Standardization training program
E-60 discipline: Control

Stars sensors terminology
and performance specification standard
E-ST-60-20C Rev. 2 (May 2019)

The ECSS E60 branch

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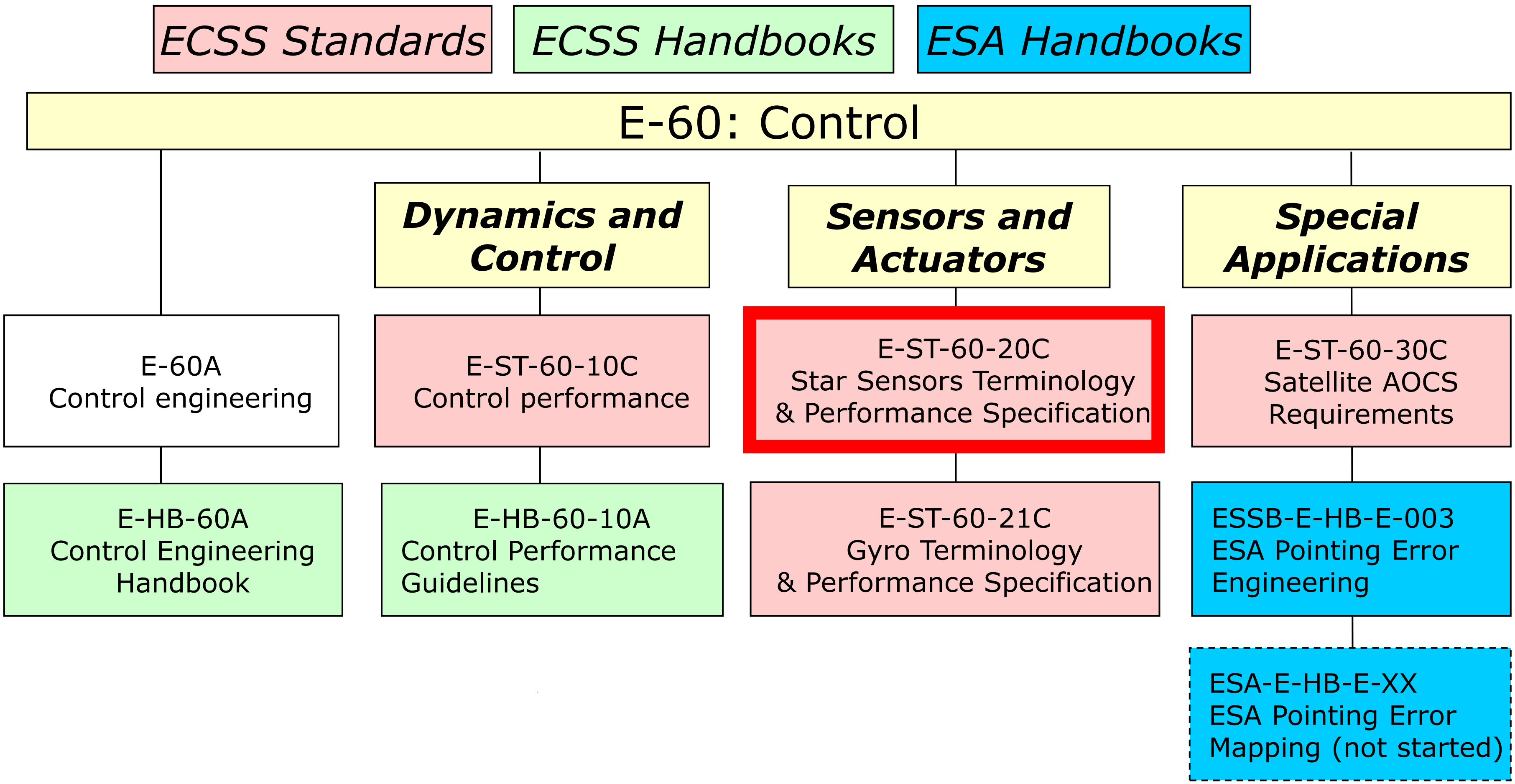
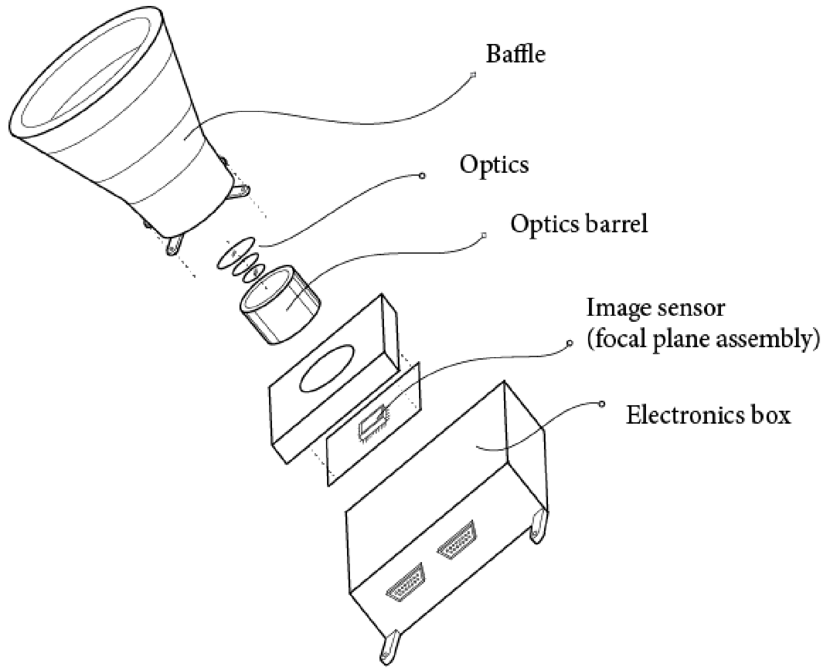


