R-Code Occultation Timing Extractor
Programmed by Robert L. (Bob) Anderson
Presentation by Tony George at the 2013 Toronto, Canada IOTA Conference

R-OTE

Major Advances Over Occular and similar ‘frequentist’ occultation signal analysis tools

- Cross-platform implementation – Windows, Mac, Linux – anything that will run R-code (current release requires Google Chrome, Firefox, Safari, or Fast Browser web browser – IE does not work)
- Uses maximum likelihood estimation (MLE) for evaluation of model fit to light curve
- D and R solutions are independently determined
- Uses Akaike Information Criterion (AIC) to select ‘best’ model solution, comparing a square wave solution against a gradual transition, for example

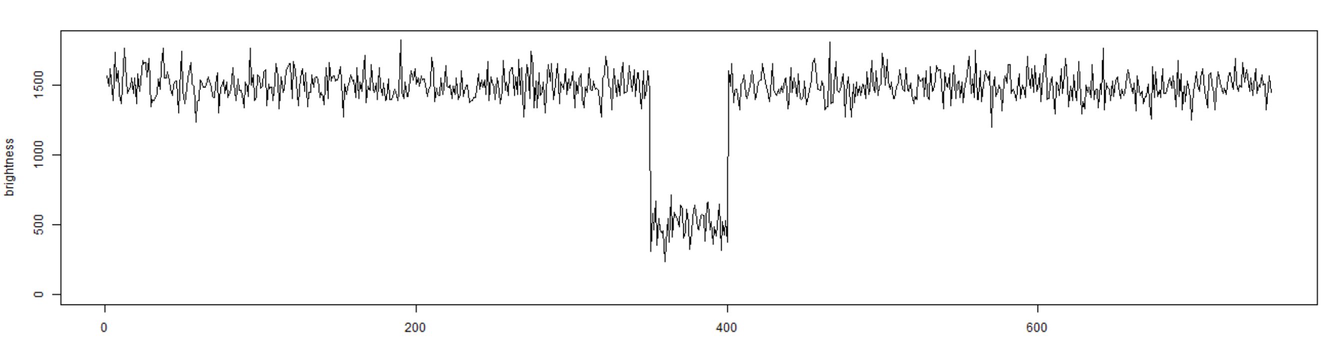
Major advances (cont.)

- Implementation of error confidence intervals based on noise SNR and noise symmetry
- Allows estimation of stellar diameters and occultation limb angles
- Incorporates stellar limb darkening models in the estimation of stellar diameters
- Introduces ‘multiple solution’ reporting concept
- Extracts difficult to see ‘events’ from low SNR light curves with high confidence – 99.9 %
- Uses MLE and AIC to exclude false positive event detections

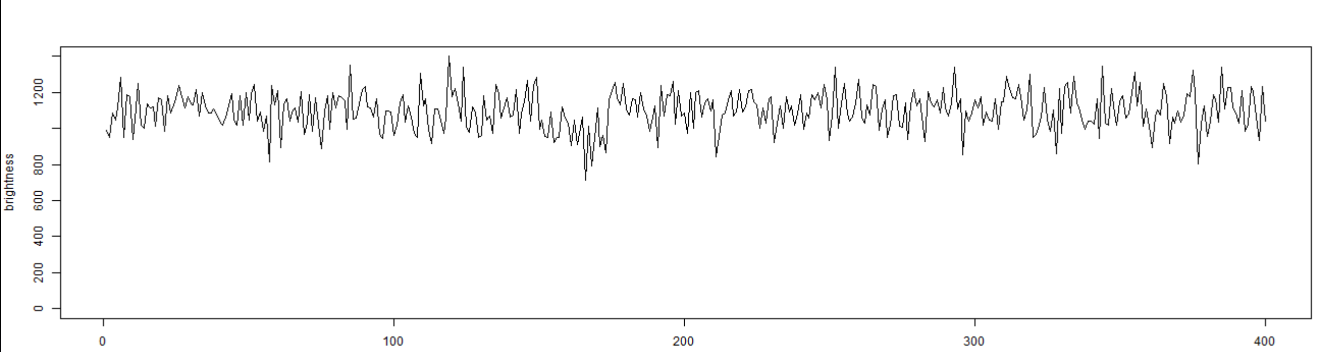
Special features

- Trimming, detrending and block integration of light curve data
- Noise analysis to assure data is independent and identically distributed
- Multipurpose synthetic light curve generator
- Graze analysis capability

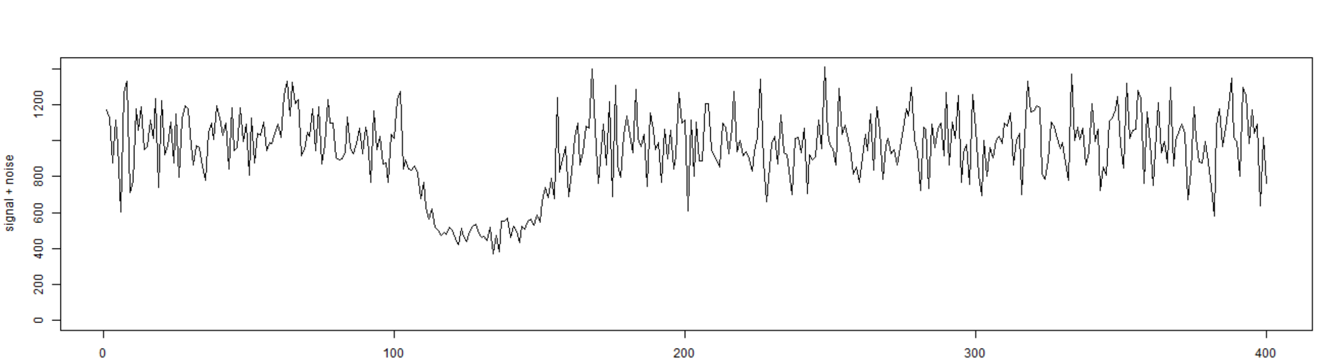
Explanation of Program Advances and Special Features – Types of Light Curves Supported



file: C:/Program Files/R/R-OTE/Test Files/HIGH-SNR SQUARE WAVE.csv



file: C:/Program Files/R/R-OTE/Test Files/LOW-SNR SHORT TEST FILE.csv



Star disk intersecting asteroid edges: sample data generated by R-OTE 3.1.1

1. High SNR square wave
2. Low SNR square wave
3. High SNR gradual transition

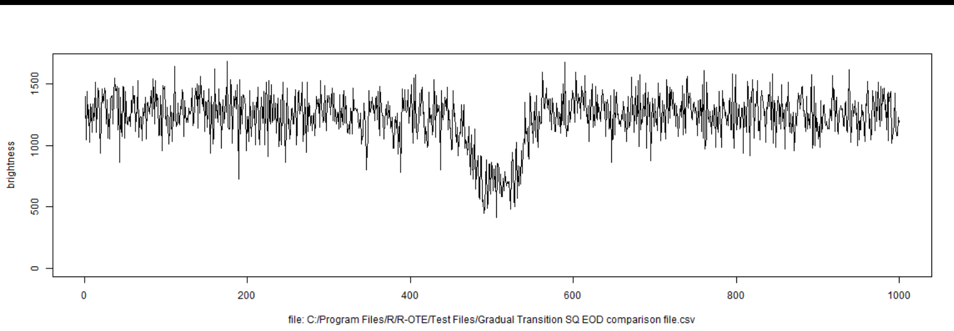
Explanation of Program Advances and Special Features – Uses maximum likelihood estimation (MLE) and Akaike Information Criterion (AIC) for light curve fit and model selection

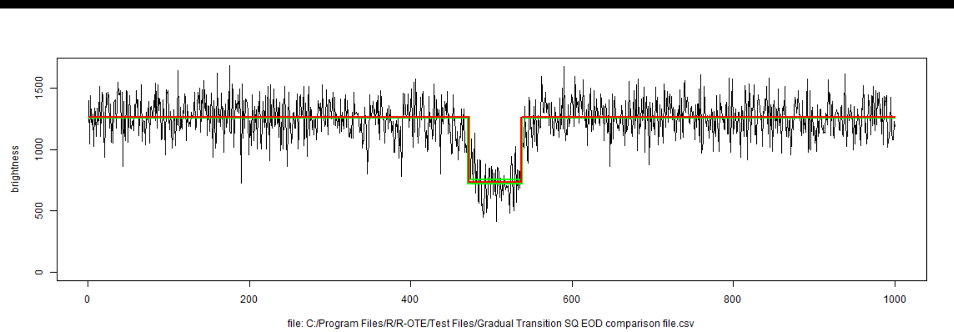
- How does an observer decide if the best solution to a light curve is a square wave or a gradual transition light curve?
- Occular and other 'frequentist' methods require the observer use 'judgment' as to what looks best.
- Different light curve models have differing 'degrees of freedom' that must be considered, otherwise the model with the greatest number of degrees of freedom will always have the best 'least squares' or similar fitting correlation coefficient – all other things being equal.

