VELOCIRAPTOR

The **V**ery **E**xtensive **L**and-based **O**bserving **C**ampaign **I**nvestigating the **R**elative **A**bundance of **P**lanets **T**ransiting **O**uter **R**egions

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Modern Astronomical Optics Team Project 1

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Fundamental Exoplanet Questions Motivate a Full Sky Transit Survey

In 2008, the NSF-NASA-DOE ExoPlanet Task Force (ExoPTF) indentified three main questions in longterm exoplanet research:

1. What are the physical characteristics of planets in the habitable zones around bright, nearby stars?
2. What is the architecture of planetary systems?
3. When, how and in what environments are planets formed?

Addressing these questions requires a much greater number of planetary systems to study. A full sky survey of exoplanets needed to constrain f_p (fraction of stars with planets) and n_e (avg # that could support life) of the Drake equation.

$$N = R^* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

Improving transit surveys

Transit statistics inform planetary formation models. Known transits can be targets for transit spectroscopy to determine atmospheric composition and structure.

Recommendation by ExoPTF (2008) for significant progress in transit surveys:

(i) Discover hundreds or more of transiting gas giants
(ii) Efficiently discover longer period planets
(iii) Discover smaller planets

Scientific Mission: An Ambitious Ground-Based Transit Survey

Primary Objective

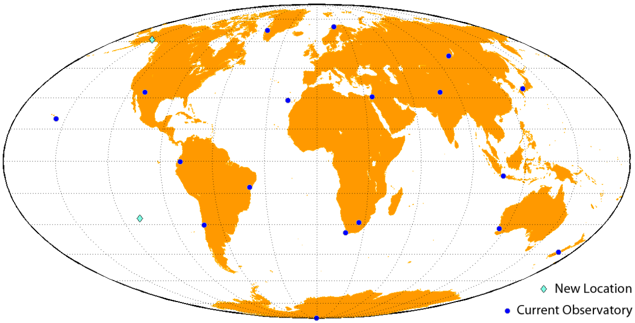
From the ground, find most (all) transits around bright stars!

	Requirement	Goal
Sky Coverage	Full Sky	Full Sky
Target magnitudes	$m_v < 15$	$m_v < 15$ (reasonable expectation of RV follow-up)
Detection Sensitivity	Most 1% transit depths	Confidently measure 0.5 % transit depth after a single transit
SNR of Detection	-	> 5
Longest Orbital Period Detected	-	12 years (Jupiter-like planets in Jupiter-like orbits!)
System Stability	-	24 years (two transits of Jupiter-like planets in Jupiter-like orbits!)
Data archives	Build catalog for follow-up observations	Build catalog for follow-up observations

Design Challenges

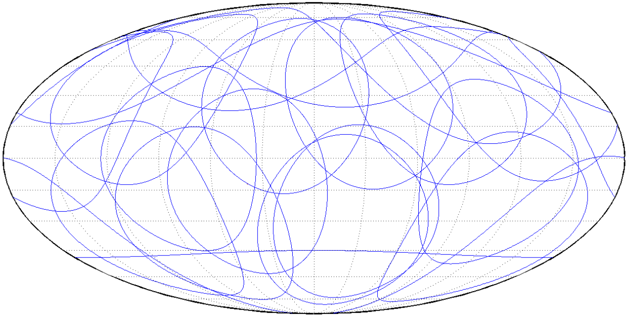
- Large, continuous field of view is required
  - Minimizing unnecessary interruptions
- Scintillation noise
  - Not all sites are ideal observing locations
- Stars with large differences in magnitude
  - Detector saturation
- Appropriate angular resolution

Survey Configuration - Earth View



- Site locations based on geographic location, elevation, and current use
- 20 total sites (10 per hemisphere)

