Simulated TESS Full Frame Images

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ABSTRACT

It will be useful to be able to generate high-fidelity TESS images for any patch of the sky. We describe a set of Python tools for creating simulated TESS full frame images. For values of R.A. and Dec. given as inputs, these tools return images containing stars, astrophysical backgrounds, cosmic rays, known noise sources, and electronics artifacts (or any subset of these). Installation instructions are included. *Please note, this is* very *early rough draft.*

1. Statement of the Problem

TESS will stored and downlink full frame images summed to a 30 minute cadence. For various purposes, we would like to know what those images will look like. Here, we aim to make as realistic of simulated TESS full frame images as possible. At the very least, the required ingredients include:

- the basic geometric description of the focal plane, including a method to convert positions on the sky (R.A. and Dec.) to pixel coordinates (x and y) on the detector
- estimates of the Pixel Response Function (PRF), for stars of different colors and at positions across the detector field of view
- an input catalog of stars, with estimates of those stars' color across the TESS bandpass
- knowledge of the astrophysical background light sources, including both static (zodiacal light and unresolved starlight) and varying (cosmics rays)
- the key electronic artifacts associated with the detector and readout

Table 1 summarizes the ingredients we have so far considered, why they might be important, how we approach modeling them, and the current status of each in the code.

Table 1:: Potential Ingredients for TESS Full Frame Images

Why do we care?	Modeling Plan	Status
Stars		
Need to assess photometry and blending of real stars, using existing catalogs as inputs.	Query Vizier to extract stars within the field of view. Use UCAC4, which is stated to be complete over the whole sky down to $r = 16$ (and appears to go fainter in some places). For most stars, both r and J magnitudes are available. Assume stars missing either r or J to have 0 color. *Currently using $r - i$ colors to estimate flux in TESS bandpass, need a calculation of $r - TESS$ as a function of $r - J$.*	*Included*
Realistic Point Spread Function Shapes		
Need to model how flux lands on the detector. PSF is complicated and varies across field.	Start with monochromatic, sub-pixel resolution, modified Zemax PSF estimates supplied by Deb Woods, which include the optics and the effects of the silicon layer. *The PSFs now being used don't have wings beyond a few pixels – need a way to simulate the them for the brightest stars, even if only approximately.*	*Included*
Color Dependence of Point Spread Function		
PSF changes with star color, affecting photometry, astrometry, and crowding. May be important for very red (= M dwarf) stars.	Infer a rough effective temperature from the $r - J$ color of a star, use weights estimated by Peter to integrate monochromatic PSFs over the TESS bandpass. *Double check I am weighting correctly, and determine how many temperature bins are really necessary.*	*Included*
Position Dependence of Point Spread Function		
The shape of the PSF changes with position in the field of view, affecting photometry, astrometry, and crowding.	Precalculate a fine-grained library of binned PSFs on a grid of equilibrium temperature $\times$ radial position in field $\times$ rotation relative to field center $\times$ subpixel offset in x $\times$ subpixel offset in y.	*Included*
World Coordinate System for Camera		

