Laboratory Testing of Photometric Precision Required to Detect Terrestrial Planets

David Koch

NASA Ames Research Center

Many others contributed and participated.

Partial list includes:

William Borucki, NASA Ames Research Center,

Doug Caldwell, Jon Jenkins, SETI Institute,

Edward Dunham, Lowell Observatory,

Dan Peters, Jeffery VanCleave, Ball Aerospace and Technologies Corp

Fred Witteborn, Orbital Sciences Corp,

Kepler Tech Demo (KTD) Has Served Two Purposes

1. Demonstrate feasibility of:

   a) an **end-to-end system** that can achieve

   b) the **differential photometric precision** and

   c) can **detect Earth-size transits** when

   d) all of the expected **confounding noise factors** are included.

2. Test the performance of the flight system design with engineering grade CCDs and proto-type electronics, referred to as the “Single String Transit Verification Test” (SSTVT)

KTD CHARACTERISITCS

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Source

Represents all of the features of the real sky that are important for ensemble photometry;

- Simulated star field that produces fluxes equivalent to 9^{th} to 14^{th} magnitude target stars
- Star spectral color similar to the Sun,
- Star field density down to 19^{th} magnitude stars,
- Several 4^{th} magnitude stars,
- Ability to generate Earth-size transits for selected stars.

Camera

Has the characteristics the Kepler photometer (telescope+focal plane).

- Fast optics with a central obscuration,
- Commercially available flight-type CCD,
- Shutterless readout,
- High speed readout electronics (1 megapixel/sec),

Facility Support

- Thermal, mechanical and RF isolation from the laboratory environment.
- Tip-tilt of camera with PZTs to simulate the spacecraft jitter
- CCD cooling system
- Prototype Flight and Ground software

Kepler Tech Demo Architecture

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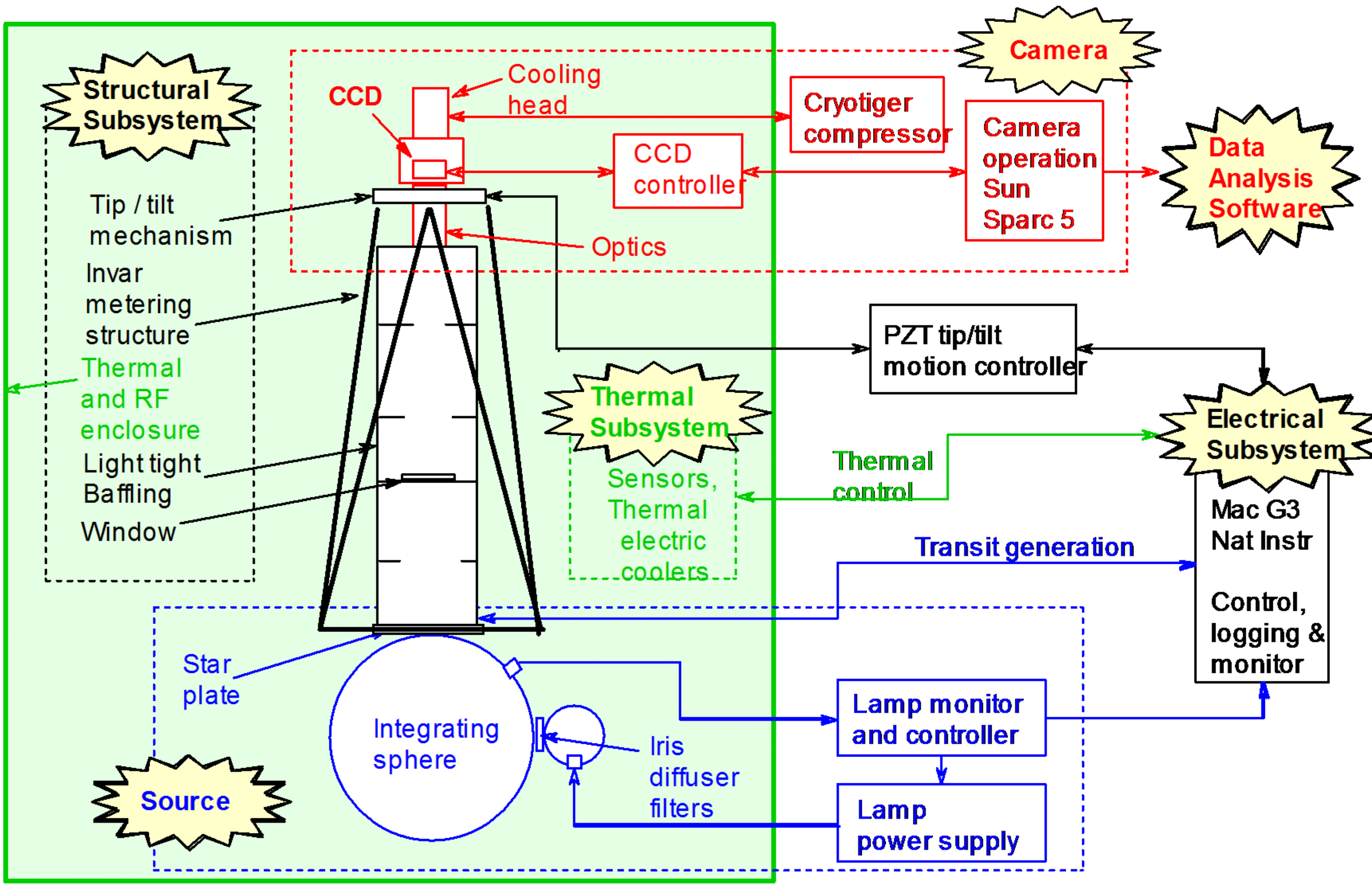

