Status Report on SOFIA Exoplanet Transit Capability

Ted Dunham

Georgi Mandushev

Daniel Angerhausen

Introduction

- Update on HD189733b transit observation on 10/1/2013 (UT) with FLIPO
  - Originally Avi Mandell's FLITECAM-only proposal
  - Search for water in HD189733b using Pa alpha filter
  - Morphed into a FLIPO demonstration transit
- Talk Outline
  - Introduction and practical matters (Ted)
  - Data analysis, systematics, and results (Georgi)
  - User's perspective and independent data analysis (Daniel)
  - Wrap-up (Ted)

Scientific Value of Transits

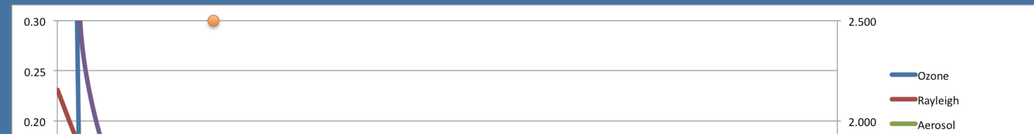
- Atmospheric structure and chemistry
  - Rayleigh scattering, scale height
  - NIR spectrophotometry
    - Search for presence of interesting compounds (e.g. water, methane)
    - Appear as apparent radius differences with wavelength
- Heat exchange -- exoplanet weather
  - Phase functions, secondary eclipse
- Starspot and plage size and color temperature
- Primary interest is in 1-5 micron range
- More later from Daniel

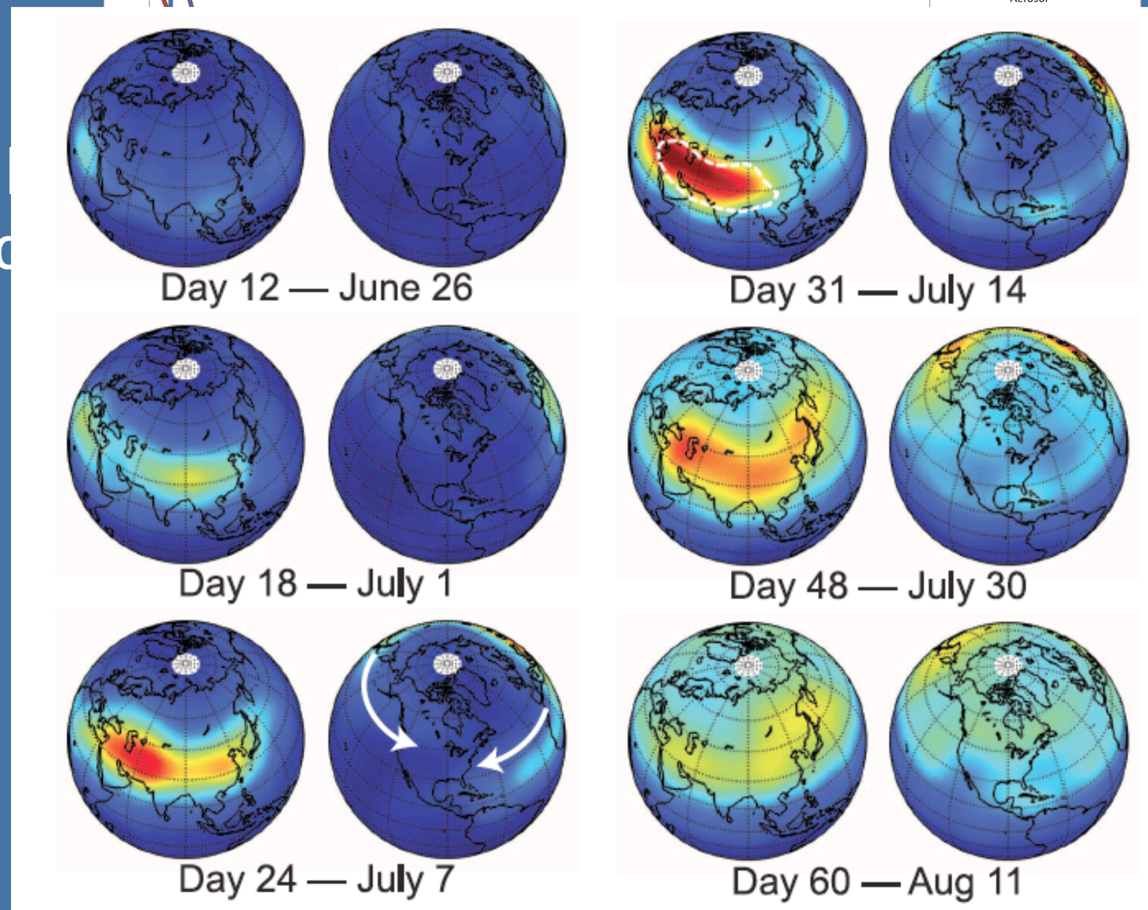
Observational Issues

- The prize is not easily grasped.
- Need to measure small features in shallow transits
  - Overall fractional error ~few x 10^{-4}
- Not easy for <u>anybody</u> – systematics dominate at this level
  - *Kepler*, HST, Spitzer, ground-based systems all have problems. We do too.
    - Bill Rose: "Why don't you pick something hard to do??? Geeeesh."
  - Known problem areas for SOFIA:
    - Water vapor, ozone, and Rayleigh extinction; static air density, Mach number (?), pointing, jitter, and focus.
  - Reliable housekeeping data essential for correcting these
  - Some instrument-specific details can be important
- Differential photometry (field standard) is NOT a cure-all
  - Usually doesn't happen anyway
  - When it does it works best if the differential correction is small

Systematics, I

- Extinction
  - Rayleigh scattering (optical; proportional to static pressure and airmass)
  - Ozone (optical)
  - Water (IR)
  - Volcanic aerosols
    - Can vary by 0.1-1%
    - Episodic problem
    - IR impact uncertain





Nabro eruption, 13 June 2011 (Bourassa, et al. (2012))

Systematics, II

- Aero-optical PSF effects
  - Optical PSF dominated by shear layer scattering
    - Refractivity (ν = n-1) is proportional to density
    - $\delta\rho/\rho_{static}$ is roughly constant
    - Image FWHM expected to scale with static density
    - Very broad PSF wings interact with aperture
      - Perceptible additional enclosed flux across entire HIPO field!
    - Rose expects FWHM dependence on Mach number
      - We don't see this, at least so far
    - So far no obvious "dome seeing" contribution

