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The Things You Can't Ignore: Evolving a Sub-Arcsecond Star Tracker

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Motivation and Context

- The S3S development project has produced the ST-16 star tracker.
- There is demand for a higher accuracy star tracker that has:
  - 1 arc-second (~ 4.8 µrad) accuracy, while slewing at
  - 1 °/s (track a target on the Earth's surface from LEO), with
  - 99% availability of an attitude fix

S3S/ST-16 Star Tracker

- This paper tries to answer the question: what modifications must be made to the ST-16 to meet these requirements?
- Can these modifications be achieved through an evolutionary approach to the ST-16 or do these changes drive a revolutionary approach where signification architecture changes are necessary?

Optical Trade Studies

Availability – the fraction of the sky where a good attitude fix is possible.

- Calculated using a sky survey, stellar detection threshold and FOV

Accuracy – expected accuracy of the sensor

- Difficult to calculate analytically because it depends on the accuracy of individual star vectors as well as their distribution in the FOV
- We examine what centroid error we must have to ensure we meet the accuracy requirements.

- How does the ST-16 optical design limit performance?
- Can we achieve better performance with better optics and detectors?
  - We look for valid designs by changing F# and D
  - Each design is assessed by its availability and accuracy

Parameter	MT9P031	CMV4000
$h\ (mm)$	4.28	11.3
$\gamma\ (\mu m)$	2.2	5.5
σ_e	3.5	13
Pix. Dim.	1944 x 2592	2048 x 2048

Table 1 – Detector Parameters

Optical Trade Studies

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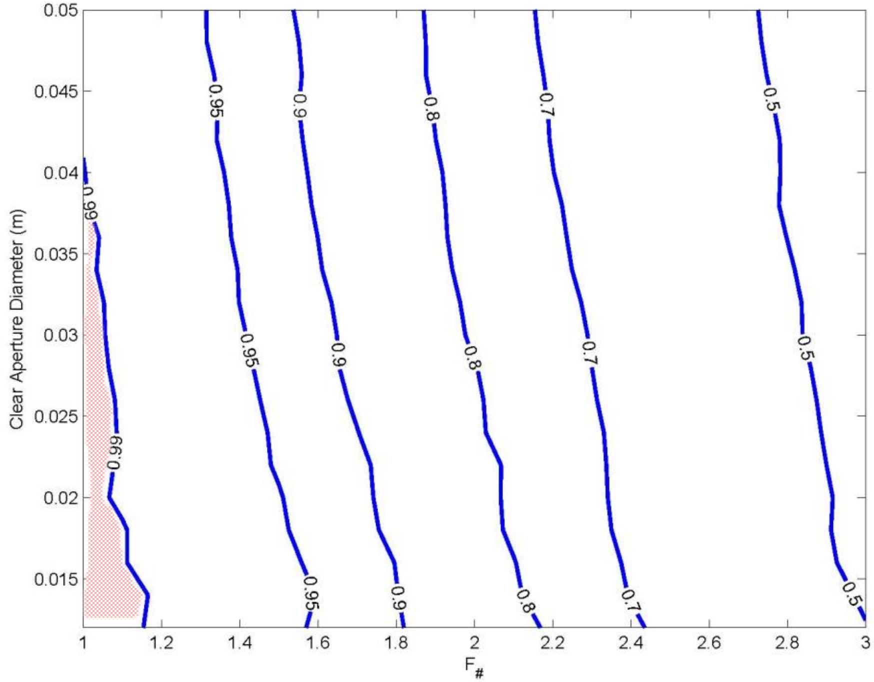
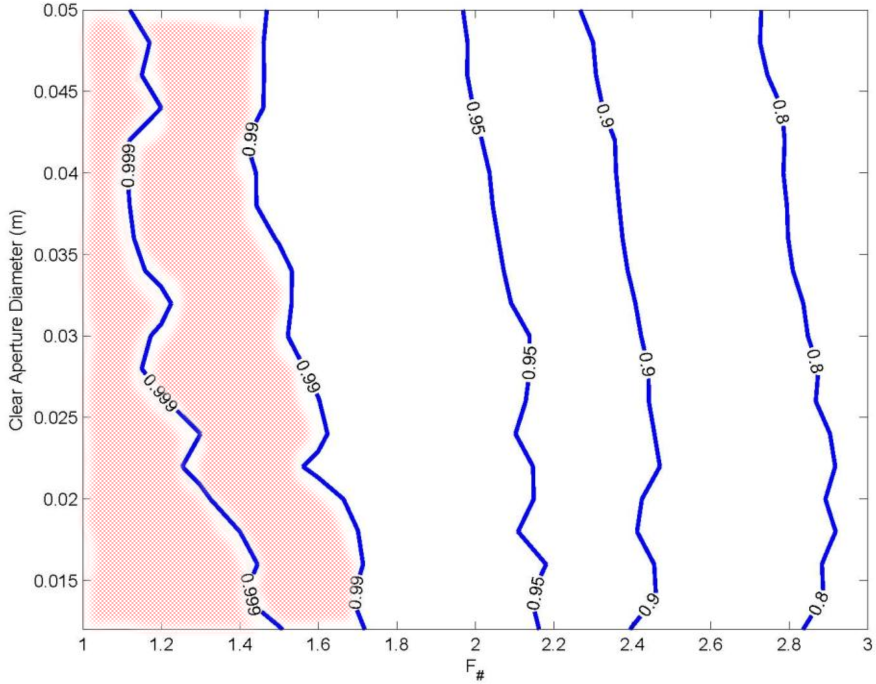
- Smaller focal lengths have a larger FOV and can thus see more stars.
- Star distribution favors increasing the # of stars in view by increasing the FOV rather than merely detecting dimmer stars via larger D.



