National Aeronautics and Space Administration

# Image Processing and Attitude Estimation Performance of Star Camera with Extended Bodies in the Field of View


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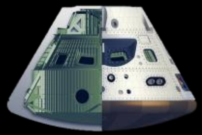
# Outline



- Background – Attitude Sensors
- STR Flight Software:  Main Functional Modules
  - Camera Control
  - Tools of Image Processing
  - Image Centroiding
- Ground Calibration for the Bore-sight Offsets and the Focal Length
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- Attitude Estimation
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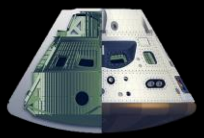
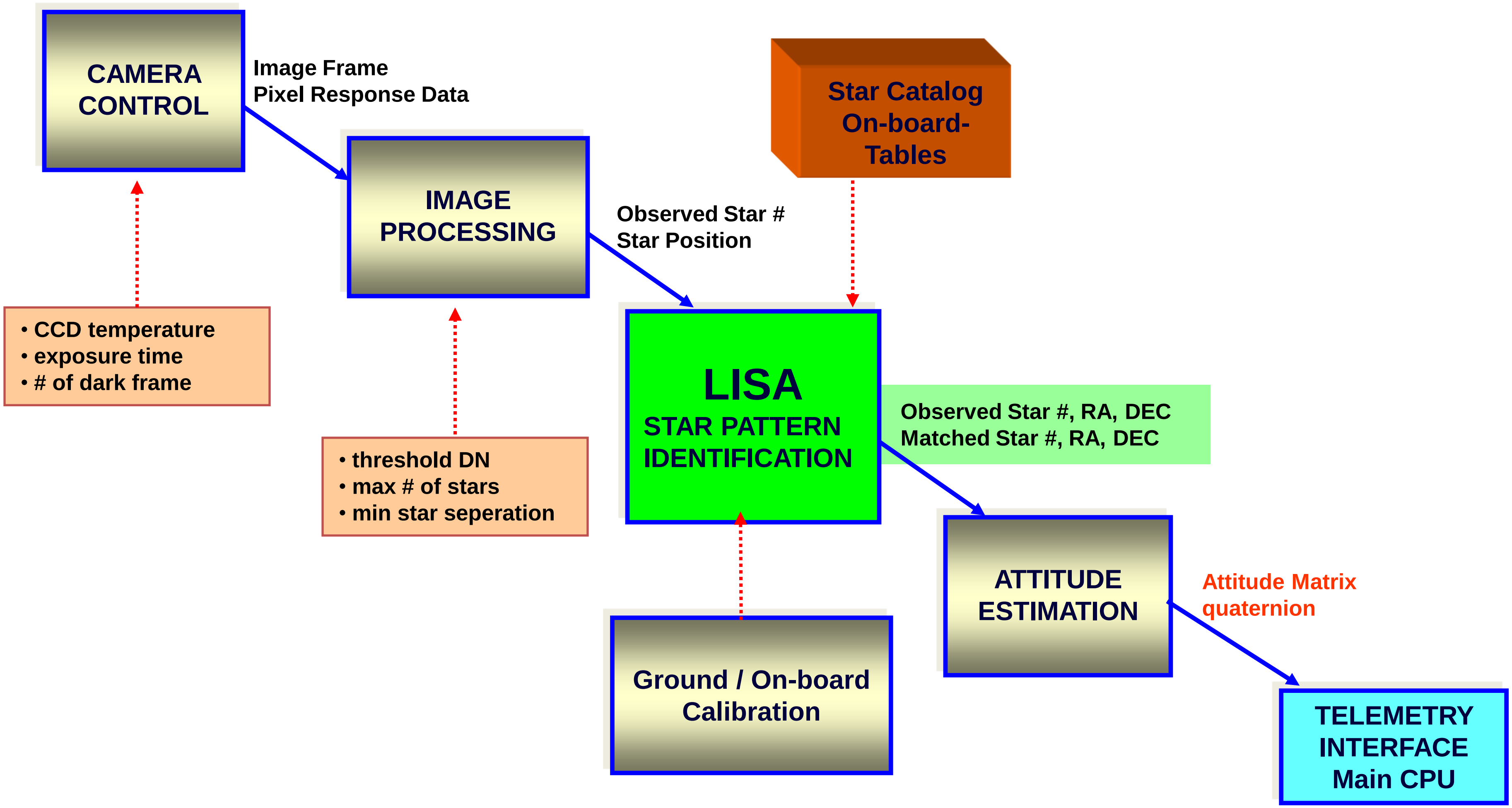
- Results and Conclusion

# Spacecraft Sensors for Attitude Determination

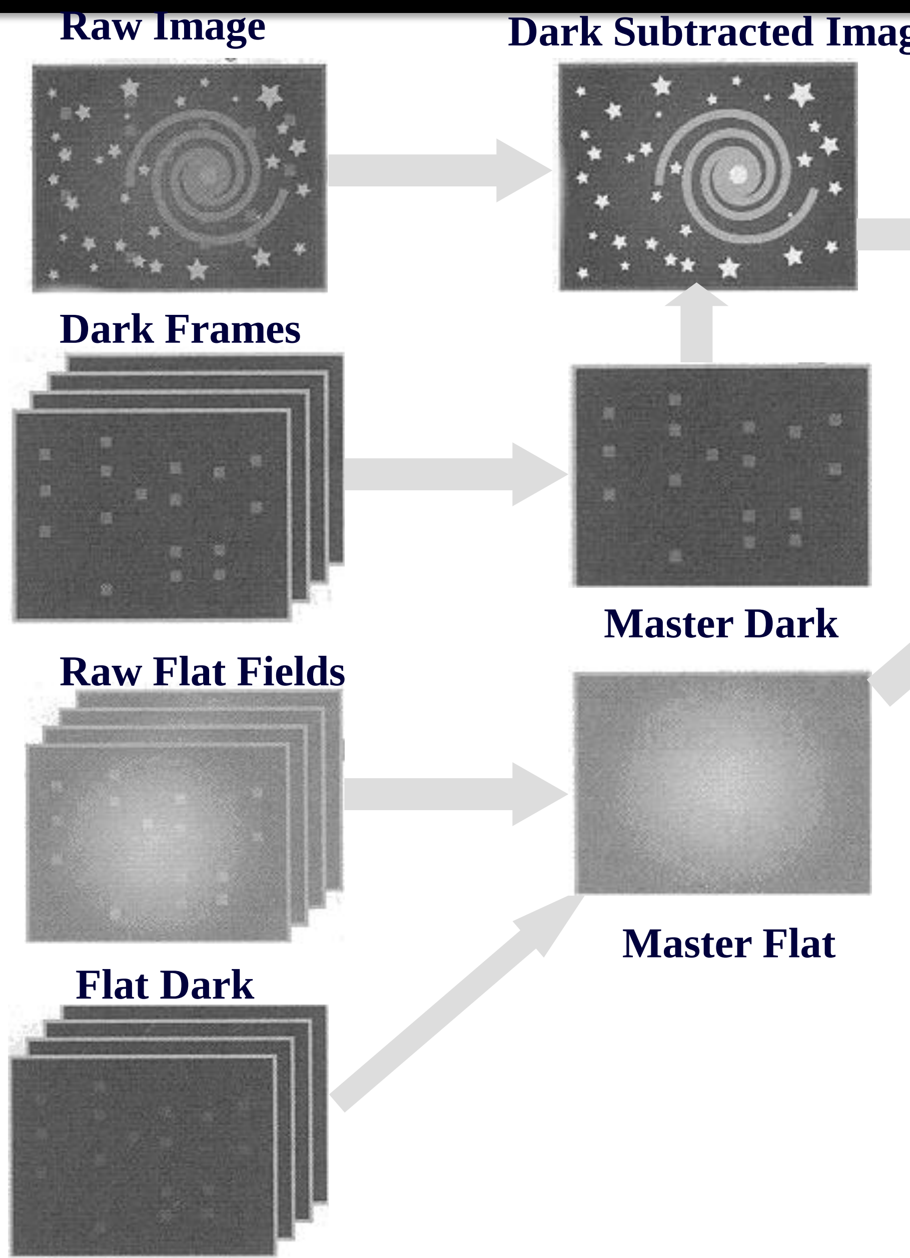


- ***To determine the attitude and the position of a spacecraft its orientation and location relative to some frame of reference of well known celestial body must be defined.***
- **Earth Horizon Sensor**
  - **Horizon sensors are infrared devices that detect the contrast of the cold of space and the warmth of the Earth**
- **Sun Sensor**
  - **Measure Sun angle by measuring the energy deposited in a photocell**
- **Magnetometer**
  - **Measure both the direction and magnitude of the magnetic field**
- **Star Sensor (Star Tracker)**
  - **Measure Starlight directions**

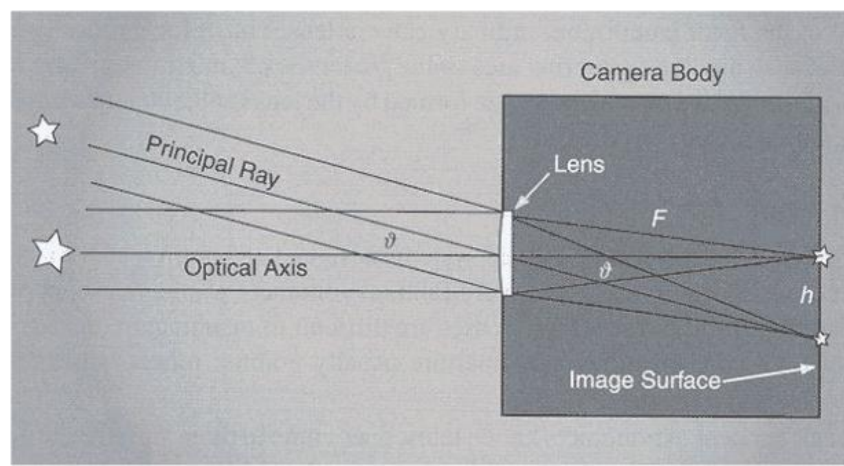
# STR Flight Software: Main Functional Modules – Current Status



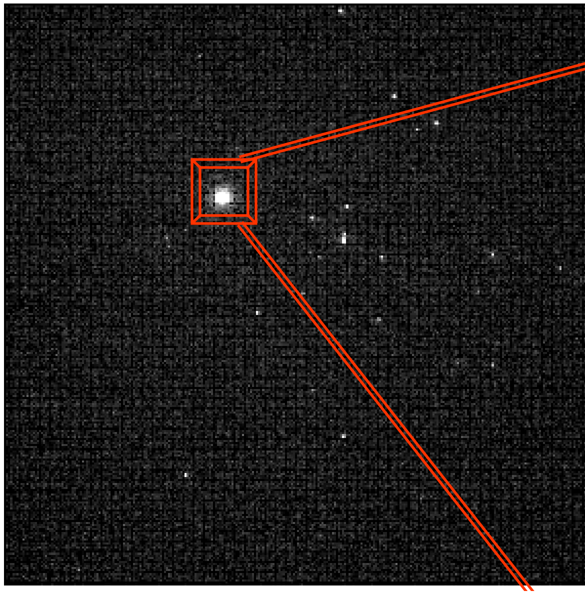
# Camera Control



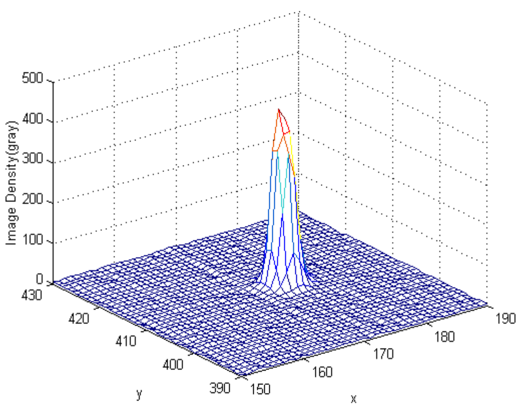




# Tools of Image Processing



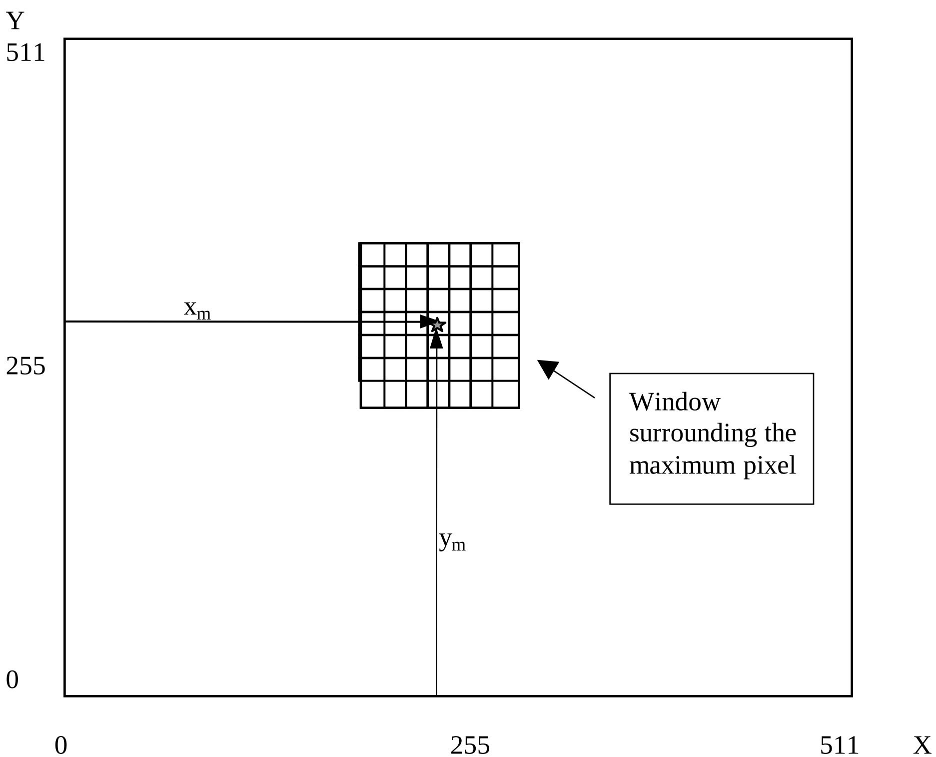
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 363 | 379 | 376 | 379 | 382 | 383 | 386 | 390 | 373 |
| 385 | 377 | 381 | 389 | 396 | 392 | 388 | 386 | 378 |
| 376 | 375 | 392 | 430 | 469 | 446 | 394 | 381 | 384 |
| 381 | 393 | 404 | 558 | 1105 | 863 | 431 | 376 | 378 |
| 380 | 396 | 418 | 668 | 2204 | 1787 | 467 | 390 | 392 |
| 380 | 386 | 398 | 539 | 1470 | 1189 | 434 | 394 | 376 |
| 379 | 383 | 384 | 413 | 541 | 491 | 389 | 379 | 381 |
| 387 | 377 | 380 | 388 | 400 | 402 | 381 | 379 | 379 |
| 369 | 374 | 384 | 380 | 378 | 378 | 372 | 376 | 374 |

