International Baccalaureate

Extended essay cover

Candidates must complete this page and then give this cover and their final version of the extended essay to their supervisor.			
Candidate session number			
Candidate name			
School number			
School name			
Examination session (May or November)	May	Year	2012

Diploma Programme subject in which this extended essay is registered: Physics

(For an extended essay in the area of languages, state the language and whether it is group 1 or group 2.)

Title of the extended essay: Telescope Tracking Error and Exoplanet Research

Candidate's declaration

This declaration must be signed by the candidate; otherwise a grade may not be issued.

The extended essay I am submitting is my own work (apart from guidance allowed by the International Baccalaureate).

I have acknowledged each use of the words, graphics or ideas of another person, whether written, oral or visual.

I am aware that the word limit for all extended essays is 4000 words and that examiners are not required to read beyond this limit.

This is the final version of my extended essay.

Candidate's signature: ______ Date: 1-18-12

Supervisor's report and declaration

The supervisor must complete this report, sign the declaration and then give the final version of the extended essay, with this cover attached, to the Diploma Programme coordinator.

Name of supervisor (CAPITAL letters) [redacted]

Please comment, as appropriate, on the candidate's performance, the context in which the candidate undertook the research for the extended essay, any difficulties encountered and how these were overcome (see page 13 of the extended essay guide). The concluding interview (viva voce) may provide useful information. These comments can help the examiner award a level for criterion K (holistic judgment). Do not comment on any adverse personal circumstances that may have affected the candidate. If the amount of time spent with the candidate was zero, you must explain this, in particular how it was then possible to authenticate the essay as the candidate's own work. You may attach an additional sheet if there is insufficient space here.

[redacted] WAS EXCEPTIONAL IN HIS INDEPENDENT WORK ON THIS ESSAY. THIS WAS AN OUTGROWTH OF AN AWARD WINNING SCIENCE FAIR PROJECT, THAT WAS ALSO PRESENT AT AN ASTRONOMY CONFERENCE. ✓

[redacted] FACED MANY OBSTICLES IN COLLECTING VIABLE DATA IN CLOUDY OREGON, BUT ULTIMATELY THROUGH DILIGENCE PERSEVERED. ✓

This declaration must be signed by the supervisor; otherwise a grade may not be issued.

I have read the final version of the extended essay that will be submitted to the examiner.

To the best of my knowledge, the extended essay is the authentic work of the candidate.

I spent 5 hours with the candidate discussing the progress of the extended essay.

Supervisor's signature: [redacted] Date: 1/25/12

Assessment form (for examiner use only)

Candidate session number	[redacted]

Achievement level

Criteria	Examiner 1	maximum	Examiner 2	maximum	Examiner 3
A research question	2	2	2	2	
B introduction	2	2	2	2	
C investigation	4	4	3	4	
D knowledge and understanding	4	4	4	4	
E reasoned argument	3	4	3	4	
F analysis and evaluation	4	4	3	4	
G use of subject language	3	4	3	4	
H conclusion	2	2	2	2	
I formal presentation	3	4	3	4	
J abstract	2	2	2	2	
K holistic judgment	4	4	4	4	
Total out of 36	33		31		

e of examiner 1: [redacted] Examiner number: [redacted]
'ITAL letters)

e of examiner 2: [redacted] Examiner number: [redacted]
'ITAL letters)

e of examiner 3: ____________________ Examiner number: ____________
'ITAL letters)

IB Cardiff use only: B: ✓

IB Cardiff use only: A: 104833 **Date:** 21/05

Telescope Tracking Error and Exoplanet Research

Research Question: in intro not on title page

What is the effect of telescope tracking error on the accuracy of exoplanet light curves?

October 2011

Topic: Physics

Word Count: 3133

Abstract

The objective of this project was to determine the effect of telescope tracking error on the quality of exoplanet light curves. Currently, members of the amateur astronomer community are attempting to contribute data towards the characterization of exoplanets in a manner similar to their contributions in the areas of variable stars and asteroids. However, limitations in the available equipment constrain the precision of their measurements. Inconsistencies in telescope tracking can result in blurred images leading to error in the calculations of the host star's relative magnitude. In order to determine the influence that blurred images have on the accuracy of exoplanet light curves, a program was designed and written to analyze images, detect signs of tracking error, and use either a user defined or statistically determined measure of tolerance in order to remove images from the data set. The remaining images were used to calculate a refined light curve. Both the original and refined light curves were compared to a light curve based on the model of the target exoplanet. The results indicate a significant correlation between a decrease in the tolerance for tracking error and an increase in the resulting accuracy of the light curve when compared to scientifically accepted values. The images used in the experiment were taken during the transits of HD189733b and of TrES-3b. The software developed for this project has potential applications for those who do not possess equipment capable of taking consistently high quality images. If widely adopted, observations which are based on amateur astronomer data could be more reliable and contribute greatly to the research of exoplanets.

Word Count: 264

2/2

Excellent.

Table of Contents:

generic

This needs to be specific to project.

investigation : some confusion about sources consulted, see biblio. where only 1 source among all sources listed have been cited in core of essay; no light curve (professional*) included; some lack of info re E. Transit tool but generally clear;
equipment + procedure fine, done with care + completeness;

analysis : info not "extracted" from light curves; lack of consistency in reg. fig. attached to Data; lack of explanation re residual plots; fig. 11 and 12 not explained + analyzed in support of statement (comparison of results); limitations (sources of) recognized;

(* qualified as "ideal" in essay)

Introduction

Purpose

The transit method of exoplanet discovery and research has led to numerous breakthroughs in the past decade. A significant portion of those were made by amateur astronomers using nonprofessional equipment. This essay was written to investigate the potential inaccuracies that can be introduced through a telescope's tracking mechanism and propose a potential solution. The data used in this project was gathered by the author and was processed using software designed by the author. The implications of this essay involve a greater understanding of exoplanets through a larger, more precise body of data. RQ ✓

Research Question

The implementation of the transit method relies on taking accurate measurements of a candidate star's magnitude in relation to comparison stars. The light curves generated from transit data can be used to find approximate parameters of the transiting object. These parameters can become inaccurate if the telescope shifts its field of view during the exposure of images taken during the transit. When these images are compiled into a light curve, the calculated, physical properties are no longer representative of the actual planet. What is the effect of telescope tracking error on the accuracy of exoplanet light curves?

