

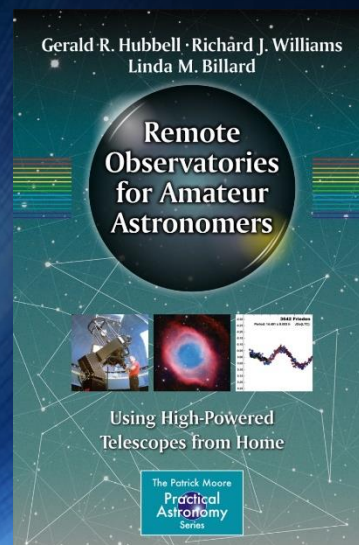
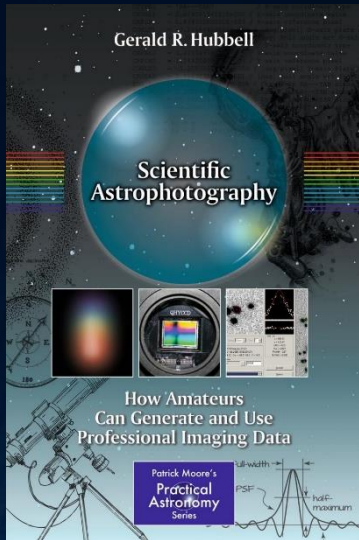
# High-Precision Photometry for Exoplanet Observations

NEW TECHNIQUES FOR PERFORMING HIGH-PRECISION PHOTOMETRIC  
MEASUREMENTS OF EXTRA-SOLAR PLANETS, MINOR PLANETS,  
AND VARIABLE STARS USING SMALL TELESCOPES

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VICE PRESIDENT OF ENGINEERING, EXPLORE SCIENTIFIC, LLC.

# Introduction – Jerry Hubbell



- **Jerry Hubbell** is currently the Vice President of Engineering for Explore Scientific, LLC. and the Principle Engineer heading the team on the development of the PMC-Eight™ mount control system.
- Retired Dominion Nuclear Instrumentation and Controls Engineer with over 35 years of experience in the Nuclear and Electric Utility business.
- The Assistant Director for the Mark Slade Remote Observatory (MSRO).
- The Assistant Coordinator for Topographical Studies, Lunar Section of the Association of Lunar and Planetary Observers (ALPO).
- Author of 2 books published by Springer Books and available on Amazon.com. *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)

# Presentation Topics

- Quick Overview of Photometry and Doing Photometric Measurements
- Why Do High-Precision Photometry?
  - Exoplanet Observations by Amateur Astronomers
  - Follow-up Ground Based Exoplanet Observations
  - High-Precision Minor Planet Light-curve Measurements
  - High-Precision Variable Star Light-curve Measurements
- High-Precision Photometric Measurement Errors
  - Sources of Photometric Measurement Errors
  - How to Minimize the Total Photometric Measurement Error



# Presentation Topics

- New Instruments and Techniques for Doing High-Precision Photometry
  - Defocus Method
  - Diffuser Method
- MSRO Diffuser Instrument Test Program
- TESS Follow-up: Ground-based Observations
- QUESTIONS?

# Quick Overview of Photometry and Doing Photometric Measurements

- Astronomical Photometry is the measurement of the brightness of celestial objects
- In the 1970's amateur astronomers used analog photoelectric photometers (scintillation tubes) with a fixed aperture size to measure stellar object brightness.
- In the mid 1990's professional techniques using CCD cameras were adopted by amateurs and software was developed for PC's to do the required analysis.

# Quick Overview of Photometry and Doing Photometric Measurements

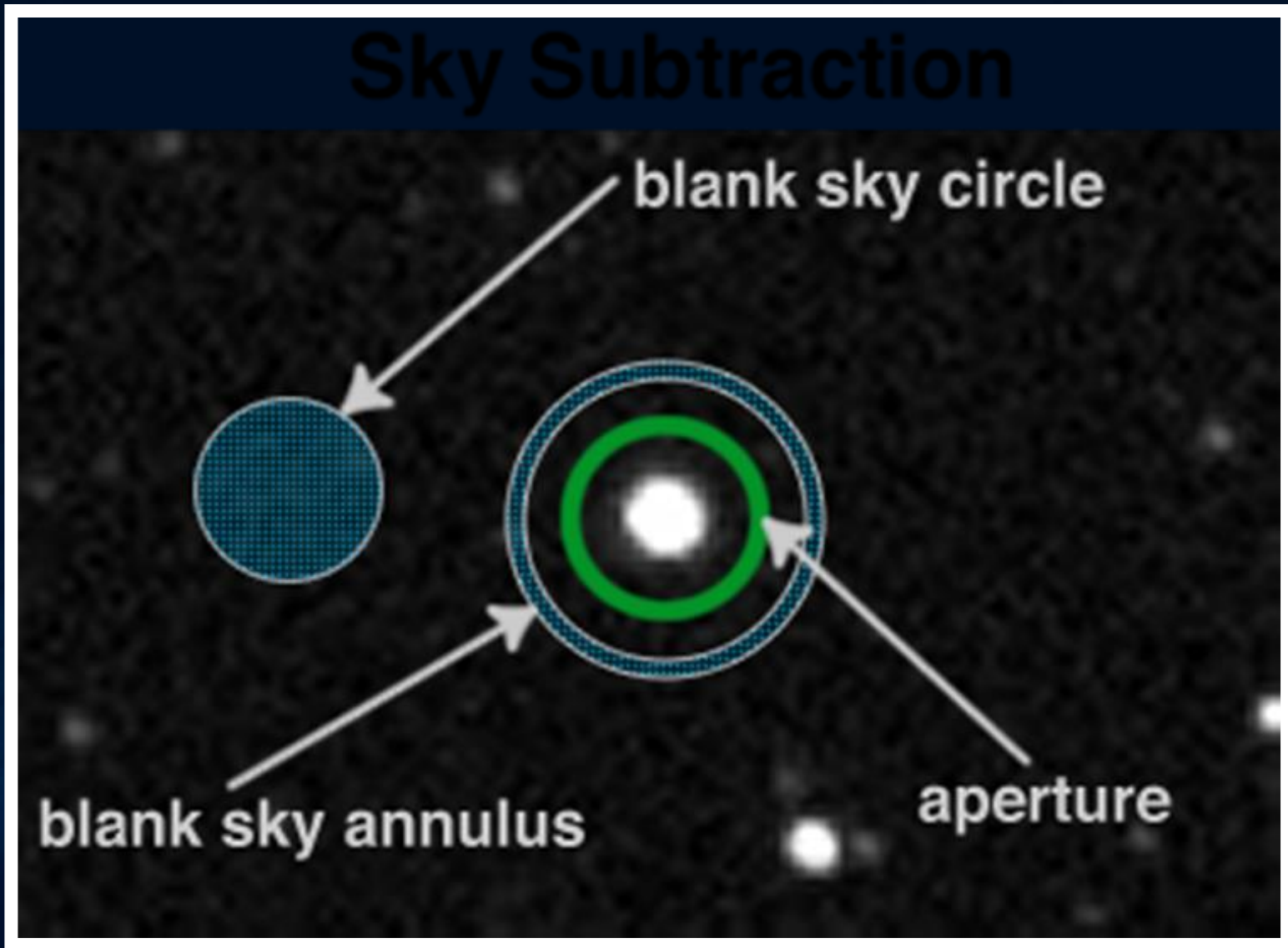
- The original idea using the photoelectric photometer was to measure a circular area encompassing the star, known as the aperture, and subtract the measured value of the sky background with the same aperture. This general technique became known as Aperture Photometry.
- The simplest type of Aperture Photometry is Differential Aperture Photometry. This is where you measure 2 objects, assuming the comparison object is of fixed brightness, and subtract the Target Object from the Comparison Object brightness.
- This Differential measurement takes care of any small changes that occur between samples by assuming that each frame is small enough to see the change occur for the Target Object and the Comparison Object.

# Quick Overview of Photometry and Doing Photometric Measurements

- In the 1970's amateur astronomers used analog photoelectric photometers (scintillation tubes) to perform Aperture Photometry.
- In the mid 1990's professional techniques using CCD cameras to perform Aperture Photometry were adopted by amateurs and software was developed for PC's to do the required analysis.

# Aperture Photometry

Aperture diagram showing object aperture, sky aperture, and object annulus for measuring the sky background and object brightness.



