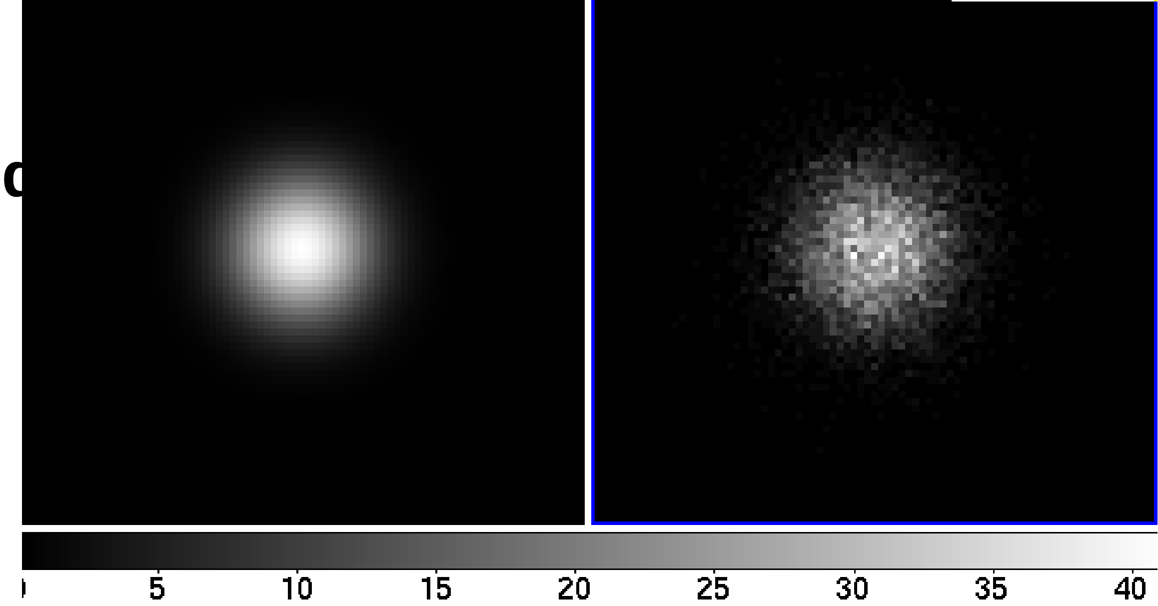
Transit photometry

OUTLINE:

Error sources

Transit surveys projects

Error Sources: Photon noise
Can an Earth transit be detected with a 1-m telescope around a m_V = 10 star ?



Photon noise = $\mathrm{sqrt}(N_{ph})$

Signal / Noise ratio (SNR) = N_{ph} / $\mathrm{sqrt}(N_{ph})$ = $\mathrm{sqrt}(N_{ph})$

Example: 1-m telescope, m_V = 10 source, 0.1 um effective bandwidth

(m_V=0 : 1e11 ph/s/m^2/um)

Earth transit duration = 0.54 day

SNR (1 sec) = 883

SNR (0.54 day) = 1.9e5 (5 ppm transit depth could be measured with SNR = 1)