An introduction to star trackers

- Camera which takes pictures of the night sky
- Match stars to a catalogue
- Provides an independent inertial attitude measurement
- ‘Lost-in-space’ mode and tracking mode
- Accurate, reliable, direct attitude measurement
- High mass/volume/power, expensive, blinded by Sun, only at low angular rates



An introduction to star trackers

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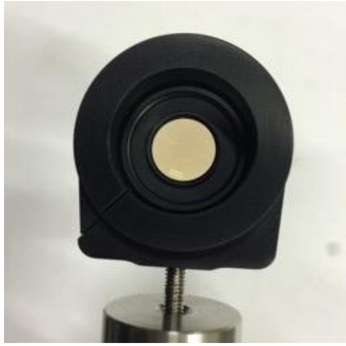
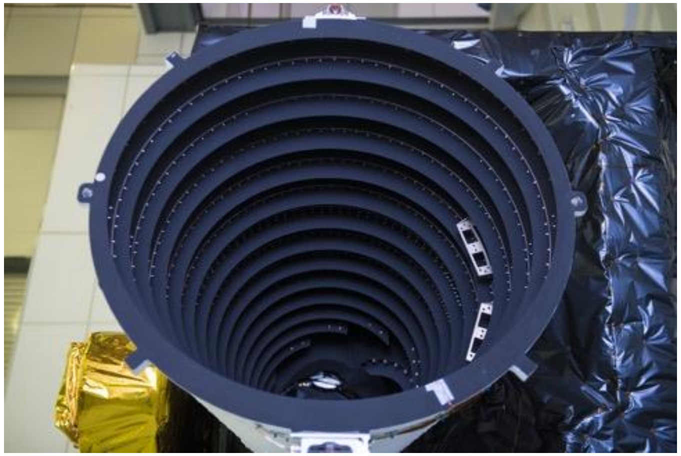
→ OPTICS

- Optical aberrations, chromatic aberrations, barreling, vignetting, focal length variations,…
- Some glasses are sensitive to radiation



→ BAFFLE

- *The sun is 1000 billion times brighter than most stars*
- Sun exclusion, Earth exclusion



An introduction to star trackers

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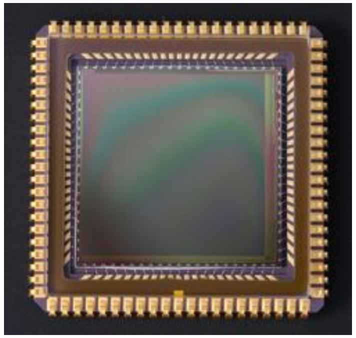

→ IMAGE SENSOR

- Solar storms, SAA passages, Van Allen belt crossings: increase in background and EDAC triggers expected
- Many noise sources: fixed pattern noise, shot noise, non-uniformities, quantization noise, smearing, blooming,…

→ ELECTRONICS

- Perform image processing at 10 Hz
- Typically tracking 10-16 stars
- Sometimes thousands of false stars in FoV

Star tracker Introduction
What is it and the place of Europe in the field

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- In recent years there have been rapid developments in star tracker technology (algorithms, detectors, optics, straylight mitigation, robustness to radiations effects), in particular with a great increase in sensor autonomy and capabilities.

