EXOPLANET IMAGING WITH SMALL APERTURE TELESCOPES

Jerry Hubbell

Assistant Director, Mark Slade Remote Observatory (MSRO)

VP Engineering, Explore Scientific, LLC.

NEAIC 2019 April 4, 2019

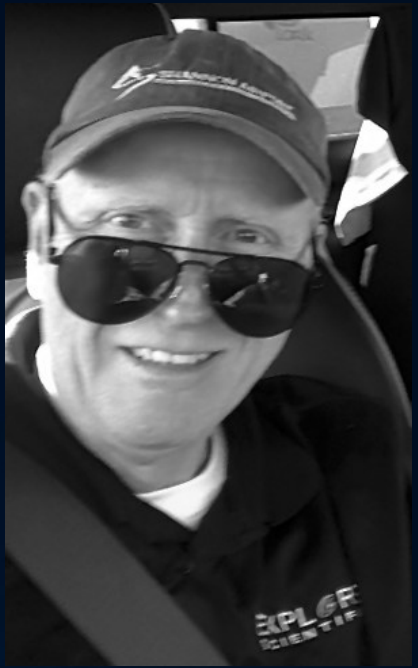
Image courtesy NASA ESA - C.Carreau (exoplanets.nasa.gov)

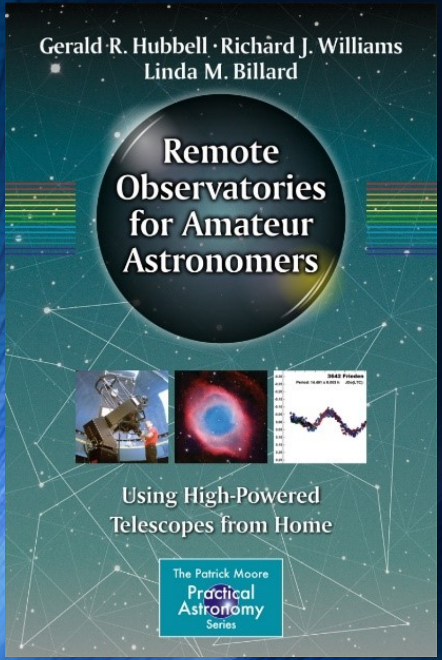
Exoplanet Imaging With Small Aperture Telescopes

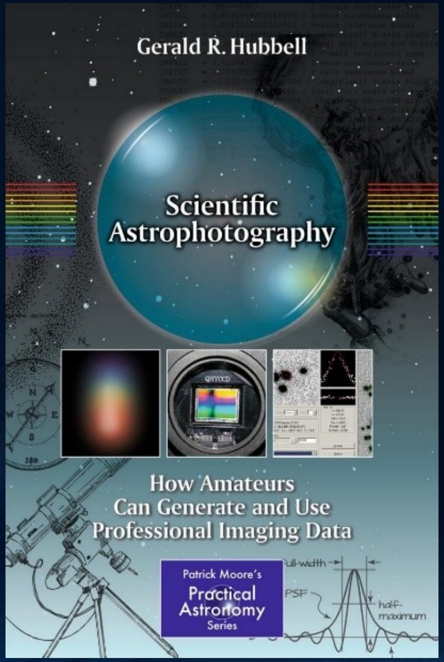
North East Astro Imaging Conference (NEAIC 2019)
April 4, 2019

HOW AMATEUR ASTRONOMERS CAN DETERMINE THE SIZE AND ORBIT OF PLANETS AROUND OTHER STARS USING THE DIFFUSER PHOTOMETRIC METHOD

JERRY HUBBELL
ASSISTANT DIRECTOR, MARK SLADE REMOTE OBSERVATORY (MSRO)
VP ENGINEERING, EXPLORE SCIENTIFIC, LLC.







Introduction – Jerry Hubbell

- **Jerry Hubbell** is a retired Dominion Energy Nuclear Instrumentation and Controls Engineer with nearly 40 years of experience in the Nuclear and Electric Utility business.
- He is the Assistant Director of the Mark Slade Remote Observatory (MSRO) W54, located in Wilderness, VA
- Jerry is currently the Vice President of Engineering for Explore Scientific, LLC. and the Principal Engineer heading the team on the development of the PMC-Eight™ mount control system.
- He is Assistant Coordinator for Topographical Studies, Lunar Section, Association of Lunar and Planetary Observers (ALPO).
- Jerry is the author of two books published by Springer Books: *Scientific Astrophotography: How Amateurs Can Generate and Use Professional Imaging Data* (2012) and *Remote Observatories for Amateur Astronomers: Using High-Powered Observatories from Home* (2015)
- He recently became the Springer Books Series Editor for the Patrick Moore Practical Astronomy Series of books.

Presentation Objectives

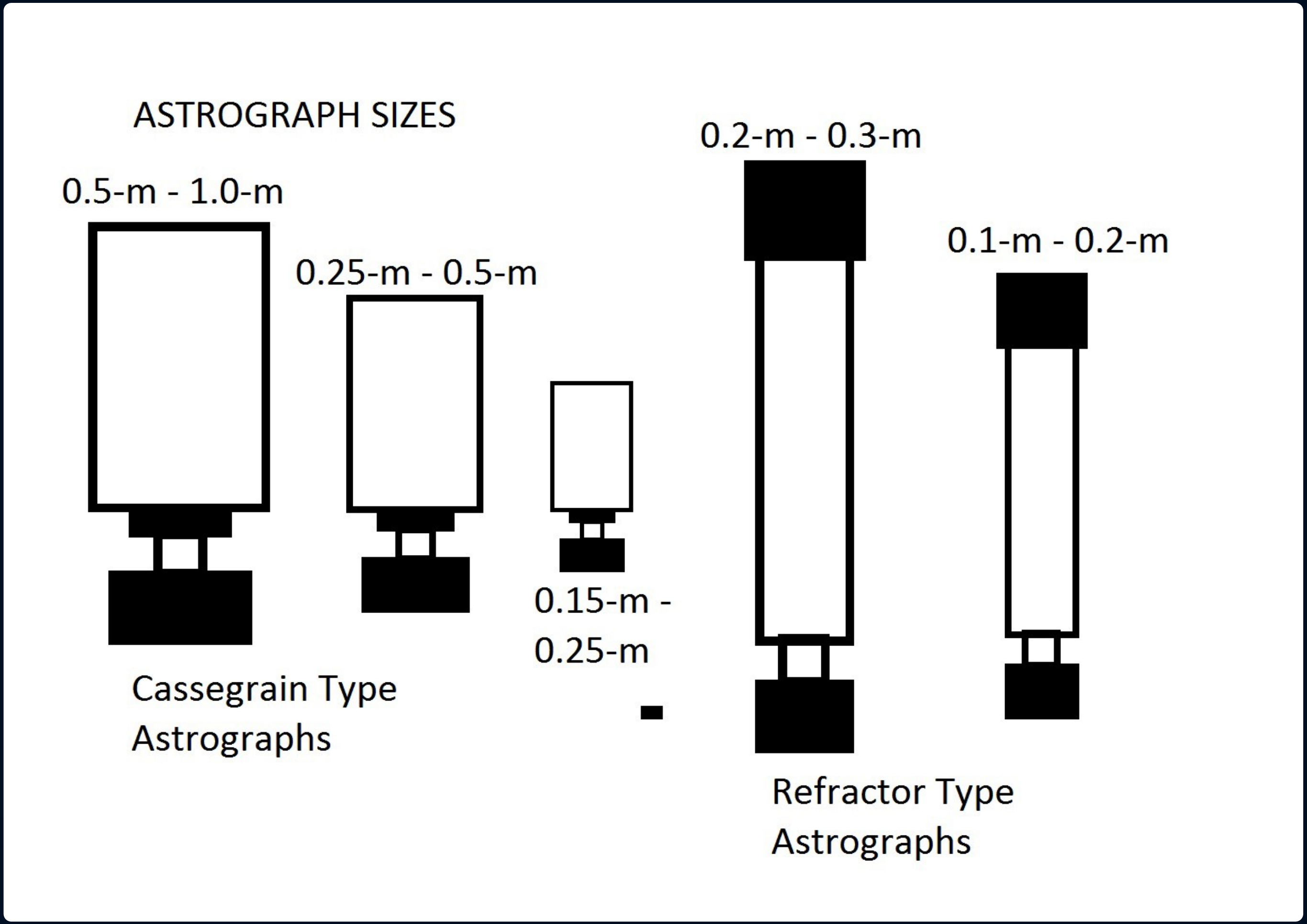
- Discuss why you would want to observe Exoplanets with Small Aperture Telescopes
- Discuss the processes used by amateurs and professionals to perform photometric measurements
- Describe the purpose of this study
- Discuss two methods used to perform High-Precision Photometry of Exoplanets, Minor Planets , and Variable Stars to obtain their light curves.

Presentation Objectives(cont'd)

- Discuss the requirements for an amateur-level astronomical imaging system (AIS) needed to successfully perform high-precision photometry
- Discuss the general process for analyzing exoplanet light curves to determine the size and orbital parameters of the planets
- Discuss the results obtained using the Defocus and Diffuser Methods
- Discuss the pros and cons of the Defocus and Diffuser Methods for performing high-precision photometry using an amateur-level AIS

What is a Small Aperture Telescope ?

- In the context of this talk (and when compared with a professional-level AIS), a small aperture telescope OTA is:
- A refractor objective size from **4 inches (0.10 m) to 7 inches (0.18 m)**
- A reflector objective size from **8 inches (0.20 m) to 14 inches (0.36 m)**



Why Use Small Aperture Telescopes to Observe Exoplanets?

- Until the 20th century, amateurs led the development of astronomy technology that was later adopted by the professional astronomical community. Wealthy amateurs made discoveries throughout the 17th–19th centuries using new techniques and equipment.
- During the 20th century, large institutions invested millions of dollars to build larger and better telescopes for professional astronomers to lead the way in new astronomical discoveries.
- In the 1990s, amateurs again began to develop new observing techniques using inexpensive CCD camera systems to acquire professional-level data and to again contribute by making new discoveries and by working with professionals in doing follow-up work.

NOTE: Bruce Gary was an early pioneer in amateur exoplanet observing and Pro/Am cooperation and has written a book called *Exoplanet Observing for Amateurs (2009)* available at http://brucegary.net/book_EOA/x.htm

Why Use Small Aperture Telescopes to Observe Exoplanets?

- Today, the technology available to the amateur astronomy community rivals that used by professionals only 20 years ago and can be used to do the follow-up work needed on new objects discovered every day.
- The professional astronomer typically relies on large telescope systems and is mostly involved with discovery. Amateurs can play an important role in doing the follow-up work that the professional community just does not have the facilities or the time to do.

Why Use Small Aperture Telescopes to Observe Exoplanets?

- NASA has acknowledged the need for amateur astronomers and has incorporated the Pro/Am model into the Transiting Exoplanet Survey Satellite (TESS) mission.
- So that the needed follow-up work can be effectively accomplished, the TESS Follow-Up Observing Program (TFOP) has been created to enable both amateur and professional astronomers to do the work necessary for the success of the TESS mission.
- The TESS mission is concentrating on close, bright stars (> 11 mag), which are the perfect targets for small aperture telescopes but not so much for very large telescopes. We will see why later on.

More Information About Pro/Am Collaboration Observing Exoplanets

- The NASA TESS Follow-Up Observing Program (TFOP) can be found online at:

  https://tess.mit.edu/followup/

- The American Association of Variable Star Observers (AAVSO) has created an Exoplanet Section headed by Dennis Conti. Dennis has held several AAVSO CHOICE classes on exoplanet observing over the past 2 years. His book on exoplanet observing using AstroImageJ is available at his website:

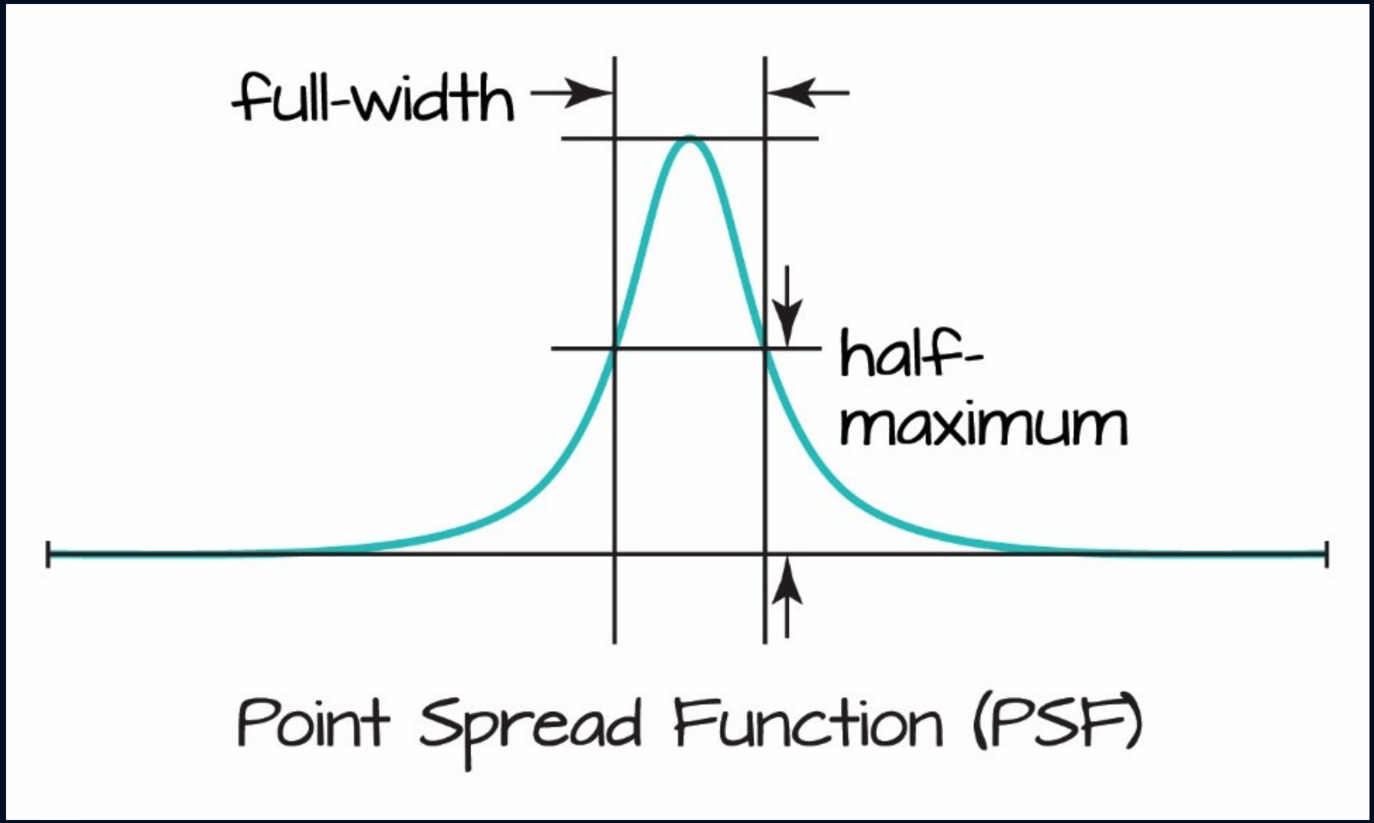
  http://www.astrodennis.com

Point Spread Function (PSF)

- The Point Spread Function is defined as the response of an optical system to a point source input.
- The light collected by the OTA is focused on the image plane of the CCD/CMOS detector and is spread out and collected by the group of pixels covered by the PSF.