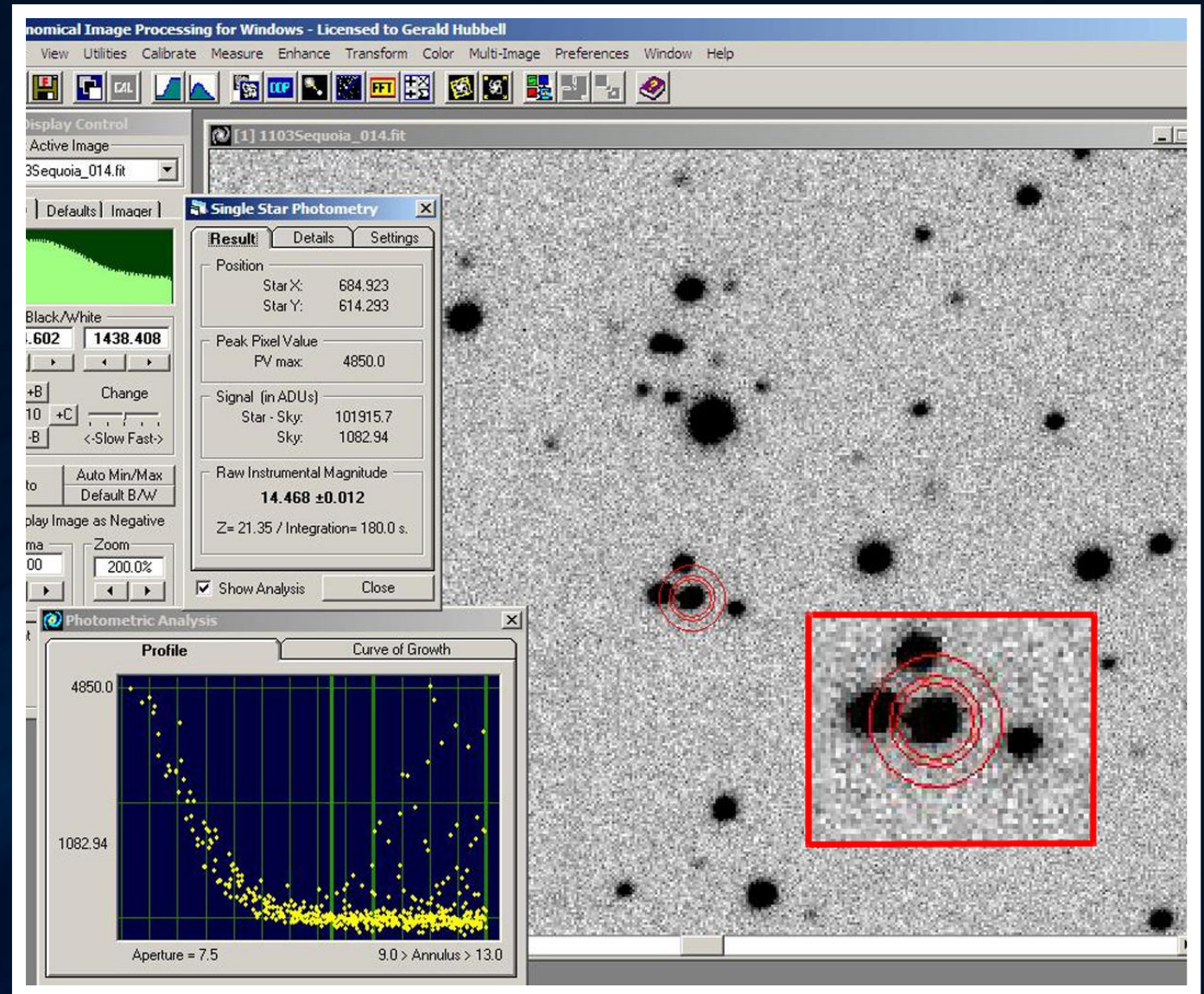


# Quick Overview of Photometry and Doing Photometric Measurements

- The Aperture Photometry technique was changed when CCD imaging was adopted to make the measurements more accurate.
- There were 2 major changes to the technique when CCD imaging was adopted:
  - Instead of using a background aperture that could be located anywhere on the image, a background annulus was used to capture the local background signal to the object being measured.
  - Image calibration data was also applied to the data (light) frames to further refine the accuracy of the measurement when using CCD cameras.
- Once light frames are calibrated then the observer can do the measurement of the star brightness in ADU counts by subtracting the annulus value from the object aperture value.

# Photometric Measurement of a Minor Planet

This is an example of a measurement of the brightness of a minor planet using an analysis tool



# Quick Overview of Photometry and Doing Photometric Measurements

- This general technique is applicable to measuring point-source celestial objects including Stars, Minor Planets, and Exoplanets.
- This general technique is the starting point for refining and improving the accuracy of the measurement
- For best results you should use an astronomical imaging camera that include a Thermo-Electric Cooling (TEC) system and is a monochrome camera that DOES NOT have a Color Filter Array (CFA) installed.
- For specific scientific measurements, broadband or narrowband filters may be placed in front of the imaging chip. A V-Band filter is a very common filter used in photometric measurements



# SBIG ST<sub>2000</sub>XM CCD TEC camera on Main Instrument at MSRO

This shows the main imaging camera at the MSRO. This system is a Thermo-Electrically Cooled camera system with integrated filter wheel system.





# Why Do High-Precision Photometry?

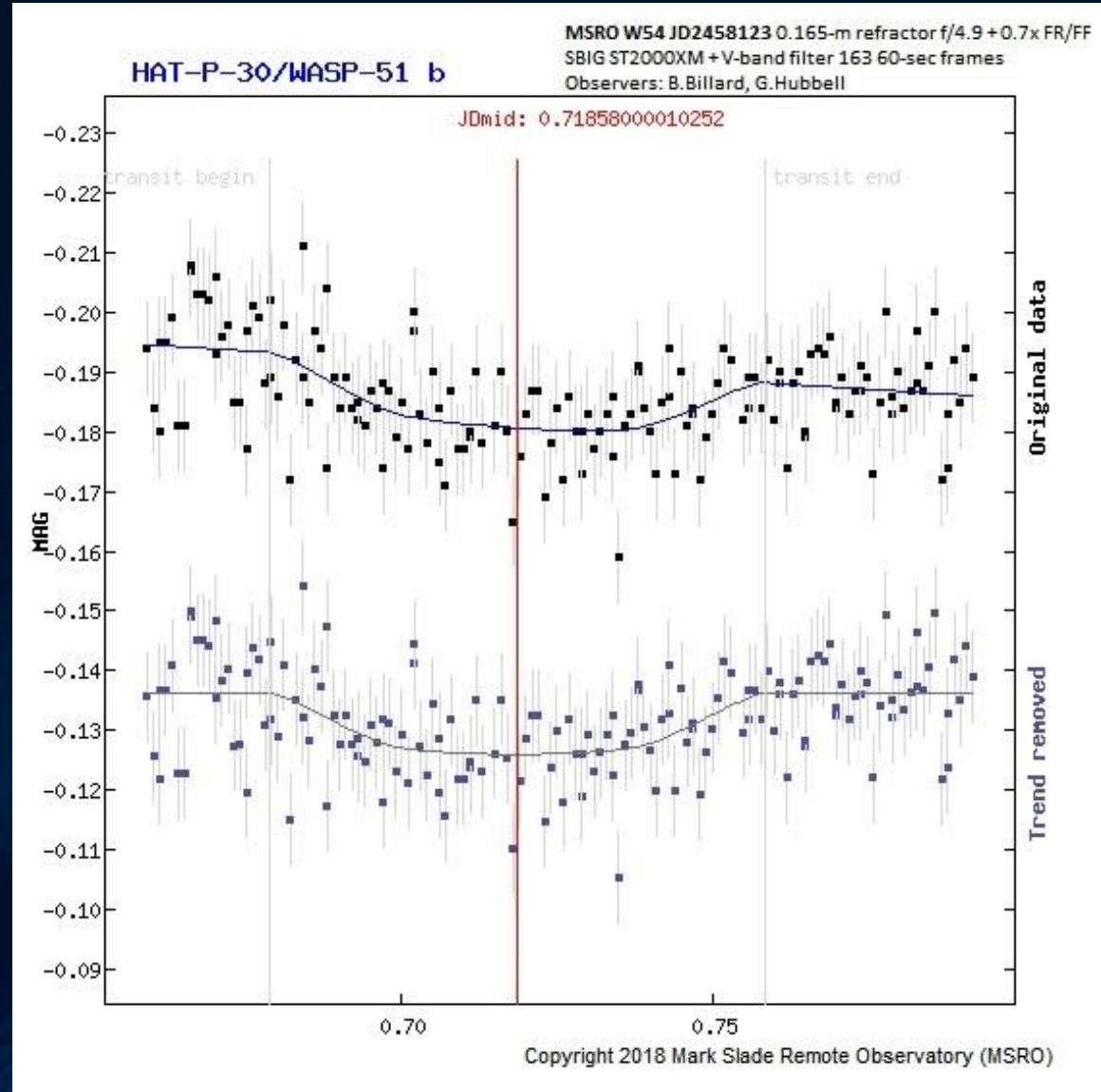
- High-Precision Photometry is defined as a higher precision object brightness measurement using enhanced instruments or techniques, or both.
- The long-held standard for amateur photometric measurements is to obtain a precision of  $\pm 0.01$  mag or about 1% error.
- High-Precision Photometry is defined as obtaining a total precision of less than half of that, or  $< \pm 0.005$  mag or as it is also known as: milli-mag error. 1 milli-mag is equal to  $\pm 0.001$  mag or  $1/1000$  mag.
- The main reason for doing High-Precision Photometry is to detect object light-curve variations at the milli-mag level.
- This is necessary when doing photometric measurements of Exoplanets, Variable Stars, and Minor Planets.