- The use of Star Tracker simplifies the Attitude & Orbit Control
  - Autonomous units working from "lost-in-space"
  - Constant 3-axis measurement of the attitude
  - No dependency to altitude
    - In comparison with Earth Sensors
  - State-of-the-art STRs are now "designed-to-be" immune to radiations SEEs.

- European Star Trackers are leading the world :
  - An estimate of 75 to 80% of the market share are for Sodern (F), Leonardo (I) and Jena-Optronik (D).
  - Example: NASA science missions and all US telecommunication satellites are using European Star Trackers

Background and motivation

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- The Star Tracker (STR) is the key sensor of all state-of-the-art AOCS
- The standard has been written to unify the naming of the terms used to specify a STR
  - Previously, major Star Tracker manufacturers were not using the same definitions for key requirements, this was leading to difficulties in comparing the products. (1σ or 3σ not mentioned, ambiguities with exclusion angles etc…).
  - Most of the satellites primes and STR suppliers were represented in the working group.
- The Standard focuses on performance specifications
  - The Standard covers all aspects of performances, including nomenclature, definitions, and performance metrics for the performance specification of star sensors.
- The Standard also specifies the verification approach
- Housekeeping data, TM/TC interface and data structures, were left outside the scope of this Standard. Rev 2 does provide a standard set of commands and telemetry (from SAVOIR)
- The control performance Standard WG was running in parallel, and the Pointing Error Handbook was not started
  - A difficulty for the Star Tracker working group.

STR terminology & performance specification overview

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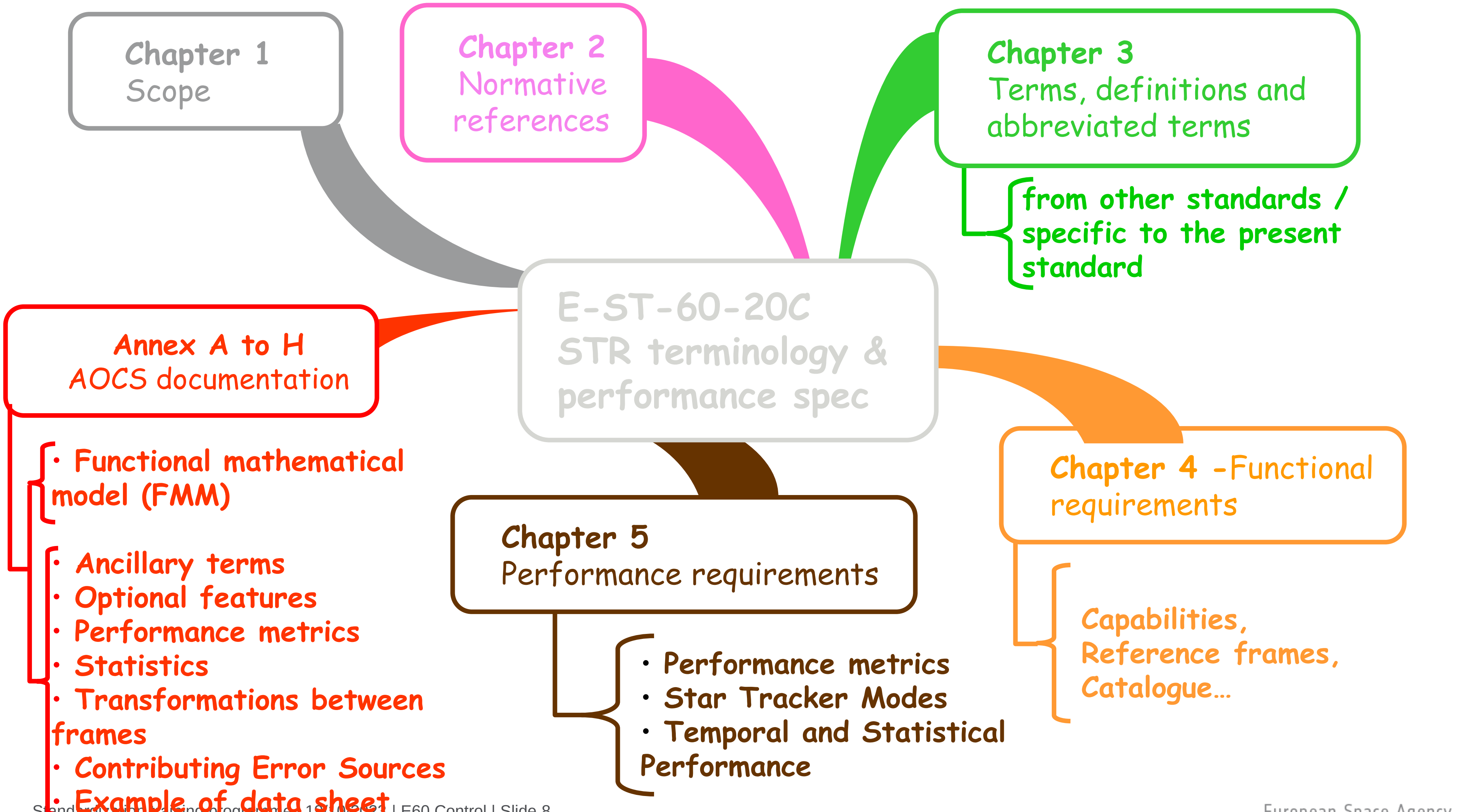