RQ 2/2

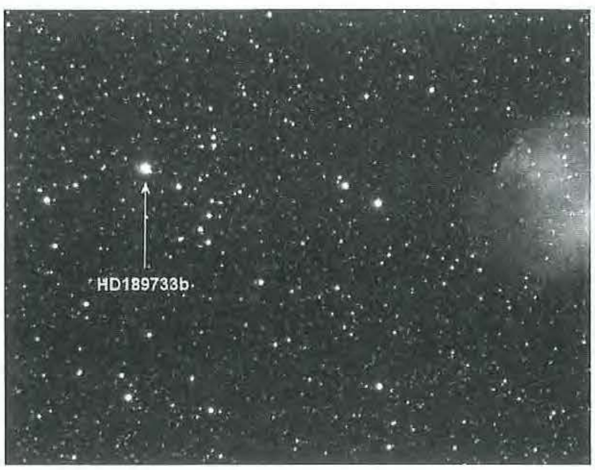


Figure 1: HD189733b alongside the Dumbell Nebula

Figure 2: Tres-3b

Explain these pictures, what they are even though their code names are listed in the abstract ... see p5 ..

any known details about these objects? give RA & Dec. values, constellation.. apparent magnitude ...

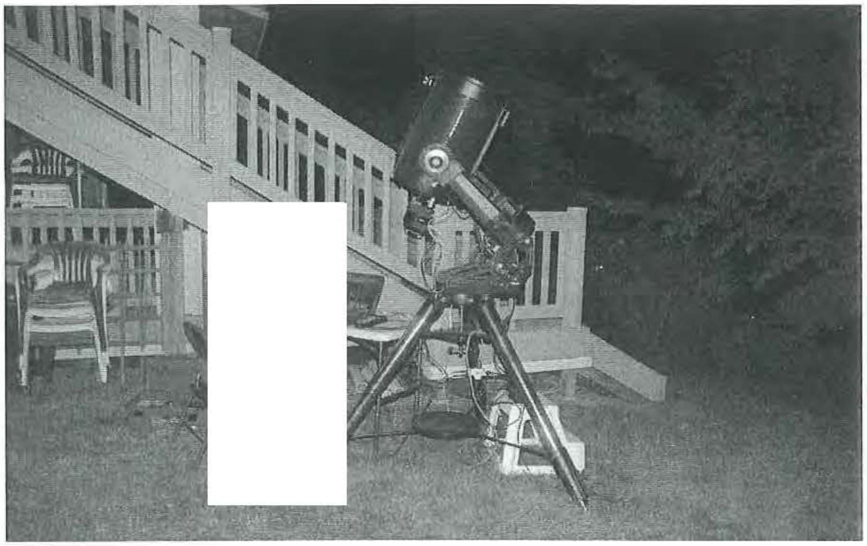
Background

Exosolar planets are objects that fit the definition of a planet but orbit a star other than the Sun. A transit is an event where an object passes between the earth and another celestial body. These happen frequently within our own solar system between the sun and Mercury or Venus. During a planetary transit between Earth and a host star, the orbiting planet blocks a portion of the light which would have otherwise traveled to earth. The transit method of exoplanet research involves the observation of a decrease in light from a host star during the transit. This effect is measured by plotting periodic measurements of the star's apparent magnitude over time. This method results in a light curve which can be used to calculate properties of the orbiting planet such as the inclination angle and radius of orbit. The composition of an exoplanet's atmosphere can be hypothesized using a light curve. Exoplanets with higher opacity material in the atmosphere will have much more extreme gradients at the sides of the light curve. Many modern telescopes are equipped with mounts which rotate to compensate for the movement of the stars in relation to Polaris. These mechanisms require the telescope's coordinates on the Earth and rely on internal gear and motor mechanisms. Through use, the internal components of the telescope will wear and become less precise. Even quality equipment will suffer from periodic error and external influences which can cause an image to appear blurred. This blurring effect spreads the light recorded by the CCD camera over a larger area of pixels. Stars imaged during these shifts tend to have asymmetric distribution and less precise boundaries causing their calculated magnitude to decrease. Because scientists utilize databases primarily supplied with amateur data, this widespread loss of accuracy can significantly hamper research.

intro: 2/2

Data Collection Setup

Data used in this project was obtained through observations of HD189733b and TrES-3b (see figures 1-2) taken on 21/10/11 and 4/26/11 respectively from Beaverton, Oregon. The images were taken using a Meade 12" LX200 SCT Telescope (Schmidt-Cassegrain design, 0.3m aperture, ~2m focal length @f6.7) and a Santa Barbara Instrument Group brand ST-7 CCD Camera (with a resolution of 765x510 pixels). Times and locations of the transits were found at the Exoplanet Transit Database (Brat). The telescope was polar aligned (oriented with respect to Polaris, the North Star) and focused prior to data collection. A laptop running *CCD Soft* (software that controls the CCD camera and can be used to take images at a regular rate) was connected to the CCD camera via parallel port and was configured to take images at regular, 4 second intervals during the transit. The internal temperature of the CCD camera was maintained at -2 degrees Celsius via an internal Peltier cooler built in to the camera. Data collection began 15 minutes prior to the start of the transit in order to get a baseline for the star's magnitude.



annotate picture or use annotated diagram that might give more info

Figure 3: Data collection setup

is this a sufficient aperture that will permit to observe very tiny light intensity variations from a star?

Materials

I C

- avoid nuts - and bolts ...
- give relevant information eg - focal reducer - differential photo. measurements - Transit Tool - role of filter

- Meade 12" LX200 SCT Telescope: 0.3m aperture, ~2m focal length @f6.7
- SBIG ST-7 CCD Camera: 765x510 pixels, Anti-blooming gate
- Astrophysics f/6.7 focal reducer
- White translucent plastic sheet
- Hewlett Packard Laptop
- Table, Chair
- Power Cords
- Deep Cycle 12V Battery

Software

- CCD Soft – Software Bisque
- Image Capture and Processing
- The Sky – Software Bisque
- Telescope Control
- Visual C++ - Microsoft
- Software Development
- Canopus - MPO
- Differential Photometry Measurements
- ExoPlanet Transit Tool – **designed by the author**
- Image Analysis and Filtering

details required see p. 9

time of observation → in November

v. brief ref. to fig. 1 on p5

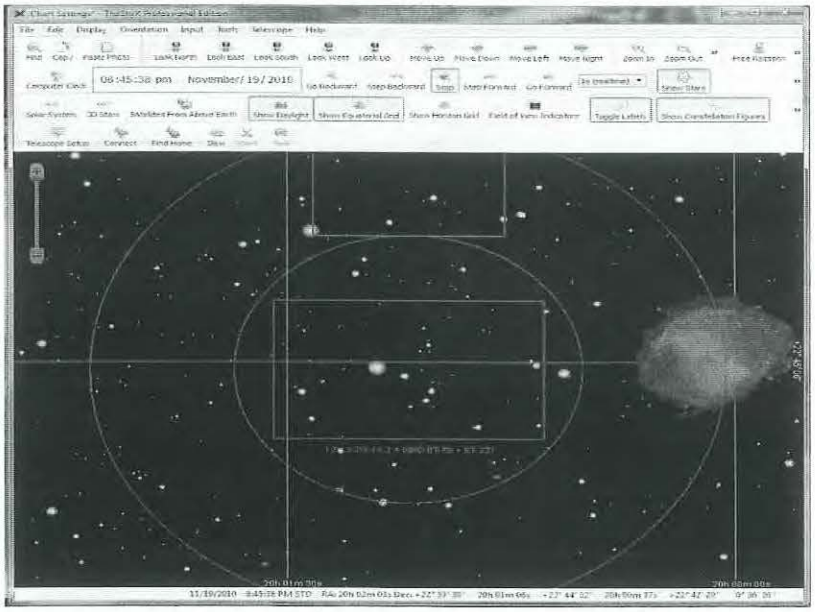


Figure 1: TheSky software - Field of view indicators for HD189733b.

