Science yield modeling with the Exoplanet Open-Source Imaging Mission Simulator (EXOSIMS)

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EXoplanet Open-Source Imaging Mission Simulator

- **EXOSIMS** - developed as part of WFIRST Preparatory Science
- Performs ensembles of simulations to determine science yield distributions
- Modular architecture, allows multiple mission designs
- [https://github.com/dsavransky/EXOSIMS](https://github.com/dsavransky/EXOSIMS)
The Scheduler – which target to observe?

- Find spacecraft orbital START positions and filter out unavailable targets (including settling time, occulter slew time)
- Calculate integration times for the preselected targets and filter out $t > \text{threshold}$ (arbitrary)
- Find spacecraft orbital END positions and filter out unavailable targets
- Filter out all previously visited targets, unless in revisit list (e.g. detected planets, but not yet characterized)
- From remaining, choose the target with highest completeness
Planet integration time – noise budget

cf. Kasdin & Braems 2006
Nemati 2014
Stark et al. 2014

Camera/detector noise:
• dark current
• clock-induced charge
• readout noise

Planet signal + star residual + exozodi light

local zodiacal light

keepout angle

sun
How do we determine integration time?

• spectral flux density electron count rate

\[ C_{F_0}(\lambda) = \epsilon A \Delta \lambda T(\lambda) F_0(\lambda) \]  
with  
\[ F_0(\lambda) = 10^{\left(\frac{\lambda - 550}{770}\right)} \]

• planet signal

\[ C_p(\lambda) = C_{F_0}(\lambda) 10^{-0.4} (\text{vmag} + \Delta \text{mag}) \]

• star residual

\[ C_{sr}(\lambda) = C_{F_0}(\lambda) 10^{-0.4} \text{vmag} Q(\lambda) \]

• background noise

\[ C_b(\lambda) = C_{sr}(\lambda) + C_{zl}(\lambda) + C_{dc} + C_{cc} + C_{rn} \]

• SNR

\[ SNR = \frac{C_p t}{\sqrt{C_p t + C_b t + (f_{pp}C_{sr}t)^2}} \]

with  
\[ f_{pp} = \text{post-processing factor} \]
Implemented detection methods

- From Nemati SPIE 2014

\[ t(\lambda) = \frac{(C_p + C_b) \text{SNR}^2}{C_p^2 - (\text{SNR} f_{PP} C_{sr})^2} \]

- From Kasdin & Braems 2006

\[ t(\lambda) = \frac{C_b}{C_p^2 \Delta \alpha} \left( z_{FA} - z_{MD} \right) \sqrt{1 + \frac{C_p \sum \overline{PSF}_{ij}^3}{C_b \sum \overline{PSF}_{ij}^2}} \]

where \( \Delta \alpha \) is the dimensionless pixel size, and \( \overline{PSF} \) is the normalized PSF.
Comparison using EXOSIMS

- method 1, Nemati 2014: setting a **SNR = 5**
- method 2, Kasdin 2006: \( P_{FA} = 3\times10^{-5} \) and \( P_{MD} = 1\times10^{-3} \)
Null hypothesis $H_0$: there is no planet.
Alternative hypothesis $H_1$: there is a planet.

- Fail to reject $H_0$ while true (True Negative):
  \[ P(\text{no detection}) = P(Z < z_{FA}) = F_Z(z_{FA}) = 1 - p_{FA} \]
- Reject $H_0$ while true (type I error, False Positive):
  \[ P(\text{false alarm}) = p_{FA} \]

- Reject $H_0$ while false (True Positive):
  \[ P(\text{detection}) = P(Z < z_{MD}) = F_Z(z_{MD}) = 1 - p_{MD} \]
- Fail to reject $H_0$ while false (type II error, False Negative):
  \[ P(\text{missed detection}) = p_{MD} \]
Probabilistic case

Case 1, no calculated SNR.

For the whole system:
- True Negative: \( P(\text{no detection}) = F_z(z_{FA}) = 1 - p_{FA} \)
- False Positive: \( P(\text{false alarm}) = p_{FA} \)

\[ H_0 \sim N(0, 1) \quad \text{and} \quad H_1 \sim N(z_{FA} + z_{MD}, 1) \]
Probabilistic case (cont’d)

Case 2.1, calculated SNR = $z_{obs} > z_{FA}$ --> reject $H_0$.
- True Positive: $P($detection$) = P(Z < z_{obs}) = F_Z(z_{obs})$
- False Positive: $P($false alarm$) = 1 - F_Z(z_{obs}) = p$-value

\[ H_0 \sim N(0, 1) \quad \text{and} \quad H_1 \sim N(z_{FA} + z_{MD}, 1) \]
Case 2.2, calculated SNR = $z_{\text{obs}} < z_{\text{FA}}$ --> fail to reject $H_0$.

- True Negative: $P(\text{no detection}) = P(Z < z_{\text{FA}} + z_{\text{MD}} - z_{\text{obs}}) = F_Z(z_{\text{FA}} + z_{\text{MD}} - z_{\text{obs}})$
- False Negative: $P(\text{missed detection}) = 1 - F_Z(z_{\text{FA}} + z_{\text{MD}} - z_{\text{obs}}) = p$-value
Backup slides
Deterministic case
We ‘know’ if there is a planet or not

Case 1, there is no planet, $H_0$ is true.

For the whole system:
- True Negative: $P(\text{no detection}) = F_Z(z_{FA}) = 1 - p_{FA}$
- False Positive: $P(\text{false alarm}) = p_{FA}$

$H_0 \sim N(0, 1)$
Case 2, there is a planet, $H_0$ is false.
- if $\text{SNR} = z_{\text{obs}} > z_{\text{FA}}$ --> reject $H_0$: True Positive (detection)
- if $\text{SNR} = z_{\text{obs}} < z_{\text{FA}}$ --> fail to reject $H_0$: False Negative (missed detection)
Populate Universe: e.g. known RV planets

M-R relation from FORECASTER (Chen and Kippling 2016) available at github.com/chenjj2/forecaster

- Volatile envelope
- Self compression
- Hydrogen burning

- Terran worlds
- Neptunian worlds
- Jovian worlds
- Stellar worlds

RV planets:
- Unknown radius
- Known radius

- $2.0 \, M_⊕$
- $0.41 \, M_J$
- $0.08 \, M_☉$
Example of joint probability density function

- PDF of planet orbital and physical properties
- Probability to detect a planet
- Updates completeness values for systems previously observed

Garrett et al. 2016
Planet integration time – noise budget (cont’d)

normalized star PSF

planets (star cancelled)

+ local zodi + exozodi
Planet integration time – noise budget (cont’d)

+ detector noise
+ residual speckles
post-processing 10x gain
post-processing 30x gain
e.g. WFIRST contrast/throughput curve

Data from Traub 2016 JATIS

Contrast/Throughput vs. Separation (arcsec)

Log scale

Log scale

Linear scale

Circles = FWHM

Log10

Log scale

Linear scale