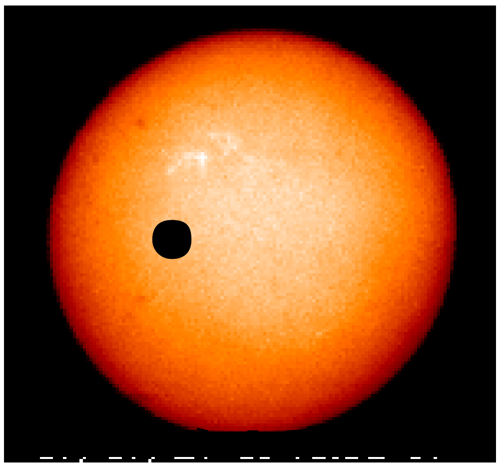
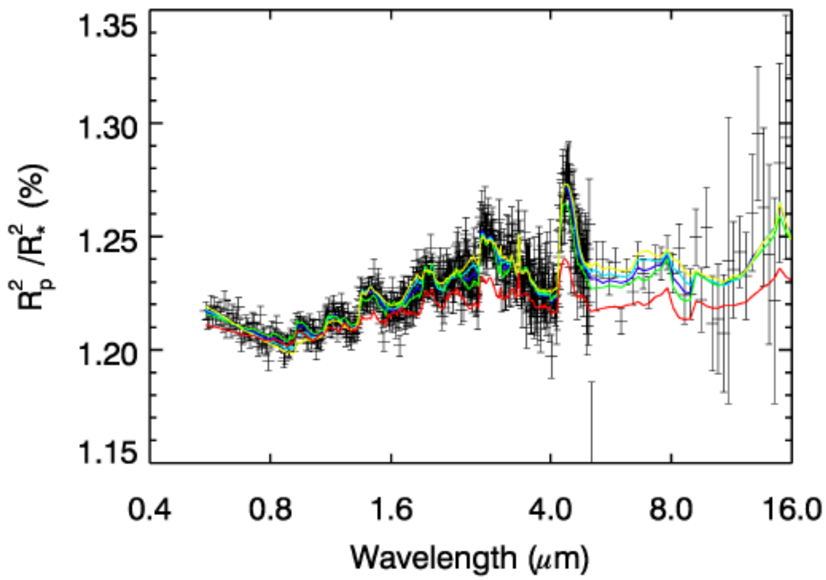
Exo-planets and the Astrophysical Time Domain with HIPO, FLIPO, and FPI+





planet Radius vs. Wavelength

Jeffrey Van Cleve

with data analysis and review by HIPO, FPI+, and FLITECAM Teams and exoplanet PI Daniel Angerhausen

Purpose of this Talk: Helping You Write a Compelling SOFIA Proposal for Precision Time-Domain Observations

So you can show that

- Science requires SOFIA-unique observations
  - Describe why ground-based or HST WFC3 won't do the job
- SOFIA instrument performance is adequate to distinguish competing models
  - Show that you understand systematic limits as well as raw SNR
- Observations with timing constraints are not unduly expensive to execute
  - $ cost of deployment and one-off instrument setups
  - Opportunity cost of science missions not flown because of flight time or $ expended on special event observations

This talk is NOT about Solar System eclipses and occultations for which SOFIA's mobility is essential regardless of instrument used

Overview

- Example Science Topics
- Introducing HIPO, FLITECAM, FLIPO, and FPI+
- Strawman Performance Requirements
- SOFIA Performance
- Constraints and Costs of fixed-time Event Scheduling

Precision (Spectro) Photometry Science

- Exoplanet Atmospheric Characterization
  - Transmission
    - Strawman Requirements
  - Reflection
  - Non-thermal equilibrium emission
  - Spatial variability
  - Temporal variability (weather)
- Asteroseismology
- Astrophysics
  - Flares
  - Starspots
  - Rotation Rate

Introducing Relevant SOFIA Science Instruments

- HIPO - High Speed Imaging Photometer for Occultation (HIPO), two simultaneous optical wavelengths
  - Many specialized readout modes for transient events
- FLITECAM - infrared camera/spectrograph operating in the 1.0 $\mu m < \lambda < 5.5 \mu m$ with spectral resolution up to ~1000
- FLIPO – simultaneous HIPO and FLITECAM mounted as one SI
- FPI+ – standard tracking camera for the SOFIA telescope with science grade CCD sensor
  - Can be paired with any other SI (including FLIPO)
  - One optical wavelength
- Other Instruments – not considered here since precision photometry (< 1000 ppm) not possible given lower SNRs and residual thermal background variation