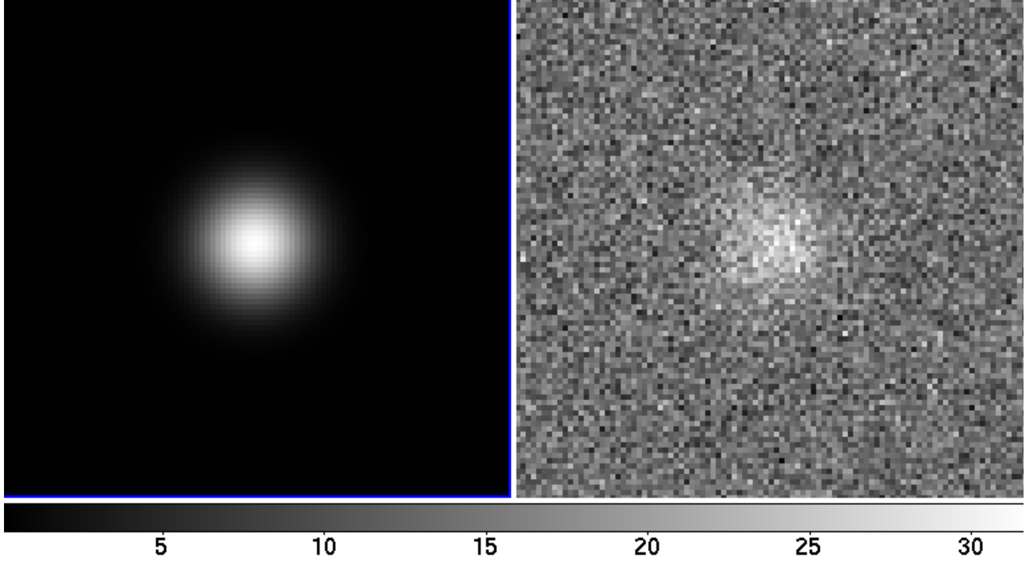
transit = 8e-5

transit SNR = 15.3 (photon noise only)

→ single Earth transit could be detected with 1-m telescope

Note : sky background has been neglected

Error Sources: Readout noise
Can an Earth transit be detected with a 1-m telescope around a $m_V = 10$ star ?



Readout noise for good detector = 10 e- per pixel
Assuming 200000e- full well depth, flux distributed over 10 pixels, 1e- per ADU

Flux = 780000 ph/s = 780000 e-/s
Max exposure time = 2.5s (to avoid saturation) → 2e6 e- per exposure
Noise = 32 e- per exposure

SNR = 6.25e4 per exposure (2.5 sec)

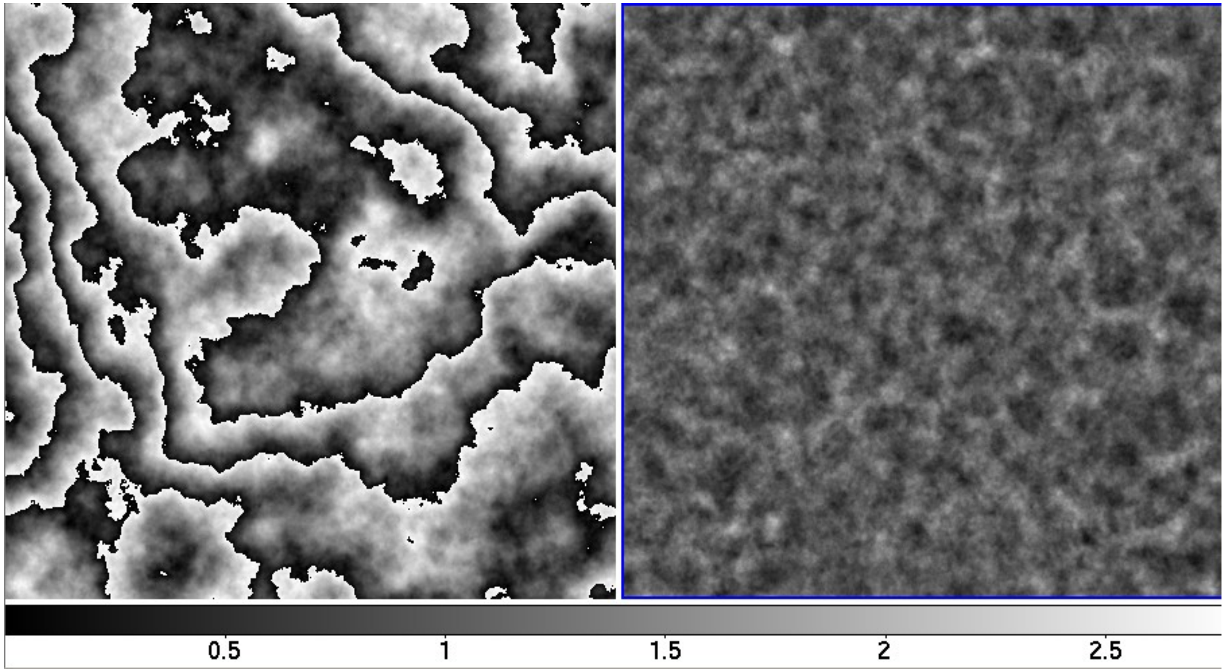
Earth transit duration = 0.54 day

SNR (2.5 sec) = 6.25e5
SNR (0.54 day) = 8.5e6

transit = 8e-5
transit SNR = 683 (readout noise only)