Data Manipulation and Analysis Procedures

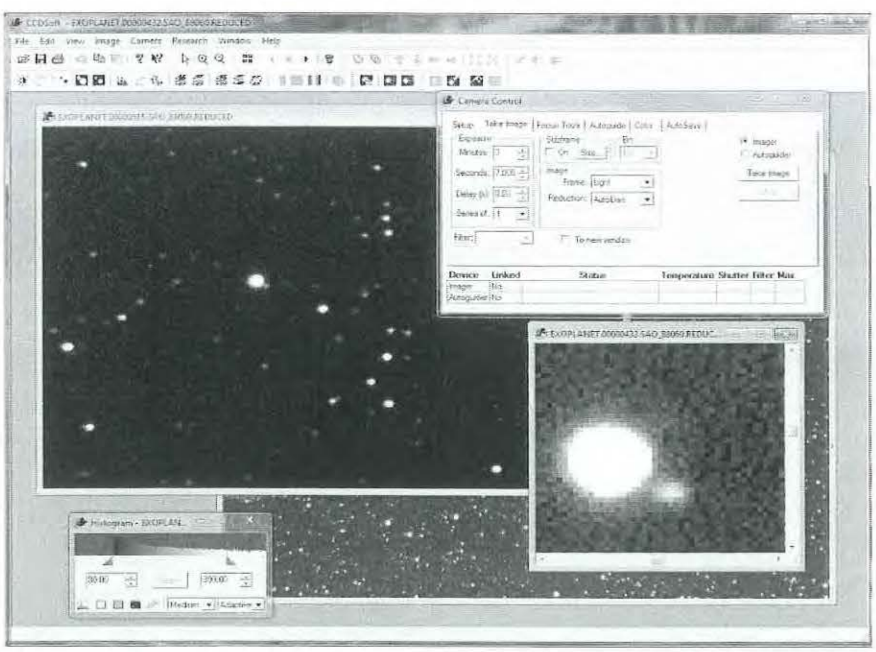
Image processing involved opening the images in CCDSoft and removing background noise caused by heat and imperfections and the camera. Before each image is taken, the camera does a matching "dark frame", where the camera closes its shutter and takes a picture without any light. The resulting image captures the heat interacting with the CCD chip at that moment. By subtracting the light in the proceeding image by the dark frame, error introduced by ambient heat is largely removed.

fig. 3

on page 5 brief reference to fig 2

elaborate explain diagram

reduced image →



← HD 189...

Figure 2: CCDSoft software – Used for camera control and image processing.

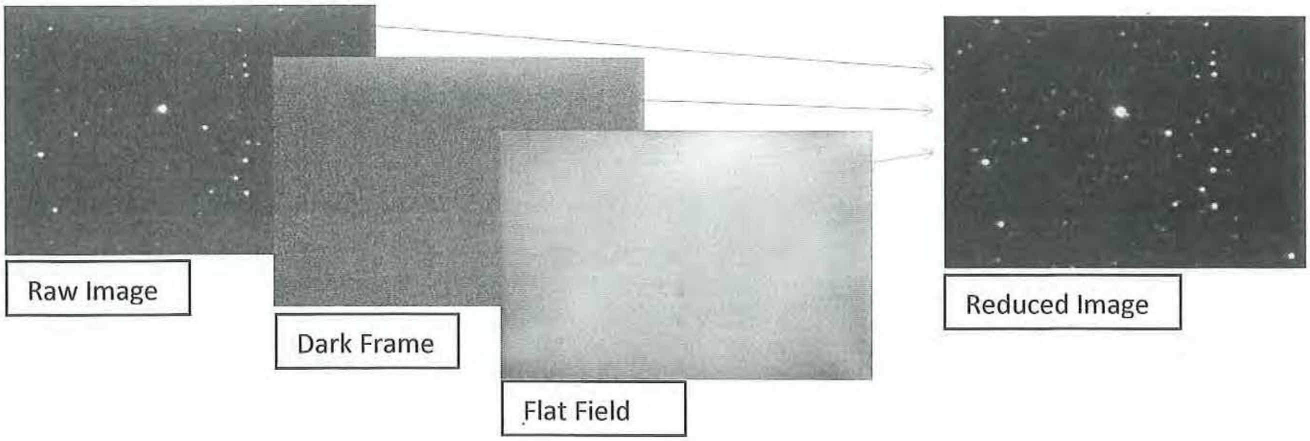


Figure 3: Image reduction process.