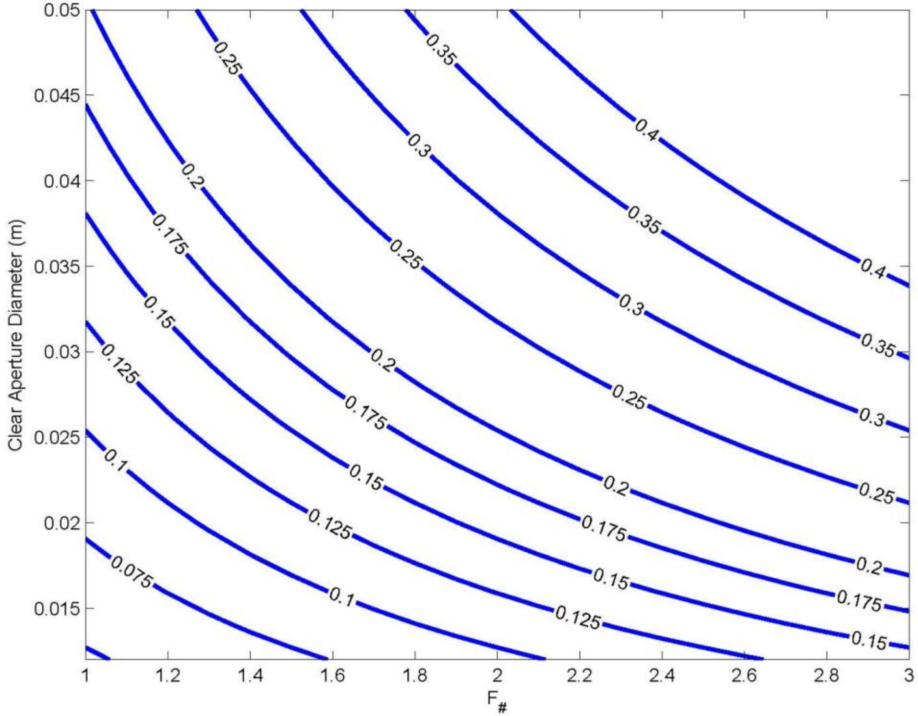
3-Star Availability from MT9P031 (@ 1°/s)



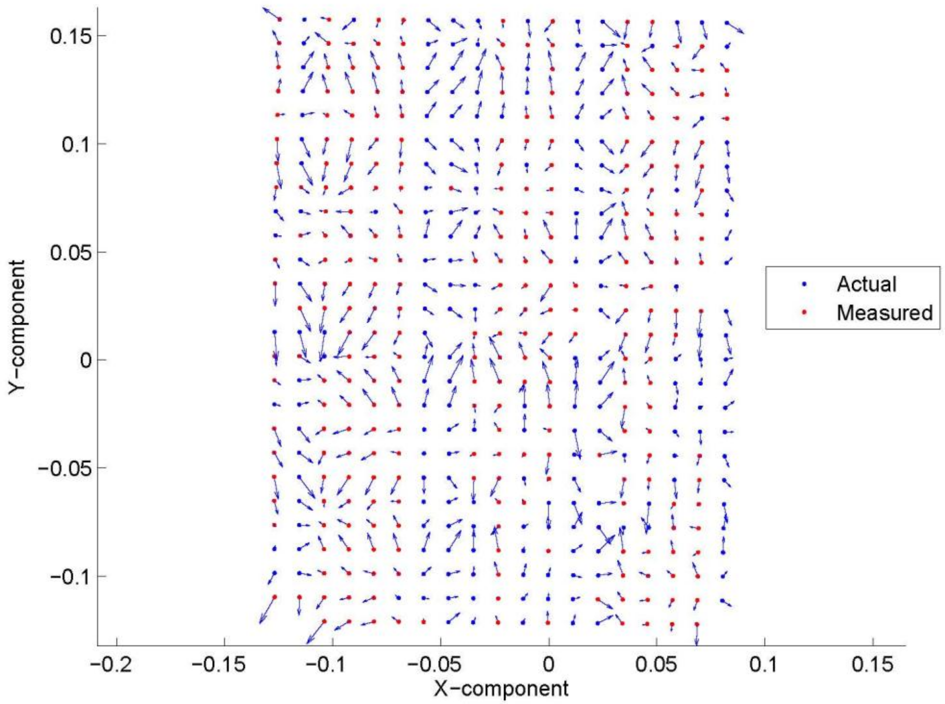
3-Star Availability from CMV400 (@ 1°/s)