TECH DEMO PHOTOGRAPH

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A double integrating sphere (blue) illuminates the star plate at the base of the Super-Invar truss. A baffle (gold anodized) sits on top of the star plate and extends to just below the camera optics. A vacuum pump line is attached to the dewar housing the CCD. The top cylinder is the CryoTiger cold finger. The interior walls are temperature regulated with thermal-electric-coolers/heaters.

DATA FLOW AND PROCESSING STEPS

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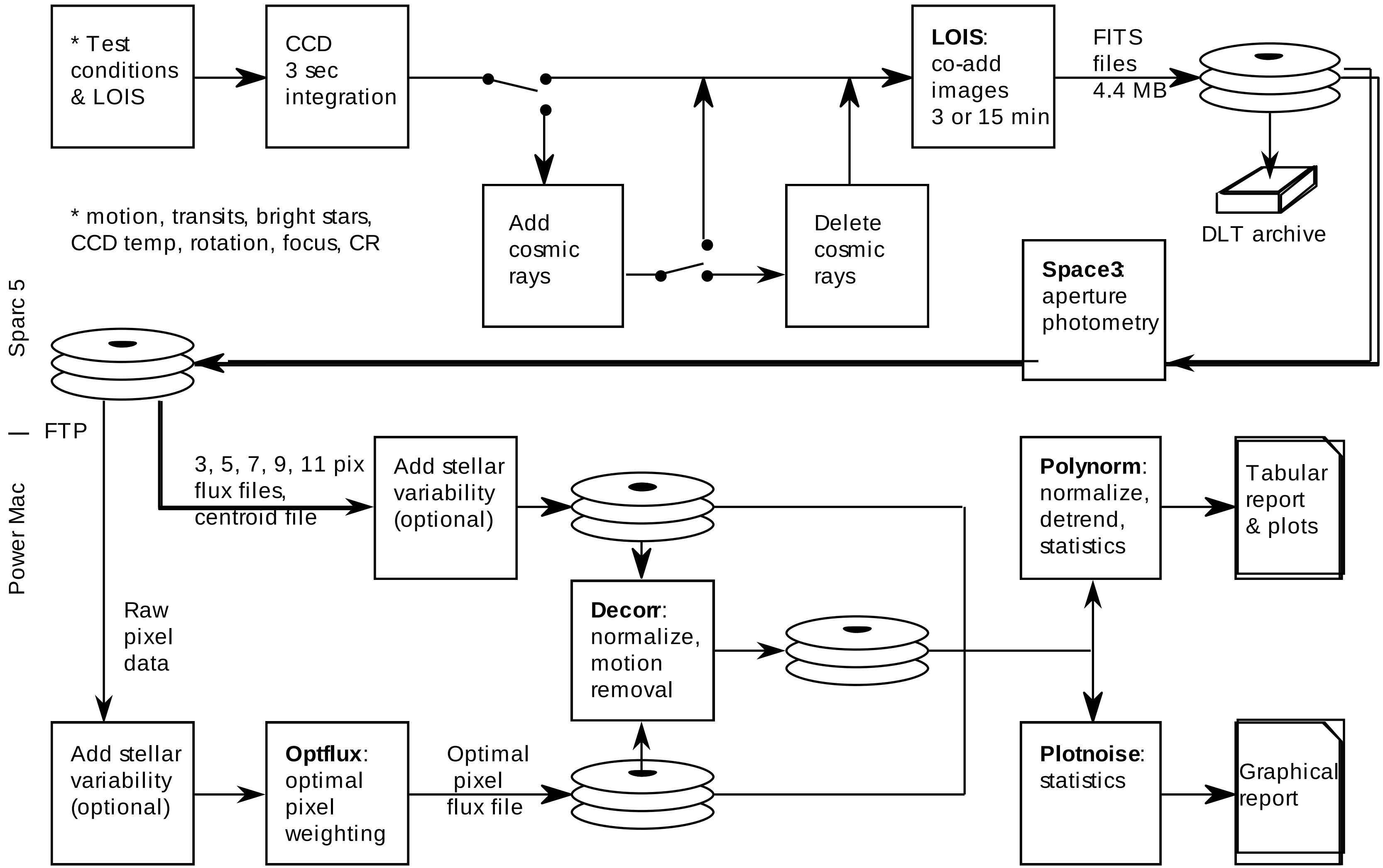

Performance Criteria Based on Design

$Noise^2 = shot\ noise^2 + stellar\ variability^2 + measurement\ noise^2$

For *Kepler*, the point design is to be able to detect an Earth-size transit of a V=12 solar-like star in 6.5 hours at 4σ. Earth-size transit=84ppm

Photometer area x efficiency for V=12 G2V star yields 5×10^9 photons/6.5 hrs => shot noise in 6.5 hrs =14.4ppm

Take stellar variability to be 10 ppm in 6.5 hrs (Sun during solar max. Most (75%) main-sequence stars $>10^9$ Gyr are less active.) Stellar variability is typically "red" and doesn't scale by SQRT(t)

Measurement noise includes multiple parts
- a) Electronic noise
- b) Image jitter and drift
- c) Background variability and shot noise
- d) Dependence on "photometric aperture" size
- e) Effects of temperatures, voltages, etc.

$Measurement\ noise^2 = (84ppm/4)^2 - 14.4ppm^2 - 10ppm^2 = 10ppm^2$

LESSONS LEARNED

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Facility Operation

1. Lamp stability (<1/1000)
2. Thermal-mechanical stability (>24hrs)
3. Mechanically separated cooling for dewar (varying load)

Differential Photometry

1. Optimal aperture (one size does NOT fit all)
2. Smear provides “fat-zero” (keeps traps filled)
3. Image stability (<50 millipixels/day)

