



Space engineering

Stars sensors terminology and performance specification

Foreword

This Standard is one of the series of ECSS Standards intended to be applied together for the management, engineering, product assurance and sustainability in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards. Requirements in this Standard are defined in terms of what shall be accomplished, rather than in terms of how to organize and perform the necessary work. This allows existing organizational structures and methods to be applied where they are effective, and for the structures and methods to evolve as necessary without rewriting the standards.

This Standard has been prepared by the ECSS-E-ST-60-20C Rev.2 Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

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Change log

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ECSS-E-ST-60-20C Rev. 2 15 May 2019	<p>First issue revision 2.</p> <p>Changes with respect to ECSS-E-ST-60-20C Rev. 1 (15 November 2008) are identified with revision tracking.</p> <p>Main changes are:</p> <ul style="list-style-type: none">• Update of several definitions in clause 3.2 including update of some of the Figures.• Update of list of Abbreviated term in clause 3.3.• Addition of the Nomenclature in clause 3.4• Addition of a standard set of core commands and telemetry (or functional interfaces) prepared in the context of SAVOIR initiative in clauses 4.1.5, 4.1.6, 4.1.7 and Annex I.• Clause 5.1.1 rewritten.• Addition of new clause 5.13 “Robustness to solar events” addressing robustness and performance in presence of solar events.• Heading of clauses 5.2, 5.2.3, 5.4 updated.• Addition of new clauses<ul style="list-style-type: none">- 5.2.4 “Provision for tests”;- 5.9.4.1 “Probability of correct attitude determination”;- 5.9.4.2 “Probability of false attitude determination”;- 5.9.4.3 “Probability of invalid attitude solution”• Update of Clause 5 and Annex B and Annex G to be fully consistent with the Control Performance Standard ECSS-E-ST-60-10 and to remove irrelevant duplications.

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Introduction

In recent years there have been rapid developments in star [sensor](#) technology, in particular with a great increase in sensor autonomy and capabilities. This Standard is intended to support the variety of star sensors either available or under development.

This Standard defines the terminology and specification definitions for the performance of star [sensors](#) (in particular, [star trackers](#) and autonomous star trackers). It focuses on the specific issues involved in the specification of performances of star [sensors](#) and is intended to be used as a structured set of systematic provisions.

This Standard is not intended to replace textbook material on star [sensor](#) technology, and such material is intentionally avoided. The readers and users of this Standard are assumed to possess general knowledge of star [sensor](#) technology and its application to space missions.

This document defines and normalizes terms used in star sensor performance specifications, as well as some performance assessment conditions:

- sensor components
- sensor capabilities
- sensor types
- sensor reference frames
- [general performance conditions including temperature, radiation, dynamic and stray light](#)
- sensor [performance](#) metrics

This document also defines a standard core of functional interfaces which help to harmonize the majority of commands and telemetry necessary to operate star sensors.

1 Scope

This Standard specifies star [sensor](#) performances as part of a space project. The Standard covers all aspects of performances, including nomenclature, definitions, and performance [requirements](#) for the performance specification of star sensors.

The Standard focuses on:

- [performance specifications \(including the impact of temperature, radiation and straylight environments\)](#);
- [robustness \(ability to maintain functionalities under non nominal environmental conditions\)](#).

Other specification types, for example mass and power, housekeeping data and data structures, are outside the scope of this Standard.

This Standard also proposes a standard core of functional interfaces defined by [unit suppliers and avionics primes in the context of Space AVionics Open Interface aRchitecture \(SAVOIR\) initiative](#).

When viewed from the perspective of a specific project context, the requirements defined in this Standard should be tailored to match the genuine requirements of a particular profile and circumstances of a project.

This standard may be tailored for the specific characteristics and constraints of a space project in conformance with ECSS-S-ST-00.

2

Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this ECSS Standard. For dated references, subsequent amendments to, or revision of any of these publications, do not apply. However, parties to agreements based on this ECSS Standard are encouraged to investigate the possibility of applying the more recent editions of the normative documents indicated below. For undated references, the latest edition of the publication referred to applies.

ECSS-S-ST-00-01	ECSS system – Glossary of terms
ECSS-E-ST-60-10	Space engineering – Control performance
ECSS-E-ST-60-30	Space engineering – Satellite attitude and orbit control system (AOCS) requirements

3

Terms, definitions and abbreviated terms

3.1 Terms from other standards

- a. For the purpose of this Standard, the terms and definitions from ECSS-S-ST-00-01, [ECSS-E-ST-60-10](#) and [ECSS-E-ST-60-30](#) apply.

NOTE Additional definitions are included in Annex B.

3.2 Terms specific to the present standard

3.2.1 Capabilities

3.2.1.1 aided tracking

capability to input information to the star sensor internal processing from an external source

NOTE 1 This capability applies to star tracking, autonomous star tracking and autonomous attitude tracking.

NOTE 2 E.g. AOCS.

3.2.1.2 angular rate measurement

capability to determine, the instantaneous sensor reference frame inertial angular rotational rates

NOTE Angular rate can be computed from successive star positions obtained from the detector or successive absolute attitude (derivation of successive attitude).

3.2.1.3 autonomous attitude determination

capability to determine the absolute orientation of a defined sensor reference frame with respect to a defined inertial reference frame and to do so without the use of any a priori or externally supplied attitude, angular rate or angular acceleration information

3.2.1.4 autonomous attitude tracking

capability to repeatedly re-assess and update the orientation of a sensor-defined reference frame with respect to an inertially defined reference frame for an extended period of time, using autonomously selected star images in the field

of view, following the changing orientation of the sensor reference frame as it moves in space

- NOTE 1 The Autonomous Attitude Tracking makes use of a supplied a priori Attitude Quaternion, either provided by an external source (e.g. AOCS) or as the output of an Autonomous Attitude Determination ('Lost-in-Space' solution).
- NOTE 2 The autonomous attitude tracking functionality can also be achieved by the repeated use of the Autonomous Attitude Determination capability.
- NOTE 3 The Autonomous Attitude Tracking capability does not imply the solution of the 'lost in space' problem.

3.2.1.5 autonomous star tracking

capability to detect, locate, select and subsequently track star images within the sensor field of view for an extended period of time with no assistance external to the sensor

- NOTE 1 Furthermore, the autonomous star tracking capability is taken to include the ability to determine when a tracked image leaves the sensor field of view and select a replacement image to be tracked without any user intervention.
- NOTE 2 See also 3.2.1.9 (star tracking).

3.2.1.6 cartography

capability to scan the entire sensor field of view and to locate and output the position of each star image within that field of view

3.2.1.7 image download

capability to capture the signals from the detector over the entire detector Field of view, within a single integration, and output all of that information to the user

- NOTE See also 3.2.1.8 (partial image download).

3.2.1.8 partial image download

capability to capture the signals from the detector over the entire detector Field of view, within a single integration, and output part of that information to the user

- NOTE 1 Partial image download is an image download (see 3.2.1.7) where only a part of the detector field of view can be output for any given specific 'instant'.
- NOTE 2 Partial readout of the detector array (windowing) and output of the corresponding pixel signals also fulfil the functionality.

3.2.1.9 star tracking

capability to measure the location of selected star images on a detector, to output the co-ordinates of those star images with respect to a sensor defined reference frame and to repeatedly re-assess and update those co-ordinates for an extended period of time, following the motion of each image across the detector

3.2.1.10 sun survivability

capability to withstand direct sun illumination along the boresight axis for a certain period of time without permanent damage or subsequent performance degradation

NOTE This capability can be extended to flare capability considering the potential effect of the earth or the moon in the FOV.

3.2.2 Star sensor components

3.2.2.1 Overview

Figure 3-1 shows a scheme of the interface among the generalized components specified in this Standard.

NOTE Used as a camera the sensor output can be located directly after the pre-processing block.

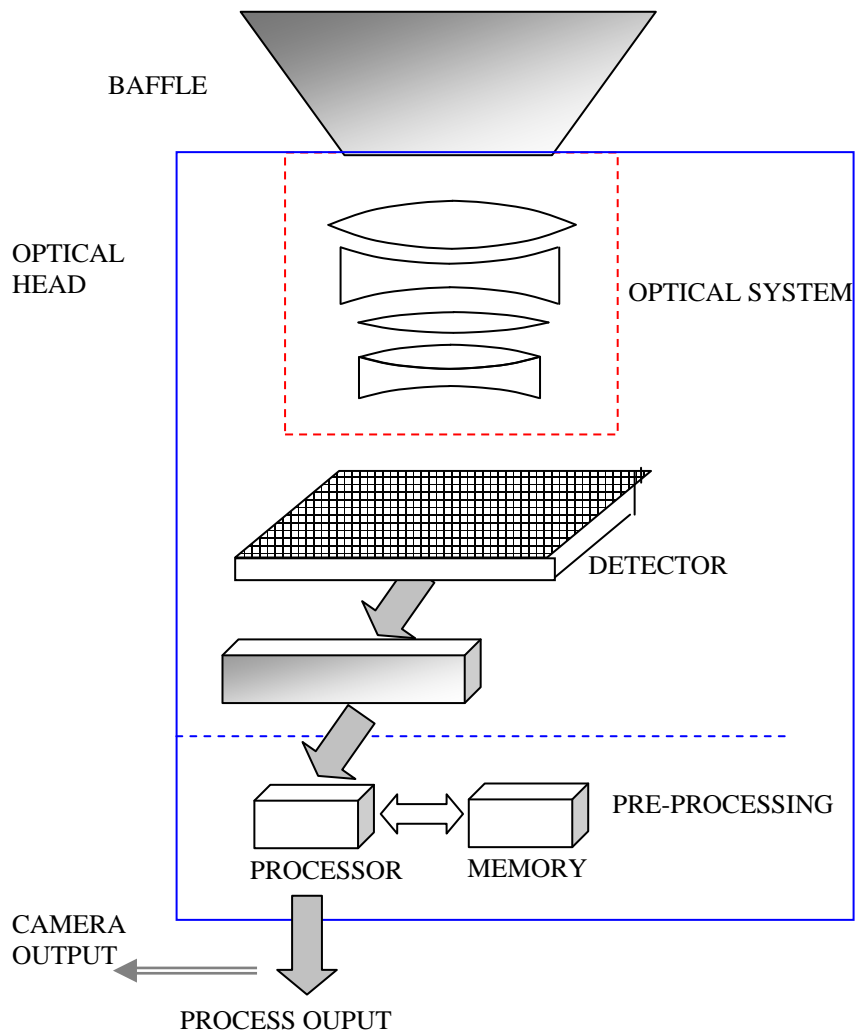


Figure 3-1: Star sensor elements – schematic

3.2.2.2 baffle

passive structure used to prevent or reduce the entry into the sensor lens or aperture of any signals originating from outside of the field of view of the sensor

NOTE Baffle design is usually mission specific and usually determines the effective exclusion angles for the limb of the Earth, Moon and Sun. The Baffle can be mounted directly on the sensor or can be a totally separate element. In the latter case, a positioning specification with respect to the sensor is used.

3.2.2.3 detector

element of the star sensor that converts the incoming signal (photons) into an electrical signal

NOTE Usual technologies in use are CCD (charge coupled device) and APS (active pixel sensor) arrays though photomultipliers and various other technologies can also be used.

3.2.2.4 electronic processing unit

set of functions of the sensor not contained within the optical head

NOTE Specifically, the sensor electronics contains:

- sensor processor;
- power conditioning;
- software algorithms;
- onboard star catalogue (if present).

3.2.2.5 optical head

part of the sensor responsible for the capture and measurement of the incoming signal

NOTE As such it consists of

- the optical system;
- the detector (including any cooling equipment);
- the proximity electronics (usually detector control, readout and interface, and optionally pixel pre-processing);
- the mechanical structure to support the above.

3.2.2.6 optical system

system that comprises the component parts to capture and focus the incoming photons

NOTE Usually this consists of a number of lenses, or mirrors and filters, and the supporting mechanical structure, stops, pinholes and slits if used.

3.2.3 Reference frames

3.2.3.1 alignment reference frame (ARF)

reference frame fixed with respect to the sensor external optical cube where the origin of the ARF is defined unambiguously with reference to the sensor external optical cube

NOTE 1 The X-, Y- and Z-axes of the ARF are a right-handed orthogonal set of axes which are defined unambiguously with respect to the normal of the faces of the external optical cube. Figure 3-2 schematically illustrates the definition of the ARF.

NOTE 2 The ARF is the frame used to align the sensor during integration.

NOTE 3 This definition does not attempt to prescribe a definition of the ARF, other than it is a frame fixed

relative to the physical geometry of the sensor optical cube.

NOTE 4 If the optical cube's faces are not perfectly orthogonal, the X-axis can be defined as the projection of the normal of the X-face in the plane orthogonal to the Z-axis, and the Y-axis completes the RHS.

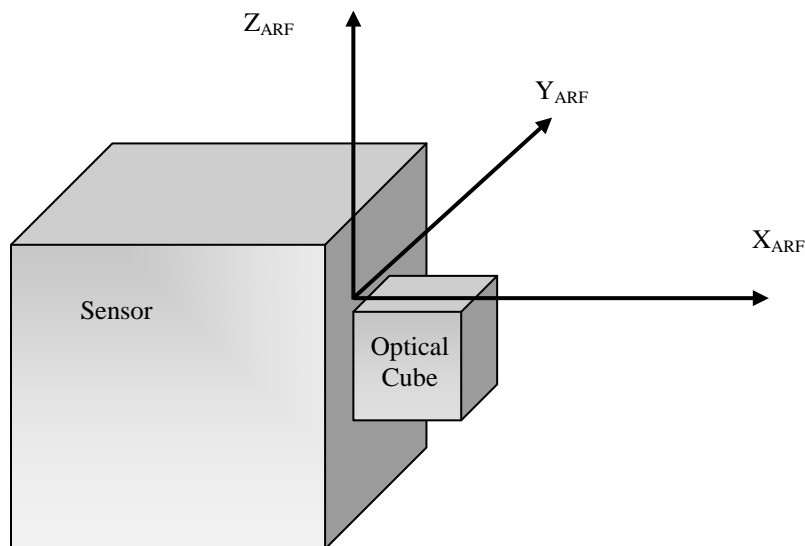


Figure 3-2: Example alignment reference frame

3.2.3.2 boresight reference frame (BRF)

reference frame where:

- the origin of the Boresight Reference Frame (BRF) is defined unambiguously with reference to the mounting interface plane of the sensor Optical Head;

NOTE In an ideally aligned opto-electrical system this results in a measured position at the centre of the detector.

- the Z-axis of the BRF is defined to be anti-parallel to the direction of an incoming collimated light ray which is parallel to the optical axis;
- X-BRF-axis is in the plane spanned by Z-BRF-axis and the vector from the detector centre pointing along the positively counted detector rows, as the axis perpendicular to Z-BRF-axis. The Y-BRF-axis completes the right handed orthogonal system.

NOTE 1 The X-axes and Y-axes of the BRF are defined to lie (nominally) in the plane of the detector perpendicular to the Z-axis, so as to form a right handed set with one axis nominally along the detector array row and the other nominally along the detector array column. Figure 3-3 schematically illustrates the definition of the BRF.

NOTE 2 The definition of the Boresight Reference Frame does not imply that it is fixed with respect to the Detector, but that it is fixed with respect to the combined detector and optical system.

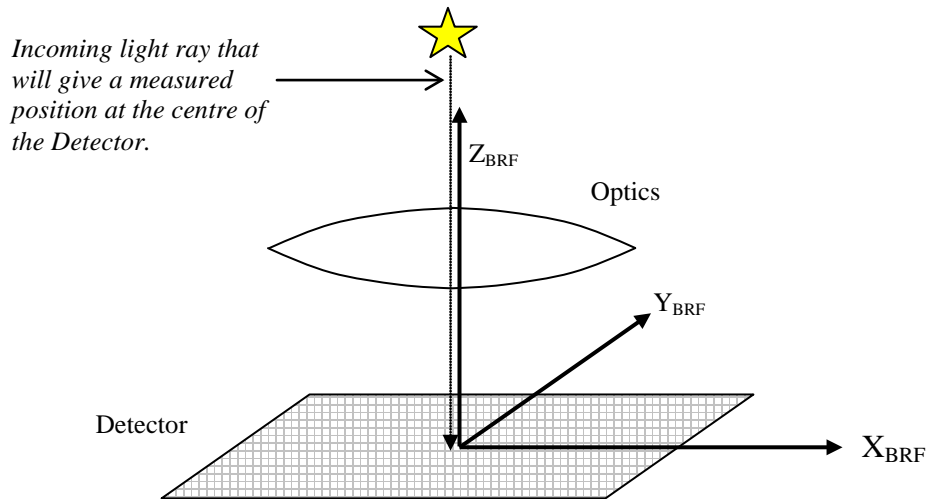


Figure 3-3: Boresight reference frame

3.2.3.3 inertial reference frame (IRF)

reference frame determined to provide an inertial reference

NOTE 1 E.g. use the J2000 reference frame as IRF as shown in Figure 3-4.