Need a way to map catalog RA & Dec to pixel x & y coordinates.	Write an ad hoc WCS header for the field of view, using the basic parameters of the camera and assuming a tangent plane projects. *Use the more detailed focal length and distortion estimates in the presentation from Michael and Kris to fit a WCS that includes distortion terms.*	*Included*
Telescope Jitter Within Exposures		
The shifting position of stars on the detector within an exposure will slightly blur the stellar images on the detector, changing both the overall shape and the integration over intrapixel sensitivity structures.	Use the simulated pointing time series provided by Roland (originally from Orbital) to generate a 2D jitter map. Convolve the high resolution PSFs with this map before binning over pixels. Effect of nominal pointing jitter (< 2 arcsec at 3σ) is small. *Currently including offsets only. Rotation about the foresight will also be important, especially for the outermost cameras.*	*Included*
Telescope Jitter Between Exposures		
The shifting position of stars on the detector from one exposure to the next, coupled with sensitivity variations, will introduce photometric trends.	Calculate pixel-binned PSFs with centroids distributed finely enough on a subpixel scale that sensitivity variations are effectively linear and can be captured by interpolation. *Test this strategy with a simulated scan of a high-resolution PSF vs. binned PSF over a grid of subpixel positions.*	*Testing*
Differential Velocity Aberration across Field of View		
Over the course of an observing segment, the changing pointing of the spacecraft relative to its velocity vector will cause stars to move relative to each other on the detector. Unimportant *(?)* on transit timescales, but will introduce photometric trends on longer timescales.	Use a simple spacecraft orbital model to calculate effect over a typical segment and nudge the x & y positions of the stars on the detector accordingly. *Is this easier to apply at the level of the stellar (a) RA & Dec, (b) WCS, or (c) x & y pixel positions?*	*Planned*
Thermal Expansion and Focus Shifts		
Changing focal length could cause stars to move and their shapes to change.	*Identify maximum amplitude of thermally driven focus shifts in the design requirements. Will this be relevant? Even small focus shifts will pick up intrapixel sensitivity variations.*	*Planned*

Intrapixel Sensitivity Variations		
Pixel sensitivity may vary within a pixel, causing small image motions ($<<$ 1 pixel) to translate into photometric jitter/trends.	Define a nominal intrapixel sensitivity map (assumed identical over all pixels) and integrate the high resolution PSFs over this map when binning to integer pixels. *Need measurement from Peter + Joel of the shape/scale of the intrapixel sensitivity map.*	*Included*
Interpixel Sensitivity Variations		
Pixel sensitivity will vary between pixels. Large image motions (1 pixel) will cause photometric jitter/trends. If substantial features are present, this flat field could have a minor effect on the number of photons detected per star, and therefore noise.	Define a static flat-field map for the detector, giving each pixel a different sensitivity, and multiply each exposure by this sensitivity map. This treats the *inter* and *intra* pixel sensitivity variations as decoupled.	*Planned*
Zodiacal Light Background		
Adds spatially varying photon noise and contamination.	Model as spatially varying and temporally constant, using analytic form from Josh & Peter's memo. Background is calculated once per pointing and added to all images.	*Included*
Unresolved Galactic Background		
Adds spatially varying photon noise, with faint stellar sources that may themselves be intrinsically variable.	Model as spatially varying and temporally constant, using (the simpler) analytic estimate from Josh & Peter's memo. Fixed image per pointing. To capture crowding/confusion, it would be better to simply include fainter stars, but perhaps more difficult.	*Included*
Bright Galaxies in Background		
Adds localized photon noise (and potentially varying sources, in the case of AGN).	*Find a complete catalog of nearby, bright galaxies with sizes, shapes, and position angles. Will use Sersic profiles to include. Galaxies will be calculated once per pointing, and added to all images.*	*Planned*
Nebulosity Backgrounds		
Adds spatially varying photon noise.	*Is it bright enough to be seen? Add in WHAM all-sky $H\alpha$ map as additional background.*	*Planned*
Cosmic Rays		

Adds flux to random pixels at random times. If not identified, can mess up photometry.	Trace straight rays through CCD silicon, depositing fixed number of electrons per distance traveled. Calculate a unique cosmic ray image for every exposure. *What is the probability distribution for electron deposition rates? Also, will cosmic ray flux stay in its own pixel or diffuse? (This latter question will matter for on-board cosmic ray rejection algorithms that depend on cosmic rays being "sharp.")*	*Included*
Saturation Bleed Trails		
Pixels near bright sources will be contaminated by overflowing electrons.	Sum all sources of flux, identify all contiguous regions of saturated pixels, shuffle excess flux to adjacent pixels in the same column, and iterate until all pixels are below saturation.	*Included*
Frame Transfer Smear		
During the transfer from the imaging array to the frame store array, every pixel in the column will be exposed to all stars in the column for a few milliseconds. The flux contaminates stars and adds additional photon noise.	Add a smeared average of all stars along their columns, with an amplitude set by the ratio of frame transfer to exposure times. *Currently assuming stars are constant flux; to correctly account for variability, we will have to couple the current exposure with the previous exposure.*	*Included*
Photon Noise		
Every photoelectron that lands on a pixel will contribute Poisson noise to the measurements.	Sum all expected fluxes (stars, backgrounds, galaxies, cosmic rays), add in a Gaussian $\sqrt{N}$ noise realization to each exposure.	*Included*
Readout Noise		
Extra noise from readout electronics.	Assume read noise is spatially constant and can be treated as Gaussian distribution with standard deviation of $\sqrt{M} \times 10e^{-}$, where M is the number of sub exposures contributing to an exposure. Add a realization of this noise to each exposure.	*Included*
Ghosting		
Internal reflections toss ghost images of bright stars across the field, contaminating target stars.	Difficult to model, but hopefully affecting a small number of pixels? *Find numbers on maximum ghosting amplitude.*	*Unnecessary?*
Scattered Light from Earth and Moon		