ECSS-E-ST-60-20C: Star sensors terminology and performance specification

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1. Scope
2. Normative References
3. Terms, definitions and abbreviated terms
4. **Functional** requirements
5. **Performance** requirements

- Annex: functional mathematical model description
- Annex: ancillary terms in star sensors
- Annex: optional features of star sensors
- Annex: performance metrics applied to star sensors
- Annex: statistics
- Annex: transformations between coordinate frames
- Annex: contributing error sources
- Annex: example of data sheet
- *Annex: command and telemetry tables (informative)*

Chapter 4 : Important functional definitions of the Standard

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- **Hardware** definitions
  - Baffle, detector, electronic processing unit, optical head, optical system
- **Reference Frames**
  - alignment reference frame (ARF),
  - boresight reference frame (BRF),
  - inertial reference frame (IRF),
  - mechanical reference frame (MRF),
  - stellar reference frame (SRF)
- **Time** and Frequency definitions.
  - integration time, measurement date, output bandwidth
- **Type** of sensors
  - Star Camera or Autonomous STR
- **Miscellaneous**
  - Field of view, Exclusions Angles
    (for Sun, Earth, Moon or other celestial bodies)
  - Correct attitude determination, false attitude determination, invalid attitude deter.

Chapter 4:
Examples of key aspects of the STR for AOCS

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- STRs provide attitude measurements
- (partial) image download
- Accuracy
  - E.g. 10 arcsec at EOL (95% confidence level)
  - Currently reaching sub-arcsec performance
- Output rate
  - E.g. 2 Hz or more
- Integrity
  - Quaternions flagged as valid have to be valid
- Autonomy (Current state-of-the-art in Europe)
  - Despite non-star objects (dust, radiation, planets,…)
  - E.g. capability to:
    - **Autonomously determine the attitude**
    - **Autonomously track the attitude**
- Sun / Earth / Moon blinding
  - Sun is 1000 billion times brighter than most other stars → baffle needed
  - Exclusion angles

Chapter 5.1, 5.2: Performance Requirements - General

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- Performance budget is not purely temporal (also ensemble statistics needed) :
  - Performances have a statistical nature and the standard presents the knowledge required to build performances up : Only an envelope of the actual performances can be provided.
  - Different statistical interpretations can be taken to handle the statistical ensemble – e.g. for bias and FoV errors, the ensemble interpretation shall be used
- Performance is to be verified in two steps:
  - **Single star performances** : These shall be validated (at zero body rates) against on-ground tests using artificial stellar sources.
  - **Attitude/Quaternion performances** : These shall be validated by analysis, against on-ground tests using artificial stellar sources or night-sky-tests.
- For each type of errors, the standard defines :
  - If the error is to be represented in the statistical ensemble or pure temporal domain.
  - The exhaustive list of contributors to be used in the budget.
  - And the verification method to be used (Analysis, Simulation or Test).
- Confidence level is to be agreed with the customer for each of the performance metrics