Systematics, III

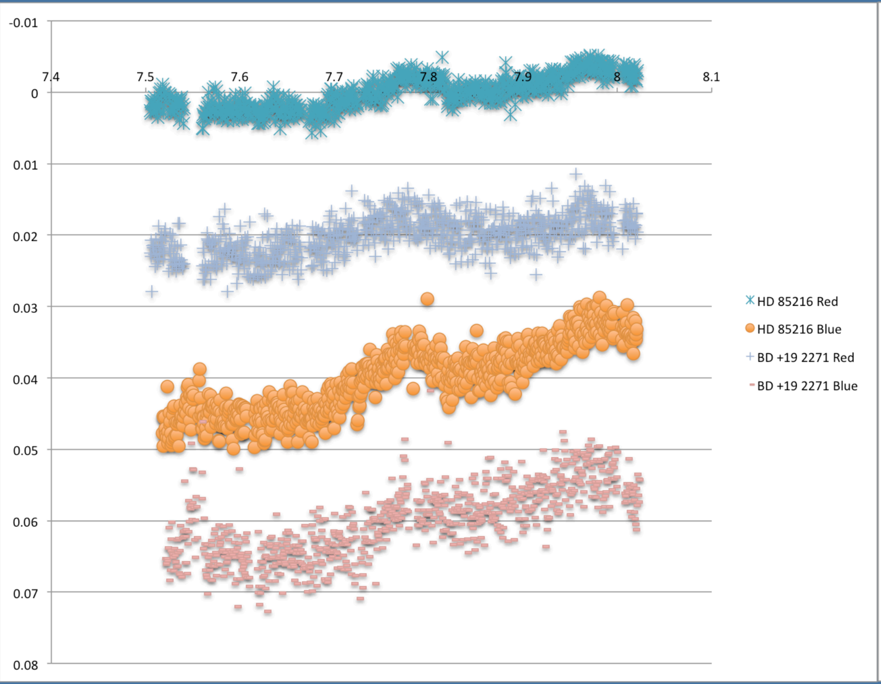
- Other PSF-related effects
  - Defocus, especially early in the flight
    - Really should have automatic SMA_T1 focus update
  - Jitter (causes erratic enlarged time-averaged PSF)
- Pointing noise
  - To first order, fixed by (proper) flat fielding, right?
    - Never really works right. Stable pointing is best, decorrelated pointing errors are second best.
  - Jitter increases noise, but uncompensated drift is fatal
    - Exoplanet science occurs at low frequency

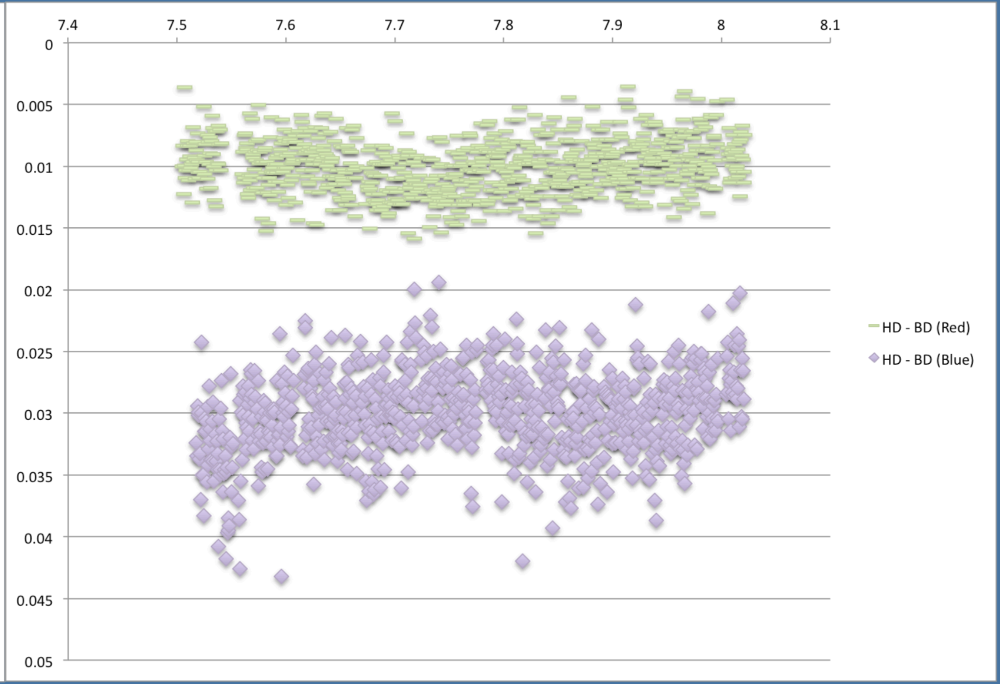
Systematics, IV

- Instrument-related effects
  - Carried out lab tests for HIPO (with small PSFs)
    - Millimag photometric changes occur with large CCD temperature changes
    - Perceptible CCD controller temperature sensitivity
      - Important to operate controller uniformly. *Kepler* lesson.
    - *Kepler*-like image position effects noticed but overwhelmed by the airborne environment
    - Overscan may be a useful decorrelating variable
  - No similar information available for FLITECAM

Differential Photometry

- SCAI-9 Test
  - HD 85216 (V=8.4, A3) and BD+19 2271 (V=8.8, F5)
  - 19" aperture (red) 26" (blue), open filters
  - Raw photometry (left), differential (right)
  - Systematics still there in differential light curves at a few millimags