Point Spread Function (PSF)

The PSF of a star is Gaussian shaped and is described by its Full-Width-Half-Maximum value (FWHM).



Point Spread Function (PSF)

- When an object is not focused on the image plane of the CCD/CMOS detector, the recorded profile may be different .
- The shape of the PSF profile is circular in the plane of the CCD/CMOS detector, and the number of photons collected per pixel follows a Gaussian function across the width of the profile.
- The profile for a reflecting OTA with a central obstruction is shaped like a donut when the image is not focused; it is Gaussian for a refracting telescope with no central obstruction.

Aperture Photometry

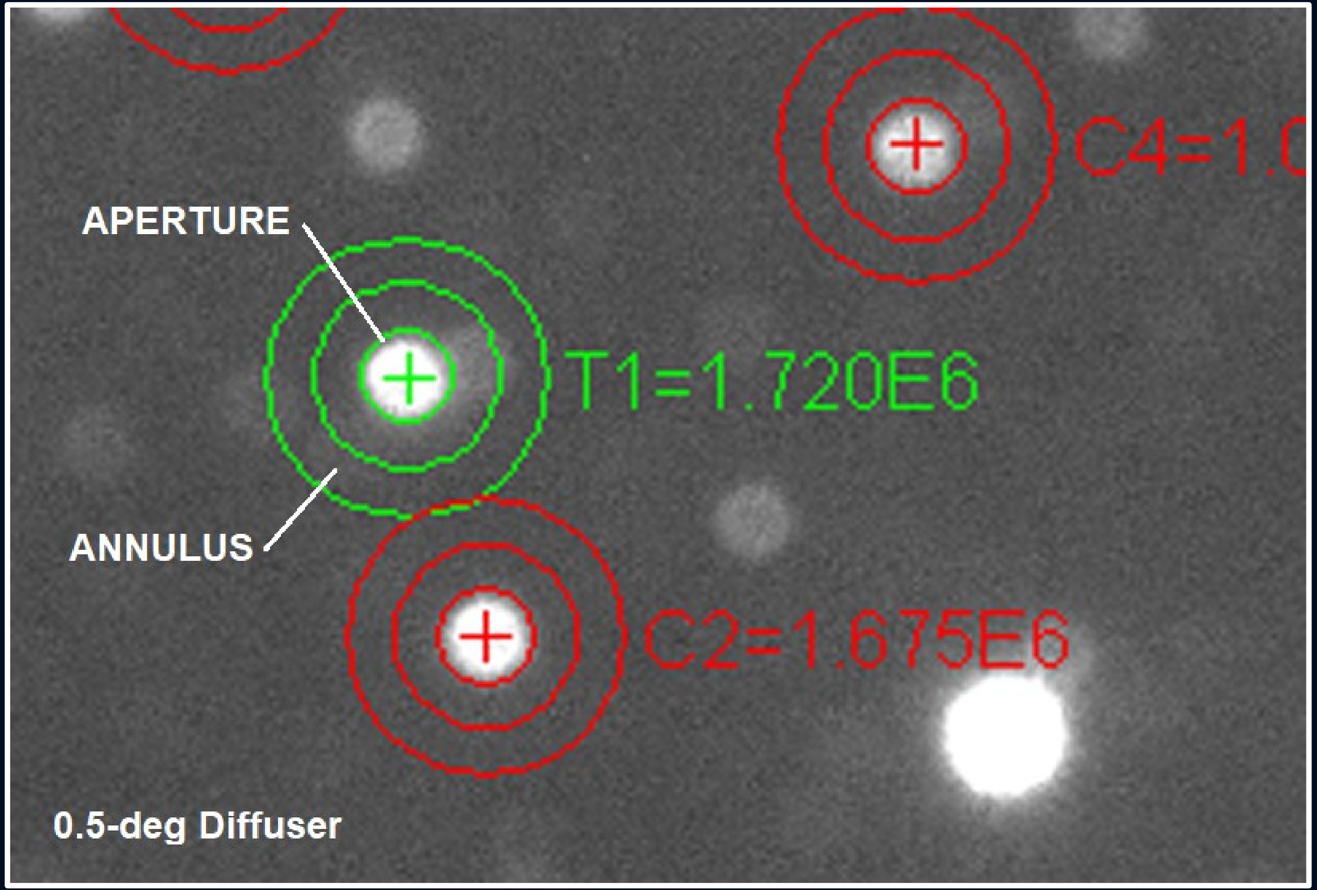
- In general, the modern photometric measurement technique using CCD/CMOS images is called *aperture photometry.*
- Two aperture types are used in conjunction when measuring the brightness of a star or other stellar-like object— the *aperture* and *annulus*.
- The aperture has a circular shape surrounding the object and measures the combined object and sky background brightness.

Aperture Photometry

- The annulus aperture has a donut shape and is used to measure the sky background level.
- The annulus brightness measurement is subtracted from the main aperture brightness measurement to get the overall object brightness.

Aperture Photometry

- Diagram showing the aperture and the annulus



Differential Aperture Photometry

- Differential aperture photometry measures the relative changes between two different objects that are subject to the same, common mode signals in the data, including instrument calibration errors, and variable sky conditions such as transparency changes.
- Large amplitude systematic errors are managed by performing effective image calibration and controlling the temperature of the camera system. Tracking errors are also minimized, typically by using an auto-guider system.
- Even after taking care of these systematic errors, small errors still remain because of uncorrelated short- and long-term scintillation differences between the Target object and the Comparison objects being measured.

Differential Aperture Photometry

- Differential aperture photometry is performed by first measuring two objects—first the Target Object and then the Comparison Object.
- The first, or Target Object, is assumed to be the variable, and the second, or Comparison Object, is considered to be fixed. The difference between the two will show the relative variation of the first object to a high level of precision.
- An advanced technique using multiple comparison stars called *ensemble photometry* improves the precision of the measurement.

Two Different Techniques to Create Profiles for High-Resolution Photometric Measurements

- The Defocus Method—This method uses the focuser to position the CCD/CMOS image plane inside or outside the nominal focus position to enlarge the profile of the PSF of the target object.
- The Diffuser Method—This method uses a specialized optical element to enlarge and create a “top-hat” shaped profile of the PSF of the target object.

Why Do This Study?

- The purpose of this study is to determine if there is a significant difference in the performance of the two methods for creating image profiles that can improve the overall precision of photometric measurements.

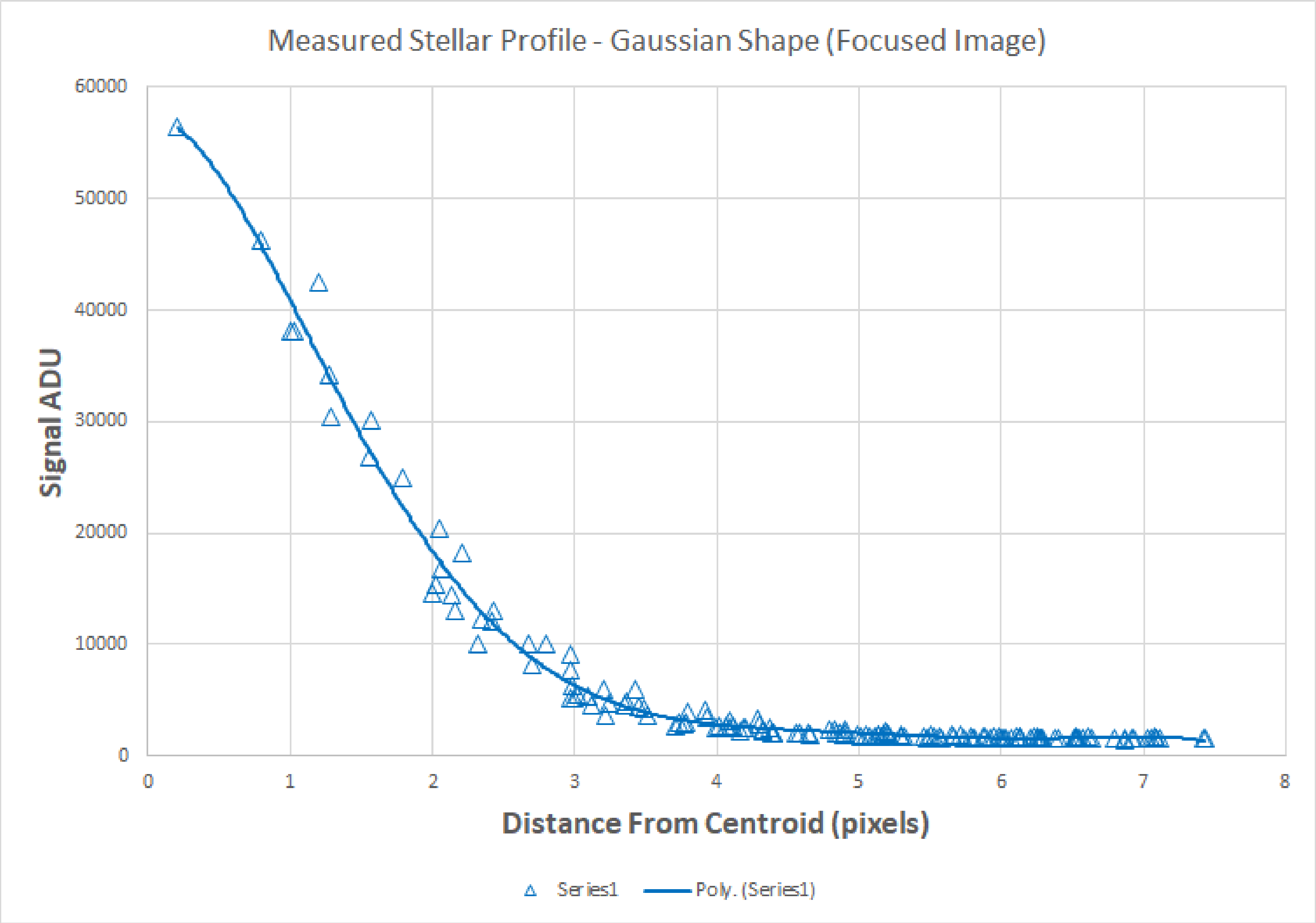
- Based on the information presented in the Stefansson, et al., paper, I developed a hypothesis:

  By using an Engineered Diffuser™, high-precision photometric measurements (total photometric error < 3 mmag RMS) can be obtained using a small aperture telescope. Shot noise and scintillation noise can be reduced accordingly without requiring near perfect tracking.

- If the hypothesis is proven true, then this would provide the opportunity for many more amateurs to get involved with observing and recording the light curves for exoplanet transits, minor planets, and variable stars

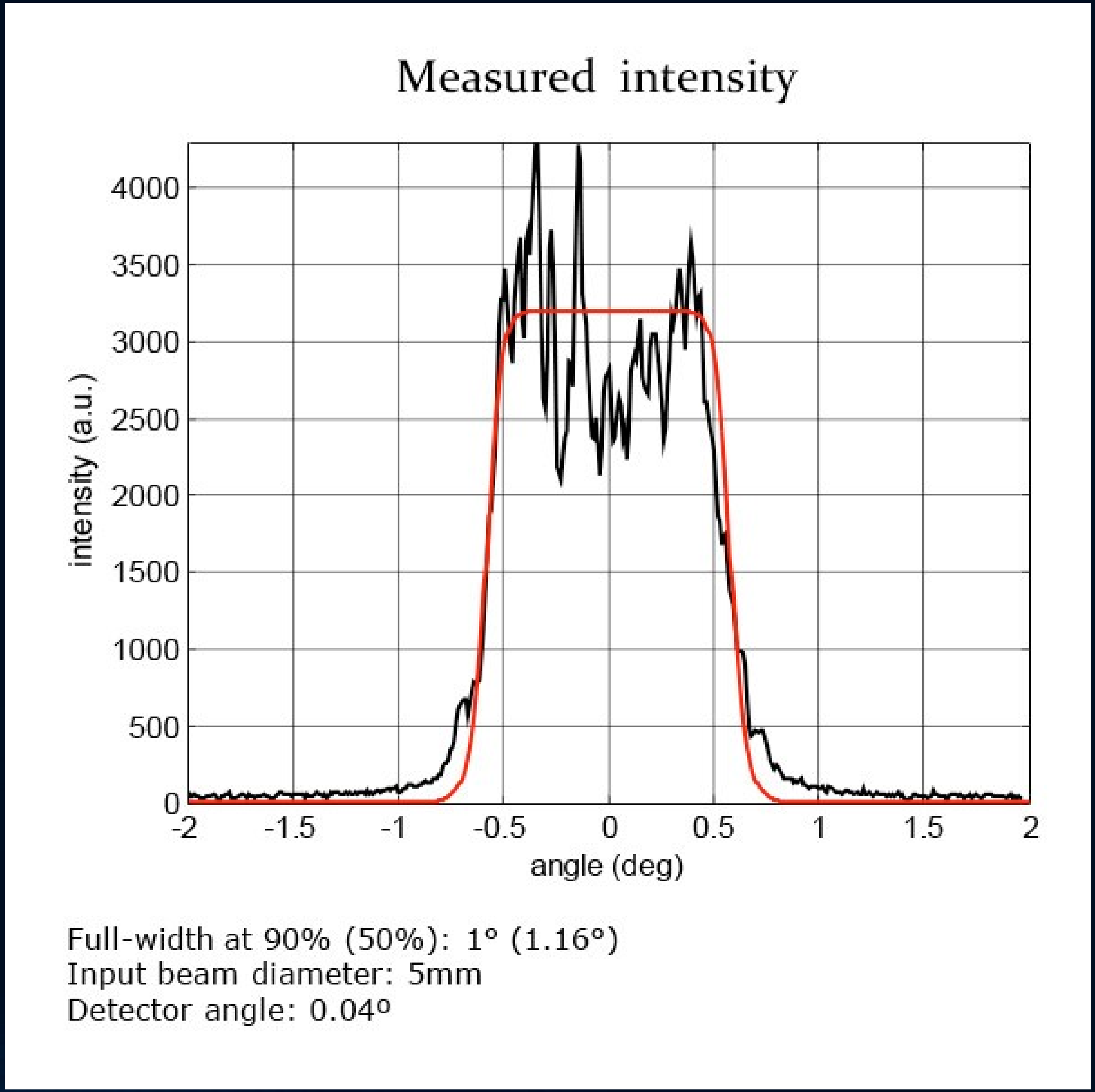
Point Spread Function (PSF)

An example measured profile of a PSF of a star image that is focused on the image plane. The measured FWHM for this star is ≈ 3 pixels.



