Vision Algorithm for the Solar Aspect System of the HEROES Mission

Alexander Cramer

Electromechanical Systems Branch

NASA Goddard Space Flight Center

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Acknowledgements

Dr. Steven Christe

Dr. Albert Shih

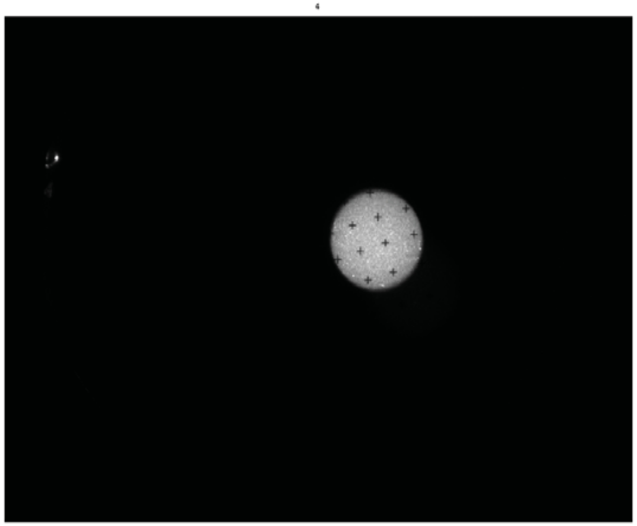
The HEROES Team

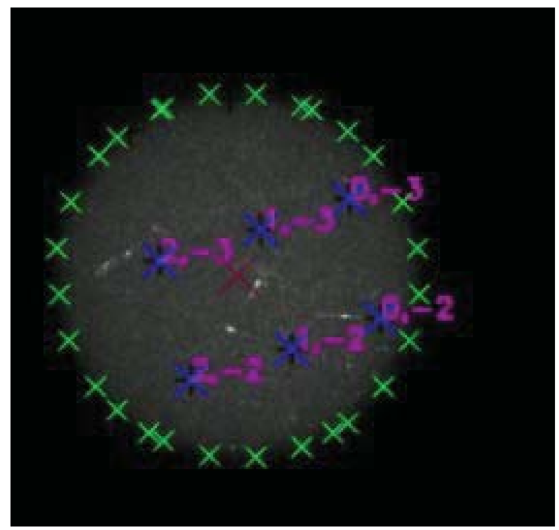
Outline

- **Introduction**
- Background
- Algorithm Details
- Performance Testing
- Lessons Learned

Introduction

A machine vision algorithm that can generate pointing solutions for the HEROES payload based on images from the Pitch and Yaw Aspect System (PYAS) in real time





Introduction

- Sun sensing is a common problem
  - Solar observatory pointing
  - General spacecraft attitude
  - Solar panel pointing
- What makes this a challenging vision problem?
  - Sub-pixel accuracy is required
  - Computation time is limited
- How was this approach unique?
  - All off-the-shelf electronics
  - Long focal length

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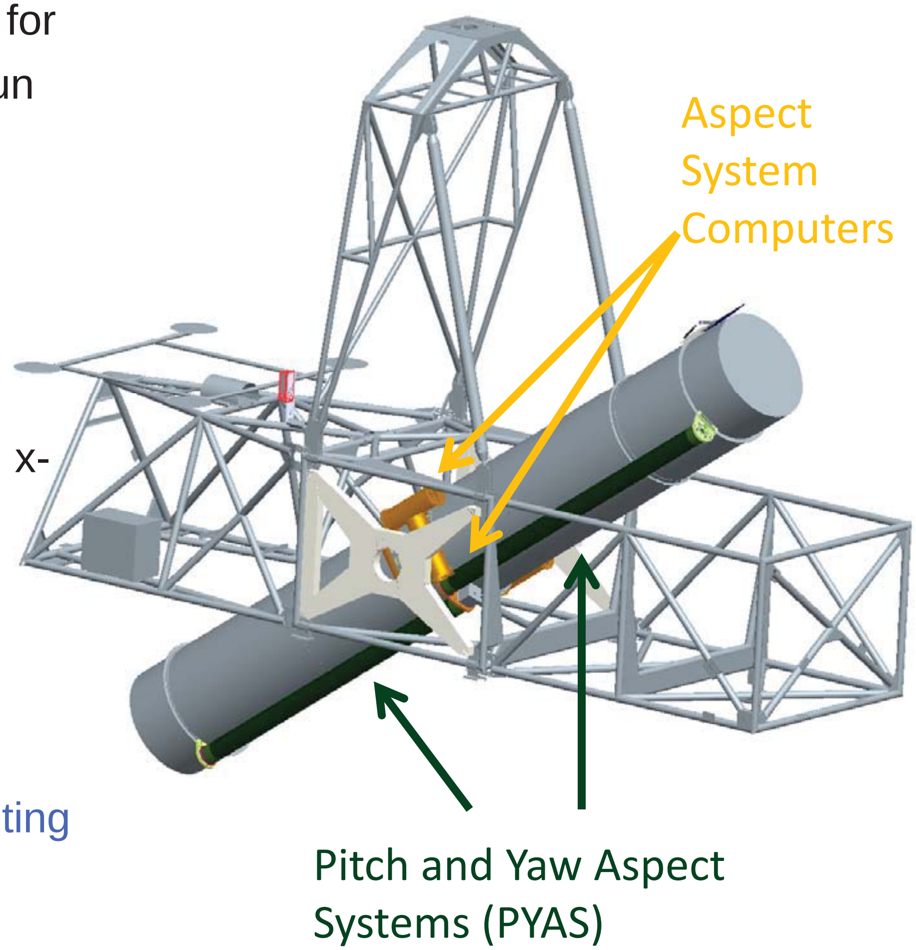
HEROES Mission

- HEROES was a high altitude balloon mission for making hard x-ray observations of both the sun and of astrophysical targets
- Launched from Fort Sumner, NM in Fall 2013
- Consisted of modifications to an existing hard x-ray telescope payload: HERO
  - HERO used a star camera for pointing
  - Star camera could not provide pointing solutions near or at the sun
  - PYAS replaced star camera for solar pointing



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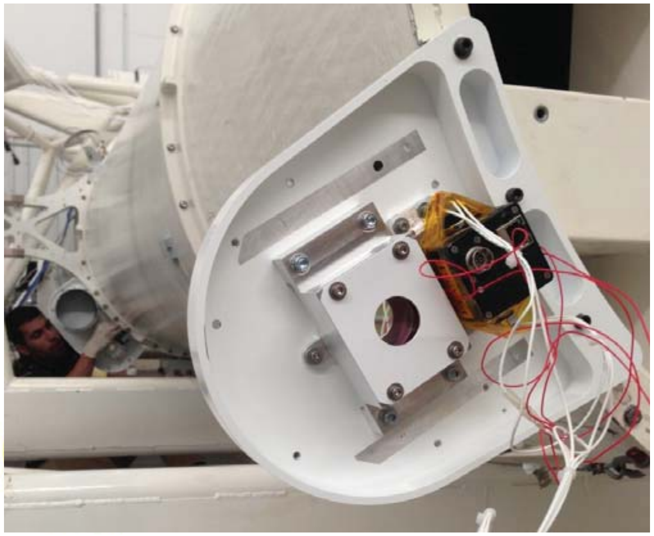
PYAS Requirements

- The star camera on HEROES provided fine pointing solutions
- During solar observation, the PYAS needed to provide solutions with similar cadence and accuracy
- PYAS needed a fully visible sun to generate fine solutions, but could generate a coarse solution with a partially-visible sun

