The TESS Rotation Collaboration

A Stellar Rotation Data Challenge

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Abstract

The TESS Rotation Collaboration (TRC) is a multi-institutional effort to compare and improve techniques for measuring stellar rotation from photometry taken by the Transiting Exoplanet Survey Satellite (TESS). **We are running a blinded injection-and-recovery data challenge to recover stellar rotation periods from real and simulated TESS data products. Our goals are to:**

1. **Provide a framework** to compare rotation-detection methods and understand which are most reliable in different parts of parameter space.
2. **Identify remaining challenges** when measuring stellar rotation with TESS.
3. **Be a "user guide"** to other astronomers looking for the best rotation-finding tool for their science case.

Background

How does stellar rotation help RV science?

Stellar rotation can cause correlated periodic variability in the RV time series, which can obscure or even masquerade as planet signals. Accurate knowledge of the rotation period can help disentangle whether signals are stellar or planetary in origin through joint modeling and other techniques.

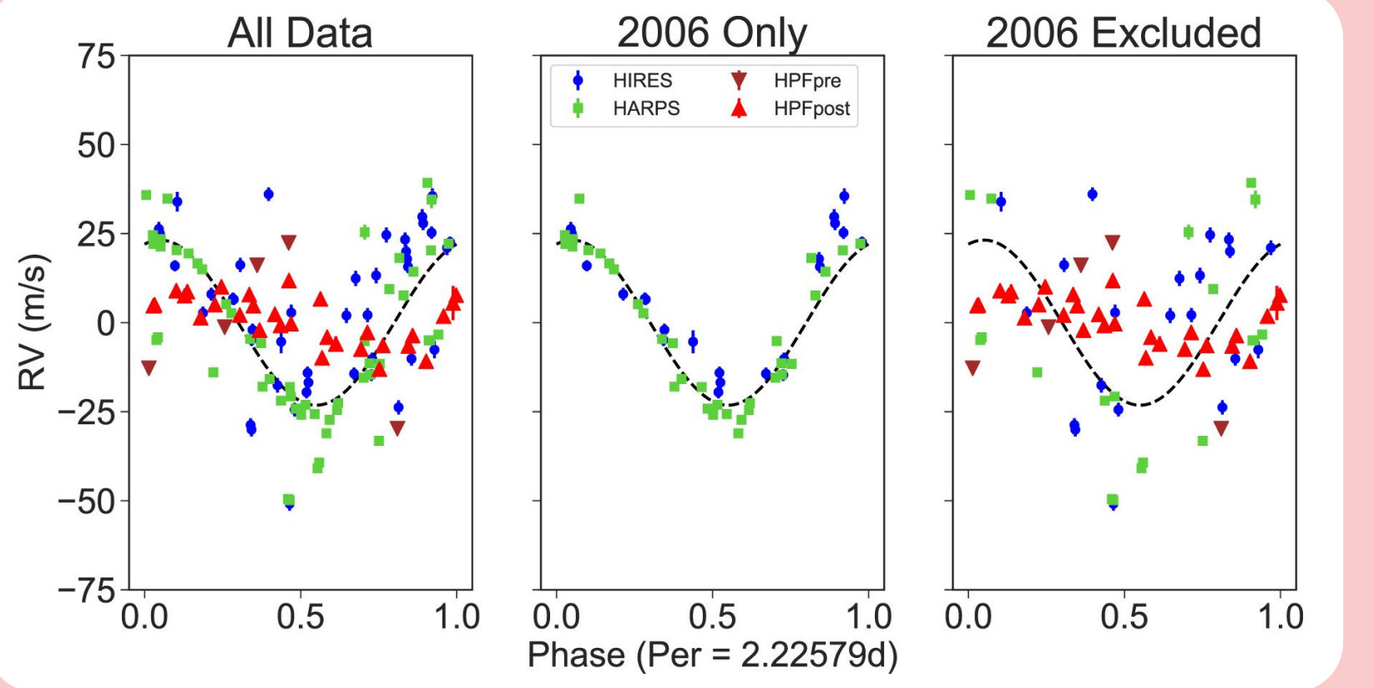
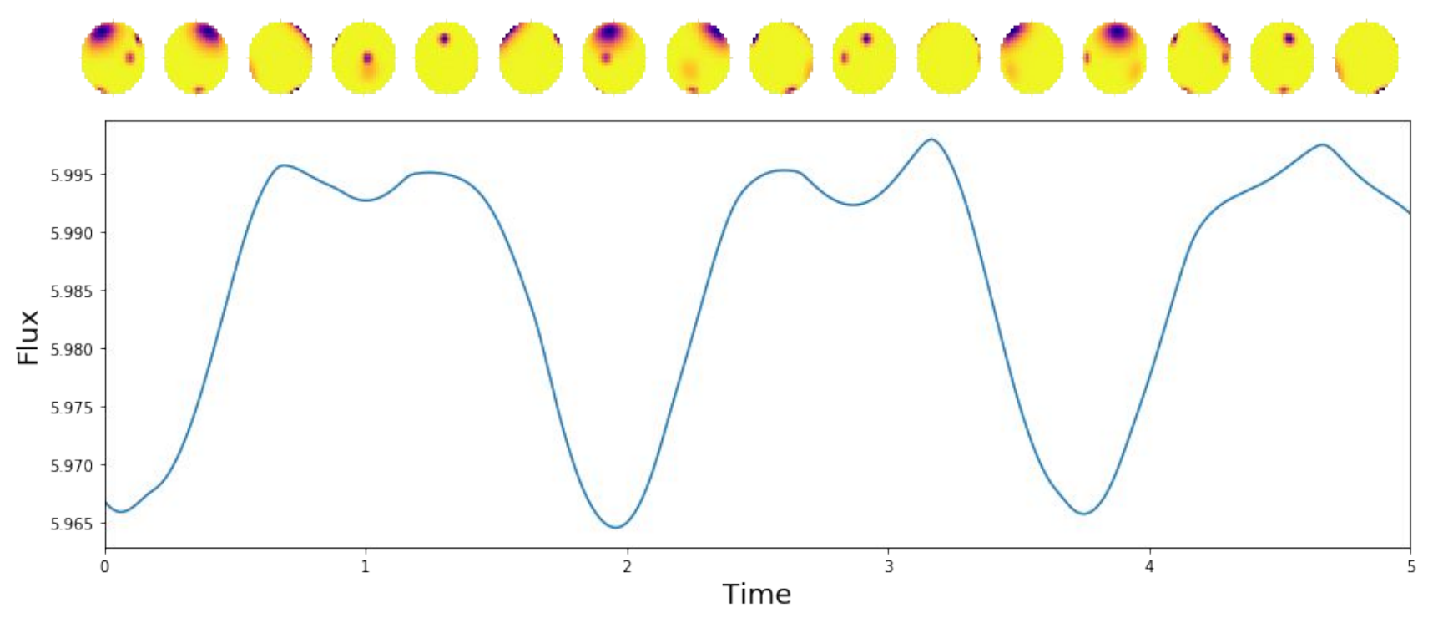