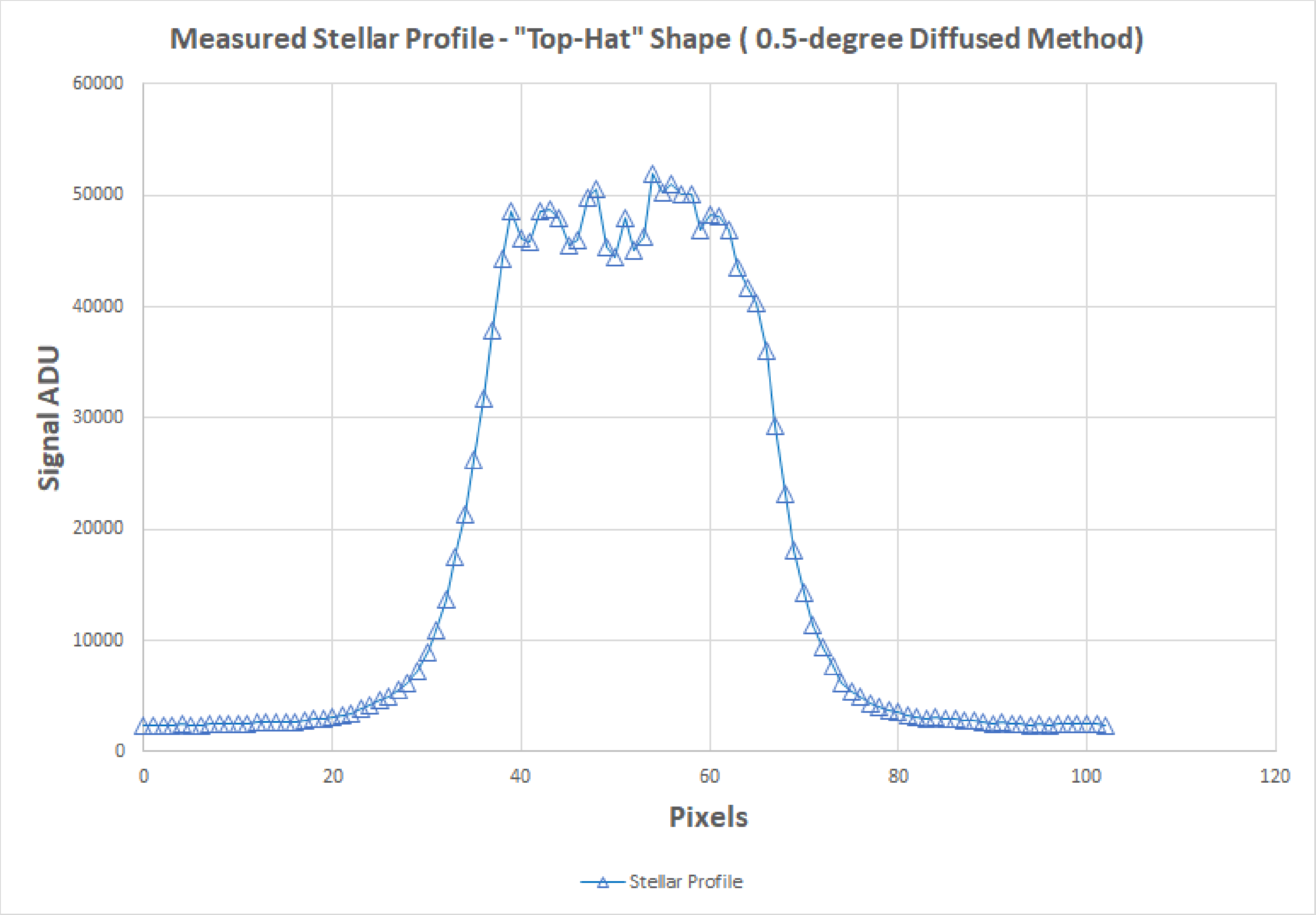
Diffuser Method Optical Element Top-Hat PSF Profile

- The top-hat PSF profile for the type of 1.0° divergence diffuser tested at the MSRO.
- Image courtesy RPC Photonics, Inc.



Diffuser Method Optical Element Top-Hat PSF Profile

- The top-hat PSF profile for the 0.5° divergence diffuser as installed in the QHY174M-GPS camera filter wheel and tested at the MSRO



Scintillation Limited vs. Shot Noise Limited Observations

- It is important when doing high-precision photometric measurements that the data acquired are *scintillation limited* instead of *shot noise limited* .
- If the data are shot noise limited , this means that not enough photons have been collected to make a good measurement—the effect of scintillation is mixed into the signal and the overall signal-to-noise (SNR) is very poor.
- For scintillation limited measurements, a large number of photons are collected and the inherent measurement error associated with the particle nature of light is minimized.
- For this reason, it is important to make sure our measurements are scintillation limited, which means we are limited by what our sky will give us.
- How do we do this? By enlarging the profile!

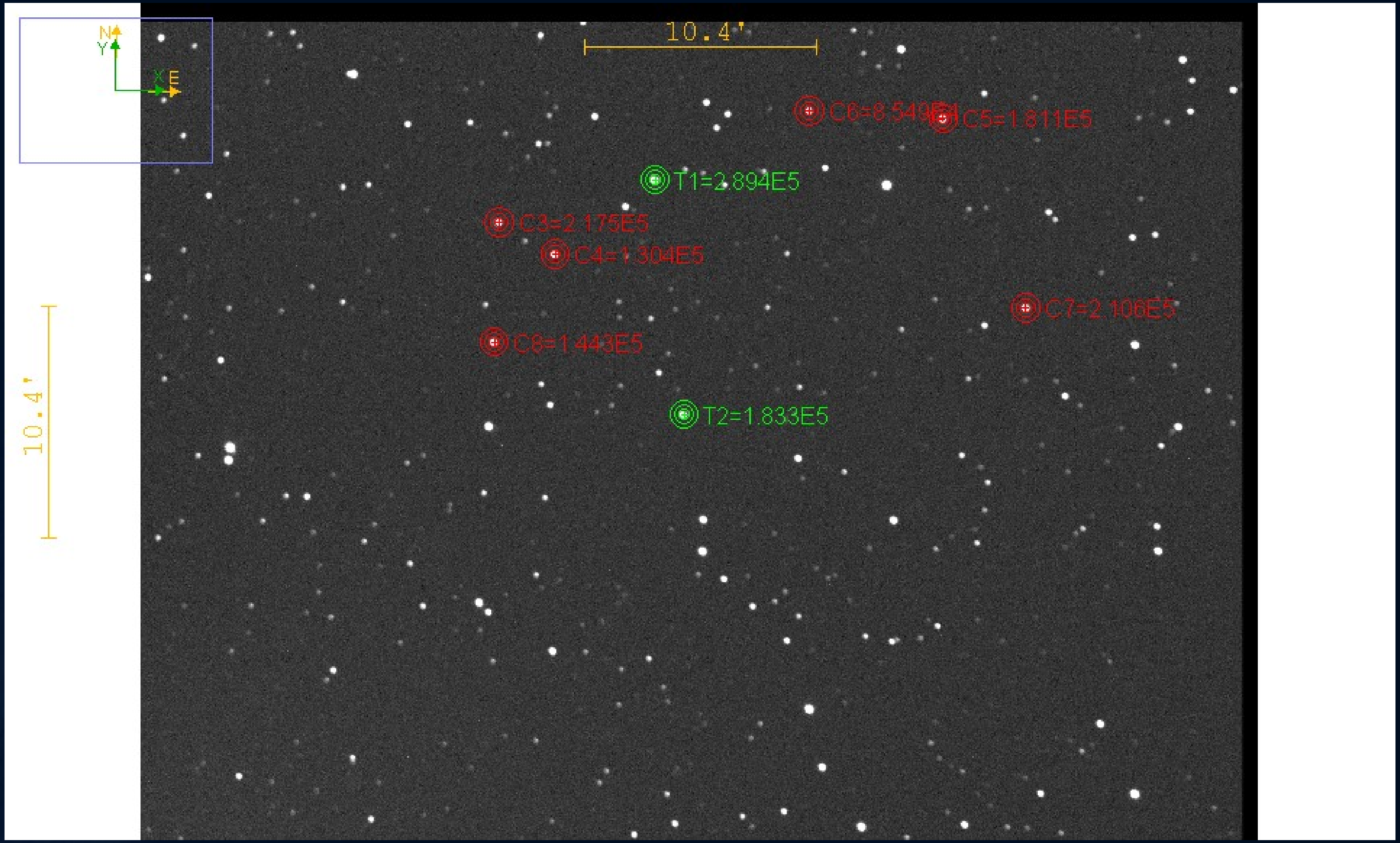
Why Do We Need to Enlarge the Profile of the PSF on the Image Plane?

- When enlarging the profile of the PSF, the light from the star is spread out over more pixels. This offers several advantages:
  - It allows larger, professional telescopes to take images of brighter stars; otherwise , the image would be overexposed and not provide good measurements.
  - It allows us to acquire a much larger number of photons from each object without saturation, which minimizes the Poisson, or shot noise associated with the particle nature of light. This helps to increase the SNR and ensures our measurements are scintillation limited .
  - It allows us to minimize any residual calibration error by integrating the measurement over a large number of pixels.
  - Depending on the method used and the type of telescope (refractor vs. reflector), the amount of scintillation can be minimized, which will increase the precision of the measurement.

The Standard Defocus Method for High-Precision Photometry

- The standard technique for doing high-precision photometry used by professionals and amateurs alike for decades is the Defocus Method
- The Defocus Method is used to spread the light out to gather more photons to decrease the shot noise and improve the SNR.
- Typical precision when using the Defocus Method for the typical amateur AIS is probably between 8 – 12 mmag RMS depending on the local sky conditions during the measurement.
- The best that could typically be expected would be 6 mmag RMS when observing in no moon, and near excellent transparency conditions.

Defocus Method Image



The AstroImageJ Measurement Field with the Target star (T1) and Comparison stars (C1, C2, C3, … Cn)

Discovering a Different Approach to High-Precision Photometry—The Diffuser Method

- In April 2018, I discovered a paper that had been released in October 2017 by Stefansson, et al.:

  Stefansson, G., Mahadevan, S., Hebb, L., & Wisniewski, J., et al. (2017, October). Towards Space-Like Photometric Precision From The Ground With Beam-Shaping Diffusers. *AstroPhysical Journal*, 5, 20-30

- The paper is available here: https://arxiv.org/pdf/1710.01790.pdf.
- I was very interested in seeing whether this method could work on the MSRO instruments.
- The paper discussed how using an Engineered Diffuser™ produced by RPC Photonics, Rochester, NY, could improve photometric measurement precision by a significant amount, help mitigate the effects of scintillation and tracking error, and minimize the systematic errors from those effects.

Beam-Shaping Diffuser Paper

- *Towards Space-Like Photometric Precision from the Ground With Beam-Shaping Diffusers, G. Stefansson, et al., (2017)*

1790v1 [astro-ph.IM] 4 Oct 2017

ACCEPTED FOR PUBLICATION IN APJ
Preprint typeset using LATEX style AASTeX6 v. 1.0

TOWARDS SPACE-LIKE PHOTOMETRIC PRECISION FROM THE GROUND WITH BEAM-SHAPING DIFFUSERS

GUDMUNDUR STEFANSSON[1,2,3,4,5], SUVRATH MAHADEVAN[1,2,3], LESLIE HEBB[6], JOHN WISNIEWSKI[7], JOSEPH HUEHNERHOFF[8,9,10], BRETT MORRIS[8], SAM HALVERSON[11,12], MING ZHAO[1,2,3,13], JASON WRIGHT[1,2,3], JOSEPH O'ROURKE[14], HEATHER KNUTSON[14], SUZANNE HAWLEY[8], SHUBHAM KANODIA[1], YITING LI[1], LEA M. Z. HAGEN[1,15], LEO J. LIU[1,2,3], THOMAS BEATTY[1,2,3], CHAD BENDER[1,2,16], PAUL ROBERTSON[11,1,2,3], JACK DEMBICKY[9], CANDACE GRAY[9], WILLIAM KETZEBACK[9], RUSSET MCMILLAN[9], AND THEODORE RUDYK[9]

[1]Department of Astronomy & Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA
[2]Center for Exoplanets & Habitable Worlds, University Park, PA 16802, USA
[3]Penn State Astrobiology Research Center, University Park, PA 16802, USA
[4]NASA Earth and Space Science Fellow
[5]Leifur Eiriksson Foundation Fellow
[6]Department of Physics, Hobart and William Smith Colleges, 300 Pulteney Street, Geneva, NY, 14456, USA
[7]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, 440 W. Brooks Street, Norman, OK 73019, USA
[8]Department of Astronomy, Box 351580, University of Washington, Seattle, WA 98195, USA
[9]Apache Point Observatory, 2001 Apache Point Road, Sunspot, New Mexico, NM 88349, USA
[10]Hindsight Imaging, Inc., 233 Harvard St. Suite 316, Brookline, MA 02446, USA
[11]NASA Sagan Fellow
[12]Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
[13]The New York Times, 620 Eight Avenue, New York, NY 10018, USA
[14]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
[15]Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
[16]Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85719, USA

ABSTRACT

We demonstrate a path to hitherto unachievable differential photometric precisions from the ground, both in the optical and near-infrared (NIR), using custom-fabricated beam-shaping diffusers produced using specialized nanofabrication techniques. Such diffusers mold the focal plane image of a star into a broad and stable top-hat shape, minimizing photometric errors due to non-uniform pixel response, atmospheric seeing effects, imperfect guiding, and telescope-induced variable aberrations seen in defocusing. This PSF reshaping significantly increases the achievable dynamic range of our observations, increasing our observing efficiency and

Diffuser Image Train

- This shows the image train with the diffuser installed in the filter wheel.
- The size of the PSF profile is based on the distance between the diffuser and the image plane and can be calculated. (value S on the figure)
- Stefansson, et al. (2017)

