

A TESS SEARCH FOR DISTANT SOLAR SYSTEM PLANETS: A FEASIBILITY STUDY

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TESS (Ricker et al. 2015) monitors the sky through four cameras, each imaging $24^\circ \times 24^\circ$, with $21''$ pixels. During its two-year mission, TESS observes most of the sky, omitting within $\sim \pm 6^\circ$ of the ecliptic. Each ‘sector’ is observed for two 13.7 day TESS orbits. In its approved extended mission, TESS will re-observe most of the sky, including two-thirds of the ecliptic, increasing sky coverage to $\sim 94\%$.

The TESS cameras operate in shutter-less mode, taking 2 s exposures. These are combined into pre-selected regions recorded at 2-min cadence and full-frame images (FFIs) recorded at 30-min cadence. Cosmic ray rejection reduces the effective FFI integration time to 1440 s.

Faint objects can be detected by combining FFIs. With TESS, the signal from a solar-color source with magnitude I_C is $S = t_{\text{exp}} A s_0 \times 10^{-0.4I_C}$, where t_{exp} is the exposure time, $A = 69 \text{ cm}^2$ is the effective area, $s_0 = 1.45 \times 10^6 \text{ ph s}^{-1} \text{ cm}^{-2}$, and the bandpass is 600-1000 nm (Sullivan et al. 2015).

We estimate the noise as $N = [S + n_{\text{pix}} Z_L t_{\text{exp}} + n_{\text{pix}} n_r R_N^2]^{1/2}$, where n_{pix} is the number of aperture pixels, the zodiacal light is $Z_L \sim 47 - 135 \text{ ph pix}^{-1} \text{ s}^{-1}$, the number of readouts is n_r , and the read noise is $R_N \sim 10 \text{ e}^-/\text{pix}$ (Sullivan et al. 2015). At faint magnitudes, zodiacal light is the dominant noise source. The aperture is dictated by the pixel response function (PRF), with 90% ensquared energy within 4 pixels (Ricker et al. 2015).

Figure 1 displays the resulting detection efficiency curves. Combining $\sim 1,300$ exposures from a TESS sector, gives a 50% detection threshold of $I_C \sim 22.0 \pm 0.5$. TESS will observe portions of the sky for $\gg 27$ days, increasing the depth.

DIGITAL TRACKING

The curves in Figure 1 also apply to moving objects. Given a *known* orbit, one can predict an object’s location in a series of background-subtracted TESS FFIs and sum the flux. Figure 1 demonstrates this for three TNOs.

To discover new objects, with unknown trajectories, we can try *all possible orbits!* Previous searches have demonstrated the power of ‘digital tracking’ to detect solar system bodies significantly fainter than single exposure limits (Gladman et al. 1998, 2001; Holman et al. 2004; Bernstein et al. 2004).

One can shift a series of images to compensate for the parallax. The remaining proper motion then yields straight line trajectories. By shifting the parallax-compensated images along all plausible linear velocities, one can sum the flux and search for significant peaks in the signal. One only needs an *approximate* orbit. In the case of TESS, the size of the PRF sets the precision with which the signal in the images must be aligned.

The basis of Bernstein & Khushalani (2000) simplifies an exhaustive orbit search. Bernstein et al. (2004) demonstrated this with an HST survey for extremely faint TNOs. The key parameters are the parallax constant $\gamma = 1/d$ for distance d , scaled radial velocity $\dot{\gamma} = \dot{d}/d$, and transverse angular velocities $\dot{\alpha}$ and $\dot{\beta}$. For short time spans, $\dot{\gamma} \approx 0$.

The sky-plane resolution, P , is similar to the pixel scale. The number of angular velocity bins required is

$$N_{\dot{\alpha}} = N_{\dot{\beta}} = 2\dot{\alpha}_{\text{max}}/\Delta\dot{\alpha} \approx 100 \left(\frac{T}{27 \text{ day}} \right) \left(\frac{d}{25 \text{ au}} \right)^{-1.5} \left(\frac{P}{21''} \right)^{-1},$$

where α_{max} is the maximum bound angular velocity, T is the span of the observations, and the angular velocity resolution is $\Delta\dot{\alpha} \lesssim P/T$. The number of distance bins is small for TESS (Bernstein & Khushalani 2000; Holman et al.