Single String Test of Flight proto-type

1. Significant over/under shoot in analog electronics

Uncorrected Signal Variation with Motion

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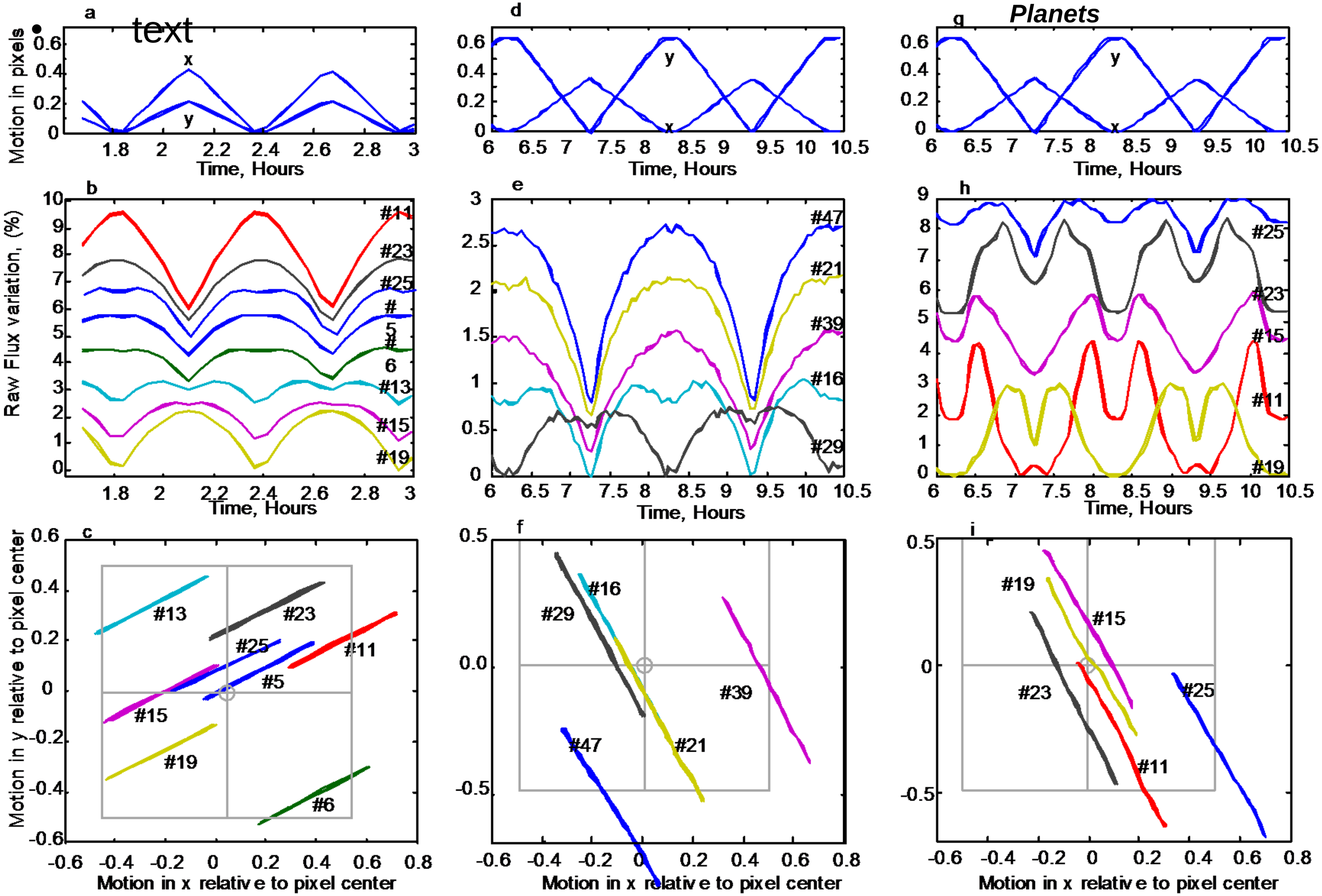