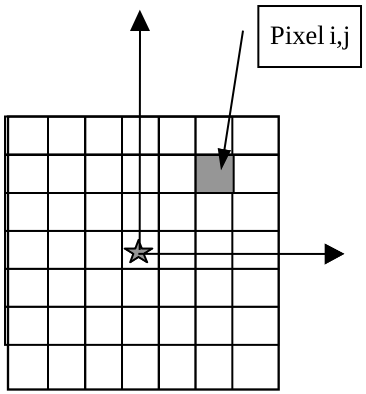



PSF response for a typical the star.

# Image Processing Technique

Image Centroiding is a fundamental process in any star sensor. It's output is the imaged star coordinates ($x$, $y$).



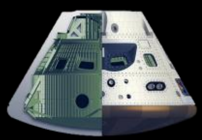




$$\hat{x} = x_m + \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij} I_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} I_{ij}}$$

$$\hat{y} = y_m + \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} y_{ij} I_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} I_{ij}}$$

$$\underline{\hat{W}}_i = \frac{1}{\sqrt{(x_i - x_o)^2 + (y_i - y_o)^2 + f^2}} \begin{pmatrix} -(x_i - x_o) \\ -(y_i - y_o) \\ f \end{pmatrix}$$

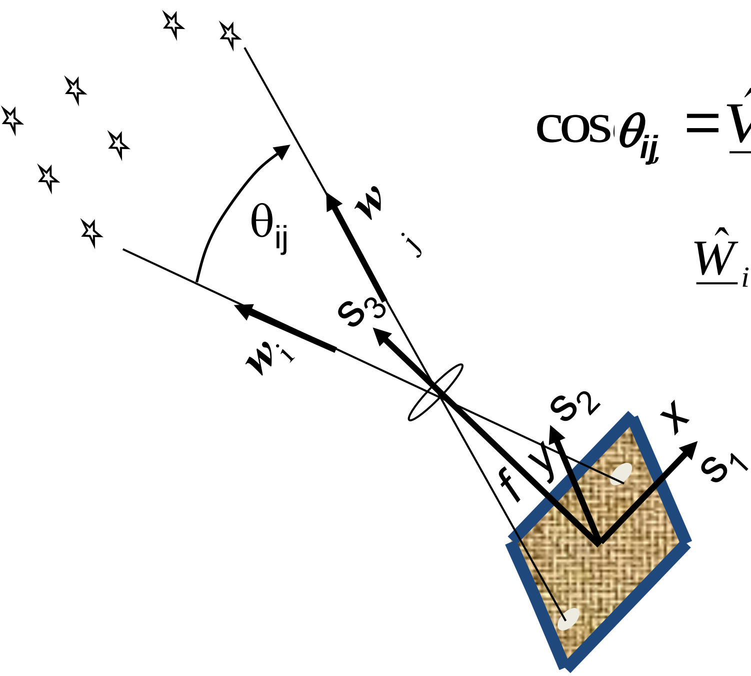
# Ground Calibration for the Bore-sight Offsets and the Focal Length



- Star Camera Calibration is an important task in attitude determination of the spacecraft.
- Generally, star cameras are calibrated on the ground in high precision laboratories. However, any significant change in the instrument or the environment can result in this calibration being in-accurate on-orbit.
- The calibration process is mainly divided into two major parts:
  - Calibration of principal point offset $(x_o, y_o)$ and focal length(f)
  - Calibration of focal plane image distortions due to all other effects (lens distortion, misalignment, detector alignment etc.)

# Ideal Camera Parameter Calibration

- The ideal camera parameter calibration algorithm is used to estimate the “accurate” values for the camera focal length and the focal plane offsets
- The Attitude Independent (AID) approach is used for calibration.




$$\cos\theta_{ij} = \hat{\underline{V}}_i^T \hat{\underline{V}}_j = \hat{\underline{W}}_i^T \hat{\underline{W}}_j + meas\ errors$$

$$\hat{\underline{W}}_i = \frac{1}{\sqrt{(x_i - x_o)^2 + (y_i - y_o)^2 + f^2}} \begin{pmatrix} -(x_i - x_o) \\ -(y_i - y_o) \\ f \end{pmatrix}$$

$$\hat{\underline{V}}_i = \begin{pmatrix} \cos\alpha_i \cos\delta_i \\ \sin\alpha_i \cos\delta_i \\ \sin\delta_i \end{pmatrix}$$

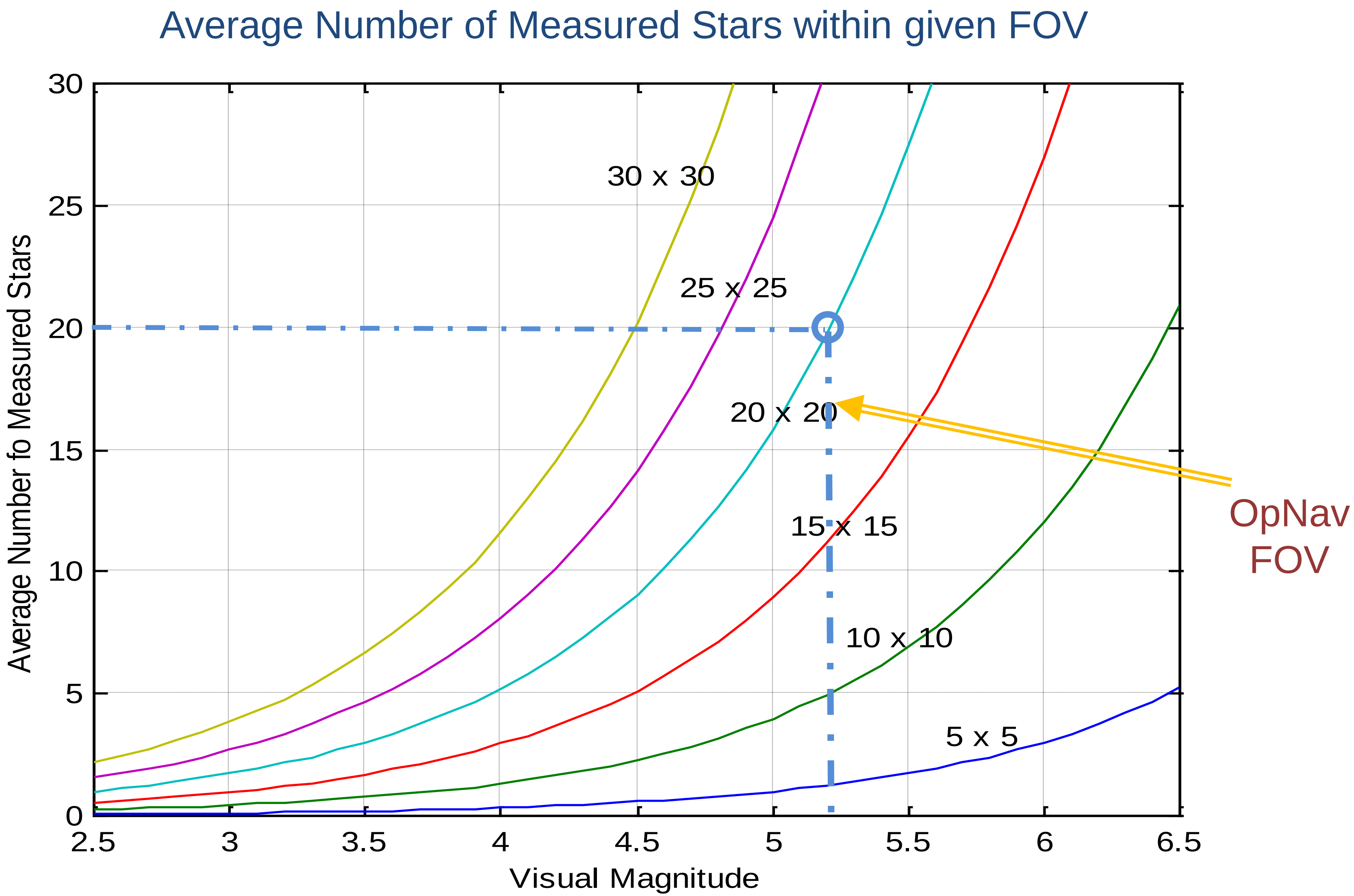
$i$=1,2,…., no. of imaged stars

# Master (on-board) Star Catalog

- Modified from Hipparcos Star Catalog
- 12,500 guide stars for Magnitude range : -1.5 to ~ 6.4
- Number of stars within mag. threshold $M_v$ <= 5.4 is about 2870 stars
- Data : Inertial direction vectors, Visual magnitude($M_v$)

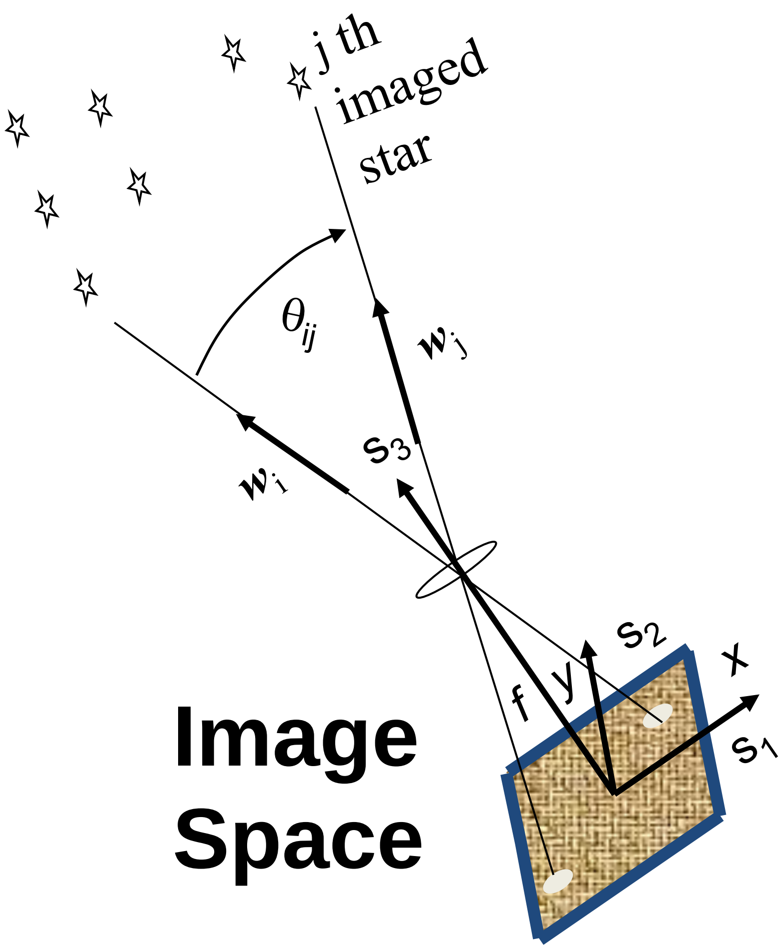
| N | Alpha (deg) | Delta (deg) | Magnitude |
|---|---|---|---|
| 1 | -172.1136 | -62.9582 | 3.8000 |
| 2 | -172.0572 | 54.5222 | 4.8000 |
| . | . | . | . |
| . | . | . | . |
| . | . | . | . |
| I | 113.7337 | 33.7954 | 5.4000 |
| . | . | . | . |
| . | . | . | . |
| . | . | . | . |
| 2869 | 179.6033 | 51.3885 | 2.8000 |
| 2870 | -179.4695 | -14.6760 | 5.4000 |

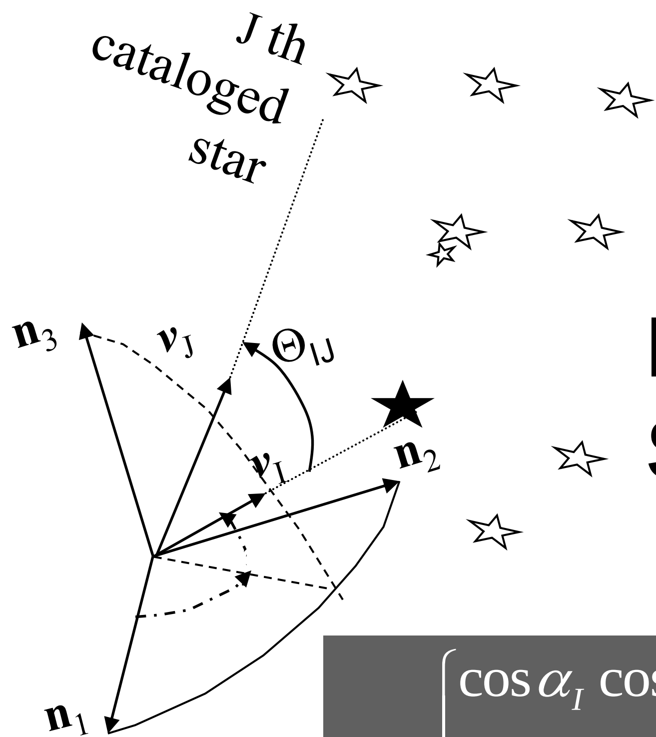
# Size of FOV vs Number of Stars/FOV



# Lost-In-Space Algorithm (LISA)

**Measured Stars in Image Space <=??=> Which Cataloged Stars?**



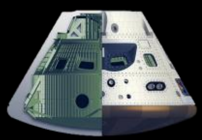




**Inertial Space**

$$v_I = \begin{Bmatrix} \cos\alpha_I \cos\delta_I \\ \sin\alpha_I \cos\delta_I \\ \sin\delta_I \end{Bmatrix}$$

- The key problem is to match imaged and cataloged stars and identify the imaged stars as particular catalogued stars ...