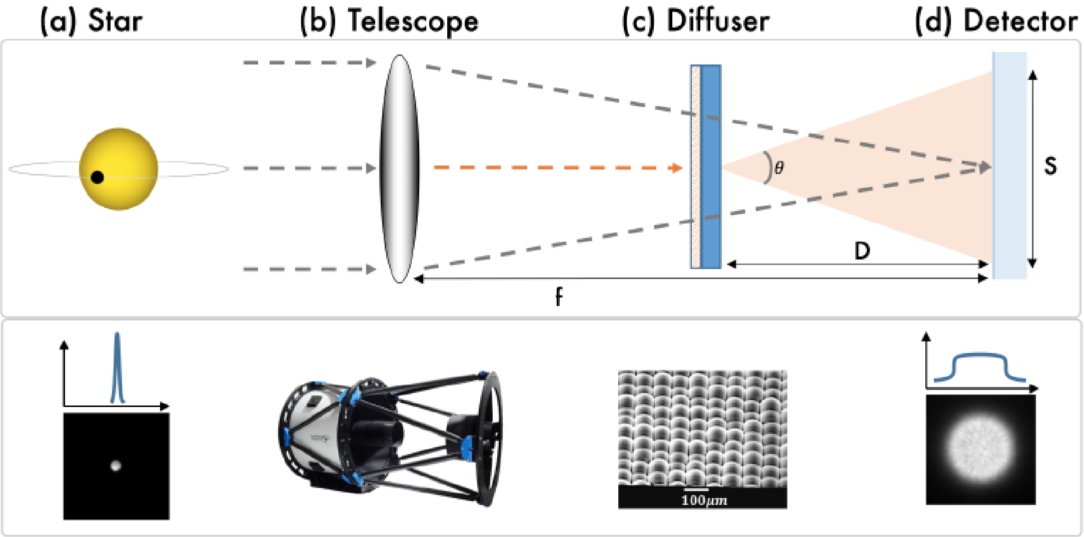


Figure 5. Diffuser usage in a telescope in a converging beam. Microscopically engineered patterns on the surface of the diffuser (c) are used to mold starlight in a converging beam (a;b) to a broad and stable top-hat shape on the detector (d). Diffuser surface structures, image credit RPC Photonics.

the ideal case, such a diffuser would create a top-hat PSF shape with steep sides and a flat top subtending many tens of pixels in diameter, minimizing the signal lost outside the photometric aperture. Furthermore, like mentioned above, a top-hat PSF is more favorable than e.g., a Gaussian-shaped PSF, which has significant slopes everywhere except in the very center, making every pixel subject to guiding errors and changes in seeing. Meanwhile, a top-hat PSF restricts guiding errors due to PSF slopes to only the edge pixels, because the inner pixels see the same flux regardless. To enable the adoption of a beam-shaping diffuser over a broad range of astronomical instrumentation and allow for maximum flexibility, the diffuser should work in both converging and collimated beams.

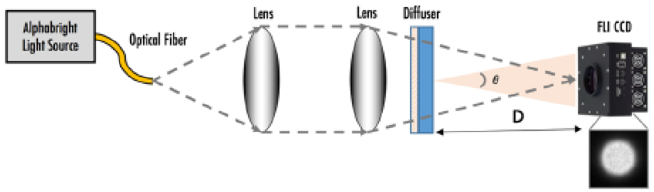


Figure 6. Lab test setup to characterize diffusers in converging and collimated beams.

To study diffuser PSFs in collimated and converging beams, and how their PSF changes with distance, we set up a dedicated test bench (Figure 6). A single mode fiber was coupled to a collimating lens system, composed of two

Discovering a Different Approach to High-Precision Photometry—The Diffuser Method

- The Diffuser Method is used to spread the light out to gather more photons and decrease the shot noise and improve the SNR as in the Defocus Method
- After studying the Stefansson, et al. paper, we developed a calculation to select the proper size Engineered Diffuser™ for use with the main instrument in the MSRO.
- At the MSRO, two different Engineered Diffusers™ were purchased from RPC Photonics to test— a 1.0°, and a 0.5° divergence diffuser. A 0.25° divergence diffuser was purchased and installed at the Conti Private Observatory (CPO.)

Discovering A Different Approach To High-Precision Photometry – The Diffuser Method

- At the MSRO, we found that the 0.5° divergence diffuser was better overall when balancing the need for gathering enough photons without overexposing the image, and also not “diffusing out” the dimmer stars so that enough comparison stars were available for the measurement.
- It is important to balance the two error terms: shot noise and scintillation noise so that we get the best results. You do not want to compromise the possible range of measurements in terms of magnitude and the lack of enough comparison stars.

Discovering A Different Approach To High-Precision Photometry – The Diffuser Method

The Stefansson, et al. paper discussed the improvement seen using the Diffuser Method in settling out the short-term scintillation.

We were able to demonstrate this with the observations made at the MSRO, but the results were ambiguous at the CPO.

This may have been due to the Diffuser PSF profile being similar in size to the Defocused PSF profile.

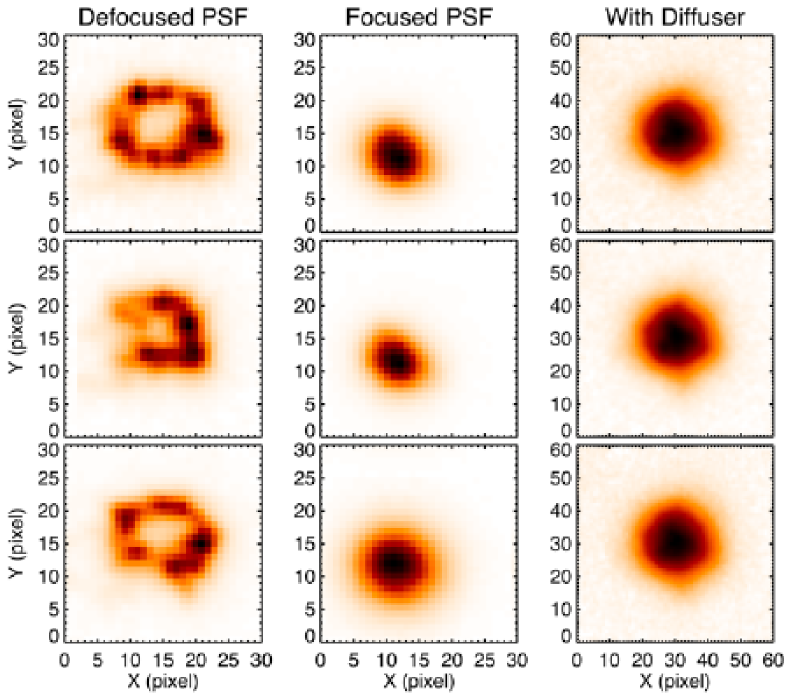
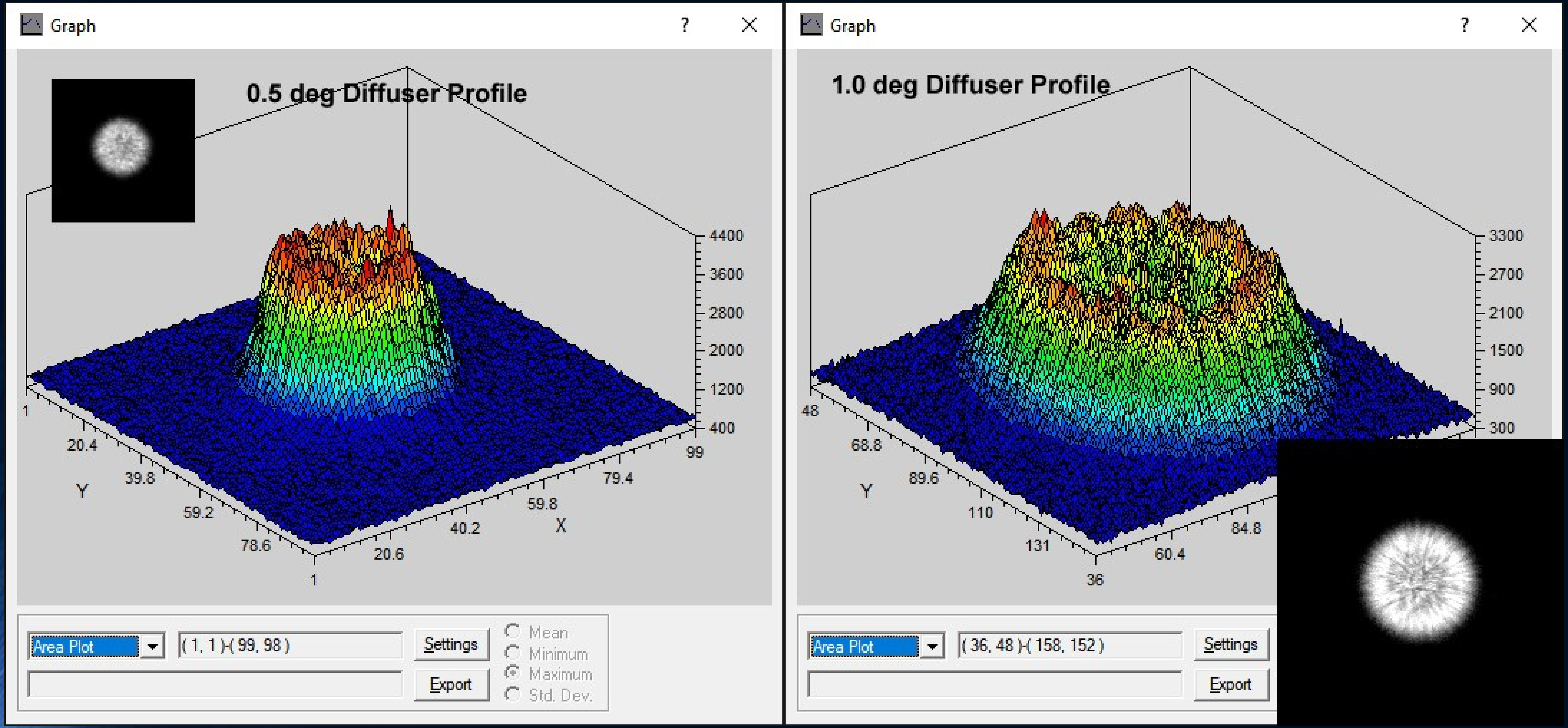


Figure 3. Comparison of Palomar/WIRC PSFs under three observing modes at different epochs: defocused, focused, and diffused. The defocused PSF shows bright spots due to astigmatism of the telescope, inducing a significant amount of "red noise" to the light curve. Both defocused and focused modes show varying PSFs due to seeing variations, while the diffused PSF stays stable in shape (flux level still varies due to telluric fluctuations). Images with the diffuser shown at a different scale for clarity. A video version of this figure can be found in the online version of the manuscript.

Engineered Diffuser™ Profile

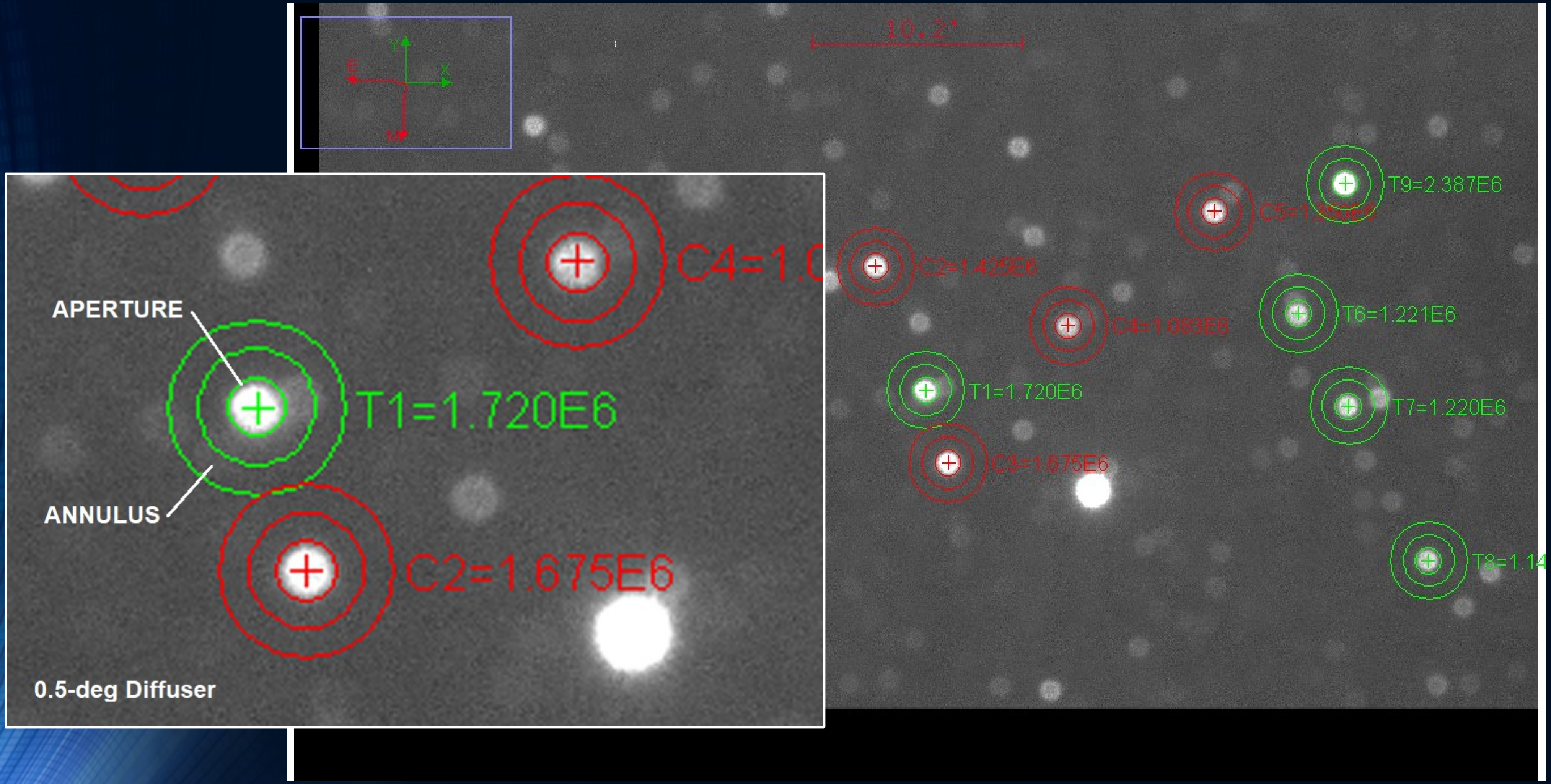


The difference between the 0.5° (40 px FWHM) and 1.0° (80 px FWHM) diffuser divergence angle mounted in the SBIG Filter Wheel as measured at the MSRO

Photometric Engineered Diffuser™

- The 0.5° Engineered Diffuser™ used in the filter wheel of the main instrument
- The diffuser is produced by RPC Photonics in Rochester, NY.