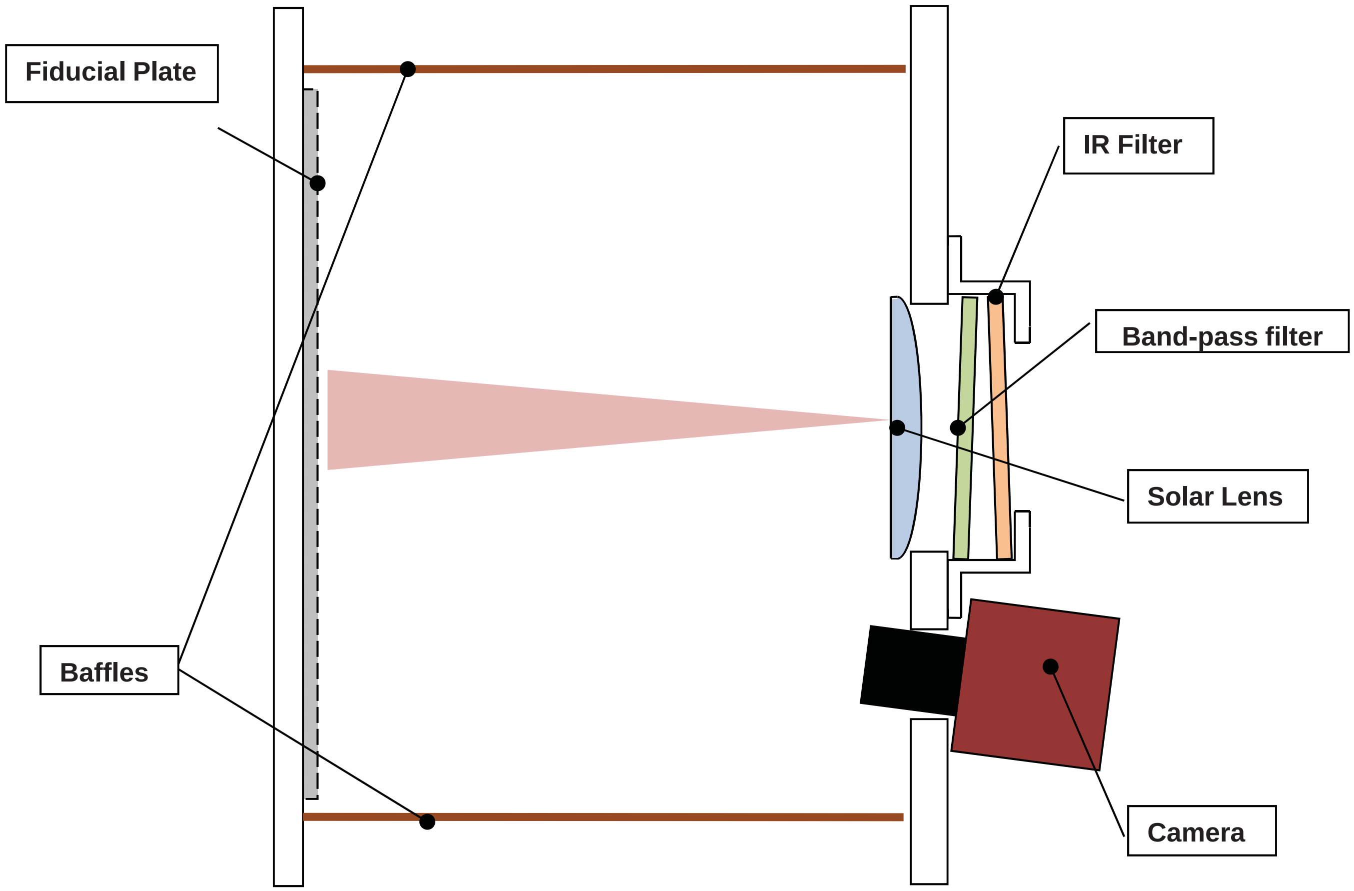
Requirement	
Cadence	1 Hz
Accuracy	20 arcsec (~1.9 pixels)
Field of View	2.8° (fine) >3.3° (coarse)

PYAS Overview

- Each PYAS system is 3 meters long
- Camera, lens and filters are at one end, fiducial plate at the other
- Optical path is enclosed with a cardboard baffle
- No moving parts or powered elements other than heaters, camera, and computer



PYAS Optical Path



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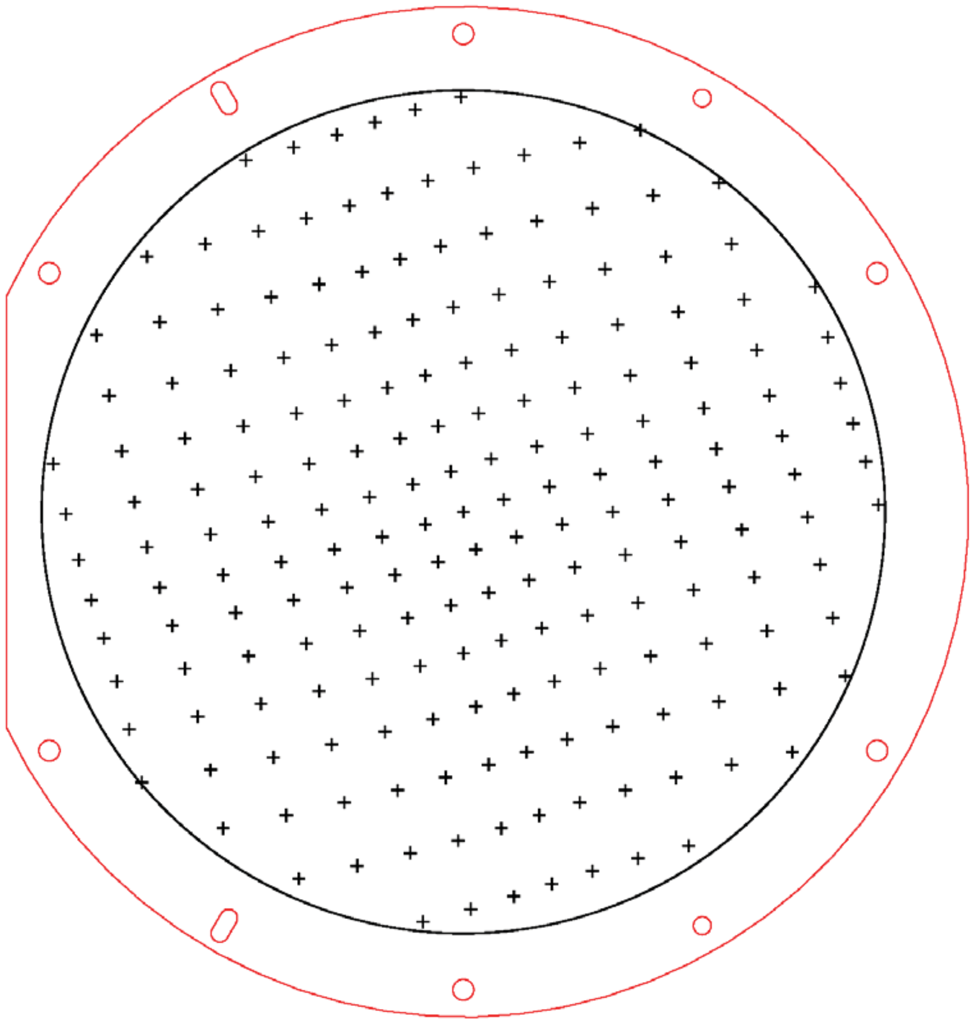
Fiducial Pattern

- Gives a way to convert from image coordinates to gondola coordinates

- Printed pattern of identical cross-shaped marks on a metal plate
- Identity of each fiducial is encoded in the distance between adjacent fiducials
- Need a minimum of 3 adjacent non-collinear fiducials to completely identify
- Only a small portion of the fiducial plate is illuminated in any PYAS image



