ON RANDOM AND SYSTEMATIC ERRORS OF A STAR TRACKER

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Comparing stated and estimated random errors

<table>
<thead>
<tr>
<th>Instrument</th>
<th>D, mm</th>
<th>F, mm</th>
<th>Ω, °</th>
<th>M×N</th>
<th>P_{sz}, µm</th>
<th>m_{lim}</th>
<th>ε_{x,y}</th>
<th>ε_{calc}</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOKZ-MF, IKI (Russia)</td>
<td>18</td>
<td>32</td>
<td>18×18</td>
<td>512×512</td>
<td>20</td>
<td>5.8</td>
<td>5&quot;</td>
<td>0.35&quot;</td>
</tr>
<tr>
<td>AD-1, Mars (Russia)</td>
<td>28.8</td>
<td>51.8</td>
<td>13×13</td>
<td>512×512</td>
<td>23</td>
<td>5.5</td>
<td>5&quot;</td>
<td>0.2&quot;</td>
</tr>
<tr>
<td>348K, Geofizika-Kosmos (Russia)</td>
<td>21</td>
<td>45</td>
<td>20×20</td>
<td>1024×1024</td>
<td>15</td>
<td>5.2</td>
<td>4&quot;</td>
<td>0.8&quot;</td>
</tr>
<tr>
<td>SED26, Sodern (France)</td>
<td>20</td>
<td>28.8</td>
<td>25¹</td>
<td>1024×1024</td>
<td>13</td>
<td>6.0</td>
<td>5&quot;</td>
<td>0.5&quot;</td>
</tr>
<tr>
<td>S3S, Sinclair Interplanetary (Canada)</td>
<td>13.3</td>
<td>16</td>
<td>20×15</td>
<td>2592×1944</td>
<td>2.2</td>
<td>5.75</td>
<td>7&quot;</td>
<td>0.15&quot;</td>
</tr>
</tbody>
</table>

¹ Circular FOV

All ε_{calc} error were calculated assuming the usage of all available stars up to 6ᵐ
Random error sources

- The effect of shot noise of star flux decreases with the increase of signal from star $\sim \frac{1}{\sqrt{F}}$
- Shot noise of background (sky & scattering)
- Random dark signal component can be reduced by cooling the sensor
- Readout noise of the sensor reading out with a lower frequency
- Estimation of random error
  \[ \delta r \sim \frac{\theta}{SNR} \]
Systematic error sources

- Image pixelization
- Limitation of the analyzed area while measuring coordinates
- Different sensitivity of the sensor elements (PRNU)
- Inhomogeneous sensitivity within a sensor element
- Dark current non-uniformity (DCNU)
- Effect of "hot" pixels
- Displacing effect of electron traps
- Various lens aberrations
- Differences in the spectral sensitivity of elements (SRNU)
- Non-uniformity of gain, bias
- Degradation of sensor and optics
- Etc.
Pixelization and bounded area errors

- Using integrated signal rather than signal distribution function across the focal plane
- Using finite area instead of whole focal plane
- i.e. using $\tilde{x}_c = \frac{\sum_{i,j} x_j F_{i,j}}{\sum_{i,j} F_{i,j}}$ instead of

$$\bar{x}_c = \frac{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} xf(x, y)dx dy}{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x, y)dx dy}$$
Pixelization and finite area errors:
Error of star image position depending on image size

Using PSF \( f(x, y) = \frac{S}{0.62\pi\alpha^2} e^{-\frac{x^2+y^2}{0.62\alpha^2}}, \)
where \( S \) – signal from the star, \( \alpha \) – radius with 80% of signal within
Pixelization and finite area errors: Shift of measured coordinates depending on position within pixel

Small size star images

![Pixelization effect](image1)

Large size star images

![Finite area effect](image2)
Dark current non-uniformity

- Sensor elements have different levels of dark current
- Non-uniformity is high (up to 40%)
- It significantly increase the coordinate error
Effect of DCNU on the position error

Note: SNR is signal-to-noise ratio with DCNU=0 and reveals the signal value.
Effect of DCNU on the star image detection

Note: SNR is signal-to-noise ratio with DCNU=0 and reveals the signal value
DCNU changes with Total Dose Irradiation and after annealing

High Accuracy Star Tracker (HAS) Version 2
CMOS Active Pixel image Sensor (CMOS APS), Cypress Semiconductors

Source: HAS2 Detailed Specification - ICD
Solutions to DCNU problem

- Cooling the sensor
  + We can forget about DS (except “hot” pixels)
    - Additional elements to design
    - More power consumption
    - Heat dumping problem
    - Increased effects of electron traps

- Dark signal estimation
  - Increasing requirements to calculation capabilities
  - Less accuracy due to additional noise
  - Recalibrations are highly recommended
Dark signal estimation

- **Calibrations**
  - DC measurements at a reference temperature
  - Building a DC map relative to a DC value from dark columns/rows

- **Data reduction**
  - Getting a DS value from dark columns/rows
  - Multiplying it by value from DC map
  - Subtracting the result from corresponding pixel value
Conclusions

- To achieve the high accuracy one should
  - Perform thorough ground-based tests and calibrations
  - Store calibration data of fair size (like bias and sensitivity maps)
  - Provide specific corrections during data reduction
  - Cool the sensor or calculate dark signal
  - Provide on-orbit calibrations
Questions