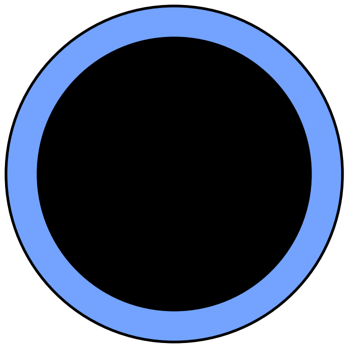
See earlier talks and Handbook for details

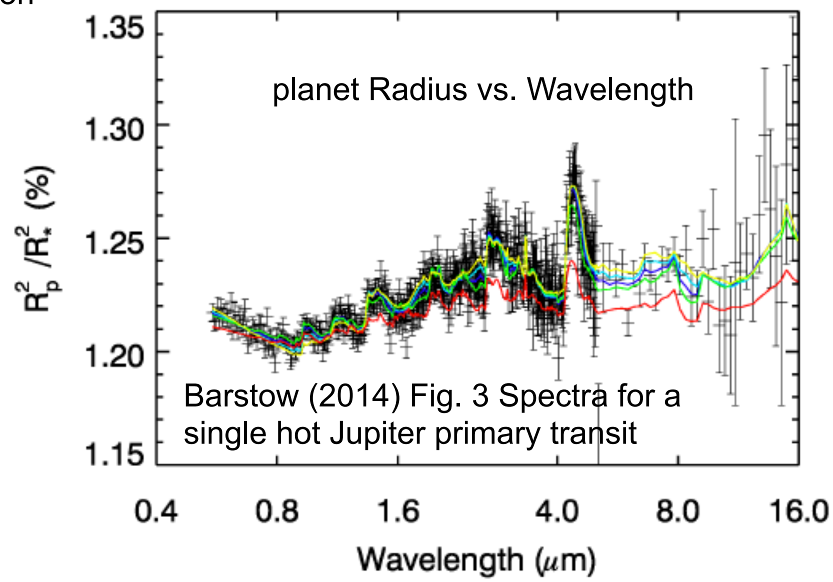
Photometric Precision Terms

- PP = Photometric precision. Usually multiplied by 10^6 to get ppm in exoplanet work
- SNR = signal-to-noise in the absence of systematic errors
  - This is what SITE will calculate for you
- LPP = Limiting photometric precision. The system cannot do better than this regardless of integration time or source flux.
  - Understanding/reduction requires capture of “instrument state vector” = engineering HK and derived image properties
  - Kepler primary mission LPP < 30 ppm
- PP = sqrt($1/SNR^2 + LPP^2$)
- Adding 1/SNR and LPP in quadrature is questionable since the noise sources contributing to LPP are typically neither white nor stationary

Photometric Performance Requirements Model

Absorpton Band Annulus simplified and exaggerated Cartoon





Tinetti, 2013

$$S_a \sim 5\left(\frac{2R_p H}{R_*^2}\right)$$

- Effective radius of planet varies with λ since light is absorbed more strongly at some λ than at others
- S_a = annulus of absorption relative to stellar area
  - Blue in cartoon is where (for example) water absorbs but other gases do not
  - Would like S_a/PP > 5
- R_p = radius of planet
- R_* = radius of star
- H = scale height of atmosphere

Photometric Peformance Requirements Results

Planet type	hot Jupiter	hot Jupiter	hot H-He Neptune	warm wate Neptune
R_p (km)	69200	69200	24500	24500
R_p/R_J	1.00	1.00	0.35	0.35
T_p (k)	1300	1300	1300	550
m (kg)	2.35E-03	2.35E-03	3.00E-03	1.80E-02
g (m/s^2)	17.4	17.4	11	11
H (km)	263.9	263.9	327.0	23.1
5*H (km)	1319.4	1319.4	1634.8	115.3

R_*	0.25	0.5	0.25	0.25
R_p/R_*	0.40	0.20	0.14	0.14
transit depth	15.84%	3.96%	1.99%	1.99%
atmos signal	6040.0	1510.0	2649.7	186.8
Required PP	1208.0	302.0	529.9	37.4