# Star ID matching criteria



Matching inter-star angles for 2 Stars to within $0.001^{o}$ :

=> probability of **wrong star ID is > 0.9** !!

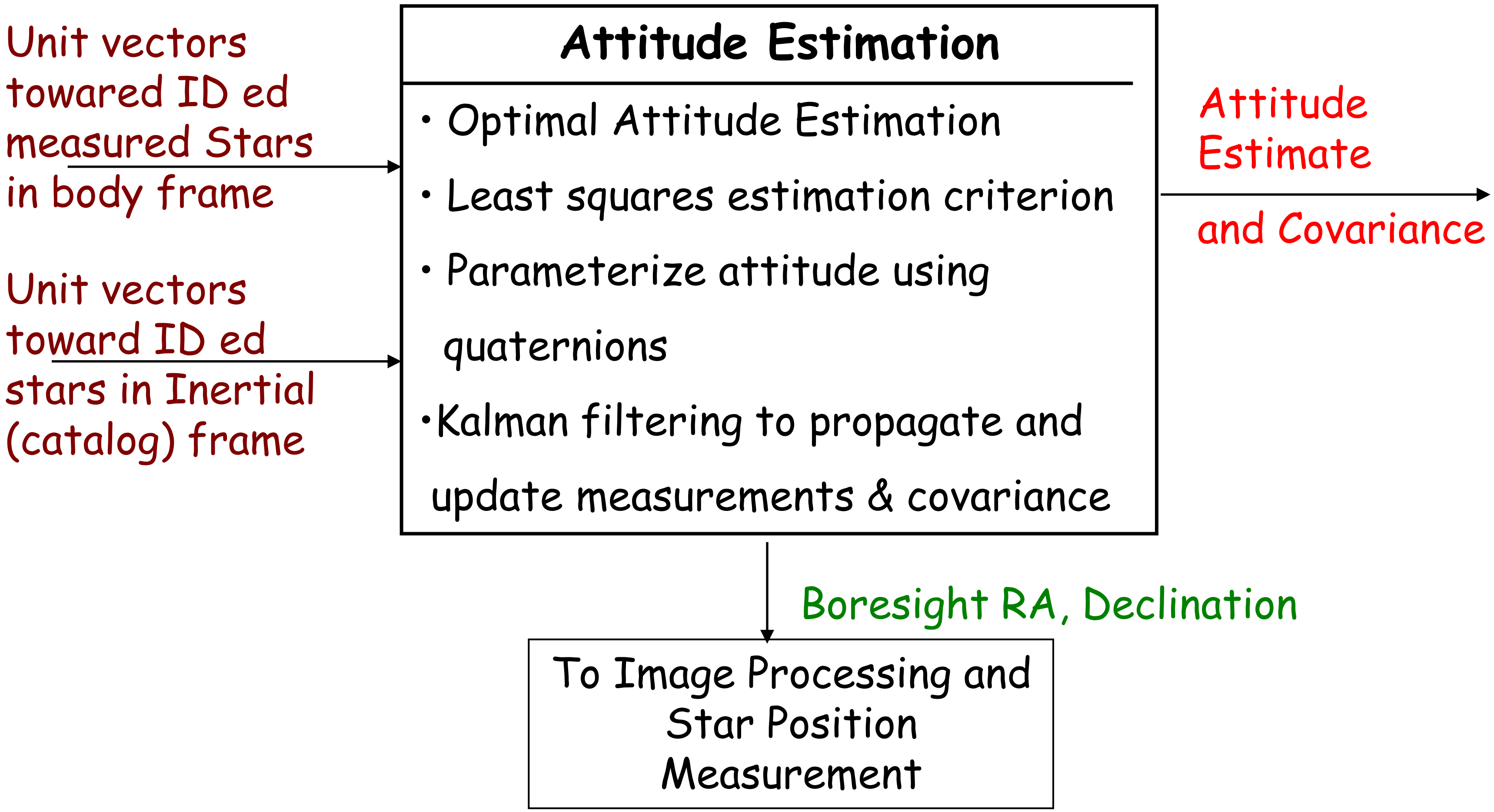
Matching angles for 3 Stars:

=> probability of **wrong star ID is ~ $10^{-4}$**

Matching angles for 4 or more Stars:

=> probability of **wrong star ID is ~ $<10^{-11}$**

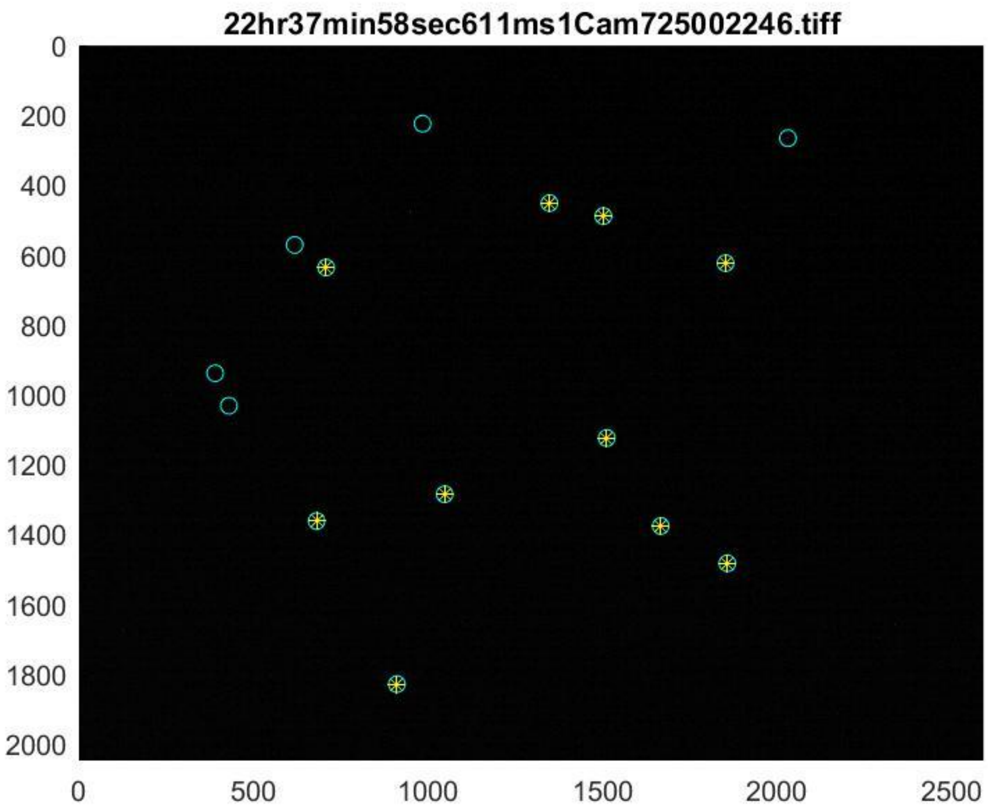
# Attitude Estimation




$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_{1\,3} \\ q_4 \end{bmatrix}$$

$$\mathbf{q}_{1\,3} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \hat{\mathbf{n}} \sin(\theta/2) \qquad q_4 = \cos(\theta/2)$$

# End-to-End test 1 –Stars only

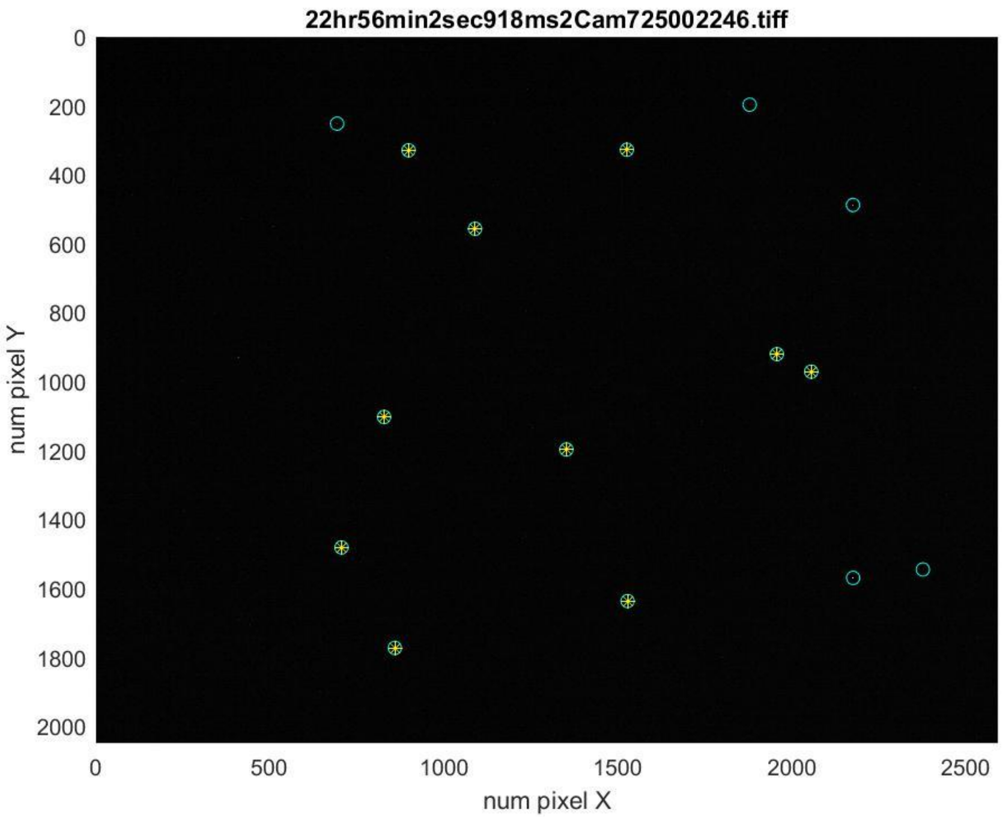



| Obj. Num | X pixel | Y pixel | Star ID | RA deg | Dec deg |
|---|---|---|---|---|---|
| 1 | 1667.3 | 1376.5 | 188 | 155.58 | 41.499 |
| 2 | 2032 | 265.9 | 0 | 0 | 0 |
| 3 | 708.7 | 636.2 | 405 | 163.33 | 34.216 |
| 4 | 1858.4 | 1483.2 | 271 | 154.27 | 42.915 |
| 5 | 1048.2 | 1285.3 | 627 | 156.97 | 36.708 |
| 6 | 429.8 | 1031.9 | 0 | 0 | 0 |
| 7 | 911.3 | 1829.2 | 900 | 151.86 | 35.245 |
| 8 | 681.1 | 1362.3 | 1155 | 156.48 | 33.796 |
| 9 | 984.9 | 224.3 | 0 | 0 | 0 |
| 10 | 1512.8 | 1124.4 | 1157 | 158.31 | 40.426 |
| 11 | 618.2 | 571.5 | 0 | 0 | 0 |
| 12 | 1853.2 | 623.6 | 1082 | 163.49 | 43.19 |
| 13 | 1503 | 488.9 | 1666 | 164.87 | 40.43 |
| 14 | 390.3 | 938.9 | 0 | 0 | 0 |
| 15 | 1348.4 | 451.8 | 1724 | 165.21 | 39.212 |

**qJ2000_Cam1 = [-0.4238 0.0858 0.8903 0.1430]**
**qJ2000_ST = [-0.4219 0.0812 0.8894 0.1560]**

**qErr before align = 1.5867 deg**
**qErr after align = 0.0032 deg = 11.6 arc-sec**
**Accuracy Cross Boresight = 3.7 arc-sec**
**Accuracy About Boresight = 11.2 arc-sec**