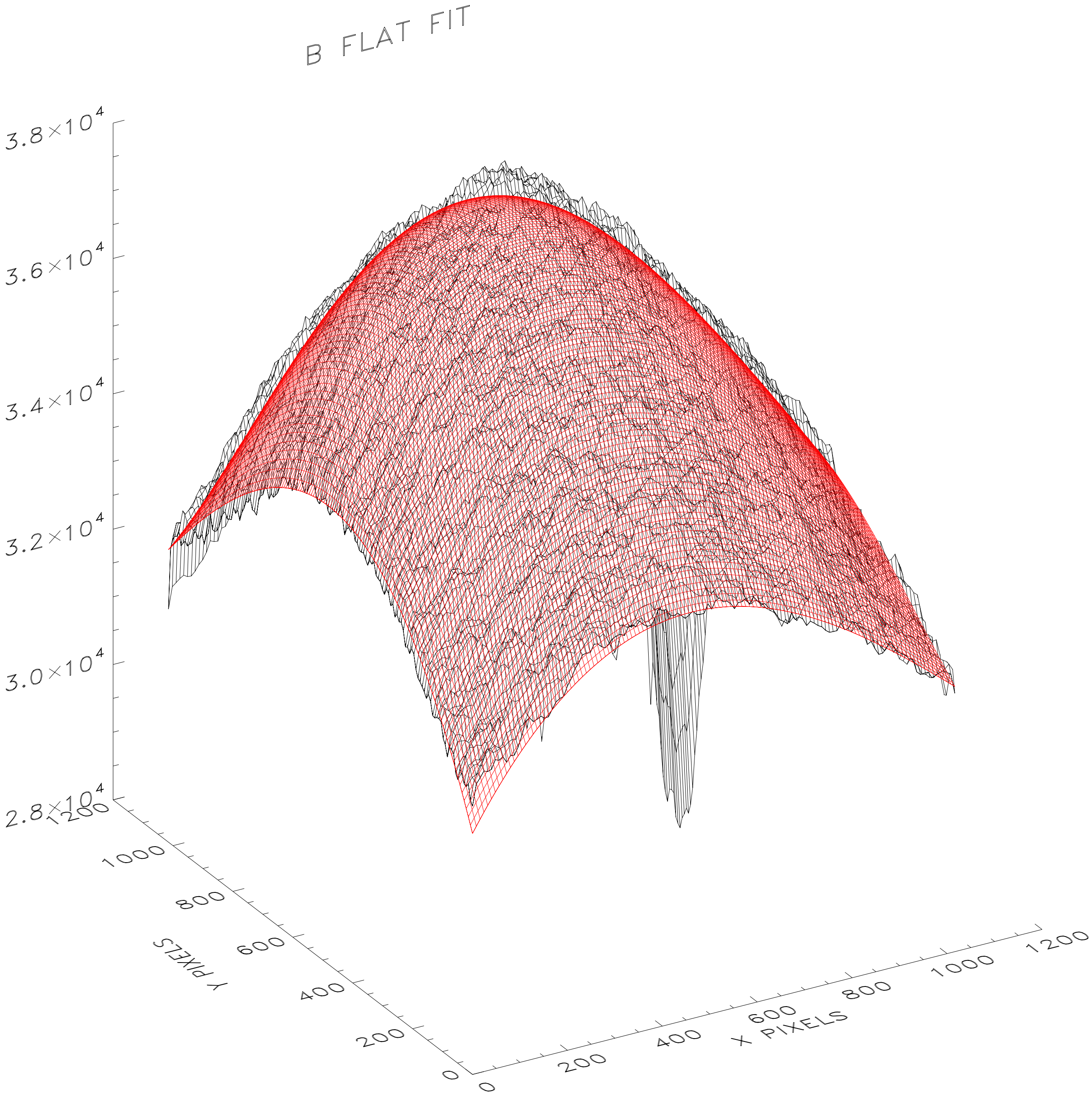


Transit Observation Circumstances

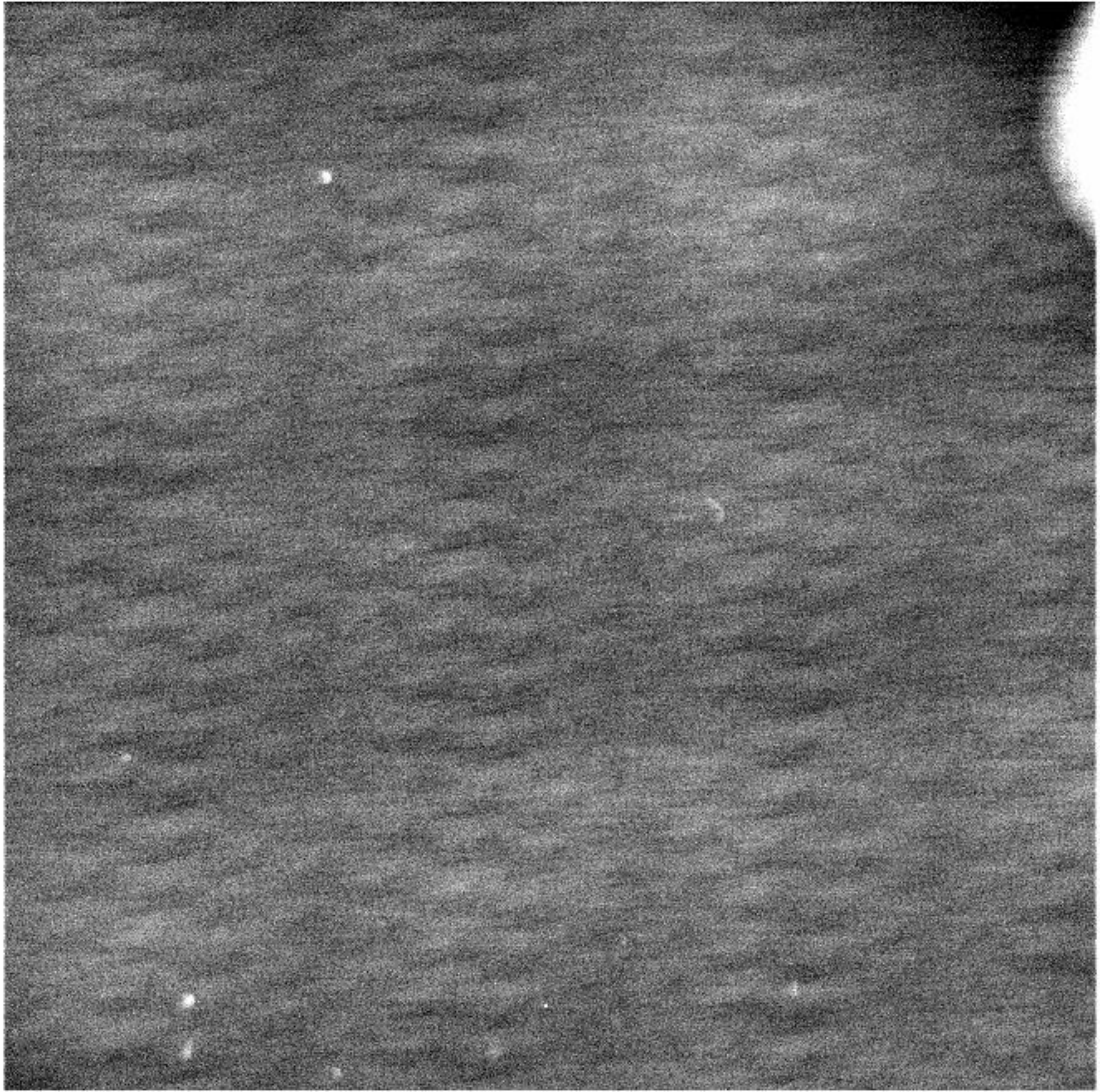
- Several problem areas known before takeoff
  - Very little baseline before the event, none after
  - Short FLITECAM LHe hold time
    - Short flight; must observe transit first thing. Focus unstable.
  - WVM not installed
- In-flight problems
  - FPI failed at start of leg (blown circuit breaker); fell back to FFI
    - HIPO guiding not properly tested, so didn't attempt that
    - Lost the little pre-transit baseline we had
  - Pointing was very poor. FFI in poor focus for a while.
- Post-flight problems
  - During data analysis found electronics-related problems in FLITECAM affecting global reset and co-adding.
  - No useful FLITECAM data obtained.