Look for SOFIA-specific opportunities where PP >= 300 ppm can do the science

SOFIA Optical Photometric Performance

- HIPO: LPP was demonstrated in-flight to be ~150 ppm (Dunham et al. 2014).
  - This is about the same as state-of-the-art ground-based VIS photometry (Nascimbeni et al., 2013)
  - Case for HIPO and FPI+ is Observatory mobility or simultaneity with IR wavelengths not accessible from ground
- FPI+: photon shot-noise limited down to 350 ppm for stars at least as bright as GJ1214 (R mag = 13.8)
  - LPP may be < 350 ppm but not yet demonstrated

SOFIA Near-IR Photometric Performance

- FLITECAM Imaging: photon shot-noise limited down to 1800 ppm in 15 min
  - Power spectrum white down to 1 mHz = 15 min so expect LPP < 1800 ppm, not yet demonstrated
  - Bean et al. (2011) obtained a PP < 450 ppm in K band photometry of GJ1214b, well above the shot noise limit
    - "… the highest-precision ground-based near-infrared transit light curve data that we are aware of."
  - J, H, and K photometry which require LPP >1000 ppm are not making good use of SOFIA compared to skilled ground-based photometry
- FLITECAM Spectroscopy: LPP not demonstrated < 10^4 ppm
  - But 1% is much better than the ground can do at water bands!
  - FLITECAM Grism calculator predicts adequate SNR > 1000 in 1 hr if you can bin spectral elements to increase SNR by sqrt(Δλ/λ) → match rebinned resolution to absorption width

Flight Planning Constraints and Costs of fixed-time Event Scheduling

- SOFIA is neither fixed to the Earth's surface or in a well-defined orbit, so flight planning has unique features
  - Direction telescope is pointing defines direction aircraft is pointing
  - Aircraft is moving 560 mph in direction it's pointing (hope so!)
  - Position of aircraft on Earth changes apparent position of target
  - Aircraft generally has to return to the same place it took off from
- Flight Planning white paper http://www.sofia.usra.edu/Science/observing/flightPlanning_whitePaper.pdf
- BG Andersson presentation earlier in this workshop

Flight Duration Constraints and Costs

- Aircraft has to take off and land from the same base
  - Palmdale or Christchurch
- Flights are 10.0 h with 2.0 h required to climb/descend, set up telescope, and turn
- 4.0 h available for an uninterrupted observation
  - Very difficult to do over Western CONUS because of restricted airspace
  - In practice, 3.0 h legs leave enough azimuthal freedom to schedule other targets, and have actually been scheduled
- Legs up to 8.0 h possible if aircraft lands somewhere besides where it takes off
  - Logistical loss of at least one other science flight
  - Science would have to be extraordinary and SOFIA-specific

Series Schedulability Risk and Costs

- The Cycle Scheduler (CS) tool approximates SOFIA as a fixed location
- CS aggregates available SOFIA flight dates for efficiency into single-instrument flight series
- If Cycle 4 is like Cycle 3, weak demand for other HIPO/ FLITECAM/FLIPO targets will give one or two week-long flight series in the entire Cycle.
- Hence your target has to have an event in a limited number of available nights if it is not to force an otherwise unneeded instrument change, which will cost as least one other science flight
- Extra thermal emission in FLIPO reduces FLITECAM SNR at $\lambda > 2.2$ μm for other people's science
  - Effectively imposes a cost in extra observing time or a lost flight to switch to FLITECAM-only mode

Single-Event Schedulability Random Phase Approximation (LRPA)

- probability that a transit of period P begins in a time interval Δt is $\Delta t/P$.
- SOFIA flight has t_f ~ 8.0 hr useful hours. Uninterrupted total time interval needed t_{tot} = transit duration d + time before ingress Δ_i + time after egress Δ_e
- the time available in a flight for a transit to start is $t_f - t_{tot}$
- the probability that this happens on a flight date is $(t_f - t_{tot})/P$
- the probability p_{fs} that this will happen at least once in a flight series of n_{ser} nights in a season is

$$p_{fs} = 1 - \left(1 - \frac{t_f - t_{tot}}{P}\right)^{n_{ser}}$$

T_{tot} = 1.5 hr, 5 night series

pfs	Period
0.98	12
0.78	25
0.50	50
0.29	100
0.15	200

To have a >50% chance of scheduling a transit, given $n_{ser} = 5$ and t_{tot} = 1.5 hr, you need P < 50 h