# End-to-End test 2 –Stars only

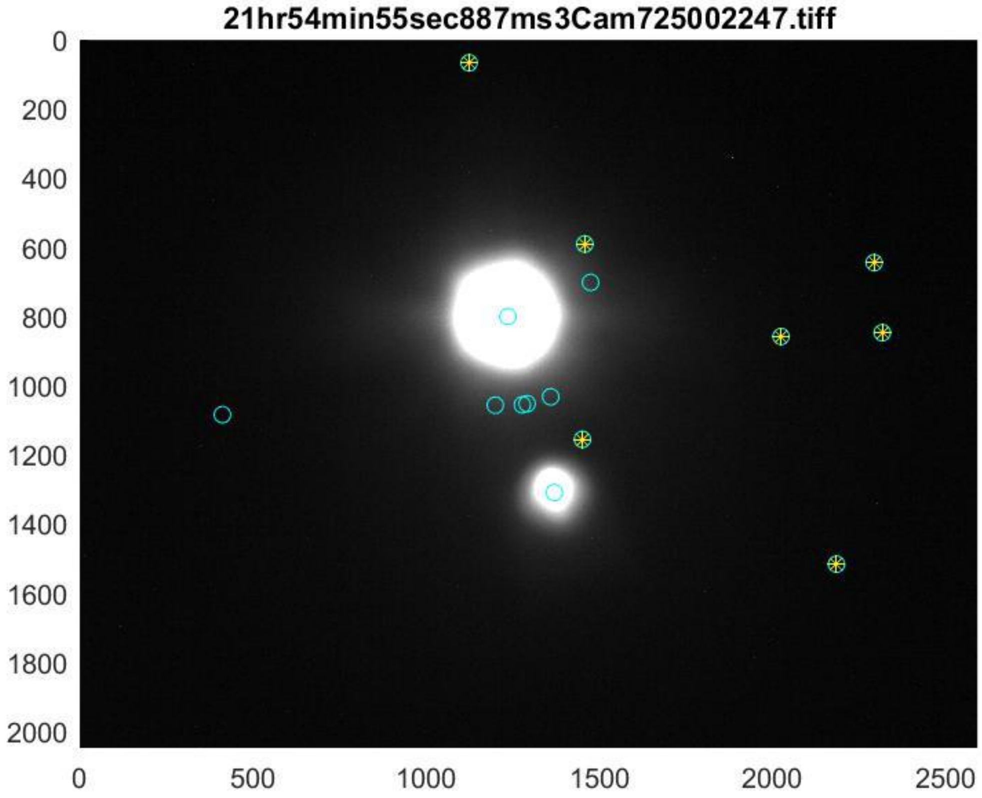



**qJ2000_Cam1 = [-0.0922 -0.4168 -0.0651 0.9020]**
**qJ2000_ST = [-0.0853 -0.4209 -0.0762 0.8999]**

**qErr before align = 1.5883 deg**
**qErr after align = 0.0048 deg = 17.35 arcsec**
**Accuracy Cross Boresight = 4.5 arc-sec**
**Accuracy About Boresight = 15.5 arc-sec**

| Obj. Num | X pixel | Y pixel | Star ID | RA deg | Dec deg |
|---|---|---|---|---|---|
| 1 | 692.9 | 251.7 | 0 | 0 | 0 |
| 2 | 898.4 | 329 | 188 | 155.58 | 41.499 |
| 3 | 1957 | 920.4 | 405 | 163.33 | 34.216 |
| 4 | 705.5 | 1481.1 | 174 | 167.42 | 44.499 |
| 5 | 2376.8 | 1545 | 0 | 0 | 0 |
| 6 | 2176.3 | 1569.4 | 0 | 0 | 0 |
| 7 | 1526 | 327.5 | 627 | 156.97 | 36.708 |
| 8 | 828 | 1102.6 | 1082 | 163.49 | 43.19 |
| 9 | 2176 | 487.6 | 0 | 0 | 0 |
| 10 | 1352 | 1196.9 | 1724 | 165.21 | 39.212 |
| 11 | 1878.9 | 196.7 | 0 | 0 | 0 |
| 12 | 2055.8 | 971.1 | 1649 | 163.94 | 33.507 |
| 13 | 1089.7 | 556.6 | 1157 | 158.31 | 40.426 |
| 14 | 1527.9 | 1636.4 | 1205 | 169.78 | 38.186 |
| 15 | 858.9 | 1772.5 | 1594 | 170.71 | 43.483 |

# End-to-End test 1 with Moon

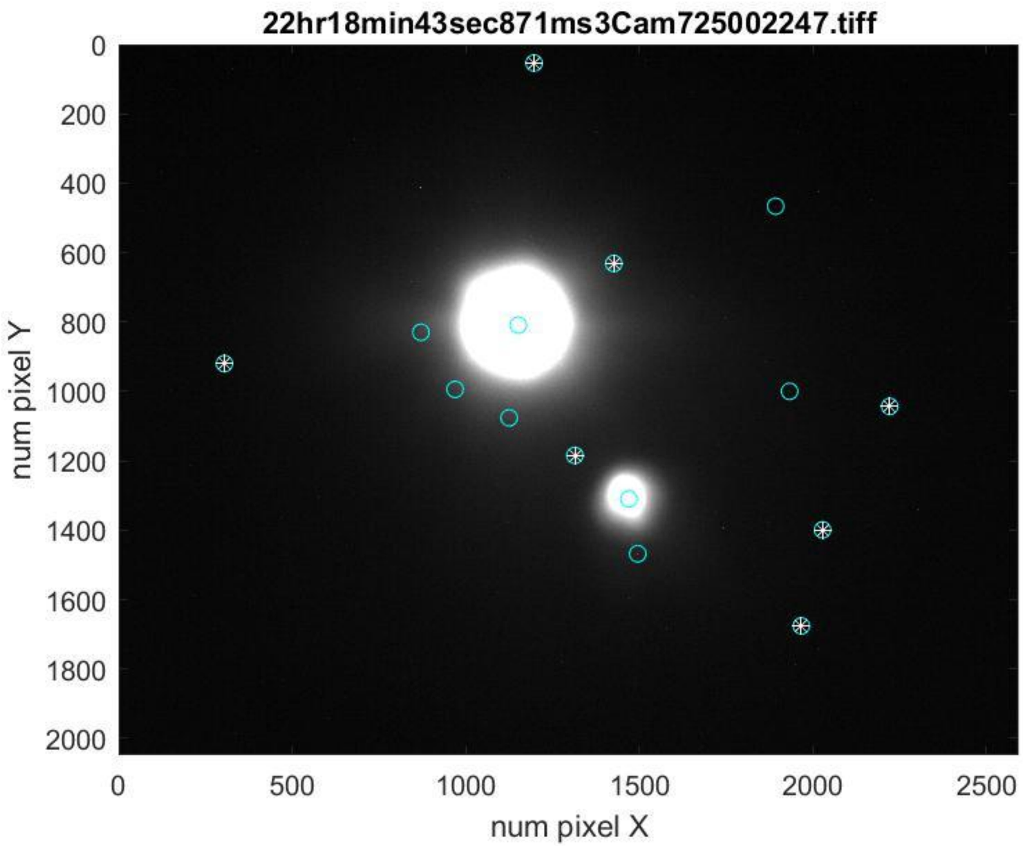



**q2000_Cam2= [-0.3031 0.5730 0.6364 -0.4182]**
**q2000_ST = [-0.1911 0.3845 0.7662 -0.4781]**

**qErr before align = 30.0831 deg**
**qErr after align = 0.0025 deg = 8.86 arc-sec**
**Accuracy Cross Boresight = 1.7 arc-sec**
**Accuracy About Boresight = 8.3 arc-sec**

| Obj. Num | X pixel | Y pixel | Star ID | RA deg | Dec deg |
|---|---|---|---|---|---|
| 1 | 1236.2 | 800.6 | 0 | 0 | 0 |
| 2 | 1370.8 | 1309.5 | 0 | 0 | 0 |
| 3 | 1124.6 | 66.7 | **278** | **151.83** | **16.763** |
| 4 | 2025.5 | 858.1 | **292** | **145.29** | **9.8924** |
| 5 | 1451.8 | 1155.7 | **1108** | **150.05** | **8.0443** |
| 6 | 412.1 | 1084.4 | 0 | 0 | 0 |
| 7 | 2185.6 | 1516.7 | **1107** | **144.61** | **4.6494** |
| 8 | 1475.4 | 701.8 | 0 | 0 | 0 |
| 9 | 1458.5 | 590.7 | **2182** | **149.56** | **12.445** |
| 10 | 1360.2 | 1032.7 | 0 | 0 | 0 |
| 11 | 1200 | 1057 | 0 | 0 | 0 |
| 12 | 1278.3 | 1055.8 | 0 | 0 | 0 |
| 13 | 2317.8 | 847.2 | **1745** | **142.99** | **9.7158** |
| 14 | 1292.2 | 1052.8 | 0 | 0 | 0 |
| 15 | 2294.3 | 644.8 | **1593** | **141.69** | **11.3** |

# End-to-End test 2 with Moon

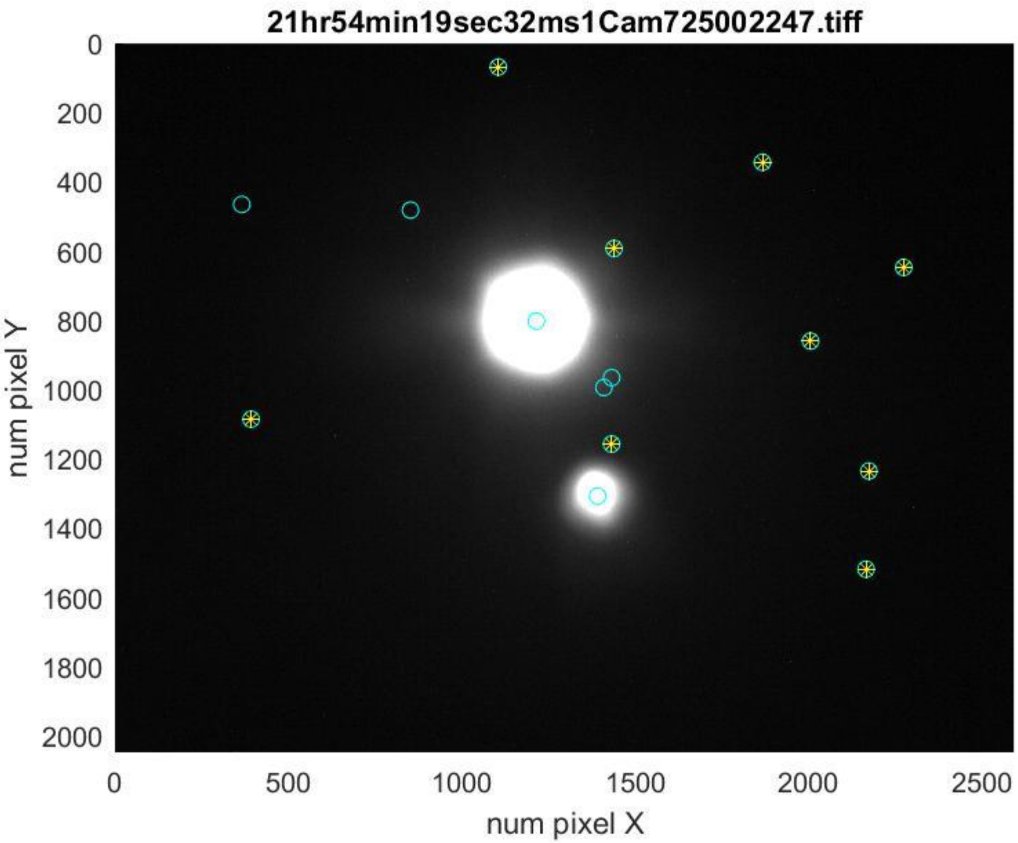



q2000_Cam2 = [ -0.3504 0.5446 0.6756 -0.3525 ]
q2000_ST = [ -0.2537 0.3466 0.7960 -0.4265 ]

qErr before align = 30.0844 deg
qErr after align = 0.0036 deg = 13.0 arc-sec
Accuracy Cross Boresight = 5.6 arc-sec
Accuracy About Boresight = 12.8 arc-sec

| Obj. Num | X pixel | Y pixel | Star ID | RA deg | Dec deg |
|---|---|---|---|---|---|
| 1 | 1151.2 | 808.7 | 0 | 0 | 0 |
| 2 | 1469.8 | 1309.6 | 0 | 0 | 0 |
| 3 | 870.6 | 829.5 | 0 | 0 | 0 |
| 4 | 1196.7 | 53.3 | 278 | 151.83 | 16.763 |
| 5 | 1932.8 | 999.6 | 0 | 0 | 0 |
| 6 | 304.8 | 919.7 | 427 | 158.2 | 9.3066 |
| 7 | 1314 | 1184.3 | 1108 | 150.05 | 8.0443 |
| 8 | 1966.7 | 1675.7 | 1107 | 144.61 | 4.6494 |
| 9 | 969.2 | 994 | 0 | 0 | 0 |
| 10 | 1125 | 1076 | 0 | 0 | 0 |
| 11 | 1892.7 | 466.2 | 0 | 0 | 0 |
| 12 | 2221.2 | 1043.3 | 1745 | 142.99 | 9.7158 |
| 13 | 1426.4 | 631 | 2182 | 149.56 | 12.445 |
| 14 | 2027.7 | 1399 | 1613 | 144.3 | 6.8358 |
| 15 | 1495.4 | 1467.8 | 0 | 0 | 0 |