0.5° Diffused Method Image



This shows the Photometry Aperture and Annulus used in the AstroImageJ Measurement Field with the Target star (T1) and Comparison stars (Cx)labeled

Basic Instrument and Software Requirements for High-Precision Photometry of Bright Stars

- High-quality astrograph: refractor 4 inches 0.10 m or reflector 8 inches 0.20 m . An Apochromatic (APO) Refractor is preferred, but an Achromat Refractor should work.
- A German Equatorial Mount (GEM) that can be precisely polar aligned and auto-guided. A GOTO mount is preferred for ease of use but is not required.
- A modern CCD or CMOS camera system that has a Thermo-Electric Cooler (TEC) and can be used to acquire light (data) frames and calibration frames (bias, darks, and flats).
- A V-band Photometric Filter can be used; a blue-blocker filter has been shown to improve the SNR.

Basic Instrument and Software Requirements for High-Precision Photometry of Bright Stars

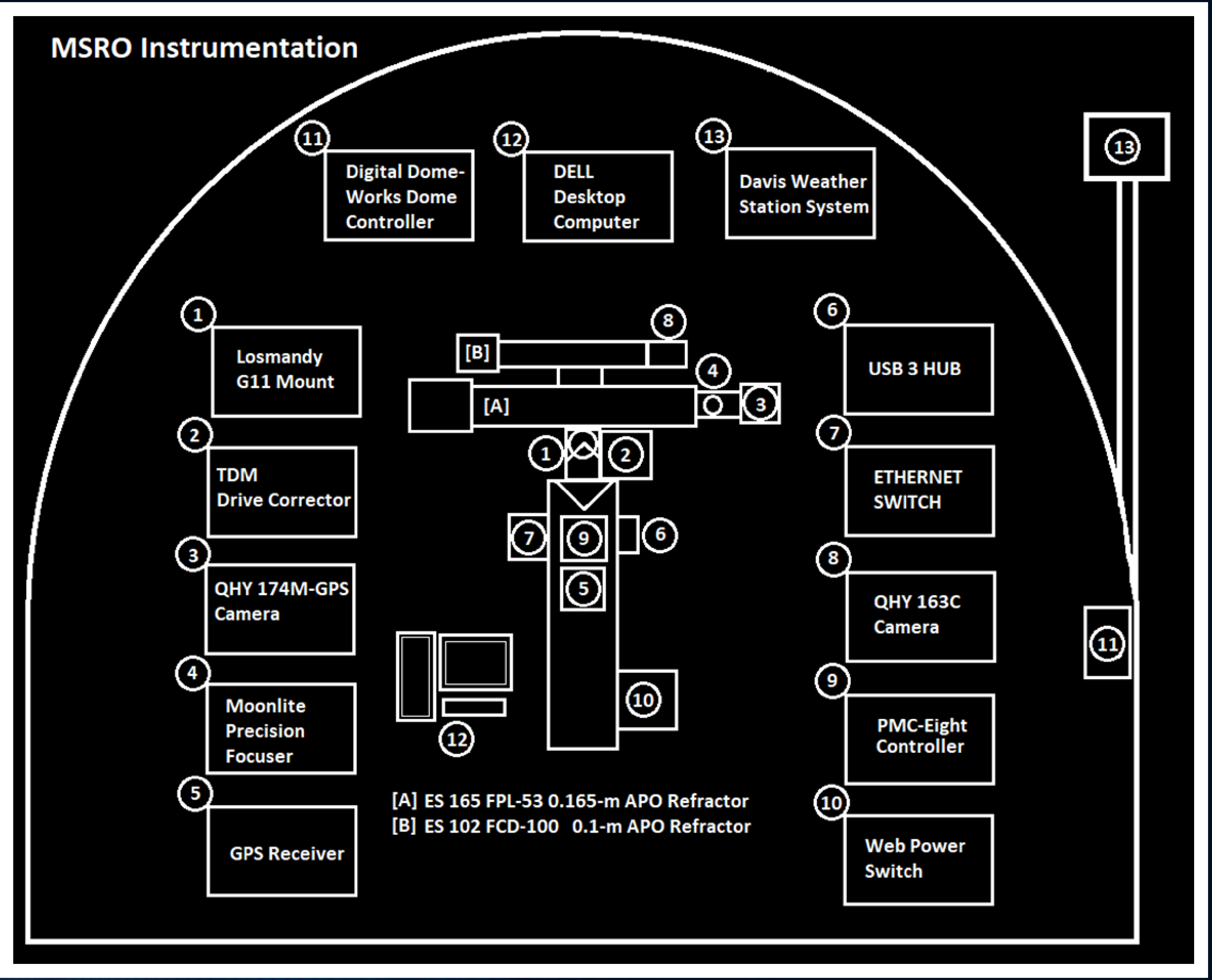
- Computer system with the following features and programs:
  - Camera control software to acquire the necessary data and store them in the FITS file format.
  - Planetarium program with the USNO UCAC4 or URAT1 catalogue to do plate solves to accurately identify targets and comparison objects. The standard TYCHO, HD, or other catalogues may be used for identification.
  - GPS or other accurate time reference to set the computer system clock and accurately timestamp the images (< 1 second precision).
  - An image acquisition program to obtain the data and perform image calibrations.
  - AstroImageJ light-curve analysis program, freely available at https://www.astro.louisville.edu/software/astroimagej/

The Mark Slade Remote Observatory (MSRO) W54, Wilderness, VA

- Director Dr. Myron Wasiuta, and Assistant Director Jerry Hubbell
- The main OTA is an ES 165 FPL-53 ED APO Carbon Fiber Refractor
- The secondary OTA is an ES 102 FCD100 ED APO Carbon Fiber Refractor

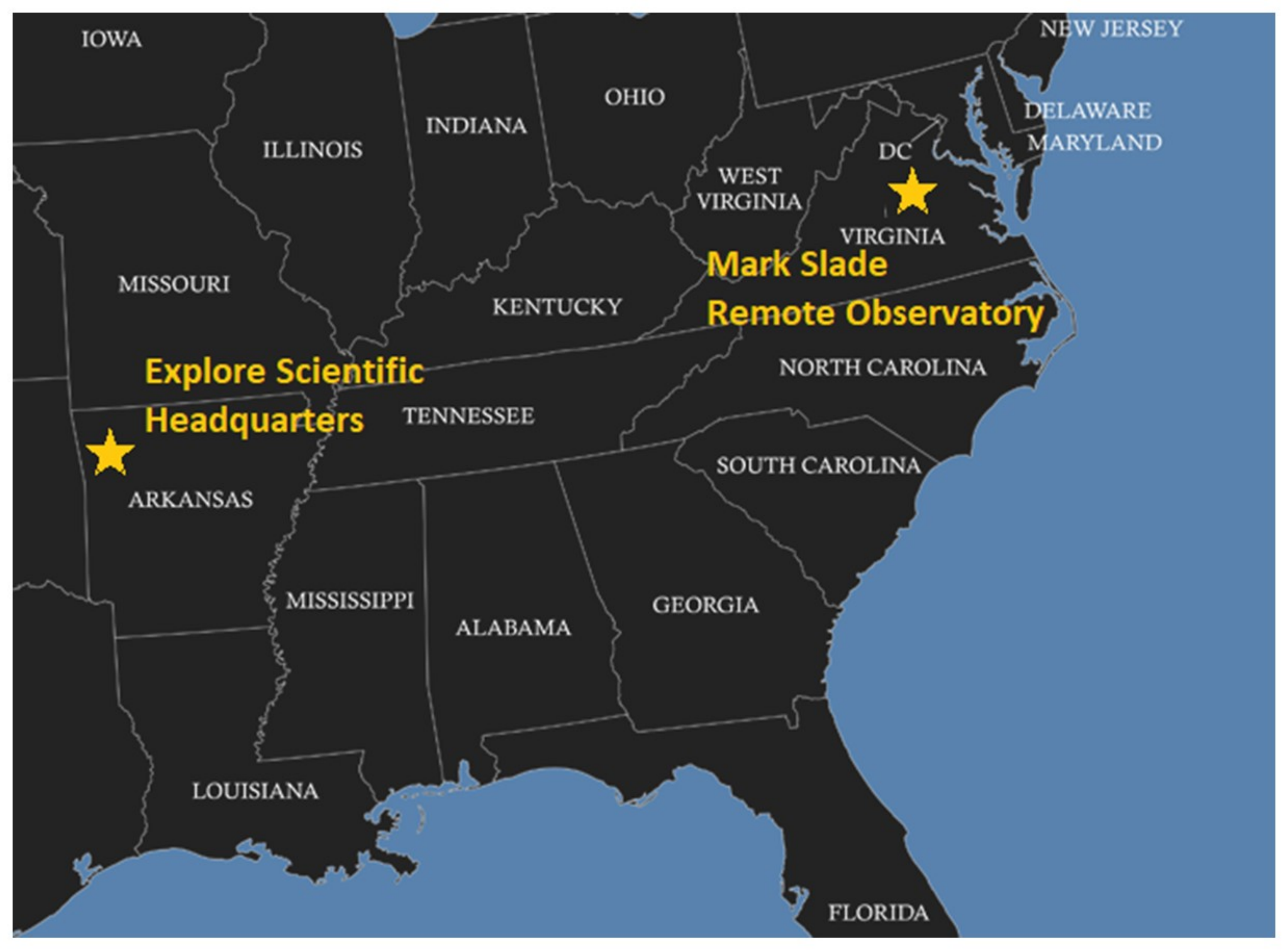
MSRO Instrumentation Diagram

- Several different systems,subsystems, and components make up the MSRO Observatory



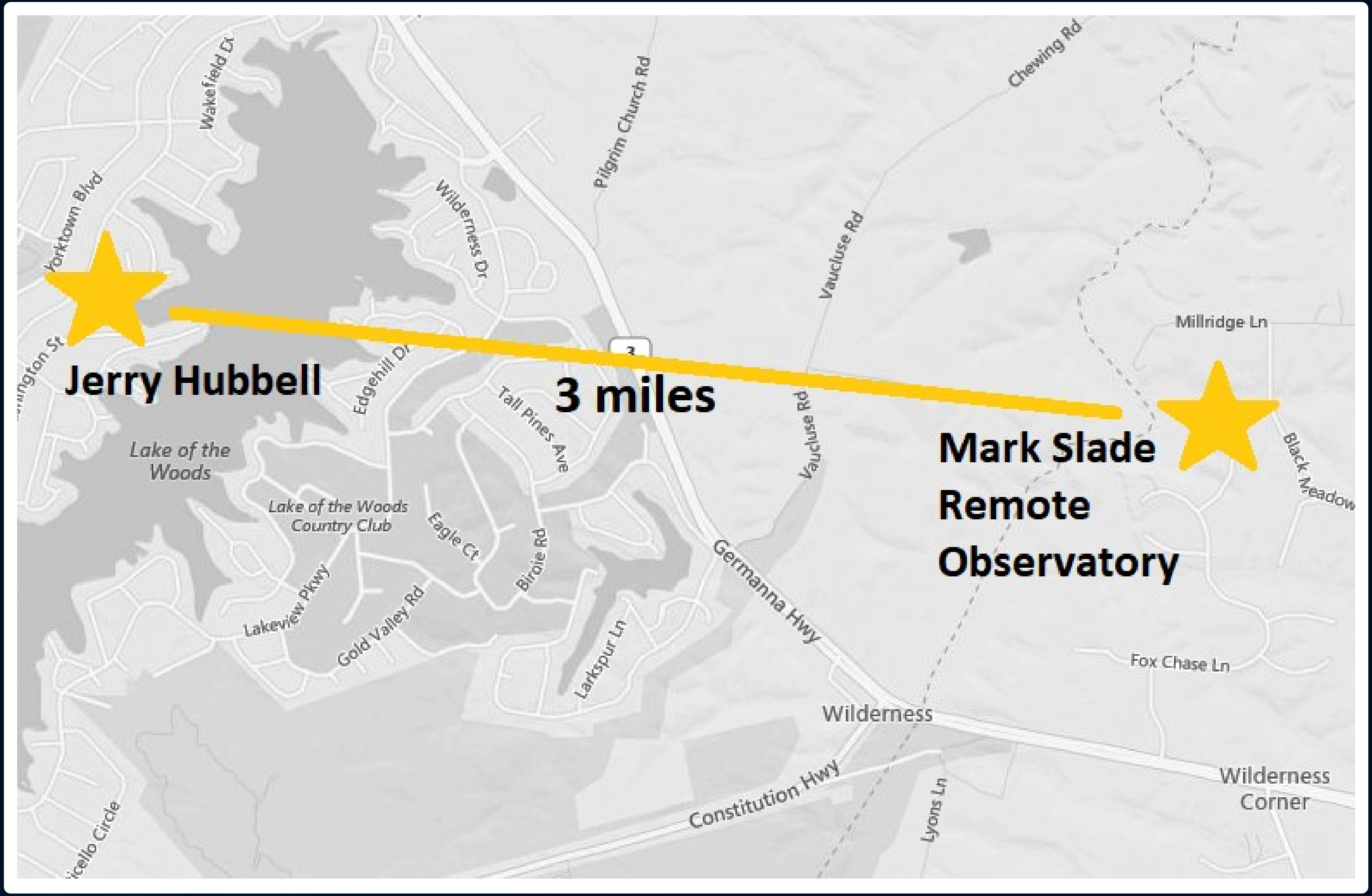
Mark Slade Remote Observatory Location

- The observatory is located in historic Wilderness, Virginia, 50 miles south of Washington, DC.



MSRO Location

- The observatory is located in Wilderness, VA, about 3 miles (as the crow flies) from Jerry Hubbell's home.



Using AstroImageJ to Analyze Exoplanet Images

- The standard today in analyzing exoplanet images and data is to use the program AstroImageJ (AIJ) developed by Karen Collins, et al. (2017)

  Collins, K. A., Kielkopf, J. F., Stassun, K. G., & Hessman, F. V. (2017, February). AstroImageJ: Image Processing and Photometric Extraction for Ultra-Precise Astronomical Light Curves. *The Astronomical Journal 153:77*, 1-13.

- This paper is available at: https://arxiv.org/pdf/1601.02622.pdf
- Dennis Conti has written an excellent tutorial on using AstroImageJ for analyzing exoplanet images and data that he uses in his AAVSO CHOICE Exoplanet Observing course.

  Conti, D.M., (2018 October). *A Practical Guide to Exoplanet Observing*.