HIPO Observational Details

- Observed in Basic Occultation mode
  - Full frames to maximize field standard possibilities
    - Field standards all very much fainter than target.
  - 3 second integrations on red side, Sloan z' filter
    - ~2700 measurements
  - 7 second integrations on blue side, Johnson B filter
    - ~1000 measurements
  - Broken into chunks to keep file sizes manageable
- Filters selected to avoid ozone problems



B FLAT FIT
3.8×10^4
3.6×10^4
3.4×10^4
3.2×10^4
3.0×10^4
2.8×10^4
Y PIXELS
0
200
400
600
800
1000
1200
X PIXELS
0
200
400
600
800
1000
1200



•

•

but

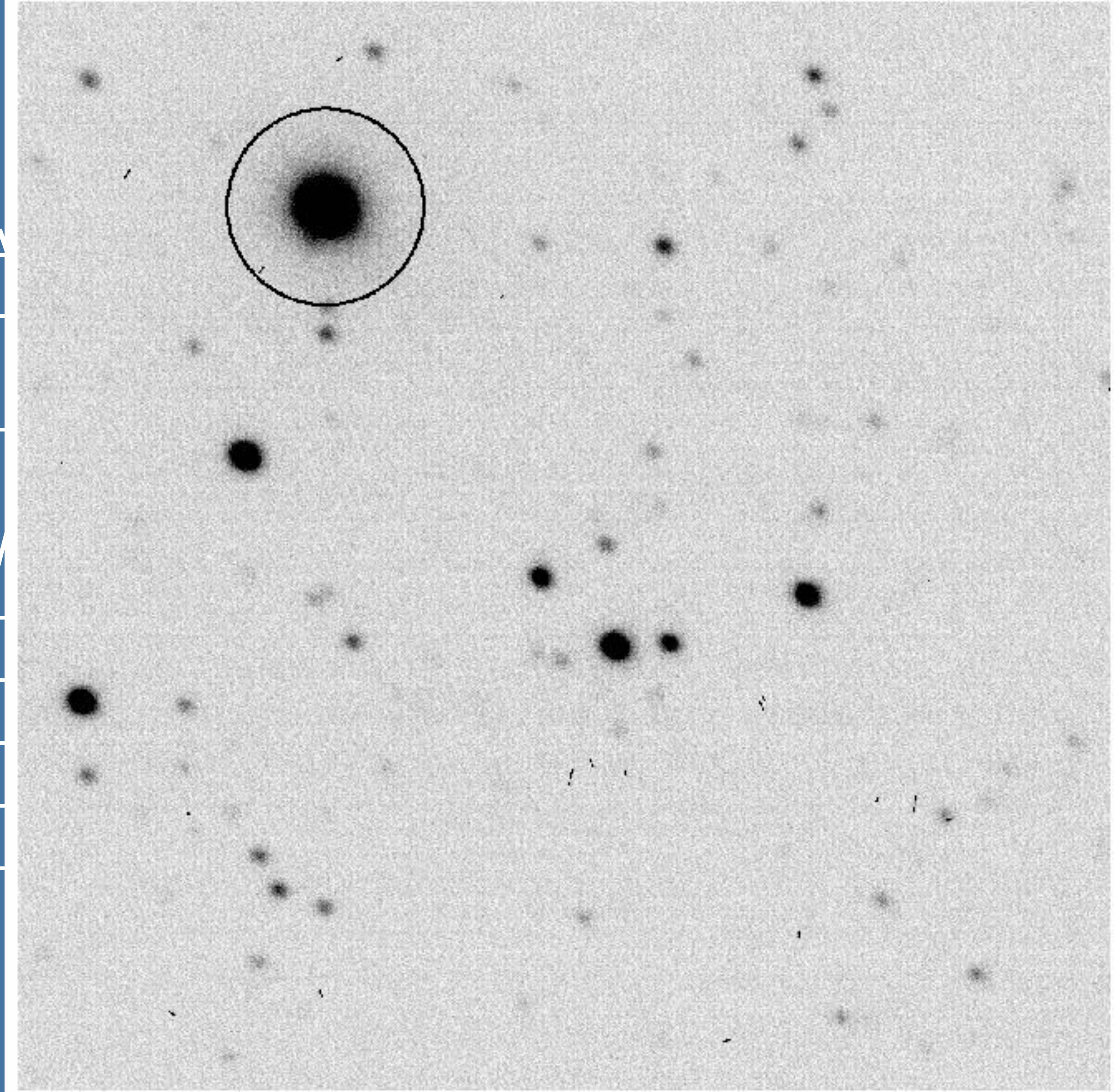
• A

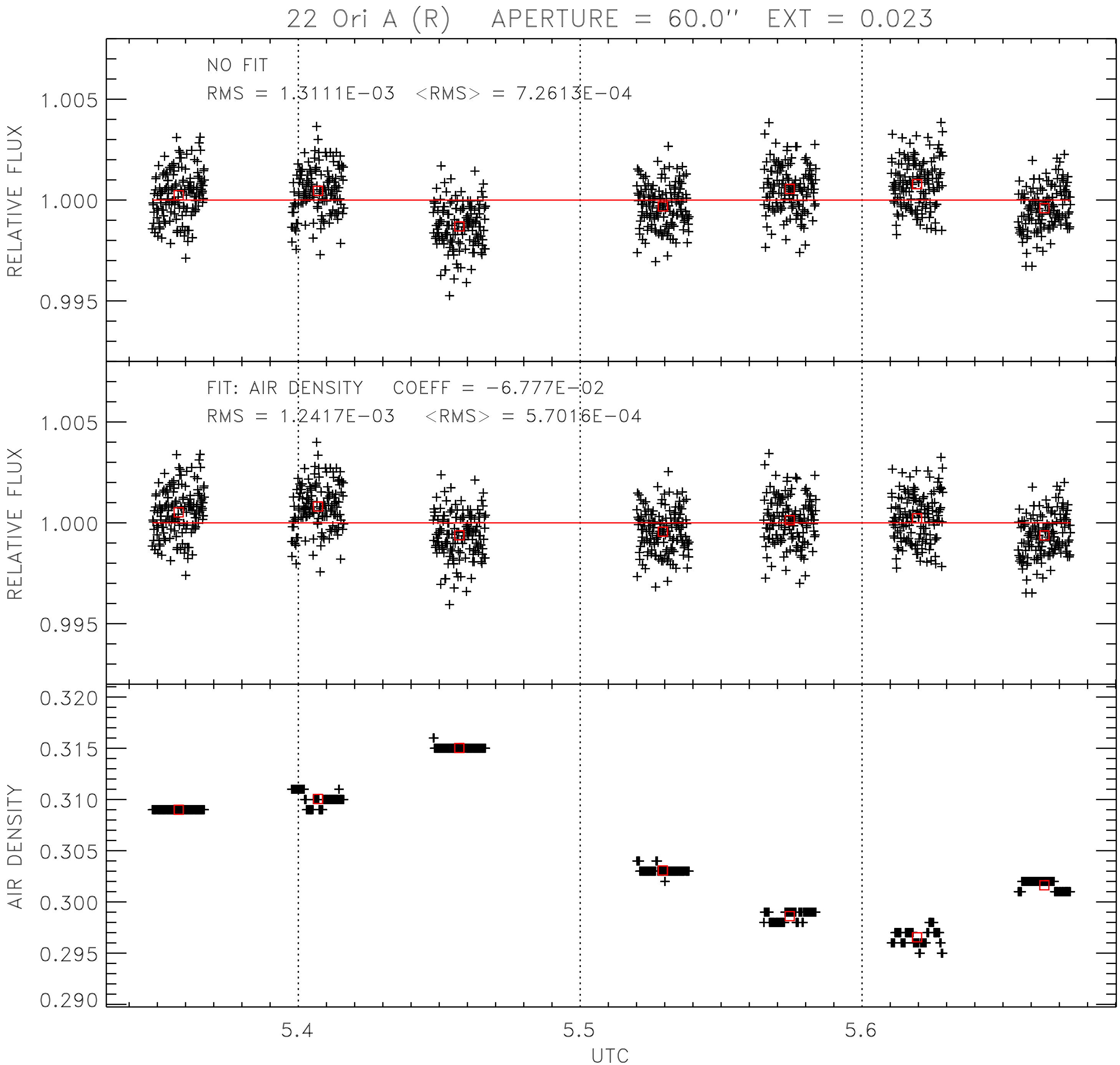
er,

e

• W

of

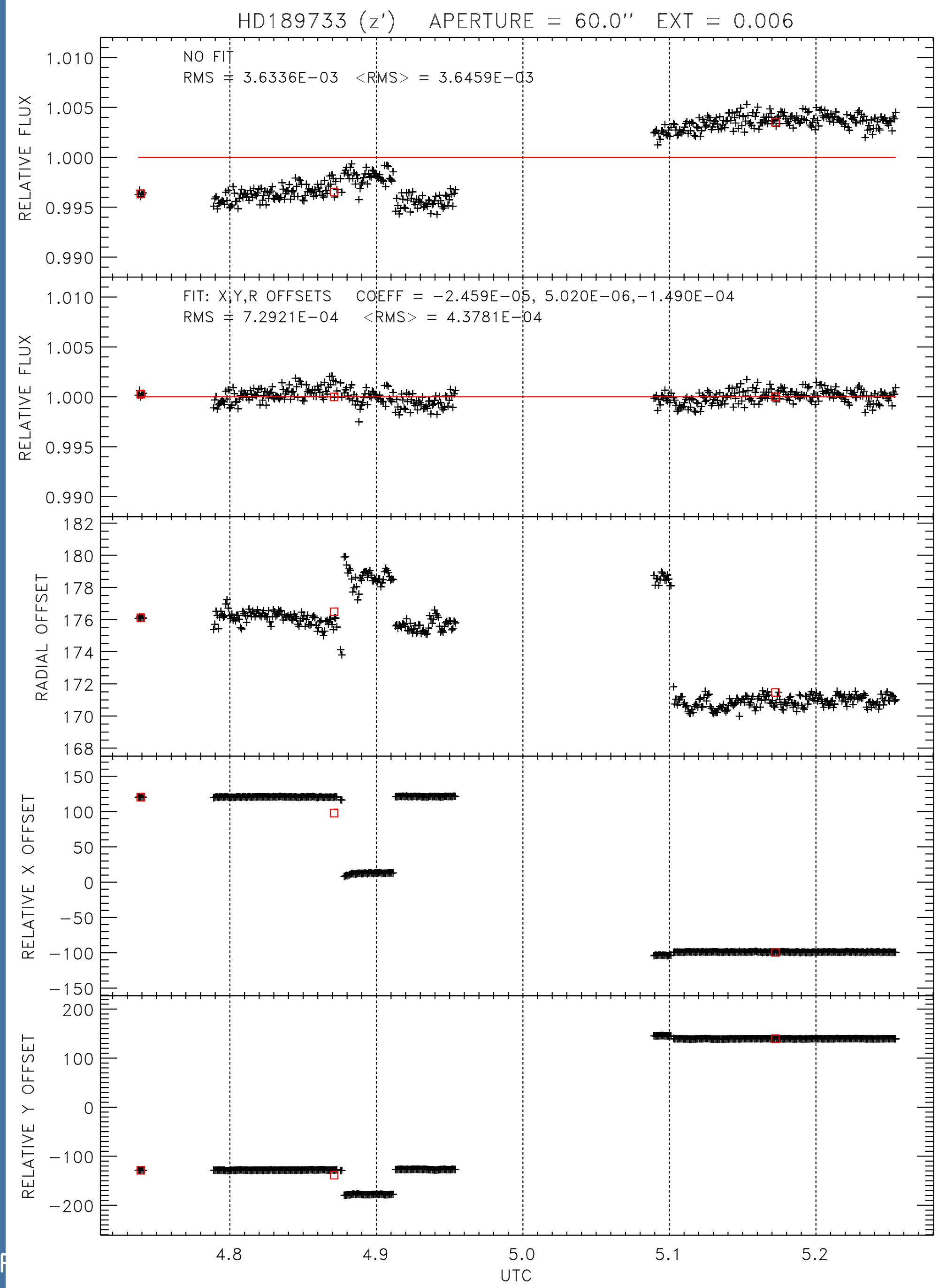




22 Ori A (R) APERTURE = 60.0" EXT = 0.023
NO FIT
RMS = 1.3111E-03 <RMS> = 7.2613E-04
FIT: AIR DENSITY COEFF = -6.777E-02
RMS = 1.2417E-03 <RMS> = 5.7016E-04
RELATIVE FLUX
1.005
1.000