PYAS Image

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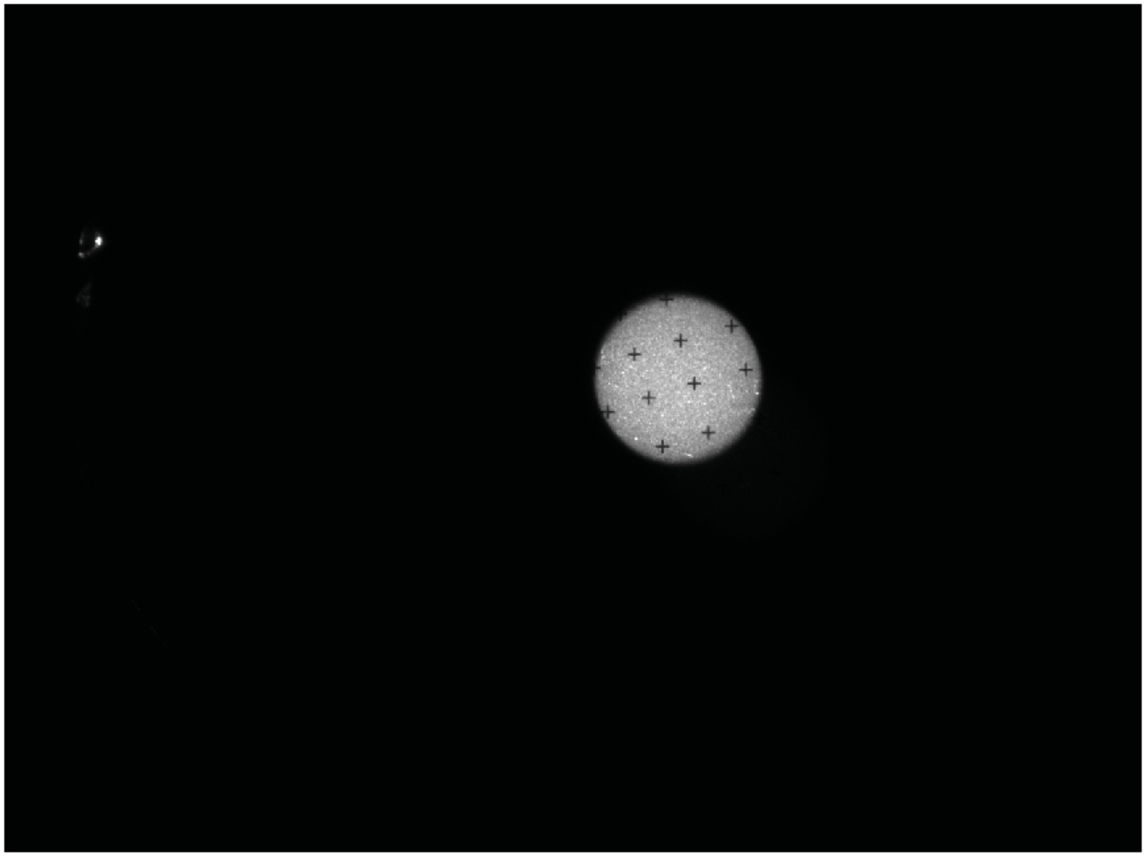

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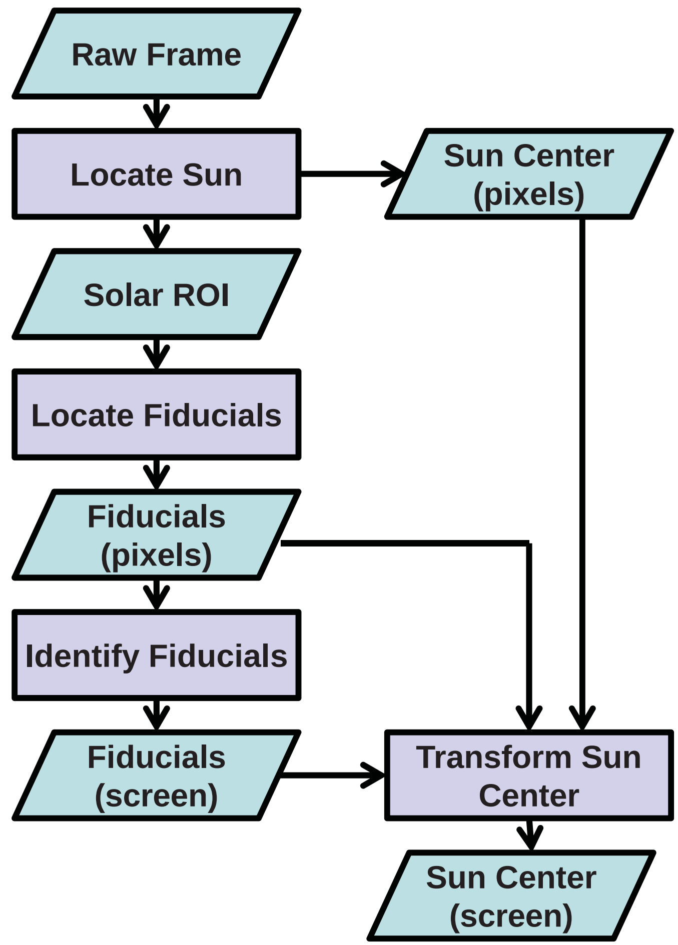
Algorithm

- The PYAS algorithm was broken into four basic stages:
  - Locate Sun
  - Locate Fiducials
  - Identify Fiducials
  - Transform Sun Center

- The algorithm takes a raw PYAS image computes location of the sun relative to the center of the fiducial screen

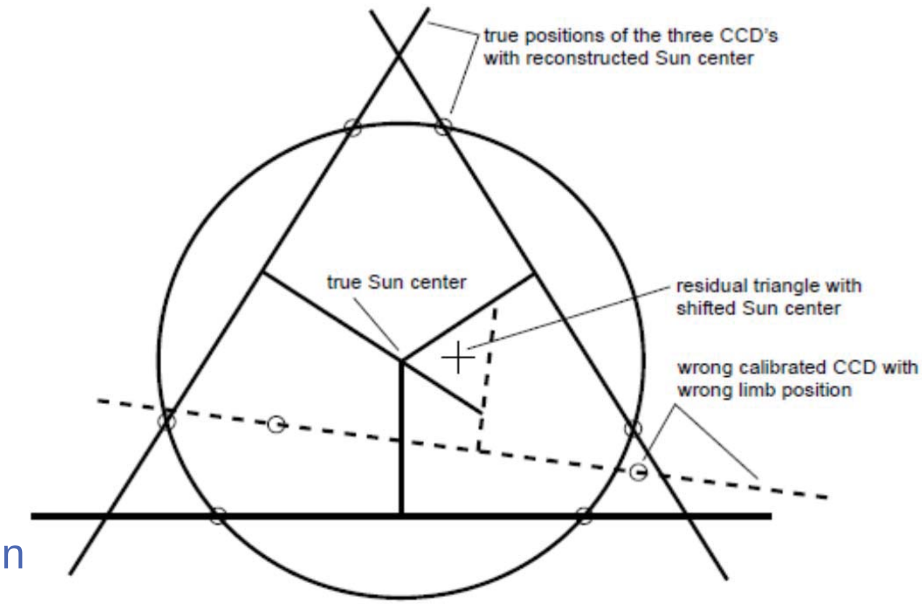


Assumptions

- There will only be one sun-like object present in each frame
- Optics and camera are approximately parallel to the fiducial plate
  - Solar image is circular rather than elliptical
  - Projective effects from the camera orientation can be approximated with a similarity transform
  - Clocking of fiducial plate relative to the camera is negligible
  - Change in distance and clocking between fiducial plate and camera will be small
- The projected solar image will not be under or overexposed, and required exposure settings will not change drastically over the duration of a flight

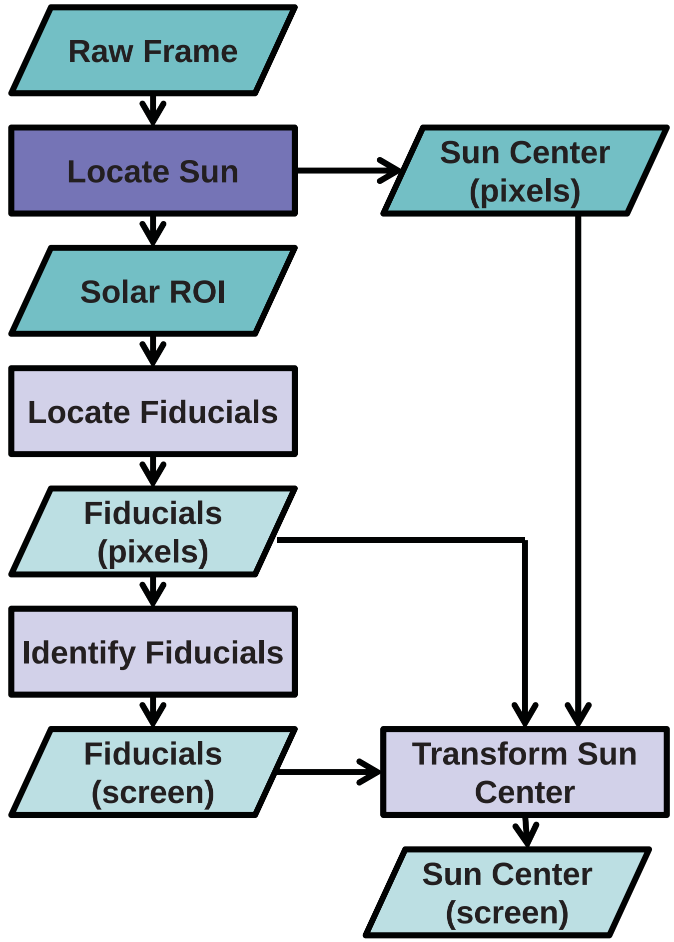
Related Work

- Sun Tracking
  - RHESSI SAS
  - Average Intersection for circles
- Fiducial Detection
  - Common machine vision problem
  - Commonly solved with intensity correlation
  - Sub-pixel location can be determined with a centroid



M. Fivian, R. Henneck, and A. Zehnder, "RHESSI Aspect System and In-flight Calibration," *Proc. SPIE*, vol. 4853, pp. 60–70, 2003.