Optical Trade Studies

- Trade studies show that without an improvement in centroid accuracy we cannot meet target requirements with just a lens change.
- If we can improve this from the current ~0.2 pixels to ~0.07 pixels, we can meet accuracy requirements.



Calibration Residual Req. – MT9P031



ST-16 Calibration Residual Plot

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Effects we can't ignore: Thermal

We consider two types of thermal deformation:

- Change in bulk temperature
  - Causes thermal expansion in the glass lens elements and in the structure that positions them.
  - Changes the index of refraction of the glass itself.
  - If we can still match stars, we can use the observed star positions to determine the effective focal length and correct these effects.
- Temperature gradients
  - Lateral temperature gradients across a cantilever lens assembly will result in bending.
  - Nothing inherent in the image that would allow for the bend angle to measured and corrected. The design must minimize the thermal gradient bending of the optics.

Effects we can't ignore: Star Positions

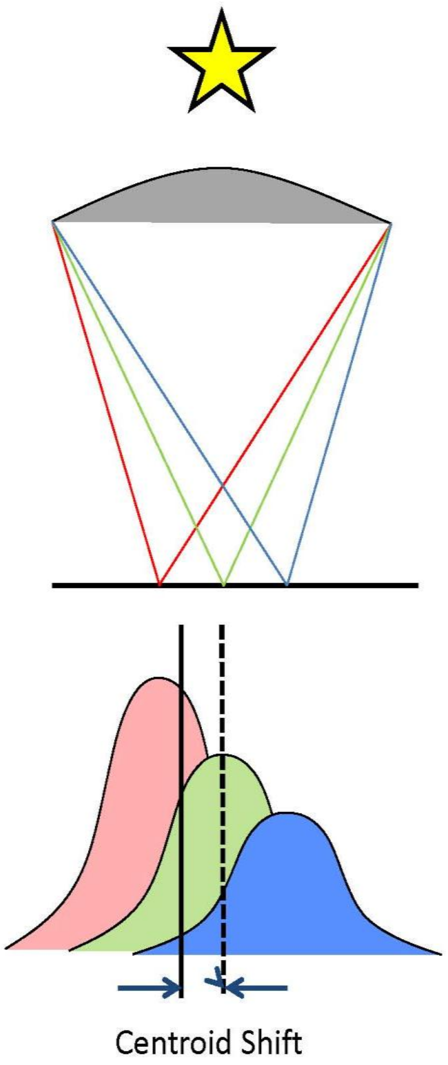
We consider three effects that can change the apparent star positions:

- Annual Parallax - Nearby stars will move slightly over six months due to the angular motion of the Earth around the Sun.
- Proper Motion – Caused by secular motion of the stars themselves
- Stellar Aberration – Angular displacement caused by the velocity of the observer (Earth around Sun ~100µrad & Satellite around Earth ~25µrad)

Effect	Magnitude	Correctable	Extra Info Required:
Annual Parallax	Small	Not Necessary	None
Proper Motion	Large	Yes	Absolute Time
Stellar Aberration	Small/Large	Yes	Ephemeris

Effects we can't ignore: Chromatic Aberration

- Effective focal length varies as a function of wavelength
- Different stars have different surface temperatures and thus different dominant colors.
- Leads to uncertainty in the true star vector
- Can be eliminated from the optics (via Hardware changes) or compensated by software.
  - Optics can be made almost achromatic by careful selection of glasses, and/or bandpass filters.
  - Can be corrected in software with a color-dependent correction. (Catalog must include spectral information)



Conclusions

Optical Trades:

- The impact of optical design on availability is well understood. Star distribution favors increasing the FOV over aperture diameter.
- The impact of optical design on accuracy is less clearly understood.

Star Tracker Calibration:

- Lab. calibration of a sub-arcsecond ST using our current setup is not feasible.
- On-orbit self calibration not only allows for high accuracy model estimates but also tolerance to dimensional changes over time.

Effects we cannot ignore:

- Chromatic aberration is significant and will require correction either via optics selection or software.
- Bulk thermal changes can be corrected using on-orbit recalibration. Temperature gradients cannot and must be minimized through mech. design.
- Stellar aberrations and proper motion can and must be corrected. To do this we need access to an accurate real-time clock and orbital ephemeris.

Thank you for you time.

Questions?