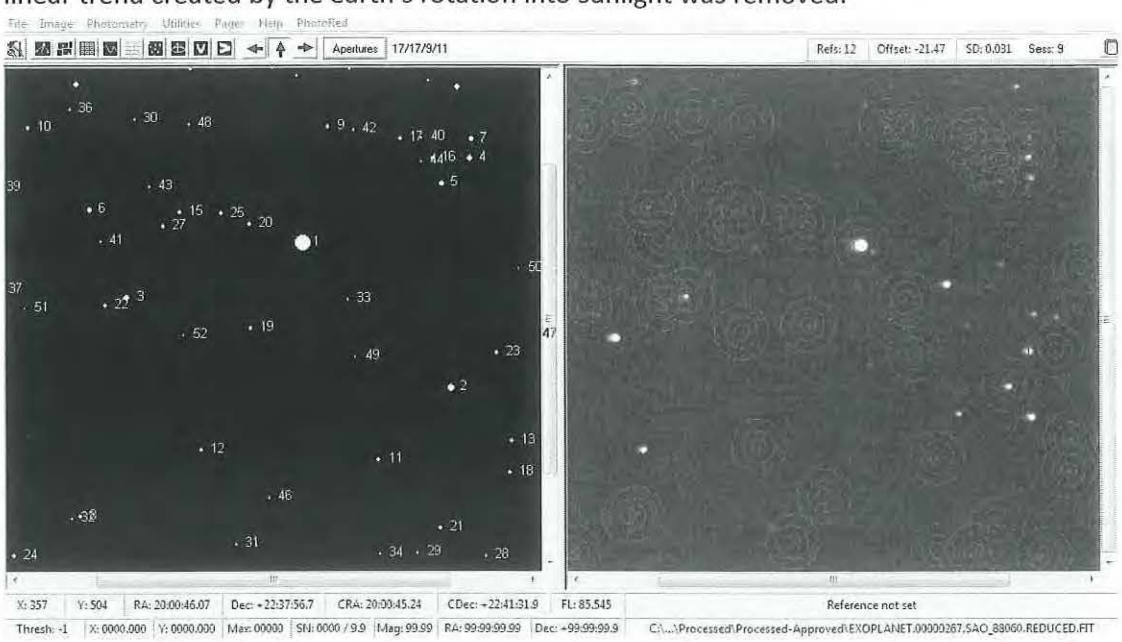
fig. 3

The purpse of a flat field image is to account for inconsitancies in the CCD camera itself. By taking an image while the telescope is pointing at a uniform source of light, these effect of these irregularities can be quantified — Fig. 4 elaborate

Light curves were generated in MPO Canopus. Originally designed for asteroid research, Canopus has a function intended to create a light curve to analyze the roll of an asteroid. Instead, these same functions were used to detect the drop in brightness during the transit. Settings in the program were matched to the particular object observed, telescope used, and location of the observation. Several comparison stars were selected based on their comparable magnitude to the target star. This measure controls for weather. If a cloud passed over during the exposure, all of the stars would be dimmed equally and so the relative decrease in magnitude in the host star could still be observed. The linear trend created by the earth's rotation into sunlight was removed.

"equally" ... if...

⇒ time of observation..



← HD 189...

Figure 4: MPO Canopus - Star field matching.

Image filtering

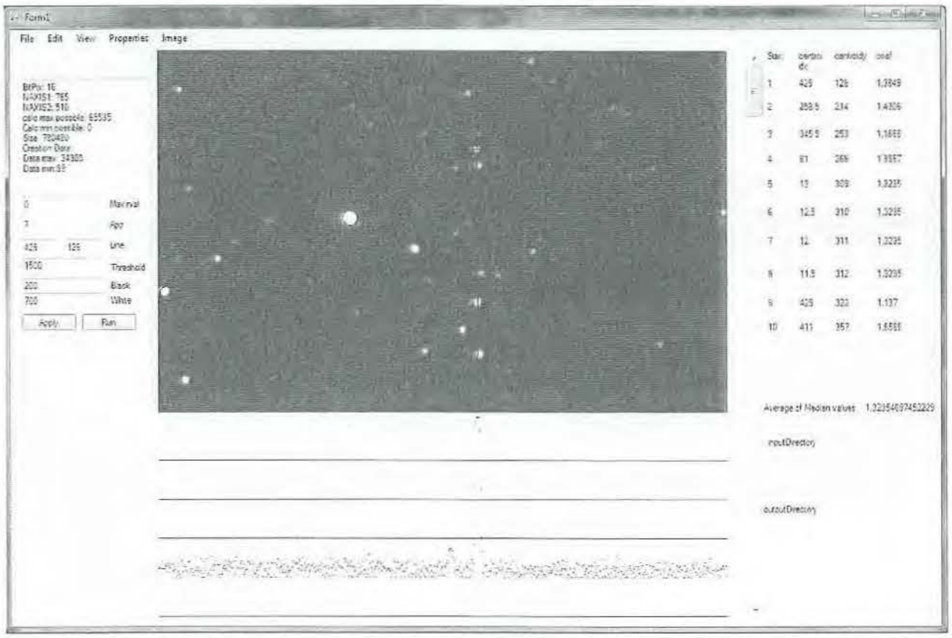
The ExoPlanet Transit Tool, developed by the author, was used to identify images which had a visible presence of tracking error. The program found vertical, horizontal, and two diagonal lengths of stars in the image. The program found the factors (greater than 1) between the widths and heights and between the two diagonals and averaged them. For example, if the width was 1.6 times longer than the height and one diagonal was 1.4 times greater than the other, the average would be 1.4. This average was referred to as a "Q-value". The closer this value was to "1" the rounder the star and, therefore, less tracking error. The threshold for acceptable irregularity or Q-value was determined statistically.

w 1.5 ?

see fig. 6

6

any details ?



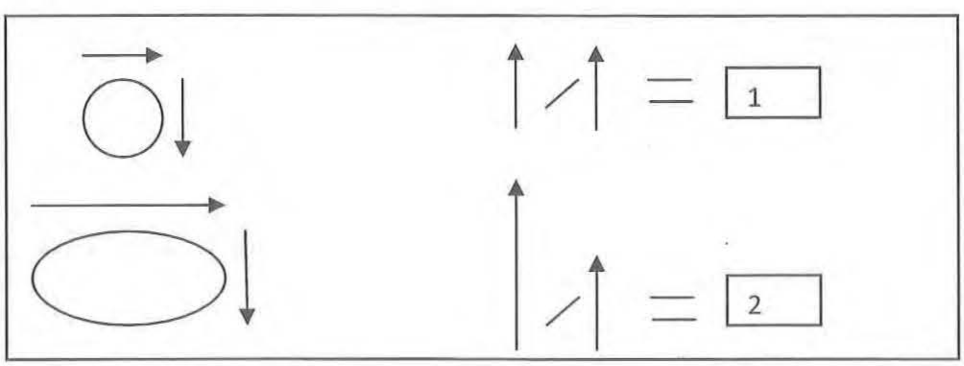
Explain ...

Figure 5: User interface of ExoPlanet Transit Tool image filtering software.3.7 Exoplanet Characterization

measures? more detail. show example

Both the filtered and unfiltered data was uploaded to the Exoplanet Transit Database run by the Czechoslovakian Astronomical Society. Functions within the database compared the light curves with scientifically accepted values. Accuracy was determined by the percent error between the measured and expected depth and duration of the light curves.