# Exoplanet Observations by Amateur Astronomers

- Exoplanet observations made by amateurs use the Transit Method. In this method we watch for the Exoplanet to pass in front of its parent star.
- Most Exoplanets discovered orbit stars that are magnitude 7 – 15. Of these, amateurs can observe Exoplanet transits around stars in the 7 – 10 magnitude range.
- Jupiter size exoplanets provide a signal change of at least 1% which is typically the amount of error for an amateur observation.
- To not just detect, but to measure accurately the time of ingress, mid-point, and egress of an exoplanet, and also the depth of the transit, a high-precision measurement must be performed.

# MSRO HAT-P-30/ WASP-51 b Exoplanet Observation

The observation of exoplanet HAT-P-30/WASP-51 b by Bart Billard and Jerry Hubbell in January 2018 using the MSRO Main Instrument.



# Follow-Up Ground Based Observations of Exoplanets

- There is a need for ground based follow-up observations of NASA Mission observations for the Kepler and the recently launched TESS Missions.
- These follow-up observations will rely on professionals with the large telescopes, but also on those interested and capable amateur astronomers with the equipment, skills, and knowledge of how to perform these observations and also analyze the data gathered during these observations



# High-Precision Minor Planet Light-curve Measurements

- There is also a need for improved Minor Planet light-curve measurements to further refine their 3D shape models and rotation rates to further characterize the population.
- These high-precision measurements will allow amateurs to demonstrate the value that we can bring to the study of the formation of the solar system.

# High-Precision Variable Star Light-curve Measurements

- Doing High-Precision Variable Star measurements will allow you to detect and measure the small fluctuations in a star's brightness to detect star spots, and other stellar behaviors that could give you further insight into the life-cycle of stars.
- These high-precision measurements will also allow amateurs to demonstrate the value that we can bring to the study of the formation of these stars and perhaps their local star systems.

# High-Precision Photometric Measurement Errors

- High-Precision Photometric Measurement Errors determine how precise we need to be in our measurements to not only detect, but accurately measure any small fluctuation on the light from the star or minor planet that we are observing. The measured error is also referred to as the uncertainty of the measurement.
- There are several different sources of error in our measurement, but there are 3 primary sources of the total error (uncertainty):
  - Poisson or Shot-Noise Error
  - Residual Calibration Noise Error
  - Scintillation Error

# High-Precision Photometric Measurement Errors

## Poisson or Shot-Noise Error

- This error is a calculated, statistically determined error value and is the result of measuring any randomly generated signal from a radiation source. The Shot-Noise Error value is calculated by taking the square-root of the measured signal, i.e., If a given CCD pixel collected 63,339 photons then the Shot-Noise Error is equal to  $\sqrt{63,339}$  or  $\pm 252$  photons. As a percent of value, the error is equal to about  $\pm 0.4\%$
- When summing all the pixels within a given aperture size, for high-precision photometry, the object photon signal should be as large as  $10E7$  or 10 million photons. This large number of photons will (theoretically) result in a small Shot-Noise Error value of about 0.0003 mag, or 0.3 milli-mag
- The actual measured value for the Shot-Noise Error includes the Residual Calibration Error Value and will be determined at the time of measurement.



# High-Precision Photometric Measurement Errors

## Residual Calibration Noise Error

- This error is determined from each image sample and changes based on the image exposure time.
- This error is not calculated, but can be determined independently of the other 2 errors; Shot-Noise and Scintillation Noise. To estimate this error you would measure the variation over several Flat calibration frames which include the impact of readout noise and thermal noise in the frame.
- This error basically sets the minimum noise value that will impact your measurement and is only as good as your image calibration data.

# High-Precision Photometric Measurement Errors

## Scintillation Error

- Scintillation is variation of the brightness of the star over both short term and long term time frames.
- This error is caused by the external environmental factors that cause the light from the object to move and vary in brightness, and size on the CCD chip. These factors include atmospheric refraction, haze or transparency changes across the image frame and also clouds in the sky.
- This motion causes the light to fall on different pixels on the image plane effecting the measured brightness value. When different pixels are used to measure the brightness of the object, you need to take into account the variation in each of the pixel calibrations and the small differences between pixel's calibrated values.

## High-Precision Photometric Measurement Errors

- These errors are not measured directly to correct for them in the High-Precision Photometry techniques developed and used at the MSRO. The values measured from all the calibrated frame data samples is first grouped into 2 categories:
  - Short Term Scintillation Value
  - Long Term Scintillation Value

## High-Precision Photometric Measurement Errors

- The Short Term Scintillation Value for each image is used to determine an equivalent of the measured Shot-Noise Error added to the Residual Calibration Noise Error. This error value is minimized by measuring the light spread out over a large number of pixels.
- The Long Term Scintillation Value is determined from all the measured Short Term Scintillation values over the session time frame, typically several hours for Exoplanet observations.
- The Long Term Scintillation Value is the statistical Standard Deviation of all the measured values. This error value is indicative of the changes in the local sky conditions due to haze, and high-altitude clouds.



# High-Precision Photometric Measurement Errors

## Spreading The Light for Greater Shot-Noise Precision

- Spreading the light over many pixels minimizes the total Shot Noise and Residual Calibration Noise errors via averaging as compared to a normal measurement using a focused object image.
- A properly focused image of a typical star displays an image profile called the Point-Spread Function (PSF). This PSF is a Gaussian Shaped profile.
- A typical number of pixels that the PSF covers when focused is about 20 for a FWHM value of 5 pixels. If you spread out the pixels to a diameter of 25 pixels, you are using a total of 490 pixels or 245 times more pixels. The average over this larger number of pixels reduces the error by a factor of  $\sqrt{245}$  or by about 16 times.

# How to Minimize the Total Photometric Measurement Error

## Total Error or Measured Precision

- For an Exoplanet Transit measurement the Total Error or Measured Precision of the observation is made up of 2 parts:
  - The Sample Precision – This is the summation of the individual Shot Noise error and the Short Term Scintillation with the Residual Calibration error included
  - The Exoplanet Depth Measurement Precision – This is the amount of scatter in the individual sample measurements as calculated for all the samples in the observation. This is the Standard Deviation of the sample scatter.
- To further increase the precision of the Exoplanet Depth Measurement, the samples can be binned by a given factor, typically 5, 10, or up to 30 samples depending on how many total samples are obtained. This will decrease the error by a factor of the square root of the binning value.

# How to Minimize the Total Photometric Measurement Error

- To minimize the Total Photometric Measurement Error it is necessary to balance the need for minimizing the Shot Noise with the amount of pixels averaged when spreading the light of the object out on the CCD chip with the amount of Scintillation Noise from the Environmental factors.
- To maximize the Sample Precision you should average the light over as many pixels as possible without sacrificing the number of comparison stars on the image due to spreading the light of dimmer stars too thin.