Figure 1. Stellar rotation can mimic planet signals, such as happened with AD Leo's 2.23 day rotation period. Prior knowledge of the rotation period helps avoid false positives, and coherent rotation signals can be subtracted from the RV time series to study planets with lower RV amplitudes. Reprinted from [5].

Photometric Measurement of Stellar Rotation

As stars rotate, dark starspots travel through the observer's line of sight and create quasi-periodic brightness modulations. With its short cadence and continuous 27-day observation cycles, TESS allows rotation searches of nearly the entire sky for the first time.

Figure 2. Simulation of how star spots can produce slow-evolving periodicity in the light curve. Reprinted from [4].



References

1. Aigrain, S., "Testing the recovery of stellar rotation signals from Kepler light curves using a blind hare-and-hounds exercise", *Monthly Notices of the Royal Astronomical Society*, vol. 450, no. 3, pp. 3211–3226, 2015. doi:10.1093/mnras/stv853.
2. Bell, K. J. and Higgins, M. E., "TESS_PRF: Display the TESS pixel response function", *Astrophysics Source Code Library*, 2022. ascl:2207.008.
3. Claytor, Z. "Recovery of TESS Stellar Rotation Periods Using Deep Learning", *The Astrophysical Journal*, vol. 927, no. 2, 2022. doi: 10.3847/1538-4357/ac498f.
4. Luger, R., "starry: Analytic Occultation Light Curves", *The Astrophysical Journal*, vol. 157, no.2, 2019. doi: 10.3847/1538-3881/aae8e5
5. Robertson, P., "Persistent Starspot Signals on M Dwarfs: Multiwavelength Doppler Observations with the Habitable-zone Planet Finder and Keck/HIRES", *The Astrophysical Journal*, vol. 897, no. 2, 2020. doi:10.3847/1538-4357/ab989f.
6. Vanderspek, R., "The Transiting Exoplanet Survey Satellite (TESS): Mission Operations and Instrument Performance", vol. 51, 2019.
7. Zhao, L. L., "The EXPRES Stellar Signals Project II. State of the Field in Disentangling Photospheric Velocities", *The Astronomical Journal*, vol. 163, no. 4, 2022. doi:10.3847/1538-3881/ac5176.