# End-to-End test 3 with Moon

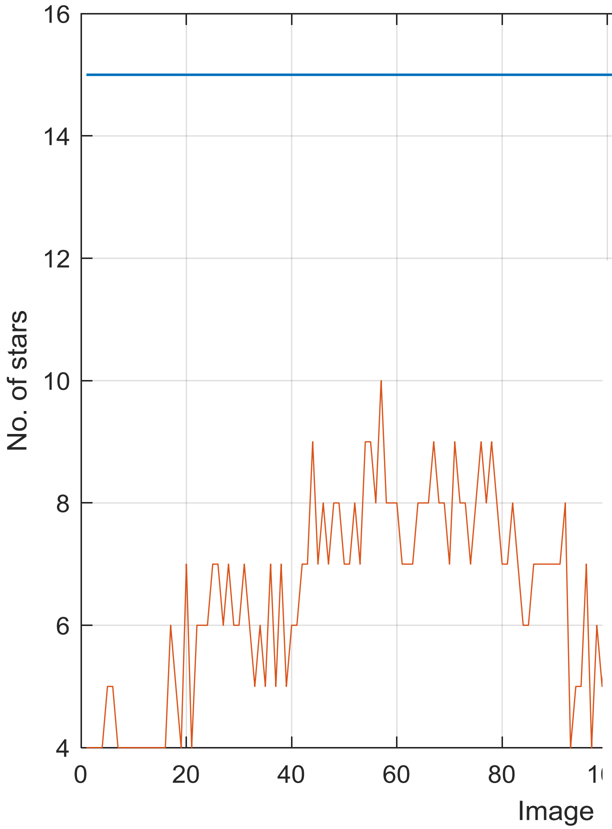



q2000_OpNav2247= [-0.3023 0.5734 0.6369 -0.4173]
q2000_ST = [-0.1905 0.3847 0.7669 -0.4771 ]

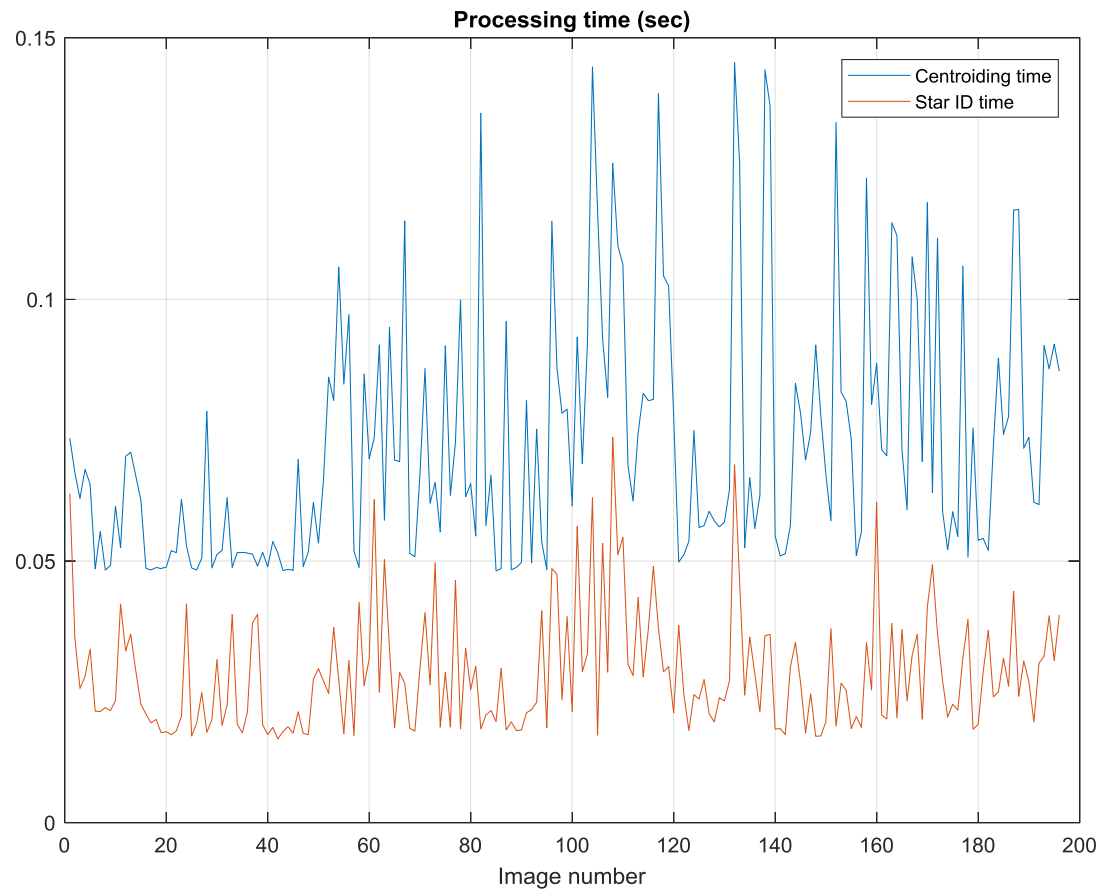
qErr before align = 30.0830 deg
qErr after align = 0.006 deg = 21.4 arc-sec
Accuracy Cross Boresight = 9.4 arc-sec
Accuracy About Boresight = 17.8 arc-sec

| Obj. Num | X pixel | Y pixel | Star ID | RA deg | Dec deg |
|---|---|---|---|---|---|
| 1 | 1215.7 | 802.7 | 0 | 0 | 0 |
| 2 | 1392.2 | 1308 | 0 | 0 | 0 |
| 3 | 1105.9 | 68.3 | 278 | 151.83 | 16.763 |
| 4 | 1432.6 | 1157.5 | 1108 | 150.05 | 8.0443 |
| 5 | 2006.4 | 860.2 | 292 | 145.29 | 9.8924 |
| 6 | 392.8 | 1085.7 | 427 | 158.2 | 9.3066 |
| 7 | 1432.6 | 965.7 | 0 | 0 | 0 |
| 8 | 2166.3 | 1518.8 | 1107 | 144.61 | 4.6494 |
| 9 | 1439.6 | 592.7 | 2182 | 149.56 | 12.445 |
| 10 | 2174.5 | 1235.5 | 1613 | 144.3 | 6.8358 |
| 11 | 1867.5 | 343.4 | 2431 | 145.93 | 14.022 |
| 12 | 2275.2 | 647.2 | 1593 | 142.99 | 11.3 |
| 13 | 1410.2 | 994.2 | 0 | 0 | 0 |
| 14 | 852.5 | 481.8 | 0 | 0 | 0 |
| 15 | 365.8 | 465.5 | 0 | 0 | 0 |

# Star ID – Att. Det. Results Cam1 0.5s exposure

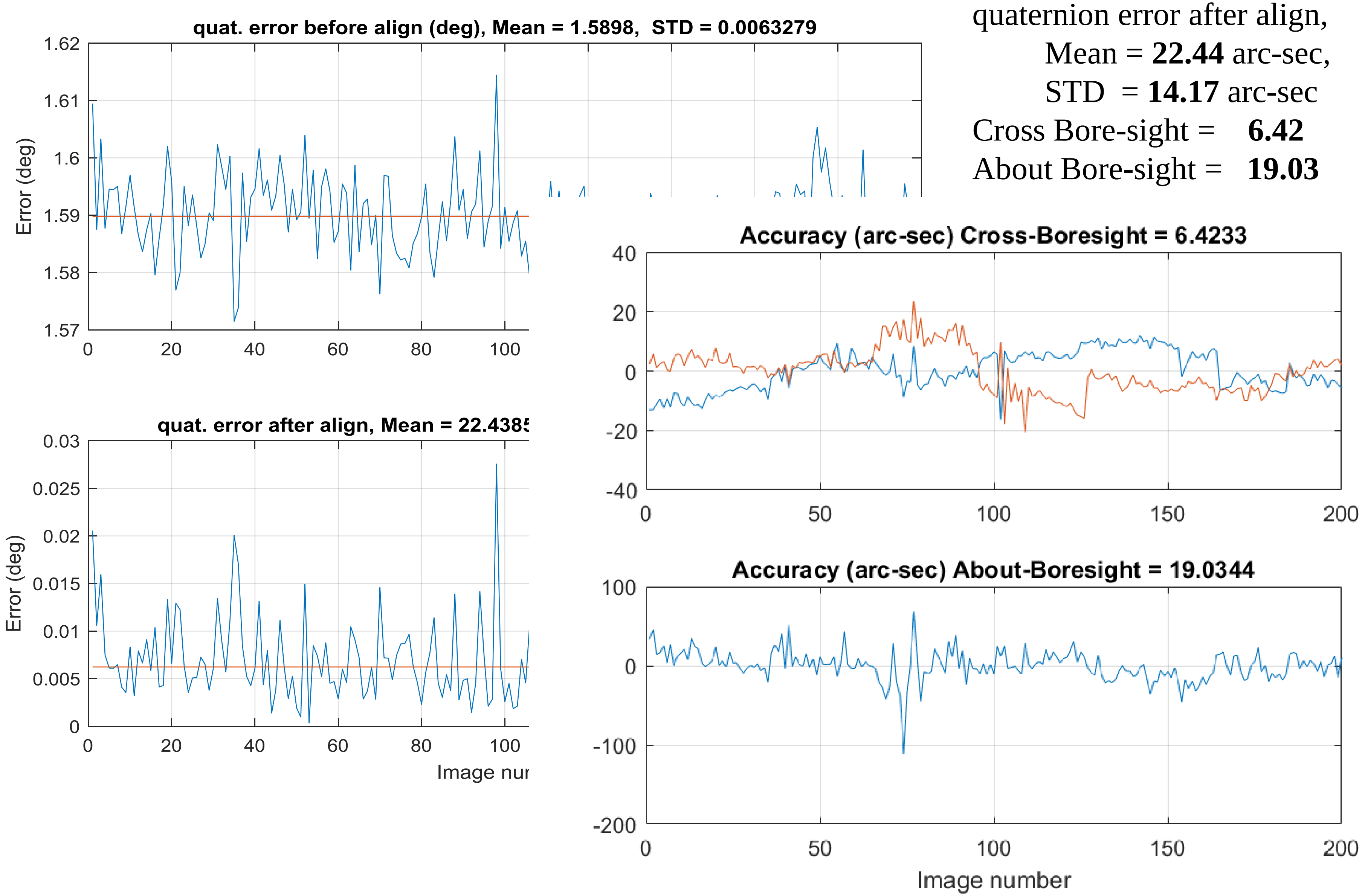



Percent SuccessID = 97.5610
Percent4StarsFound = 11.219
badImgCount = 0

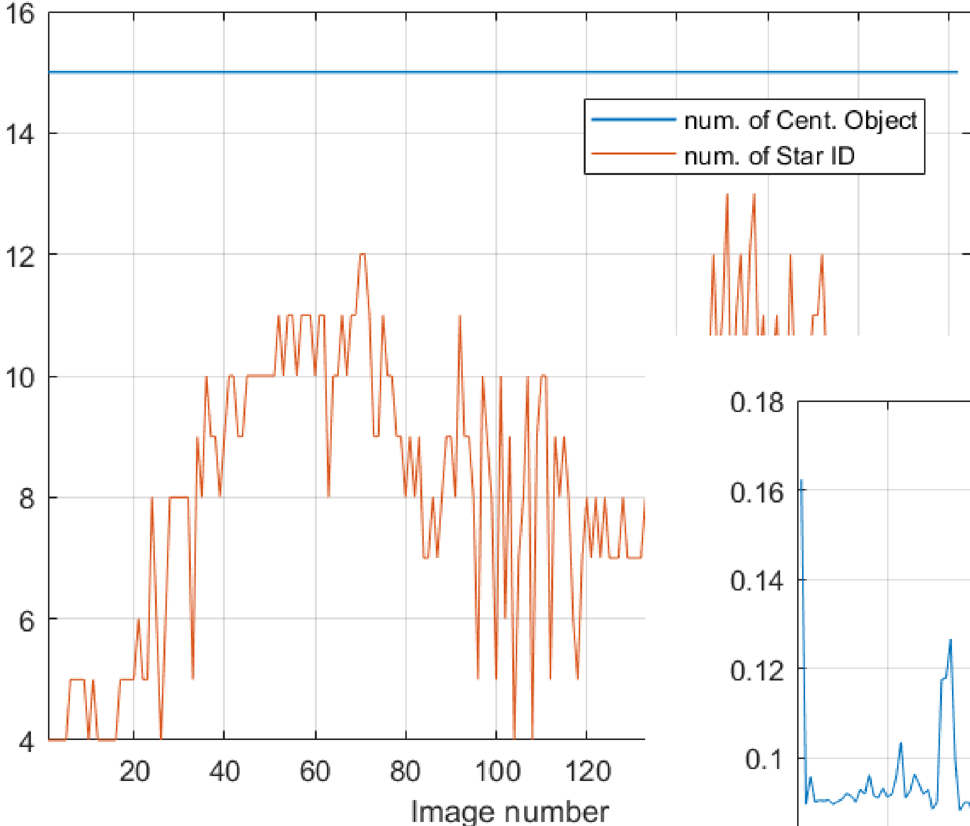


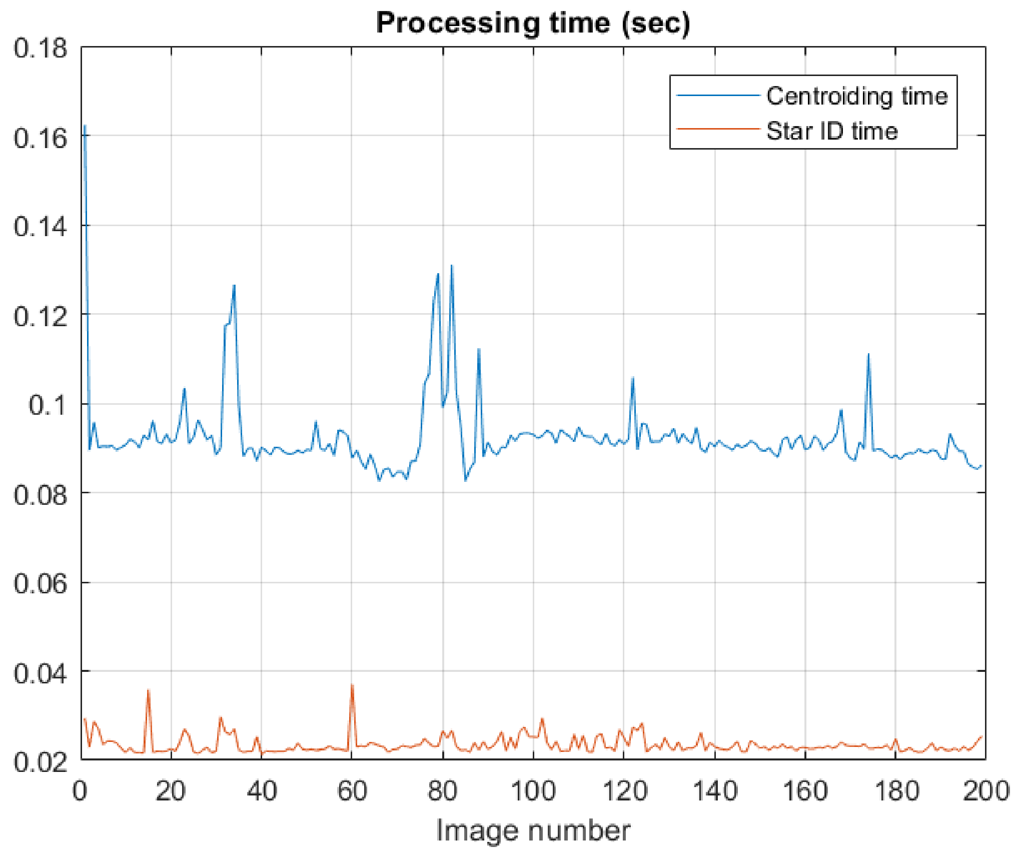
# Star ID – Att. Det. Results Cam1 0.5s exposure

quaternion error after align,
Mean = **22.44** arc-sec,
STD = **14.17** arc-sec
Cross Bore-sight = **6.42**
About Bore-sight = **19.03**