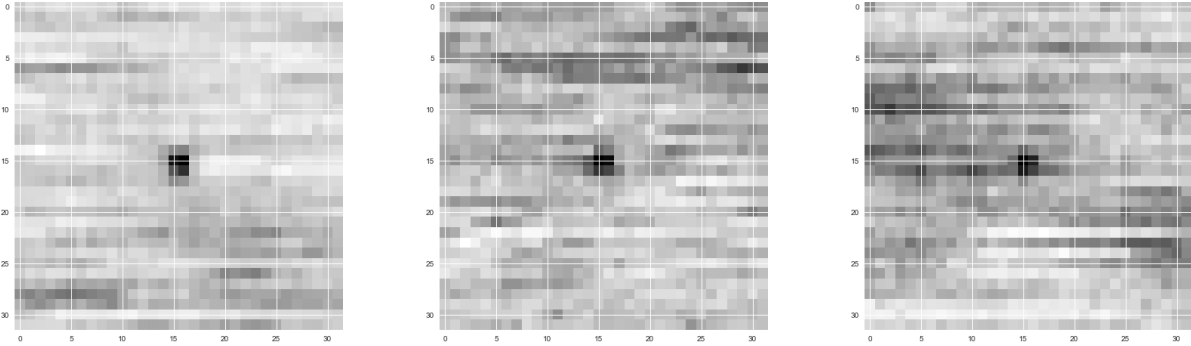
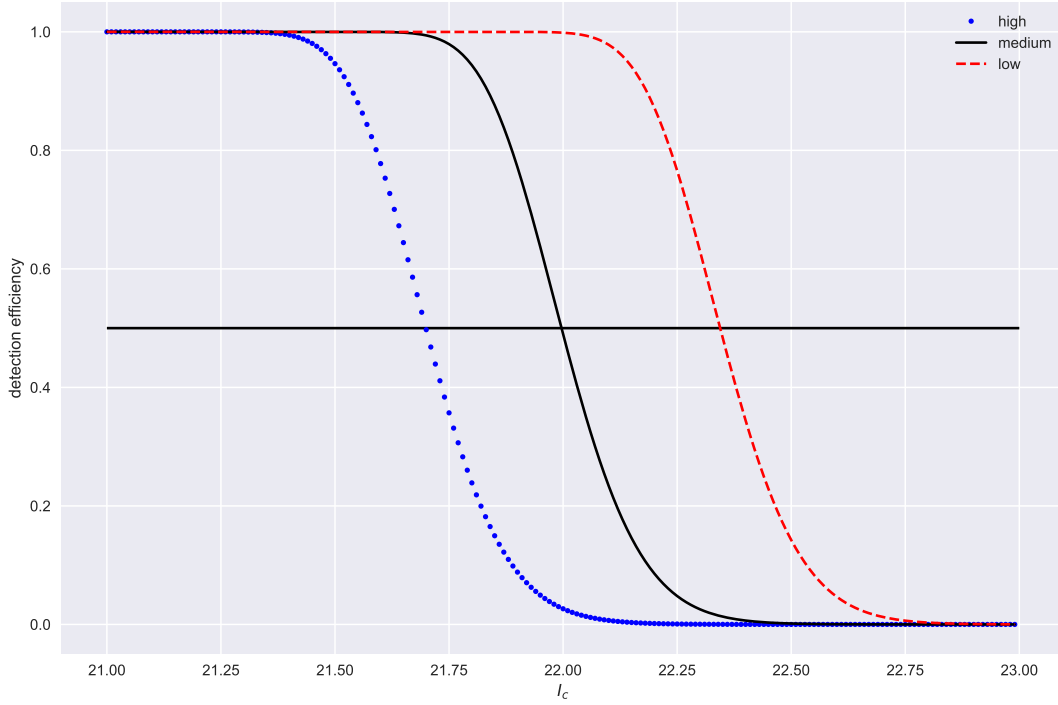


Figure 1. **Top:** Predicted detection efficiency $f = \frac{1}{2} [1.0 - \text{erf}(X/2)]$, where $X = n_\sigma - \text{S/N}$, and $n_\sigma = 5$. The curves correspond to zodiacal light values of $47 \text{ ph pix}^{-1} \text{ s}^{-1}$, $135 \text{ ph pix}^{-1} \text{ s}^{-1}$, and $270 \text{ ph pix}^{-1} \text{ s}^{-1}$. The third value doubles the maximum estimated zodiacal light value, to account for unmodeled noise. We assume $n_{pix} = 4$. **Bottom:** Differential TESS data stacked around the predicted locations of (90377) Sedna ($I_C \sim 20.2$), 2015 BP519 ($I_C \sim 21.6$), and 2015 BM518 ($I_C \sim 21.6$), left to right. Their S/N values are 11.1, 8, 7, and 7.3, respectively. Images created and processed using FITSH (Pál 2012).

2018):

$$N_\gamma = \gamma / \Delta\gamma \sim \left(\frac{T}{27 \text{ day}} \right) \left(\frac{P}{21''} \right)^{-1} \left(\frac{d}{25 \text{ au}} \right)^{-1} \sim 1.$$

The total number of operations is

$$N_{\text{op}} = N_{\text{sec}} N_{\dot{\alpha}} N_{\dot{\beta}} N_\gamma N_{\text{pix}} N_{\text{exp}} \sim 5 \times 10^{15} \left(\frac{N_{\text{sec}}}{26 \text{ sectors}} \right) \left(\frac{T}{27 \text{ day}} \right)^3 \left(\frac{P}{21''} \right)^{-3} \left(\frac{d}{25 \text{ au}} \right)^{-4} \left(\frac{N_{\text{exp}}}{1,300} \right) \left(\frac{N_{\text{pix}}}{16 \text{ Mpix}} \right),$$

where N_{sec} is the number of sectors, $N_{\text{pix}} \propto P^{-2}$ is the number of pixels, and N_{exp} the number of exposures. The Bernstein et al. (2004) search required $N_{\text{op}} \sim 10^{16}$ operations.

TESS can detect objects at $d \lesssim 900 \left(\frac{5 \text{ pix}}{n_p} \right)$ au, assuming a minimum $n_p \sim 5$ pixel displacement. The hypothesized Planet Nine (Trujillo & Sheppard 2014; Brown & Batygin 2016), has an expected magnitude of $19 < V < 24$ (Fortney et al. 2016; Batygin et al. 2019), raising the possibility that TESS could discover it!

The expected yield of a TESS search for TNOs and Centaurs will be the subject of a future investigation.

ACKNOWLEDGMENTS

We acknowledge Charles Alcock, Michele Bannister, Jason Eastman, Adina Feinstein, Wes Fraser, Pedro Lacerda, Ben Montet, George Ricker, Scott Sheppard, David Trilling, Chad Trujillo, Deborah Woods, Roland Vanderspek, and grants from NASA (NNX16AD69G, NNX17AG87G), Hungary (NKFIH-K125015), and the Smithsonian.

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