NOTE 2 The J2000 reference frame (in short for ICRF – Inertial Celestial Reference Frame at J2000 Julian date) is usually defined as Z IRF = earth axis of rotation (direction of north) at J2000 (01/01/2000 at noon GMT), X IRF = direction of vernal equinox at J2000, Y IRF completes the right-handed orthonormal reference frame.

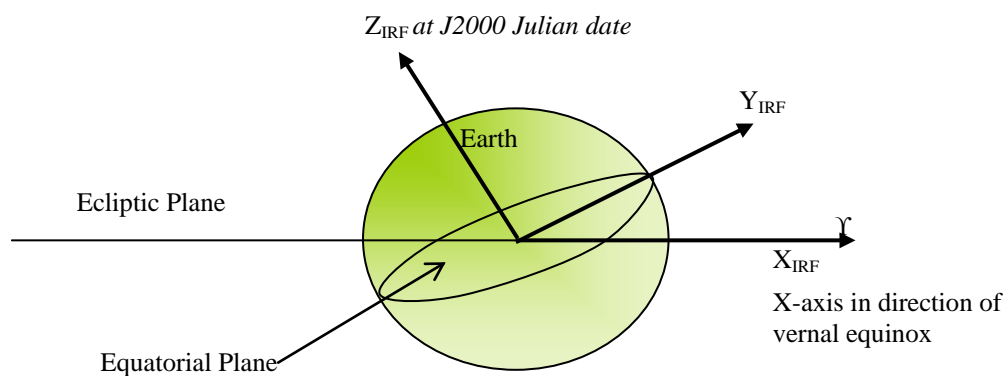


Figure 3-4: Example of Inertial reference frame

3.2.3.4 mechanical reference frame (MRF)

reference frame where the origin of the MRF is defined unambiguously with reference to the mounting interface plane of the sensor Optical Head

NOTE 1 E.g. the Z-axis of the MRF is defined to be perpendicular to the mounting interface plane. The X- and Y-axes of the MRF are defined to lie in the mounting plane such as to form an orthogonal RHS with the MRF Z-axis.

NOTE 2 Figure 3-5 schematically illustrates the definition of the MRF.

NOTE 3 For Fused Multiple Optical Head configurations, MRF should be discussed and agreed between supplier and customer.

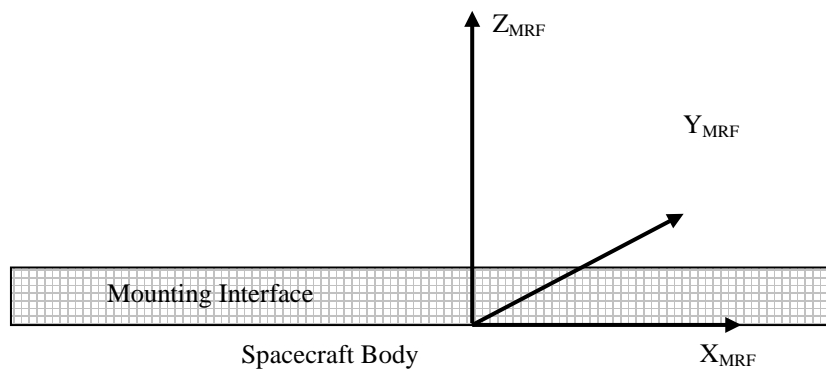


Figure 3-5: Mechanical reference frame

3.2.3.5 stellar reference frame (SRF)

reference frame for each star where the origin of any SRF is defined to be coincident with the Boresight Reference Frame (BRF) origin

NOTE 1 The Z-axis of any SRF is defined to be the direction from the SRF origin to the true position of the selected star Figure 3-6 [schematically illustrates the definition of the SRF](#). Figure 3-7 gives a schematic representation of the reference frames.

NOTE 2 The X- and Y- axes of the SRF are obtained under the assumption that the BRF can be brought into coincidence with the SRF by two rotations, the first around the BRF X-axis and the second around the new BRF Y-axis (which is coincident with the SRF Y-axis).

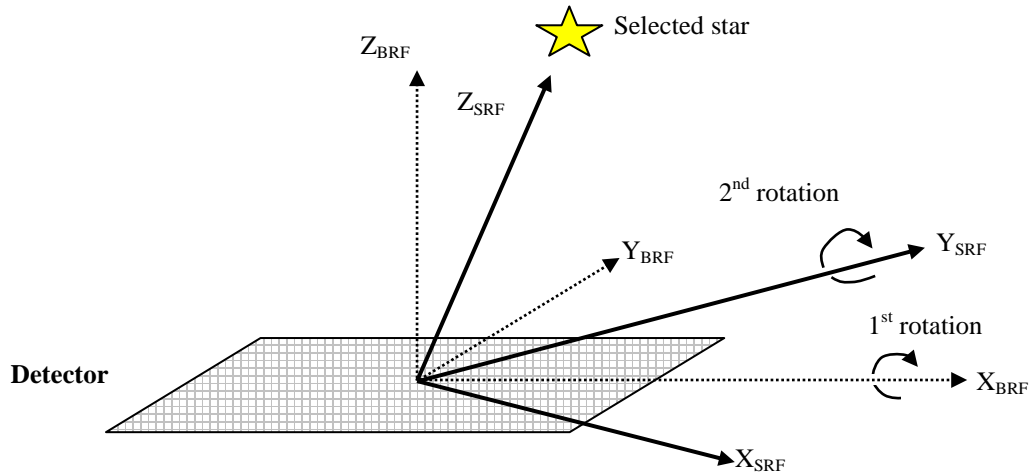


Figure 3-6: **Stellar reference frame**

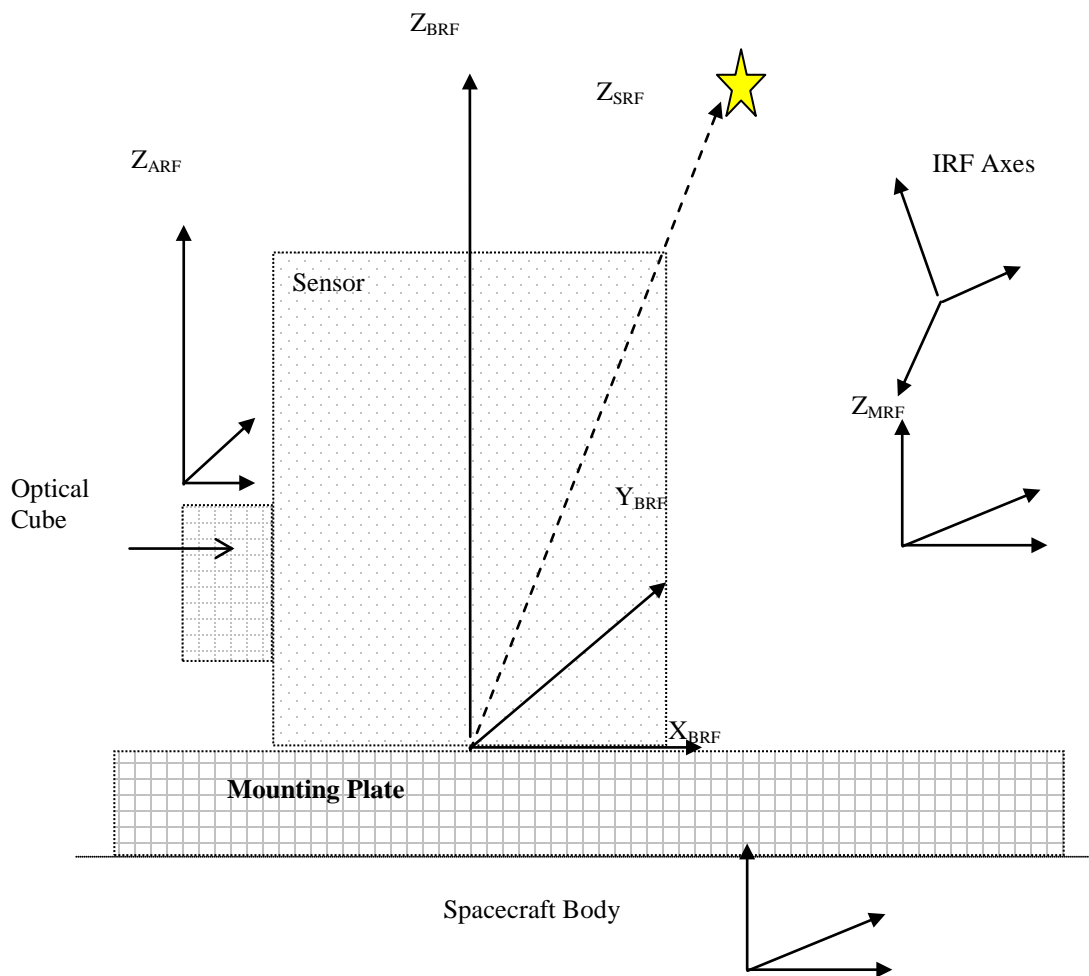


Figure 3-7: **Schematic illustration of reference frames**

3.2.4 Definitions related to time and frequency

3.2.4.1 integration time

exposure time over which photons were collected in the detector array prior to readout and processing to generate star positions or attitude

NOTE 1 Integration time can be fixed, manually adjustable or autonomously set.

NOTE 2 Figure 3-8 illustrates schematically the various times defined together with their inter-relationship. The figure includes data being output from two Optical Heads, each of which is separately processed prior to generation of the sensor output. Note that for a Fused Multiple Optical Head sensor; conceptually it is assumed that the filtered output is achieved via sequential processing of data from a single head at a time as the data is received. Hence, with this understanding, the figure and the associated time definitions also apply to this sensor configuration.

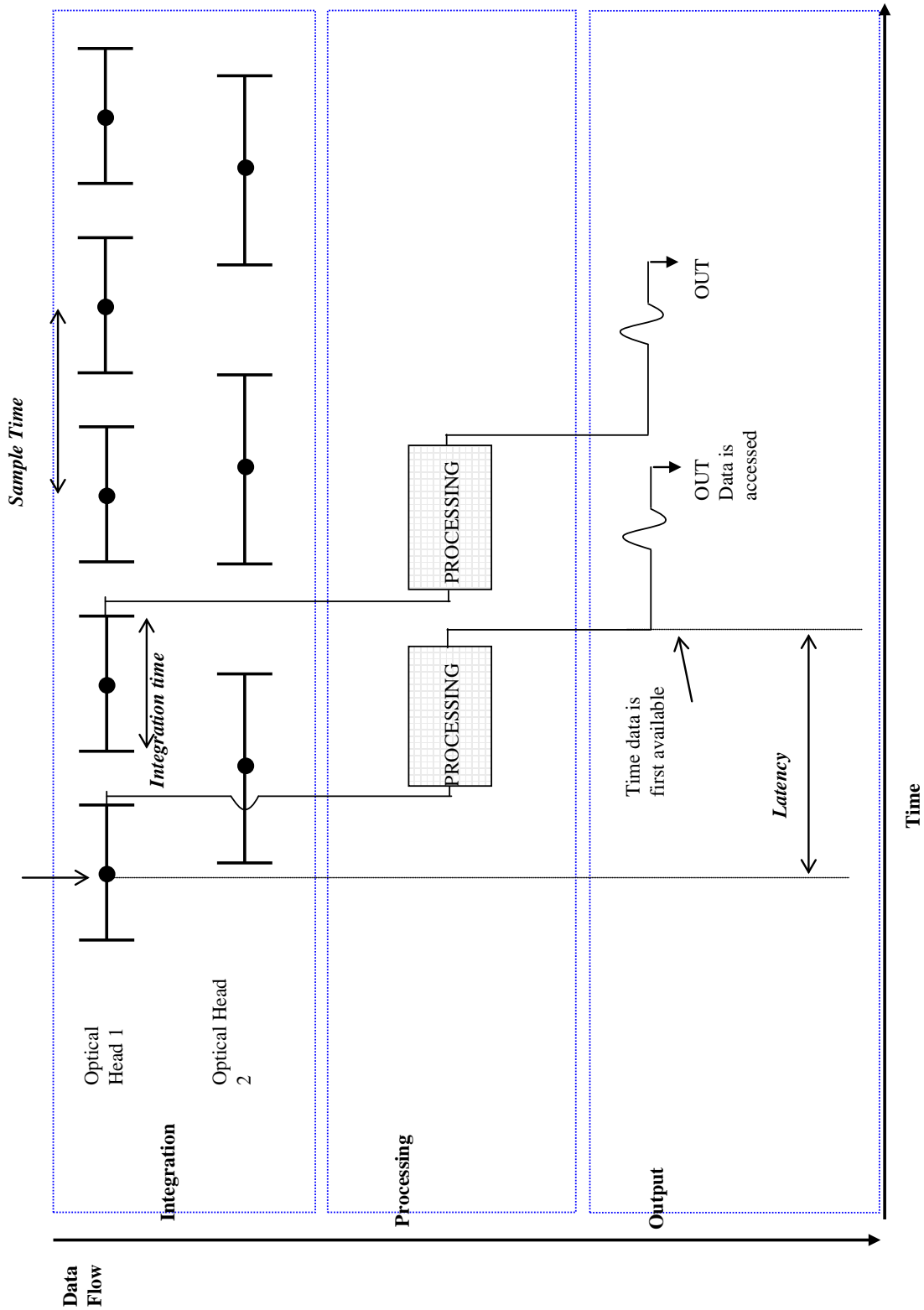


Figure 3-8: Schematic timing diagram

3.2.4.2 measurement date

date of the provided measurement

NOTE 1 In case of on board filtering the measurement date can deviate from individual measurement dates.

NOTE 2 Usually the mid-point of the integration time is considered as measurement date for CCD technology.

3.2.4.3 output bandwidth

maximum frequency contained within the sensor outputs

NOTE 1 The bandwidth of the sensor is limited in general by several factors, including:

- integration time;
- sampling frequency;
- attitude processing rate;
- onboard filtering of data (in particular for multiple head units).

NOTE 2 The output bandwidth corresponds to the bandwidth of the sensor seen as a low-pass filter. *In general, the bandwidth is the lowest of the cut-off frequencies implied by the factors listed in NOTE 1.*

3.2.5 Field of view

3.2.5.1 half-rectangular field of view

angular region around the Boresight Reference Frame (BRF) frame Z-axis, specified by the angular excursions around the BRF X- and Y-axes between the BRF Z-axis and the appropriate rectangle edge, within which a star produces an image on the Detector array that is then used by the star sensor

NOTE 1 This Field of View is determined by the *optical system* and Detector design. This is schematically illustrated in Figure 3-9.

NOTE 2 In the corners, the extent of the FOV for this definition exceeds the quoted value (see Figure 3-9).

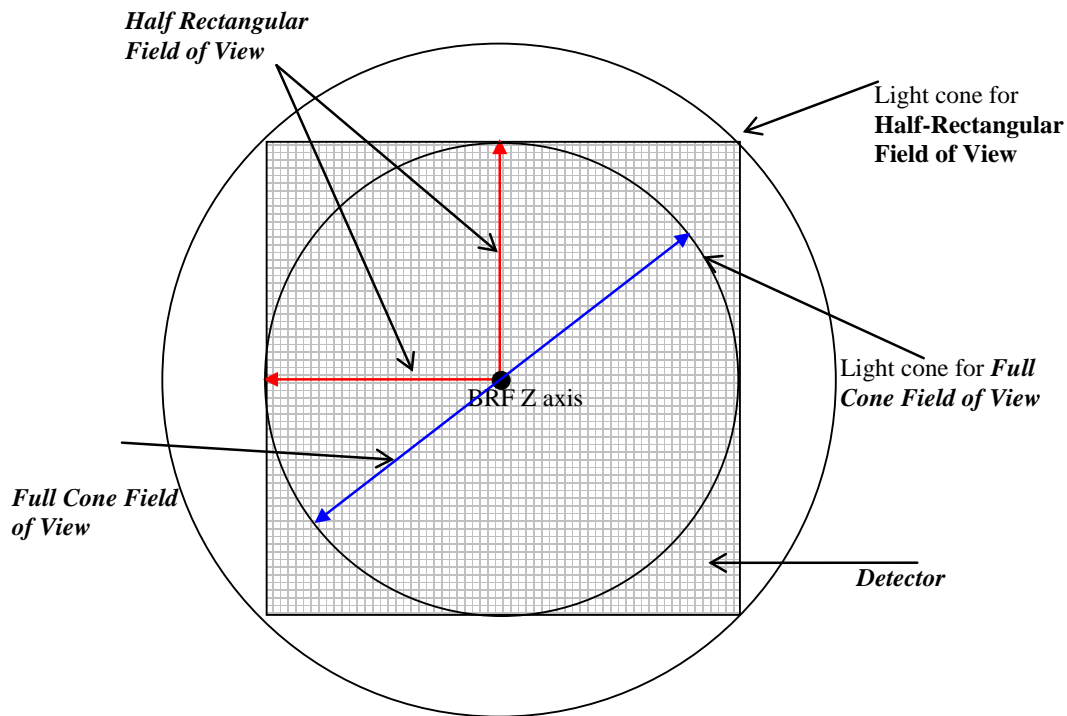


Figure 3-9: Field of View

3.2.5.2 full cone field of view

angular region around the Boresight Reference Frame (BRF) frame Z-axis, specified as a full cone angle, within which a star produces an image on the Detector array that is then used by the star sensor

NOTE This Field of View is determined by the [optical system](#) and Detector design. This is schematically illustrated in Figure 3-9.