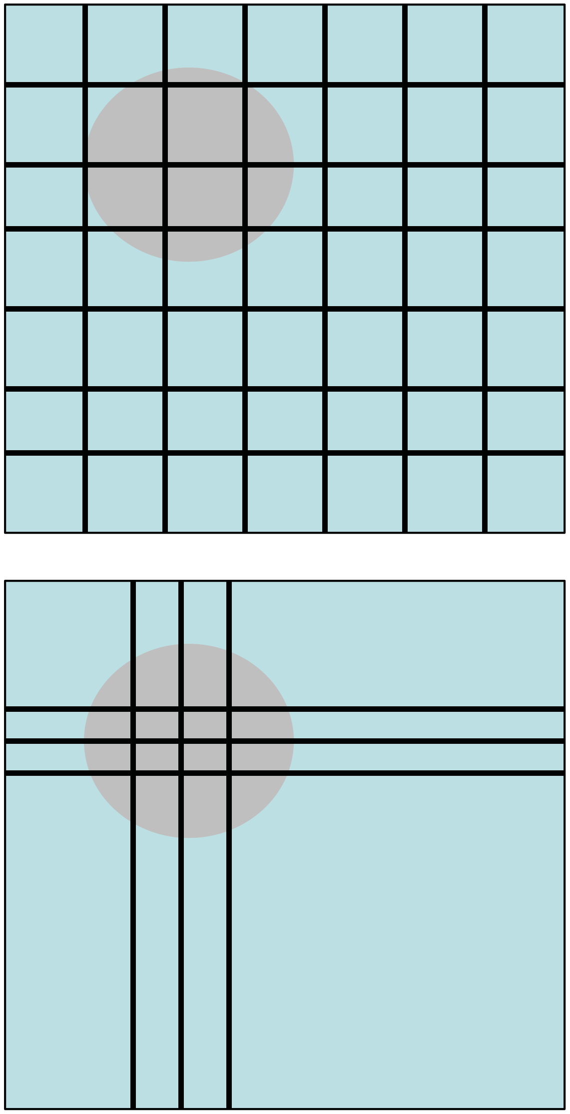
Algorithm



Raw Frame
Locate Sun
Sun Center (pixels)
Solar ROI
Locate Fiducials
Fiducials (pixels)
Identify Fiducials
Fiducials (screen)
Transform Sun Center
Sun Center (screen)

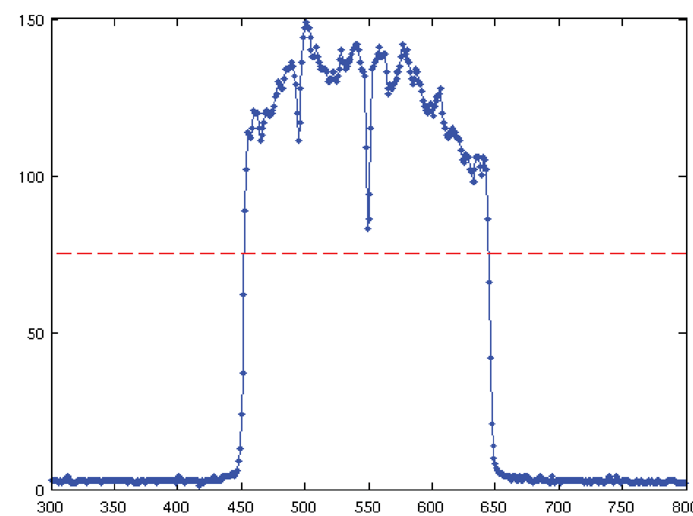
Chord Placement

- Motivated by RHESSI Solar Aspect System
- Allows for an easy trade between computational complexity and accuracy
- Made use of two grids, coarse and fine
  - Coarse grid looks for chords evenly distributed over entire image
  - Fine grid looks for chords only where the sun is expected to be



Chords Algorithm

- Multiple rows and columns are inspected in each image
- Each is compared against a set of criteria to assess whether or not it is a chord through the sun
- Valid chords are compared against a brightness threshold to determine the location of the solar limb



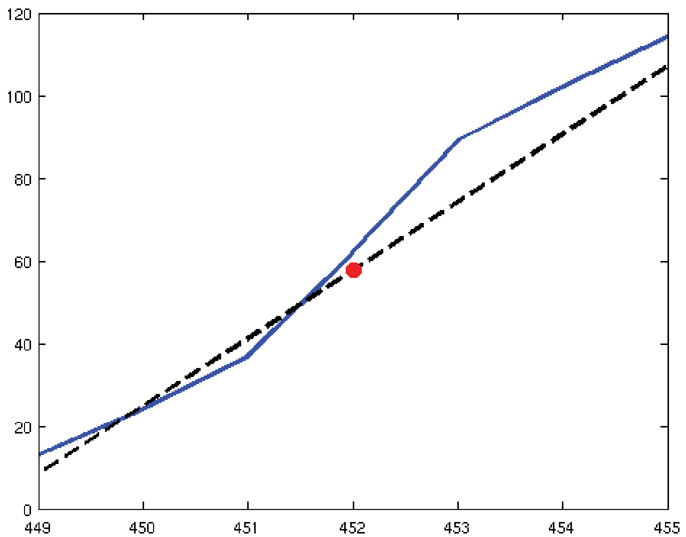
Chords Algorithm

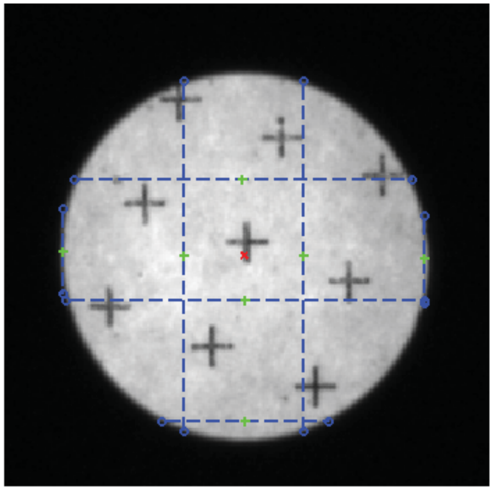
•For each chord, edges of the sun are located and refined with a linear fit in intensity

•Edges are averaged to get midpoint of the chord

•The resulting midpoints are averaged for each axis to determine the center of the sun