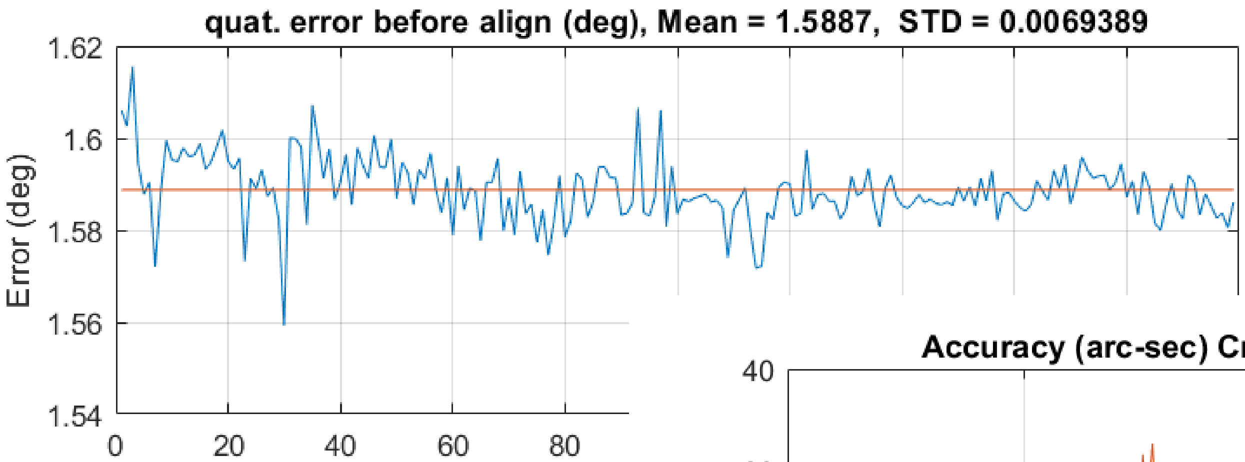
# Star ID – Att. Det. Results Cam1 1.0s exposure



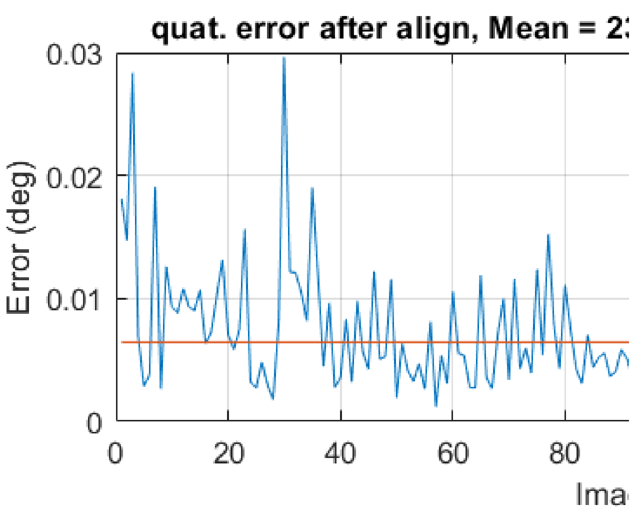



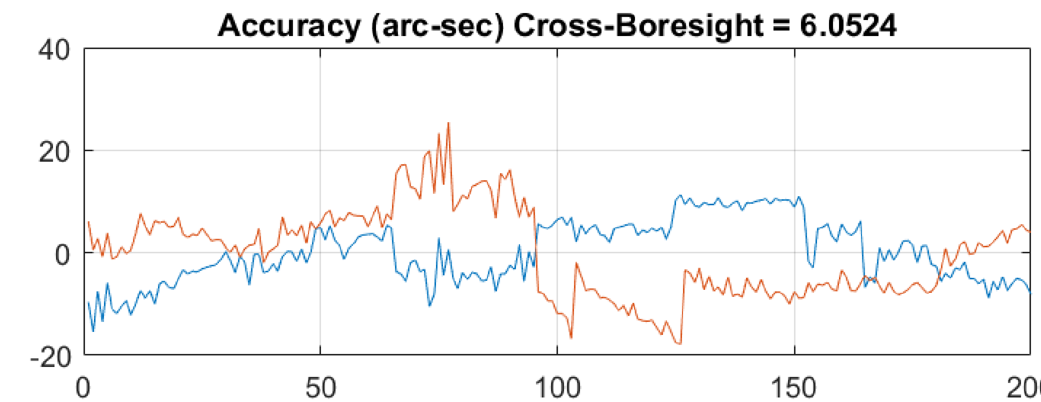

Percent SuccessID = 98.5366
Percent4StarsFound = 7.3171
badImgCount = 0

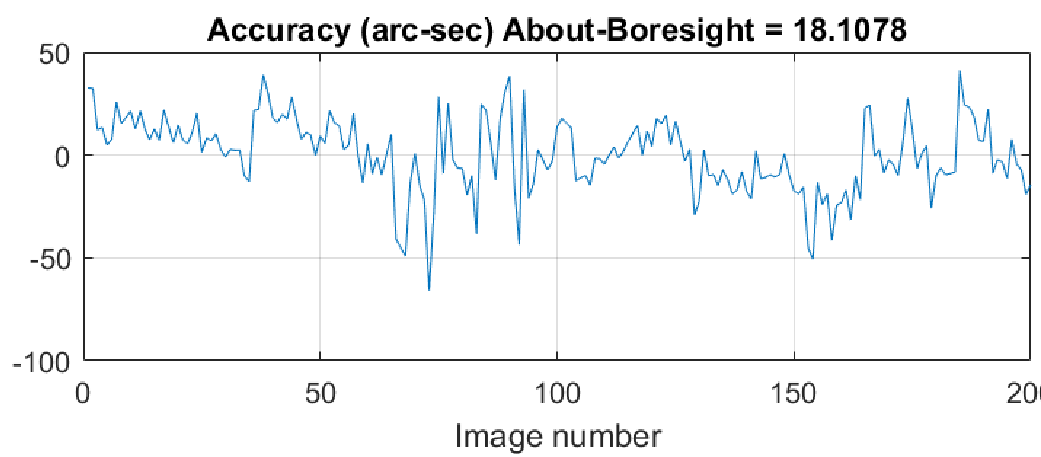
# Star ID – Att. Det. Results Cam1 1.0s exposure



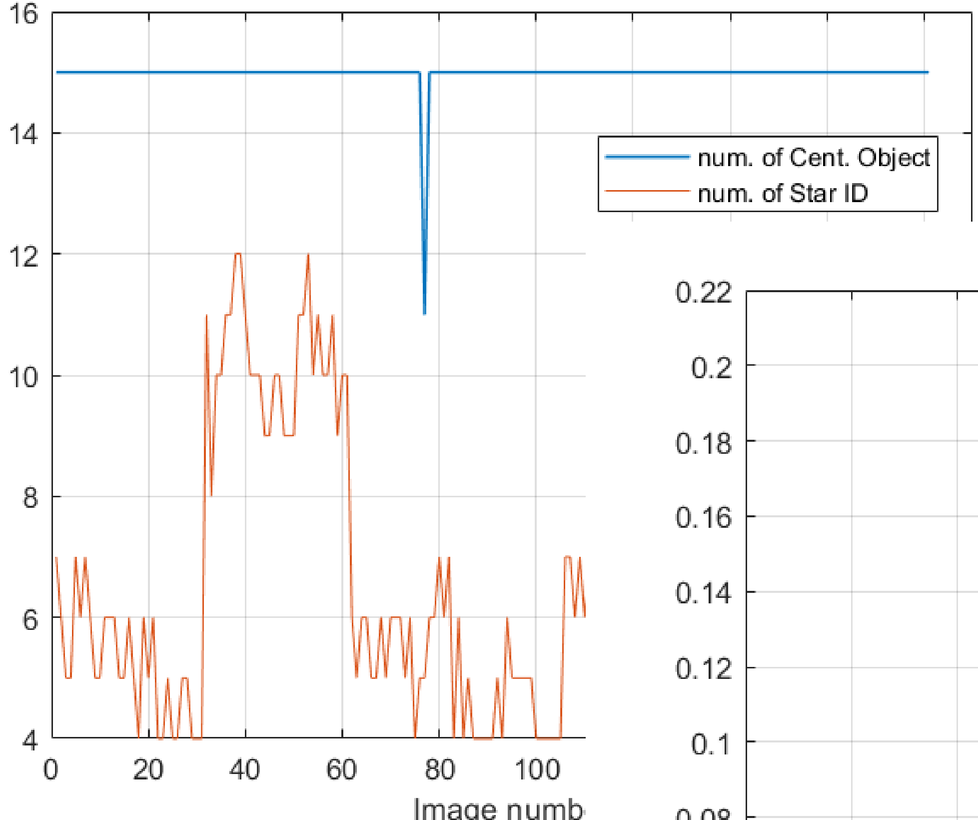

quaternion error after align,
Mean = **23.23** arc-sec,
STD = **15.98** arc-sec
Cross Bore-sight = **6.05**
About Bore-sight = **18.17**