3.2.5.3 pixel field of view

angle subtended by a single Detector element

NOTE Pixel Field of View replaces (and is identical to) the commonly used term Instantaneous Field of View.

3.2.6 Angles of celestial bodies

3.2.6.1 aspect angle

half-cone angle between the Boresight Reference Frame (BRF) Z-axis and the nearest limb of a celestial body

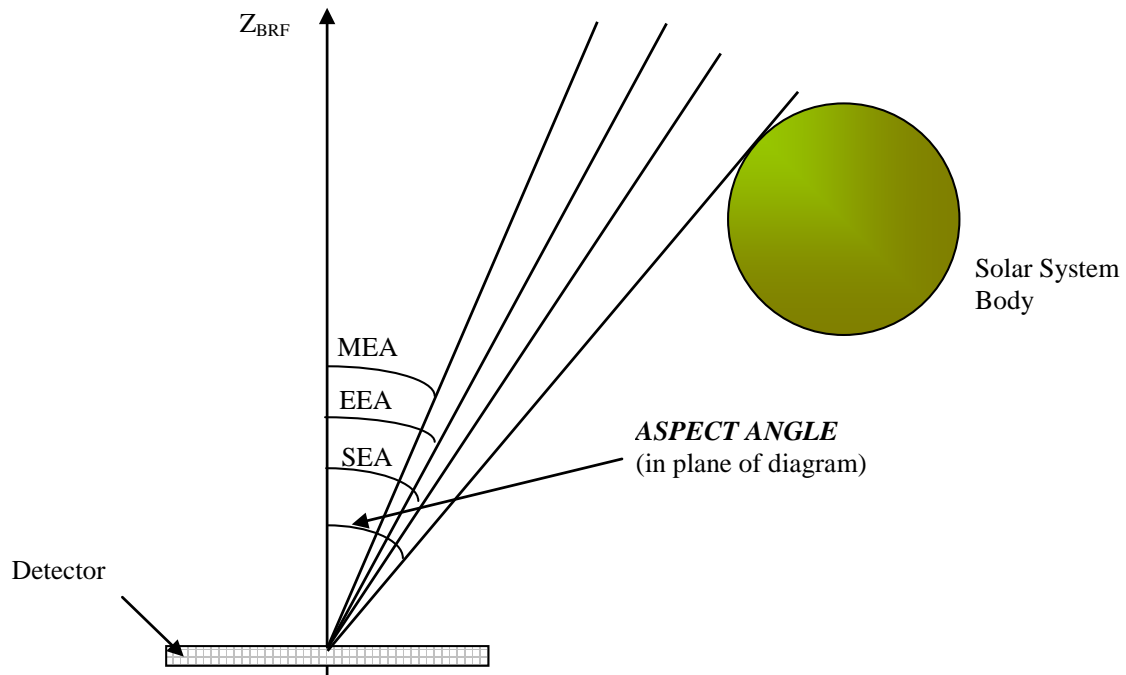


Figure 3-10: Aspect angle to planetary body or sun

3.2.6.2 exclusion angle (EA)

lowest aspect angle of a body at which quoted full performance is achieved

NOTE 1 The following particular exclusion angles can be considered:

- The Earth exclusion angle (EEA), defined as the lowest aspect angle of fully illuminated Earth (including the Earth atmosphere) at which quoted full performance is achieved, as shown schematically in Figure 3-10.
- The Sun Exclusion Angle (SEA), defined as the lowest Aspect Angle of the Sun at which quoted full performance is achieved, as shown schematically in Figure 3-10.
- The Moon Exclusion Angle (MEA) is defined as the lowest Aspect Angle of the Full Moon at which quoted full performance is achieved, as shown schematically in Figure 3-10.

NOTE 2 The value of any EA depends on the distance to the object.

3.2.7 Most common terms

3.2.7.1 correct attitude

attitude for which the quaternion absolute measurement error is lower than a given threshold

3.2.7.2 false attitude

attitude which is an [incorrect](#) attitude

3.2.7.3 false star

signal on the detector not arising from a stellar source but otherwise indistinguishable from a star image

NOTE This definition explicitly excludes effects from the Moon, low incidence angle proton effects etc., which can generally be distinguished as non-stellar in origin by geometry.

3.2.7.4 image output time

time required to output the detector image

3.2.7.5 statistical ensemble

set of [not actually built](#) sensors on which the performances are assessed by use of statistical tools on a set of observations and observation conditions

NOTE 1 The statistical ensemble is defined on a case-by-case basis, depending on the performances to be assessed.

NOTE 2 See 5.1 and Annex E for further details.

3.2.7.6 maintenance level of attitude tracking

total time within a longer defined interval that attitude tracking is maintained with a probability of 100 % for any initial pointing within the celestial sphere

NOTE This parameter can also be specified as Mean Time between loss of tracking or probability to loose tracking per time unit.

3.2.7.7 multiple star tracking maintenance level

total time within a longer defined interval that at least 'n' star tracks are maintained with a probability of 100 %

NOTE 1 This covers the case where the stars in the FOV are changing, such that the star tracks maintained evolve with time.

NOTE 2 [During this time interval no attitude acquisition is performed.](#)

3.2.7.8 night sky test

test performed during night time using the sky as physical stimulus for the star sensor.

NOTE The effect of [atmospheric extinction](#) is generally taken into account and reduced by appropriate choice of the location for test.

3.2.7.9 probability of correct attitude determination

probability that a correct attitude solution is obtained and is flagged as valid, within a defined time from the start of attitude determination with the sensor switched on and at the operating temperature

NOTE 1 Time periods for other conditions, like recovery after the Sun entering the FOV or a cold start, can be defined as the time needed to reach the start time of the attitude determination. The total time needed is then the sum of the time needed to reach the start time of the attitude determination and the time period related to this metric.

NOTE 2 Attitude solution flagged as valid means that the obtained attitude is considered by star sensor suitable for use by the AOCS. The validity is independent of accuracy.

NOTE 3 Correct attitude solution means that stars used to derive the quaternion have been correctly identified, i.e. error on delivered measurement is below a defined threshold.

3.2.7.10 probability of false attitude determination

probability that not correct attitude solution is obtained, which is flagged as valid, within a defined time from the start of attitude determination with the sensor switched on and at the operating temperature

3.2.7.11 probability of invalid attitude solution

probability that an attitude solution, that can be either correct or not correct, is obtained and it is flagged as not valid, within a defined time from the start of attitude determination with the sensor switched on and at the operating temperature

NOTE 1 The value of the Probability of Invalid Attitude Solution is $1 - (\text{Probability of Correct Attitude Determination} + \text{Probability of False Attitude Determination})$.

NOTE 2 Invalid attitude solutions include cases of silence (i.e. no attitude is available from star sensor).

3.2.7.12 sensor settling time

time period from the first quaternion output to the first quaternion at full attitude accuracy, for random initial pointing within a defined region of the celestial sphere

NOTE The time period is specified with a probability of $n\%$ - if not quoted, a value of 99 % is assumed.

3.2.7.13 single star tracking maintenance probability

probability to be maintained by an existing star track over a defined time period while the tracked star is in the FOV

3.2.7.14 star image

pattern of light falling on the detector from a stellar source

3.2.7.15 star magnitude

magnitude of the stellar image as seen by the sensor

NOTE Star magnitude takes into account spectral considerations. This is also referred to as instrumental magnitude.

3.2.7.16 validity

characteristics of an output of the star sensor being accurate enough for the purpose it is intended for

NOTE E.g. use by the AOCS.

3.2.8 Error sources

3.2.8.1 aberration of light

Error on the position of a measured star due to the time of propagation of light, and the linear motion of the STR in an inertial coordinate system

NOTE 1 The Newtonian first order expression of the rotation error for one star direction is:

$$\vec{\varepsilon} = \frac{V}{c} \sin(\theta) \vec{u}$$

where:

V is the magnitude of the absolute linear velocity \vec{V} of the spacecraft w.r.t. to an inertial frame

c is the light velocity (299 792 458 m/s)

θ is the angle between the \vec{V} vector and the star direction \vec{n}

$$\vec{u} = \frac{\vec{V} \wedge \vec{n}}{\|\vec{V} \wedge \vec{n}\|}$$

NOTE 2 For a satellite on an orbit around the Earth, the absolute velocity is the vector sum of the relative velocity of the spacecraft w.r.t the Earth and of the velocity of the Earth w.r.t the Sun.

NOTE 3 For an Earth orbit, the magnitude of this effect is around 25 arcsec (max). For an interplanetary spacecraft the absolute velocity is simply the absolute velocity w.r.t. the sun.

NOTE 4 The detailed contributors to the relativistic error are given in Annex G.

3.2.8.2 bias

error on the knowledge of the orientation of the BRF including [the initial alignment measurement error and the alignment stability error](#)

NOTE 1 The initial alignment measurement error is between the Alignment Reference Frame (ARF) and the sensor Boresight Reference Frame (BRF) as measured during on ground calibration.

NOTE 2 The Alignment Stability Error (Calibration to Flight) is the change in the transformation between the sensor Mechanical Reference Frame (MRF) and the sensor Boresight Reference Frame (BRF) between the time of calibration and the start of the in-flight mission.

NOTE 3 The bias can be for the BRF Z-axis directional or the rotational errors around the BRF X, Y- axes.

NOTE 4 For definition of directional and rotational errors see B.5.2.

NOTE 5 Due to its nature, the bias metric value is the same whatever the observation area is.

NOTE 6 The detailed contributors to the bias are given in [clause 5.5](#).

3.2.8.3 FOV spatial error

error on the measured attitude quaternion due to the individual spatial errors on the stars

NOTE 1 This error has a spatial periodicity, whose amplitude is defined by the supplier. It ranges from a few pixels up to the full camera FOV.

NOTE 2 FOV spatial errors are mainly due to optical distortion. These errors can be converted to time domain using sensor angular rate. Then, from temporal frequency point of view, they range from bias to high frequency errors depending on the motion of stars on the detector. They lead to bias error in the case of inertial pointing, while they contribute to random noise for high angular rate missions.

NOTE 3 The detailed contributors to the FOV spatial error are given in [clause 5.5](#).

3.2.8.4 pixel spatial error

Measurement errors of star positions due to detector spatial non uniformities and star centroid computation

NOTE 1 Because of their 'spatial' nature – these errors vary with the position of stars on the detector – they are well captured by metrics working in the angular domain. The pixel spatial errors are then well defined as the errors on the measured attitude

(respectively the measured star positions) due to star measurement errors with spatial period of TBD angular value. Several classes of spatial periods can be considered.

NOTE 2 These errors can be converted to time domain using sensor angular rate. Then, from temporal frequency point of view, they range from bias to high frequency errors depending on the motion of stars on the detector. They lead to bias error in the case of inertial pointing, while they contribute to random noise for high angular rate missions.

NOTE 3 The detailed contributors to the pixel spatial error are given in [clause 5.5](#).

NOTE 4 [Spatial non uniformities include PRNU, DSNU, dark current spikes and FPN.](#)

NOTE 5 [Inter-pixel crosstalk.](#)

NOTE 6 [Star centroid computation is also called interpolation error.](#)

3.2.8.5 temporal noise

Temporal fluctuation on the measured quaternion due to time variation error sources

NOTE 1 Temporal noise is a white noise.

NOTE 2 The detailed contributors to the temporal noise error are given in [clause 5.5](#).

3.2.8.6 thermo elastic error

deviation of BRF versus MRF for a given temperature variation of the mechanical interface of the optical head of the sensor and thermal power exchange with space

NOTE The detailed contributors to the thermo elastic error are given in [clause 5.5](#).

3.2.9 Star sensor configurations

3.2.9.1 centralized software configuration

[one or more optical heads directly connected to the On-board Computer](#)

NOTE [The STR processing software is located in the On-Board Computer.](#)

3.2.9.2 fused multiple optical head configuration

more than one Optical Head, each with a Baffle, and a single Electronic Processing Unit producing a single set of outputs that uses data from all Optical Heads

3.2.9.3 independent multiple optical head configuration

more than one optical head, each with a baffle, and a single electronic processing unit producing independent outputs for each optical head

3.2.9.4 integrated single optical head configuration

single optical head plus baffle and a single electronic processing unit contained within the same mechanical structure

3.2.9.5 separated single optical head configuration

single optical head plus baffle and a single electronic processing unit which are not collocated within the same mechanical structure

3.3 Abbreviated terms

For the purpose of this Standard, the abbreviated terms from ECSS-S-ST-00-01, [ECSS-E-ST-60-10](#), [ECSS-E-ST-60-30](#) and the following apply:

Abbreviation	Meaning
APS	active pixel sensor
ARF	alignment reference frame
AST	autonomous star tracker
BRF	boresight reference frame
BOL	beginning-of-life
CCD	charge coupled device
CTE	charge transfer efficiency
DSNU	dark signal non-uniformity
EEA	Earth exclusion angle
EOL	end-of-life
FMM	functional mathematical model
FOV	field of view
FPN	fix pattern noise
IRF	inertial reference frame
LOS	line of sight
MEA	Moon exclusion angle
MRF	mechanical reference frame
PRNU	photo response non-uniformity
RHS	right handed system
SEA	Sun exclusion angle
SEU	singe event upset
SET	single event transient
SRF	stellar reference frame
STC	star camera
STM	star mapper
STR	star tracker
STS	star scanner
TEC	thermos-electric cooler
TDI	time delay integration

3.4 Nomenclature

The following nomenclature applies throughout this document:

- a. The word “shall” is used in this Standard to express requirements. All the requirements are expressed with the word “shall”.
- b. The word “should” is used in this Standard to express recommendations. All the recommendations are expressed with the word “should”.

NOTE It is expected that, during tailoring, recommendations in this document are either converted into requirements or tailored out.

- c. The words “may” and “need not” are used in this Standard to express positive and negative permissions, respectively. All the positive permissions are expressed with the word “may”. All the negative permissions are expressed with the words “need not”.
- d. The word “can” is used in this Standard to express capabilities or possibilities, and therefore, if not accompanied by one of the previous words, it implies descriptive text.

NOTE In ECSS “may” and “can” have completely different meanings: “may” is normative (permission), and “can” is descriptive.

- e. The present and past tenses are used in this Standard to express statements of fact, and therefore they imply descriptive text.

4

Functional requirements

4.1 Star sensor capabilities

4.1.1 Overview

Clause 4.1 describes the different main capabilities of star sensors. These capabilities are defined with respect to a generalized description of the reference frames (either sensor-referenced or inertially referenced in clause 3). This set of capabilities is then later used to describe the specific types of star sensor and their performances.

In order to describe the star sensor capabilities, the following generalized sensor model is used:

A star sensor comprises an imaging function, a detecting function and a data processing function. The imaging function collects photons from objects in the field of view of the sensor and focuses them on a detecting element. This element converts the photons into an electrical signal that is then subject to some processing to produce the sensor output.

A schematic of this sensor model is presented in Figure 4-1.

For each capability the nominal outputs and additional outputs are defined. These functional data should be identified in the telemetry list coming from the star sensor.

The outputs as defined in this document are purely related to the performance of the sensor, and represent the minimum information to be provided by the sensor to possess the capability. Other aspects, such as sensor housekeeping data and data structures, are outside the scope of this Standard.

NOTE 1 The same capabilities can be defined for Star Sensors employed on spinning spacecraft (Star Scanner) where star images are acquired at angular rate up to tens of deg/s driving the detector with a dedicated technique. For Star Sensor based on CCD detector, an example of this technique is the Time Delay Integration (TDI). It is outside the scope of this specification to give detailed capability definitions for this kind of sensor.

NOTE 2 Optional features are included in Annex C.