Adds time-variable background flux and photon noise.	Difficult to model, but hopefully affecting a small number of exposures. Presumably these images will simply be removed from consideration?	*Unnecessary?*
Electronic Crosstalk Pixels are weakly coupled between different regions of the detector. Bright stars can contaminate fainter targets.	*Talk to Joel about expected cross talk geometry and amplitude. Include as a nominal model?*	*Planned*
Non-linearity Detector response may be slightly non-linear up to saturation. Bright stars and faint stars on different parts of the non-linearity curve will respond differently to flux changes (and various systematics).	*In a meeting, this was said to be very small up to 150K electrons. Confirm and quantify this statement, include a nominal non-linearity correction?*	*Planned*
Asteroids (and Comets) For any given pixel, effectively an impulsive time variable background. Modeling them may be helpful for testing efforts to identify cosmic rays on-board the spacecraft. It would be interesting to see what TESS could do for solar system objects.	*Take bright objects from Minor Planet Center, treat each as ensemble of point sources, with RA and Dec calculated at many time points throughout an exposure.*	*Planned*
Proper Motion and Parallax Stars move over time. Barnard's star moves 10" = 1/2 pixel per year. Proper motion the TESS mission will have a small effect on light curves for a small number of (the most interesting!) stars. The bigger issue will be testing that codes know where to look for these stars in the first place.	*Learn more about UCAC4 proper motions, make sure I know what is going on with the rumored problems for high proper motion stars (and the fix), and propagate positions over time.*	*Planned*
Fringing Interference within detector leads to spatially varying background.	Supposedly very low in the deep depletion devices. *Do we know the expected amplitude? In space, it should be temporally constant?*	*Unnecessary?*

Stellar Variability		
Variability, both from target and from nearby blended stars, will make transit detection more difficult.	*Many different ways to approach this problem – use Kepler light curves?*	*???*
Transits		
We want to detect them!	*Use TESS Draft Target Catalog to populate stars with planets and transits, using the Kepler occurrence rates.*	*???*

2. Installation Instructions

- First, you will need a Python distribution, with access to `matplotlib`, `numpy`, and `scipy`. If you do not already have such a distribution installed, the STScI package Ureka (`http://ssb.stsci.edu/ureka/`) is an easy way to get an astronomer-friendly Python setup on your own computer.
- You will need several astronomy specific packages. If you have `pip` (which you should through Ureka), then install these from the command line with

  ```
  pip install astropy
  pip install astroquery
  ```
- Download the most recent `SPyFFI-**.tar.gz` file, unpack it, and from within the created directory run `python setup.py install`.
- Populate the `inputs/` directory. *Figure out good way to distribute the input files.*
- Usage, from within Python terminal (or, preferably, iPython terminal):

  ```
  # import the FFI package
  from SPyFFI.TESS import *

  # create a camera, this sets up the focal plan geometry
  C = Camera()

  # point the camera somewhere on the sky (in decimal degrees)
  C.point(82.0, 1.0)
  ```

```
# create an image of that patch of the sky
I = Image(C)
```