width height

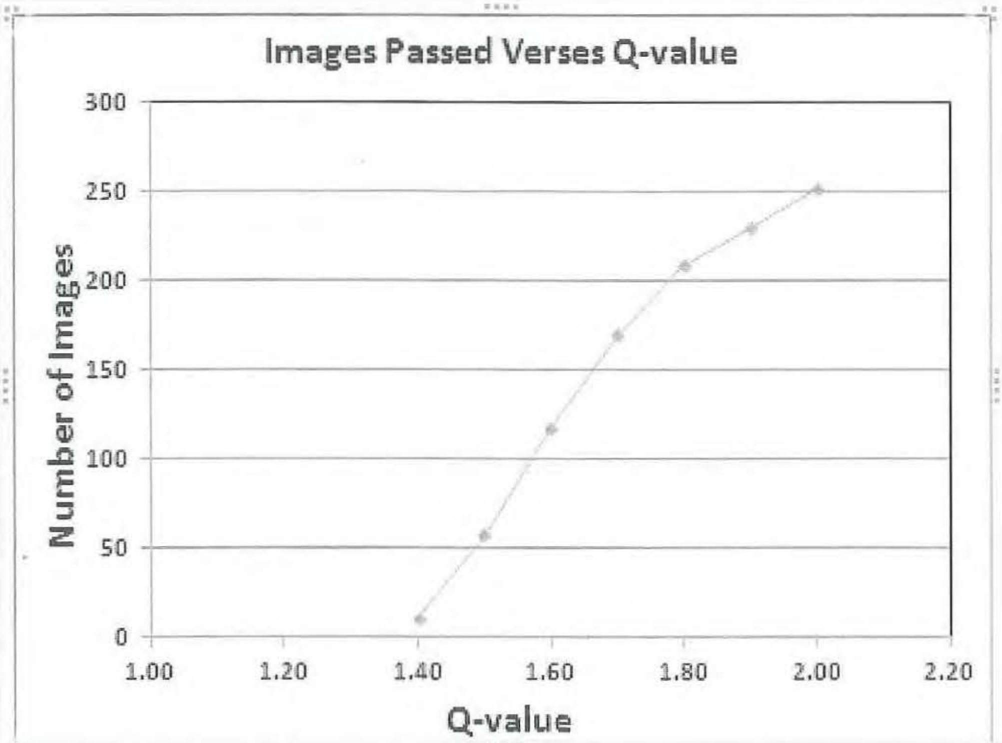


1/1

2.5/1.2 = 2.1

Figure 6: User interface of ExoPlanet Transit Tool image filtering software.3.7 Exoplanet Characterization

Results



should be an "histogram"

Passing Q value	1.40	1.50	1.60	1.70	1.80	1.90	2.00
Images Passed (from 354)	11	58	118	170	209	230	252

? →

Figure 7: User interface of ExoPlanet Transit Tool image filtering software.3.7 Exoplanet Characterization

✓ Image Number	570	284	325	620	474	573	574
✓ Median Q value	1.42	1.45	1.55	1.67	1.91	2.2	3.01

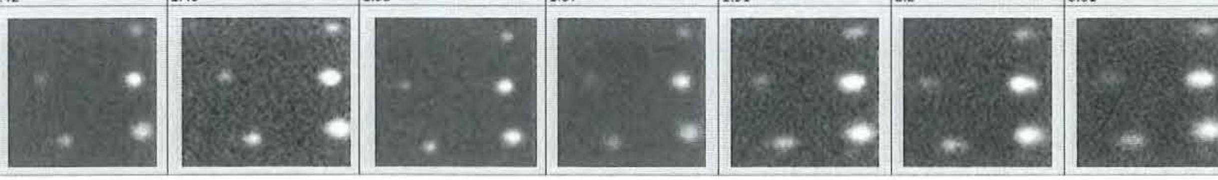


Figure 8: User interface of ExoPlanet Transit Tool image filtering software.3.7 Exoplanet Characterization

(6) This graph demonstrates the removal of images preformed by the Exoplanet Transit Tool depending on a user set Q-value. The image below demonstrates the increase in q-value with images with higher distortion. ?

above ?

we removed full see here

(7) Processed Data - HD189733b

(current top of p.11

HD 189...

source? any professional light curve of HD 189...? see p. 9 re ETD from C. Astro. Society p 9

Explain

Raw Data

Predicted:

Transit Mid: 2455490.777 (JD)

Duration: 209.6 (min)

Depth: 0.148 (mag) magnitude ?

Measured (Full image set): Q value ?

Transit Mid: 2455490.784 (JD)

Duration: 49 (min)

Depth: 0.033 (mag)

Comparison (Measured to Predicted)

Transit Mid: +10 (min) .... ? ..

Duration: 23%

Depth: 22%

Measured (Filtered image set Q<1.6)

Transit Mid: 2455490.777 (JD)

Duration: 93(min)

Depth: 0.045 (mag)

Comparison (Measured to Predicted)

Transit Mid: 0 (min)