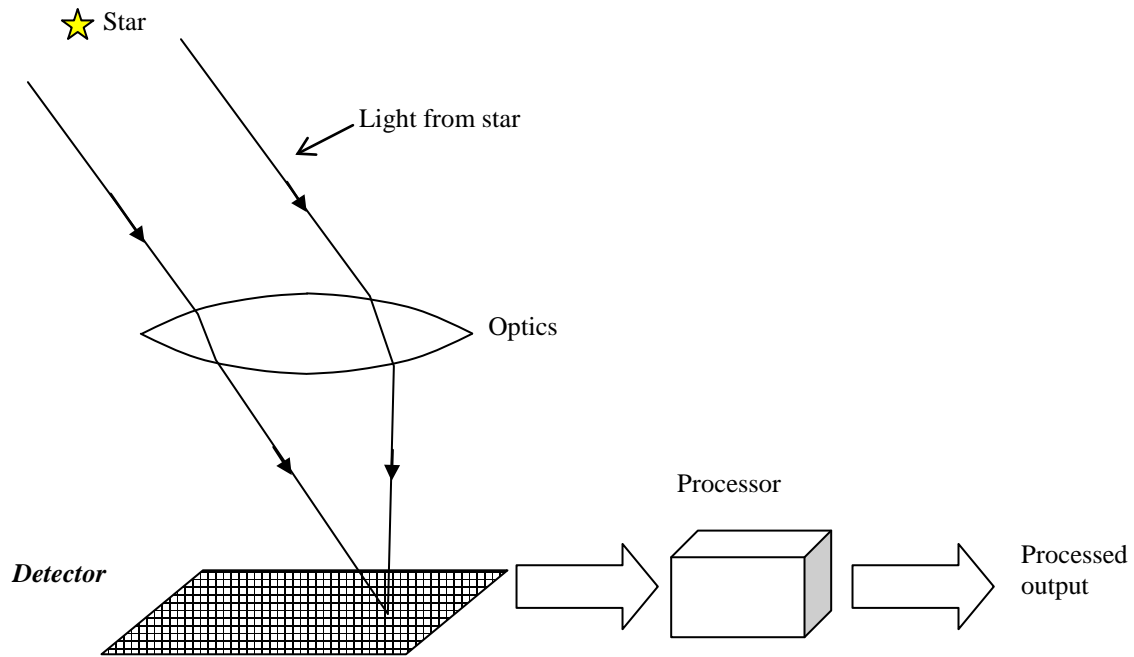


Figure 4-1: Schematic generalized Star Sensor model

4.1.2 Cartography

4.1.2.1 Inputs

ECSS-E-ST-60-20_0920001

- a. The acquisition command shall be supplied as minimum set of inputs.

4.1.2.2 Outputs

ECSS-E-ST-60-20_0920002

- a. A sensor with cartography capability shall have the following minimum outputs:

1. star position,
2. measurement date.

ECSS-E-ST-60-20_0920003

- b. When the Star Image is measured in a Detector-fixed frame which is not the same as the Boresight Reference Frame (BRF), the output shall be converted into the Boresight Reference Frame (BRF).

NOTE The output parameterization is the Star Image position in the Boresight Reference Frame (BRF), given by the two measures of the angular rotations which define the transformation from the BRF to the star Stellar Reference Frame (SRF).

ECSS-E-ST-60-20_0920004

- c. The date of measurement shall be expressed as a (scalar) number indicating the delay relative to a known external time reference agreed with the customer.

4.1.3 Star tracking

4.1.3.1 Inputs

ECSS-E-ST-60-20_0920005

- a. The minimum set of inputs to be supplied in order to initialize the Star Tracking shall be:
1. the initial star position;
 2. the angular rate;
 3. validity date.

ECSS-E-ST-60-20_0920006

- b. For aided tracking, data specified in 4.1.3.1a shall be supplied regularly by the spacecraft, at an update rate and accuracy agreed by the customer.

ECSS-E-ST-60-20_0920007

- c. The unit of all inputs shall be indicated.

4.1.3.2 Outputs

ECSS-E-ST-60-20_0920008

- a. A sensor with the star tracking capability shall have the following minimum outputs:
1. the position of each Star Image with respect to a sensor-defined reference frame;
 2. focal length if star position on the detector chip is output in units of length;
 3. the measurement date.

NOTE 1 The initial selection of the star images to be tracked by the sensor is not included within this capability and sometimes cannot be done without assistance external to the sensor.

NOTE 2 The output parameterization is the Star Image position in the Boresight Reference Frame (BRF), given by the two measures of the angular rotations $s_{MEAS} = [s_{X,MEAS}, s_{Y,MEAS}]$ which define the transformation from the BRF to the star Stellar Reference Frame (SRF).

NOTE 3 This capability does not imply to autonomously identify the star images as images to be tracked or explicitly identified by the unit. However, it does include the ability to maintain the identification of each star image and to correctly update the co-ordinates of each image as it moves across the detector due to the angular rate of the sensor.

4.1.4 Autonomous star tracking

4.1.4.1 Inputs

ECSS-E-ST-60-20_0920009

- a. The minimum set of inputs to be supplied in order to initialize the Autonomous Star Tracking shall be:
1. the angular rate;
 2. the validity date.

ECSS-E-ST-60-20_0920010

- b. For aided tracking, data specified in 4.1.4.1a shall be supplied regularly by the spacecraft, at an update rate and accuracy agreed by the customer.

ECSS-E-ST-60-20_0920011

- c. The unit of all inputs shall be indicated.

4.1.4.2 Outputs

ECSS-E-ST-60-20_0920012

- a. A sensor with the autonomous star tracking capability shall have the minimum outputs:
1. the position of each star image with respect to a sensor-defined reference frame;
 2. the Measurement date.

NOTE This capability does not imply the stars to be explicitly identified by the unit. However, it does include the ability to maintain the identification of each star image once selected, to correctly update the co-ordinates of each image as it moves across the detector, and autonomously manage the set of star images being tracked.

4.1.5 Autonomous attitude determination

4.1.5.1 Inputs

ECSS-E-ST-60-20_0920013

- a. The acquisition command shall be supplied as a minimum set of inputs.

NOTE When a priori initial attitude information for example an initial quaternion or a restriction within the celestial sphere, is supplied by the ground the capability is referred as Assisted Attitude determination.

- b. The set of core commands defined in Annex I should be used.

4.1.5.2 Outputs

ECSS-E-ST-60-20_0920014

- a. A sensor with autonomous attitude determination shall have the minimum outputs:

1. the relative orientation of the defined sensor reference frame with respect to the defined inertial reference frame;
2. the Measurement date;
3. a validity index or flag estimating the validity of the determined attitude.

NOTE The relative orientation is usually expressed in the form of a normalized attitude quaternion.

- b. The set of core telemetries defined in Annex I should be used.

4.1.6 Autonomous attitude tracking

4.1.6.1 Inputs

ECSS-E-ST-60-20_0920015

- a. The minimum set of inputs to be supplied in order to initialize the Autonomous Attitude Tracking shall be:

1. the attitude quaternion;
2. the 3-dimension angular rate vector giving the angular rate of the sensor BRF with respect to the IRF;
3. the validity date for both supplied attitude and angular rate.

NOTE The 3-dimension angular rate vector is expressed in the sensor BRF.

ECSS-E-ST-60-20_0920016

- b. For aided tracking, data specified in 4.1.6.1a shall be supplied regularly by the spacecraft, at an update rate and accuracy agreed by the customer.

ECSS-E-ST-60-20_0920017

- c. Except for attitude quaternion, the unit of all inputs shall be indicated.

ECSS-E-ST-60-20_0920018

- d. The supplier shall document whether the star sensor initialization uses either:
 - 1. Internal initialization, or
 - 2. Direct initialization.

NOTE 1 For internal initialization, the information to initialize the sensor is provided by the attitude determination function of the star sensor.

NOTE 2 For direct initialization, the information to initialize the sensor is supplied by an external source e.g. AOCS.

- e. The set of core commands defined in Annex I should be used.

4.1.6.2 Outputs

ECSS-E-ST-60-20_0920019

- a. A sensor with autonomous attitude tracking capability shall have the following minimum outputs:
 - 1. the orientation of the sensor defined reference frame with respect to the inertially defined reference frame (nominally in the form of an attitude quaternion);
 - 2. the Measurement date;
 - 3. a validity index or flag, estimating the validity of the determined attitude;
 - 4. measurement of Star Magnitude for each tracked Star Image.
- b. The set of core telemetries defined in Annex I should be used.

4.1.7 Angular rate measurement

ECSS-E-ST-60-20_0920020

- a. A sensor with angular rate measurement capability shall have the following minimum outputs:
 - 1. the instantaneous angular rates around the Boresight Reference Frame (BRF) axes relative to inertial space;
 - 2. the Measurement date.

ECSS-E-ST-60-20_0920021

- b. The date of measurement shall be expressed as a (scalar) number indicating the delay) relative to a known external time reference agreed with the customer.

NOTE The intended use of this capability is either when the attitude cannot be determined or to provide an angular rate.

- c. The set of core commands and telemetries defined in Annex I should be used.

4.1.8 (Partial) image download

4.1.8.1 Image download

ECSS-E-ST-60-20_0920022

- a. A sensor with the (partial) image download capability shall have the following minimum outputs:
1. the signal value for each relevant detector element;
 2. the Measurement date.
 3. the integration time (optional).

ECSS-E-ST-60-20_0920023

- b. Any use of image compression (e.g. for transmission) shall be documented.

NOTE 1 The definition of the capability is intended to exclude 'lossy' image compression, though such compression can be a useful option under certain circumstances.

NOTE 2 Image compression is used for example for transmission.

4.1.8.2 Image Output Time

ECSS-E-ST-60-20_0920024

- a. The supplier shall specify the number of bits per pixel used to encode the detector image.

ECSS-E-ST-60-20_0920025

- b. The image output time shall be verified by test using the hardware agreed between the customer and supplier.

NOTE 1 The hardware used to perform the test is the hardware used to download the image from the star sensor.

NOTE 2 For example:

- “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.”
- “The Star Sensor shall be capable of performing a partial Image Download at 12-bit resolution of a $n \times n$ section of the Field of View. The image output time shall be less than 10 seconds.”

4.1.9 Sun survivability

ECSS-E-ST-60-20_0920026

- a. A sensor with the sun survivability capability shall withstand direct sun illumination along the bore sight axis, for at least a given period of time agreed with the customer, without subsequent permanent damage.

ECSS-E-ST-60-20_0920027

- b. A sensor with the sun survivability capability shall recover its full quoted performances after the sun aspect angle has become greater than the sun exclusion angle.

4.2 Types of star sensors

4.2.1 Overview

[Clause 4.2](#) specifies the nomenclature used to describe the different types of star sensors. Their classification is based on the minimum capabilities to be met by each type.

The term star sensor is used to refer generically to any sensor using star measurements to drive its output. It does not imply any particular capabilities.

NOTE The term Star Scanner is used to refer to a Star Sensor employed on spinning spacecraft. This kind of sensor performs star measurements at high angular rate (tens of deg/s). Formal capability definition of the Star Scanner, together with defined performance metrics are outside the scope of this specification.

4.2.2 Star camera

ECSS-E-ST-60-20_0920028

- a. A star camera shall include cartography as a minimum capability.

4.2.3 Star tracker

ECSS-E-ST-60-20_0920029

- a. A star tracker shall include the following minimum capabilities:
 - 1. cartography;
 - 2. star tracking.

NOTE If the autonomous star tracking capability is present, the cartography capability is internal to the unit when initializing the tracked stars and hence transparent to the ground.

4.2.4 Autonomous star tracker

ECSS-E-ST-60-20_0920030

- a. An autonomous star tracker shall include the following minimum capabilities:
 - 1. autonomous attitude determination ('lost in space' solution);
 - 2. autonomous attitude tracking (with internal initialization).

ECSS-E-ST-60-20_0920031

- b. The supplier shall document whether the autonomous attitude determination capability is repetitively used to achieve the autonomous attitude tracking.

4.3 Reference frames

4.3.1 Overview

The standard reference frames are defined in 3.2.3.

Other intermediate reference frames are defined by the manufacturers in order to define specific error contributions, but are not defined here, as they are not used in the formulation of the performance metrics. See also Annex F.

4.3.2 Provisions

ECSS-E-ST-60-20_0920032

- a. Any use of an IRF shall be accompanied by the definition of the IRF frame.

ECSS-E-ST-60-20_0920033

- b. Any use of an attitude quaternion shall be accompanied by the definition of the attitude quaternion.

4.4 On-board star catalogue

ECSS-E-ST-60-20_0920034

- a. The supplier shall state the process used to populate the on-board star catalogue and to validate it.

ECSS-E-ST-60-20_0920035

- b. The process stated in 4.4a shall be detailed to a level agreed between the customer and the supplier.

ECSS-E-ST-60-20_0920036

- c. The supplier and customer shall agree on the epoch at which the on-board star catalogue is valid.

NOTE In this context, 'valid' means that the accuracy of the on-board catalogue is best (e.g. the effect of proper motion and parallax is minimized).

ECSS-E-ST-60-20_0920037

- d. The supplier shall state the epoch range over which performances are met with the on-board star catalogue.

ECSS-E-ST-60-20_0920038

- e. The supplier shall deliver the on-board star catalogue, including the spectral responses of the optical chain and detector.

ECSS-E-ST-60-20_0920039

- f. If the star sensor has the capability of autonomous attitude determination, the supplier shall deliver the on-board star pattern catalogue.

ECSS-E-ST-60-20_0920040

- g. The maintenance process of the on-board star catalogue shall be agreed between the customer and the supplier.

NOTE 1 The maintenance process includes the correction of parallax and the correction of the star proper motions in the on-board star catalogue.

NOTE 2 The maintenance process includes the correction of the on-board catalogue errors identified in flight (e.g. magnitude, coordinates).

ECSS-E-ST-60-20_0920041

- h. The supplier shall state any operational limitations in the unit performance caused by the on-board catalogue.

NOTE For example autonomous attitude determination not possible for some regions in the sky.

- i. Limitations as per requirement 4.4h shall be agreed upon between the supplier and the customer.

Performance requirements

5.1 Use of the statistical ensemble

5.1.1 Overview

The star sensor is one element affecting the system level pointing performance and as such is a pointing error source which needs to be properly specified by the customer and precisely verified and characterised by the supplier.

A performance requirement is a specification that the output of the system does not deviate by more than a given amount from the target output. For example, it can be requested that the boresight of a telescope payload does not deviate by more than a given angle from the target direction.

In practice, such requirements are specified in terms of quantified probabilities. Although given in different ways, these all have a common mathematical form:

$$\text{prob}(|X| < X_{\max}) \geq P_C$$

To put it into words, the physical quantity X to be constrained is defined and a maximum value X_{\max} is specified, as well as the probability P_C that the magnitude of X is smaller than X_{\max} .

The quantities to be constrained at system level are specified through appropriate indices (e.g. Absolute Knowledge Error AKE, Relative Knowledge Error RKE) as defined in the Control Performance standard ECSS-E-ST-60-10.

At system level, the pointing error engineering process starts with the unambiguous formulation of pointing error requirements and leads to the evaluation of the system pointing error through the following analysis steps presented in ESSB-HB-E-003:

- Step 1: characterization of individual pointing error sources,
- Step 2: transfer analysis from the point of origin to the point of interest (through coordinate frames, control systems or mechanical structure),
- Step 3: contribution of each error source to pointing error indices,
- Step 4: compilation of pointing error budgets at system level.

Although the analysis steps presented above are performed by the customer (satellite prime contractor), a clear understanding of the mathematical framework of the performance analysis process is necessary from the supplier.

The probability that each quantity lies within the specified range is often called the confidence level.

NOTE 1 A performance confidence level of 95 % is equivalent to a 2 sigma confidence level for a Gaussian distribution.

NOTE 2 A performance confidence level of 99,7 % used is equivalent to a 3 sigma confidence level for a Gaussian distribution.

Performances have a statistical nature, because they vary with time and from one realization of a sensor to another. Only an envelope of the actual performances can be provided. Central to this is the concept of a 'statistical ensemble', made of 'statistical' sensors (i.e. not necessarily built, but representative of manufacturing process variations) and observations (depending on time and measurement conditions).

Three approaches (called statistical interpretations) can be taken to handle the statistical ensemble:

- a. Temporal approach: performances are established with respect to time.
- b. Ensemble approach: performances are established on statistical sensors (i.e. not necessarily built), at the worst case time.
- c. Mixed approach, which combines both the approaches above.

Refer to Annex E for further details.

The conditions elected to populate the statistical ensemble are defined on a case-by-case basis for each performance parameter, as described in the following clauses.

5.1.2 Provisions

ECSS-E-ST-60-20_0920042

- a. The **worst case** performances shall be assessed by using the worst-case sensor of the statistical ensemble.

ECSS-E-ST-60-20_0920043

- b. The statistical ensemble shall be characterized and agreed with the customer.

ECSS-E-ST-60-20_0920044

- c. The performances shall be assessed by using the sensor EOL conditions agreed with the customer.

NOTE 1 The EOL conditions include ageing effects and environmental effects (e.g. radiation dose, UV, ATOX, contaminations and micrometeorites).

NOTE 2 If a calibration is needed at BOL and performance before the calibration is worse than EOL

performance, the BOL conditions can be also specified.

5.2 Verification methods

5.2.1 Overview

Simulations efficiently support the verification of performances. A set of simulations provides an estimate of a performance, obtained by processing the simulation results in a statistical fashion. Because the set of simulations is limited, the performance estimated by simulations has a given accuracy, essentially depending on the number of simulations.