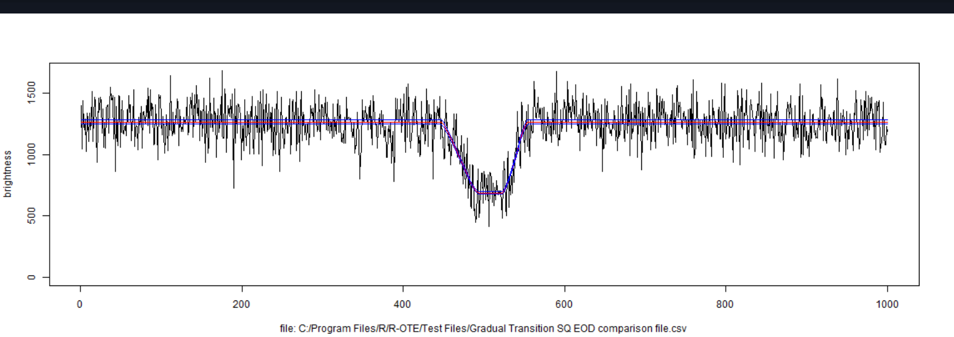
Explanation of Program Advances and Special Features – Uses maximum likelihood estimation (MLE) and Akaike Information Criterion (AIC) for light curve fit and model selection

- R-OTE solves this problem by using MLE and AIC. MLE delivers a repeatable model fit statistic – the logLikelihood of the solution. AIC compares the logLikelihood of each model solution and adjusts the rating of each model based on the degrees of freedom in the model.
- R-OTE compares all solutions to a straight line with noise added to ensure that the event detect is not mistaken for a 'miss' with just a noisy light curve.
- AIC then provides a rating of each model in the form of a percentage relative likelihood. Users can easily evaluate the relative likelihood rating to select the best model.

Explanation of Program Advances and Special Features – Uses maximum likelihood estimation (MLE) and Akaike Information Criterion (AIC) for light curve fit and model selection





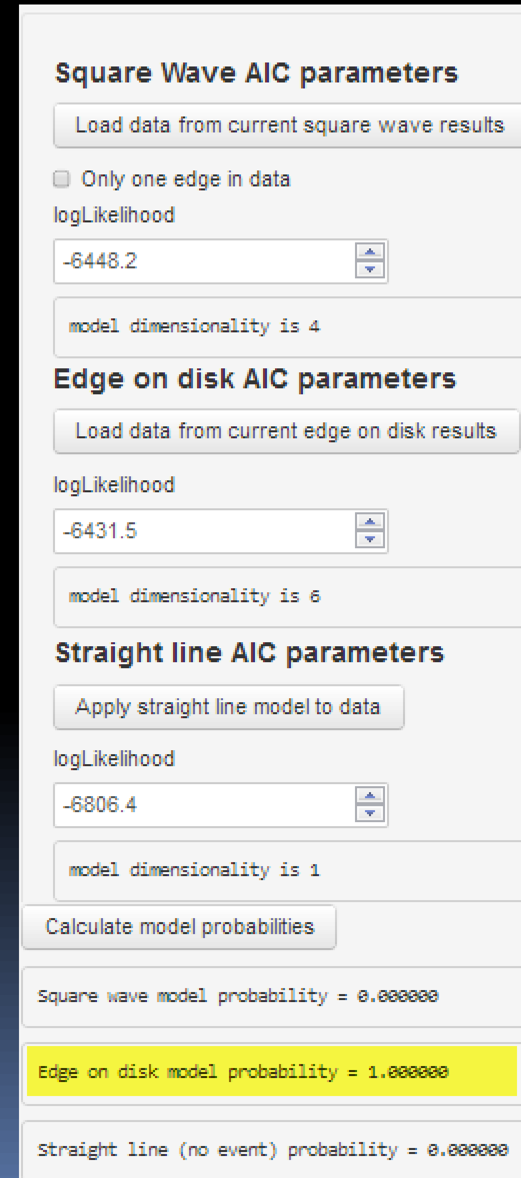


Top chart is a synthetic light curve.

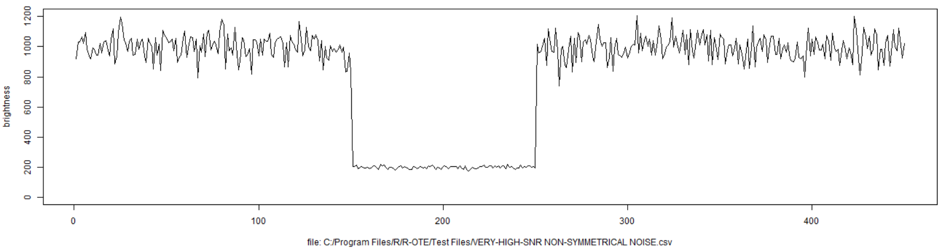
Which model best fits this data – square wave or gradual transition?

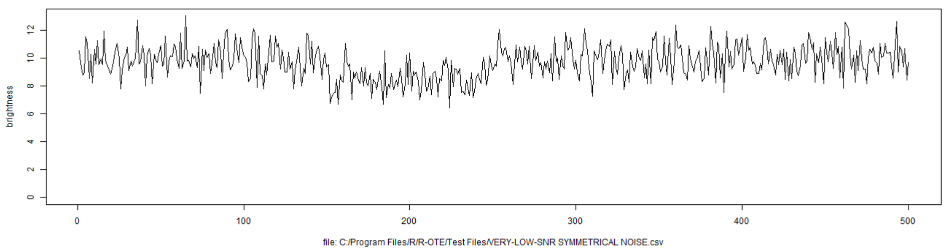
The AIC model comparison at right gives us an answer.

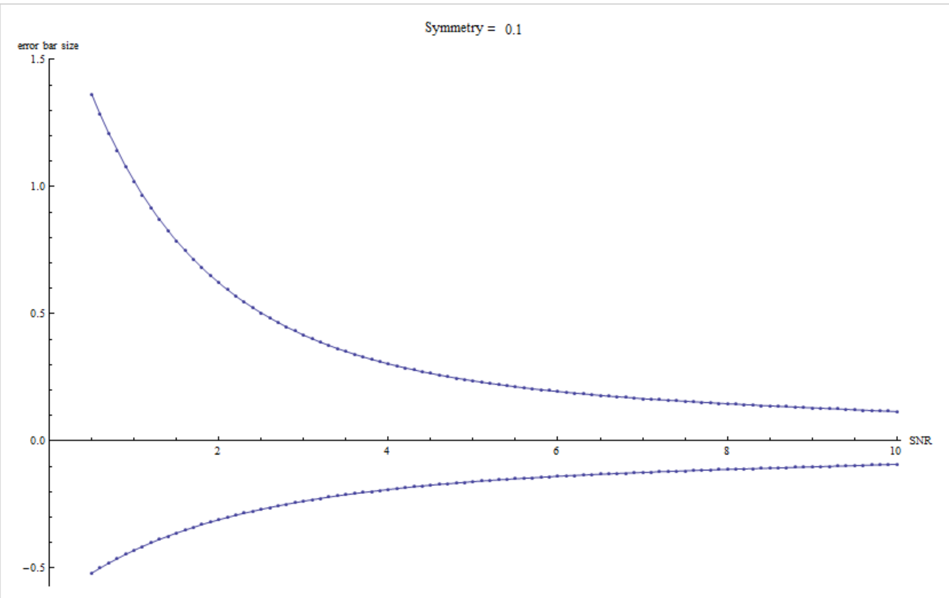
The gradual transition model probability is 1.00 or 100% the best fit to the light curve.