LONG DURATION WITH ALL CONFOUNDING FACTORS

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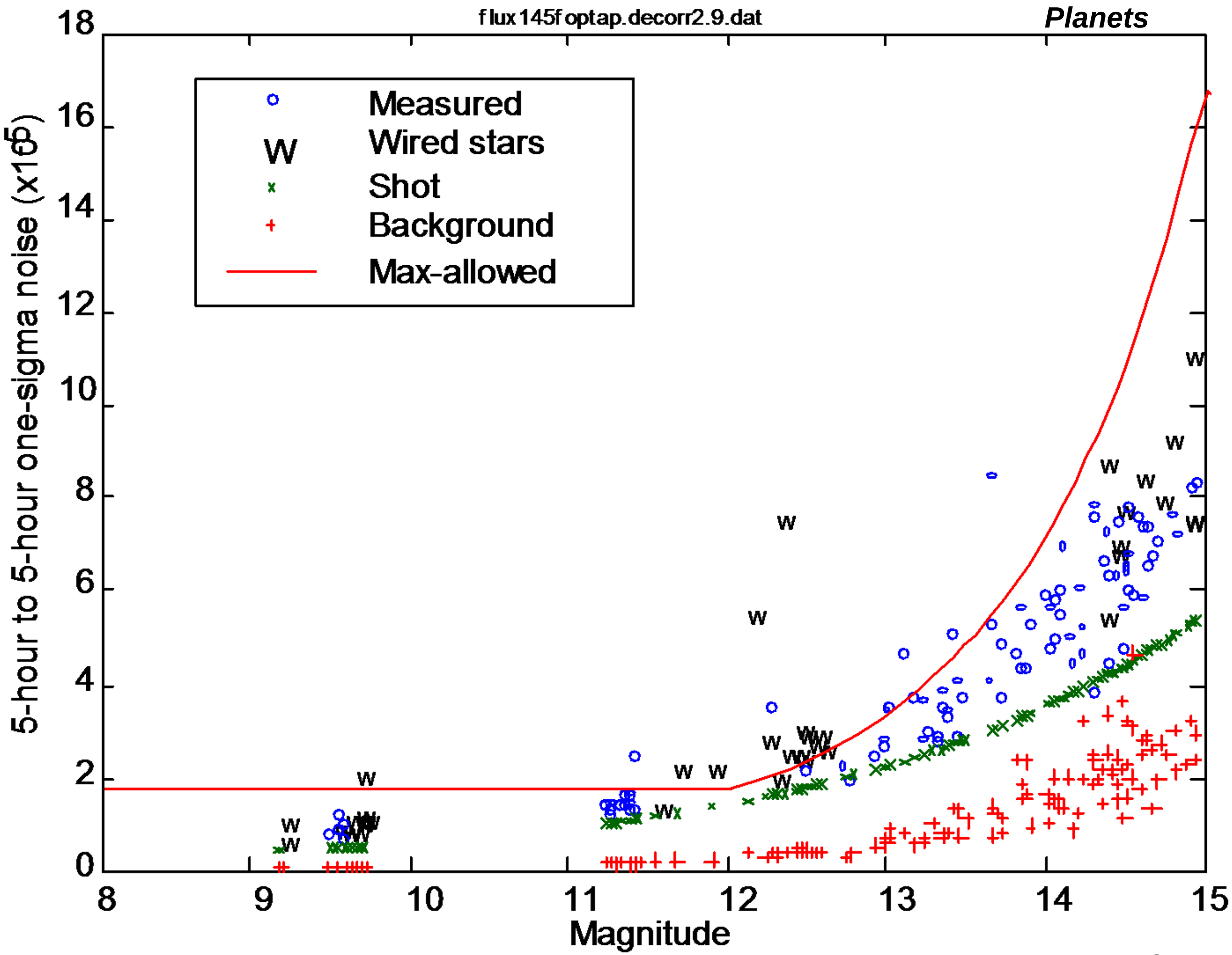