5.2.2 Provisions for single star performances

ECSS-E-ST-60-20_0920045

- a. Software models of single star measurement error shall be validated for single star performance (at zero body rates) against on-ground tests using artificial stellar sources.

NOTE Denoting the confidence level to be verified as P_c , and assuming that the performance confidence level result to be obtained is to an accuracy ΔP with 95 % estimation confidence level, the number of Monte-Carlo runs to be performed is greater than $\frac{4P_c(1-P_c)}{\Delta P^2}$.

5.2.3 Provisions for attitude performances

ECSS-E-ST-60-20_0920046

- a. Software models of attitude error shall be validated against on-ground tests using artificial stellar sources or with on ground tests agreed by the customer.

NOTE 1 Denoting the confidence level to be verified as P_c , and assuming that the confidence result to be obtained is to an accuracy ΔP with 95 % confidence, the number of Monte-Carlo runs to be performed is greater than $\frac{4P_c(1-P_c)}{\Delta P^2}$.

NOTE 2 Refer to Annex E.1 for further details.

5.2.4 Provision for tests

- a. The test method to verify performance specification shall be justified by the supplier.
- b. The validation of test raw data post-processing shall be demonstrated by the supplier.
- c. The adequacy of test equipment accuracy shall be agreed with the customer.
- d. The test success criteria shall be derived from the customer requirements taking into account the test setup error budget.
- e. The test inputs shall be in accordance with the required observability in terms of operational range and in terms of the test resolution.
- f. The validation of the post processing tools shall be performed using a set of reference or simulated data.
- g. The performance requirements verification shall be done with individual tests or by combined tests.

NOTE One test serves the verification of several performance requirements.

- h. The unit calibration shall be performed before and after the whole set of environmental tests.
- i. The stability of the initial and final compensation parameters shall be compliant w.r.t. the performance requirements.
- j. The user shall state if raw or compensated measurements are used.
- k. For star sensor errors the thermal sensitivity shall be verified in the specified temperature range.

NOTE For example unit environmental temperature, unit internal temperatures, at electronics or at sensing level.

- l. The testability limits shall be declared by the supplier and agreed by the customer.

NOTE The verification requirements listed in this clause can be complemented, as needed, with requirements found in ECSS-E-ST-10, ECSS-E-ST-10-02, ECSS-E-ST-10-03 and ECSS-E-ST-60-30.

5.3 <<deleted>>

ECSS-E-ST-60-20_0920047

- a. <<deleted>>

5.4 General performance requirements

ECSS-E-ST-60-20_0920048

- a. The performance conditions of the 'statistical ensemble' shall be used to encompass the following conditions for EOL:
1. worst-case baseplate temperature within specified range;
 2. worst-case radiation flux within specified range;
 3. worst-case stray light from solar, lunar, Earth, planetary or other sources.

NOTE 1 In addition values for BOL can be given.

NOTE 2 Worst-case stray light conditions are with the Sun, Earth and (where appropriate) Moon simultaneously at their exclusion angles together with worst-case conditions for any other light sources.

NOTE 3 Guidelines and clauses for robustness to solar events are proposed in clause 5.13.

ECSS-E-ST-60-20_0920049

- b. The maximum magnitude of body rate shall be used.

NOTE The maximum body rate is the worst case condition for most missions. For specific cases, the worst case can be adapted, e.g. to include jitter.

ECSS-E-ST-60-20_0920050

- c. The supplier shall identify the worst case projection in BRF of the value defined in 5.4b.

NOTE Different angular rates can be specified with associated required performance.

ECSS-E-ST-60-20_0920051

- d. The maximum magnitude of angular acceleration shall be used.

NOTE The maximum angular acceleration is the worst case condition for most missions. For specific cases, the worst case can be adapted, e.g. to include jitter.

ECSS-E-ST-60-20_0920052

- e. The supplier shall identify the worst case projection in BRF of the value de-fined in 5.4d.

NOTE Different angular accelerations can be specified with associated required performance.

ECSS-E-ST-60-20_0920053

- f. For multiple head configuration the worst case conditions of angular rate and stray light of each optical head shall be discussed and agreed between supplier and customer.

ECSS-E-ST-60-20_0920054

- g. Single star position measurement performance within the verification simulations shall be:
 - 1. validated against on-ground test data for fixed pointing conditions, and
 - 2. able to predict metric performance under these conditions with an accuracy of 10 %.

ECSS-E-ST-60-20_0920055

- h. If test data is available for the individual error sources, the simulation shall be validated against this data with an accuracy of 10%.

ECSS-E-ST-60-20_0920056

- i. Detector error sources in the simulation shall also be validated using direct data injection into the electronics and analysis of the test outputs.

ECSS-E-ST-60-20_0920057

- j. The simulation shall allow 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.

ECSS-E-ST-60-20_0920058

- k. EOL simulations used to predict EOL performance shall be verified by test cases verifiable against measurable BOL data.

ECSS-E-ST-60-20_0920059

- l. The impact of individual star errors on the overall rate accuracy shall be provided via simulation.

ECSS-E-ST-60-20_0920060

- m. No aided tracking shall be considered.

5.5 General performance metrics

5.5.1 Overview

Clause 5.5 presents the general performance metrics for the error contributing to the star sensor performances. In Annex H, an example of data sheet built on the performance metrics is given.

5.5.2 Bias

5.5.2.1 General

ECSS-E-ST-60-20_0920061

- a. A confidence level for the bias shall be specified by the customer.

ECSS-E-ST-60-20_0920062

- b. The 'Ensemble' interpretation shall be used.

NOTE The Ensemble interpretation is described in Annex E.2.

ECSS-E-ST-60-20_0920063

- c. The bias performance shall be specified for a defined ambient temperature.

NOTE The initial alignment is an instantaneous measurement error at the time of calibration. For the purposes of error budgeting it can be considered to be an invariant error.

5.5.2.2 Contributing error sources

ECSS-E-ST-60-20_0920064

- a. The following types of error source shall be included:

1. On-ground calibration error between the sensor Alignment Reference Frame (ARF) and the sensor Boresight Reference Frame (BRF).
2. Launch induced misalignments of BRF with respect to MRF.

NOTE 1 This arises typically from accuracy limitations within the measurement apparatus used to perform the calibration.

NOTE 2 Refer to the Annex G for the contributing error sources description.

5.5.2.3 Verification methods

ECSS-E-ST-60-20_0920065

- a. The calibration shall be performed via ground-based test using an optical bench set-up to determine the sensor Alignment Reference Frame (ARF) - sensor Boresight Reference Frame (BRF) alignment.

ECSS-E-ST-60-20_0920066

- b. The bias error shall be validated by analysis, test or simulation, taking into account calibration test bench accuracy.

NOTE 1 Initial alignment verification cannot be done without verification of the measurement accuracy of the set-up used for calibration.

NOTE 2 E.g. "The Star Sensor initial alignment shall have an initial alignment error (X-, Y-axes rotation) of less than 10 arcsec at a quoted ambient temperature (the temperature during alignment)."

5.5.3 Thermo elastic error

5.5.3.1 General

ECSS-E-ST-60-20_0920067

- a. A confidence level for the thermos elastic error shall be specified by the customer.

ECSS-E-ST-60-20_0920068

- b. The 'Ensemble' interpretation shall be used.

NOTE The 'Ensemble' interpretation is described in AnnexE.2

5.5.3.2 Contributing error sources

ECSS-E-ST-60-20_0920069

- a. Error sources that gradually change the alignment of the sensor Mechanical Reference Frame (MRF) and the sensor Boresight Reference Frame (BRF) from the start of the in-flight mission shall be included.

NOTE 1 E.g. "The thermal sensitivity to temperature of line of sight stability shall be less than 1 arcsec/Kelvin."

NOTE 2 Refer to the Annex G for the contributing error sources description.

5.5.3.3 Verification methods

ECSS-E-ST-60-20_0920070

- a. Thermally induced error contributions to the thermo elastic error shall be verified by the use of thermal models supported and validated by ground test results performed under thermal vacuum conditions.

5.5.4 FOV spatial error

5.5.4.1 General

ECSS-E-ST-60-20_0920071

- a. A confidence level for the FOV spatial error shall be specified by the customer.

ECSS-E-ST-60-20_0920072

- b. The 'Ensemble' interpretation shall be used.

NOTE The Ensemble interpretation is described in Annex E.2.

ECSS-E-ST-60-20_0920073

- c. The performance shall be specified under the related performance general conditions.
- d. The error classification of the FOV spatial error shall be discussed and agreed between supplier and customer.

NOTE The temporal behaviour of the FOV spatial error is a function of the star velocity across the STR field of view. FOV errors lead to bias error in the case of inertial pointing, while they contribute to random noise for angular rate.

5.5.4.2 Contributing error sources

ECSS-E-ST-60-20_0920074

- a. Contributing Error Sources shall include:
1. point spread function variability across the FOV;
 2. residual of calibration of focal length (including its temperature sensibility) and optical distortions (including chromatism);
 3. residual of aberration of light in case where it is corrected at quaternion level and not at star level;
 4. CCD, CTE effect (including its degradations due to radiations);
 5. catalogue error (including star proper motion and parallax).

NOTE Refer to the Annex G for the contributing error sources description.

5.5.4.3 Verification methods

ECSS-E-ST-60-20_0920075

- a. The measurement of the FOV spatial error shall be performed via ground test for contributing error sources 5.5.4.2a.1 and 5.5.4.2a.2, and by analysis for contributing error sources 5.5.4.2a.3, 5.5.4.2a.4 and 5.5.4.2a.5.

ECSS-E-ST-60-20_0920076

- b. Radiation effects shall be supported by test results.

NOTE E.g. "The Star Sensor shall have a FOV spatial error less than 10 arcsec on X,Y axes and 40 arcsec on Z axis for spatial period smaller than 5 degrees."

5.5.5 Pixel spatial error

5.5.5.1 General

ECSS-E-ST-60-20_0920077

- a. A confidence level for the pixel spatial error shall be specified by the customer.

ECSS-E-ST-60-20_0920078

- b. The 'Ensemble' interpretation shall be used.

NOTE The Ensemble interpretation is described in Annex E.2.

ECSS-E-ST-60-20_0920079

- c. The performance shall be specified under the related performance general conditions.
- d. The error classification of the Pixel spatial error shall be discussed and agreed between supplier and customer.

NOTE The temporal behaviour of the Pixel spatial error is a function of the star velocity across the detector plane (i.e. a function of the AOCS). Pixel spatial errors lead to bias error in the case of inertial pointing, while they contribute to random noise for angular rate.

5.5.5.2 Contributing error sources

ECSS-E-ST-60-20_0920080

- a. Contributing error sources shall consist of at least:
1. detector Photo Response Non Uniformity (PRNU);

2. detector Dark Signal Non Uniformity (DSNU);
3. detector dark current spikes - if relevant according to the detector technology;
4. detector Fixed Pattern Noise (FPN) - if relevant according to the detector technology;
5. star centroid computation error (interpolation error).

NOTE Refer to the Annex G for the contributing error sources description.

ECSS-E-ST-60-20_0920081

- b. All other error sources with relevant spatial behaviour shall be identified by the supplier and used for the assessment of performances.

5.5.5.3 Verification methods

ECSS-E-ST-60-20_0920082

- a. Contributing error sources shall be verified by on ground tests.

ECSS-E-ST-60-20_0920083

- b. Pixel spatial errors shall be verified by analysis and simulations using verified budgets of contributing error sources methods.

NOTE E.g. "The Star Sensor shall have a pixel spatial error of less than 5 arcseconds (resp. 30) around X and Y axes (resp. Z axis) for spatial period of 400 arcsecond, and less than 2 arcseconds (resp 10) around X and Y axes (resp. Z axis) for spatial period of 100 arcsecond."

5.5.6 Temporal noise

5.5.6.1 General

ECSS-E-ST-60-20_0920084

- a. A confidence level for the temporal noise shall be specified by the customer.

ECSS-E-ST-60-20_0920085

- b. The 'temporal' interpretation shall be used.

NOTE The Temporal interpretation is described in Annex E.2.

- c. The performance of the temporal noise shall be specified under the related performance general conditions specified in clause 5.4.

5.5.6.2 Contributing error sources

ECSS-E-ST-60-20_0920086

- a. The Contributing Error Sources shall include:
1. shot noise on star signal;
 2. shot noise on background signal and dark current;
 3. read-out noise ;
 4. quantification noise ;
 5. datation noise.

NOTE 1 Temporal noise depends on exposure time and detector temperatures.

NOTE 2 Noise contributors at star level depend on star magnitude angular rates/acceleration, and optics/detector characteristics (e.g. exposure time, optical contamination, transmission loss, defocus).

NOTE 3 Datation noise is the temporal noise part of the measurement date error described in 5.5.8.

NOTE 4 [Refer to the Annex G for the contributing error sources description.](#)

5.5.6.3 Verification Methods

ECSS-E-ST-60-20_0920087

- a. Temporal noise shall be estimated by simulation.

ECSS-E-ST-60-20_0920088

- b. Error source contributors 5.5.6.2a.1, 5.5.6.2a.2, 5.5.6.2a.3, 5.5.6.2a.4 shall be validated against on ground test data at BOL for finite scenarios.

ECSS-E-ST-60-20_0920089

- c. Error source contributor 5.5.6.2a.5 shall be assessed by analysis.

NOTE 1 Night Sky tests are not used as single verification method due to experimental conditions. Night sky tests can be used to assess temporal noise in addition to other required verification methods (simulations and on-ground tests).

NOTE 2 E.g. "The Star Sensor shall have 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."

5.5.7 Aberration of light

5.5.7.1 General

ECSS-E-ST-60-20_0920090

- a. The supplier shall document what type of relativistic correction is performed.

ECSS-E-ST-60-20_0920091

- b. The supplier shall document the maximum error and minimum frequency of the spacecraft velocity provided to the sensor.

5.5.7.2 Contributing error sources

ECSS-E-ST-60-20_0920092

- a. The contributing Error Sources shall include:
 1. Absolute linear velocity of the spacecraft with respect to the sun.
 2. Accuracy of the velocity information (or propagation) used for correction.

NOTE Refer to the Annex G for the contributing error sources description.

5.5.7.3 Verification methods

ECSS-E-ST-60-20_0920093

- a. The correction software shall be validated, comparing the computed correction term with the analytical expression.

NOTE 1 This error correction is difficult to verify since it is a theoretical term of error.

NOTE 2 E.g. "The relativistic effect has an impact of less than 0,07'' (3σ) at quaternion level. The needed accuracy of the velocity of the spacecraft delivered to the star sensor shall be better than 100 m/s, at a frequency of 0,1 Hz."

5.5.8 Measurement date error

ECSS-E-ST-60-20_0920094

- a. The confidence level for the measurement date error shall be specified by the customer.

ECSS-E-ST-60-20_0920095

- b. The Measurement date Error shall be verified by test.

NOTE E.g. "The Measurement date Error shall be less than 0,1 ms."

5.5.9 Measured output bandwidth

ECSS-E-ST-60-20_0920096

- a. The bandwidth shall be verified by analysis of the Integration Time, output Sampling Time and any on-board data filtering that can be present.

ECSS-E-ST-60-20_0920152

- b. On-ground tests **should** be performed.

NOTE E.g. "The Star Sensor shall have a Measured Output Bandwidth of greater than 10 Hz."

5.6 Cartography

ECSS-E-ST-60-20_0920098

- a. For star position measurements, the performance conditions of the 'statistical ensemble' shall be used to encompass the following conditions for BOL:
1. worst-case star location in FOV;
 2. worst-case Star Magnitude within specified range.

5.7 Star tracking

5.7.1 Additional performance conditions

ECSS-E-ST-60-20_0920099

- a. For star position measurements, the performance conditions of the 'statistical ensemble' shall be used to encompass the following conditions for BOL:
1. worst-case star location in FOV;
 2. worst-case Star Magnitude within specified range.

5.7.2 Single star tracking maintenance probability

ECSS-E-ST-60-20_0920100

- a. The following conditions shall be met:
1. quote the maximum body rate $\omega_{\text{CROSS, MAX}}$ around the sensor Boresight Reference Frame (BRF) X- or Y-axes and $\omega_{\text{Z, MAX}}$ around the BRF Z-axis for which the single star tracking maintenance probability is achieved over the defined time period;
 2. quote the maximum body angular acceleration around the sensor boresight reference frame (BRF) X- or Y- axes and the maximum body angular acceleration around the BRF Z-axis for which the single star tracking maintenance probability is achieved over the defined time period.

NOTE E.g. "The Track Maintenance Probability shall be greater than 99 % over a time period of 1 minute for a tracked Star Image (of magnitude less than tbd mi) remaining within the sensor FOV, for rates around any axis of up to 100 arcsec/s at EOL, with accelerations up to 10 arcsec/s²."

5.8 Autonomous star tracking

5.8.1 Additional performance conditions

ECSS-E-ST-60-20_0920101

- a. For star position measurements, the performance conditions of the 'statistical ensemble' shall be used to encompass the following conditions for BOL:
1. worst-case star location in FOV;
 2. worst-case Star Magnitude within specified range.