Survey Configuration - Sky View

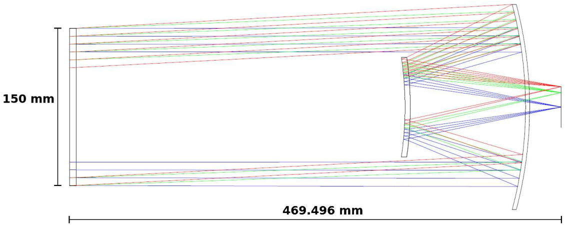


- Each site is purposefully limited to $\pm 45^\circ$ field of regard (reduces effects of scintillation and extinction)
- Field overlap also gives flexibility during weather and maintenance issues

Optical Design

- Need enough aperture to beat down noise
  - 6" required
- Need to cover full sky
  - $41,253$ square degrees
- Need to provide adequate resolution
  - $\sim 10''$ required
- Systems Considered:
  - COTS Refractors/Reflectors
  - Custom Refractors
  - Custom Reflectors

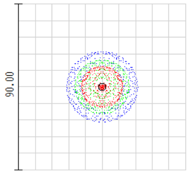
Optical Design



- Schmidt Camera
- 150 mm Entrance Pupil
- F/2.5
- 30 Square Degrees FOV
- 44 % Obstructed

Optical Design Details

- $7.8''$ resolution
- $\sim 14\mu$m RMS Spot Size



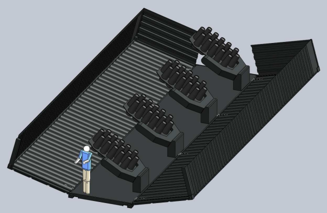
- Apogee ALTA U16M
- Actively Cooled CCD
- 4096×4096 array, 9 μm $\times 9\mu$m pixels
- 9e$^-$ noise; $100,000e^{-1}$ well depth

Error Budget

This is our original slide...please see the additional slides for a more detailed error budget analysis

- Photon Noise (M15, half day transit duration)
  - M15: 1e11 ph sec^{-1} m^{-2} μm^{-1}, 0.1 μm bandpass, 12 hrs
  - SNR 15.5 for a 1% transit depth
- Readout Noise
  - SNR $\sim$ 1000
- Scintillation
  - 3000 ft elevation, 90° zenith, 12 hrs
  - SNR 62
- Other Sources

Site Configuration



- For full sky coverage, each site is responsible for $\sim$ 2100 sq. deg.
- Allowing 10% field overlap, plus 30% for weather/down site allowance, $\sim$ 102 telescopes are needed per site
- We anticipate 14 telescopes per mount, 8 mounts per sites, 20 sites –> 2240 telescopes

Observation Scenario

- Autonomous operation
- 6 hours of observing per night
- Dedicated field for each mount
- Alternating exposure times
  - 300 ms
  - 10 s

Anticipated Results: How Many Planets?

Note this slide has been updated as requested

-> At transit depth of 1% : > Jupiter radius planets

Estimating the Number of planets expected:

(i) 20 million stars of < 15 magnitude

(ii) Use same assumptions as the Monte Carlo model employed for the TESS study (Ricker et al, 2010), (Brown et al, 2008)

(iii) Assume a flat #/a

-> 20,000 planet candidates!

Can we find rocky planets?

Note this slide has been updated as requested

Most optimistic measurements: all transits coadded with minimum SNR=5
Coadded signal scales as $(\frac{r_{planet}}{r_{star}})^2 \frac{1}{T_{planet}}$, where T is the orbital period.

- Mercury: 16 million (assumptions extrapolated this far may not be valid)
- Venus: 2 million
- Earth: none, $1.3R_e$: 1.4 million
- Mars: none
- Jupiter: 20,000

Smallest planets in Mercury-sized orbit

Note this slide has been updated as requested

Most optimistic measurements: all transits coadded with minimum SNR=5.

SNR$= 5 = N_{transits} * \frac{depth}{noise}$ For lowest noise limit shown in error budget

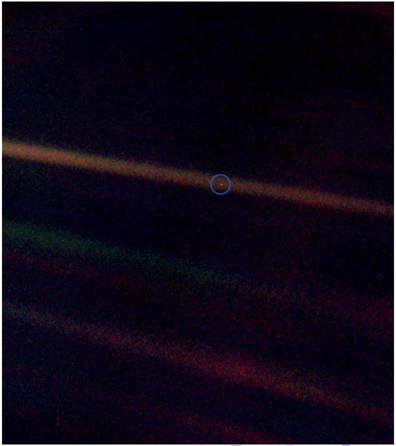
(brightest stars, coadded), we could detect a planet the size of the moon.