Chapter 5.4:
Performance Requirements - Conditions

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- The performance conditions of the 'statistical ensemble' shall be used to encompass the following conditions for EOL:
    - worst-case conditions (temperature, stray light)
    - Including ageing effects (radiation, UV, ATOX, contaminations)
- The maximum magnitude of body rate and acceleration shall be used.
- Single star position measurement performance within the verification simulations shall be:
    - validated against on-ground test data for fixed pointing conditions, and
    - able to predict metric performance under these conditions with an accuracy of 10 %.
- The simulation allows the verification to cover the full range of conditions, including stray light, finite rates/accelerations, full range of instrument magnitudes, and the worst-case radiation exposure.
- Impact of individual star errors on the overall rate accuracy shall be provided via simulation.

Chapter 5.5: Performance Requirements – Definition of error contributors

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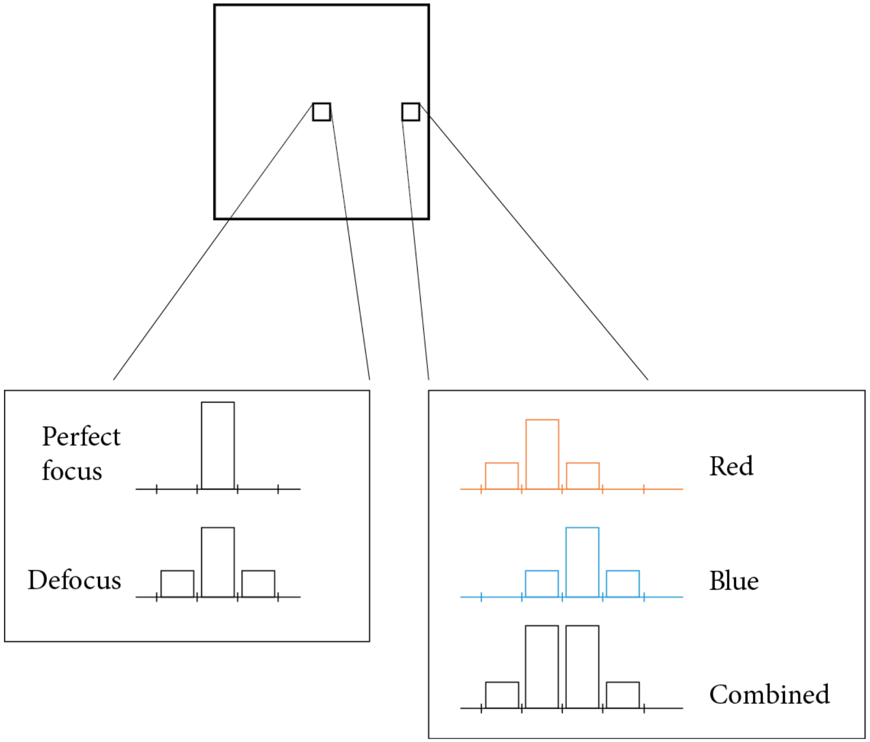
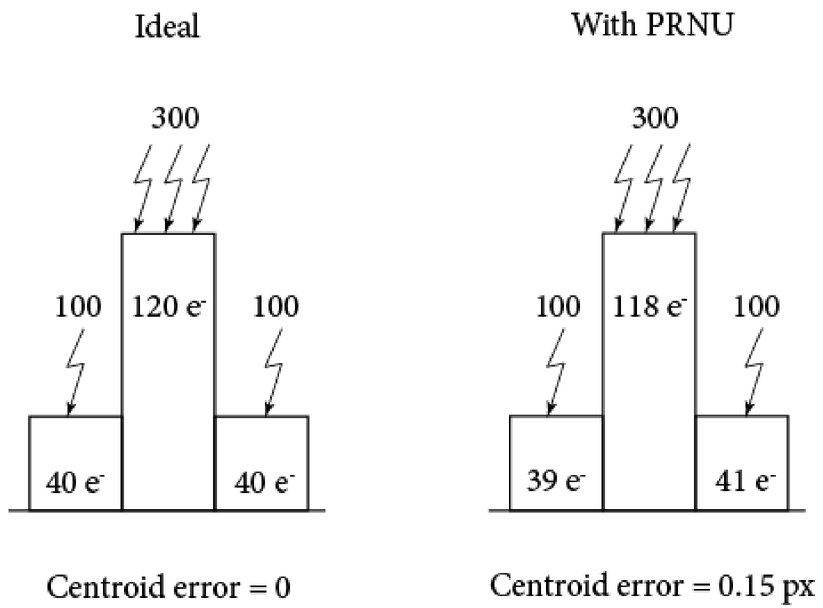
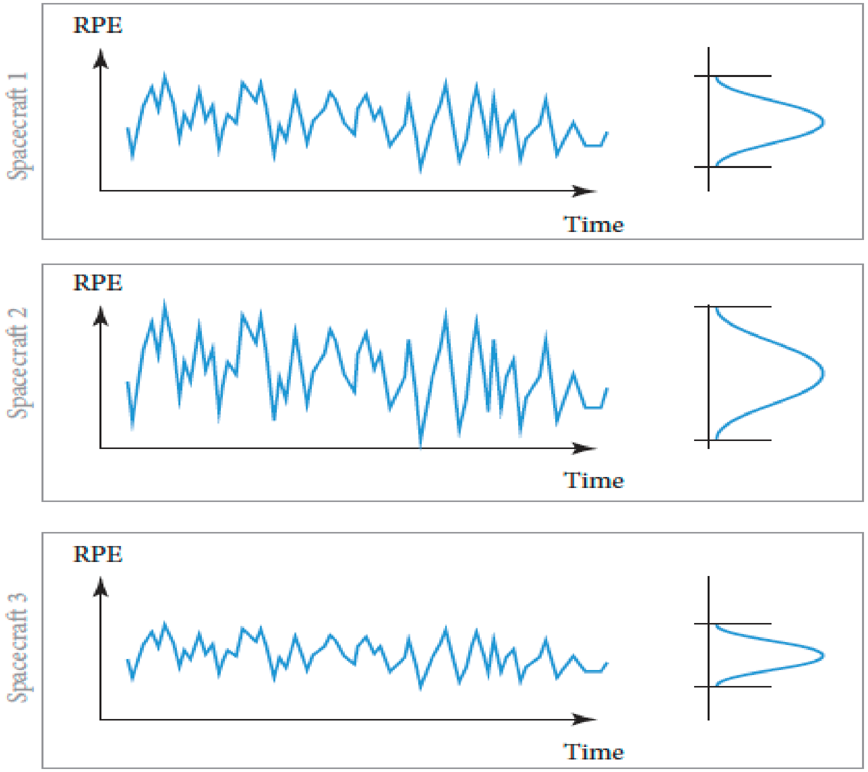
- Static bias
  - Driven by on-ground calibration residuals, launch misalignment
- Thermo elastic error
- FOV spatial error
  - Driven by optics distortion, star shape over the field of view, focal length over temperature, background and straylight
  - Aberration and catalogue errors
- Pixel spatial error
  - Driven by detector non uniformities (PRNU, FPN,…)
  - Lead to bias error in the case of inertial pointing, while they contribute to random noise for high angular rate missions.
- Temporal noise
  - White noise
  - Driven by star signal shot noise, background signal shot noise (straylight level, detector temperature…), read-out noise, quantification noise, datation noise
- Aberration of light or residual of aberration is also addressed to help the future user to chose which type of compensation is the most suitable.