ECSS-E-ST-60-20_0920102

- b. The following additional performance metrics shall be established: track maintenance probability, as specified in 5.7.2.

ECSS-E-ST-60-20_0920103

- c. For the statistical ensemble, provisions in 5.2.2 shall be applied.

NOTE The same definition for the 'statistical ensemble' given in 5.1.1 applies.

5.8.2 Multiple star tracking maintenance level

ECSS-E-ST-60-20_0920104

- a. The following conditions shall be met:
1. quote the maximum body rate $\omega_{\text{CROSS, MAX}}$ around the sensor Boresight Reference Frame (BRF) X- or Y-axes and $\omega_{\text{Z, MAX}}$ around the BRF Z-axis for which the multiple star tracking maintenance level is achieved over the defined time period;
 2. quote the maximum body angular acceleration around the sensor boresight reference frame (BRF) X- or Y- axes and the maximum body angular acceleration around the BRF Z-axis for which the single star tracking maintenance probability is achieved over the defined time period;
 3. The general provisions in 5.2.2 are applied.

NOTE E.g. "The Maintenance Level of Star Tracks shall be at least 5 tracks for a total time of 995 s within any 1000 s period, for rates around any axis of up to 100 arcsec/s at EOL, and for accelerations up to 10 arcsec/s²."

5.9 Autonomous attitude determination

5.9.1 General

ECSS-E-ST-60-20_0920105

- a. When Autonomous Attitude Tracking is performed by using repetitive Autonomous Attitude Determination the metrics relative to autonomous attitude tracking specified in 5.10 shall be applied.

NOTE This capability is often referred to as the ability to solve the 'lost in space' problem. The orientation, or attitude, measurement is nominally in the form of a quaternion that parameterizes the transformation between the Inertial reference frame and the sensor-defined reference frame. The determination is nominally performed by comparing star images measured on a detector to known star positions and characteristics stored in a star catalogue within the sensor.

ECSS-E-ST-60-20_0920106

- b. When Autonomous attitude determination is only used for autonomous attitude tracking initialization the general performance metrics shall not be used.

5.9.2 Additional performance conditions

5.9.2.1 Autonomous attitude determination

ECSS-E-ST-60-20_0920107

- a. The Autonomous attitude determination shall be subjected to the following attitude determination probability performance metrics:
1. probability of correct attitude determination;
 2. probability of false attitude determination;
 3. probability of invalid attitude determination.

NOTE The validity flag needs not a performance metric.

5.9.2.2 Lunar and planetary effects on performance

ECSS-E-ST-60-20_0920108

- a. If a statement of operation with the Moon in the FOV is specified, the attitude determination probabilities shall be quoted for the 'Moon in FOV' scenario.

ECSS-E-ST-60-20_0920109

- b. If a statement of operation with planetary objects in the FOV is specified, the attitude determination probabilities shall be quoted for the 'Planet in FOV' scenario.

ECSS-E-ST-60-20_0920110

- c. The attitude determination probabilities specification shall be quoted with the maximum number of False Stars in the FOV for which the specification is satisfied.

5.9.3 Verification methods

ECSS-E-ST-60-20_0920111

- a. The probabilities of attitude determination specification shall be verified by applying the general provisions in 5.2.2 and 5.2.3.

ECSS-E-ST-60-20_0920153

- b. Functional verification may be performed by means of a night sky test.

5.9.4 Attitude determination probability

ECSS-E-ST-60-20_0920113

- a. <<deleted, modified and moved to 5.9.4.1>>

ECSS-E-ST-60-20_0920114

- b. <<deleted, modified and moved to 5.9.4.2>>

ECSS-E-ST-60-20_0920115

- c. <<deleted, modified and moved to 5.9.4.3>>

5.9.4.1 Probability of correct attitude determination

- a. The probability of correct attitude determination shall be estimated considering all possible initial pointing directions within a defined region within the celestial sphere.
- b. The probability of correct attitude determination shall be estimated under the conditions given in 5.4 and 5.9.2.
- c. The probability of correct attitude determination shall be verified using the method specified in 5.9.3.

NOTE E.g. "An example of requirement specification is the following: 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."

5.9.4.2 Probability of false attitude determination

- a. The probability of false attitude determination shall be estimated considering all possible initial pointing directions within a defined region within the celestial sphere.
- b. The probability of false attitude determination shall be estimated under the conditions given in 5.4 and 5.9.2.
- c. The probability of false attitude determination shall be verified using the method specified in 5.9.3.

NOTE E.g. "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."

5.9.4.3 Probability of invalid attitude solution

- a. The probability of invalid attitude solution shall be estimated considering all possible initial pointing directions within a defined region within the celestial sphere.
- b. The probability of invalid attitude determination shall be estimated under the conditions given in given in 5.4 and 5.9.2.

- c. The probability of invalid attitude determination shall be verified using the method specified in 5.9.3.

NOTE E.g. "The probability of invalid attitude solution shall be less than 0,1 % for random initial pointing 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."

5.10 Autonomous attitude tracking

5.10.1 Additional performance conditions

ECSS-E-ST-60-20_0920116

- a. For both BOL and EOL, the performance metrics shall be specified either:
1. From the whole celestial sphere including the vault in the statistics, or
 2. From a set of fixed directions in the celestial sphere.

NOTE The statistical ensemble is then composed of measurements randomly performed on the entire celestial vault.

ECSS-E-ST-60-20_0920117

- b. If the metrics are specified from a set of fixed directions in the celestial sphere when satisfying conditions detailed in 5.10.1a the following shall be met:
1. assess the metrics for each direction, limiting the statistical ensemble to measurements performed in this direction to compute the performance;
 2. Specify all or part of the following:
 - (a) The mean performance among all performances achieved in the directions of the celestial sphere,
 - (b) The value achieved on $n\%$ of the celestial sphere,
 - (c) The value achieved in the worst-case direction of the celestial sphere.

NOTE 1 In point (b), this is the performance achieved for $n\%$ of the pointing directions within the whole celestial vault. If n is not quoted, a value of 99% is assumed.

NOTE 2 In point (c), this direction is related to the worst distribution of stars over the star sensor Field of View, taking into account embedded algorithms and catalogues. The statistical ensemble is then

reduced to measurements performed in this direction.

ECSS-E-ST-60-20_0920154

- c. Performances may also be specified for a restricted area of the celestial sphere agreed with the customer, in which case the performance metrics are then specified in the same way, limiting the statistical ensemble to the specified area.

ECSS-E-ST-60-20_0920119

- d. For Lunar and planetary effects on performance the following conditions shall be met:
 - 1. If a statement of operation with the Moon in the FOV is specified, quote the probability of maintenance of tracking for the 'Moon in FOV' scenario.
 - 2. If a statement of operation with planetary objects in the FOV is specified, quote the probability of maintenance of tracking the 'Planet in FOV' scenario.

ECSS-E-ST-60-20_0920120

- e. For the effect of False Stars the following condition shall be met:
Quote the maintenance level of tracking with the maximum number of False Stars in the FOV for which the specification is applicable.

ECSS-E-ST-60-20_0920121

- f. For the effect of single event upsets (SET's) the following condition shall be met:
Quote the maintenance level of tracking with the maximum number of SET's per second for which the specification is applicable.

5.10.2 Maintenance level of attitude tracking

5.10.2.1 General

ECSS-E-ST-60-20_0920122

- a. The performance shall be specified under the conditions given in 5.10.1 and 5.10.2.2a.

5.10.2.2 Verification methods

ECSS-E-ST-60-20_0920123

- a. The maintenance level of tracking shall be verified by applying the general provisions in 5.2.2.

NOTE E.g. "The maintenance level of tracking shall be more than 995 s within a 1000 s period, for rates around any axis of up to 100 arcsec/s at EOL, and for accelerations up to 10 arcsec/s²."

5.10.3 Sensor settling time

ECSS-E-ST-60-20_0920124

- a. The performance shall be specified under the conditions given in 5.10.1.

ECSS-E-ST-60-20_0920125

- b. For lunar and planetary effects on performance the following conditions shall be met:
1. If a statement of operation with the Moon in the FOV is specified, quote the Sensor Settling Time for the 'Moon in FOV' scenario.
 2. If a statement of operation with planetary objects in the FOV is specified, quote the Sensor Settling Time for the 'Planet in FOV' scenario.

ECSS-E-ST-60-20_0920126

- c. For the effect of False Stars the following condition shall be met:
1. Quote the Sensor Settling Time with the maximum number of False Stars in the FOV for which the specification is applied.
 2. Consider the effect of convergence of internal algorithm.

ECSS-E-ST-60-20_0920127

- d. The Sensor Settling Time shall be verified by applying the general provisions in 5.2.2.

NOTE E.g. "Sensor Settling Time shall be less than 5s for more than 99 % of random initial pointing 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."

5.11 Angular rate measurement

5.11.1 Additional performance conditions

ECSS-E-ST-60-20_0920128

- a. Additional performance conditions, defined in 5.10.1 shall be applied.

ECSS-E-ST-60-20_0920129

- b. Contributing error sources shall be established.

NOTE They are a function of the precise technique used to determine the rate.

5.11.2 Verification methods

ECSS-E-ST-60-20_0920130

- a. Performance at finite rates and accelerations, and for all scenarios under the specified conditions, shall be verified by simulation.

NOTE E.g. The Star Sensor shall have an angular rate measurement around any BRF axis of less than 100 arcsec/s, at rates around any axis of up to 10 deg/s at EOL and for accelerations up to 1 deg/s².

5.12 Mathematical model

ECSS-E-ST-60-20_0920131

- a. The supplier shall deliver a temporal functional mathematical model of the performance of the star sensor.

NOTE This is essential for some capabilities (e.g. autonomous attitude tracking).

ECSS-E-ST-60-20_0920132

- b. The functional mathematical model shall be representative of the sensor actual temporal performances for realistic kinematic profiles.

ECSS-E-ST-60-20_0920133

- c. The functional mathematical model shall include environmental parameters.

ECSS-E-ST-60-20_0920134

- d. The functional mathematical model shall be established with customer approved methods.

ECSS-E-ST-60-20_0920135

- e. The functional mathematical model shall be validated against the actual temporal performances of the sensor.

ECSS-E-ST-60-20_0920136

- f. The supplier shall deliver:

1. either the FMM software used by the supplier to assess the sensor performances and its associated documentation (e.g. user manual) in a format agreed with the customer, or
2. the FMM DRD of the sensor model used by the supplier to assess the sensor performances, in conformance with Annex A.

5.13 Robustness to solar events

5.13.1 Additional robustness conditions

When talking about star trackers, robustness is intended to mean the ability to maintain functionalities (possibly with reduced performance) under non-nominal conditions. Most of these non-nominal conditions are covered in the previous clauses:

- Non-Stellar Objects in the FoV: Moon, planets, artificial satellites,
- Cometary dust

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

NOTE 1 The effect in the South Atlantic Anomaly and the radiation belts is basically the same as during a solar flare, but the fluxes are in general significantly lower and energy profiles different.

NOTE 2 High energy protons, such as those in the South Atlantic Anomaly, the radiation belts or released during solar flares, create electrons when they interact with the imaging area of the pixel array. Each proton can create a trail of electrons that affects anything from one to several hundred pixels and do so with a variety of signal levels. The effect can be quantified precisely knowing the impacting angle of each incoming particle, its energy and the sensitive volume of the pixels.

5.13.2 Continuity of tracking during a solar event

- a. The functionality of continuity of tracking during a solar event relevant for the advanced capabilities, presented in clause 4.1.4 "Autonomous star tracking" and 4.1.6 "Autonomous attitude tracking", with or without aided tracking shall be analysed.

NOTE Robustness in tracking mode is easier to achieve than in acquisition mode, when the use of

windows limits the area considered (and hence the number of events). Algorithms have been developed to identify and remove the majority of protons impacts and to ensure congruity checks between stars to ensure only non-corrupted stars are used.

- b. The verification of continuity of tracking shall follow the following steps:
 - 1. Use of an high-fidelity simulation model in order to cover the whole celestial vault with sufficient granularity.
 - 2. Ensure that the distribution of the single effects, coming from protons impacted the detector, are statistically distributed over the detector.
 - 3. Ensure that each pointing direction assessed is analyzed with several distributions.
 - 4. Take into account, when possible, the energies of the protons spectrum to determine the actual charges deposited in each pixels.
 - 5. Verify end-to-end robustness by a combination of test and simulation to be agreed between the customer and supplier.

NOTE 1 A night sky test, instrumental to demonstrate general functionality and performance, cannot be used to demonstrate the capability to deal with solar events.

NOTE 2 The assessment of the robustness and the performance during a solar event makes use of a large set of pointing directions, since the star population in the field of view is impacted (the centroid accuracy depends on the star magnitude and the energy of the impinging particle).

5.13.3 Ability to solve the lost in space problem during a solar event

- a. The functionality of ability to solve the lost in space problem during a solar event, relevant for the advanced capabilities presented in clause 4.1.5 "Autonomous attitude determination", with or without assistance shall be analyzed.

NOTE Acquisition mode uses large portions of the detector up to full frames and has to rely on other, more computationally intensive techniques such as double integration and multi-stage acquisition in addition to the techniques used in tracking mode.

- b. Similarly to the verification in tracking mode, both optical and electrical stimuli shall be used as well as simulations using high fidelity model to guarantee sufficient sky vault coverage.

5.13.4 Flux levels

- a. The orbit, the Space Radiation model to be used and the availability requirement shall be provided in order to specify the level of perturbation that is handled by the star tracker.

NOTE 1 The orbit is a key element since it determines the protection provided, for instance in Earth vicinity, by the Van Allen belts. In interplanetary missions, the orbit is also key since the strength of the solar flare fluxes scales with square of the distance to the sun below 1 AU, as described in ECSS-E-ST-10-04 "Space environment".

NOTE 2 The Space Radiation model generally used as a reference is CREME96 – October 1989 event.

- b. The complete immunity of star tracker to flux levels shall be demonstrated.

NOTE By tolerance it is meant that determined error rates/probabilities are compliant with customer requirements

- c. To fulfil requirement 5.13.4b, the worst case peak fluxes as defined in ECSS-E-ST-10-04 "Space environment " shall be used.

NOTE In general the peak fluxes are defined for a timeframe of 5 minute, 1 day or 1 week of worst conditions during mission and consists of solar, trapped and galactic cosmic ray particles.

- d. However, depending on the mission requirements and pending customer approval, no acquisition may be allowed in case of extreme fluxes specified by the customer.

NOTE 1 Example: The 5 minute peak of the October 1989 (worst solar event detected) leads to a flux of 28000 protons/cm²/sec with a margin of 2, in GEO orbit and with an Al shielding around the detector of 15 mm (mean value). Such a value can only be computed by the star tracker supplier since the level of shielding around the detector varies from unit to unit.

NOTE 2 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.

Annex A (normative)

Functional mathematical model (FMM) description - DRD

A.1 DRD identification

A.1.1 Requirement identification and source document

This DRD is called from ECSS-E-ST-60-20, requirement 5.12f.

A.1.2 Purpose and objective

The functional mathematical models are established to serve as input for detailed AOCS analyses and detailed performance simulations.

A.2 Expected response

A.2.1 Scope and content

<1> Introduction

ECSS-E-ST-60-20_0920137

- a. The FMM description shall contain a description of the purpose, objective, content and the reason prompting its preparation.

ECSS-E-ST-60-20_0920138

- b. Any open issue, assumption and constraint relevant to this document shall be stated and described.

ECSS-E-ST-60-20_0920139

- c. Status and limitations of the model shall be described in detail.

<2> Applicable and reference documents**ECSS-E-ST-60-20_0920140**

- a. The FMM description shall list the applicable and reference documents in support to the generation of the document.

<3> Definitions and abbreviations**ECSS-E-ST-60-20_0920141**

- a. The FMM description shall list the applicable directory or glossary and the meaning of specific terms or abbreviations utilized in the FMM.

<4> Functional mathematical model (FMM)**ECSS-E-ST-60-20_0920142**

- a. The steps from the actual quaternion in inertial frame to the sensor outputs shall be documented, including:
1. star identification;
 2. pattern recognition;
 3. star corrections;
 4. quaternion computation;
 5. filtering.

NOTE Examples for star corrections are: optical aberration correction, relativistic aberration correction.

ECSS-E-ST-60-20_0920143

- b. The outputs of the FMM shall include:
1. the measured quaternion and time delivered by the sensor;
 2. the star measurements and times delivered by the sensor;
 3. the star identification information.

ECSS-E-ST-60-20_0920144

- c. The outputs of the FMM shall include the outputs of the sensor detailed in clauses 4.1.2.2, 4.1.3.2, 4.1.4.2, 4.1.5.2, 4.1.6.2, and 4.1.8.2, according to the sensor capabilities.

ECSS-E-ST-60-20_0920145

- d. The parameters of the FMM shall be documented.

