Reference systems, Conventions and Notations for Gaia

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Abstract

The aim of this document is to establish some standards about reference systems and other conventions and notations for Gaia. Such standards are needed to ease communication within the community, and to help make technical documents from various parties consistent with each other. The document is intended to be used as a reference guide for the scientific community and the industrial development teams.
The present issue 7 constitutes a long-overdue deep refurbishment and extension, more than twelve years after the previous issue 6. The major changes are listed in the document history. No previous conventions are changed, nor really new ones created, but many that have come into usage in DPAC during these years have now been added to the document. In addition, many clarifications and explanations are added to the text.

Document History

Issue	Revision	Date	Author	Comment
7	0	2020-05-18	BAS	Comments from AB see file bas-003-v7_AB-1.pdf on svn; all done.
7	D	2020-02-17	BAS	issue 7 draft for circulation; comments from DPACE solicited
7	D	2020-02-16	BAS	section on Gaia Parameter Database as a “standard”
7	D	2020-02-16	BAS	Time tagging of epoch data added; LL-080 introduced; some minor editorial improvements
7	D	2020-02-14	BAS	Klioner’s comments on Time Chapter worked in
7	D	2020-02-06	BAS	section on source identifiers done
7	D	2020-02-05	BAS	answers on open questions from CU5 incorporated; a few small refinements in several places
7	D	2020-02-04	BAS	TransitId section completed; Photometry Chapter completed; open questions emailed to CU5 leader(s)
7	D	2020-02-03	BAS	Chapter 6 completed; in particular some numerical errors in 6.1 corrected
7	D	2020-02-03	BAS	new chapter 7 SourceId, TransId introduced; still empty
7	D	2020-02-03	BAS	chapters 4 and 5 completed; many conceptual updates and clarifications; in 4.3.3.1 also some errors corrected; the mess concerning CCD numbering explained and warned of (5.2.1)
7	D	2020-01-20	BAS	time chapter draft complete; sent to Klioner
7	D	2020-01-19	BAS	section on OBT and OBMT added)
7	D	2020-01-11	BAS	Jira issue C3-ACT-148 done (Unix time)
7	D	2020-01-10	BAS	Jira issue C3-ACT-2 done (def of UTC)
7	D	2020-01-09	BAS	re-start of work on issue 7draft; all figures revised to pdf; not all in good shape yet
7	D	2017-09-12	BAS	start of work on issue 7draft
1-6	0	2007-07-05	BAS	issues 1.0 to 6.1, history see in issue 6.1 on Livelink

The source files for this document can be found in the Gaia svn repository in the folder
https://gaia.esac.esa.int/dpacsvn/DPAC/CU1/docs/BAS-003-conventions/

Contents

1 Introduction (original from 2003/2007)

With the continuing development of the Gaia project, it gets more and more important that the various groups working on Gaia develop a common language for the basic aspects of the mission and of the measurements to be performed with it. The present document wants to serve this purpose.

Many of the concepts are analogous to those of Hipparcos, due to the fact that the basic geometry of the measurements is the same. Thus it is attempted to preserve as many notations as possible from Hipparcos usage, in particular from Vols. 2 and 3 of the printed Hipparcos Catalogue documentation (7). However, there are some marked differences to Hipparcos, due to the fact that the signal detection of Gaia is radically different. In these cases, and whenever the Hipparcos terminology was inconsistent or ambiguous, the following notations differ from the Hipparcos heritage.

Also, of course, an attempt is made to take developments into account that have already taken place independently within the Gaia project, in order to avoid confusion and revision of existing documents as much as possible. This in particular refers to the Gaia "White Book" (14), the "Basic Principles and Main Technical Assumptions" from the CCD and FPA Technology Demonstrators study (9), updated by the EADS-Astrium Proposal to ESA 2005 (34), the "Proposal for a Gaia Parameter Database" (10), especially Appendix B, several notes on Gaia data reduction aspects by L. Lindegren, and several Astrium documents from the Gaia-SRR package 2006.

It is evident that this work has to further evolve and grow, along with the concept of Gaia itself. Any comments, suggestions, additions are welcome at any time.

1.1 Purpose and Scope

The document is intended to be used as a reference guide for the scientific community of Gaia and the industrial development teams. In other words, the aim of this document is to establish some standards about reference systems and related conventions and notations for Gaia. Such standards are needed to ease communication within the community, and to help make technical documents from various parties consistent with each other.