Timeline

Winter 2022

Gather Collaborators
Reach out to individuals & advertise the data challenge.

Spring 2023

Generate Data Set
Creation of simulated TESS data products

Summer 2023

Distribute Data to Teams
1-2 month window for each team to analyze the sample and submit results

Fall 2023

Analysis
Consolidation and analysis of all teams' results.

Fall/ Winter 2023

Writing & Publication

The TRC Data Challenge

What is the TRC Data Challenge?

In Summer 2023, we will release a sample of 10,000 TESS data products to the stellar rotation community with a simple directive: Which of these stars are rotating, and what are their periods?

The data set will include target pixel files (TPFs) and light curve files for each star, which may be injected with a rotation period of between 0.1 - 100 days. These data products are made from a combination of real and simulated TESS data.

After each team submits their findings, we will perform a meta analysis to compare the performance of different methods and answer key questions about the current state of our ability to measure stellar rotation with TESS.

Why Do a Data Challenge?

Widefield photometric surveys performed by *Kepler* and TESS have revolutionized the study of stellar rotation. In response, astronomers have developed a variety of new statistical tools to measure rotation, including Fourier-based periodograms, autocorrelation analysis, gaussian process modeling, machine learning, and more. In order to rigorously compare the performance of these methods, they need to be tested on a unified data set. Following in the footsteps of previous data challenges such as the *Kepler* Hound-and-Hare Exercise [1] and the EXPRES Stellar Signals Project [7], we aim to fill this need for TESS science.

What Questions Will We Answer?

- For each method, what is the **yield** (% of rotators recovered) and **accuracy** (false positive rate) for fast vs. slow rotators?
- Can we recover rotation **periods longer than a TESS sector**?
- What are **common false positives** due to TESS systematics, crowding, and contamination?
- Overall, how confident can we be in rotation periods measured with TESS? To what extent do multiple sectors of data increase that confidence?
- What challenges remain?

Get Involved!

Email rjholcom@uci.edu or scan below for updates & data access in Summer 2023.

Simulating TESS Data

How to Build a TESS Image

Our simulated target pixel files (TPFs) are made by modeling stellar rotations signals and injecting them at the pixel level. To increase the verisimilitude of our data products, we use incorporate information from real TESS TPFs and spacecraft instrument data when modeling the background and various instrumental effects.

Background: The background is estimated as a low-order polynomial fit of a real TPF. This approach captures the effects of the changing sky brightness, as well as some effects of scattered light.