Duration: 44%

Depth: 30%

magnitude

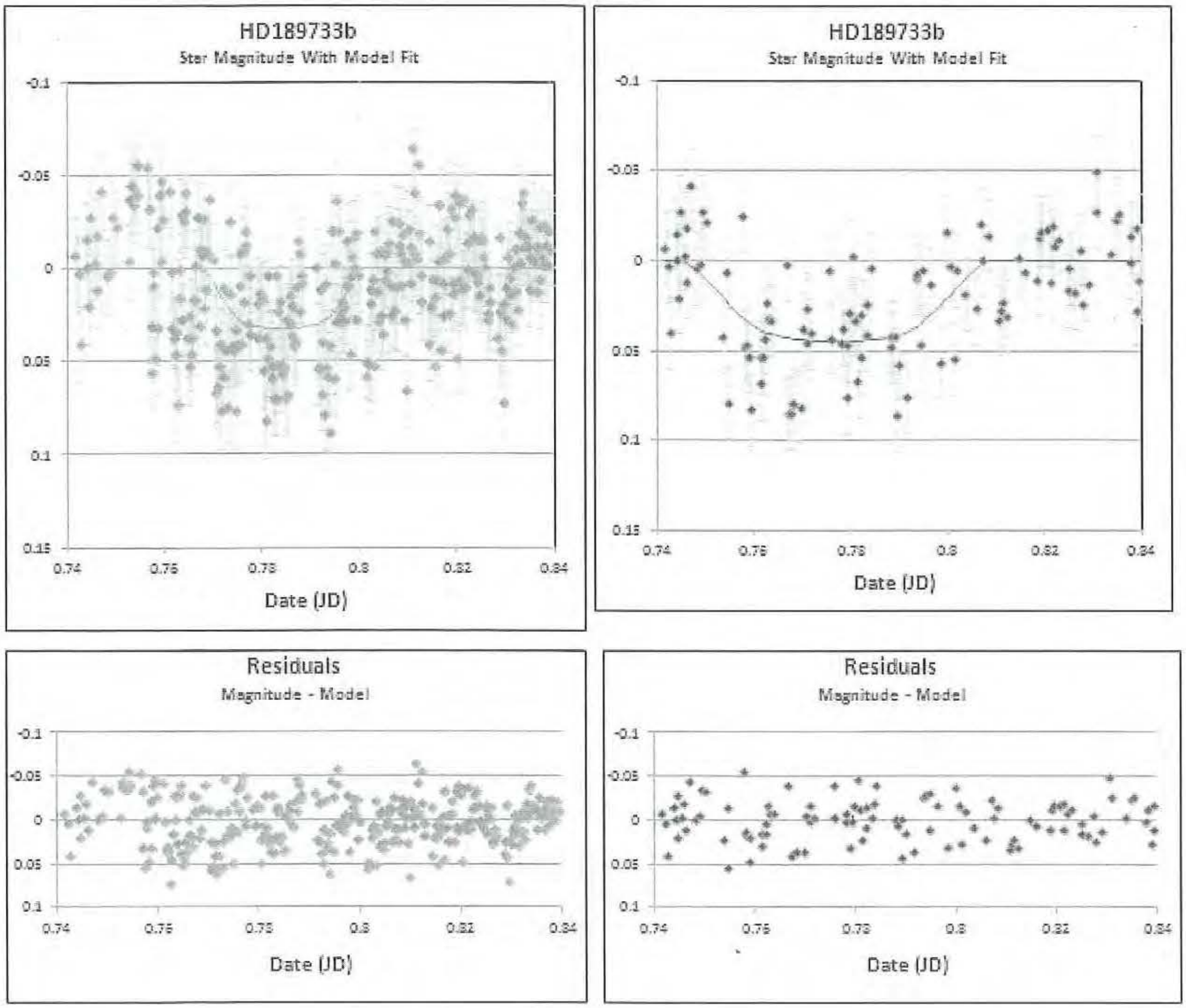


Figure 9: User interface of ExoPlanet Transit Tool image filtering software.3.7 Exoplanet Characterization

Fig. 9

These charts show the light curve before (top left) and after (top right) processing by the Exoplanet Transit Tool. The duration of the transit, determined by the width of the trough, increased from 29 minutes to 93 minutes increasing the accuracy of the observations from 23 to 44 percent. The depth of the curve also became more accurate after applying the filter, increasing from 22 to 30 percent. The residual plots below the light curves indicate a decrease in variance as a result of the filter.

49 min

(role of filter)

against that baseline?

refer to page 11

show how info extracted from graphs

✓ Data – TrES-3b

Predicted:

Transit Mid: 2455674.961 (JD)

Duration: 77.4 (min)

Depth: 0.164 (mag)

Measured (Full image set): (any Q value ?)

Transit Mid: 2455674.963 (JD)

Duration: 79 (min)

Depth: 0.040 (mag)

Comparison (Measured to Predicted)

Transit Mid: +2 (min)

Duration: 102%

Depth: 24%

Measured (Filtered image set Q<1.6)

Transit Mid: 2455674.9612 (JD)

Duration: 78 (min)

Depth: 0.042 (mag)

Comparison (Measured to Predicted)

Transit Mid: +1 (min)

Duration: 101%

Depth: 26%

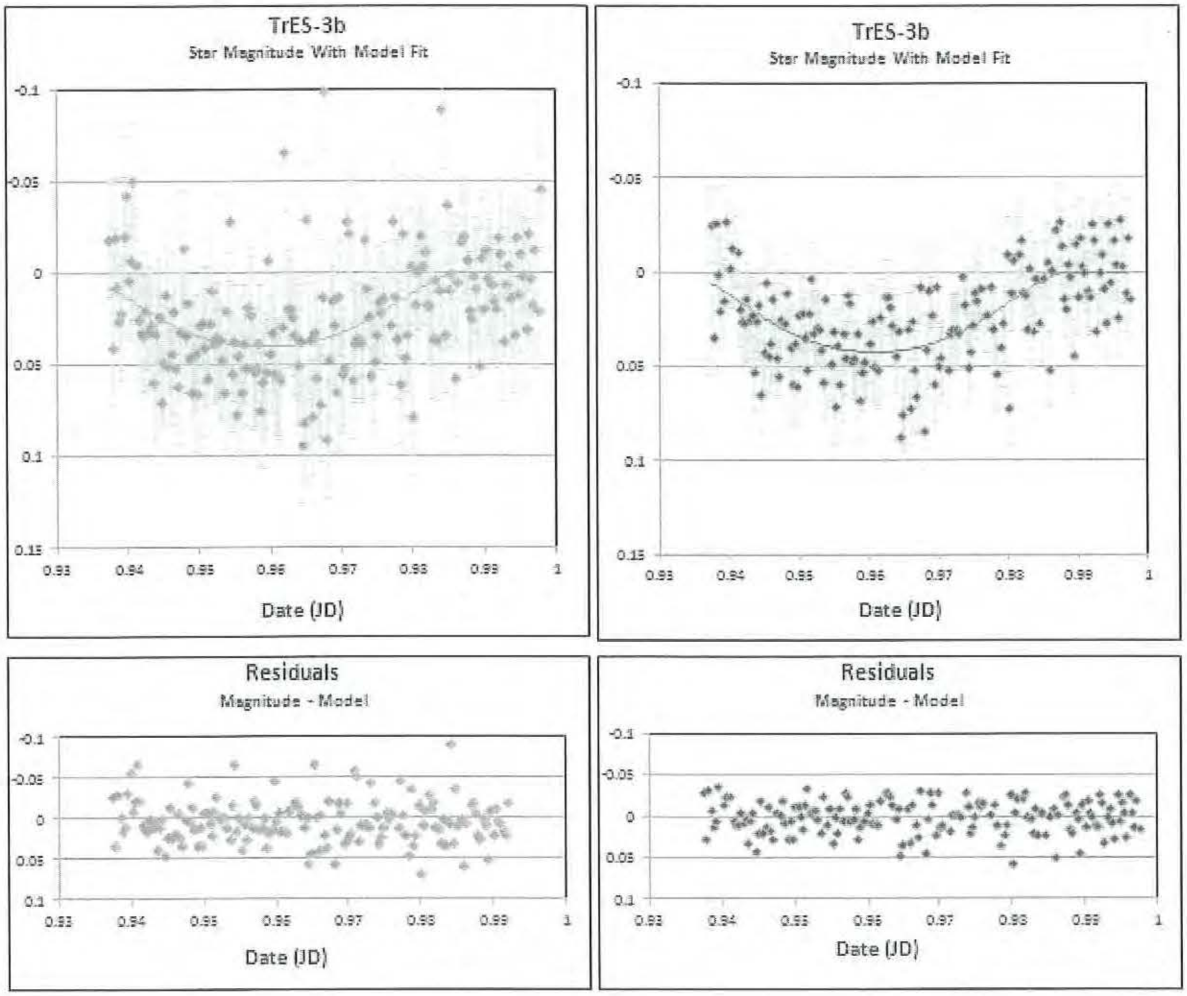


Figure 10: User interface of ExoPlanet Transit Tool image filtering software.3.7 Exoplanet Characterization

Due to overcast skies, data collection began close to the start of the transit. As a result, the light curves do not exhibit a line leading into the drop in brightness. Similar to the previous exoplanet data, TrES-3b's light curve depth and duration increases in overall accuracy after implimenting the filter.