Note that there are other efforts having similar aims, i.e. to set standards and conventions on a project-wide scale. Such are, for instance, the Gaia Parameter Database at ESTEC (10), the Gaia Java Toolbox "GaiaTools" (5) and the central list of acronyms (at ESTEC). These efforts are complementary to, not competing with the present document. Ultimately they will have to form an integral, consistent package.

The present document is intended to be self-contained and self-explaining. The numerous references are not considered to be necessary for the practical usage of this document, but only to give additional information and understanding to the interested reader.

The present issue makes all previous issues obsolete, as well as the precursor document by J. Portell et al. (2).

1.2 Purpose and Scope of the Present Version

The present issue 7 constitutes a long-overdue deep refurbishment and extension, more than twelve years after the previous issue 6. The major changes are listed in the document history. No previous conventions are changed, nor really new ones created, but many that have come into usage in DPAC during these years have now been added to the document. In addition, many clarifications and explanations are added to the text.

Comments, corrections, suggestions for additions etc. are kindly requested to be sent to U. Bastian (`bastian@ari.uni-heidelberg.de`).

1.3 Document Overview

Section 1 provides a fairly standard set of introductory and administrational sections, including a glossary of notations and acronyms.

Section 2 prescribes the choice and representation of physical units, while Section 3 deals with the complexities of time scales and time notations.

The non-astrometrists in the Gaia community may quickly skim over Section 4 (at least during the first reading of this document). That section introduces a number of reference systems (coordinate systems) which are necessary for the astrometric interpretation of the Gaia data.

Section 5, on the contrary, will be relevant for everybody. It defines CCD-related terminology and conventions. A particularly complex detail of this general theme — the labelling of pixels, samples, windows and star images within the data streams from Gaia's CCDs — is elaborated in Section 6.

Section 7 defines the important concepts of the unique DPAC Transit Identifier for the individual, elementary observations done by Gaia, and of the DPAC Source Identifiers for the physical objects in the sky corresponding to such observations.

Section 8 contains some conventions on photometric issues.

Finally, Section 9 provides a miscellaneous collection of further conventions on different aspects of the mission and the data reductions.

The document is completed by a number of appendices (presently only one) and a bibliography.

Throughout the document the reader will find short paragraphs set in small italic font and in narrower layout, like this one. They contain various sorts of comments, such as justifications for specific choices of coordinates or terms, remarks on ongoing discussions, open issues, missing parts etc. — They can be skipped in the first reading of the document.

1.4 List of Notations and Acronyms

The following list is sorted kind of lexicographically, with the Latin alphabet first, followed by the Greek alphabet, then followed by special characters. The list contains only notations and acronyms actually used in the present document.

a	ISO notation for the time unit (Julian) year
A	Ampere; SI unit of electric current
A	general attitude matrix
Å	Ångstrom; non-SI unit of length, to be avoided
AC	across scan
ACS	Attitude Control System
AF	Astrometric (Main) Field
AL	along scan
arcmin	arcminute, minute of arc; unit of angle
arcsec	arcsecond, second of arc; unit of angle
ARI	Astronomisches Rechen-Institut, Heidelberg
ASCII	American Standard Code for the Interchange of Information
au	astronomical unit (lower case to be used according to IAU resol. 2012-B2)
b	bit; unit of information
B	byte; unit of information, 8 bits
BAM	Basic-Angle Monitoring device
BCRS	Barycentric Celestial Reference System
CCD	Charge-Coupled Device; the type of photoelectric detector used for Gaia
CCSDS	Consultative Committee for Space Data Systems
cd	candela, SI unit of luminous intensity
CDU	Clock Distribution Unit
CID	Charge Injection Device
CIPM	Comité International des Poids et Mésures
CIS	Charge injection structure (of a CCD)
CoMRS	Center-of-Mass Reference System (of Gaia)
CU	Coordination Unit (top-level subdivision of the DPAC)
DE	Development Ephemeris
deg	degree, unit of angle
DPAC	Gaia Data Processing and Analysis Consortium