- http://astrodennis.com/Guide.pdf
- You can download the tutorial, other example files and support documents at: http://astrodennis.com

Using AstroImageJ to Analyze Exoplanet Images

There are a few steps in the processing of exoplanet image data. At the MSRO, we used MaxIm DL™ (MDL) and AstroImageJ (AIJ) in combination, along with Microsoft Excel™ to do further analysis. The basic process is:

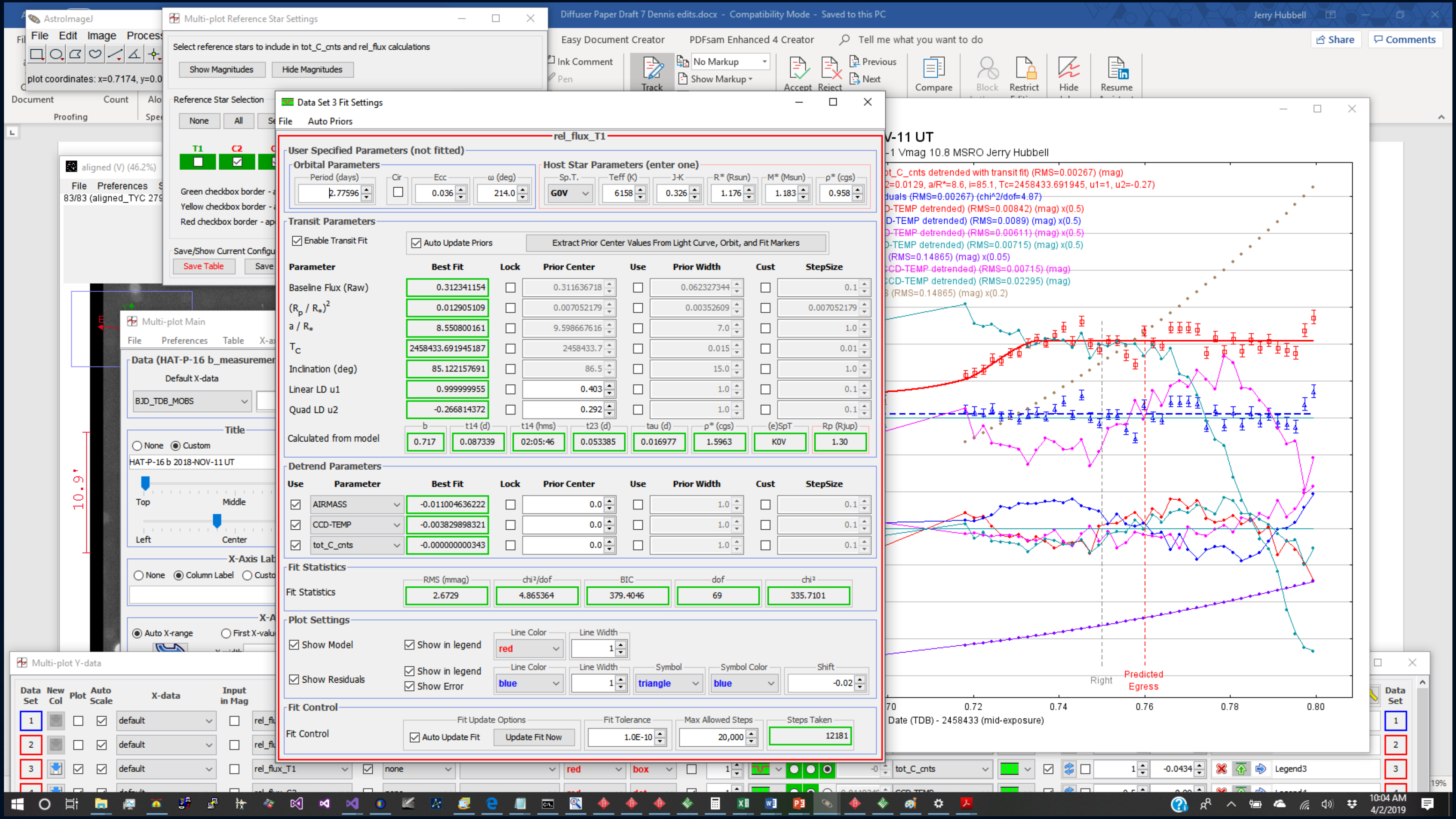
1. Acquire raw FITS file images using MDL
2. Calibrate raw FITS file Images using MDL
3. Import calibrated images into AIJ
4. Align calibrated images in AIJ
5. Identify Target and Comparison Stars in AIJ

Using AstroImageJ to Analyze Exoplanet Images

6. Perform Differential Aperture Photometry in AIJ
7. Gather Exoplanet catalog data from the Exoplanet Transit Database, or the NASA Exoplanet Archive and enter the data into the model
8. Fit an Exoplanet Light Curve Model to the measurements to determine transit length, geometry, and depth.
9. Determine the basic Exoplanet parameters from the model fit for:
   - Planet Radius
   - Planet Mass
   - Midpoint time of Transit
   - Orbital Inclination
10. For further details on measuring image data and determining Exoplanet parameters, see http://astrodennis.com/Guide.pdf

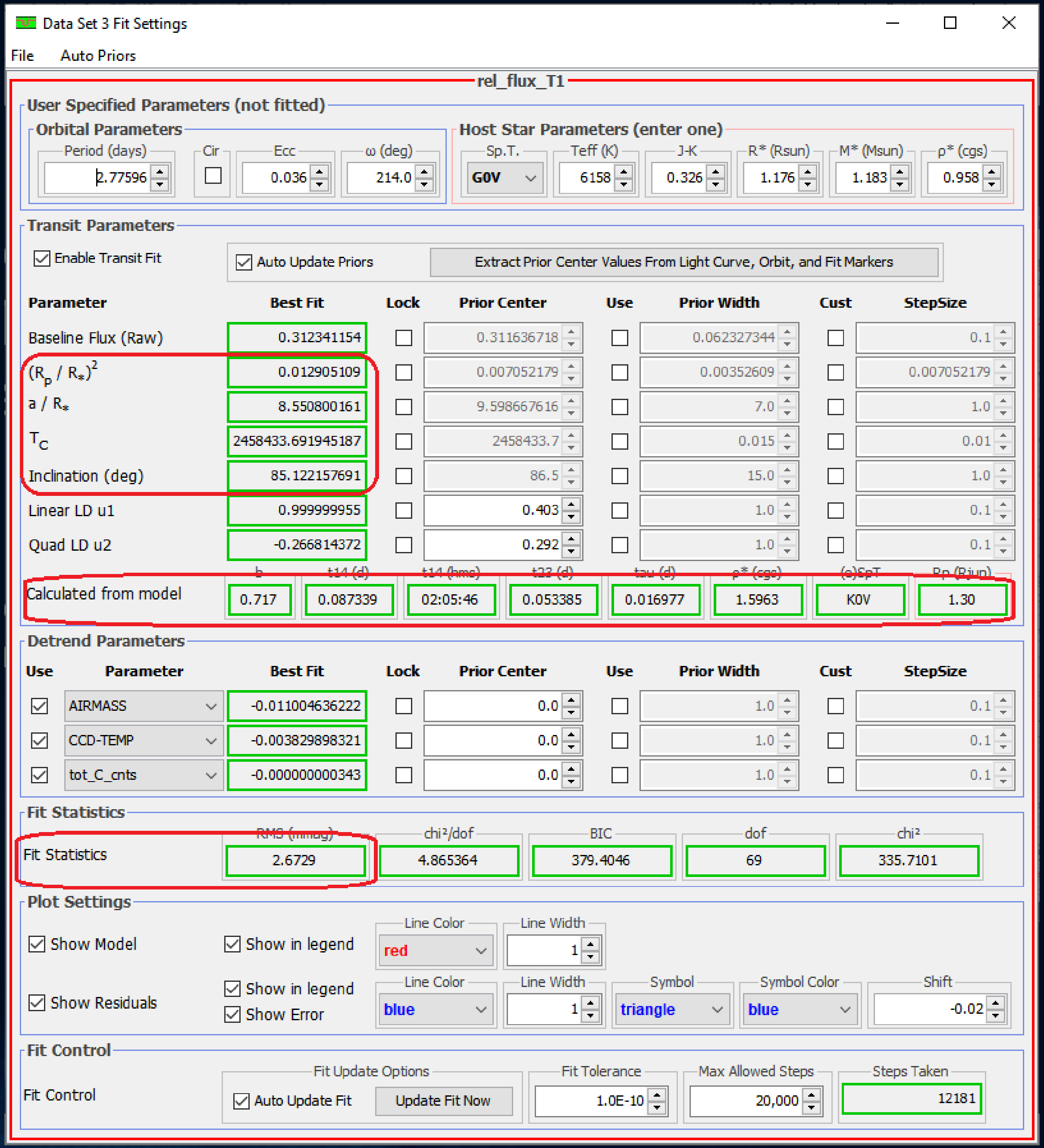
Exoplanet HAT-P-16 AIJ Analysis

- A screenshot of the AIJ analysis of an exoplanet



Exoplanet HAT-P-16 AIJ Analysis

- A screenshot of the AIJ Exoplanet Transit Model Fit
- Once the model parameters are set, the size of the planet and orbital inclination are calculated.



A Comparison of the Results Using Two Different Techniques for High-Resolution Photometric Measurements

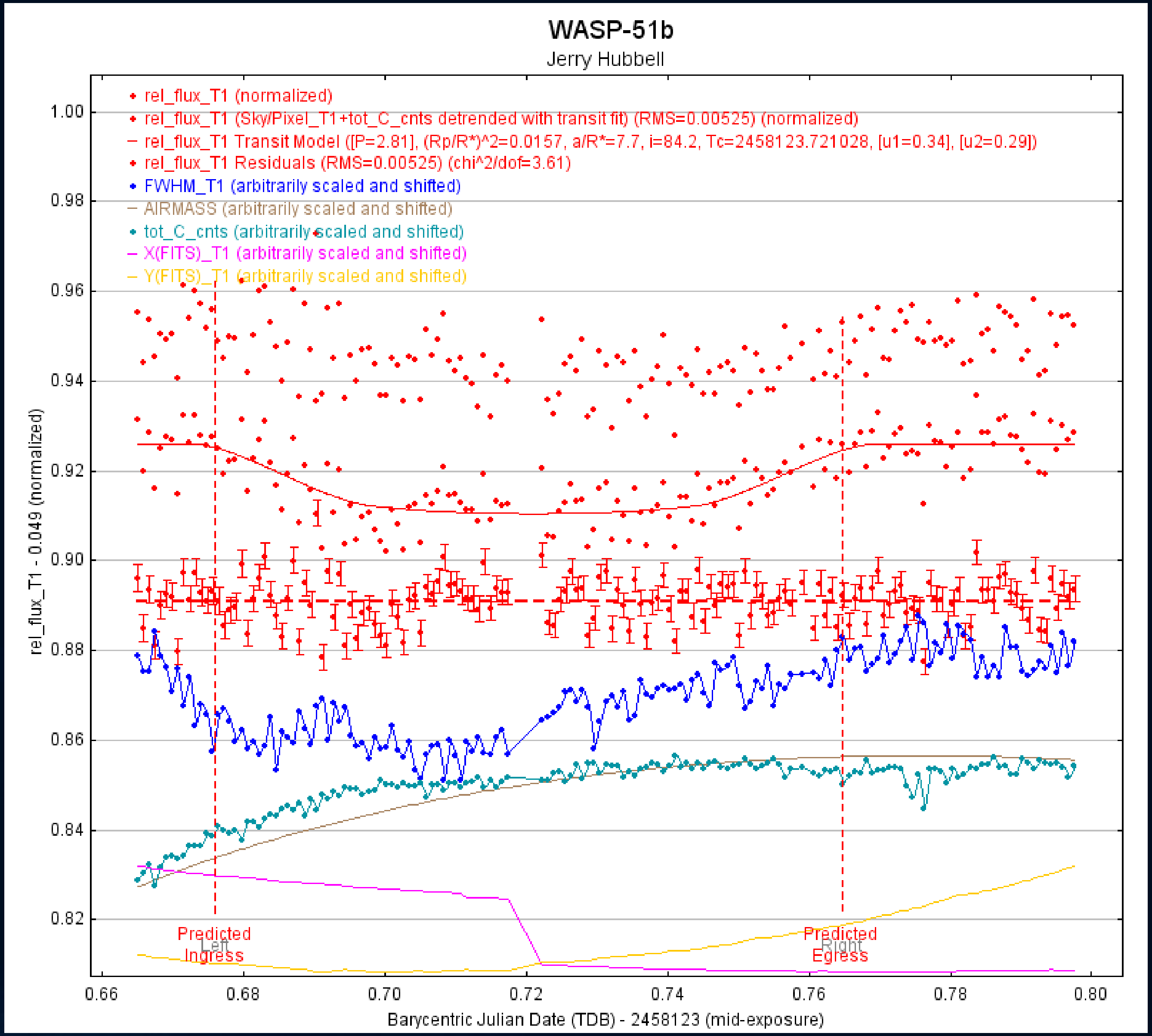
- Our first complete exoplanet transit observation of HAT-P-30/WASP-51 b in January 2018 used the Defocus Method and resulted in a precision of ≈ 8 mmag RMS. This method is limited by both shot noise and scintillation.
- We successfully observed several stars of varying magnitude from about 6 to 11 over the summer of 2018 using the Diffuser Method with both the 1.0° and 0.5° diffuser and were encouraged by the results.

A Comparison of the Results Using Two Different Techniques to Create Profiles for High-Resolution Photometric Measurements

- We successfully observed exoplanet HAT-P-16 b in November 2018 using the Diffuser Method which resulted in a total precision of ≈ 3 mmag RMS for 3 minute exposures, with the Shot Noise component < 1 mmag RMS.
- Our work thus far has shown that the Diffuser Method can minimize errors due to Shot-Noise, Tracking, and Image Calibration, and provide measurements that are only scintillation limited with results down to < 5 mmag RMS for 1 minute exposures, and ≈2 mmag RMS for 5 minute exposures.