•ROI around this center is used for fiducial detection





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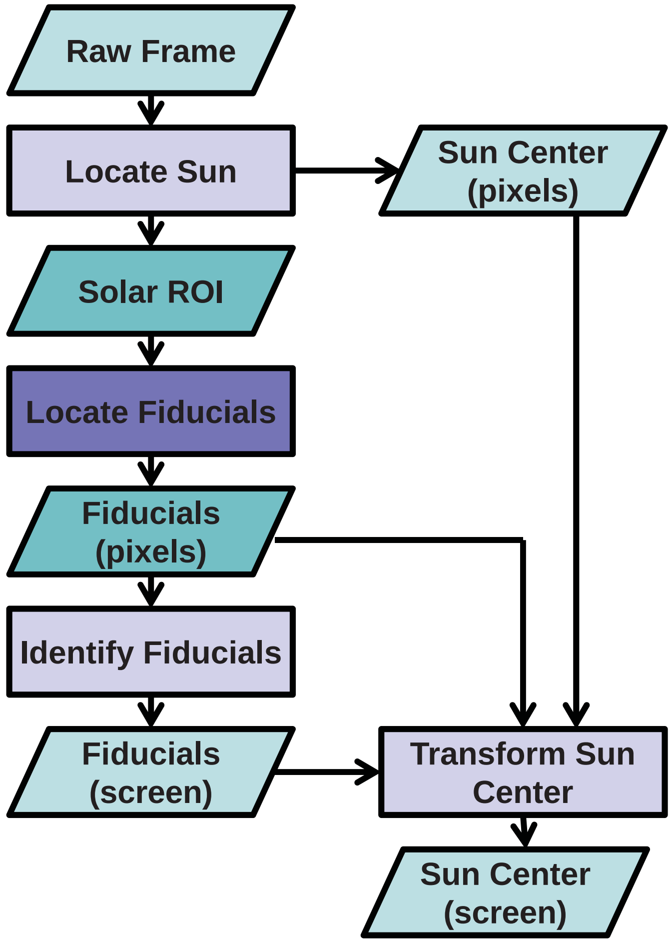
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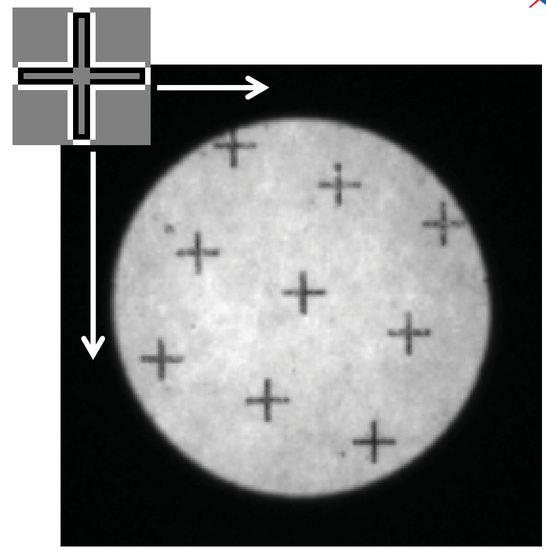
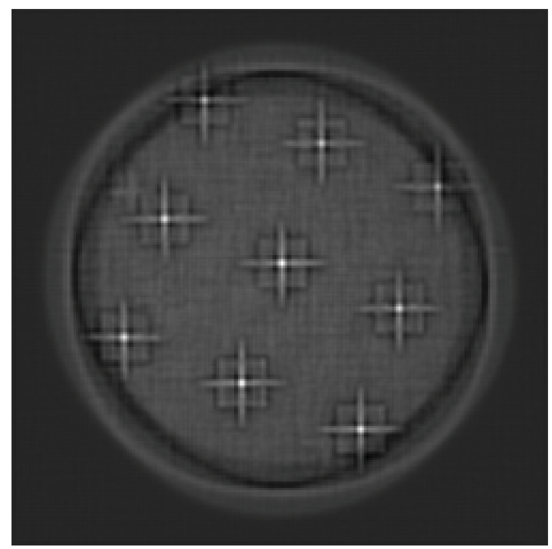
Fiducial Detection

- Fiducials are located using an edge-based shape detection mask
- Correlation with the mask yields an image with local maxima at the locations corresponding to fiducials
- Location is refined to sub-pixel level with a centroid around correlation maxima





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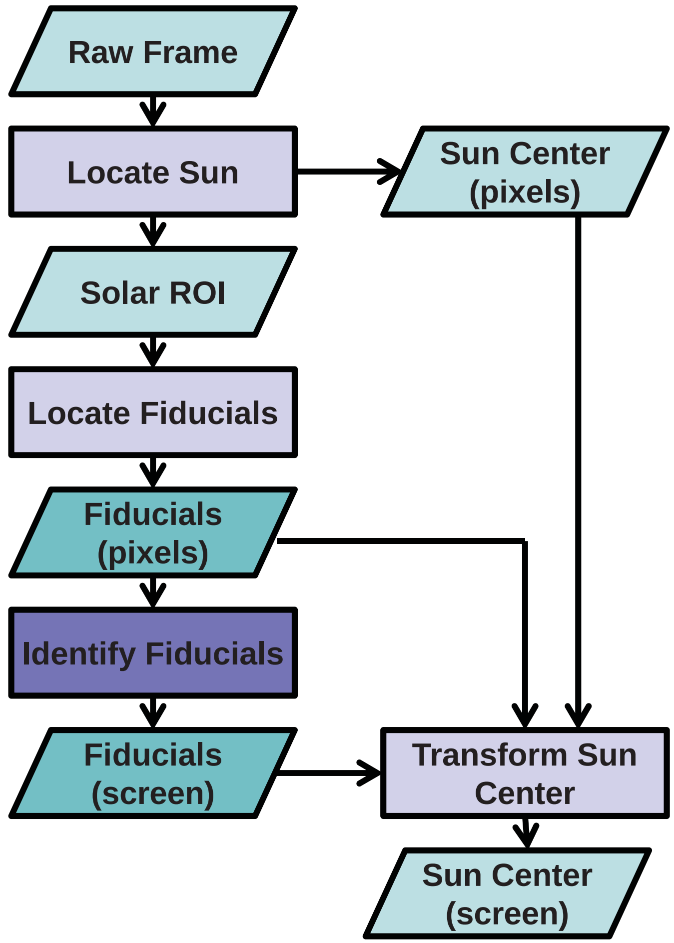
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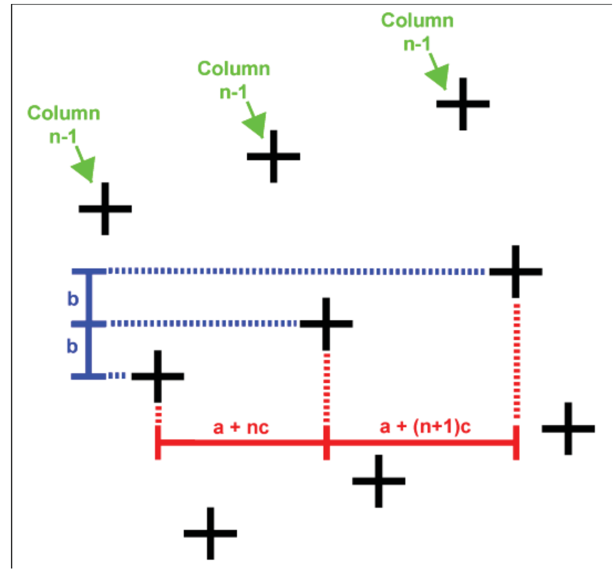
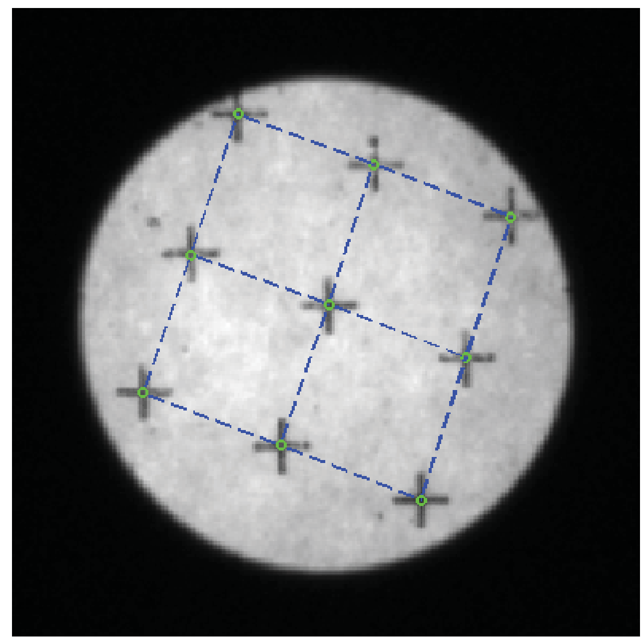
Fiducial Identification

- Inter-fiducial distances are computed along rows and columns of the image for every pair of detected fiducials
- Recall that fiducials are spaced a fixed distance apart along rows or columns with the same ID
- The list of distances is searched for any that match the fixed spacing
- For each match, the other axis is compared to the list of valid spacings
- If there is a match, each fiducial in the pair is identified in that axis