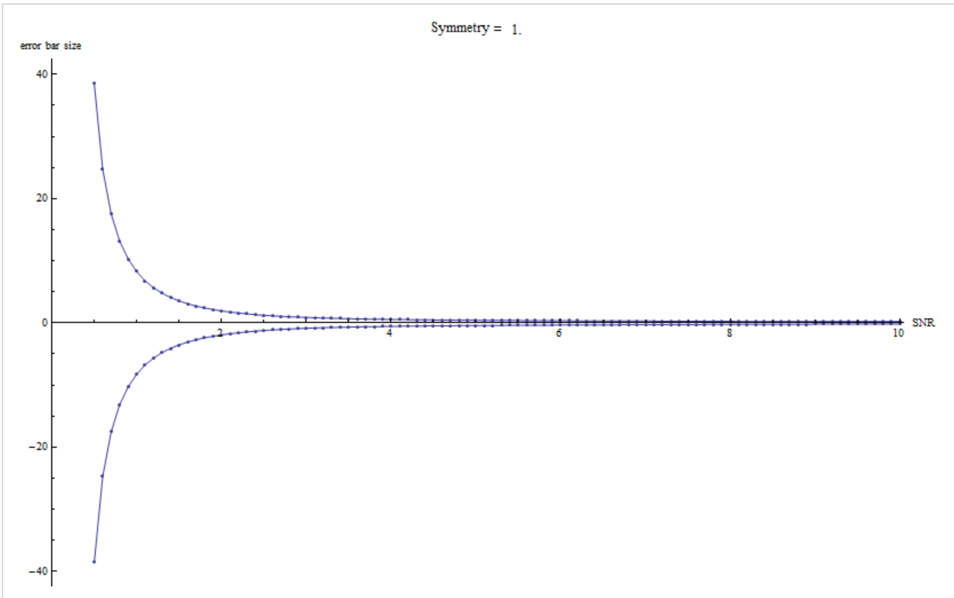


Explanation of Program Advances and Special Features – confidence intervals based on noise SNR and noise symmetry







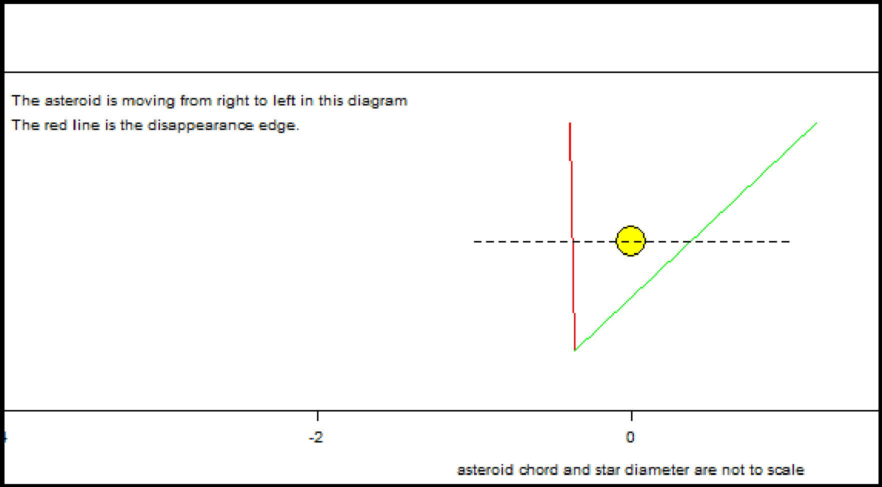


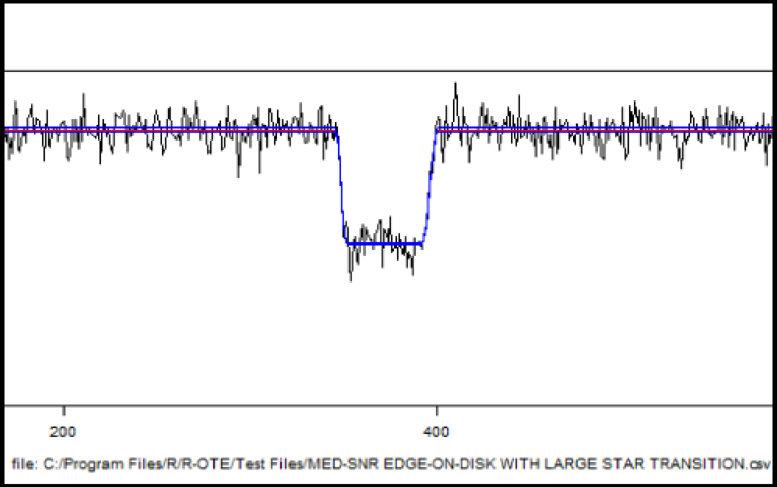
Left panel: symmetry = 0.1

Right panel: symmetry = 1.0

Future enhancement of error bar simulation tables should improve (reduce) error bar estimates

Explanation of Program Advances and Special Features – estimation of stellar diameters and occultation limb angles