Test run from Feb 2000

Completed Star Plate with Transit Wires

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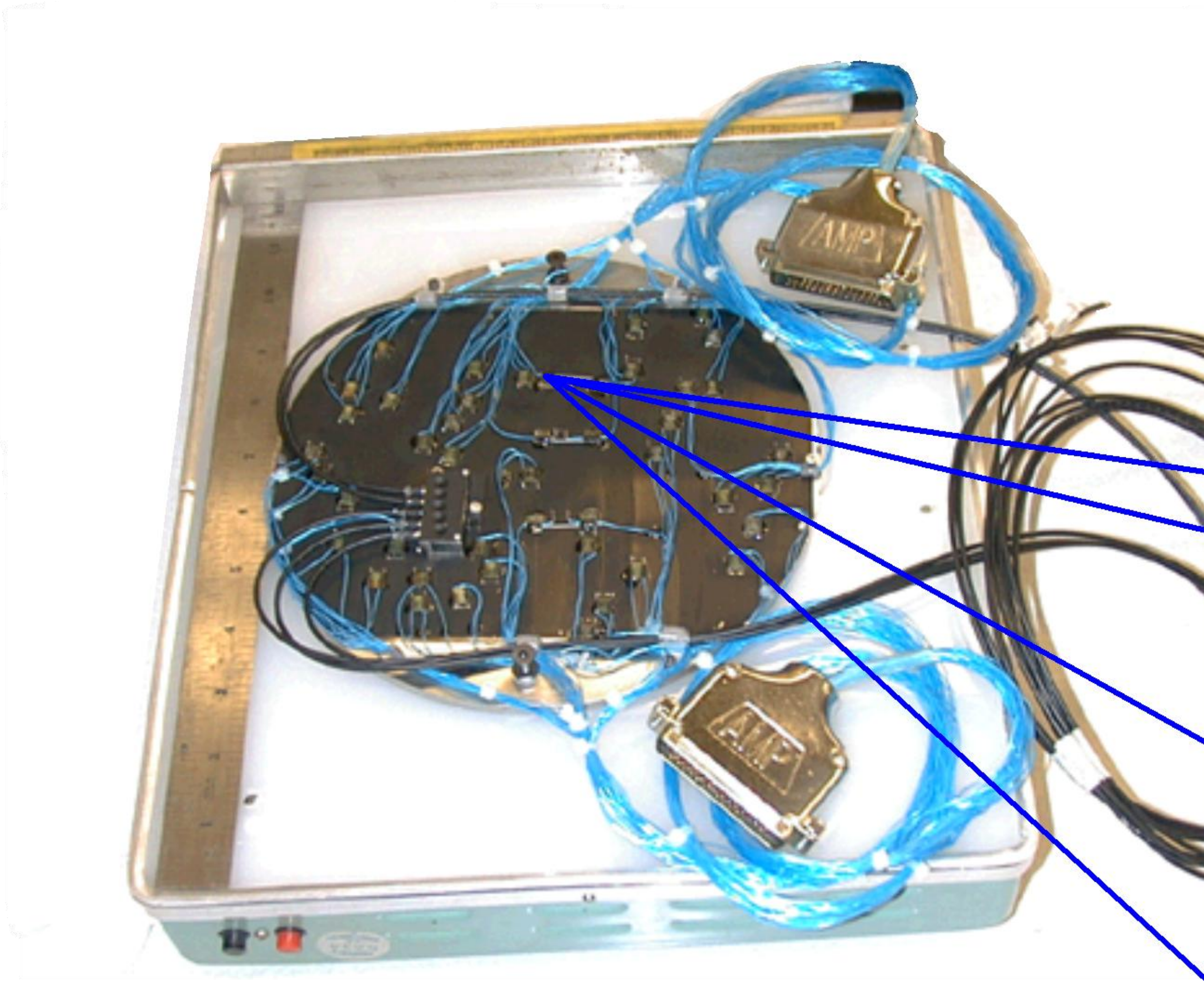
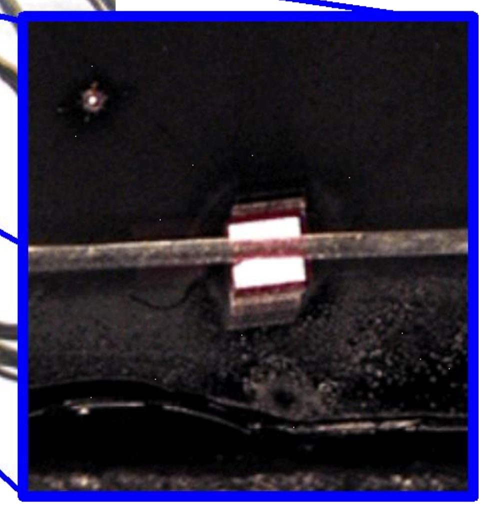


Transit wire (127µm wide) on an mv=9 star hole (300 µm sq) with an mv=14 nearby background star (30µm rnd hole) in the upper left.