# New Instruments and Techniques for Doing High-Precision Photometry

- At the MSRO we are developing new instruments and techniques to further improve the precision of the photometry of exoplanets, stars, and minor planets.
- There are 2 ways to increase the Shot Noise precision:
  - Defocus Method
  - Diffuser Method
- The Defocus Method has been around for a long time and can be used to spread the light of the object over a large number of pixels to minimize the Shot Noise error and to minimize the chances of saturating any pixels for brighter objects.
- The Defocus Method does not mitigate the effects of tracking error on the amount of Residual Calibration Error on the CCD image.

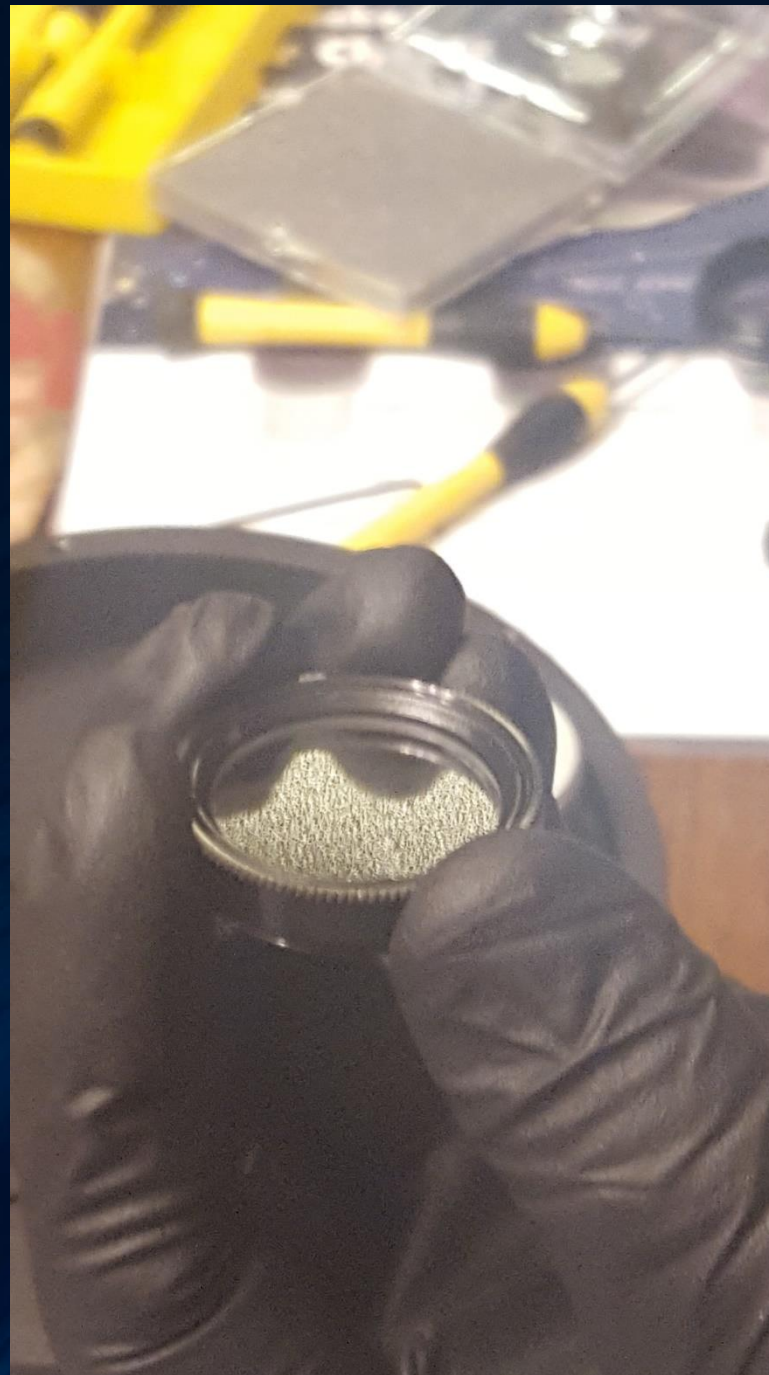


# New Instruments and Techniques for Doing High-Precision Photometry

- The Diffuser method uses a special type of diffusing element that improves upon the defocus method for maximizing the precision by minimizing the Shot Noise Error.
- The diffusing element also helps to minimize the effects of tracking error that can limit the precision of the measurement because of the impact of Residual Calibration Errors.
- RPC Photonics has developed an Engineered Diffuser™ for this purpose based on research documented in the paper "*TOWARDS SPACE-LIKE PHOTOMETRIC PRECISION FROM THE GROUND WITH BEAM-SHAPING DIFFUSERS*"
- <https://arxiv.org/pdf/1710.01790.pdf>

# Engineered Diffuser™

The RPC Photonics 0.5 degree Engineered Diffuser™ installed in the SBIG ST2000XM Filter Wheel.



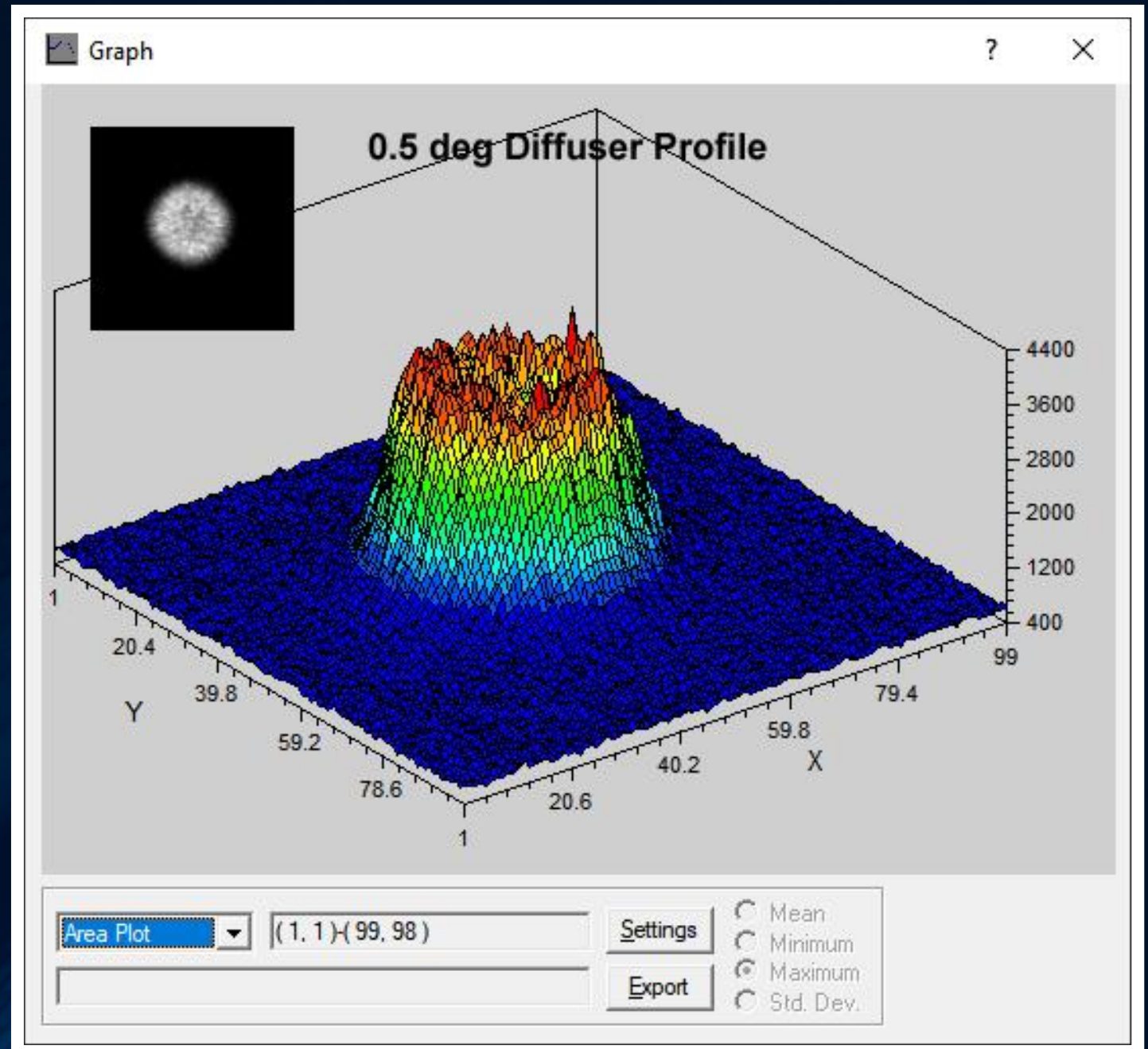
# New Instruments and Techniques for Doing High-Precision Photometry

- The Diffuser creates an alternative Point Spread Function profile that resembles a “Top Hat” versus the standard Gaussian profile that the Defocus method provides.
- This “Top Hat” profile further reduces the impact of tracking errors over a session lasting several hours, and also mitigates the impact of a “meridian flip” when using a GEM mount and re-acquiring the target after passing the meridian.
- Additionally, there is no need to refocus the camera when flipping between a standard, or no filter and the diffuser as the diffuser can tolerate a large change in focus position with no impact to the object profile.