Computations results

```
star diameter (readings) =  5.00 (+/-) 1.596

theta D  (degrees)  =  1.00 (+53.330/-0.990)
theta R  (degrees)  = 46.78 (+15.100/-46.780)
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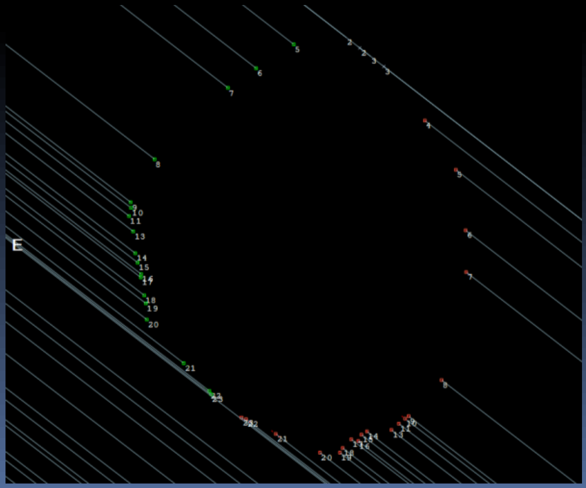
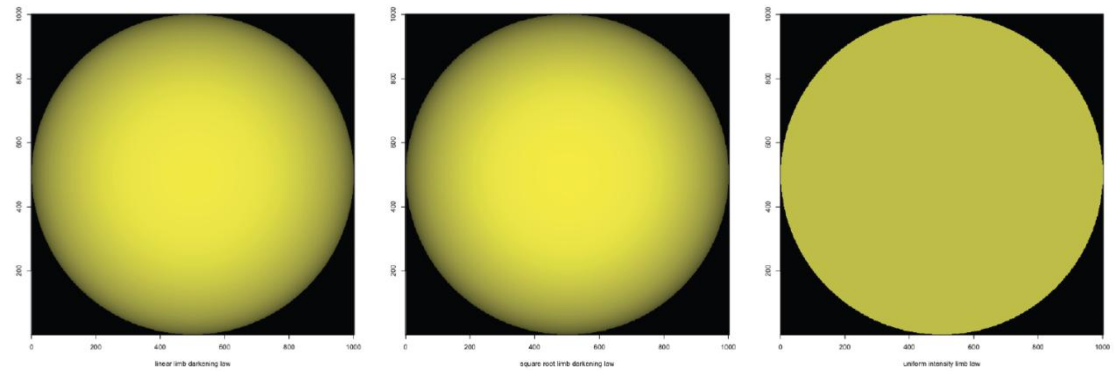
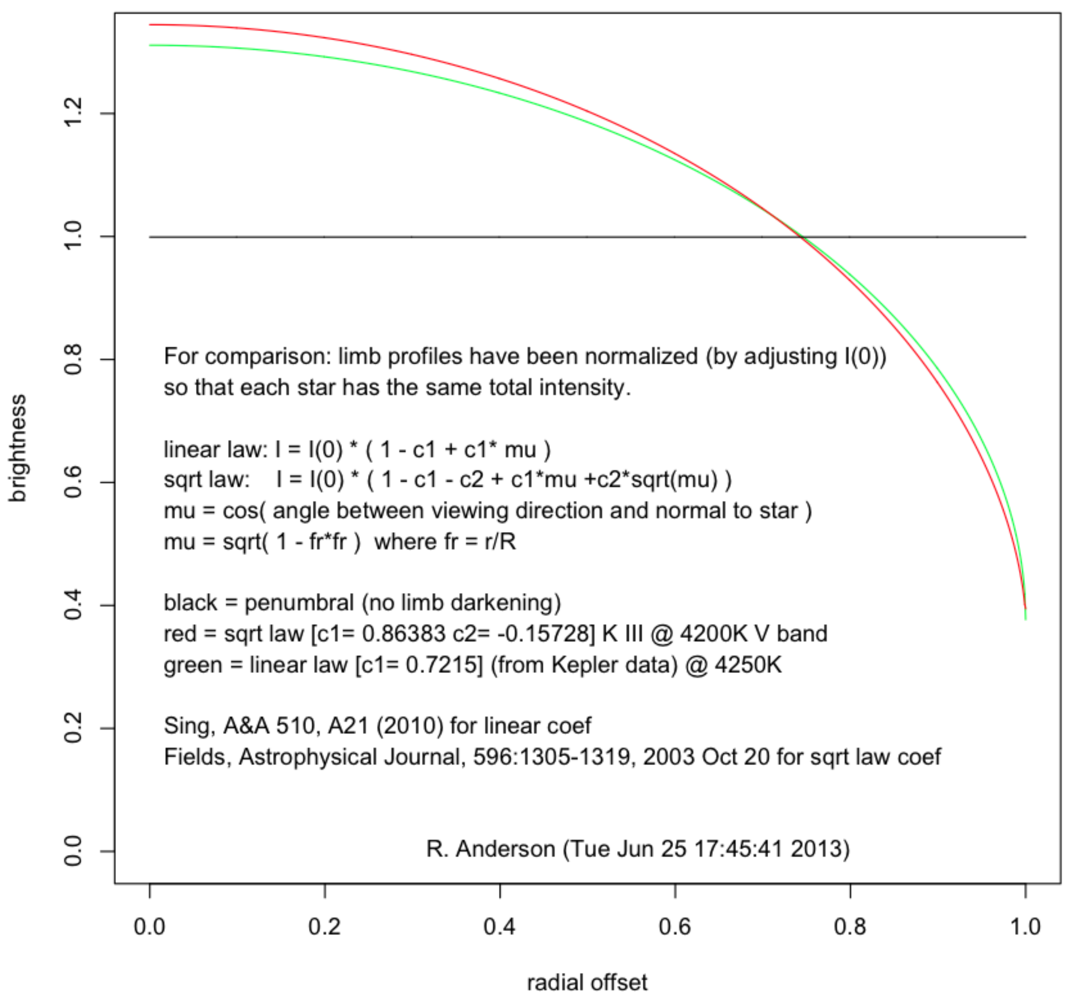






Explanation of Program Advances and Special Features – Stellar Limb Darkening Models Supported

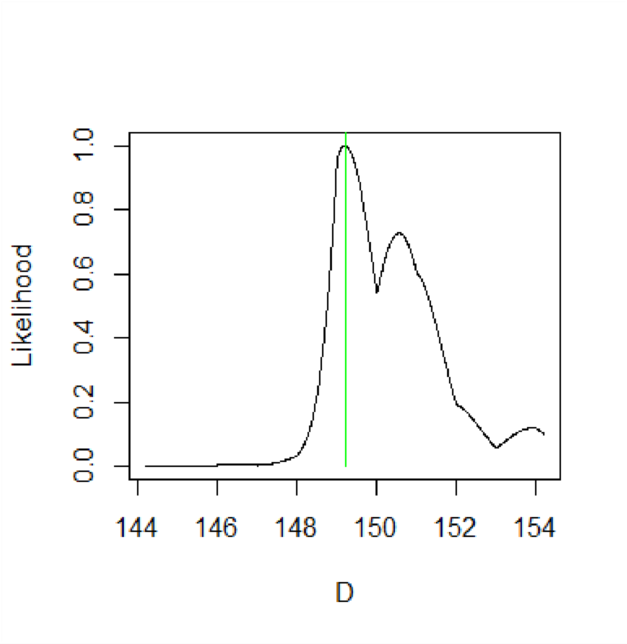
Left image: linear law model

Middle image: sqrt law model

Right image: no limb darkening

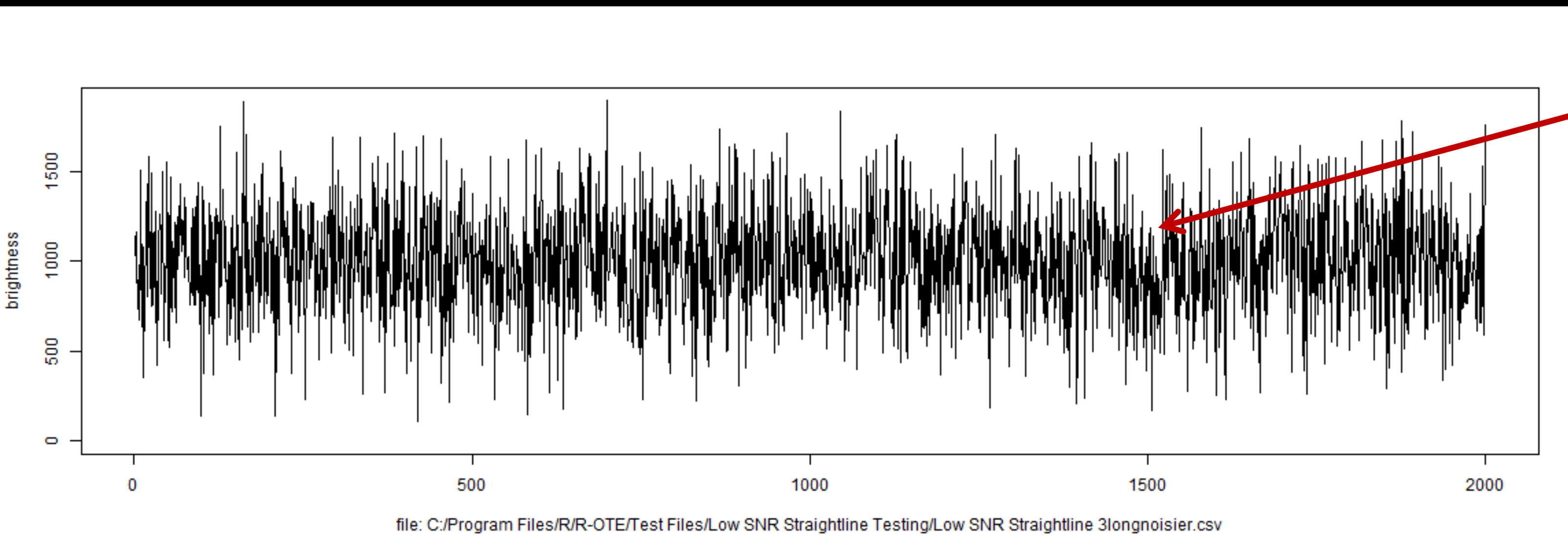
Note: Future improvements to R-OTE will be able to support irregular star shapes and star spots

Explanation of Program Advances and Special Features – Multiple Square Wave Solutions



- The window at the upper right shows a plot of the relative likelihood of a solution for various possible solutions (readings) in the light curve.
- The highest peak at 149.20 is the most likely solution to a 'synthetic event with a D of 150. The secondary peak to the right at 150.56 is another possible solution with a relative likelihood of around 0.75
- The weighted average of both peaks is 149.77.
- R-OTE allows the user to report the highest peak, or any secondary peak, or the weighted average of the peaks, as the D event.
- Which one is the correct solution? Ah, good question. Normally, we will pick the one with the highest relative likelihood, however, if there is a secondary peak, like with this example, we might want to report both as possible solutions, or the weighted average of both.