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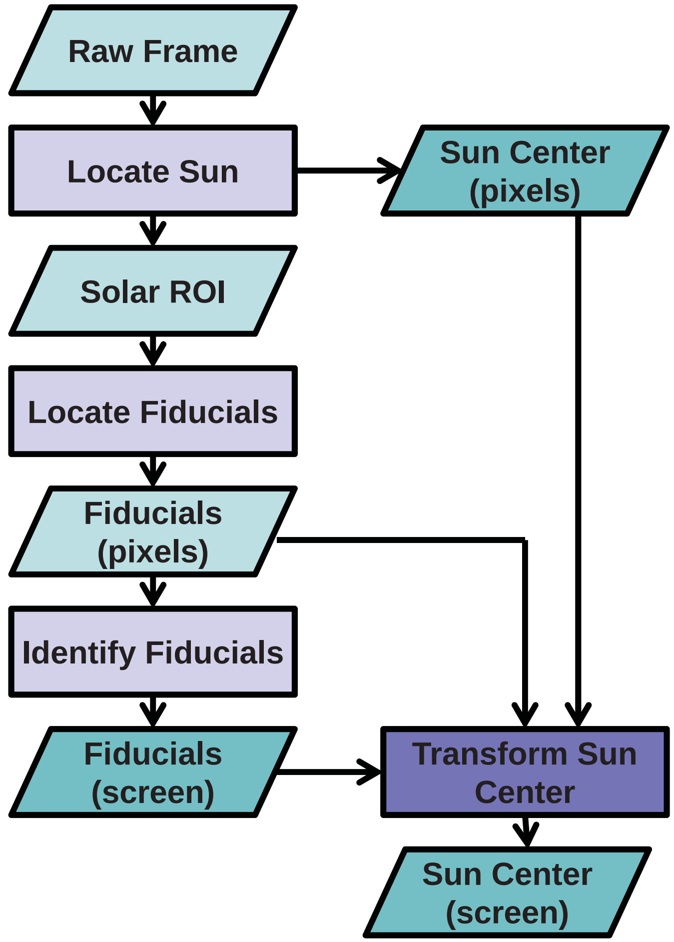

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Mapping

- Converting from pixel space to gondola coordinates was handled with a pair of linear fits
- Once fiducials are identified, their locations on the plate could be looked up, giving a correspondence pair between the camera and the plate
- A separate scale and offset was computed for each axis to convert from the camera coordinate system to the fiducial plate
- Calibrations on the ground gave the mapping between the plate and the gondola coordinate system used by the HEROES pointing controller

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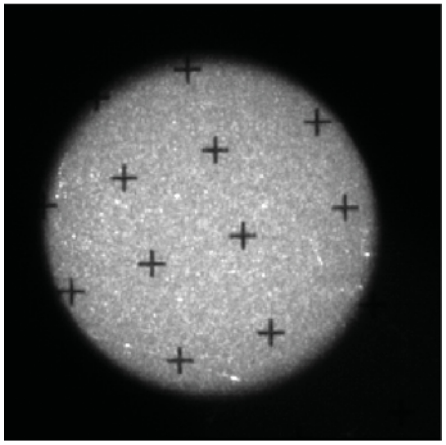
Performance Testing

- Synthetic Data
  - Circle Finding
  - Fiducial Detection
- PYAS Test Data
  - Fiducial Identification
  - Mapping
- Flight Performance

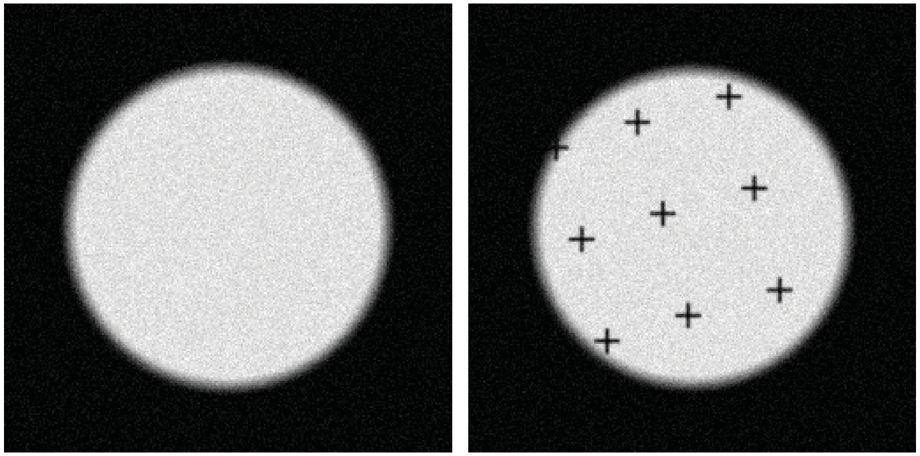
Circle Finding Tests

- Could not devise a test setup with a known reference
- Tests were all performed synthetic data
- Looking to measure
  - Jitter in solution
  - Error bias
  - Trade between chords and accuracy
  - Effects of noise
  - Effect of fiducials



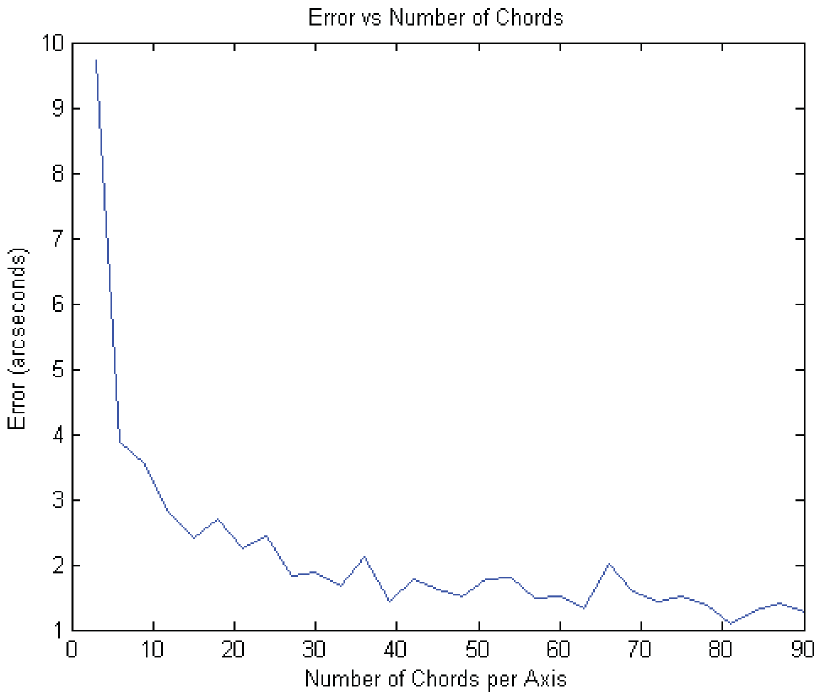
Real Data

Synthetic Data



Circle Finding: Number of Chords

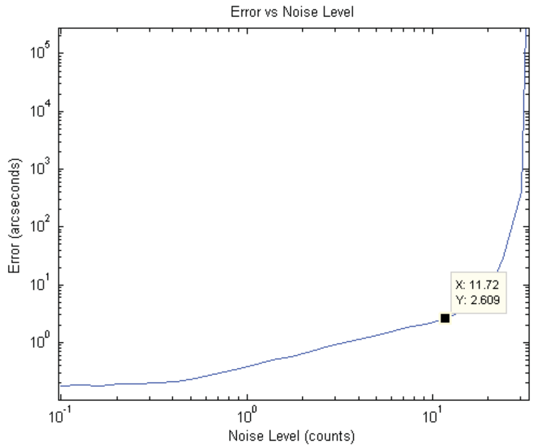
- Interested in how error is affected by the number of chords used to generate a solution
- Observed a sharp decline in error as a function of chords used
- Errors were roughly converted from pixels to arcseconds with ideal scale factor
- Severely diminishing returns after 10 chords per axis

