Looking for Zebras When There Are Only Horses

by

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“When you hear hoofbeats, think of horses not zebras”

• Coined in the late 1940s by Dr. Theodore Woodward, professor at the University of Maryland School of Medicine

• Still used today to remind medical students to look for the more “common” diagnosis rather than the “exotic”

• In our search for astrophysical events, such as exoplanet transits, it is easy for us to think that we are looking at a zebra, when in fact it is just a horse
Why is this important?

• In the era of TESS, follow-up, ground-based observations will be needed to help identify (astrophysical-based) false positives
  ➢ Example: to distinguish whether a perceived transit is due to an exoplanet vs. an eclipsing binary

• But first, it is important to understand any non-astrophysical sources that may cause a horse to look like a zebra
How Horses Can Mask As Zebras
(or Vice Versa!)

• External effects (atmospheric extinction, light pollution)

• Operational errors (polar misalignment)

• Instrumentation effects (inadequate autoguiding)

• Processing effects introduced during calibration, differential photometry, and transit modeling phases
Some Real Life Examples

• The “Pokémon” star

• A variable star in the ensemble of comp stars

• The lights from a nearby high-rise

• The light dome of a nearby urban center
Dissecting an Exoplanet Observation: A Zebra or a Horse?
Target and Initial Comp Star Selection
Initial Fit: It Clearly Looks Like a Horse!
So Let’s Perform a Dissection

Source Counts from aperture

Sky Background Counts from annulus

Source Counts - Sky Background

Relative flux of Target =

Target’s Source Counts - Sky Background

________________________________________
Sum of Comp Stars’ Source Counts - Sky Background
Transparency Conditions

HAT-P-16b, UT2017-09-13
Conti [SX685, CBB, 30 sec exposure]

- AIRMASS (arbitrarily scaled and shifted) Inverted
- tot_C_chis (arbitrarily scaled and shifted)

(Inverse)
AIRMASS

Comp Star Counts

Barycentric Julian Date (TDB) - 2458000 (mid-exposure)
Changes in Background Sky

Sky Background Counts per Pixel

HAT-P-16b, UT2017-09-13
Conti [Sx695, CBB, 30 sec exposure]

Sky/Pixel_T1 (normalized)
Sky/Pixel_C2 (normalized)
Sky/Pixel_C3 (normalized)
Sky/Pixel_C4 (normalized)
Sky/Pixel_C5 (normalized)
Sky/Pixel_C6 (normalized)
Sky/Pixel_C7 (normalized)
Sky/Pixel_C8 (normalized)
AIRMASS (slightly scaled and shifted) inverted
tot_C_ents (slightly scaled and shifted)

C2, C7, C8
Detection of Differences in Stellar Type

Source Counts less Sky Background

C2, C7, C8

C3, C5
After Deselection of Problematic Comp Stars

It is a zebra!!

Exoplanet Model Fit

Comparison Stars: C4, C6
Initial Fit

Exoplanet Model Fit

Comparison Stars: C2-C8
Preparing for TESS

• Seeing limited, follow-up observations will be part of the pipeline to help identify false positives

• The large number of TESS candidate targets will require a larger number of qualified observers

• High precision photometry and multi-wavelength measurements will be desirable for false positive detection
Traditional Off-Axis Guiding

Guide Camera

Visible+NIR

Pickoff Mirror

Visible+NIR

Imaging Camera
High Precision Autoguiding Techniques

• Goal: minimize movement of target and comp stars during a multi-hour observing session

• Active optics correct for rapid gear errors

• Traditional auto-guiding uses an off-axis guider - field rotation still an issue

• On-axis guiding techniques:
  ➢ use science image as source of guide star (useful when guide corrections times can be = or > science image exposure times)

  ➢ use an on-axis guider (ONAG)
On-Axis Guiding

Innovations Foresight, LLC

Filter Wheel

Guide Camera

Autoguiding Software

Guide Star

Target Star

Visible+NIR

Dichroic Beam Splitter

NIR>750nm

Guide Camera

Visible
Simultaneous, Multi-band Measurements

• Traditional approach: use a single camera with alternating filters
  – Disadvantages: reduces cadence in each band, potential introduction of systematics

• A new approach: repurpose the ONAG to allow for simultaneous measurements in NIR and in one or more visible bands
  – Advantages: maximizes cadence in each band, reduces systematics
  – Supports autoguiding as well!
Using ONAG for Dual-band Measurements

- Imaging Camera-1
- (Optional) Guide Camera
- Filter Wheel
- ONAG
- Visible Beam Splitter
- Visible+NIR
- NIR>750nm
- Imaging Camera-2

Innovations Foresight, LLC
Dual Bandwidth Measurements During an Exoplanet Transit

HAT-P-16b, UT2017-09-03

Conti (SBIG in NIR at 120 sec, Sx694 in CBB at 30 sec)

- rel_flux_11_dfn_model(binSize=2)_SBIG
- rel_flux_11_dfn_model(binSize=2)_Sx694

Barycentric Julian Date (TDB) - 2458000 (mid-exposure)
Dual Bandwidth Measurements During an Eclipsing Binary Transit

KELT Target, UT2017-09-23
Content (SBIG, V filter, 60 sec and Sx694, NIR, 60 sec)

- rel_fuc_T1_n_SBIG (bin size = 2)
- rel_fuc_T1_n_Sx694 (bin size = 2)

Barycentric Julian Date (TDB) - 2458020 (mid-exposure)
Aids to Help Diagnose Horses vs. Zebras

  – 1,916 unique visiting users from 68 countries
  – 466 downloads of the Guide

• Training: AAVSO online course on Exoplanet Observing
  – 80 participants to-date

• Tools:
  – Sample Datasets (Conti)
  – Observation worksheet with hot links (Conti)
  – AstroImageJ (Collins)
  – Speckle Toolbox (Rowe)

• Improved techniques for:
  – higher precision autoguiding
  – simultaneous, dual-band measurement
Summary

• Understand what’s behind the results
• Pursue the reasons for any perceived anomalies
• Eliminate any effects due to outliers
• Understand why outliers are happening

However, don’t be afraid to stick your neck out like a giraffe since that horse may very well be a zebra!
Addendum
Precision Comparison: Off-Axis vs. On-Axis Guiding

- Conditions:
  - target: HIP 94083
  - location: +76.8° declination, 41° altitude
  - exposures: 548 at 5 seconds for 1 hour
  - polar alignment: excellent

- Results:

<table>
<thead>
<tr>
<th></th>
<th>Off-Axis</th>
<th>On-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>6/10/17</td>
<td>6/8/17</td>
</tr>
<tr>
<td>Seeing</td>
<td>2.6”</td>
<td>3.1”</td>
</tr>
<tr>
<td>Tracking error (in RA)</td>
<td>0.41”</td>
<td>0.46”</td>
</tr>
<tr>
<td>Max. deviation:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at center of FOV</td>
<td>6.3 pixels</td>
<td>1.8 pixels</td>
</tr>
<tr>
<td>at edge of FOV</td>
<td>8.1 pixels</td>
<td>3.2 pixels</td>
</tr>
</tbody>
</table>

Under worse seeing conditions, On-Axis Guiding provided a 71% improvement over traditional Off-Axis Guiding!