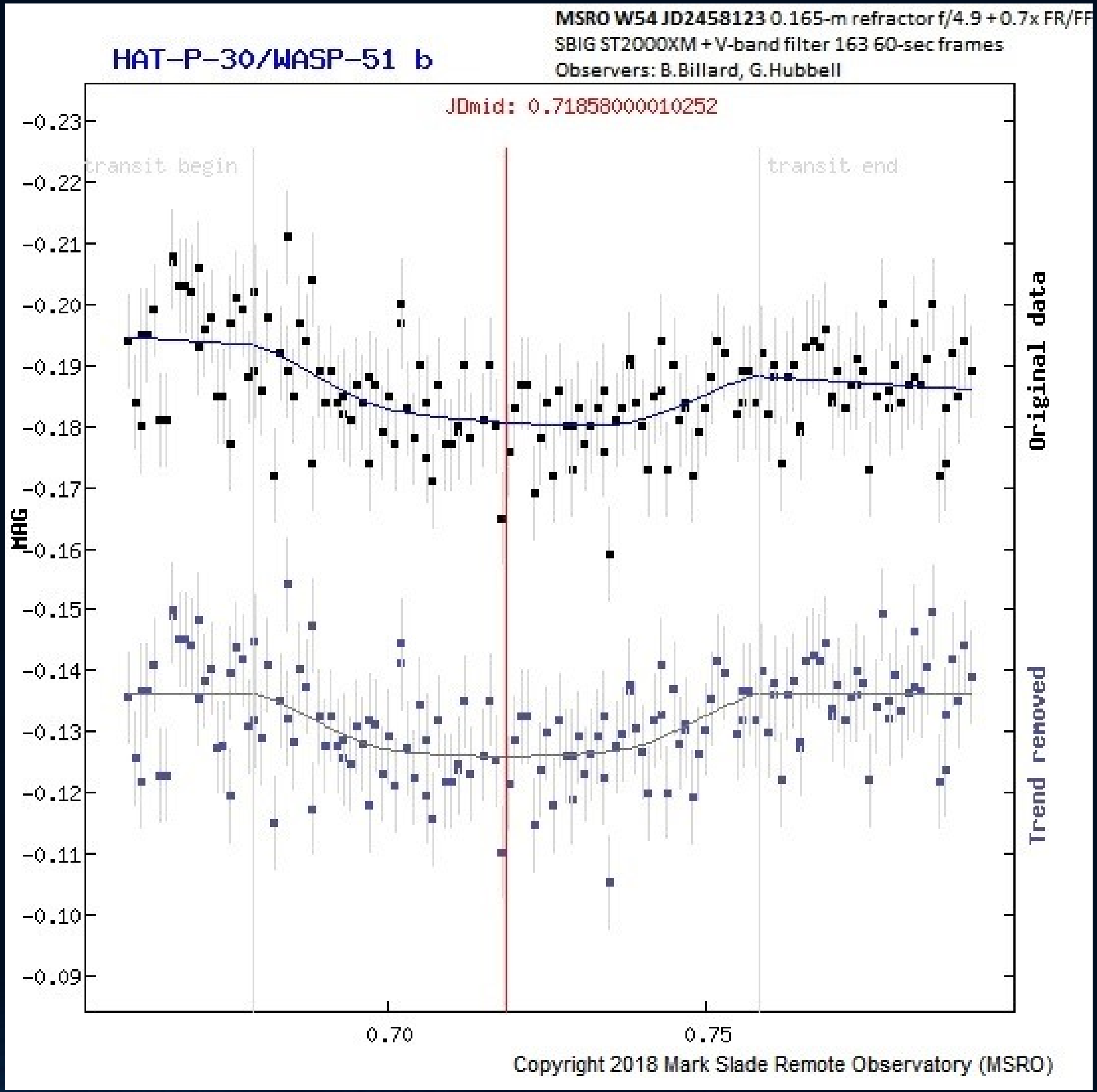
Exoplanet HAT-P-30/WASP-51 b Observed at MSRO

- Observed by Dr. Bart Billard and Jerry Hubbell on January 4, 2018 at MSRO and submitted to the Exoplanet Transit Database (ETD)
- Measured using AstroImageJ with data taken using the Defocus Method



Exoplanet HAT-P-30/WASP-51 b Observed at MSRO

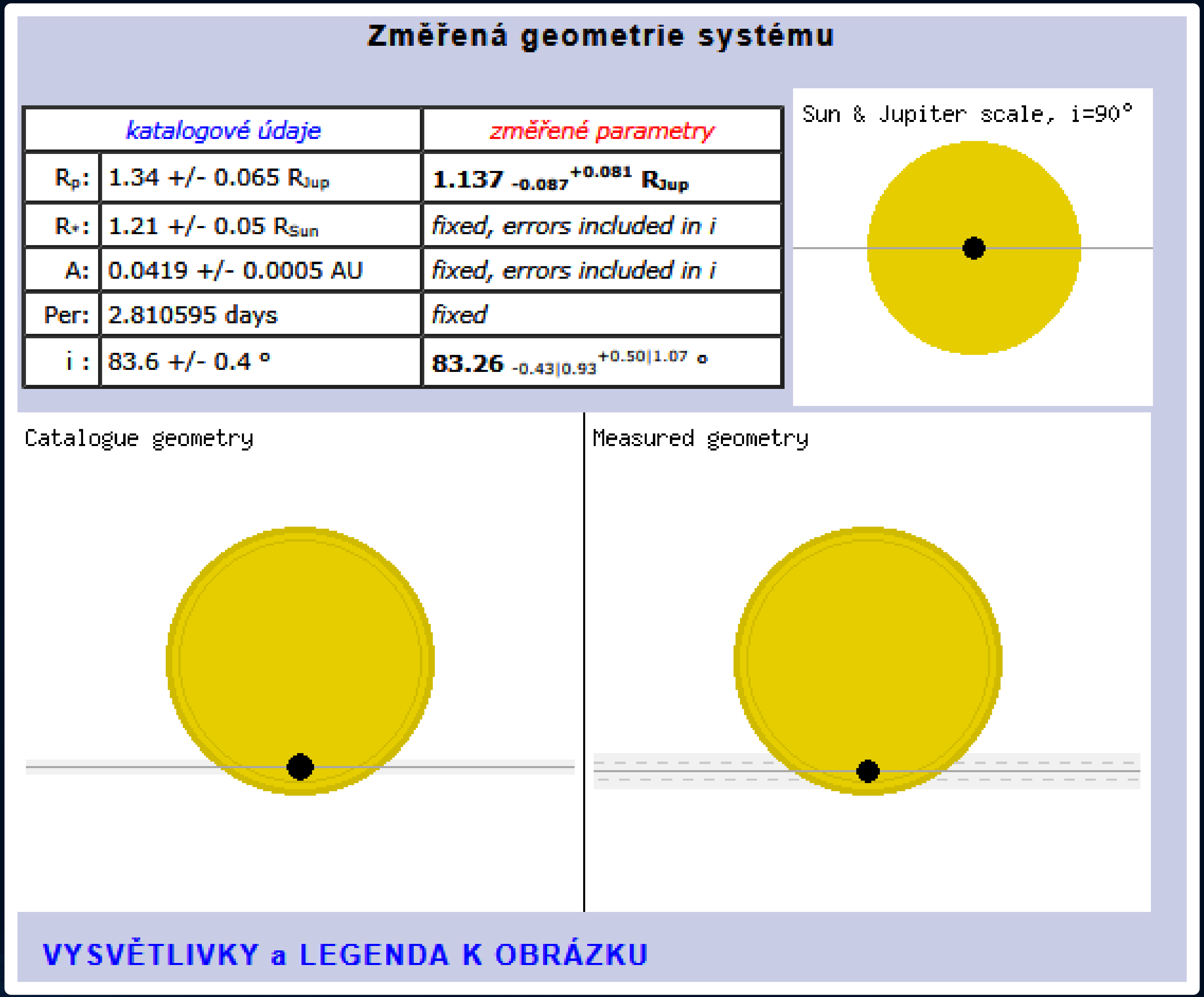
- Observed by Dr. Bart Billard and Jerry Hubbell on January 4, 2018 at MSRO and submitted to the Exoplanet Transit Database (ETD)
- Measured using the Defocus Method with a measured transit depth of 10.1 mmag



Exoplanet HAT-P-30/WASP-51 b Planet Geometry◊

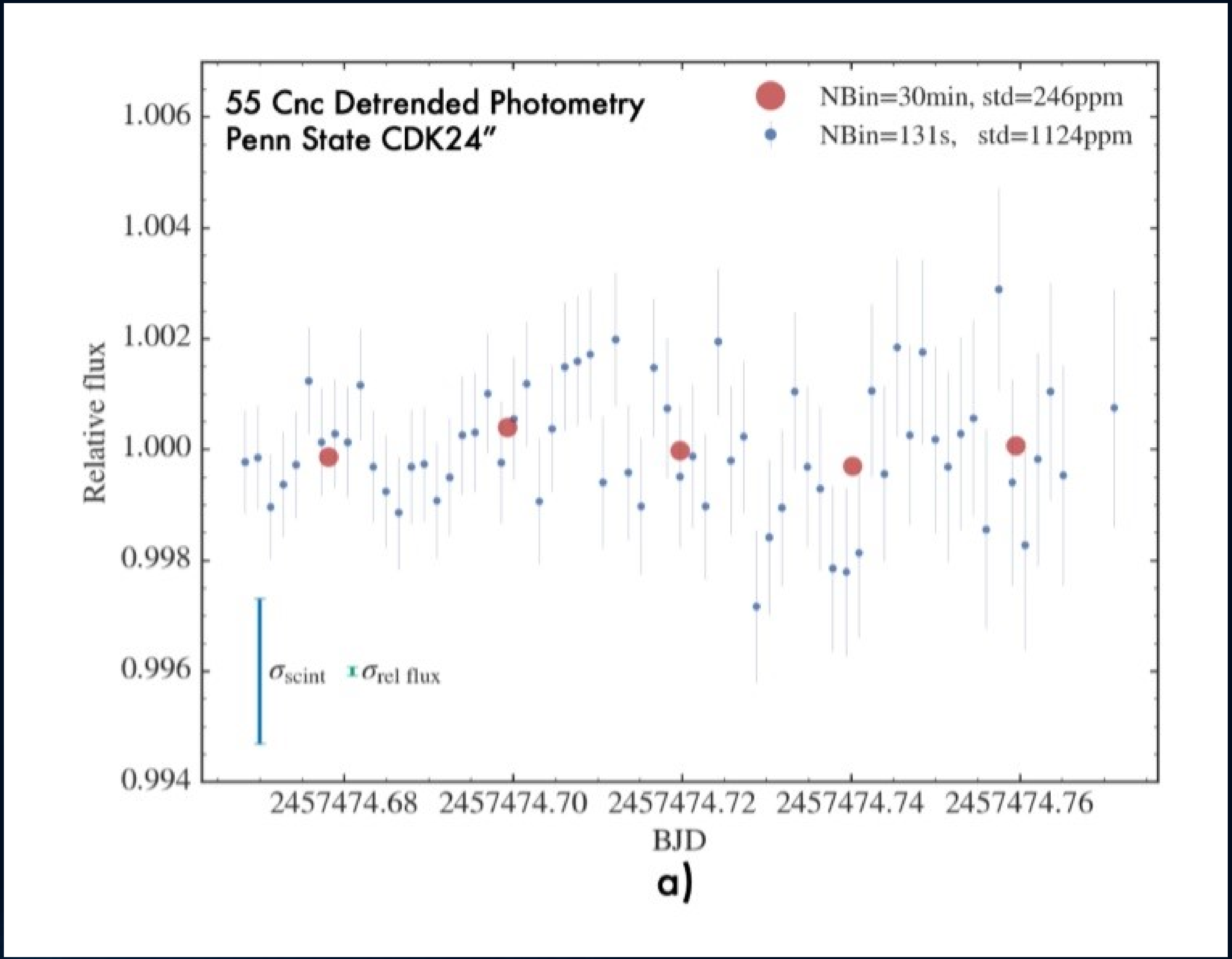
- Measured Planet Radius, R_p = 1.137 ±0.09 R_{jup}
- Measured Orbit Inclination, i = 83.26 ±0.5°

◊As determined by the ETD modeling program



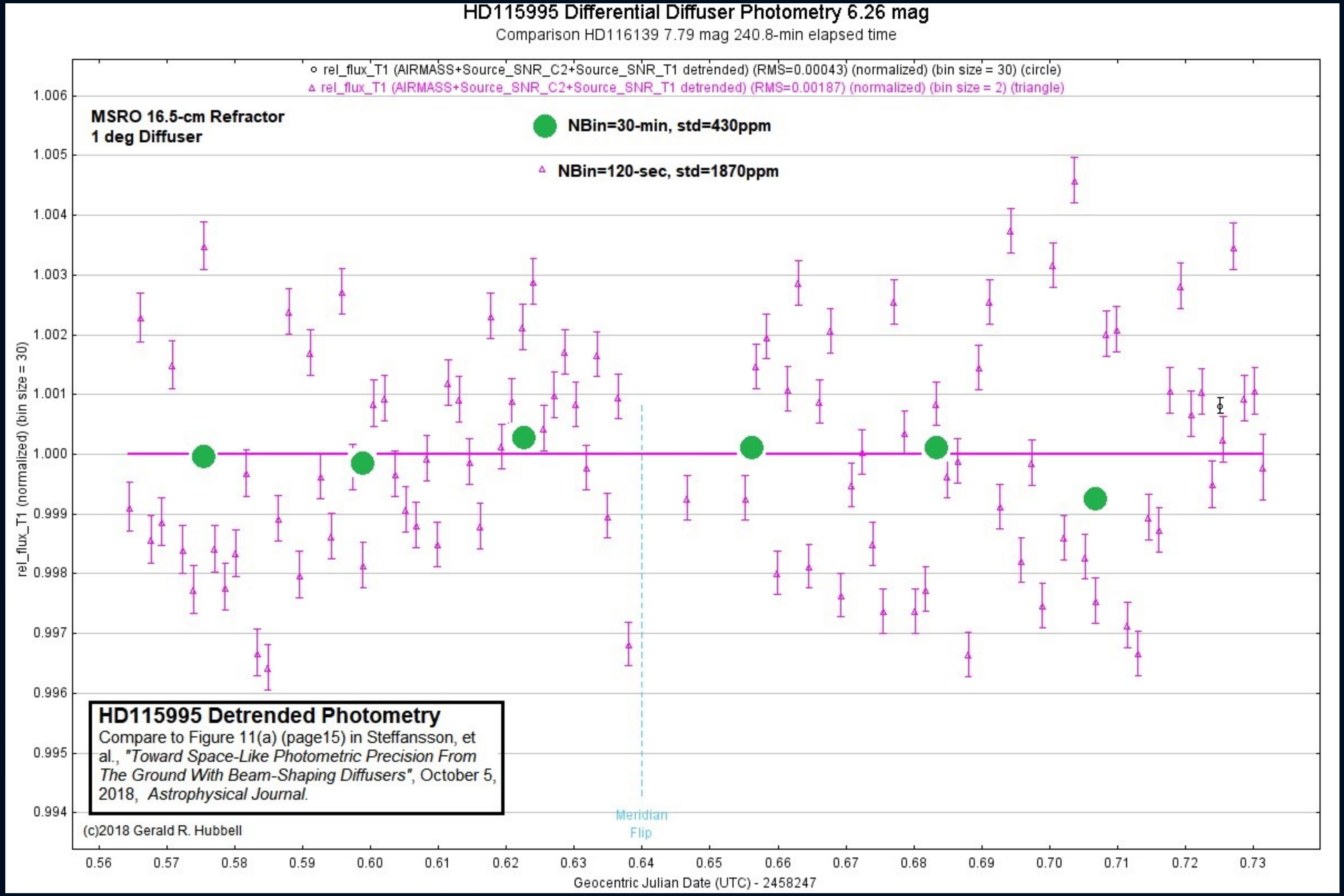
2-minute Exposure Diffuser Performance on 6.3 mag Star 55 Cnc at Penn State