# Engineered Diffuser™ Image Profile

This shows the Point Spread Function profile of a star when using the Engineered Diffuser™. This shows the typical “Top Hat” profile expected when using this instrument.





## MSRO Diffuser Instrument Test Program

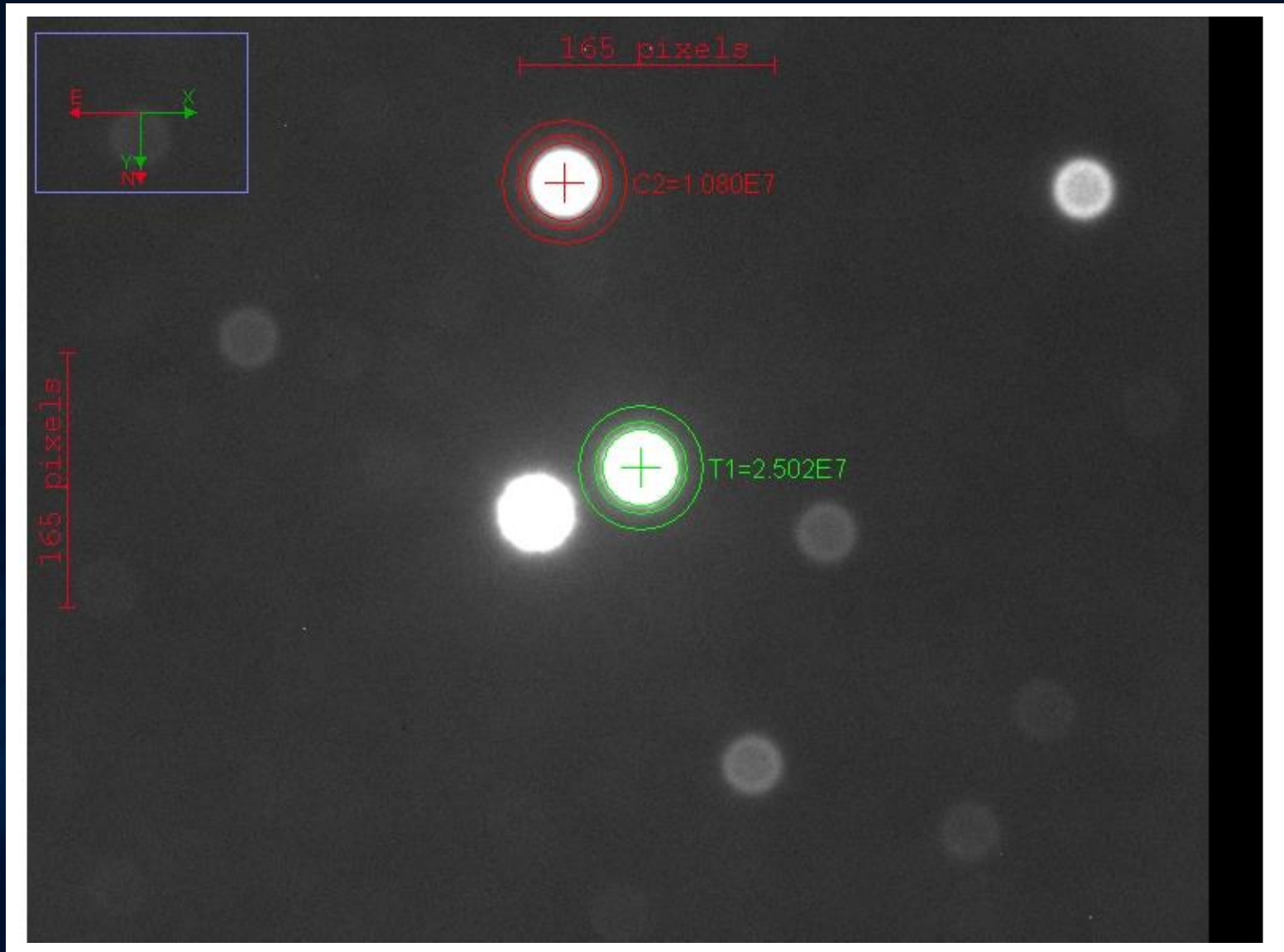
- Dr. Myron Wasiuta, Dr. Bart Billard, and Jerry Hubbell have been conducting a test program on the Engineered Diffuser™ instrument since May 2018. Several observing sessions using the diffuser have been completed and the final results of the test program are being compiled for publications.
- The diffuser test program has been conducted with the assistance of the AAVSO Exoplanet Program manager Dr. Dennis Conti. Dennis Conti is a designated NASA TESS Mission liaison to the amateur community and supports amateurs in their exoplanet observations
- Bart and Jerry completed the AAVSO Exoplanet Observation Training in March 2017 given by Dr. Dennis Conti.

## MSRO Diffuser Instrument Test Program

- The goal of the Diffuser Instrument Test Program is to validate the use of the diffuser by observing fixed, variable, and exoplanet stars and to develop and test procedures for acquiring high quality data.
- Through the observation of fixed, non-variable stellar sources, the amount of error and the improvement of the precision of the photometric measurements can be determined.
- It was hoped that an improvement of up to a factor of 5 from a precision of 1% or 10 milli-mag, to a precision of 0.2% or 2 milli-mag would be demonstrated through the use of the diffuser system.