Projected Cost

		Number of Items	Cost Per Item	Total Cost
Equipment:	Telescope	2240	$ 3,000	$ 6,720,000
	Detectors	2240	$ 10,000	$ 22,400,000
	Mounts	160	$ 30,000	$ 4,800,000
	Enclosures	40	$ 15,000	$ 600,000
Logistics:		-	-	TBD
Operations:		-	-	TBD
Total:				> $30,452,000

Summary

- 2240 telescopes
- 20 sites
- 30 sq deg FOV per telescope
- 24 year program
- Will find Sun/Jupiter systems
- Will inform follow-up missions
- First glimpse into outer regions of solar systems similar to our own



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Requested Supplementary Slides

Cost Analysis

We estimate the projected cost of the entire project as follows:

- Estimate equipment costs based on optical design
- Allow 5 FTES for design labor for first 3 years of project
- 11 FTEs for operations cost during operations phase (include 0.5 FTE per established site and 1 FTE at new sites)
- 4 FTEs for 5 years to developed data pipeline
- 2 FTEs for data scientists in operations phase
- Management costs equivalent to 50 percent of total payroll
- Equipment maintanence of 1 percent total inital equipment cost per annum
- Estimate transportation and electricity costs per site considering expected power usage
- Archival costs based on 4 times data compression at 300 dollars per terabyte of data
- All projections corrected for inflation except maintenance and archival costs (cost of storage per TB should decrease over time)

Cost Analysis continued:

The next three slides include:

1. Itemized yearly projected cost table
2. Chart of yearly projected costs
3. Chart of cummulative project cost over the project duration

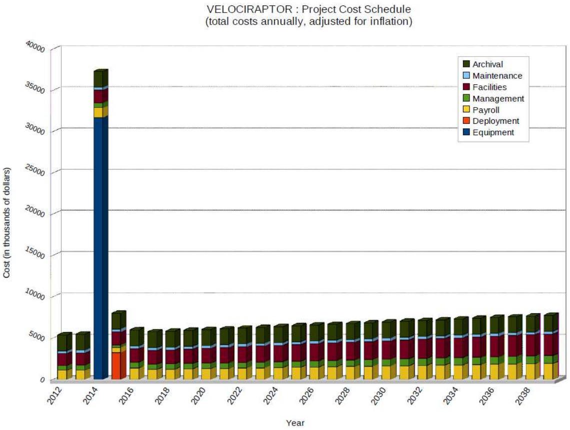
VELOCIRAPTOR: Projected Project Cost Estimates

(costs in thousands of dollars adjusted for 3 percent annual inflation)