Consider in Your Proposal

- How the science depends critically on wavelengths where SOFIA is superior to the ground and HST WFC3 ($\lambda > 1.7$ μm)
- Whether you can do the science with only one optical wavelength at a low frame rate (< 4 Hz), simultaneous with your near-IR data
  - If 2 or more optical colors or high-speed sampling are critical you will need the FLIPO configuration
- The minimum amount of time you need before and after the event
- Whether the science can be done with a partial event
- Why SOFIA's estimated photometric precision is adequate
- If there's a target of interest opposite the Galactic Center (16h < RA < 20h, DEC > +60), a chronically undersubscribed region
  - 3+ hr chunks of time often available before/after GC legs

BACKUP SLIDES

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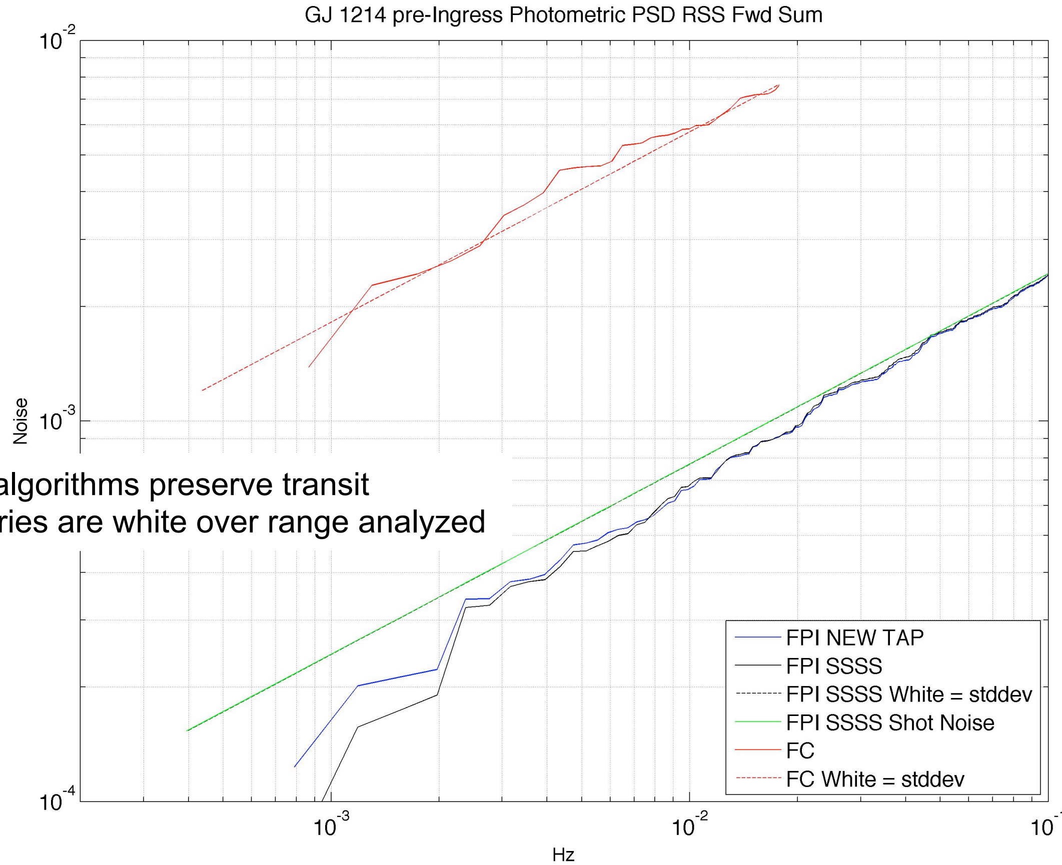
Photometric Precision Forward Sums for SOFIA



- Time series correction algorithms preserve transit
- Error-corrected time series are white over range analyzed

Definition of Power Spectral Density Forward Sum (PSDFS):

$$PSDFS(\upsilon) = \sqrt{\int_0^{\upsilon} |F(S(t))|^2 \, d\upsilon'}$$ where F is the Fourier transform.

Data from Angerhausen, Dreyer et al, in prep

Multi-Event LRPA

- If *m* observable events of the same object must occur within the same flight series

$$p_{fs}(\geq m) = \sum_{n=m}^{n_{ser}} \frac{n_{ser}!}{n!(n_{ser}-n)!} \left(\frac{t_f - t_{tot}}{P} \right)^n \left(1 - \frac{t_f - t_{tot}}{P} \right)^{n_{ser}-n}$$