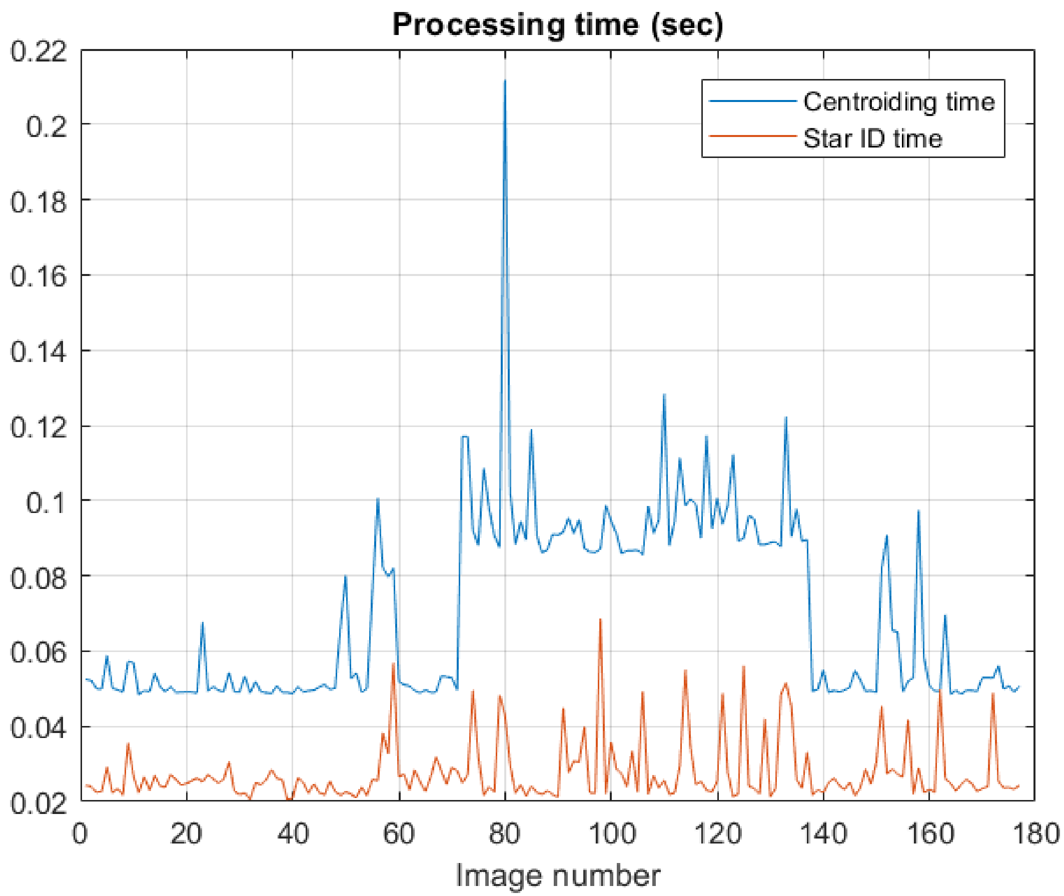


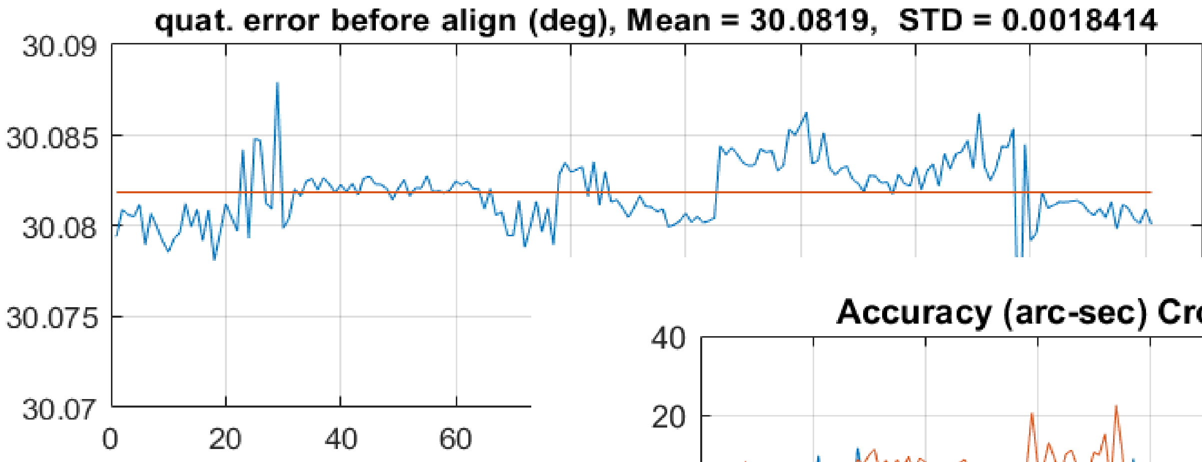
# Star ID – Att. Det. Cam2 with Moon 0.5s exposure



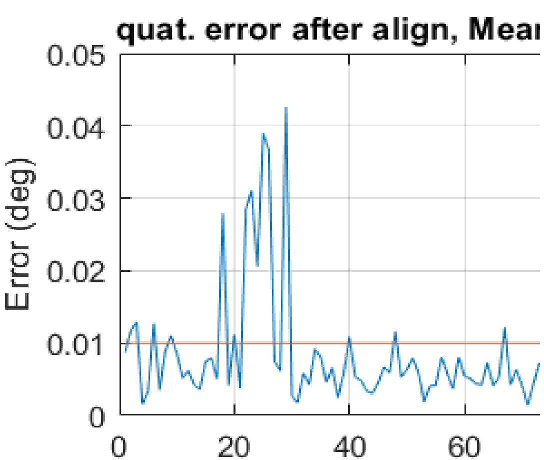



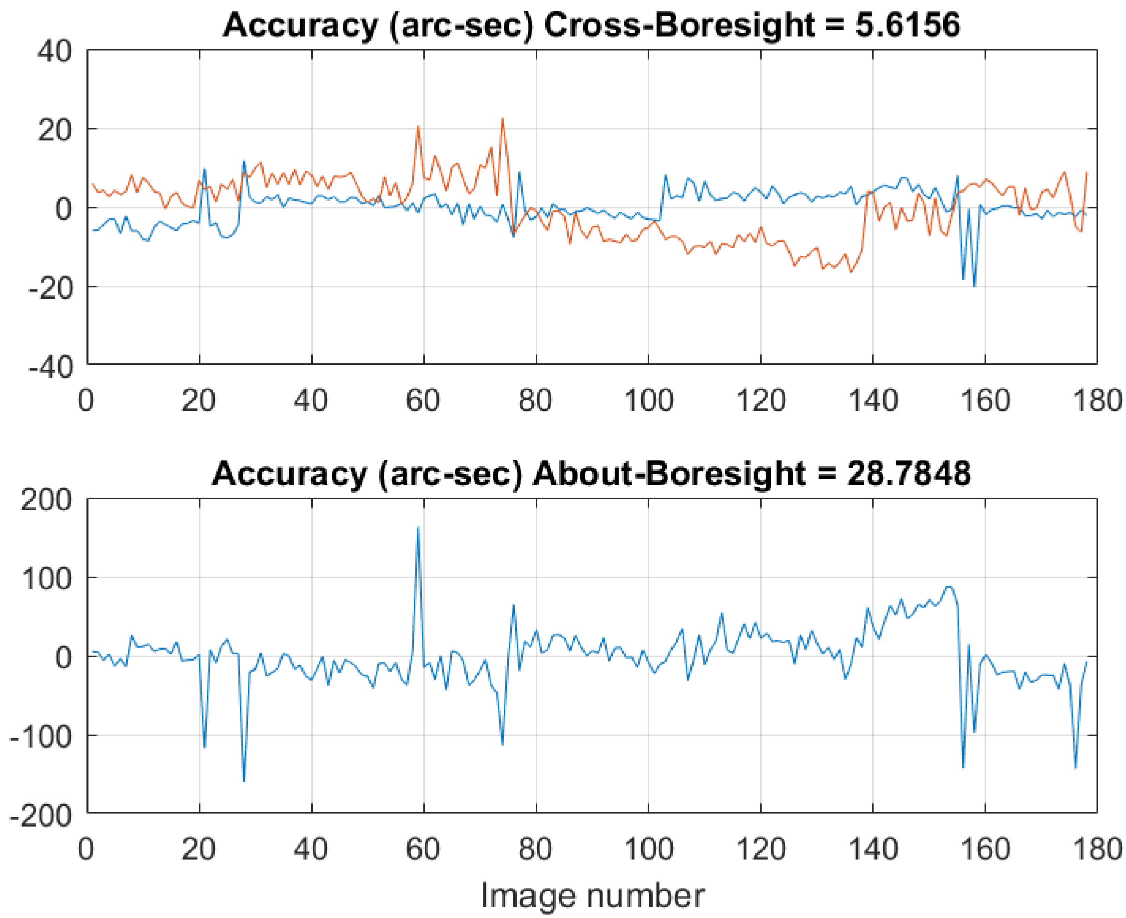

Percent SuccessID = 86.3415
Percent4StarsFound = 15.6098
badImgCount = 3
ImgWithMoonCount = 70
60 identified images with moon

# Star ID – Att. Det. Cam2 with Moon 0.5s exposure



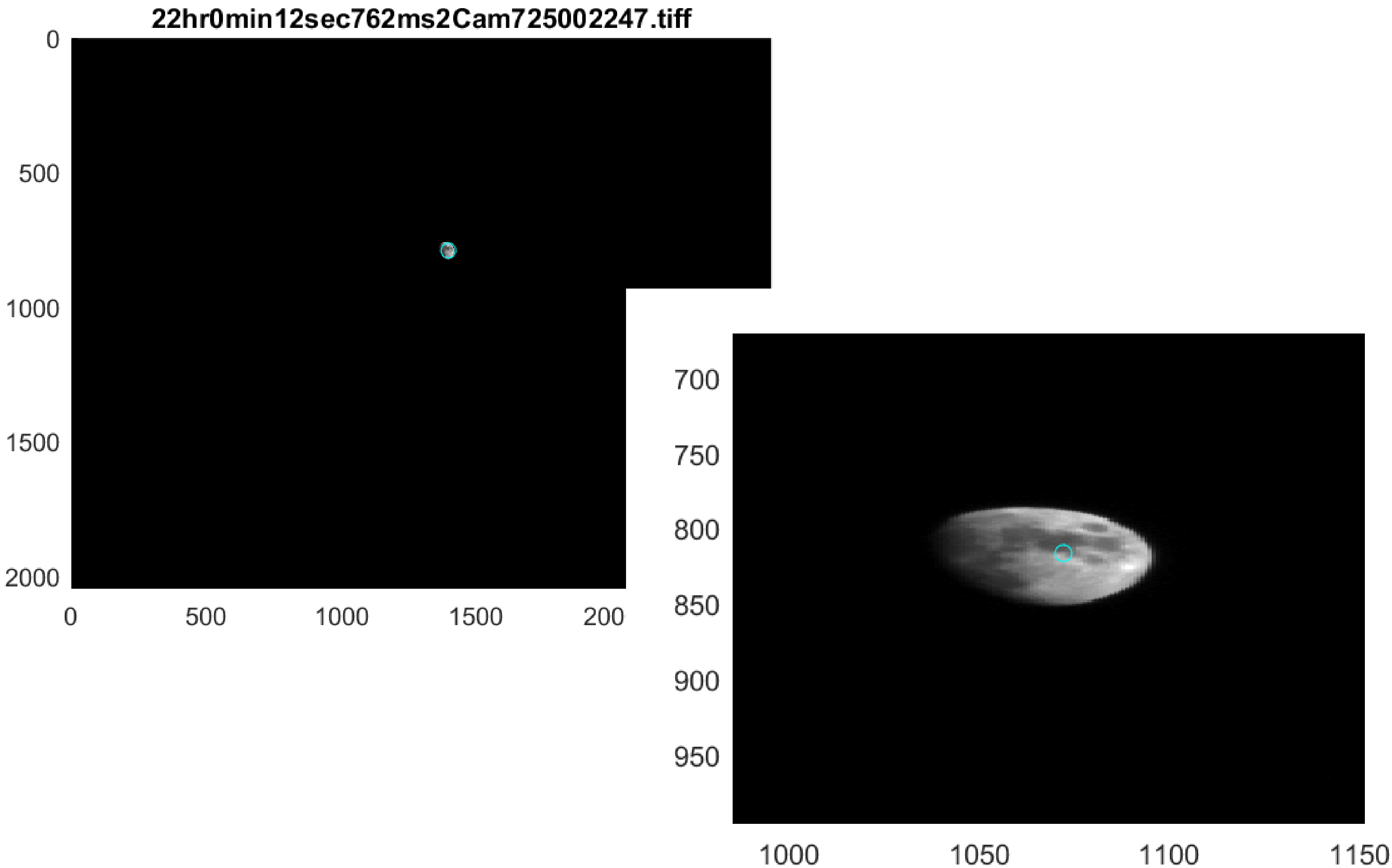

quaternion error after align,
Mean = **35.96** arc-sec,
STD = **29.03** arc-sec
Cross Bore-sight = **5.61**
About Bore-sight = **28.78**