0.995
AIR DENSITY
0.320
0.315
0.310
0.305
0.300
0.295
0.290
5.4
5.5
5.6
UTC

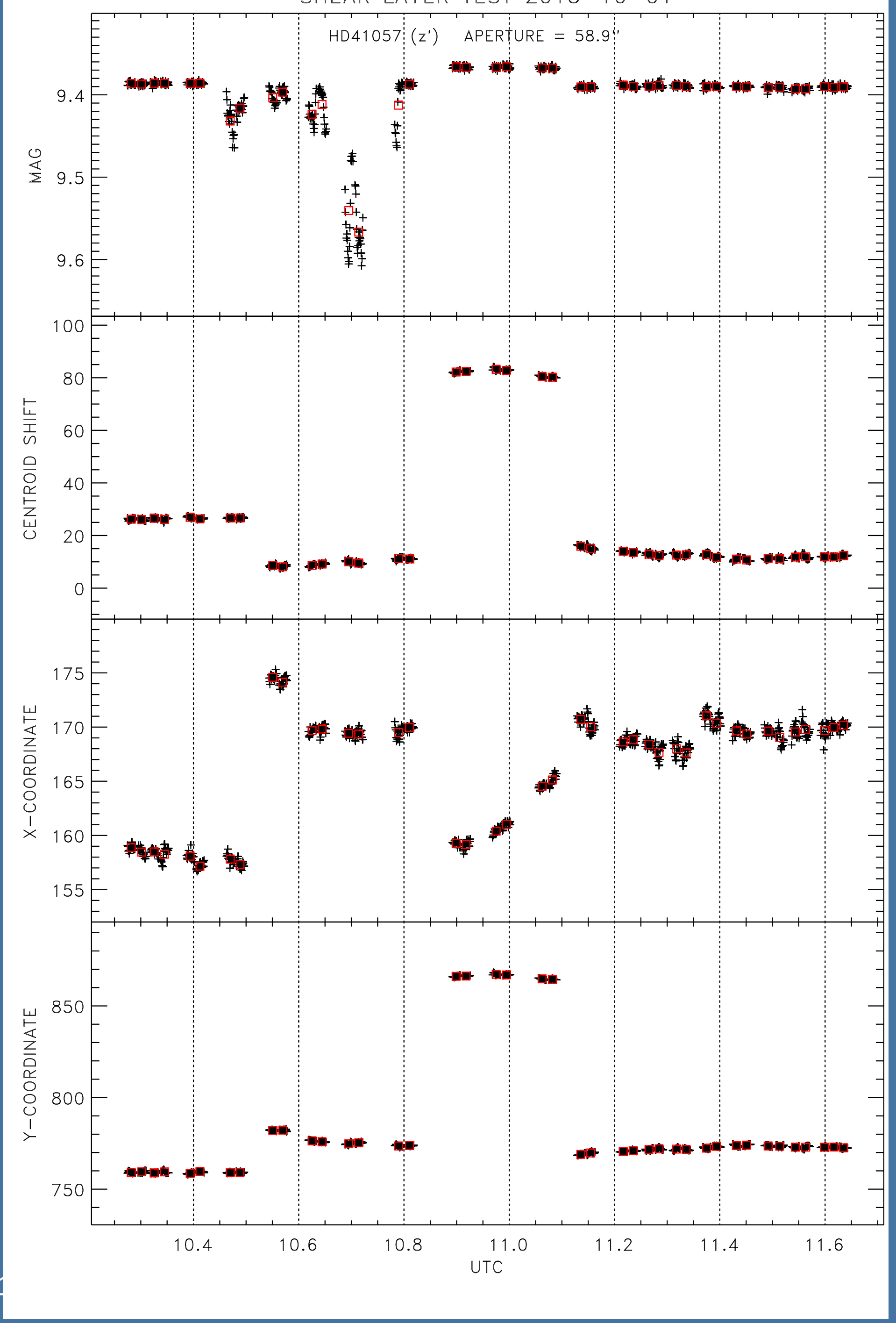
Corrections, II

- Setup leg, 2013-09-27 UT
  - Short leg, little change in density or Mach number
  - Strong positional effects
    - Star moved across field
      - Setting up position on FLITECAM array
  - Position correction
    - Fit and subtract polynomial of position jointly in X&Y
    - Use this approach for correcting transit data