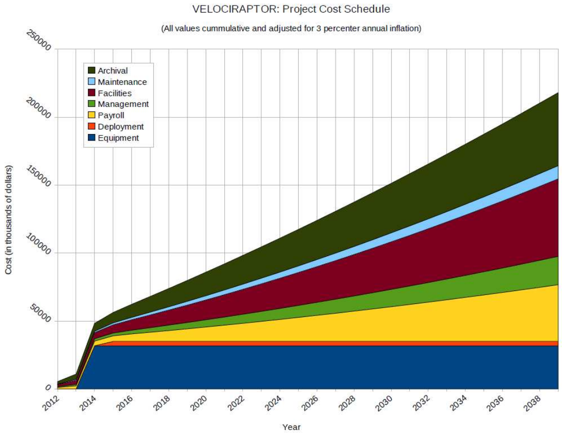
	2012	2013	2014	2015	2016	2017	2018	-> maintain same funding level through 2039 ->	Total
								...	
Project Phase	Design	Design	Construction	Deployment	Operations	Operations	Operations	...	
Equipment								...	
Telescopes	-	-	6720	-	-	-	-	...	6720
Detectors	-	-	22400	-	-	-	-	...	22400
Mounts	-	-	4800	-	-	-	-	...	4800
Enclosures	-	-	600	-	-	-	-	...	600
Site Computing	-	-	224	-	-	-	-	...	224
Payroll								...	
Design Team	563	580	597	-	-	-	-	...	1740
Pipline Developement	375	387	398	409	420	-	-	...	1988
Operators	-	-	-	-	688	708	729	...	22208
Computer Archivists	188	193	199	204	210	216	221	...	7396
Data Scientists	-	-	-	-	-	188	193	...	5750
Deployment								...	
Shipping, land procurement, facilities				3000				...	3000
Management	563	580	596	307	700	611	627	...	19891
Facilities								...	
Electricity	1250	1287	1325	1362	1400	1437	1475	...	49175
Transport/Incidentals	200	206	212	218	224	230	236	...	7868
Maintenance	348	348	348	348	348	348	348	...	9744
Archive Costs	1920	1920	1920	1920	1920	1920	1920	...	53760
								...	
Totals:	5407	5501	40339	7768	5910	5658	5749	...	217264.

TOTAL PROJECT COST ESTIMATE: $ 217,264,000

Annual Projected Cost



Cummulative Cost Over Project Lifetime



Error Budget: Flux Constraints

Observing $4 > m_V < 15$ stars is a challenge to dynamic range

Flux on each exposed detector pixel

$$F(\Delta t) = F_{0,V} \times 2.512^{-m_V} \times \pi r^2 \times \Delta\lambda \times \zeta \times (1. - obs) \times \Delta t \times n_{pix}^{-1}$$

$F_{0,V} = 9.97 \times 10^{10}$ ph sec^{-1} m^{-1} μm^{-1} m_V - visible magnitude of source; range from 4 to 15

r - radius of entrance pupil (collecting area), designed at 75 mm

$\Delta\lambda$ - wavelength bandpass of observation, assume 0.1 μm

ζ - total efficiency, assumed to be 50 percent (the detector quantum efficiency is 60-70 percent)

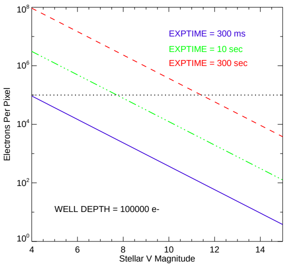
obs - total obstruction of the entrance pupil (44% in our design)

ΔT - total exposure time

n_{pix} - RMS spot size in number of pixels (4 in our design)

(gain is assumed to be 1)

Error Budget: Flux Constraints



- Detector well depth is $100,000\ e^-$
- Must minimize exposure time to not saturate bright stars
- Longer exposure times needed to increase counts for dimmer sources
- Must be aware of both the saturation level and detector noise sources to constrain error budget.

Error sources

Photon Shot Noise

$\sigma = \sqrt{F(\Delta t)}$

Background Sky Noise

$\sigma = \sqrt{F_{sky}(\Delta t)}$
We assume a visible sky brightness of 19 arcsec^2, on a resolution element of $(7.8'')^2$

Detector Readout Noise

Set by detector -> The ALTA U16M detector has 9 e^- readout noise per exposure.

Detector Dark Current Noise

$\sigma = \sqrt{F_{dc}(\Delta t)}$,
where $F_{dc}(\Delta t)$ is the dark current of the detector
The ALTA U16M detector gives 0.2 e^- per pixel per second of exposure.

Atmospheric Scintillation

$S = 0.004 airmass^{-3/2} D^{-2/3} t^{-1/2} exp(-h/h_0)$
We use an airmass at a 45 degree zenith angle, and a height of 1 km. $h_0 = 8km$
D is the diameter of the telescope and t is the exposure time

Notes regarding coadding of errors

- All noise sources are added in quadrature.
- The relative error decreases as multiple signal frames are coadded. This reduction in error is proportional to $1./\sqrt{n_{exp}}$
- However, this gain is only achieved when the planet is transiting (i.e. during the signal), and is thus a function of orbital period (and so also semimajor axis)
- In the following plots, we show the results for an absolutely "ideal" case where a planet transits once an observing day for 8 hours.
- In this idealized case, coadded multple transits of an assumed oribital period grants high gains in sensitivity.
- In what follows, we can rocky Earth-type planets for dim stars, if those planets orbit very frequently.

