.5 Measurement Phase

☐ Measurement started

☐ Asteroid tracking verified visually

☐ No error messages during processing

☐ Measurement completed successfully

☐ Session saved to database

12.6 Analysis Phase

☐ Session loaded in Lightcurve Analysis

☐ Coarse period search completed (2–20 hr range)

☐ Candidate period(s) identified

☐ Fine period search performed

☐ Optimal Fourier order determined (typically 2–4)

☐ Phased lightcurve inspected for quality

☐ Double-peaked structure observed (typical)

☐ Amplitude in reasonable range (0.1–1.0 mag)

☐ Aliasing checked (period not near 24h, 12h, etc.)

☐ Data scatter consistent with error bars

12.7 Export & Reporting Phase

☐ Lightcurve plot exported (PNG/PDF)

☐ Period spectrum saved

☐ Data table exported (CSV/TXT)

☐ ALCDEF file generated

☐ ALCDEF metadata verified complete

☐ Period and uncertainty documented

☐ Amplitude documented

☐ Publication checklist items prepared

13 Additional Resources

13.1 Software & Tools

- **MPO Canopus:** https://minorplanetobserver.com/
- **DS9 Image Viewer:** https://sites.google.com/cfa.harvard.edu/saoimageds9
- **Astrometrica:** https://www.astrometrica.at/ (plate solving)

13.2 Catalogs & Databases

- **Minor Planet Center:** https://minorplanetcenter.net/
- **VSX (Variable Star Index):** https://www.aavso.org/vsx/
- **APASS (photometric catalog):** https://www.aavso.org/apass
- **LCDB (Lightcurve Database):** https://alcdef.org/
- **Gaia Archive:** https://gea.esac.esa.int/archive/

13.3 Educational Materials

- **ALCDEF Standard:** https://alcdef.org/alcdef-standard
- **MPO Canopus Manual:** Included with software installation
- **Asteroid Photometry Handbook:** Available from MPO website

13.4 Scientific Background

- Harris et al., "Photoelectric Observations of Asteroids," *Icarus* (various)
- Pravec et al., "Asteroid Rotations," chapter in *Asteroids IV* (2015)
- Warner et al., "The Asteroid Lightcurve Database," *Icarus* 202, 134 (2009)

This guide is intended as a practical reference and does not replace the official MPO Canopus documentation. Always consult the latest software manual for version-specific features and updates.

For questions or feedback, contact the MPO user community via the Minor Planet Mailing List or the MPO support forum.

Clear skies!