DPACE	Gaia Data Processing and Analysis Consortium Executive
doy, DOY	day of year (counting from Jan. 1 within each year)
ESOC	European Space Operations Centre, Darmstadt, Germany
ESTEC	European Space Research and Technology Centre, Noordwijk, The Netherlands
f	FoVRS principal axis in focal direction
f	FoVRS focal-direction field coordinate
FITS	Flexible Image Transport System
FoV	Field of View
FoVRS	Field-of-View Reference System(s)
FPA	Focal-Plane Assembly
FPRS	Focal-Plane Reference System
G	broad-band Gaia magnitude from unfiltered CCDs
GAIA	this once used to be an acronym for 'Global Astrometric Interferometer for Astrophysics', but now is just a name for the mission
Gaia	new spelling for GAIA (as of June 2003)
GCRS	Geocentric Celestial Reference System
GDAAS	Gaia Data Access and Analysis Study
Gi	Gigabinary, Gibi; units prefix for 2^{30}=1024*1024*1024
GST	Gaia Science Team
HK	Housekeep
Hz	Hertz; SI unit of frequency
I	size of a window along scan (in units of samples)
IAU	International Astronomical Union
ICRS	International Celestial Reference System
ICRF	International Celestial Reference Frame
IMCCE	Institut de Mécanique Céleste et de Calcul des Éphémérides, Paris
ISO	International Organisation for Standardization, Geneva, Switzerland
JD	Julian Date; a notation for time
JED	Julian Ephemeris Date; to be avoided, see also JD
K	Kelvin; SI unit of temperature
k	kilo-; SI units prefix for 10^3
k	along-scan pixel coordinate of a TDI pixel (integer)
k_s	along-scan pixel coordinate of a CCD sample (integer)
k_w	along-scan pixel coordinate of a CCD window (integer)
kg	kilogram; SI unit of mass
Ki	kilobinary, kibi; units prefix for 2^{10}=1024
L	size of a window across scan (in units of samples)
LSB, lsb	least-significant bit
m	across-scan pixel coordinate of a TDI pixel (integer)
m_s	across-scan pixel coordinate of a CCD sample (integer)
m_w	across-scan pixel coordinate of a CCD window (integer)
m	meter; SI unit of length
M	mega-; SI units prefix for 10^6

mas	milliarcsecond, 10^{-3} arcseconds
MDB	Gaia Main Database
Mi	Megabinary, Mibi; units prefix for 2^{20}=1024*1024
MJD	Modified Julian Date; to be avoided, see also JD
MRS	obsolete term ('Mechanical Reference System'), replaced by SCRS
MSB, msb	most-significant bit
mu	ASCII-environment degenerate of μ as SI units prefix
muas	ASCII-environment degenerate of μas
n	CCD chip designator (running number or mnemonic code) on a Gaia focal plane
N	Newton; SI unit of force
NSL	Nominal Scanning Law
OBT	on-board time; the actual reading of Gaia's master clock; see also T_G
OBMT	on-board mission timeline; see Section 3.7
OBMT50	reduced-resolution version of OBMT
OGA	on-ground attitude (or on-ground attitude reconstruction)
$\mathbf{q}$	quaternion; an attitude representation
$\mathbf{q_i}$	quarternion components, Euler symmetric parameters
r	ordinate; RGC latitude coordinate; see also v
$\mathbf{R}$	general rotation matrix
$\mathbf{R}_\psi$	rotation matrix from SRS to FoVRS
REMAT	Relativistic Models and Tests, Subtask of DPAC Coordination Unit 3; also the working group of people in charge of this task
RGC	Reference Great-Circle
RGCS	Reference Great-Circle System
ROA	read-out amplifier (of a CCD)
RON	read-out noise (of a CCD)
ROR	read-out register (of a CCD), also called serial register
RVS	Radial-Velocity Spectrometer
s	second; SI unit of time
S_{kmn}	photometric signal in the sample with pixel coordinates k, m, n.
SBT	Satellite Base Time; the practical representation of OBT
SCRS	Spacecraft Reference System
SI	International System of units; defined by ISO
SM	Sky Mapper
SR	summing register (of a CCD), also called summing well
SRS	Scanning Reference System
T	any ephemeris time coordinate
T_{DE405}	time coordinate of specific ephemeris DE405
T_G	proper time of Gaia (abstract physical time); see also OBT
TAI	International Atomic Time
tbc	to be confirmed
tbd	to be determined
TCB	Barycentric Coordinate Time