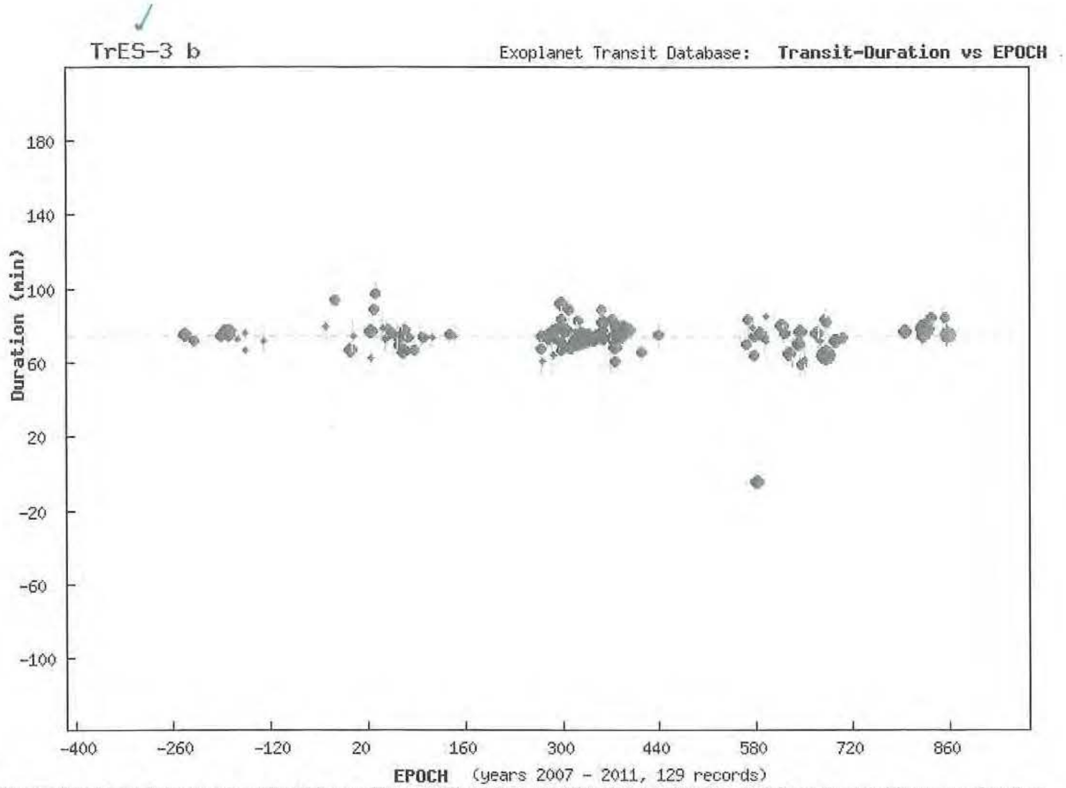


Figure 11: User interface of ExoPlanet Transit Tool image filtering software.3.7 Exoplanet Characterization

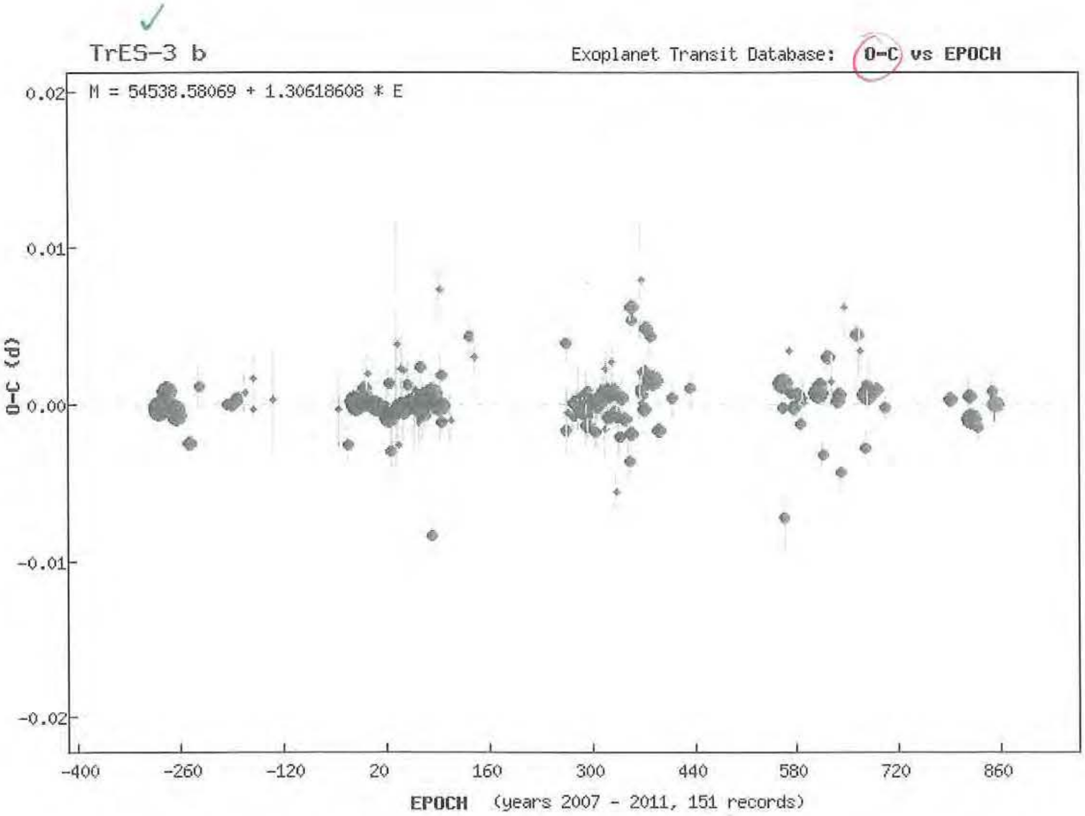


Figure 12: User interface of ExoPlanet Transit Tool image filtering software.3.7 Exoplanet Characterization

— it does not

Figure 11 and 12 compare the data taken in this experiment with other transit observations of TrES-3b in the Czech Astronomical Society's database. The x-axis shows the date, in Julian time, of the observation while the y-axis shows either the duration or depth of the observed transit compared to the expected (dotted grey line). The clusters that appear at regular intervals along the x-axis are a result of prime observing conditions between August and October where the host star is highest in the sky. These graphs show that my observations are comparable to those taken by other contributing astronomers.

how it

argument reasoning (E)

where are they on the graph?