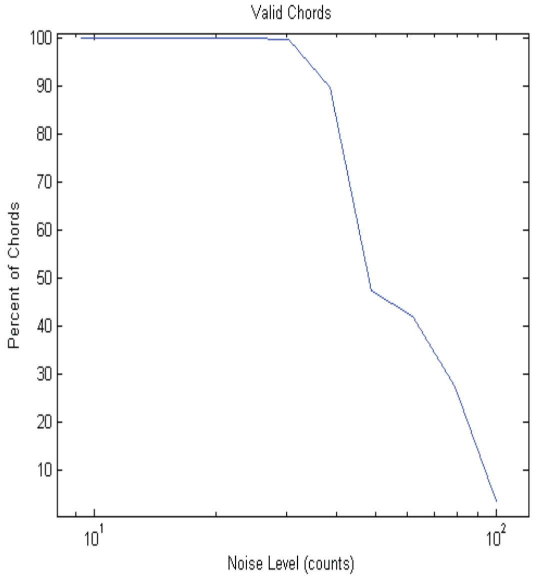


Circle Finding: Noise Tolerance

- Average Intersection is known to be very vulnerable to noise
- With a fixed number of chords, noise level was varied to assess impact on precision and valid chords
- Number of usable chords falls off sharply and error begins to climb if noise is beyond 15 LSB

- PYAS test data was measured to have a noise level of approximately 10 LSB





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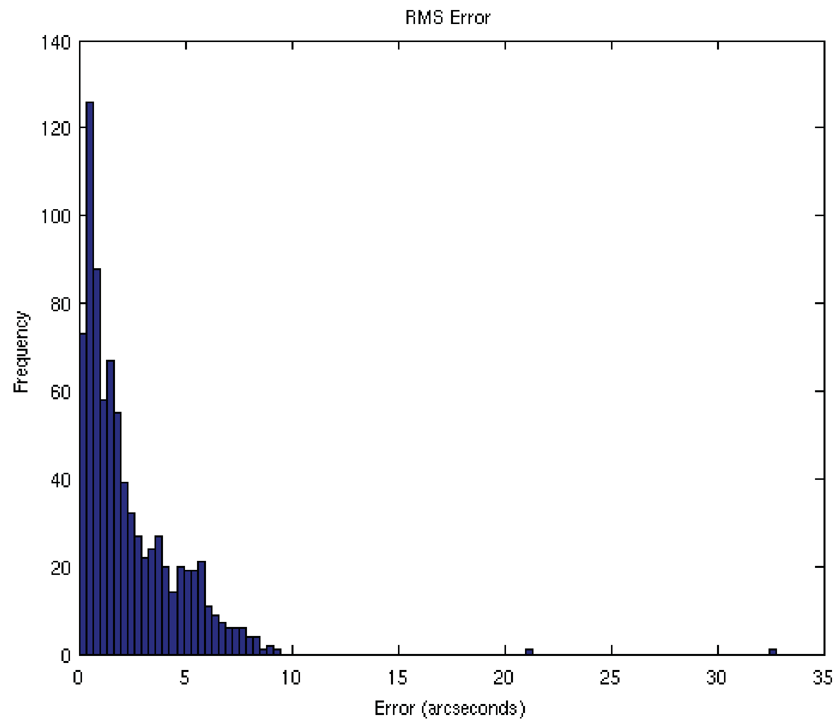
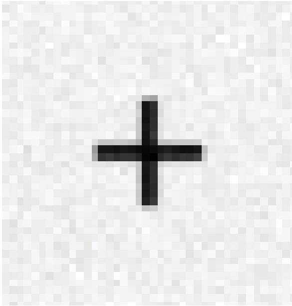
Circle Finding: Effect of Fiducials

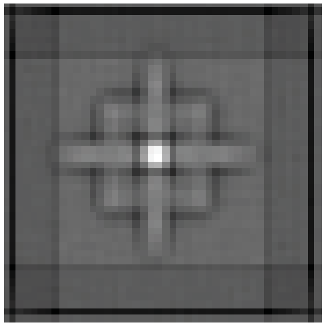
- Tests were performed on artificial data with a fiducial field added
- Test data had a fixed center but a wide range of fiducial locations
- A histogram of error magnitude is plotted at left
- Almost all values fall below 10 arcsec



Fiducial Detection Tests

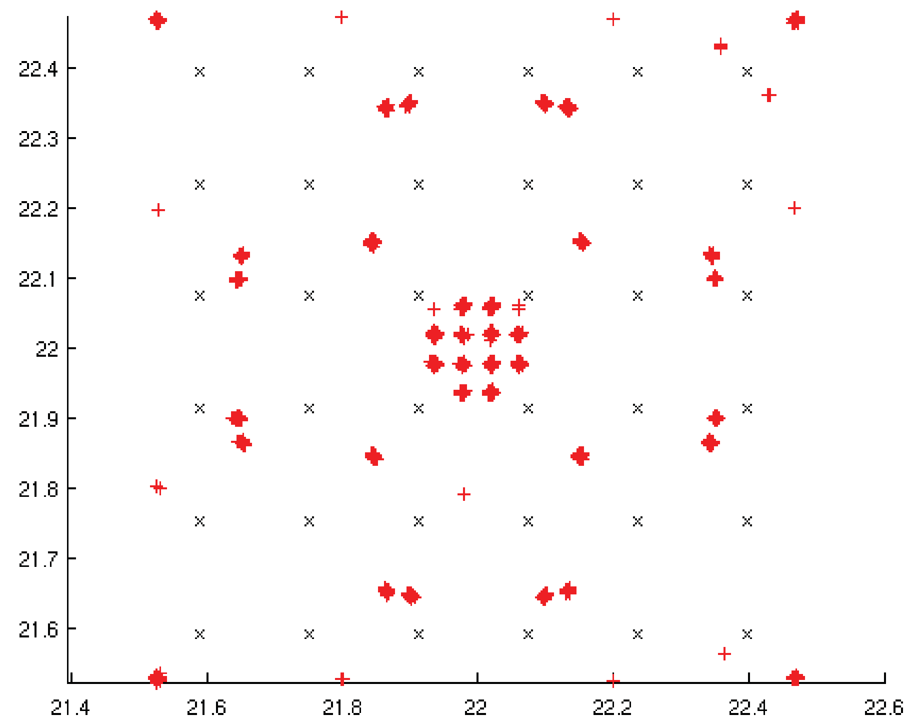
- Effects of error in fiducial location will be rolled into testing of mapping
- More concerned here to see if fiducial detection has any systematic error
- Tests were run on images of a single artificially generated fiducial





Fiducial Detection

- Fiducial detection showed an average error of 1.55 arcsec on synthetic data
- Closer inspection shows that systematic error was introduced when refining the location of the fiducial to sub-pixel levels
- Centroid was computed on pixels near peak which were above a threshold
- By not subtracting that threshold, points on the edge of the neighborhood had strong effect on the center



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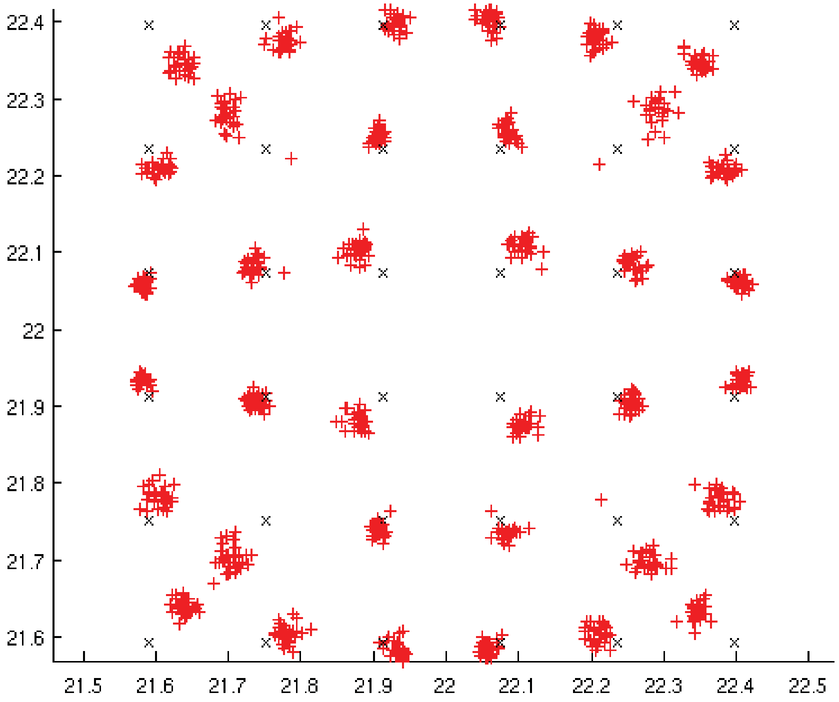
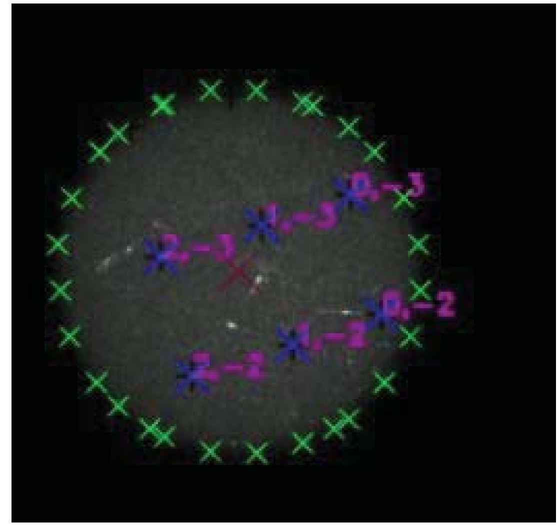
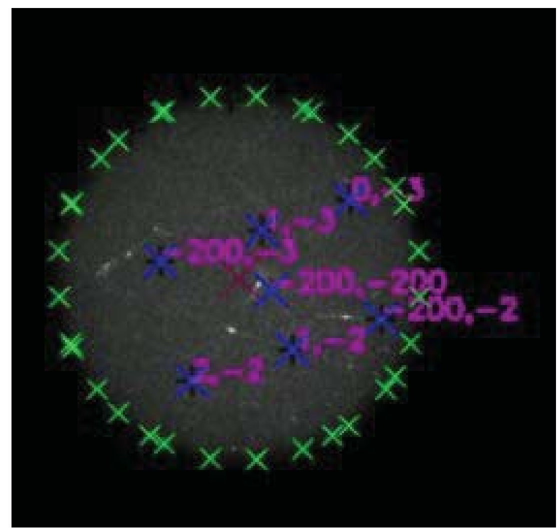