ECSS-E-ST-60-20_0920146

- e. Modelling constraints and critical implementation issues shall be described and their relevance on performance be indicated.

ECSS-E-ST-60-20_0920147

- f. The FMM shall present the expected temporal outputs of the sensor model for given input profiles.

<5> Modes

ECSS-E-ST-60-20_0920148

- a. For sensors with the autonomous attitude determination capability, the FMM description shall include the autonomous attitude determination capability.

ECSS-E-ST-60-20_0920149

- b. For sensors with the autonomous attitude tracking capability, the FMM description shall include the autonomous attitude tracking capability.

<6> Software tools

ECSS-E-ST-60-20_0920150

- a. The software tools to be used for development of the FMM shall be specified.

<7> Files and lists

ECSS-E-ST-60-20_0920151

- a. The following information shall be attached to the document:
 - 1. identification of delivered computer files;
 - 2. FMM source lists based on applied tools.

A.2.2 Special remarks

None.

Annex B (informative)

Ancillary terms in Star Sensors

B.1 Overview

This annex standardizes the meaning of terms that, although not used in this document, are used in star sensors engineering.

B.2 Time and frequency

B.2.1 frame frequency

inverse of the frame time

B.2.2 frame time

time interval between two consecutive beginnings of integration time of each output of a single Optical Head

B.2.3 internal sampling time

time interval between the Measurement Dates of consecutive measurements from a single Optical Head

B.2.4 internal sampling frequency

inverse of the internal Sampling Time

B.2.5 latency

time between the measurement date and the output date

B.2.6 output date

date of the first availability of the output data for use external to the sensor

NOTE Sensors can either be operated asynchronously (output provided when available based on sensor clock) or synchronously (when the sensor is a slave to an external clock pulse). In the latter case the

output data sometimes cannot be accessed and placed in TM until some time after it was made available. This additional delay is specifically excluded from the latency definition.

B.2.7 output rate

rate at which the sensor delivers its data for each output of a single Optical Head

B.3 Angles of celestial bodies

B.3.1 acquisition angle with Moon angle (AAM)

lowest Aspect Angle of the Full Moon at which the Autonomous Attitude Determination is operating successfully but with degraded performance

NOTE 1 AAM is less or equal to MEA and is expected to be greater or equal to TAM.

NOTE 2 AAM and TAM define the robustness of the behaviour of the star sensor when the Moon enters the field of view.

B.3.2 tracking angle with moon in the FOV (TAM)

lowest Aspect Angle of the Full Moon at which the Autonomous Attitude Tracking is still operating successfully but with degraded performance

NOTE 1 TAM is less or equal to MEA.

NOTE 2 TAM and AAM (see B.3.1) define the robustness of the behaviour of the star sensor when the Moon enters the field of view.

B.4 Full sky

celestial sphere covering the complete 4π steradian solid angle with respect to the sensor

B.5 Measurement error metrics

B.5.1 rotational error

Each of the metrics defined in clause B.5 is parameterized by 3 rotations ε_j around axis ' j ' of a specific frame F. With respect to this frame, the rotational error R_j around each axis ' j ' of the F frame is given by:

$$R_j = |\varepsilon_j|$$

NOTE 1 The rotational error is illustrated in Figure B-1.

NOTE 2 The applicability of the specification formulation in terms of directional and rotational errors allows separate specification and performance statements relative to the direction of the sensor LOS and around the sensor LOS. This is useful since the performance in these 2 areas is typically significantly different for single optical head configuration and hence requires separate specification.

B.5.2 directional error

The directional error $D(j)$ for axis ' j ' is defined as the half-cone angle between the measured and reference position of axis ' j ' and is given (for small rotation angles) by:

$$D_j = \sqrt{\varepsilon_k^2 + \varepsilon_l^2}$$

where ' k ' and ' l ' are the two axes perpendicular to axis ' j '.

NOTE 1 The directional error is illustrated in Figure B-1.

NOTE 2 The applicability of the specification formulation in terms of directional and rotational errors allows separate specification and performance statements relative to the direction of the sensor LOS and around the sensor LOS. This is useful since the performance in these 2 areas is typically significantly different for single optical head configuration and hence requires separate specification.

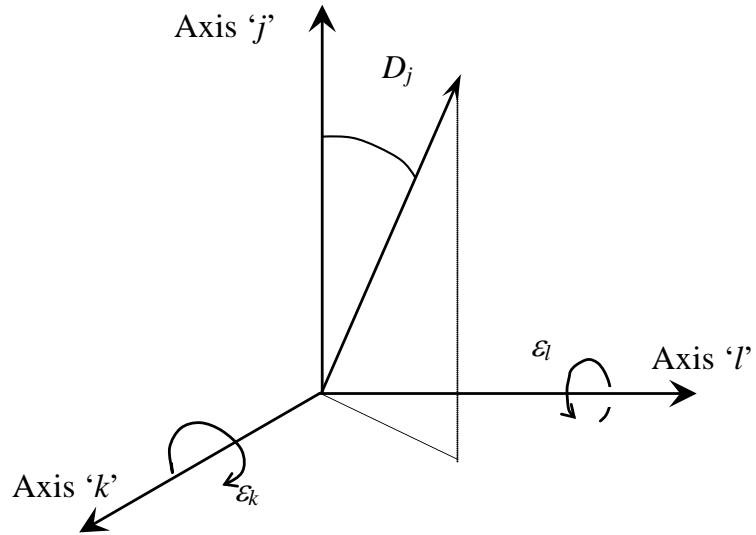


Figure B-1: Rotational and directional Error Geometry

Annex C

Annex C (informative)

Optional features of star sensors

C.1 Overview

This annex defines optional features or capabilities of star sensors. It follows the same structure as the clause 4 to allow for a direct link between requirements and options.

C.2 Cartography

A sensor with cartography capability can have the following additional outputs: measurement of star magnitude of each detected star image.

NOTE The star images obtained need not be captured at the same instant in time.

C.3 Star tracking

- a. The following additional inputs to launch tracking can be provided:
 1. the angular acceleration and jerk of the sensor BRF with respect to the IRF, with their validity dates;
 2. the accuracy of supplied inputs.

NOTE 1 Angular acceleration and jerk are supplied in the form of 3-dimension vectors giving the angular acceleration and jerk of the sensor BRF with respect to the IRF. These vectors are expressed in the sensor BRF.

NOTE 2 In the case of external inputs coming from the spacecraft the star sensor supplier can indicate the minimum required accuracy for supplied data in order to properly switch into tracking.

- b. A sensor with the star tracking capability can have the following additional outputs: measurement of star magnitude for each tracked star image.

C.4 Autonomous star tracking

- a. The following additional inputs to launch tracking can be provided:
 1. The angular acceleration and jerk of the sensor BRF with respect to the IRF, with their validity dates.

2. The accuracy of supplied inputs.

NOTE 1 Angular acceleration and jerk are supplied in the form of 3-dimension vectors giving the angular acceleration and jerk of the sensor BRF with respect to the IRF. These vectors are expressed in the sensor BRF.

NOTE 2 In the case of external inputs coming from the S/C the star sensor supplier can indicate the minimum required accuracy for supplied data in order to properly switch into tracking.

- b. A sensor with the autonomous star tracking capability can have the following additional outputs: measurement of star magnitude for each tracked star image.

C.5 Autonomous attitude determination

- a. A sensor with autonomous attitude determination can have the following additional outputs:
 1. a measurement quality index or flag, estimating the accuracy of the determined attitude;
 2. An inertial angular rate measurement projected on a sensor-defined reference frame;
 3. a list of the star catalogue numbers for each star used in the determination;
 4. the position of each star image with respect to a defined sensor reference frame;
 5. measurement of star magnitude for each tracked star image.
 6. the identification of the optical head(s) used for the attitude determination when multiple head configuration is used.

C.6 Autonomous attitude tracking

- a. The following additional inputs to launch tracking can be provided:
 1. the angular acceleration and jerk of the sensor BRF with respect to the IRF, with their validity dates;
 2. the accuracy of supplied inputs including, in the case of attitude control, the accuracy around each axis of the sensor BRF.

NOTE 1 Angular acceleration and jerk are supplied in the form of 3-dimension vectors giving the angular acceleration and jerk of the sensor BRF with respect to the IRF. These vectors are expressed in the sensor BRF.

NOTE 2 In the case of external inputs coming from the S/C the star sensor supplier indicates the minimum

required accuracy for supplied data in order to properly switch into tracking.

- b. A sensor with autonomous attitude tracking capability can have the following additional outputs:
 - 1. a measurement quality index or flag estimating the accuracy of the determined attitude;
 - 2. an angular rate measurement around a sensor defined reference frame;
 - 3. a list of the star catalogue numbers for each star used in the determination;
 - 4. the position of each Star Image with respect to a defined reference frame;
 - 5. the identification of the optical head(s) used for the attitude tracking when multiple head configuration is used.

C.7 Angular rate measurement

- a. A sensor with angular rate measurement capability can have the following outputs:
 - 1. a measurement quality index or flag, estimating the accuracy of the determined angular rate;
 - 2. a validity index or flag, estimating the validity of the determined angular rate.

C.8 Types of star sensors

C.8.1 Star camera

- a. A star camera can include the following additional capabilities: (partial) image download.

C.8.2 Star tracker

- a. A star tracker can include the following additional capabilities:
 - 1. autonomous star tracking;
 - 2. (partial) image download.

C.8.3 Autonomous star tracker

- a. An autonomous star tracker can include the following additional capabilities:
 - 1. cartography;

2. star tracking;
3. autonomous star tracking (attitude acquisition with assisted attitude determination);
4. autonomous attitude tracking (with direct initialization);
5. angular rate measurement;
6. (partial) image download.

C.8.4 Summary

- a. The specified minimum and additional capabilities for each type of sensor are summarized in Table C-1.

Table C-1: Minimum and optional capabilities for star sensors

Type of sensor	Capabilities						
	Cartography	Star Tracking	Autonomous Star Tracking	Autonomous Attitude Determination	Autonomous Attitude Tracking	Angular Rate Measurement	Partial Image Download
Star Camera	X						(X)
Star Tracker	X	X	(X)				(X)
Autonomous Star Tracker	(X)	(X)	(X)	X	X	(X)	(X)
Key: X = Mandatory, (X) = Optional							
Table Rows: type of star sensors; table columns: capability							

Annex D (informative)
<<deleted>>

Annex E

Annex E

Annex E

Annex E (informative)

Statistics

E.1 Confidence level

E.1.1 Overview

The performances have a statistical nature, because they vary with time and from one realization of a sensor to another. Therefore, only an envelope of the actual performances can be specified and provided.

This envelope is the combination of an upper limit and a performance confidence level.

The performance confidence level indicates the proportion of the actual performances below the upper limit.

For example, the X absolute [knowledge](#) error can be 10 arcsec with a performance confidence level of $P_c = 95\%$. This means that the actual errors from one sample to another are below 10 arcsec for 95 % of the cases.

NOTE Performance confidence level is usually 99,7 % (corresponding to a 3 sigma values for Gaussian distributions).

E.1.2 Accuracy on the confidence level

The verification of the specifications can only be done on a limited set of samples of the whole statistical population:

- On a limited time span
- On a limited number of sensors

The larger the set of samples, the better the knowledge on the performance confidence level (P_c).

This implies that the actual confidence level is not perfectly known, but is estimated with a certain accuracy ΔP , also called accuracy on the confidence level.

This qualitative notion can be mathematically expressed by using:

- The performance confidence level (P_c): it applies to the performances quoted by manufacturers and specified by customers (usually as 3 sigma values).
- And the estimation confidence level. It applies to the estimation of the performance confidence level (defined [in clause 5.1.1](#)). It represents the confidence that the sample is representative of the overall ensemble.

If not specified, confidence level means performance confidence level, and is denoted P_c in this document.

The confidence estimation accuracy (ΔP) being fixed, the minimum number of samples (N) depends on the estimation confidence level.

- For an estimation confidence level 95%, then the minimum number of samples is given by $N = \frac{4P_c(1-P_c)}{\Delta P^2}$. It means that if the number of samples is larger than N , then the actual confidence level lies in the range $[P_c - \Delta P; P_c + \Delta P]$ in 95 % of the cases
- For an estimation confidence level 99,7 %, then the minimum number of samples is given by $N = \frac{9P_c(1-P_c)}{\Delta P^2}$. It means if the number of samples is larger than N , then the actual confidence level lies in the range $[P_c - \Delta P; P_c + \Delta P]$ in 99,7 % of the cases

NOTE E.g. If the performance confidence level is 99,7 % and the accuracy is $\Delta P = 0,1$ %, then at least 11964 samples are considered to actually demonstrate that the actual performance confidence level is between 99,6 % and 99,8 % (i.e. it is known with an accuracy of 0,1 %), with a confidence of 95 %.

E.1.3 Mathematical derivation

N samples of a random variable x from a probability distribution function $p(x)$ are considered. Denote the actual performance confidence level of interest by P_c , with true value x_c . Then the number of samples N_c within the set N lying below x_c is sampled from a binomial distribution with mean and variance given by:

$$\text{Mean}(N_c) = P_c N$$

$$\text{Var}(N_c) = P_c(1 - P_c)N$$

The estimate \hat{P}_c of the performance confidence level at x_c is given as follows:

$$\hat{P}_c = \frac{N_c}{N}$$

Therefore the mean and variance of the estimate \hat{P}_c of the performance confidence level is given by:

$$\text{Mean}(\hat{P}_c) = P_c \text{ (i.e. the mean value of the estimate is the actual value)}$$

$$\text{Var}(\hat{P}_c) = \frac{P_c(1 - P_c)}{N}$$

Now, let ΔP be the estimation confidence accuracy, such that the actual value P_c of the performance confidence level lies in the range $[\hat{P}_c - \Delta P; \hat{P}_c + \Delta P]$, with a given estimation confidence level.

The variations of \hat{P}_c are supposed to follow a Gaussian distribution. With this assumption, if the estimation confidence level is set to 95 %, (which corresponds to $\pm 2\sqrt{\text{Var}(\hat{P}_c)}$), then the minimum number of samples in the set N to be calculated is:

$$N = \frac{4P_c(1 - P_c)}{\Delta P^2}$$

For a 99,7 % estimation confidence level on \hat{P}_c , the formula becomes $N = \frac{9P_c(1 - P_c)}{\Delta P^2}$, because 99,7 % corresponds to a 3 sigma value for a Gaussian distribution.

More generally, $N = \frac{n_c^2 P_c(1 - P_c)}{\Delta P^2}$ for a n_c -sigma estimation confidence level of a Gaussian distribution.

NOTE For example, if the performance confidence level on the error is 99,7 % and the accuracy is $\Delta P = 0,1$ %, then at least 11964 samples are the minimum number of samples used to actually demonstrate that the actual confidence level is between 99,6 % and 99,8 % (i.e. it is known with an accuracy of 0,1 %), with an estimation confidence level of 95 %.

E.1.4 <<deleted>>

E.2

E.2 Statistical interpretation of **knowledge** error metrics

Each of the metrics defined in clause B.5 is typically specified and used with an associated confidence level.

Any performance metrics depends on several variables:

- the time t ;
- the realization of the sensor (involving the manufacturing process);
- the observation conditions in which the performances are obtained (e.g. angular rate applied on the sensors, orientation with respect to the celestial vault).

As it is not possible to build a representative sample set of sensors, the notion of statistical ensemble is used. A statistical ensemble of sensors is defined as a collection of sensors representative of the manufacturing process, in which not all sensors are necessarily built.

Because a metrics depends on several variables, there are several ways to interpret a specification and its confidence level:

- Temporal interpretation
 - The worst case combination of sensors and observations is considered.
 - The worst-case sensor/observation combination is defined as the worst-case sensor observing the worst-case direction in the celestial vault under the worst-case observation conditions. The worst-case direction is the one leading to the worst performance of the sensor. It is related to the worst distribution of stars over the star sensor field of view, taking into account embedded algorithms and catalogues.
 - The performances are established with respect to time.
 - The specification metric is 'less than S for $n\%$ of the time for a worst-case sensor/observation from a statistical ensemble of sensors/observations'.
- Ensemble interpretation
 - A statistical collection of sensors is arbitrarily chosen.
 - A given set of observations is arbitrarily chosen.
 - The time is set to the worst case time, i.e. when the performances obtained for a given sensor and observation are worst.
 - The specification metric for this type of variability is 'less than the level S in confidence level $n\%$ of a statistical ensemble of sensors/observations for the worst-case time'.
- Mixed interpretation
 - The mixed interpretation combines the ensemble and temporal variation to capture the error variability both over time and across the ensemble.
 - The specification metric for this type of variability is 'for a random sensor/observation from the statistical ensemble, and at a random time, the metric is less than S with a probability of $n\%$ '.

For a generic measurement error source with an amplitude and a time variation, the ensemble interpretation gives the distribution of the error amplitude over the statistical ensemble of sensors/observations, while the temporal interpretation covers the error variation over time for the worst-case amplitude.