Explanation of Program Advances and Special Features -- MLE and AIC to analyze low SNR light curves



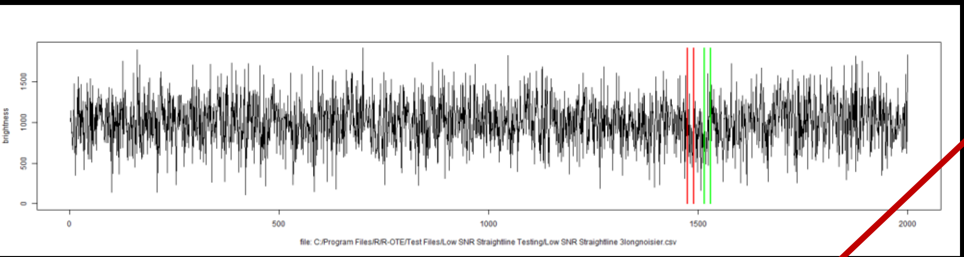
Is this a possible event?

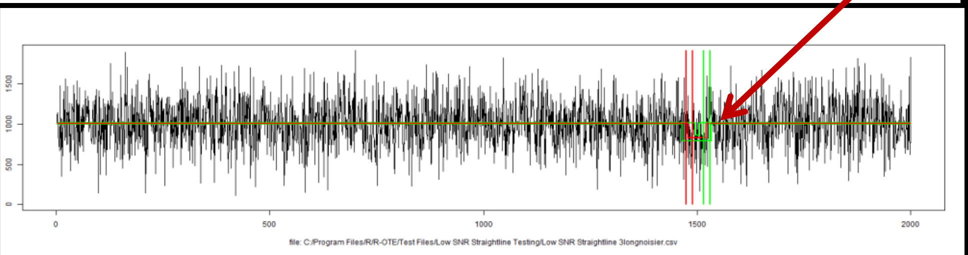
Here is a straight line with noise added. There is no occultation event in the data. Our eye sees a possible event. Could an event be hiding in the data? R-OTE searched all possible combinations of event durations and magnitude drop to find an event. It doesn't. At 99.9% confidence level the AIC test indicates there is no occultation embedded in the data.

Table of candidates

	Status
1	No significant feature meeting the supplied limits on magDrop and event size was found

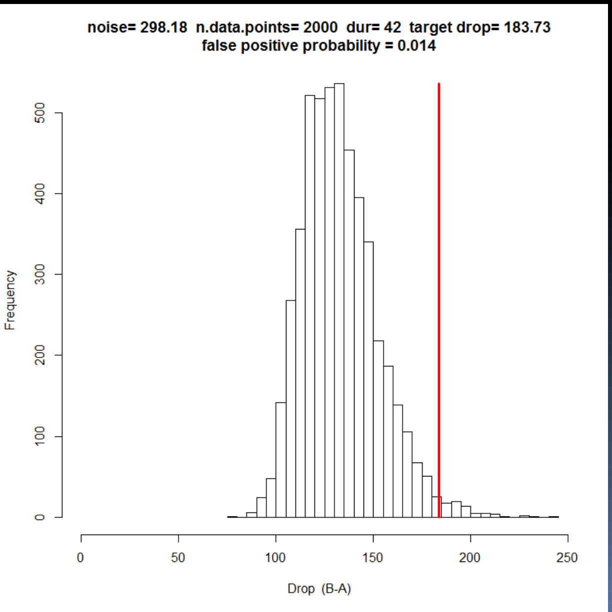
Explanation of Program Advances and Special Features -- MLE and AIC used in False Positive Calculator

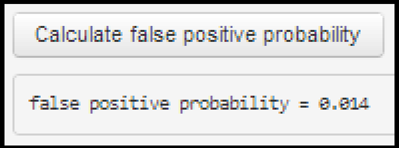




Is this a possible event?

Here is the same straight line with noise added as used in the last slide. There is no occultation event in the data. We can force R-OTE to find a solution. The most likely event has a 42 reading duration and 0.22 mag drop. We can use the False Positive Calculator to evaluate if this might be due to noise.



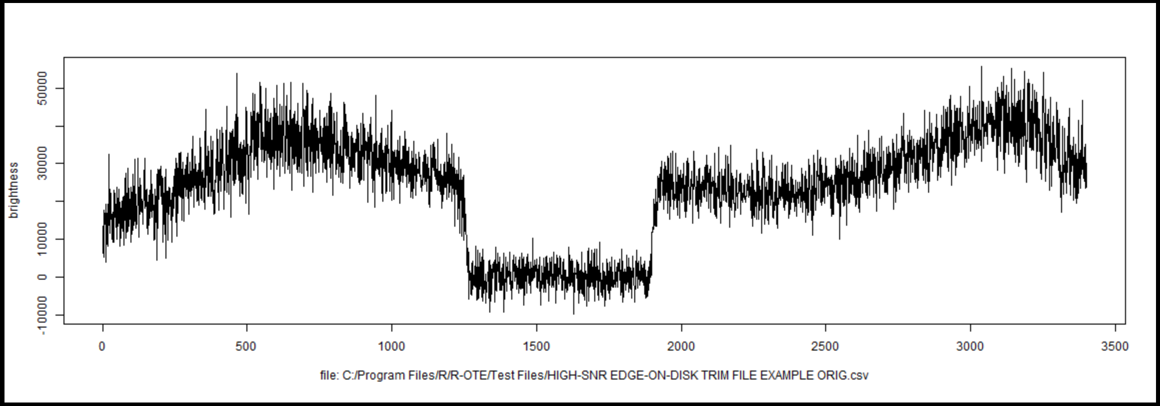


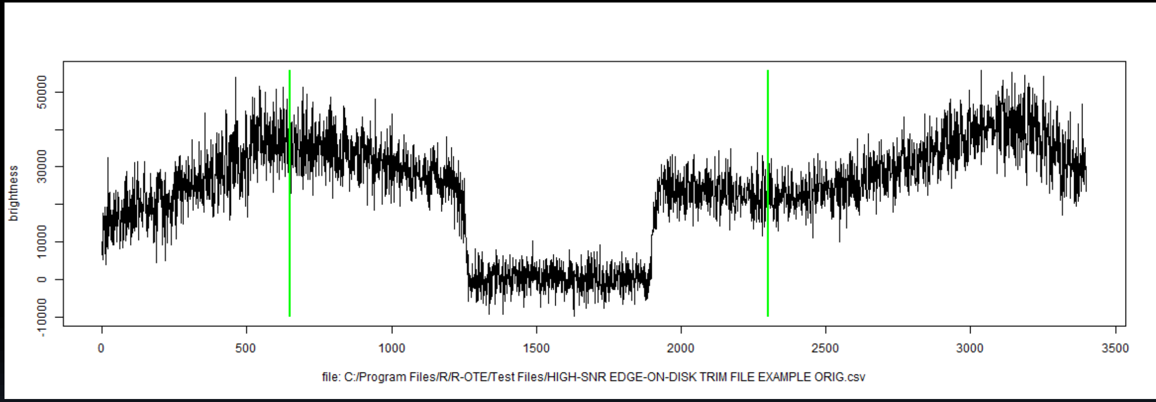
The red bar represents the 'event'. The histogram shows other events of equal duration found in noise.