→ single Earth transit could be detected with 1-m telescope

Error Sources:
Atmospheric scintillation



Atmospheric phase ***Atmospheric ampl. (scintillation)***

Scintillation noise (multiplicative)
$= 0.004 \text{ airmass}^{3/2} D^{-2/3} t^{-1/2} \exp^{-h/h0}$

~ 1/cos(zenith angle) — Tel diam [m] — exp time [sec] — altitude / 8km

0.54 day long transit → Relative error = 1.85e-5

SNR = 0.23

→ ATMOSPHERIC EFFECTS DOMINATE FUNDAMENTAL NOISE EXCEPT FOR FAINT STARS

PSF variations, interaction with pixels can also be important

Error Sources: Atmospheric extinction

Wavelength (nm)	Extinction (mag / air mass)
310	1.37
320	0.82
340	0.51
360	0.37
380	0.30
400	0.25
450	0.17
500	0.13
550	0.12
600	0.11
650	0.11
700	0.10
800	0.07
900	0.05

Mauna Kea extinction

Air is not perfectly transparent

transmission = $2.5119^{-(\text{extcoeff x airmass})}$

~ 1/cos(zenith angle)

Transmission varies across the image
This variation is time-dependent due to object trajectory on sky
→ if the reference is not co-located with target,
this will create a **time-dependent differential extinction**

Example: 10 deg diameter field, zenith angle = 45 deg
Airmass varies from 1.305 to 1.556 across the field
Transmission at 550 nm varies from 0.842 to 0.866

→ differential extinction = 2.36%

Note that extinction is also color-dependent: problem since target color is different from reference color

Calibration technique for accurate photometry from the ground (& from space ?)

Differential photometric measurement:
Simultaneous target photometry $F_m(t)$ and reference $F_R(t)$ photometry
Wide field imaging system used to acquire simultaneous measurements

Calibrated photometry : $F(t) = F_m(t) / F_R(t)$

F(t) is insensitive to common extinction

Improvements on this scheme:

(1) Use a **combination of several reference stars** to create $F_R(t)$

(2) Carefully **select stars used to construct reference**: similar airmass, color, brightness as target

(3) Measure correlation between target flux and candidate reference star(s) flux to identify best reference star(s). **Construct linear combination of reference stars flux that optimally reproduces target flux variations**, and use this as $F_R(t)$

(4) Remove trends that are not part of a transit signal

Calibration technique for accurate photometry from the ground

Example :
robotic DSLR camera system
(see www.naoj.org/staff/guyon)

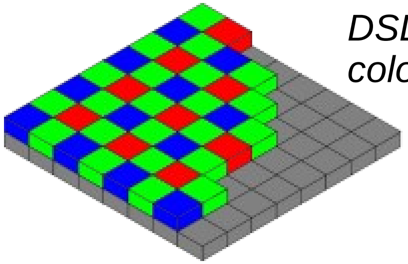
Robotic imaging system at Mauna Loa obs
Uses two Canon DSLR cameras + lenses

DSLR camera system is a cost effective solution:

- multiple units can be deployed at small cost

But color pixels are a huge problem for photometry...

(Star falling on a red filter will look red)