Completed star plate with 1600 laser drilled holes, 42 transit wires and 5 fiber optics for bright stars.

Transits for 9th, 12th and 14th Mag Stars

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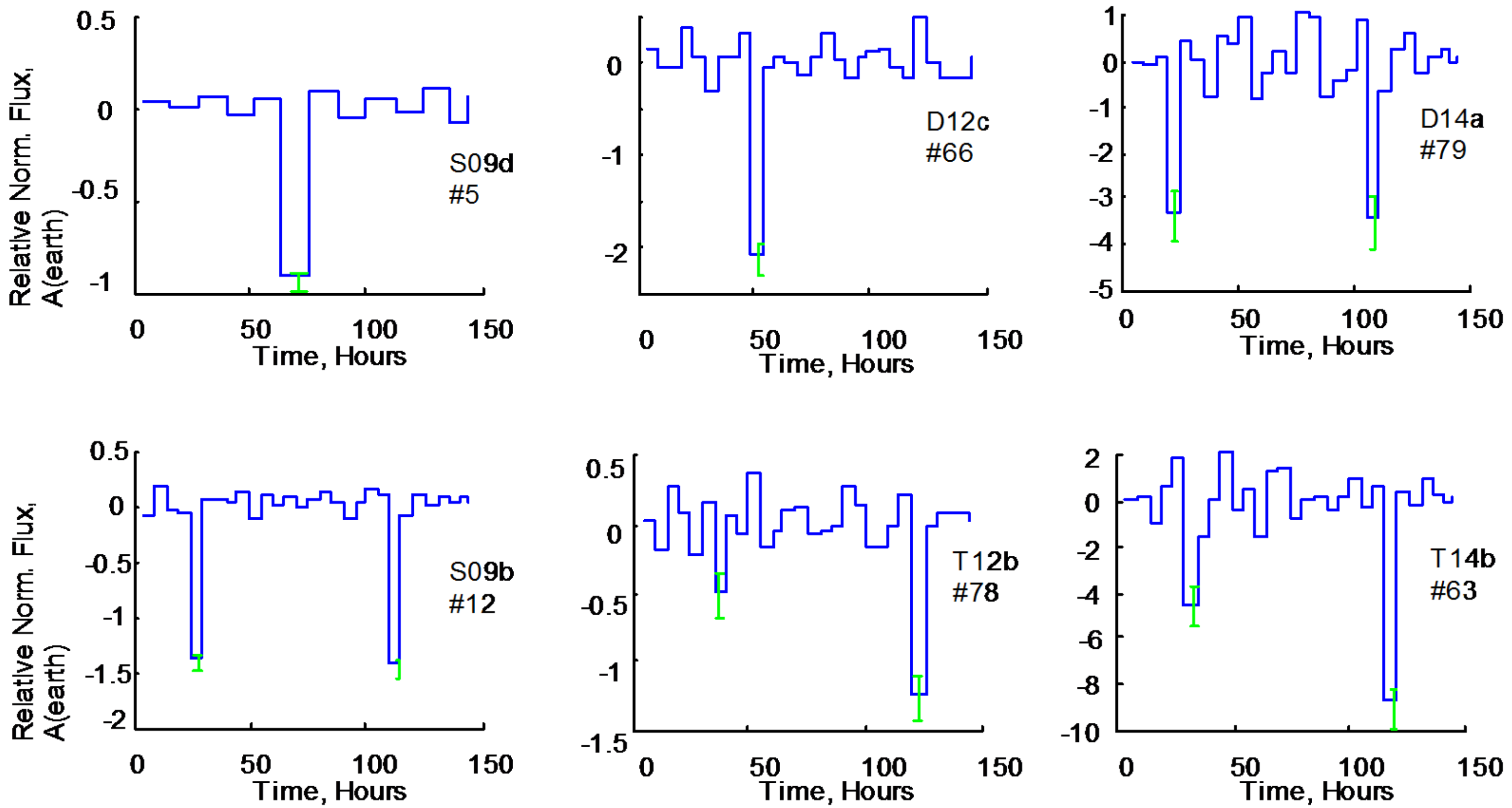

Transits produced and detected during the running of the long-duration test with all confounding factors. Transit depth is given in equivalent Earth-area and one sigma error bars are shown for the noise.