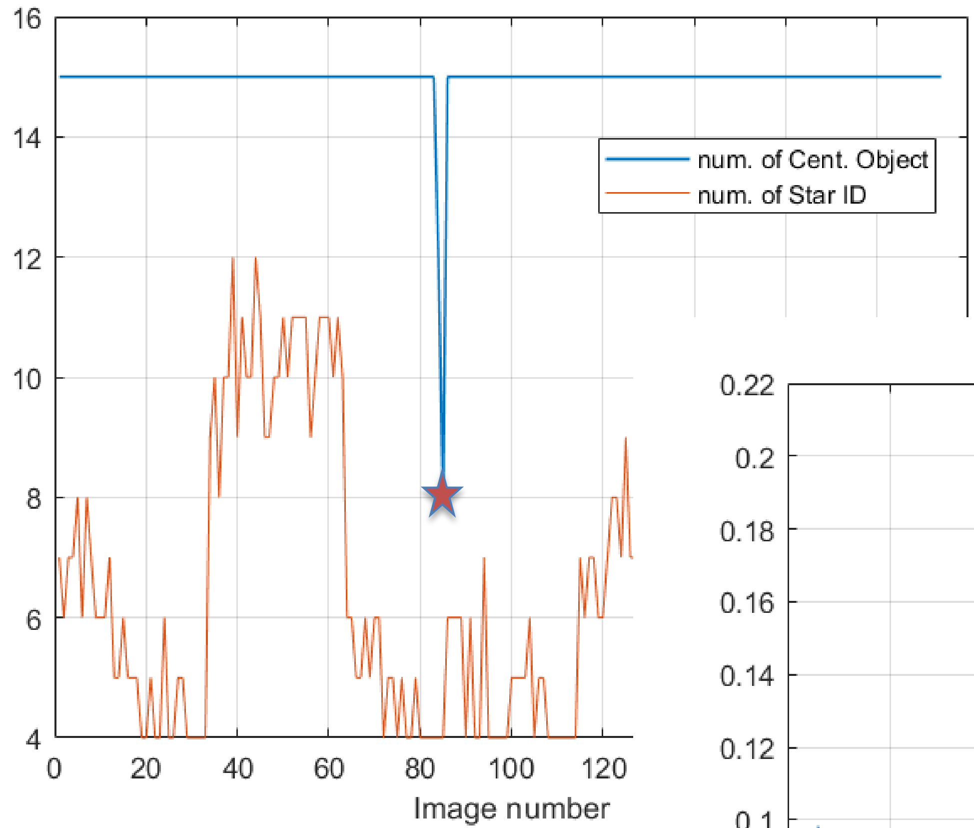



# Bad Image

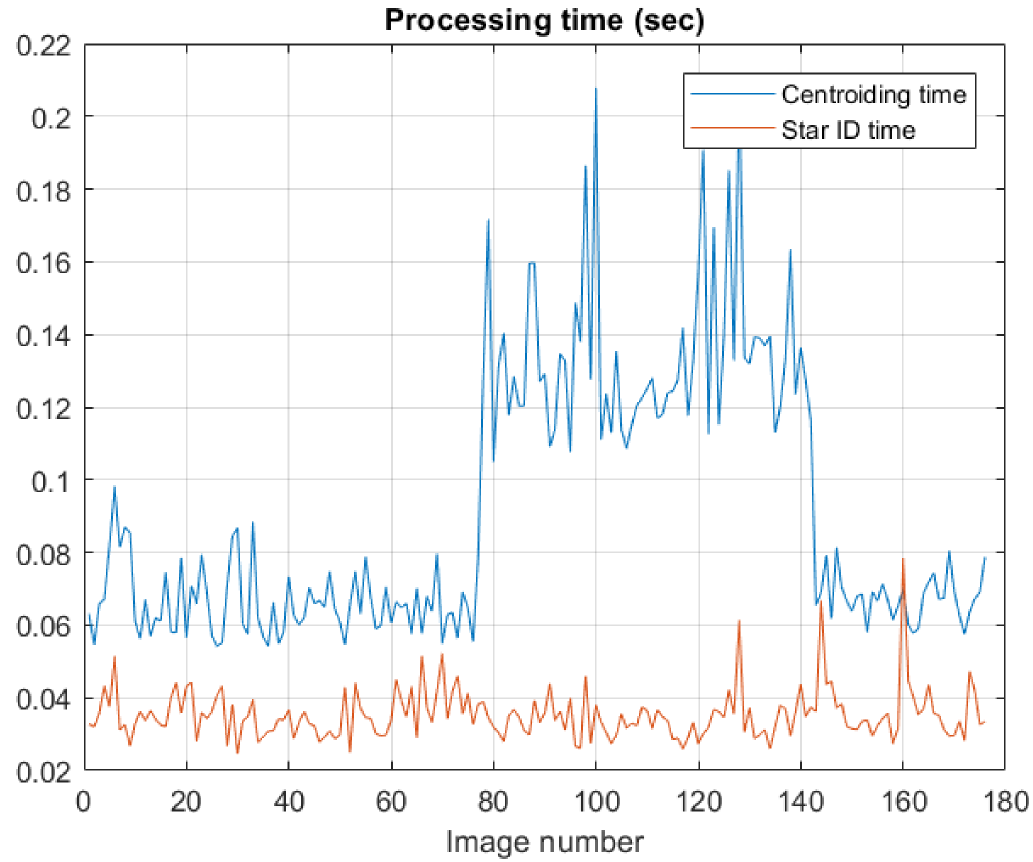
- If the number of centroids < 4 object – no possible StarID- consider bad



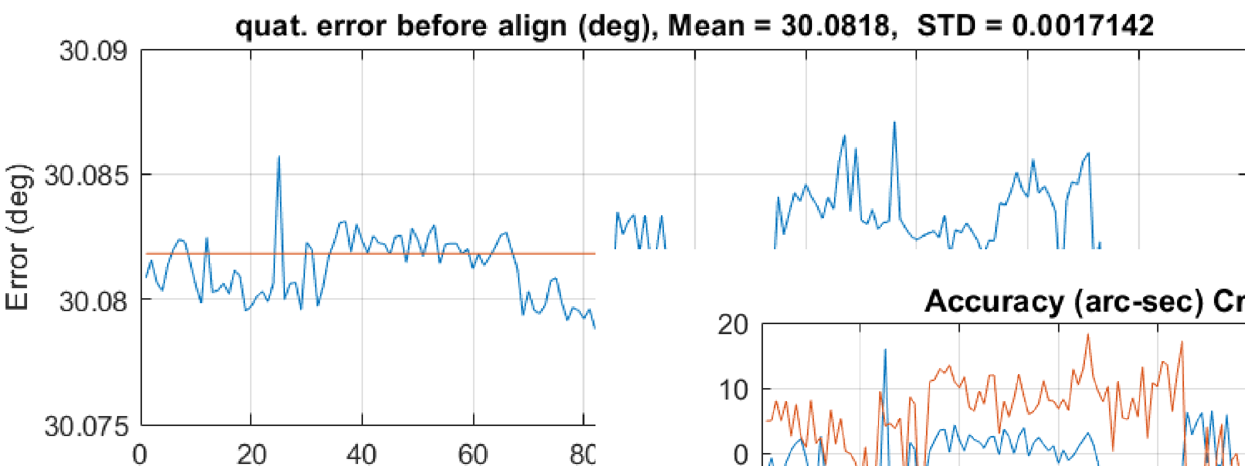
# Star ID – Att. Det. Cam2 with Moon 1s exposure



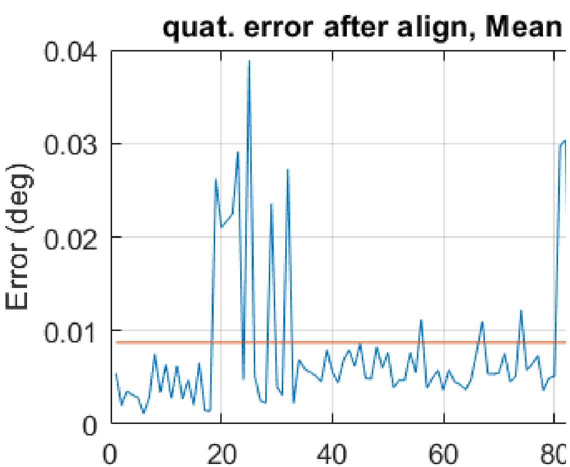

Percent SuccessID = 87.8537
Percent4StarsFound = 12.6829
badImgCount = 4
ImgWithMoonCount = 70
66 identified images with moon

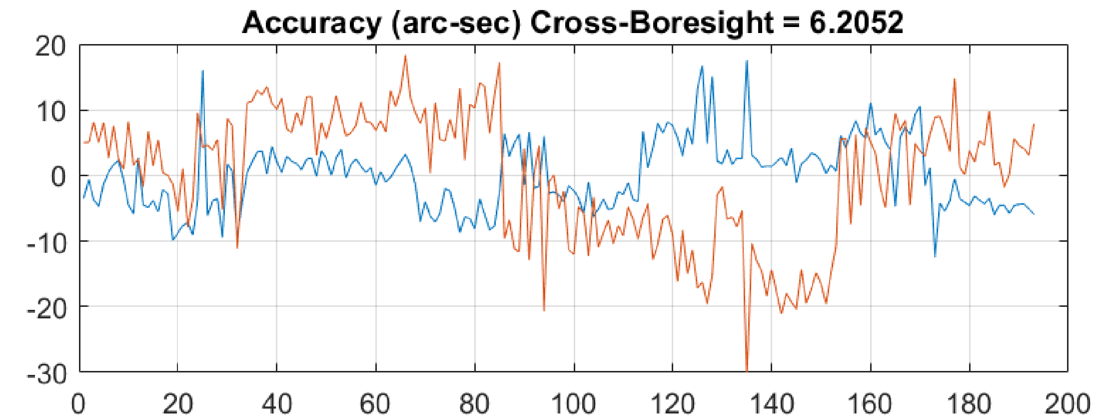


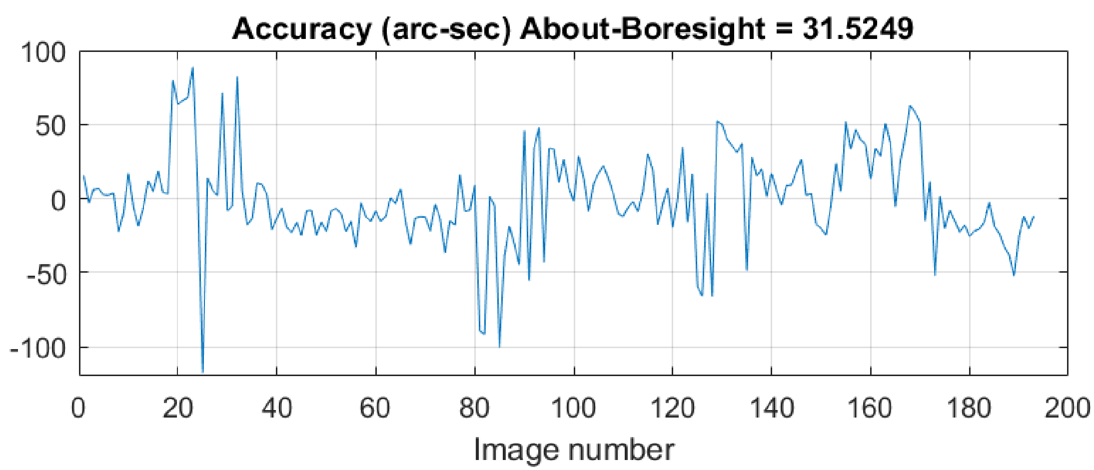
# Star ID – Att. Det. Cam2 with Moon 1s exposure



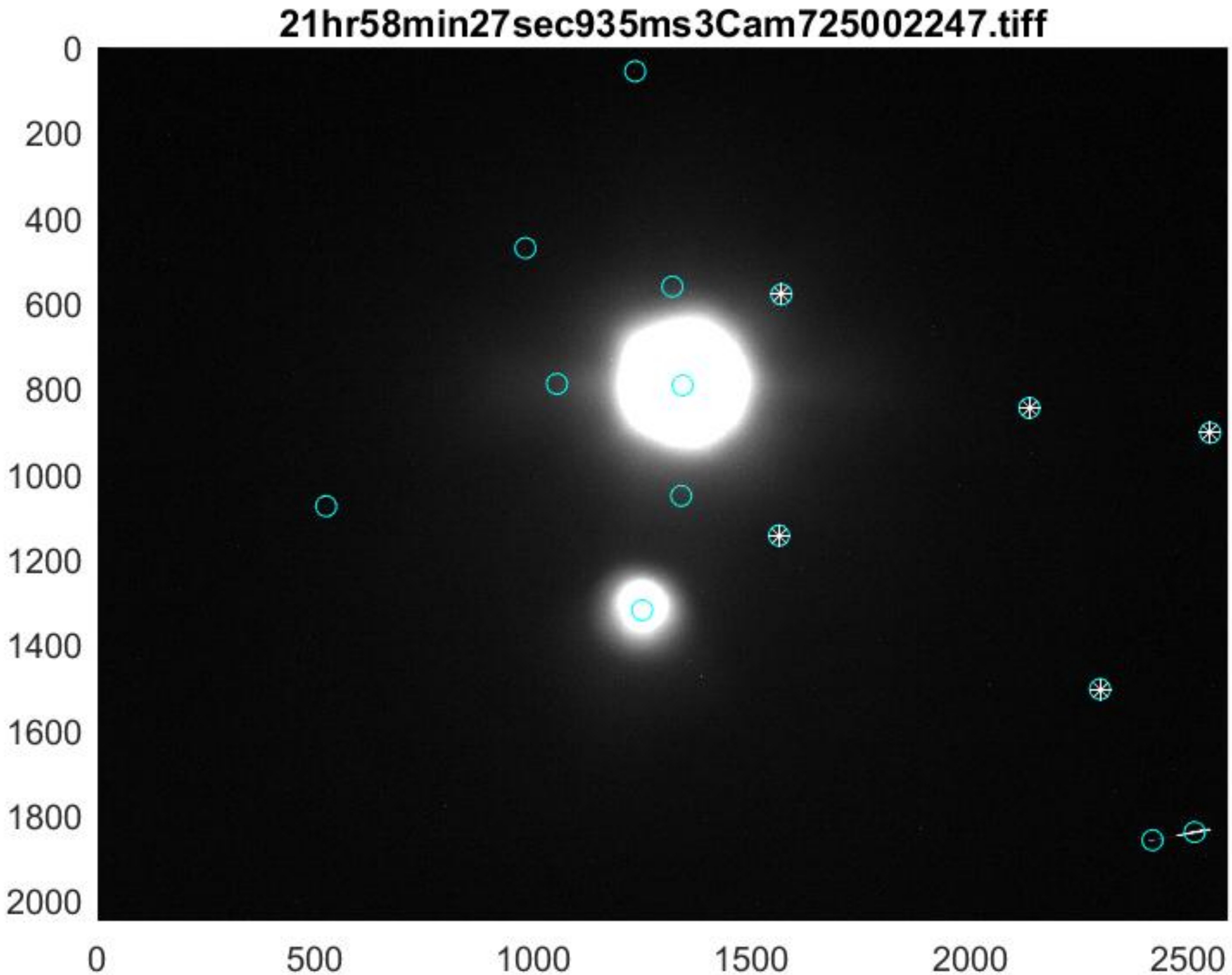

quaternion error after align,
Mean = **31.47** arc-sec,
STD = **23.42** arc-sec
Cross Bore-sight = **6.20**
About Bore-sight = **31.5**



# Image with stars, moon and debris (plane!)




Error = 66.8 arc-sec

# Results/Statistics

- **For the Star1 Camera**
  - **615 total images processed (0.5 – 1.0 sec Int. time),**
  - **0 bad image (no Centroiding with at least 4 stars)**
  - **Success star id count = 608 = 98.9 %**
  - **4 Stars identified count = 60 = 9.75 %**
  - **Quaternion Error (with ST quat.):**
    - bias = **23 arc-sec,** standard deviation = **16 arc-sec**
    - Cross Boresight **=** **6.14 arc-sec** About Boresight **=** **19.56 arc-sec**
- **For the Moon Camera**
  - **615 total images processed (0.5 – 1.0 sec Int. time),**
  - **40 bad image (no Centroiding with at least 4 stars)**
  - **Success star id count = 530 = 92.14 %**
  - **4 Stars identified count = 85 = 14.85 %**
  - **Images with Moon count = 210 images**
  - **Quaternion Error (with ST quat.):**
    - bias = **34 arc-sec,** standard deviation = **27 arc-sec**
    - Cross Boresight **=** **5.71 arc-sec** About Boresight **=** **29.16 arc-sec**