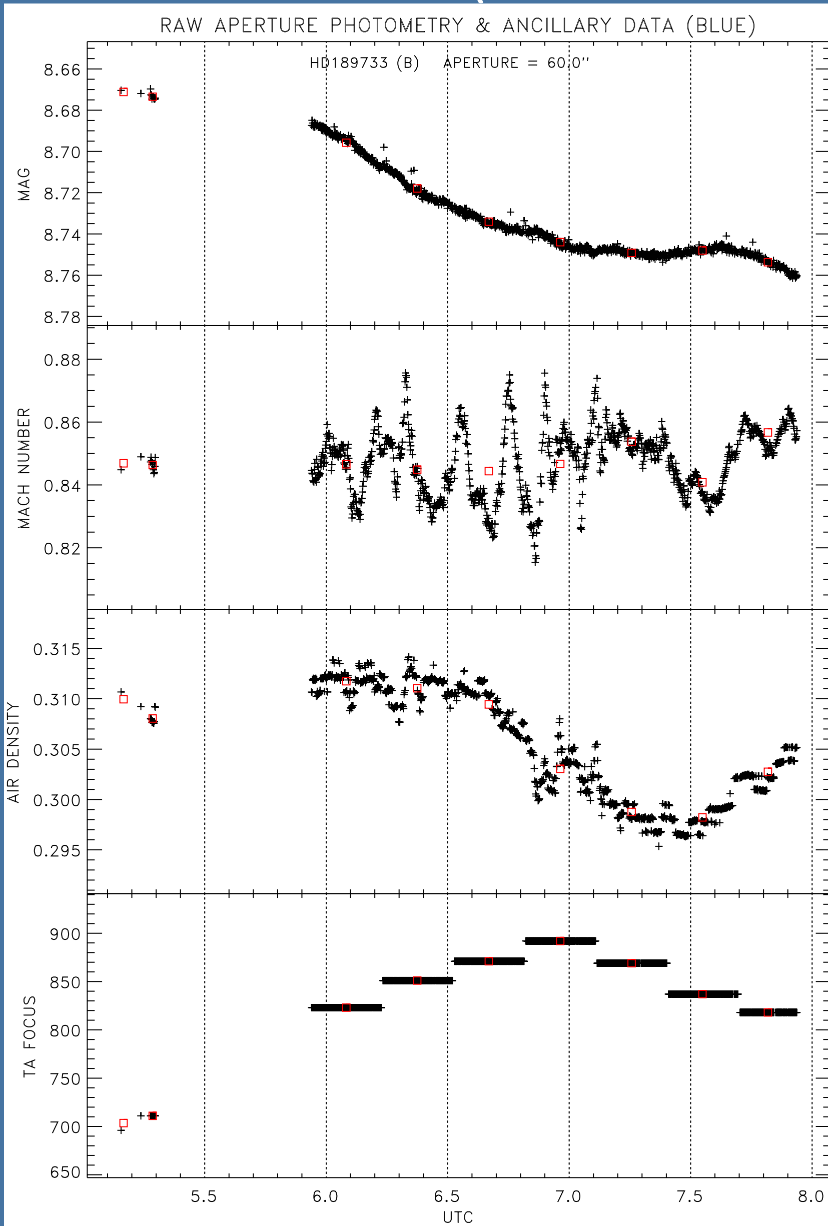
Corrections, III

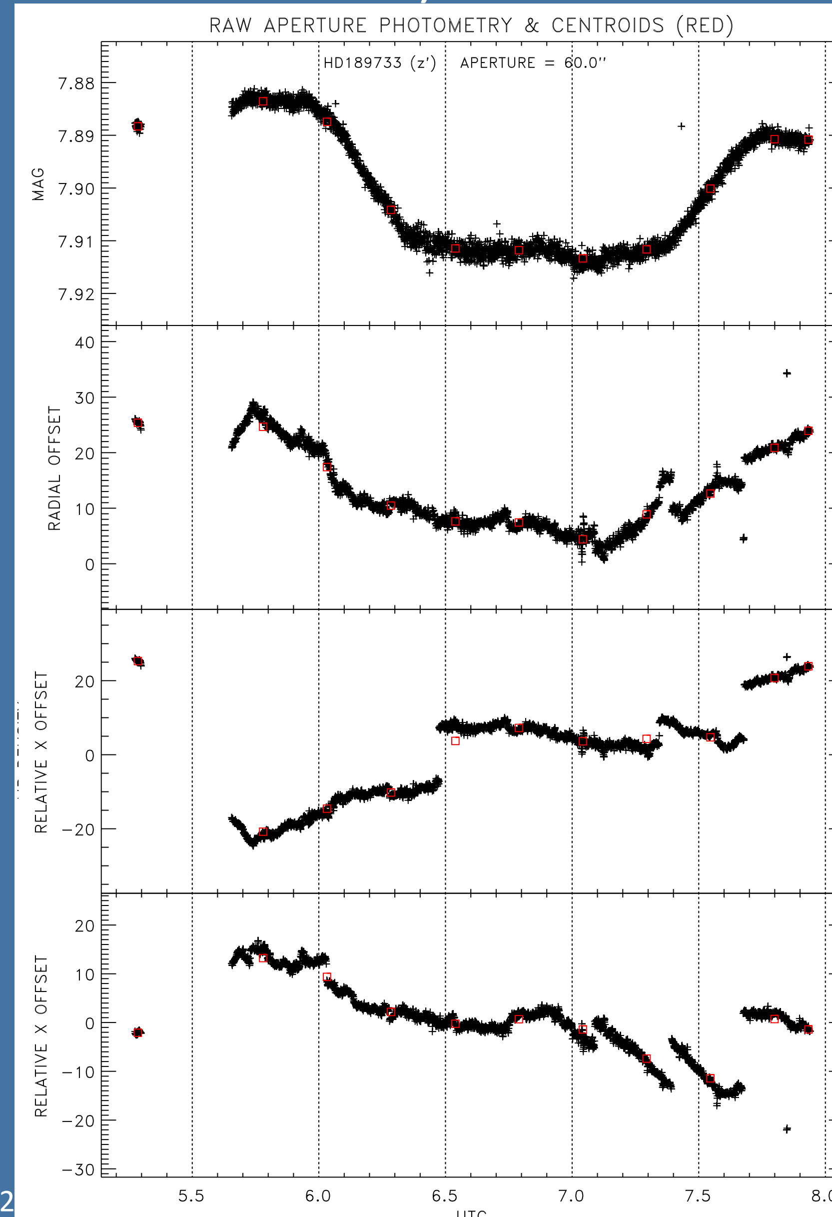
- Re-measure density/ Mach/focus dependence
  - Intended to do this with FLITECAM -- didn't work
  - Beautifully executed test on 2013-10-01 flight
    - Density section ruined by *clouds* at 40000 feet!
  - Will try again next month with FLITECAM
- Why the bump in the Mach number test?
  - Centroid offset