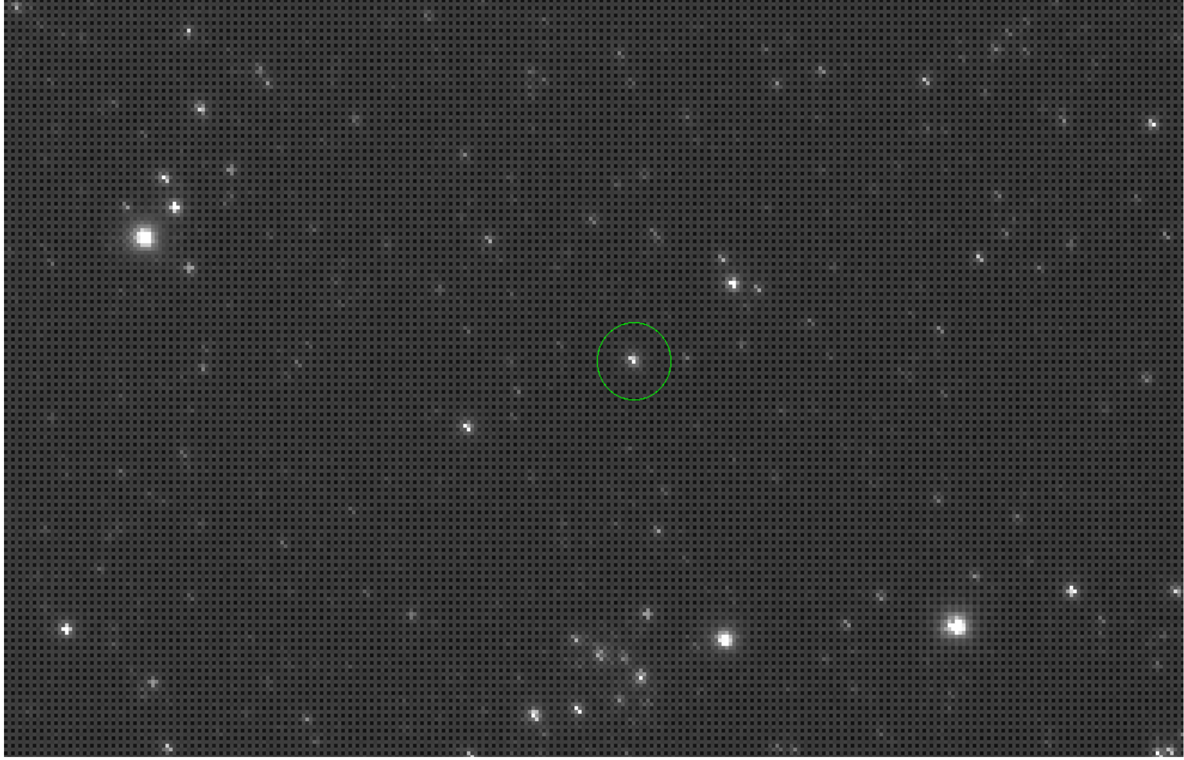


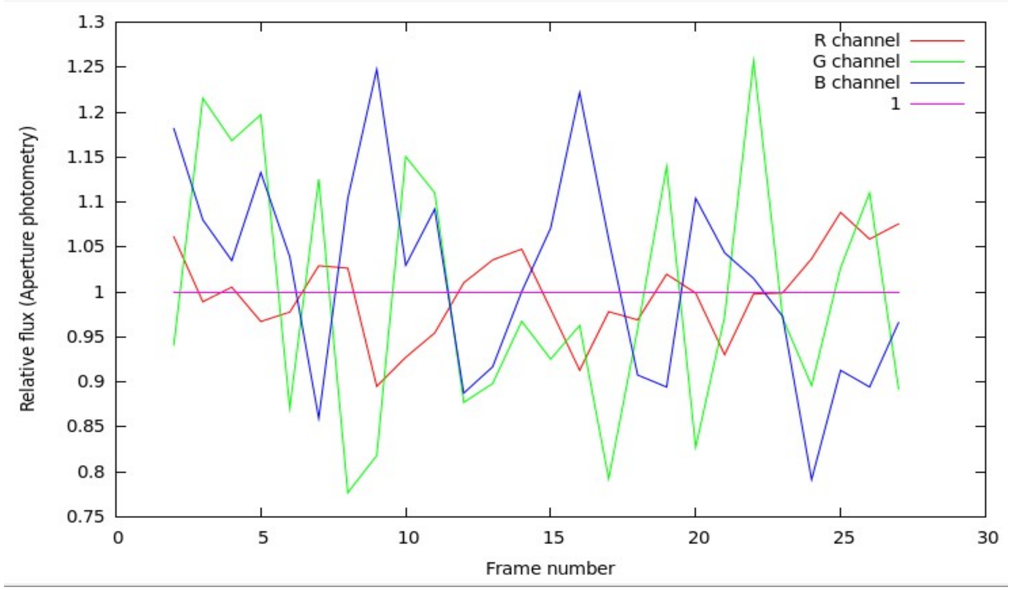
DSLR detector layout
color filters deposited on CMOS chip

Careful selection of reference stars (same color, same fractional pixel position) allows percent-level photomety in 1 min, while conventional aperture photometry limited to ~10% precision