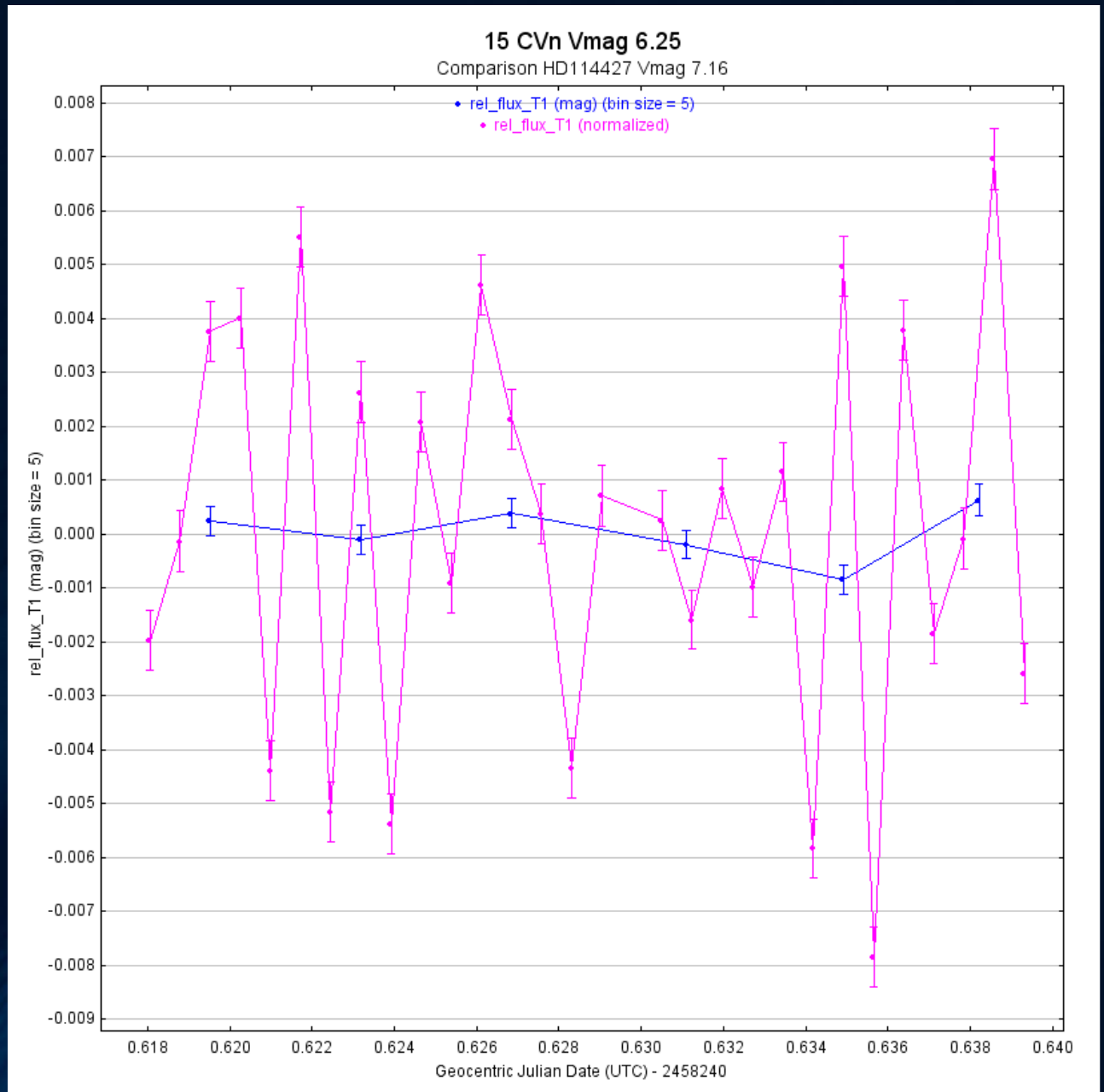
# Light-Curve Measurement of 15 CVn

High-Precision Photometric  
measurement of star 15 CVn by  
Jerry Hubbell on 02 May 2018



# Light-Curve Measurement of 15 CVn

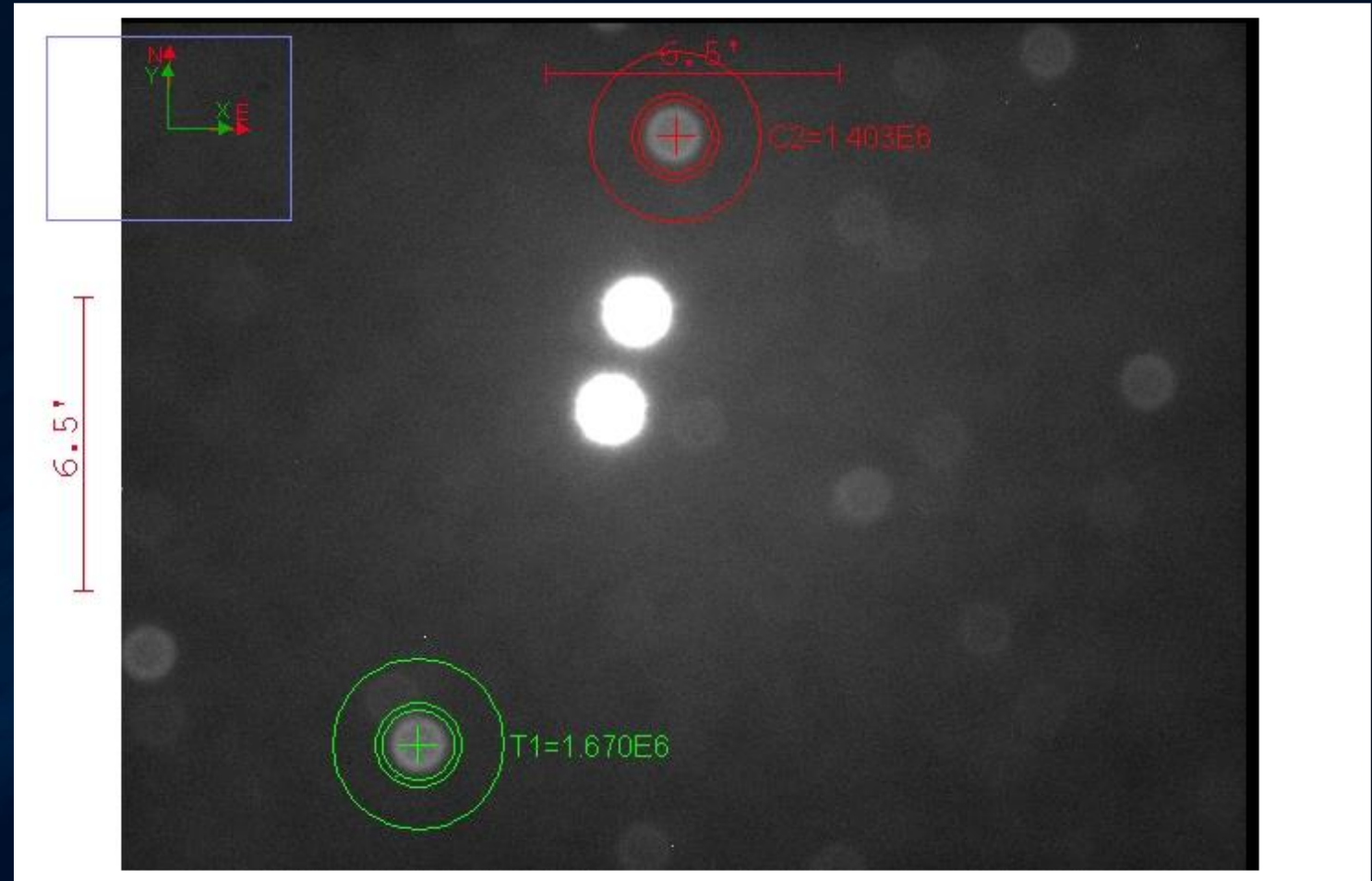
High-Precision Photometric  
measurement of star 15 CVn by  
Jerry Hubbell on 02 May 2018





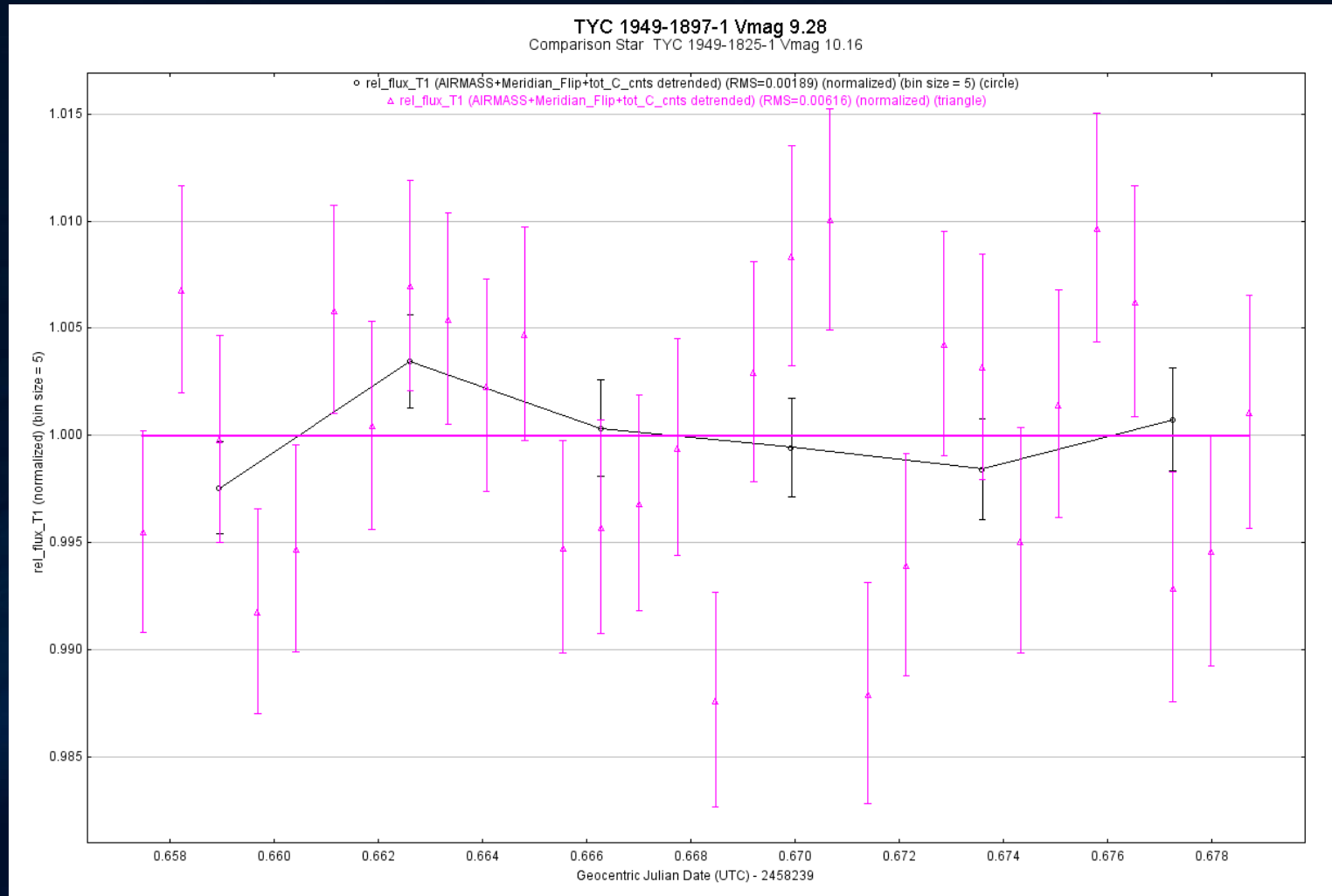
# Light-Curve Measurement of Star TYC 1949- 1897-1