Light curves

(bias subtracted, Blue side flattened)





Transit Fit, I

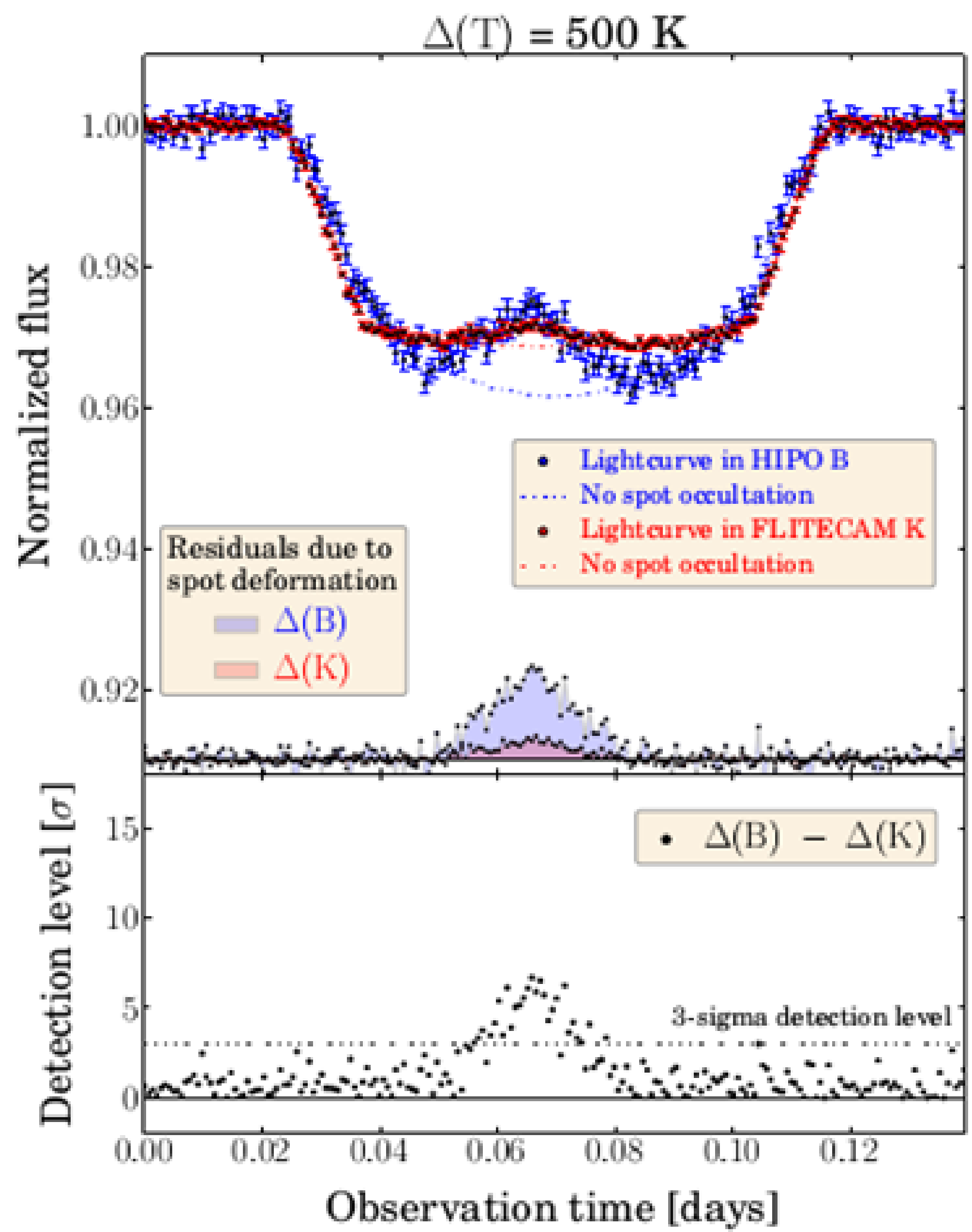
- To fit or not to fit:
  - Ideally fit for astrophysical parameters only
  - Important corrections need fitting too
  - Try to fix the parameters you can
- Fix variables we think we understand
  - System parameters from HST data; limb darkening
    - Epoch, period, impact parameter, radius, inclination
  - Fix density.
    - When fit the coefficient becomes too large to believe
    - Possibly real structure is obliterated
    - Weak point – we still need a better handle on this

Transit Fit, II

- Fitted parameters include:
  - Flux zero point in B and z’
  - Differential atmospheric extinction in B & z’
    - After removing measured extinction from Landolt stars
  - Centroid corrections
    - Differential X and Y offsets in B and z’
    - Radial offset in B and z’
- Fit is done simultaneously to both datasets

Transit Fit, III

- What can we say about this?
  - How much is real?
    - 189733 is active
  - How much is not?
    - Without baseline, can't tell
  - Density glitch is close to "star spot".
    - Cause & effect or coincidence?
    - Klaus Huber's model - hmmmmm



Switch to Daniel's File Here

Improvements for next time

- Get good FLITECAM data!
  - Need WVM operating; calibration not required
- Repeat shear layer test with FLITECAM (no clouds)
- Observe bright stable star pair for a LONG leg
  - Search for other possible systematic effects
- Keep pointing and focus under tight control
  - HIPO guiding, possibly automatic focus update
- Get plenty of pre- and post-transit baseline!

Longer Term Issues

- Deployments will be involved
  - Short SOFIA leg lengths are a serious impediment
- Sunrise constraint needs to be eliminated
- Install Nasmyth blower
  - Cool FLIPO periscope & FLITECAM window
  - Biggest background contributors for FLITECAM
- Install the fully reflective tertiary
  - Systematics dominate only when shot noise is low enough.
  - We're stuck with an observing efficiency hit of 20% to 60%
    - Using the FPI only wins back part of that
  - But it's worse – with time-limited events you can't even make it up with more observing time.