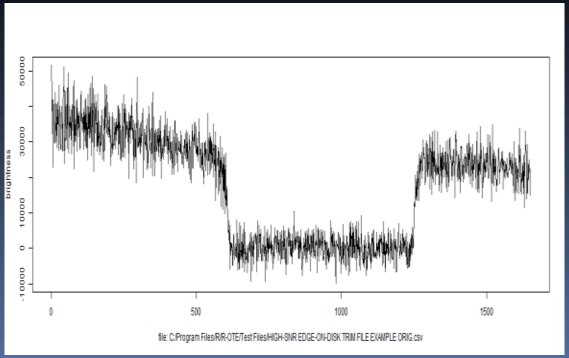
After running 5000 simulations, the False Positive Calculator returns a histogram of results and a false positive probability. The results show the probability of a 42 duration event with mag drop of 0.22 being found 'randomly' in a straight line with similar noise added.

The probability is 0.014, or 14 times in 1000 tries. The authors recommend that any event that scores 0.001 or higher be rejected as a probable false positive.

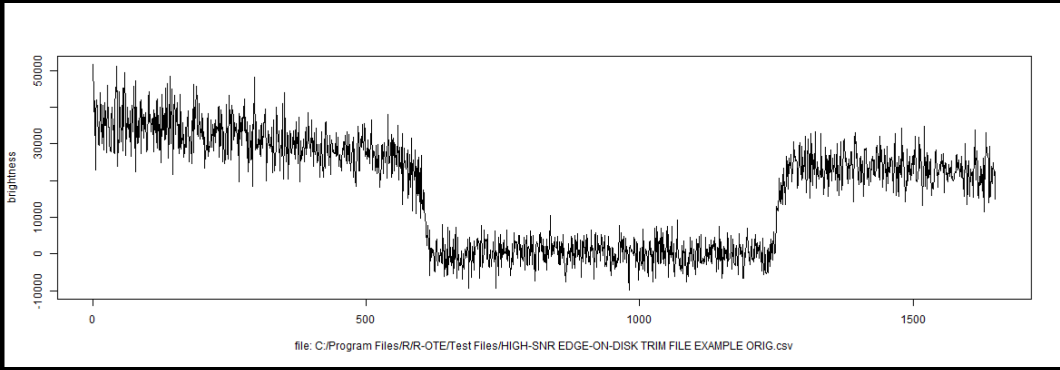
Explanation of Program Advances and Special Features – Trimming

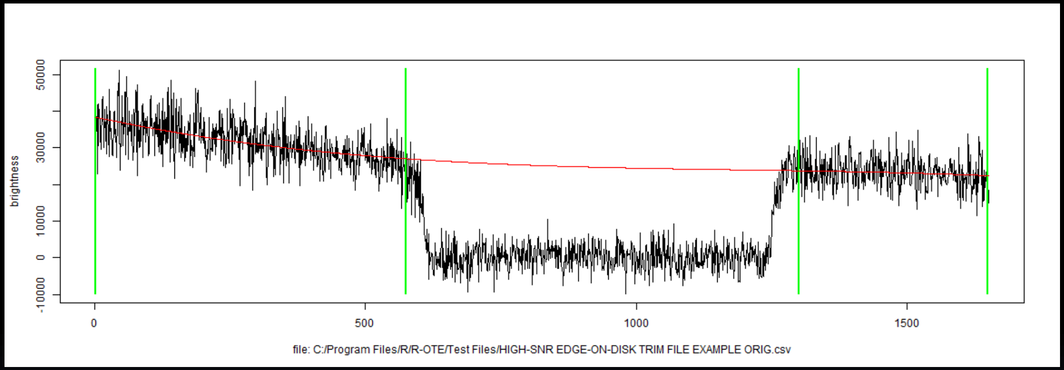


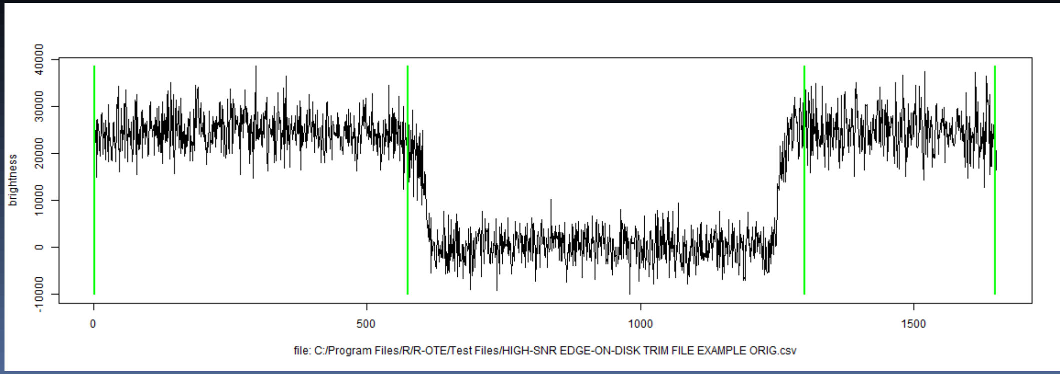




Explanation of Program Advances and Special Features – Detrending



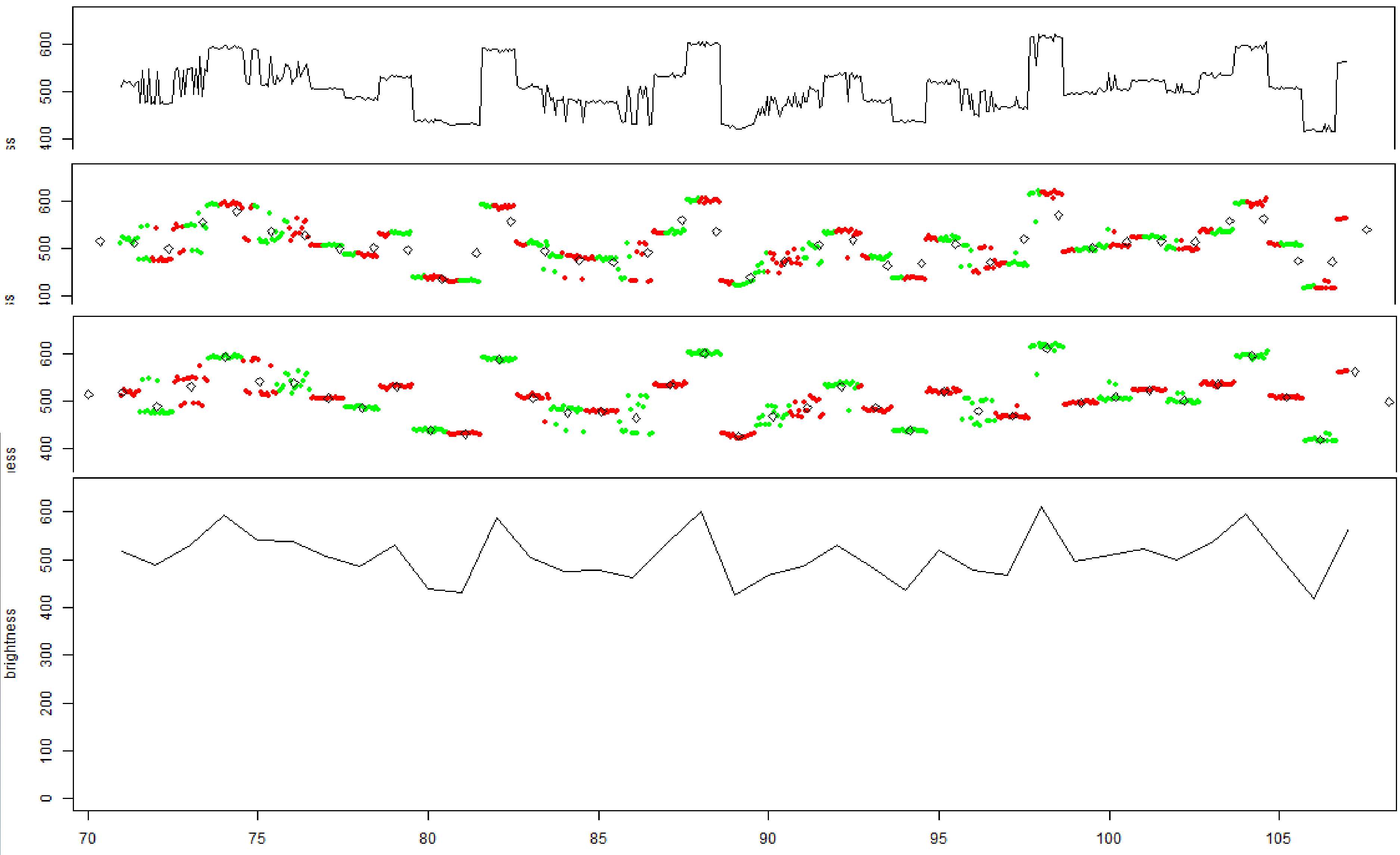




Three detrending models are supported in R-OTE:

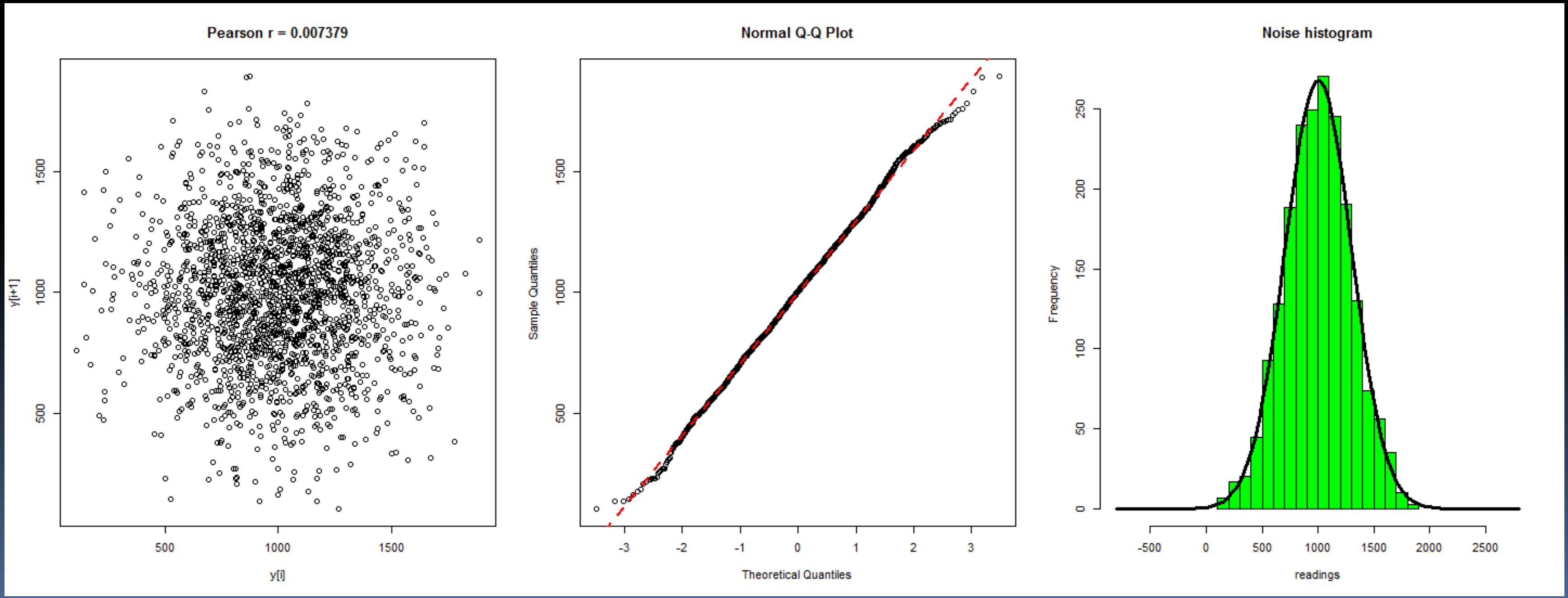
1. Linear
2. Parabolic
3. Third-order

Explanation of Program Advances and Special Features – Block Integrating

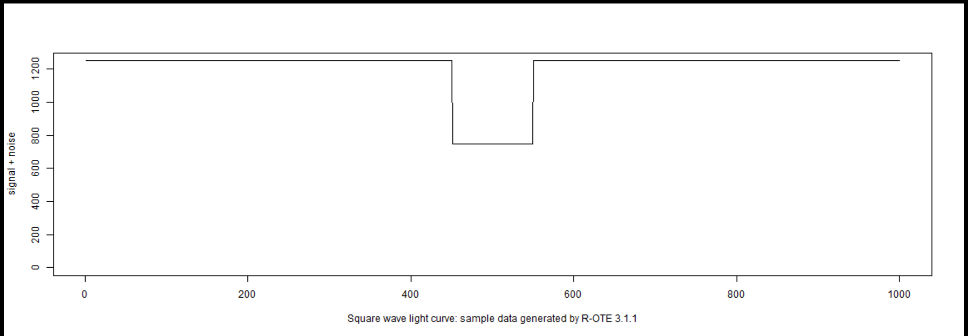


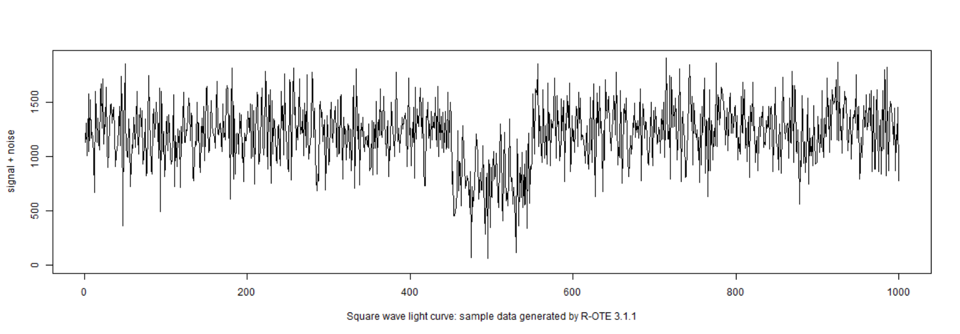
Explanation of Program Advances and Special Features – Noise analysis

R-OTE uses maximum likelihood estimation to find the best light curve model to fit the light curve data. MLE requires the data to be 'independent and identically distributed.' If adjacent data points are uncorrelated, then the data is independent. If the noise fits a Gaussian distribution, it is identically distributed. R-OTE uses the Pearson's r test to verify the data is uncorrelated and uses the Gaussian Q-Q plot to verify the distribution is Gaussian.