High-Precision Photometric  
measurement of star TYC 1949-  
1897-1 by Jerry Hubbell on 01 May  
2018



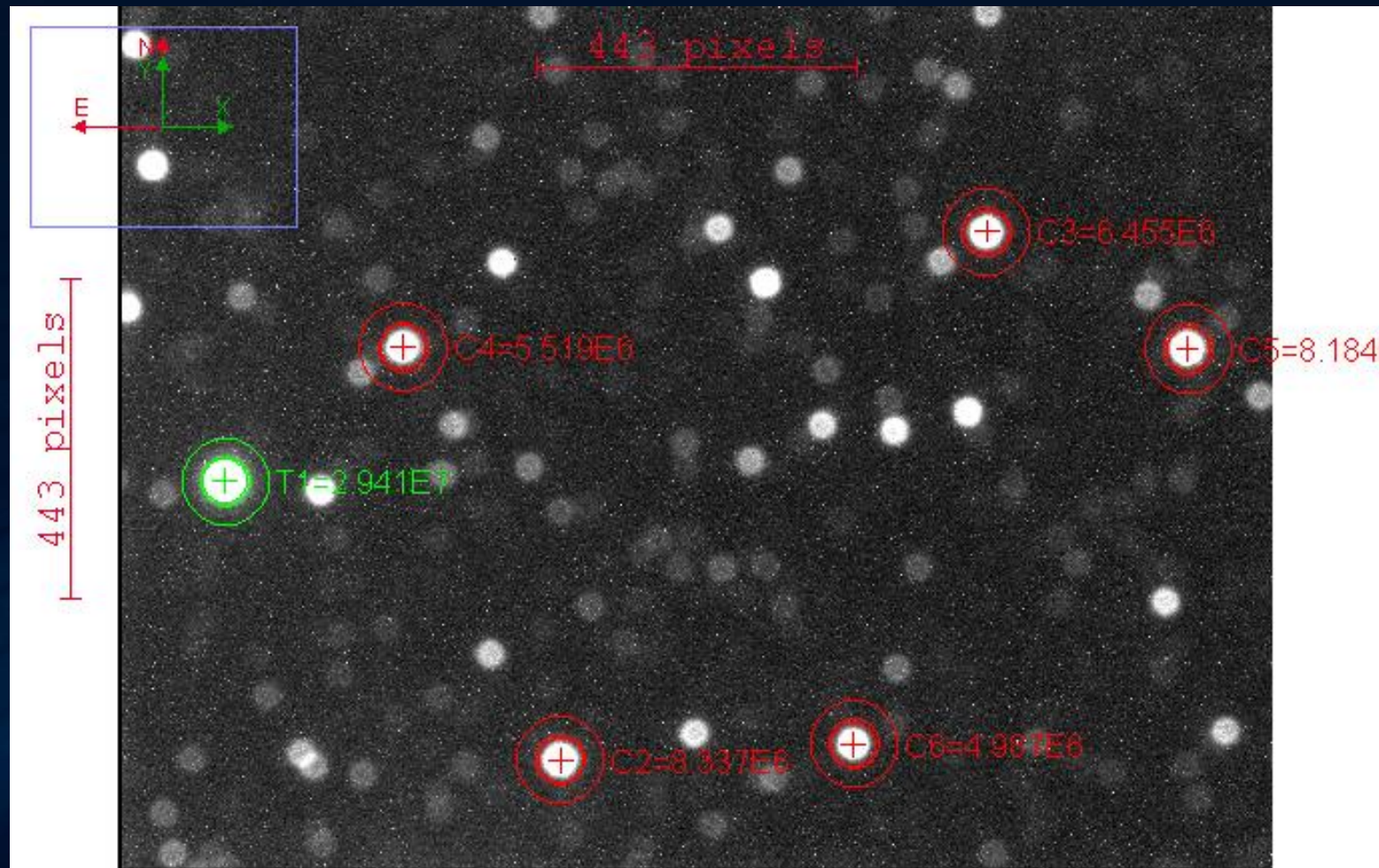
# Light-Curve Measurement of Star TYC 1949-1897-1

High-Precision Photometric measurement of star TYC 1949-1897-1 by Jerry Hubbell on 01 May 2018



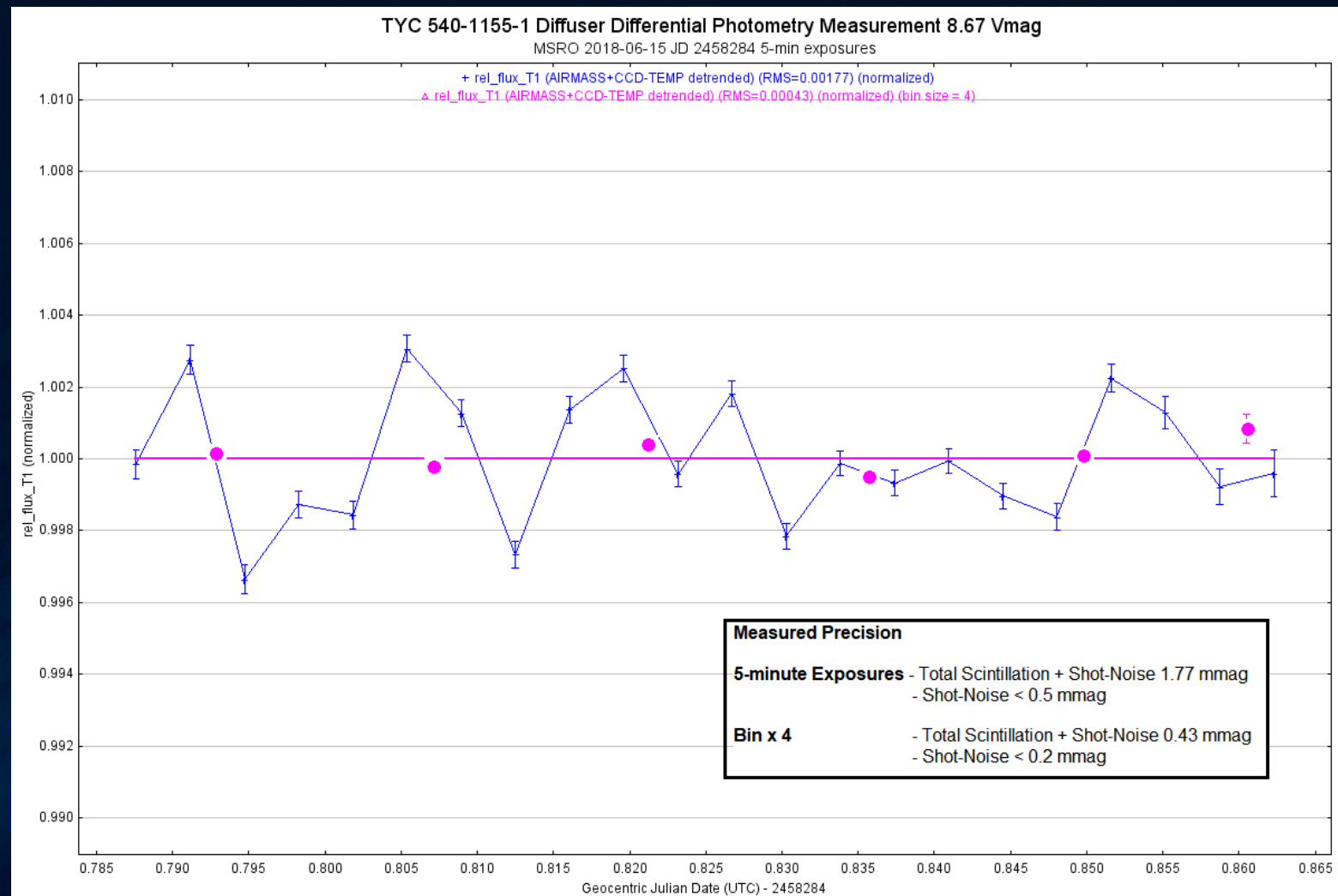
# Test Results from observing TYC 540-1155-1

TYC 540-1155-1 Sample Image  
showing Target and Comparison  
Stars.