Fiducial Identification

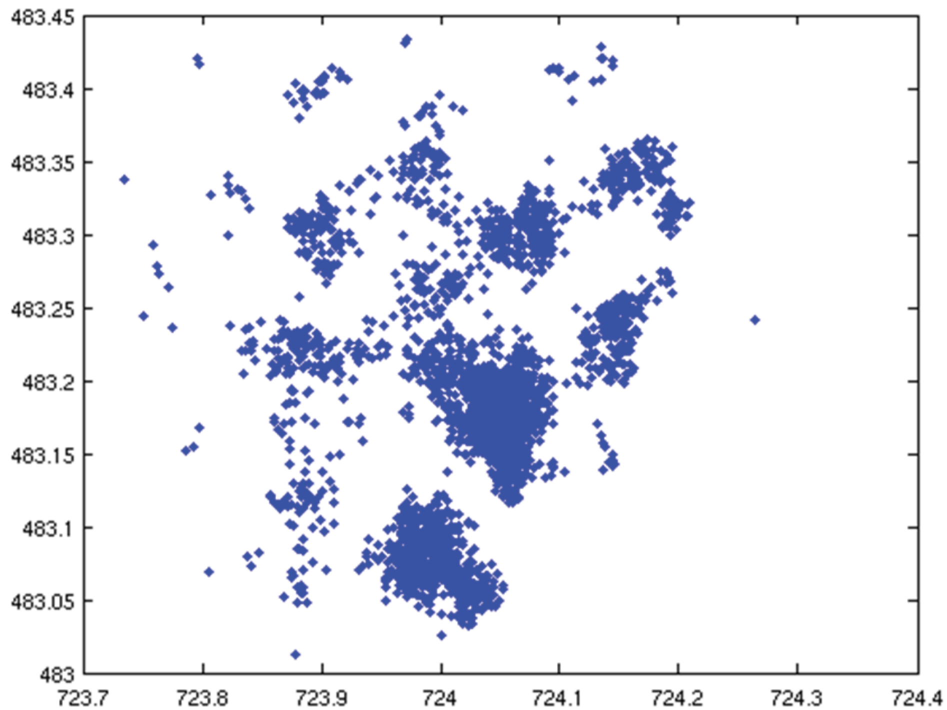
- Difficult to test in any way other than manual inspection
- Fully illuminated fiducials were correctly identified in ground testing
- Partially illuminated fiducials were often not found or identified, but were not often falsely identified
- Scratches tripped false fiducials in testing, were removed by adjusting brightness of brightest points in the image
- Removed by adjusting outlier brightness





Mapping Tests

- Effects of mapping from the camera plane to the fiducial plane were measured directly on PYAS test data
- Noise in fiducial locations led to noise in mapping coefficients, which in turn introduced noise in the pointing solution
- Applying measured jitter in mapping coefficients from real data to jitter in sun center from synthetic data, overall jitter had a 3σ of **19.5 arcsec**



Distribution of measured fiducial location for a single fiducial from a PYAS test

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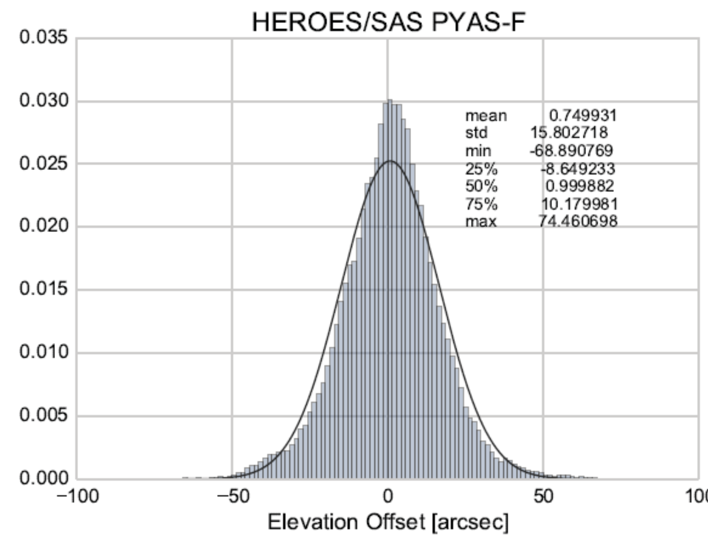
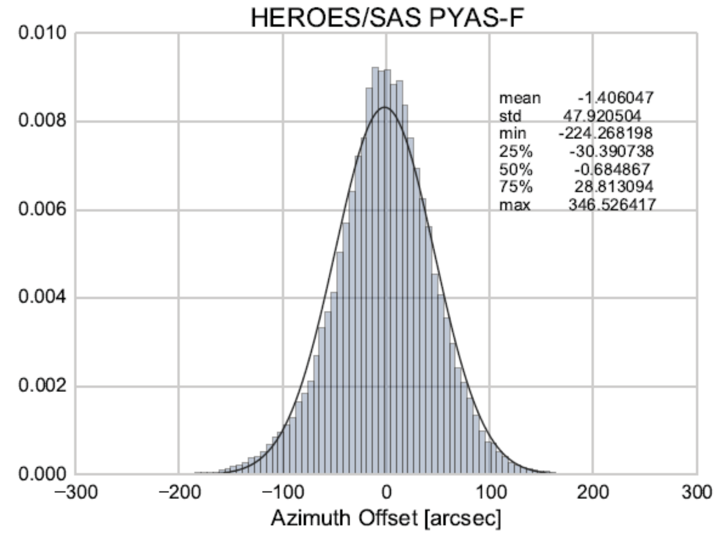
Flight Performance

- HEROES launched on Sep 21, 2013
- Flight lasted over 24 hours, with 7 devoted to solar observation
- PYAS maintained a cadence of 3.97 Hz
- Requirement for overall pointing was that it be within 60 arcseconds of the target 50% of the time
- PYAS showed a a 50th percentile of 10 arcsec and 30 arcsec in azimuth and elevation respectively





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S. Christe, A. Shih, et. al, "A Solar Aspect System for the HEROES Mission," *IEEE Aerosp. Conf.*, 2014.

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Lessons Learned

- Basing algorithm on RHESSI seemed like a good at the outset, in hindsight a more conventional approach would likely have been better
- Algorithm would benefit from a complete restructuring, locating fiducials before searching for sun center
- Circular fiducials may have been easier to detect, a more complicated fiducial pattern might have been easier to identify
- Improvements to computer hardware, image storage, or smarter camera interactions could allow for higher cadence and more complex algorithms

Questions?