Observations

It was observed that the removal of poor quality images produced more accurate values to a point. When the number of images which exhibited tracking error was decreased, the light curve that was generated with the data approached the scientifically accepted parameters. However, if the quality threshold was set so high that fewer than 150 images passed the filter, the ETD fitting algorithm began to show erratic results.

how obtained? (source)

transit data base

no statistical criterion given previously

Earlier versions of the Exoplanet Transit Tool used a quality calculation which used the Pearson Weighted Correlation Coefficient. Unfortunately, the values it produced did not appear to correspond to the apparent quality of the star images. The weighted correlation values appeared to be very sensitive to the image noise. This was replaced with a routine that determines roughly the symmetry of the star's shape. This approach did match with the visual appearance of the stars. Also, filtering based on this approach produced increasingly accurate results for depth and duration.

An observed irregularity in earlier images appeared to be ice crystals which formed as a result of moisture in CCD camera. To prevent ice crystals from ruining new images, the temperature setting for the CCD camera's built-in climate control was modified so the system remained above freezing. This modification was a trade off because while there were no later appearances of ice crystals, background noise as a result of heat worsened.

what is the improvement ...

During the first attempt to capture a transit event, the images were taken with an exposure time over one minute in length which consequently overwhelmed the photosites of the CCD chip. As a result, the expected decrease in brightness was not detected. During later experimentation, images were taken prior to the transit to ensure the maximum brightness of the star was still well below the maximum capacitance that the CCD chip could measure.

During the development of the Exoplanet Transit Tool, cross sections of images showed that light values across a star resembled an approximate bell curve. Cross-sections nearer to the center of the star exhibited a larger width which was used in early star detection routines. The Exoplanet Transit Tool identifies when the range of the bell curves decreases across horizontal cross-sections. If a narrower bell curve is detected, the program identifies the previous cross-section as the approximate center of the star. Using the same method with cross-sections along the y axis, the approximate centroid of the star is found. When attempting to attribute weighted correlation values to stars, it appeared that there was no clear association between correlation values and the presence of tracking error. One potential explanation is that because all of the stars were fairly round regardless of tracking error, the correlation values became so small that even the slightest difference in background noise around the star could skew the result.

Light pollution also was observed to have a significant impact on the transit light curves. Light pollution is the presence of ambient light often from nearby cities and streetlights that illuminate any haze in the air. During the second attempt to image the star during transit, the night was lit by a gibbous moon. When measuring the apparent magnitude of stars against the background sky, this additional light diminished the accuracy of the light curve.

Another important observation was the effect of increased moisture in the air during transit viewing. During the latest transit image collection, condensation began to appear on the corrector plate on the telescope. Stopping image collection every ten minutes, a hairdryer was used to dispel the moisture and then image collection was resumed. The data reflects how moisture accumulated and caused a gradual decrease in the overall brightness of the images. The hairdryer proved effective at restoring image brightness but condensation should be considered as a prohibitive condition to whether it is appropriate to attempt image collection during that transit.

CCD pixels suffer from the occasional tendency to leak charge, resulting in a hot pixel. When these electrons are leaked from the photosites, they are stored by the capacitors and included in the image. A hot pixel is evident when a single pixel is significantly brighter than the surrounding pixels. Initially, due to their high brightness level, early star detection in my software methods identified hot pixels as stars. This was remedied when later tests examined surrounding pixels before identifying the location of a star.

see also p. 8 fig 3

During image processing for earlier transits, formations of what appeared to be dust spots appeared in the image. In order to remove these defects, after future transits were photographed, a flat frame image was taken. During a flat frame, a uniform light is shown down the telescope and the image that is taken displays all of the defects in the camera itself. By dividing all of the transit images by the flat frame, these flaws were removed.

see p. 16

Other irregularities in earlier images appeared to be ice crystals which formed as a result of moisture in CCD camera. To prevent ice crystals from ruining new images, the CCD camera's built in climate control system was modified so the system remained above the freezing temperature. Before the next imaging session the desiccant in the camera was heated to remove the moisture allowing below freezing temperature settings.

Conclusion 2/2

In each trial, the data of two different light curves were compared with their currently established values. The first light curve contained all of the images that were taken during the transit while the second light curve contained images of the same transit but images which had detectable tracking error were removed from the calculation. The predicted duration of the transit of HD 189733b, given current knowledge of the exoplanet, was 109.6 minutes. The unfiltered light curve plotted a transit duration of 48.8 minutes, only 44.5% of the accepted value. The light curve generated after the tracking error

49 min on p.11

209.6 min on p.11 ?

=> filtered image

93 min on [illegible]

images were removed resulted in a transit duration of 92.0 minutes, a significantly larger 83.9% of the original value. The depths of the light curves were compared to the calculated ideal of .148. The original light curve had a depth of .0326 while the light curve with the tracking error removed had a depth of .0450. Through the removal of images which exhibit tracking error, the depth and duration of the transit light curve are were improved significantly. These results support the hypothesis and imply the effectiveness of the Exoplanet Transit Tool. Extensions to this experiment could take many forms. The use of additional exoplanets with different light curves and host stars would further test the effectiveness of the Exoplanet Transit Tool. Expanding the variety of mounts and other equipment testing in the experiment would also provide more universal observations about the error caused by observing equipment.

0.033

predicted

The Exoplanet Transit Tool has the potential to be expanded to not only perform image processing but also to perform magnitude measurements. Continuing development of the program may involve the addition of functionality which would be able to plot light curves after automatically removing sources of error. One disadvantage to the software in its current state is that it analyses the position and dimensions of stars based on whole pixel values. Through more accurate calculations based on fractional pixels could potentially result in more effective star identification routines. Finally, to enhance the ease of use, compatibility between the Exoplanet Transit Tool and other CCD camera software could be implemented.

? ..

An exemplary project

Works Cited

only sources cited, in core of essay

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any scientific paper on transit light curve & interpretation? ...

Criterion	Comment	
A RQ	Well formed + clearly expressed.	2
B Intro	Clear introduction with necessary information well presented	2
C Invest	Very aware of getting quality results + adjusting procedure accordingly.	4
D Kn & Un	Clear + sophisticated understanding evident.	4
E Argu	Sound, but a bit weak / cursory in places.	3
F An & Ev	Highly critical + well able to identify main sources of error or uncertainty.	4
G Lang	Not always clear what graphs showed from the labelling. Otherwise excellent.	3
H Conc	Very clear!	2
I Pres	Cut. generic. Otherwise OK.	3
J Abst	Excellent.	2
K Hol	Considerable intellectual determination. Excellent scientist in the making.	4