# Test Results from observing TYC 540-1155-1

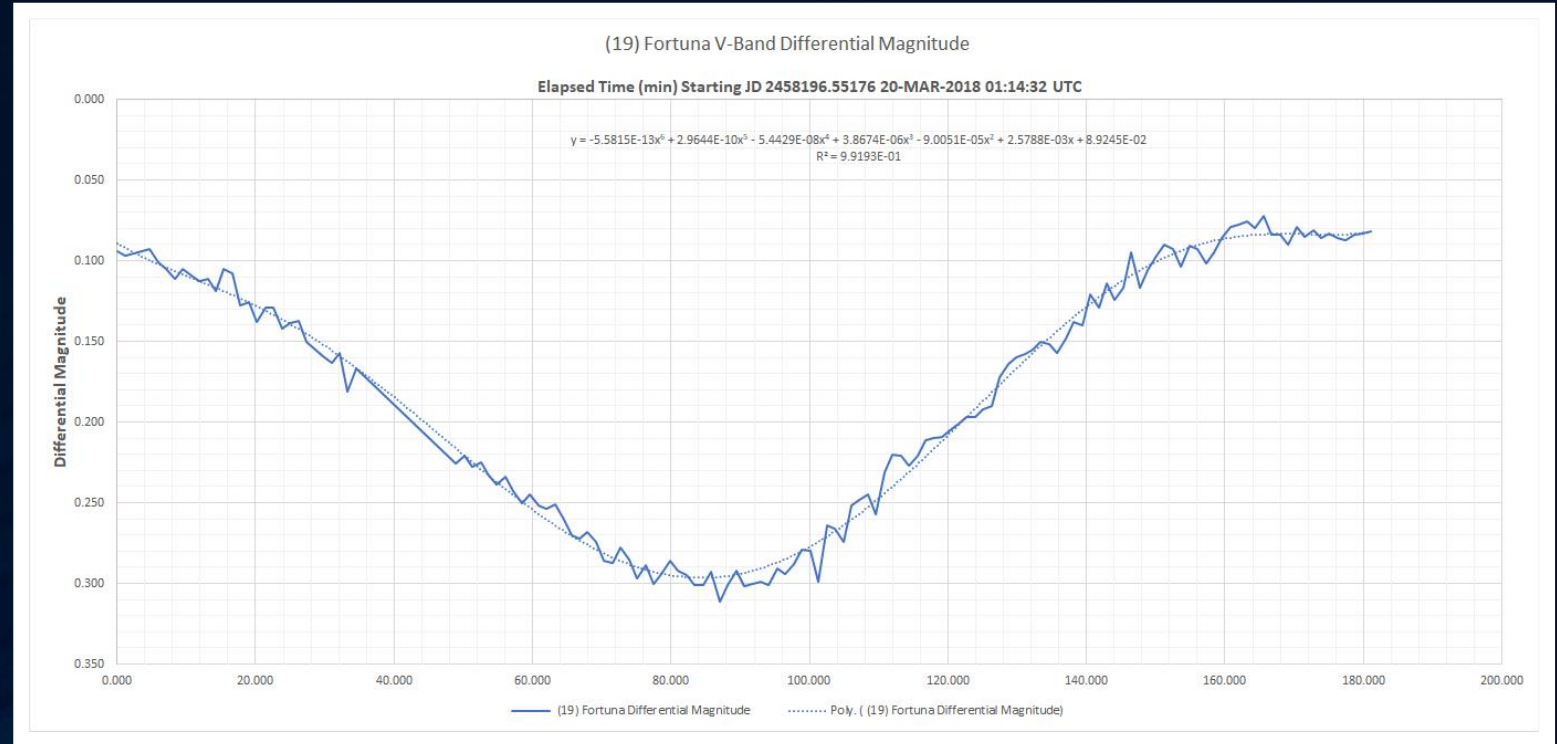
Total Scintillation + Shot Noise  
5-min exp. Results –  $\pm 1.77$  mmag  
4x binning Results -  $\pm 0.43$  mmag





# Light-Curve Measurement of Minor Planet (19) Fortuna

High-Precision Photometric  
measurement of Minor Planet (19)  
Fortuna by Jerry Hubbell on 20  
March 2018



## TESS Follow-up: Ground-based Observations

- The Transiting Exoplanet Survey Satellite Mission was developed and launched as a follow-up to the KEPLER Exoplanet Mission.
- The main goals of the TESS mission are to:
  - Perform an all sky survey to monitor stars that are 30-100 times brighter (up to 6 magnitudes) than the KEPLER mission
  - Monitor up to 200,000 stars that can provide bright candidates for further characterization via ground based follow-up observations
  - Partner with Amateur Astronomers for follow-up work to be able to process the very large amount of data that is expected from the mission.
- Dr. Dennis Conti is the AAVSO TESS Follow-Up Coordinator and will mentor those who wish to learn how to observe Exoplanets.



# Transiting Exoplanet Survey Satellite

## Launch Vehicle



- SpaceX Falcon 9 Full Thrust
- High Earth Orbit (HEO)

## Observatory



- Orbital LEOStar-2
- Instrument-in-the-loop attitude control

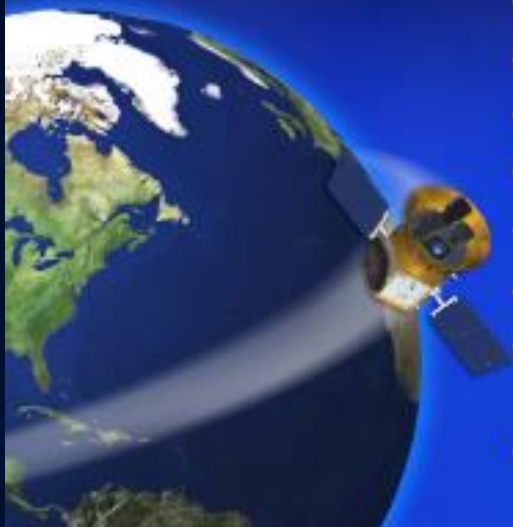
## Science Instrument



- Four Wide Field-of-View CCD Cameras
- 24°x 24° Field-of-View
- Well defined spacecraft interfaces

## Project Overview

- Transiting exoplanet discovery mission
- 2 month Commissioning period
- 2 year all-sky survey (3 year science mission)
- Identifies best targets for follow-up characterization
- Deep Space Network (DSN) primary support
- Category II, Class C
- Launch Readiness Date: March 2018
  - Agency Baseline Commitment: June 2018
- PI Cost Cap: \$228.3 M (RYS)





## TESS Follow-up: Ground-based Observations

- The Transiting Exoplanet Survey Satellite (TESS) will discover thousands of exoplanets in orbit around the brightest stars in the sky. In a two-year survey of the solar neighborhood, TESS will monitor more than 200,000 stars for temporary drops in brightness caused by planetary transits. This first-ever spaceborne all-sky transit survey will identify planets ranging from Earth-sized to gas giants, around a wide range of stellar types and orbital distances.
- <https://tess.gsfc.nasa.gov/>



## Q&A

- Questions, Comments?
- Contact: [jerry.hubbell@comcast.net](mailto:jerry.hubbell@comcast.net)