Note regarding plots:

The following graphs give the contributions of the different noise sources to the relative error, not simply the noise.

Thus, the photon noise does not decrease for dim stars, rather its relative error contribution decreases as the measured flux begins to be dominated by the sky brightness.

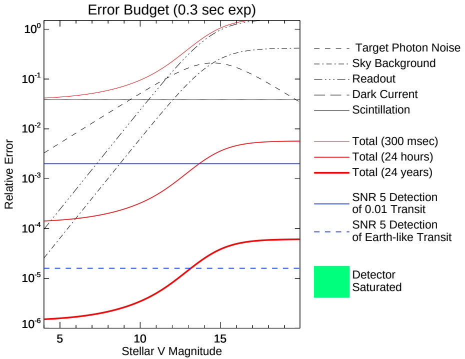
Error Budget: Lowest exposure time (300 ms)

Advantages

- Bright stars do not saturate
- We can detect rocky Earth-type planets for bright stars using 24 years worth of observations
- Can detect 0.01 transit depth for brighter stars ($m_V > 13$)from one day's worth of observations

Disadvantages

- Cannot detect 0.01 transit depth for dim stars from one day's worth of observations
- Dim star observations dominated by readout noise of the detector



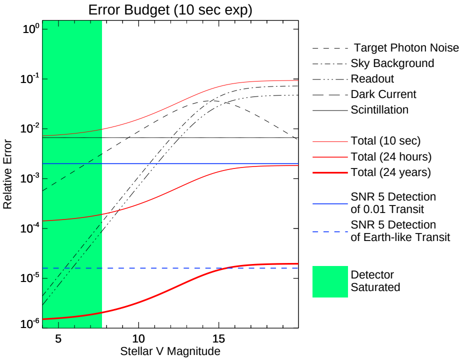
Error Budget: 10 second exposure time

Advantages

- Dim stars not dominated by readout noise, but rather photon and sky background noise
- We can detect rocky Earth-type planets for dim ($m_V = 15$) stars using 24 years worth of observations
- One day's observations enough for 0.01 transit detection (SNR =5) for $m_V = 15$ stars.

Disadvantages

- Bright stars ($m_V > 7.65$) saturate



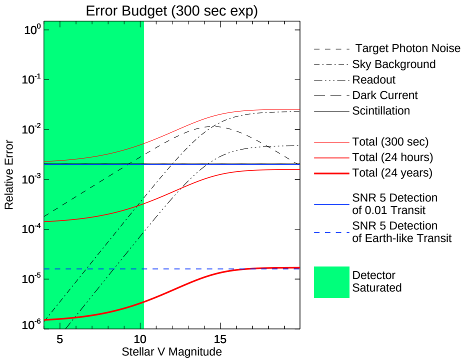
Error Budget: 300 second exposure time

Advantages

- Dim stars not dominated by readout noise
- Can still detect Earth-like planets for dimmest target stars ($m_V = 15$) using 24 years worth of observations
- Easy detection of 0.01 transit depth from one day's observations for all stars

Disadvantages

- Bright stars saturate ($m_V > 10.25$)
- Sky brightness dominates very dim stars
- Not a significant advantage over 10 second observations.



Error Budget Conclusions

- Only two exposure times necessary.
  - 300 milliseconds exposures necessary to detect 0.01 transits around bright stars without detector saturation.
  - 10 second exposures necessary to reduce readout noise for dim stars
  - 300 second exposures not necessary to achieve goals -> sky brightness dominates dimmest stars
- For 24 years worth of observations, rocky Earth-like planets of short orbital periods can be found for all target stars