At 14th magnitude the minimum detectable planet size expected is 3.5 Earth-area due to a higher shot noise.

TRANSITS FROM PROTO-TYPE TESTS

Kepler

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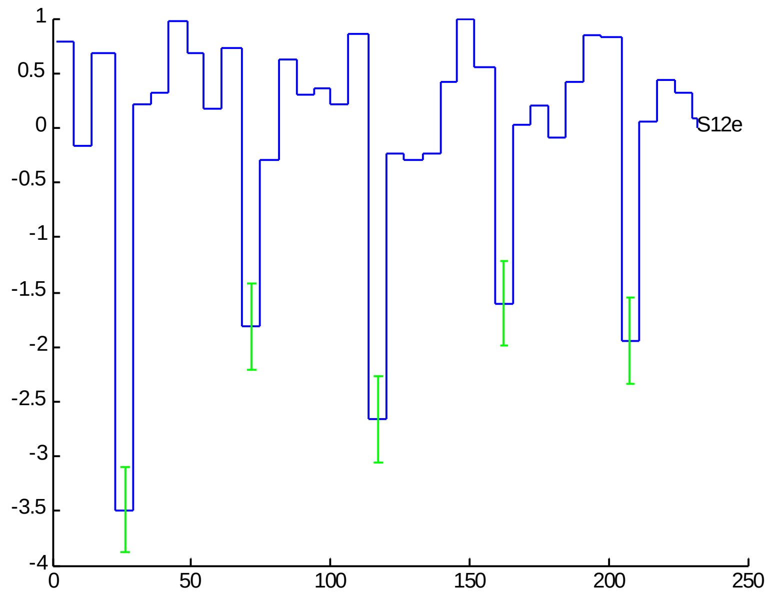

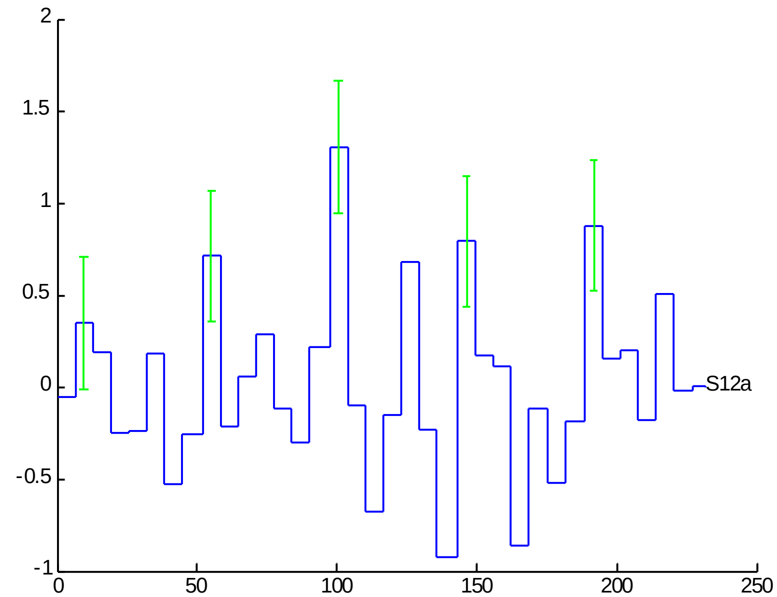

Transits produced and detected for two 12th mag. stars during the long-duration test with "engineering grade" CCD and electronics Feb 2007. Transit depth is given in equivalent Earth-area and one sigma error bars are shown for the noise. "Anti-transits" caused by either the hole being heated or the wire twisting or moving.

http://Kepler.NASA.gov