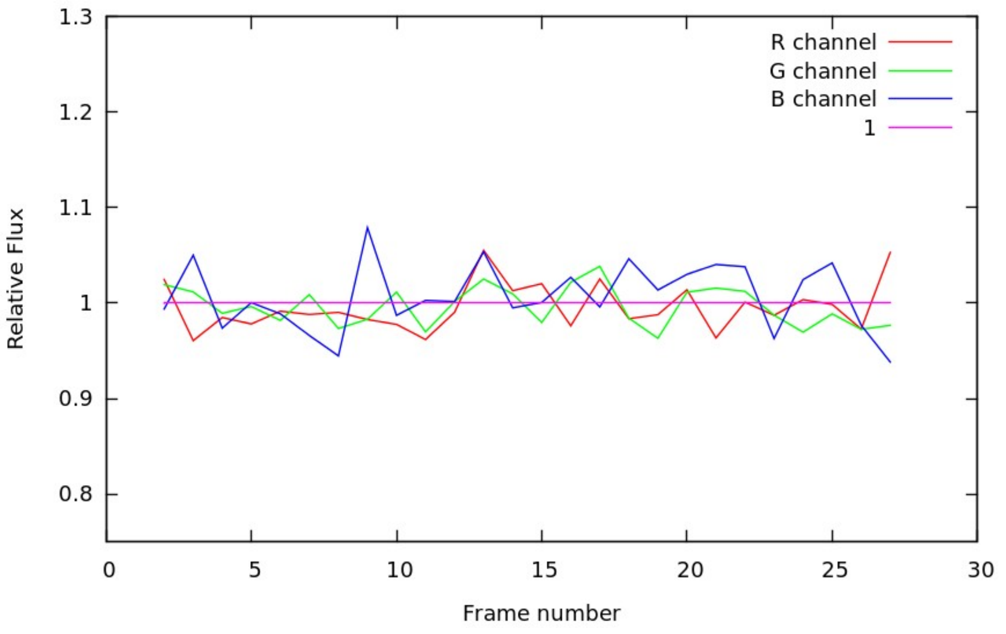
Calibration technique for accurate photometry from the ground