- 144-minute Observing Session
- Shot Noise: ± 0.1 mmag
- Total Scintillation + Shot Noise
- 2-min exp. Result: ±1.124 mmag
- 30-min bin Result: ±0.246 mmag
- Stefansson, et al. paper (2017) page 15, figure 11(a)



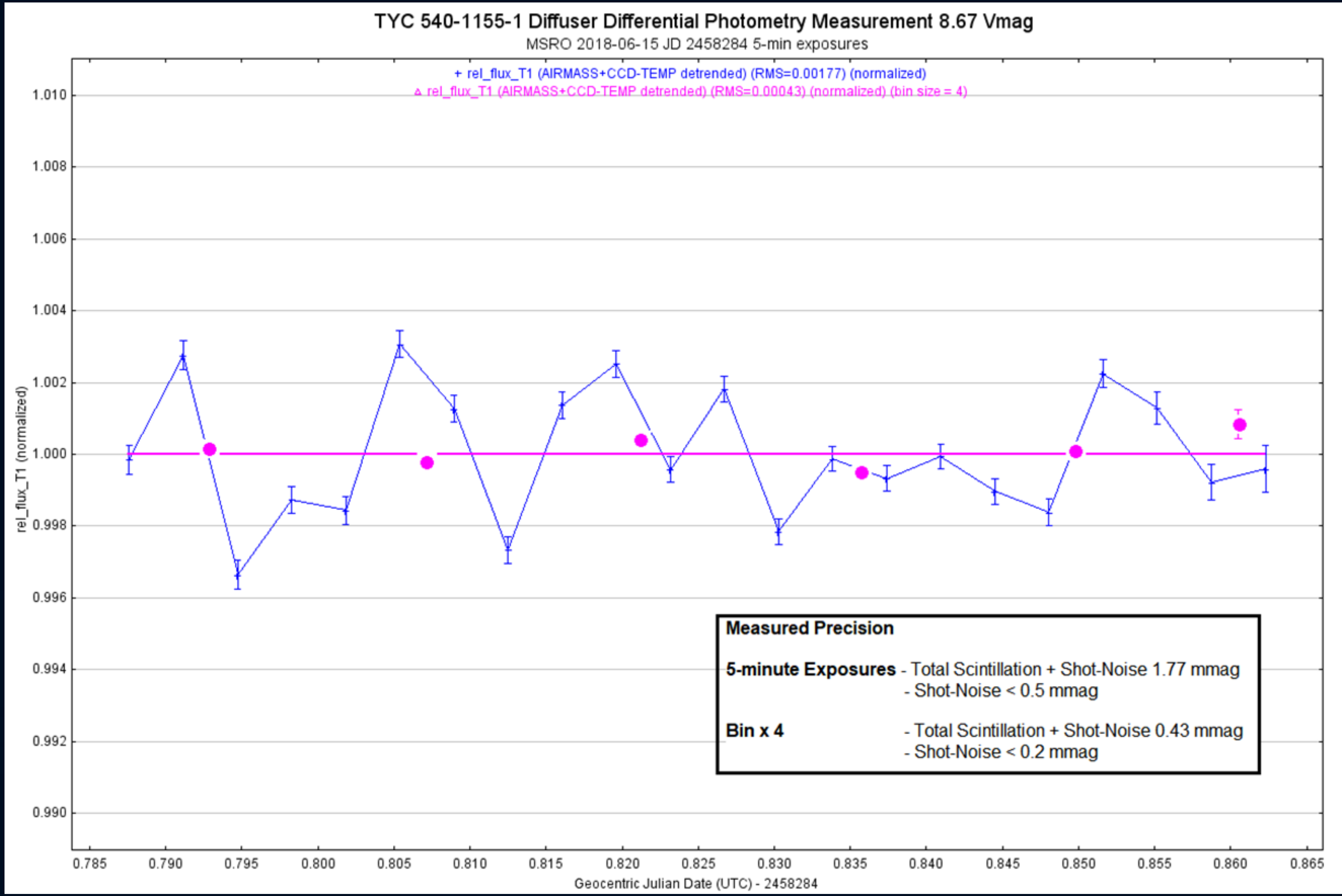
2-minute Exposure Diffuser Performance on 6.3 mag Star 55 Cnc at MSRO

- 241-minute Observing Session
- Shot Noise: ± 0.4 mmag
- Total Scintillation + Shot Noise
- 2-min exp. Result: ±1.87 mmag
- 30-min bin Result: ±0.43 mmag
- Observed 2018 May 8



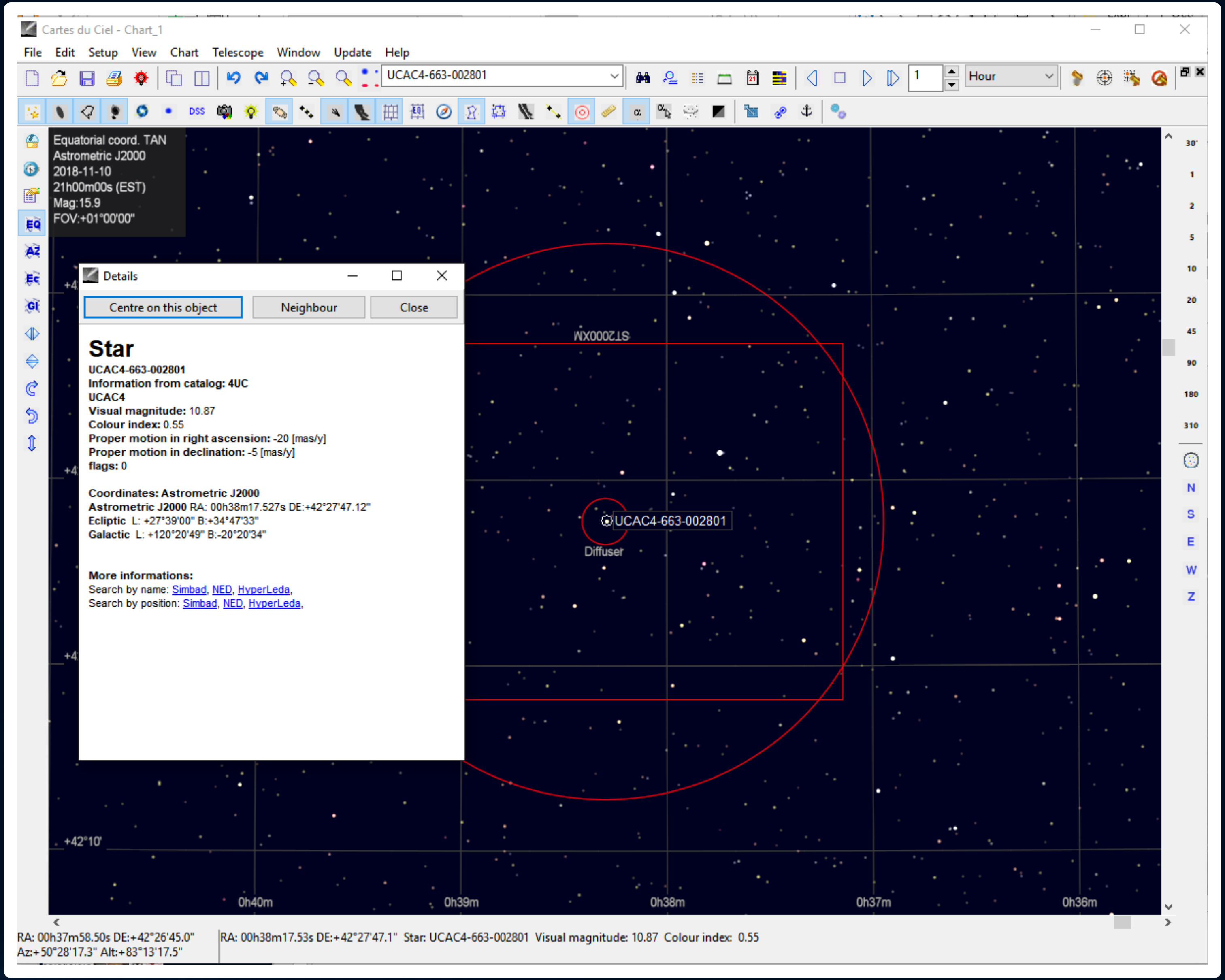
5-minute Exposure Diffuser Performance on a Bright 8.7 mag Star at MSRO

- 110-minute Observing Session
- Shot Noise: ±0.5 mmag
- Total Scintillation + Shot Noise
- 5-min exp. Result: – ±1.77 mmag
- 20-min bin Result: - ±0.43 mmag
- Observed 2018 June 15



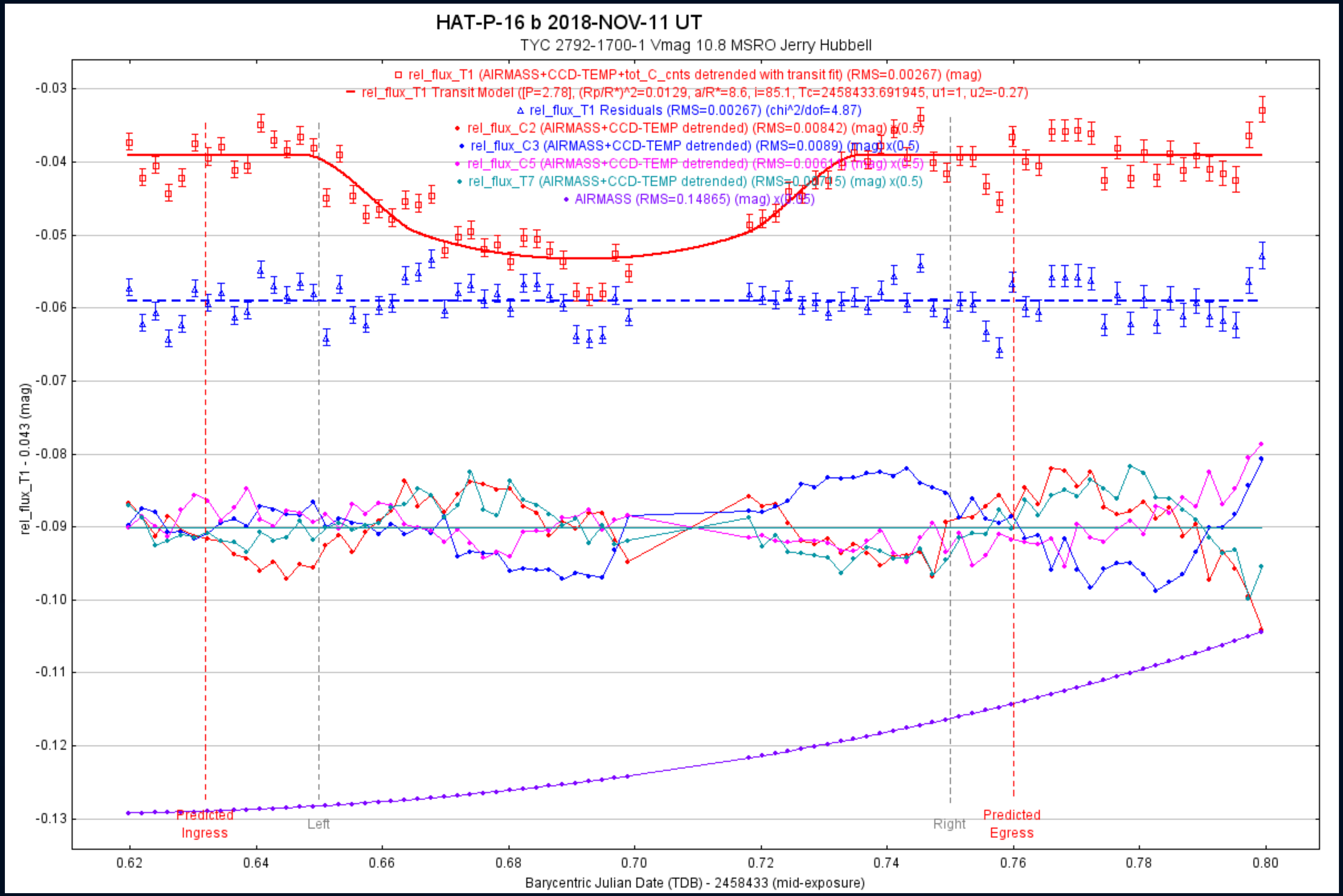
Exoplanet HAT-P-16 b (And) Close-up Chart

- Star TYC 2792-1700-1 hosts exoplanet HAT-P-16 b (And)
- Vmag 10.8
- Expected Transit Depth 10.1 mmag



Exoplanet HAT-P-16 b Observed at the MSRO

- Observed by Jerry Hubbell on November 11, 2018 at the MSRO.
- Measured using the Diffuser Method with a measured transit depth of 12.9 mmag
- Shot Noise Precision: ≈ 1.0 mmag RMS
- Total Scintillation + Shot Noise Precision: ≈ 2.7 mmag RMS



Modeling Results for Exoplanet HAT-P-16 b

Parameter	Catalog Value	Measured Value
Rjup	1.29 ± 0.065	1.19
Orbital Inclination	86.6° ±0.7	86.31°
Transit Depth	11.47 ±0.30 mmag	10.76 ±0.33 mmag
Transit Midpoint BJD	2458433.69585 ±0.0037	2458433.6921
Transit Length	02h 07m 42s	02h 04m 28s

The Pros and Cons of the Defocus Method vs. the Diffuser Method

- In our study, we have been able to establish that using the Diffuser Method , as described in the Stefansson, et al. paper, for high-precision photometry can reduce the shot noise to ≤ 1 mmag RMS. This helps to ensure a scintillation limited observation.
- A highly tuned AIS using an OTA with a central obstruction and an effective auto-guiding system will provide observations that are scintillation limited in good to excellent skies (high transparency , no moon). Using the Defocus Method with this system will provide results similar to those obtained using the Diffuser Method

The Pros and Cons Between the Defocus Method and the Diffuser Method

- The Diffuser Method is best suited to those who wish to perform high-precision measurements of exoplanets without an auto-guiding system where you have some drift due to Periodic Error (PE) and you need to align the images after the fact. An excellent physical polar alignment is suggested in this case so that the only drift is due to your mount's PE.
- We have also found that using the Diffuser Method will ensure that the observation is Scintillation Limited and will help to minimize the amount of total scintillation measured.
- Using the Diffuser Method will also mitigate the impact of lower transparency and when the moon is up during the observation.

Questions/Comments ??

Contact Information

- Email:
  hubbell_jerry@yahoo.com
- MSRO Webpage :
  https://www.raclub.org/MSRO/
- MSRO Facebook Page :
  https://www.facebook.com/remotetelescope/
- Explore Scientific Webpage:
  ExploreScientificUSA.com
- ES Facebook:
  https://www.facebook.com/ExploreScientificUSA/