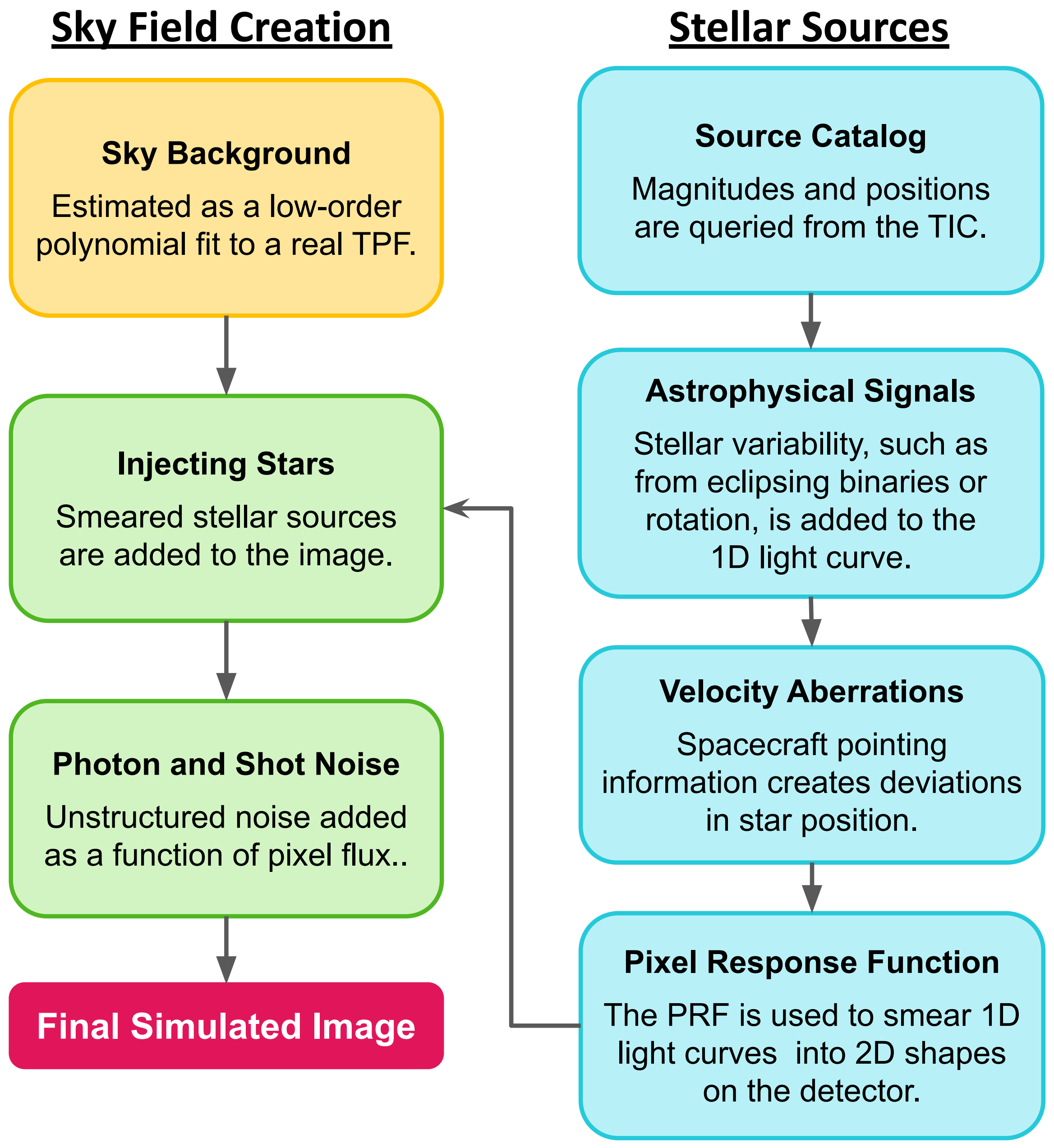
Choosing Sources: We query the TESS Input Catalog (TIC) for positions and magnitudes of all sources with magnitude T < 16 within the field. Sources are smeared using the instrument PRF and their positions deviated according to the positional corrections reported in the real TPFs (see DVA below.)

Astrophysical Variability: We use the Butterpy spot generation model to create the light curves of rotating stars [3]. Background stars are injected with signals modeled on the most common types of astrophysical variability, including eclipsing binaries, pulsating variables, rotational spot modulation.

Pixel Response Function (PRF): The PRF defines how light from a source will be distributed across the detector, which can affect the aperture appropriate for a star. We use the TESS PRFs available through MAST.

Differential Velocity Aberration (DVA): Velocity differences across a TESS orbit result in changes stellar position on the detector on the order of ~0.1 pixel [6], which can introduce brightness variations within an aperture. We use the DVAs reported by the TPF pipeline to introduce positional variation into our images.

Empirical Noise Model: All detectors have an inherent level level of unstructured noise, which can be attributed to photon noise and similar sources. We use an empirical noise model developed by calculating the typical amplitude of short timescale fluctuations as a function of pixel brightness in real TESS TPFs.



Sky Field Creation

Sky Background
Estimated as a low-order polynomial fit to a real TPF.

Injecting Stars
Smeared stellar sources are added to the image.

Photon and Shot Noise
Unstructured noise added as a function of pixel flux..

Final Simulated Image

Stellar Sources

Source Catalog
Magnitudes and positions are queried from the TIC.

Astrophysical Signals
Stellar variability, such as from eclipsing binaries or rotation, is added to the 1D light curve.

Velocity Aberrations
Spacecraft pointing information creates deviations in star position.

Pixel Response Function
The PRF is used to smear 1D light curves into 2D shapes on the detector.