Example :
robotic DSLR camera system





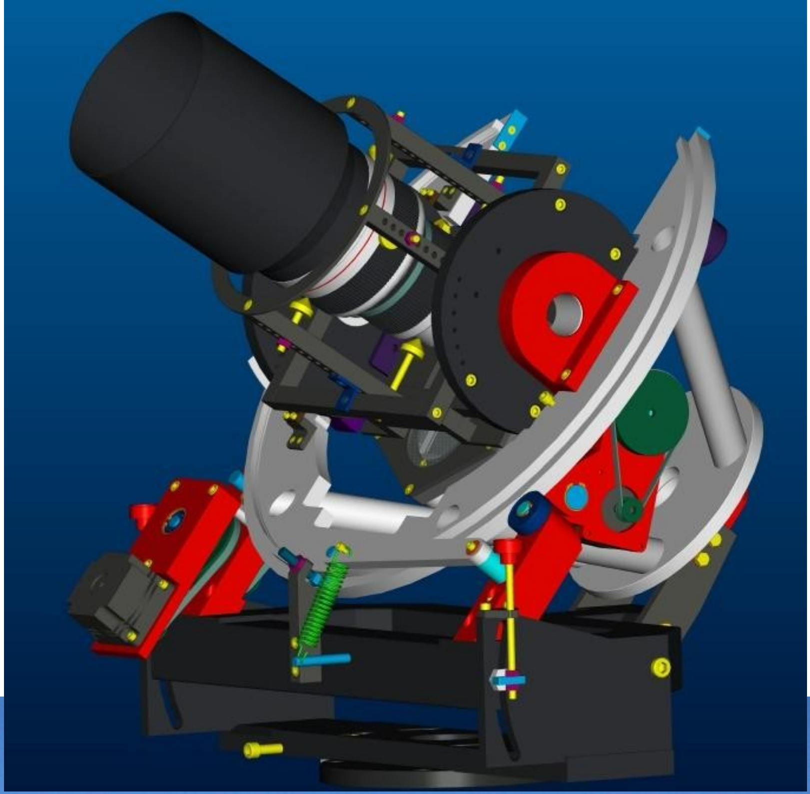
standard aperture photometry

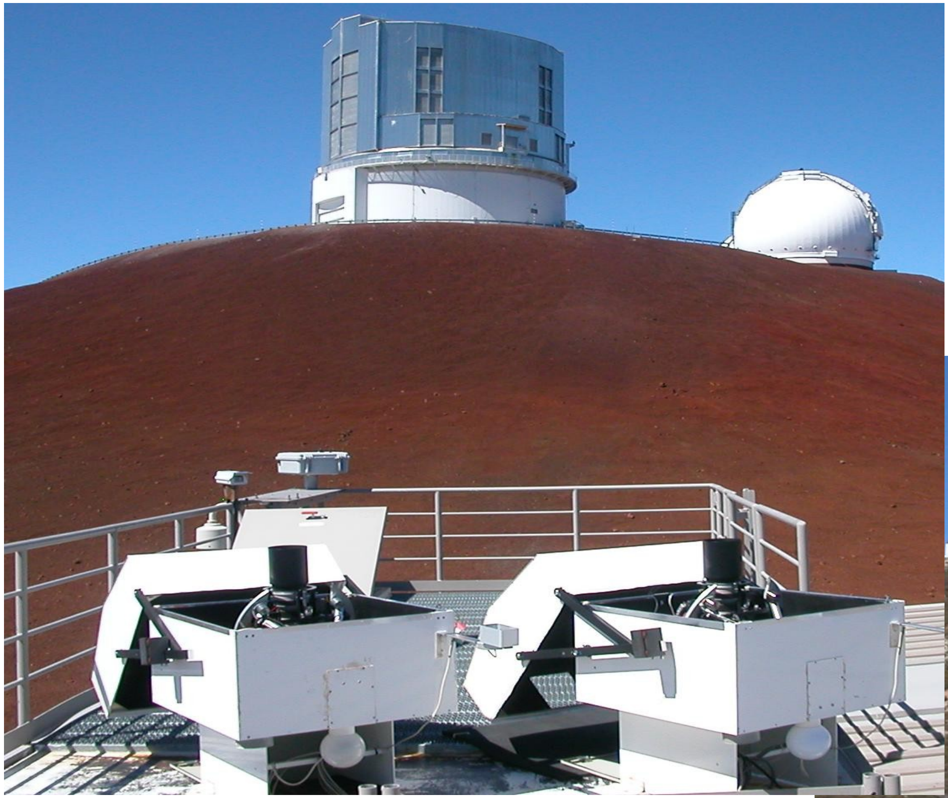


Detrending using optimal calibrators

Example small telescope survey project: HATnet

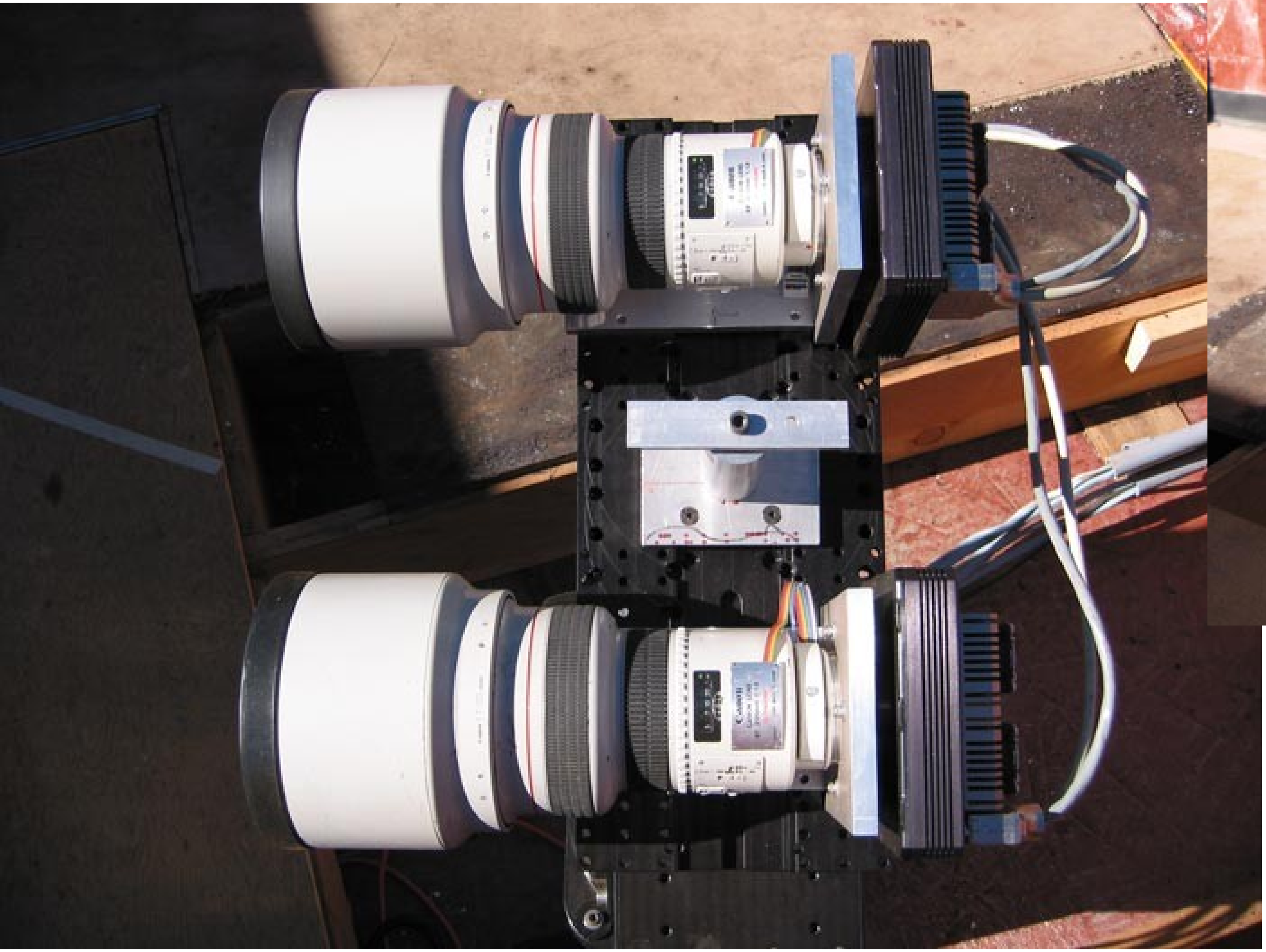
Multiple small aperture wide field imaging systems





Example small telescope survey project: XO

200mm F1.8 lenses + CCD cameras
Located in Hawaii (Haleakala, Maui)

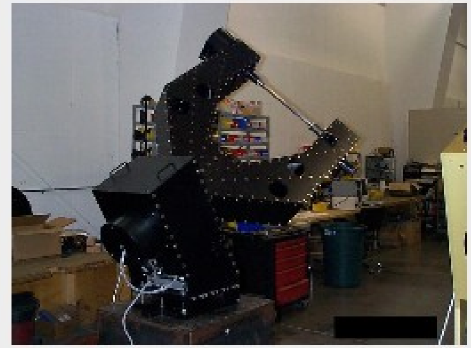


Wide Angle Search for Planets WASP

200mm F1.8 lenses + CCD cameras

65 planets discovered

- **The *Torus* Fork Mount**



Weight	>400 Kg
Pointing error	30 arcsec RMS full sky
Tracking error	< 0.01 arcsec per second
Controls	Stepper motors driven by Torus motion control electronics
Weather System	Full local weather monitoring
Time Standard	GPS receiver gives better than 1s synchronisation with UTC
Control and server computers	Linux O/S

- **The CCD Cameras**

Lens	Canon 200mm f/1.8
Aperture	11.1 cm
CCD	2048 x 2048 thinned e2v produced by Andor of Belfast
Pixel size	13.5 micrometers
Readout noise	12-18 e- (in 1MHz pixel readout speed)
Gain settings	2, 1.4, 0.7 e-/ADU
Maximum pixel count	80,000 e-
Field of View	7.8 x 7.8 degrees (61 sq. degrees)
Plate Scale	13.7 arcsec/pixel
Operating Temperature	-50 degree C
Cooling Mechanism	3-stage Peltier

- **The Enclosure**

The enclosure is made from reinforced fibreglass, of dimensions 3.5m x 6.5m, split into two sections. The first section houses the *Torus* mount and cameras and has a slide-away roof. The second section houses the associated computers. The roof is operated hydraulically with a quick manual release mechanism for emergencies. The building is designed to tolerate < 200 km/hr wind and several metres of snow. The roof has a heating wire to prevent the build-up of ice.