Field of view & pixel spatial errors





Statistical interpretation



- Ensemble interpretation: worst case in time.
- Temporal interpretation: for the worst case member of the statistical ensemble.
- Mixed interpretation: any time, any member.

Statistical interpretation

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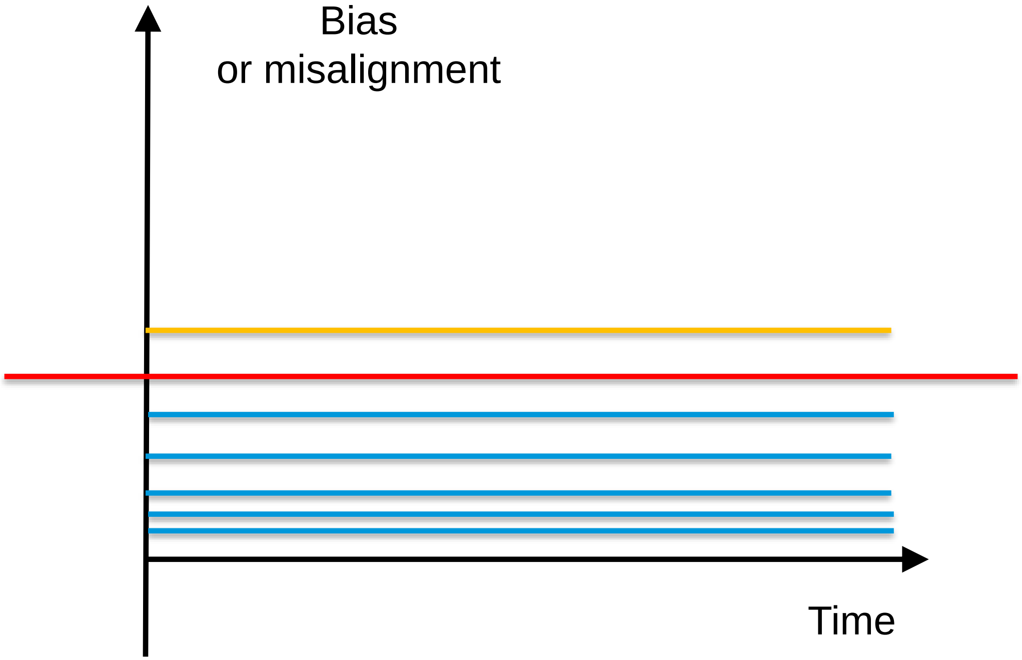

- Ensemble interpretation: worst case in time.
- Temporal interpretation: for the worst case member of the statistical ensemble.
- Mixed interpretation: any time, any member.

Statistical interpretation

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- The *n-σ* notation shall be restricted to cases where the Gaussian distribution holds. (due to central limit theorem, this hypothesis may be applicable)

- Ensemble interpretation: The error is less than X_{max}, for P_c members of the statistical ensemble, at the worst case in time.
- Temporal interpretation: The error is less than X_{max}, for P_c of the time, for the worst case member of the statistical ensemble.
- Mixed interpretation: The error is less than X_{max}, with probability P_c for a random member of the statistical ensemble, at a random time.

Note: for the temporal interpretation, often the members of the ensemble that are outliers (e.g. outside of 3σ) are discarded. Similarly, for Gaussian random errors, the ensemble interpretation takes the 3σ as the worst-case in time.

Chapter 5.5
Examples of requirements

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- *The Star Sensor shall have a temporal noise of less than 10 arcsec around any axis up to 10 deg/s at EOL and for accelerations up to 1,0 deg/s²*
- *The Measurement date error shall be less than 0,1 ms*
- *The probability of correct attitude determination within 10 s shall be greater than 99,99 % for random initial pointings within the entire celestial sphere, for rates around any axis of up to 100 arcsec/s at EOL and for accelerations up to 10 arcsec/s²*
- *The probability of false attitude determination within 10 s shall be less than 0,1 % for random initial pointings within the entire celestial sphere, for rates around any axis of up to 100 arcsec/s at EOL and for accelerations up to 10 arcsec/s².*
- *The Star Sensor shall be capable of performing a full image download of the entire Field of View at 12 bit resolution. The image output time shall be less than 10 seconds*

Chapter 5.13: Star Tracker robustness to solar flares

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- Severe conditions can appear in case of solar events. In case of severe solar flare, the requirement is not anymore the performance level but the functionality itself which can completely fail.

- Two different capabilities are concerned:
  - Continuity of tracking during a solar event
  - Ability to solve the lost in space problem during a solar event

- Verification is done by high fidelity simulations

- *Typical requirement: "The star tracker shall be able to acquire in 60 s from OFF condition without aiding, over 99,7 % of the celestial sphere in presence of the 5 minute peak flux of the October 1989 solar event from the CREME96 Space Radiation model."*

Conclusion

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- The same **definitions** are now shared between all STR manufacturers (In Europe)
- **Performance budgets** are now based on the same structure.
  However a frequency characterisation of the performance is desirable e.g. to analyse gyrostellar hybridisation
- A harmonisation of **functional interfaces** of Star Trackers is suggested in rev.2 (telemetry table)
  - Under SAVOIR initiative, a SAVOIR SAFI WG has been created between satellite primes and all four main Star Trackers manufacturers to agree on a common core of data and commands. This has been added as an Appendix of the Standard rev 2.
- Additional requirements on **the robustness to solar flares** is included in rev.2
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