Annex F (informative)

Transformations between coordinate frames

Transformations between any two co-ordinate frames, A and B can be described by the transformation matrix T_{A-B} which transforms the components of a vector from 'B' frame to 'A' frame:

$$\underline{r}_A = T_{A-B} \underline{r}_B$$

where \underline{r}_A are the components of the vector \underline{r} in the 'A' frame, and \underline{r}_B are the components of the same vector \underline{r} in the 'B' frame.

The discrepancy between both frames 'A' and 'B' is defined by 3 Euler angles around 3 distinct axes. In this Standard, the rotations are always small, therefore the order of the rotations is not important and these rotations can be taken to be rotations around the X-, Y- and Z-axes of either frame.

The transformation is simply:

$$T_{A-B} \approx \begin{bmatrix} 1 & \Delta\psi & -\Delta\theta \\ -\Delta\psi & 1 & \Delta\phi \\ \Delta\theta & -\Delta\phi & 1 \end{bmatrix}$$

where $\Delta\phi$, $\Delta\theta$ and $\Delta\psi$ are the 3 small rotations respectively around X, Y and Z axes transforming the 'B' frame into the 'A' frame.

The discrepancy between both frames 'A' and 'B' is:

$$\varepsilon = \begin{bmatrix} \Delta\phi \\ \Delta\theta \\ \Delta\psi \end{bmatrix}$$

The discrepancy is a function of the time.

For star sensors, this vector typically represents the angular errors between a measured quantity and its actual value.

NOTE E.g. With 'A' frame being the actual star sensor frame and 'B' frame being the measured star sensor frame, then ε represents the measurement errors of the star sensor (see Figure F-1).

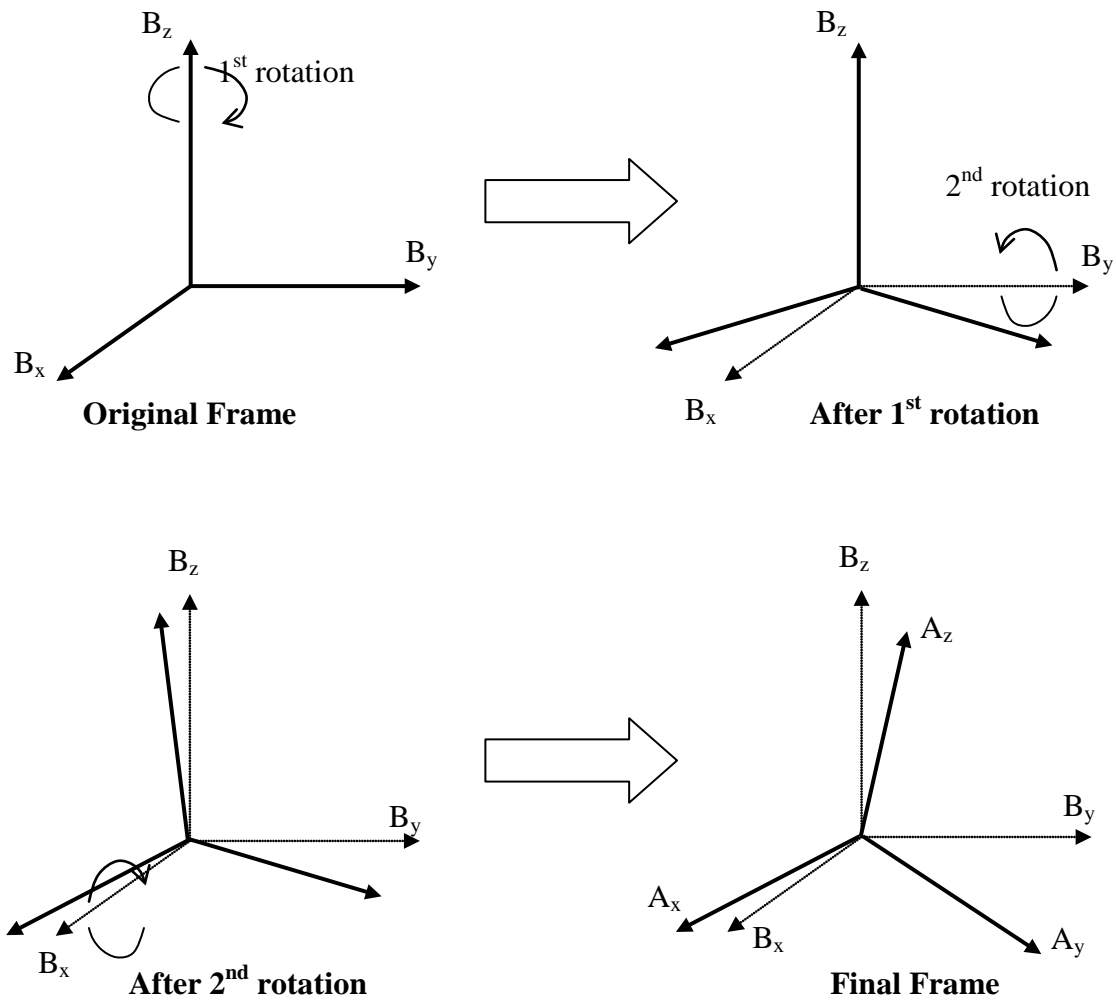


Figure F-1: Angle rotation sequence

In this case the 3-axis Euler rotation parameterization corresponds to rotations around the B-frame axes.

The separation of two frames A and B, defined in the ESA Pointing Error Handbook and written as $sep(T_{A-B})$ is defined as:

$$sep(T_{A-B}) = \varepsilon = \begin{bmatrix} \Delta\phi \\ \Delta\theta \\ \Delta\psi \end{bmatrix}$$

This function represents the discrepancy between the two frames and is used to measure the star sensor performances.

Annex G (informative) Contributing Error Sources

G.1 Overview

This annex summarises the error contributors and the elements to be specified by the customer and characterised and verified by the supplier. The mathematical framework is explained in ECSS-ST-60-10 (Control performance standard) and ESSB-E-HB-E-003 (ESA pointing error engineering handbook)

Table G-1: Contributing error sources

Error contributors	Statistical properties	Example
<p>Bias</p> <ul style="list-style-type: none"> on-ground calibration residual launch-induced misalignment (vibrations, depressurization, gravity...) BRF vs MRF misalignment due to after-launch ageing 	<ul style="list-style-type: none"> Statistical Interpretation: Ensemble Interpretation Temporal Behaviour: Time constant Class: Bias 	<p>Temporal distribution: discrete (no distribution)</p> <p>Ensemble distribution: uniform</p> <p>Error magnitude: +/- b1" (maximum) normal to LOS +/- b2" (maximum) along LOS</p> <p>Error model: zero-mean constant random variable with distribution U(0,b1) about LOS and U(0, b2) along LOS.</p> <p>NOTE: The uniform ensemble distribution is justified by the assumption that the probability of obtaining a bias error within a given accuracy range of the calibration process is equal. The same is assumed for the launch effects contribution.</p>
<p>Thermo elastic error</p> <p>BRF vs MRF stability due to :</p> <ul style="list-style-type: none"> stabilized optical head temperature gradient caused by conductive and radiative effects 	<ul style="list-style-type: none"> Statistical interpretation: Ensemble Interpretation Temporal behaviour: Time-random Class: Periodic 	<p>Temporal distribution: bimodal</p> <p>Ensemble-distribution: uniform</p> <p>Error magnitude: ε_1" peak-to-peak for minimum operational temperature and ε_2" peak to peak for maximum operational temperature.</p> <p>Error model: periodic signal at orbital frequency with amplitude uniformly distributed as a function of the operational temperature P(1/orbit, U($\varepsilon_1, \varepsilon_2$)).</p> <p>NOTE: A linear dependence on operational temperature is assumed.</p>

Error contributors	Statistical properties	Example
<p>FOV spatial errors</p> <ul style="list-style-type: none"> Point Spread Function variability across the FOV residual of calibration of focal length (including its temperature sensibility) and optical distortions (including chromatism) residual of aberration of light in case where it is corrected at quaternion level and not at star level Detector CTE effect (including its degradations due to radiations) catalogue error (including star proper motion and parallax) 	<ul style="list-style-type: none"> Statistical Interpretation: Ensemble Interpretation Temporal behaviour: Time-Random Class: Bias(t) + Random 	<p>Temporal distribution : Gaussian</p> <p>Ensemble distribution: N/A</p> <p>Error magnitude and error model: power spectrum (PSD in $"/\sqrt{\text{Hz}}$) obtained on the basis of datasheet parameters and of star velocity across the detector plane.</p>
<p>Pixel spatial errors</p> <ul style="list-style-type: none"> detector spatial non uniformity : PRNU, DSNU, dark current (spikes), inter-pixel crosstalk... star centroid computation (rate dependent) 	<ul style="list-style-type: none"> Statistical Interpretation Ensemble Interpretation Temporal Behaviour: Time-Random Class: Bias(t) + Random 	<p>Temporal distribution: Gaussian</p> <p>Ensemble distribution: N/A</p> <p>Error magnitude and error model: power spectra (PSD₁ in $"/\sqrt{\text{Hz}}$ normal to LOS and PSD₂ in $"/\sqrt{\text{Hz}}$ along LOS) obtained on the basis of datasheet parameters and of star velocity across the detector plane.</p>
<p>Temporal noise</p> <ul style="list-style-type: none"> star signal shot noise depending on star signal (Star Magnitude, exposure time, optical contamination, transmission loss, defocus, rate...) background signal shot noise (straylight level, detector temperature...) read-out noise quantification noise datation noise 	<ul style="list-style-type: none"> Statistical Interpretation: Temporal Interpretation Temporal Behaviour: Time Random Class: Random 	<p>Temporal distribution: Gaussian</p> <p>Ensemble distribution: N/A</p> <p>Error magnitude: ε_1'' (3σ) normal to LOS ε_2'' (3σ) along LOS</p> <p>Error model: zero-mean band-limited white noise model defined by $G(0, \varepsilon_1/3)$ normal to LOS, $G(0, \varepsilon_2/3)$ normal to LOS, and sensor output frequency.</p>

Error contributors	Statistical properties	Example
<p>Aberration of light or residual of aberration of light correction if corrected at star level</p>	<p>Mission specific (function of the type of correction and of spacecraft instantaneous inertial velocity).</p>	<p>As this error is very deterministic, it is possible to correct it inside the star sensor - supposing that the velocity information is given to the star sensor. A few cases are quoted:</p> <ol style="list-style-type: none"> 1) a correction is performed for every star direction, 2) a unique correction is performed globally for a unique direction (example: line of sight, or barycentre of the measured stars) and applied on the quaternion or on each star measurement, 3) a correction is performed only for the Earth / Sun velocity, 4) no correction is performed. <p>Depending on the correction, the error residual is:</p> <ul style="list-style-type: none"> • a FOV spatial error if the correction is performed globally (case 2) • an orbital error in the case 3 (depending also on the attitude of the spacecraft) • a long term error (one year) + orbital error for the case 4.

Annex H

Annex H (informative) Example of data sheet

The data sheet in Figure H-1 shows an example of data sheet for autonomous star tracker.

The fields that can be filled in are identified in an italic font.

The example values filled in are just for formatting purposes and do not relate to an existing star sensor.

Annex I (informative)

Command and telemetry tables

I.1 Introduction

Table I-1 and Table I-2 are recommended for the most currently used star trackers, which have the capabilities described in clauses 4.1.5, 4.1.6 and 4.1.7: autonomous attitude determination, autonomous attitude tracking and angular rate measurement.

The following sets of commands and telemetries have been harmonized in the context of SAVOIR (Space AVionics Open Interface aRchitecture) initiative.

Table I-1: Command table

Command Number – Name Mandatory/ Optional	Parameter – Name (within command)	Description	Format
STR C 01 - CmdReset Mandatory	Reset_type	Reset Command	Reset_type = 0 Reset command of the complete STR (mandatory)
STR C 02 - CmdTEC Optional (in case of no TEC)	1 – TEC_ON_OFF	ON/OFF command	TEC_ON_OFF = ON/OFF command
	2 – TEC_Tmp		Target temperature in °C
STR C 03 - UploadDate Optional	Date	Upload Date to STR	CCSDS Unsegmented Code (CUC) time code format This command is implemented according to the communication layer standard, if any
STR C 04 - CmdStandbyMode Mandatory		If STR ON → switch from current mode to STR Standby Mode	n = 0 → STR standby mode (all OH), Mandatory. n > 0 → Free to be customised by STR supplier
STR C 05 - CmdAcquisition Mandatory		Starts the STR autonomous attitude determination (“lost in space” acquisition) process	
STR C 06 - CmdAidedTracking Optional	1 – AttitudeDesignation_STR	Forces STR into Tracking mode providing attitude and angular rate initialisation	Refer to STR D 01 (i=0 case) Minimum accuracy required is indicated in STR ICD.
	2 – RateDesignation_STR		Refer to STR D 03 (i=0 case) Minimum accuracy required is indicated in STR ICD
	3 – Attitude&RateTimeStamp		Date relative to parameter 2 and 3 STR propagated time in CCSDS Unsegmented Code (CUC) time code format

Command Number – Name Mandatory/ Optional	Parameter – Name (within command)	Description	Format
	1 – AberrationCorrectionType	Manage aberration correction	AberrationCorrectionType: 0 = No Aberration correction. 1 = Enable Aberration correction based on velocity. 2 = Enable aberration correction based on STR internal orbital propagation (optional)
	2 – Velocity		S/C velocity vector = vector (3) in ICRS J2000 frame Velocity relative to next synchro. (e.g. PPS)

Table I-2: Telemetry table

Parameter Number – Name Mandatory/Optional	Description	Format
STR D 01 – QuatSTRwrtIRF Mandatory	Attitude Quaternion provided by STR	<p>$q = [\text{scalar}; \text{vector}(3)]$</p> <p>Reference frame: J2000 frame \rightarrow STR frame</p> <p>NOTES: each STR provides the data in the above format. Additional ways to present the quaternion (format and frames) can be provided by the STR (upon customer choice). No constraint on quaternion components sign.</p>
STR D 02 - DateQuat Mandatory	Time associated to STR D 01	<ul style="list-style-type: none"> • Baseline: Time elapsed between the last synchronisation signal and attitude measurement. • Option (non mandatory): STR propagated time in CCSDS Unsegmented Code (CUC) time code format. <p>NOTE: both Default and Option formats are not intended to constrain the way the STR is working i.e. free running or synchronised.</p>
STR D 03 - RateSTRwrtIRF_STR Optional	Final Angular Rate vector	<p>Angular rate = vector(3)</p> <p>Angular rate corresponds to STR frame w.r.t. Inertial Frame</p> <p>Reference frame: vector expressed in STR frame</p>
STR D 04 - DateRate Optional	Time associated to STR D 03	<ul style="list-style-type: none"> • Baseline: Time elapsed between the last synchronisation signal and attitude measurement. • Option (non mandatory): STR propagated time in CCSDS Unsegmented Code (CUC) time code format. <p>NOTE: both Default and Option formats are not intended to constrain the way the STR is working i.e. free running or synchronised.</p>

Parameter Number – Name Mandatory/Optional	Description	Format
STR D 05 - Mode Mandatory	STR mode (typically a number)	<ul style="list-style-type: none"> • Mandatory Principal modes: <ul style="list-style-type: none"> 1 – Standby Mode (No measurement available) 2 – Attitude Acquisition Mode (Autonomous or Aided Attitude Determination) 3 – Attitude Tracking Mode (Autonomous or Aided Attitude Tracking, i.e. routine attitude measurements) • Optional Modes: Angular Rate mode, Photo mode, Recovery mode, etc.
STR D 06 - QualityQuat Mandatory	Quality Index of STR D 01	Dimensionless scalar quality index scaled between 0 and a max value.
STR D 07 - ValidityQuat Mandatory	Validity Flag of STR D 01	Boolean value
STR D 08 – CountSinceReset Optional	Counter since last Reset	Cycles counter (once the values reaches max value wraps back to 0)
STR D 09 – HealthStatus Mandatory	STR Health status (typically a number)	<ul style="list-style-type: none"> • Mandatory states: <ul style="list-style-type: none"> 1 – OK 2 – OK, however do not restart STR now (e.g. EEPROM Update in progress) 3 – STR warning (Restart not necessary) (*) 4 – STR Severe warning (request for Power OFF) • Optional sub-states can be defined. <p>(*) Spacecraft can continue nominal operation but flag to be sent to ground for diagnostic</p>

Bibliography

ECSS-S-ST-00	ECSS system – Description, implementation and general requirements
ESSB-E-HB-E-003	ESA Pointing Error Engineering Handbook
ECSS-E-ST-10	Space engineering – System engineering general requirements
ECSS-E-ST-10-02	Space engineering – Verification
ECSS-E-ST-10-03	Space engineering - Testing
ECSS-E-ST-10-04	Space engineering - Space environment