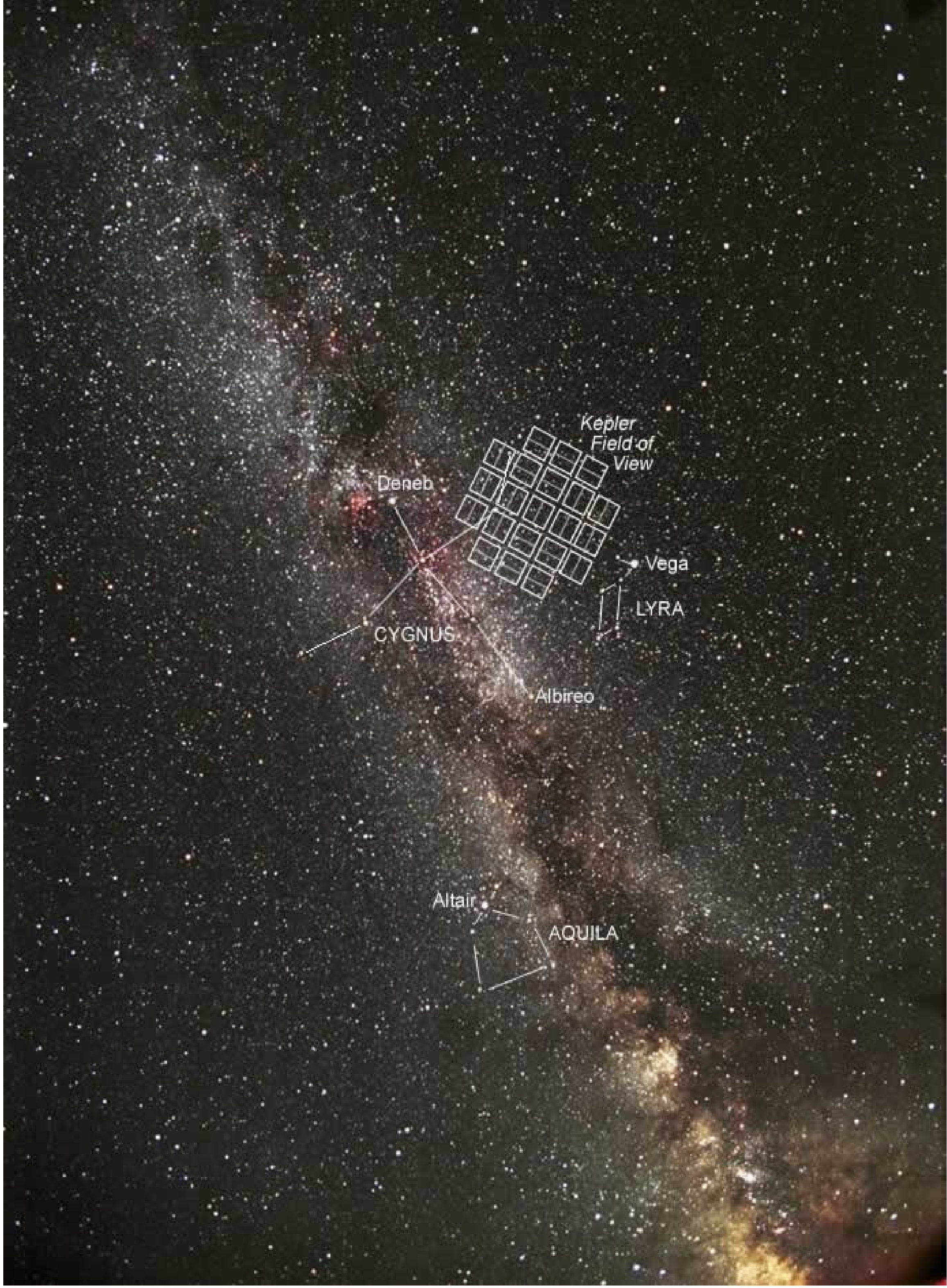
Mearth

8 identical telescopes: 16” diameter (400mm) telescopes, 2048x2048 CCDs
Located on Mt Hopkins, AZ

Monitoring 2000 M-type stars

Kepler

0.95m aperture space telescope,
100 sq deg field of view
continuously stares at a field in Cygnus



TESS

6 cameras
18 x 18 deg FOV each

2.5e6 stars observed
(not continuously)
$4.5 < m_V < 13.5$

~1000 planets expected

(Note: mission under design/study)