Explanation of Program Advances and Special Features – Synthetic Light Curve Generator

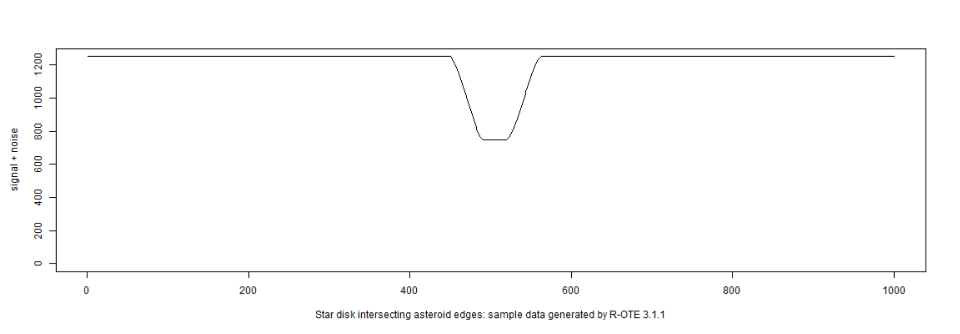




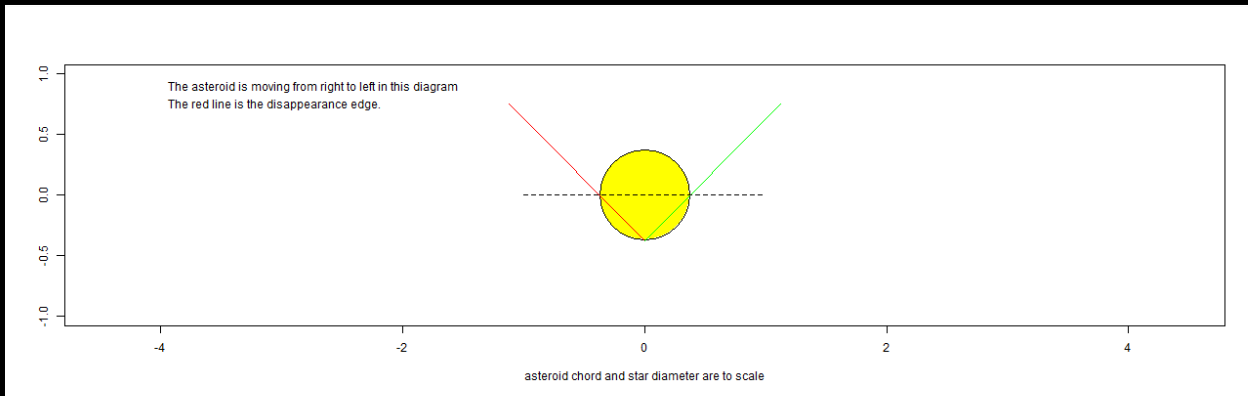
Graphs at right show a synthetic square wave and the same light curve with Gaussian noise added (noise level is user selectable)

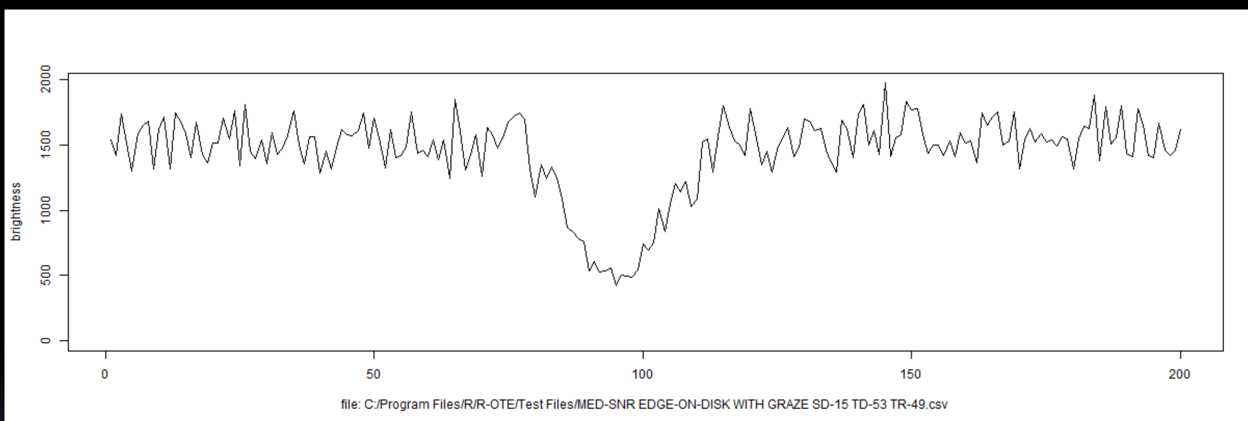
Graph at bottom shows a similar synthetic event with gradual transitions. Gaussian noise can be added to this curve as in the square wave.

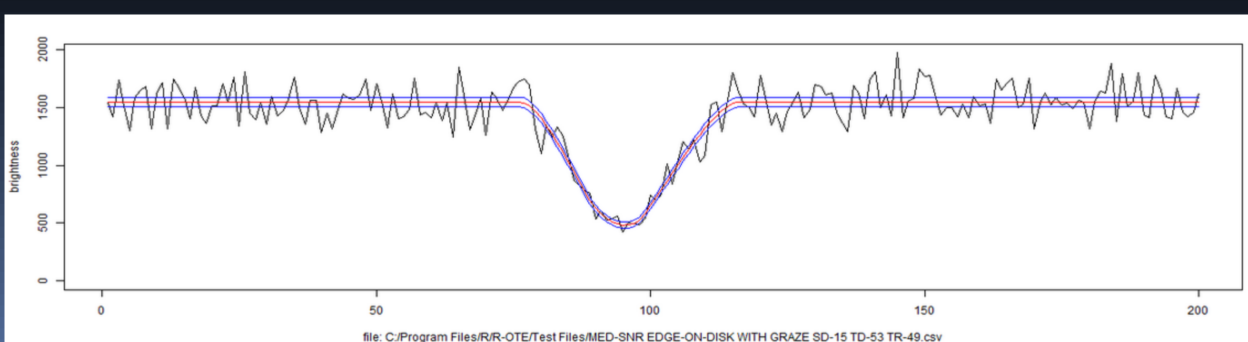
Noise levels can be adjusted at different levels: baseline noise can be higher than event bottom noise (noise symmetry can be < 1.0)



Explanation of Program Advances and Special Features -- Grazing Occultation Analysis

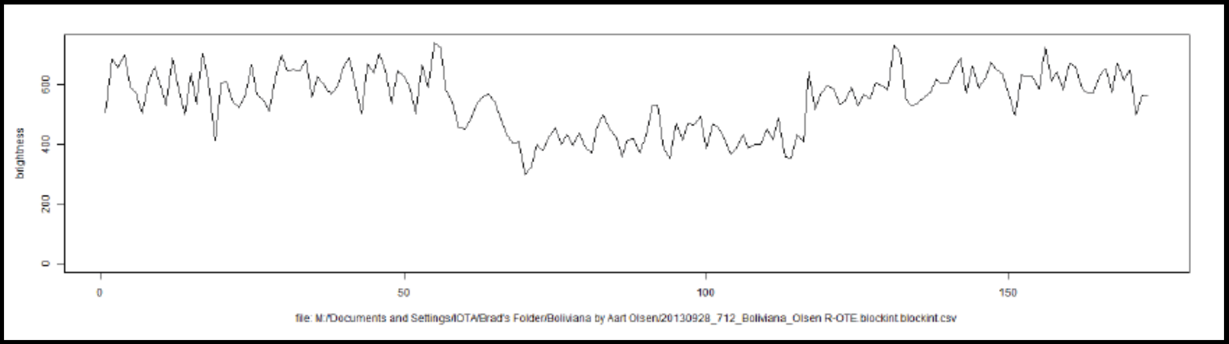




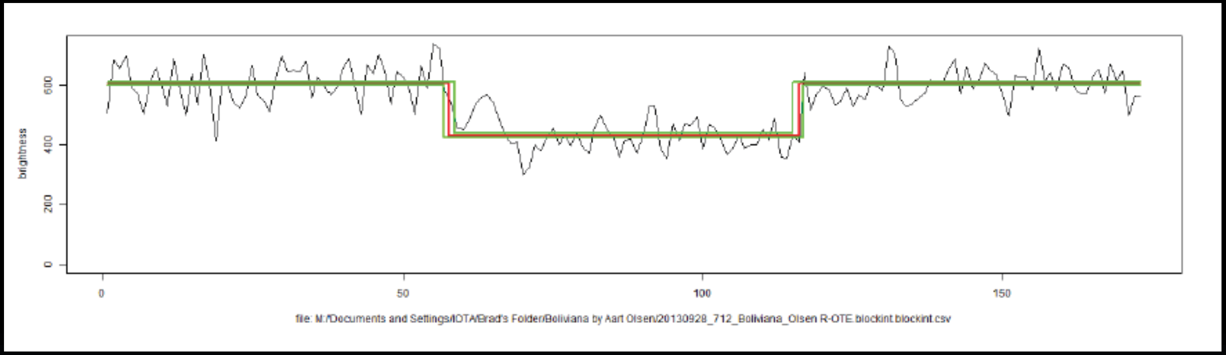


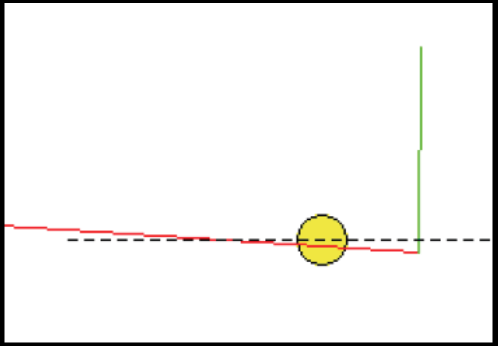
The graze analysis in R-OTE is not an exact solution when the graze geometry is less than 50% of the diameter of the star. This issue will be corrected in a future upgrade of R-OTE.

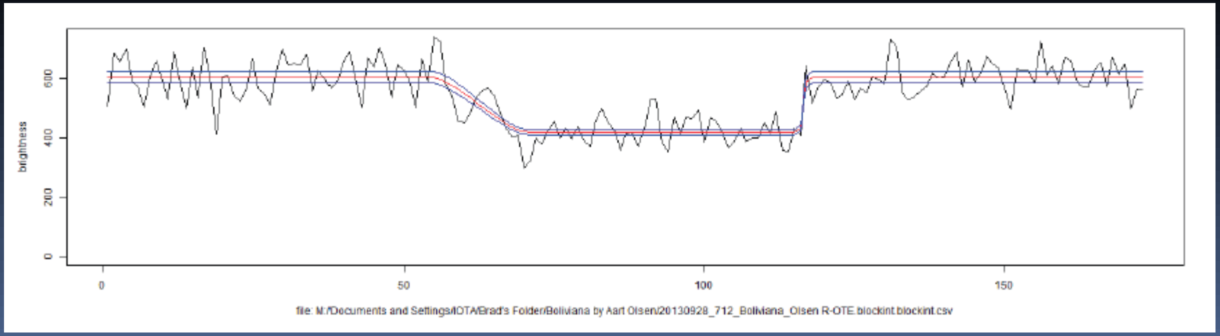
Let's look at a real world example…



Boliviana occultation of 2UCAC 39081155 on September 28, 2013 by Aart Olson







Calculate model probabilities

Square wave model probability = 0.024925

Edge on disk model probability = 0.975075

Straight line model not applied

Who should download R-OTE?

- Individuals who have been consistent past users of Occular 4.0
- Experienced observers who collect lots of data with hard to extract low SNR light curves – someone like Scotty Degenhardt
- Software programmers who would like to consider implementing R-OTE approaches into their software.
- Other interested IOTA observers who have good technical software skills, who can follow detailed complex instruction manuals, and who have lots of time and lots of patience.

Future work

R-OTE is a work in progress. Future work is planned to improve the concepts and to make the program accessible to software programmers who can make the program more user friendly

- Error confidence intervals will be reprogrammed to allow user-selectable intervals
- Development of exact solutions for all graze events
- Sharing methodology with software programmers so that R-OTE advances can be incorporated into other popular software programs
- Implementation of a multi-chord version of R-OTE to enable the complete solution of asteroid size and shape profiles, stellar diameters, and stellar limb darkening model

Acknowledgements

- Steve Preston
- Brad Timerson

For program suggestions and beta testing

- Dr. Eric Feigelson, Department of Astronomy and Astrophysics, Penn State University
- Dr. G. Jogesh Babu, Department of Statistics, The Pennsylvania State University

For advice in establishing the statistical analysis approaches used in R-OTE

Thank you