TCG	Geocentric Coordinate Time
TDB	Barycentric Dynamical Time
TDI	time delay integration (Gaia's CCD operating mode), also called drift-scan mode
TT	Terrestrial Time
$type$	window type
u	general unit vector
UTC	Coordinated Universal Time
V	Volt; SI unit of voltage
VLBI	Very-Long-Baseline Interferometry
W	Watt; SI unit of power
w	FoVRS principal axis along scan
w	FoVRS along-scan field coordinate
WG	Working Group
x, y, z	SRS principal axes (but see also **z** below)
x, y, z	SRS cartesian coordinates (but see also z below)
X, Y, Z	ICRS principal axes
X, Y, Z	ICRS cartesian coordinates
Xfpa, Yfpa, Zfpa	FPRS principal axes
$Xfpa, Yfpa, Zfpa$	FPRS cartesian coordinates
$\mathbf{X}_s, \mathbf{Y}_s, \mathbf{Z}_s$	SCRS principal axes
X_s, Y_s, Z_s	SCRS cartesian coordinates
z	FoVRS principal axis across scan
z	FoVRS across-scan field coordinate
z	"zulu" = UTC
α	right ascension; ICRS coordinate; more generally an equatorial longitude coordinate
$\alpha_\wp$	right ascension of an RGC pole
γ	basic angle of the Astro instrument
δ	declination; ICRS coordinate; more generally an equatorial latitude coordinate
$\delta_\wp$	declination of an RGC pole
Δ_k	size of a sample along scan (in units of pixels)
Δ_m	size of a sample across scan (in units of pixels)
ζ	(1) FoVRS across-scan field angle
ζ	(2) SRS across-scan field angle; to be avoided
η	(1) FoVRS along-scan field angle
η	(2) SRS along-scan field angle; to be avoided
κ	along-scan pixel coordinate of a star image, transit time
μ	(1) across-scan pixel coordinate of a star image
μ	(2) micro-; SI units prefix for 10^{-6}
μas	microarcsecond, 10^{-6} arcseconds
ν	frequency (of radiation)
σ	general standard error
ψ	general rotation angle from SRS to FoVRS (there are two different ones)
υ	abscissa; RGC longitude coordinate; see also r

°	degree; unit of angle
’	arcminute, minute of arc; unit of angle
”	arcsecond, second of arc; unit of angle

2 Physical Units

This section sets a number of conventions on the usage and notation for physical and astronomical units. It is an almost unchanged but slightly extended copy of Appendix B of (10). That, in turn, is mainly based on the ‘Units home page’ of the National Institute of Standards and Technology (NIST; `http://physics.nist.gov/cuu/Units/`), which generally agrees with IAU recommendations
(`http://www.iau.org/IAU/Activities/nomenclature/units.html`).

2.1 SI units

In summary, we propose to use ‘acceptable SI units’ (as defined below) as default. We propose also to accept units of Julian years, parsecs, astronomical units, and magnitudes.

Following (1), notably his §5.4, we interpret the term ‘SI units’ as the seven SI base units (kg, m, s, mol, A, K, cd; see §4.1 in (1)), plus the 20 SI derived units (N, V, Hz, Gy, W, etc.; see §4.2 in (1)), plus the two SI supplementary units (rad and sr; §4.2.2 in (1)), including multiples and submultiples of these units formed by using SI prefixes ($\mathrm{M} = 10^6$, $\mathrm{k} = 10^3$, $\mu = 10^{-6}$, etc.; Table 5 in (1)). The term ‘acceptable SI units’ is taken to denote the ‘SI units’ (as defined above), plus those units accepted by the CIPM (Comité International des Poids et Mesures) for use with the SI (notably angular degree, arcminute, arcsecond, minute, hour, and day; Tables 6 and 7 in (1)), plus those units *temporarily* accepted for use with the SI (Table 9 and §5.2 in (1)), including multiples and submultiples of these units.

We also follow (1) and the IAU by recognizing that the use of time intervals expressed in units of Julian years (year), distances in units of parsecs (pc) or astronomical units (au), and source brightness/luminosity in units of magnitudes (mag) is allowed. The use of the non-SI unit Å is ‘temporarily accepted’ by (1) and ‘deprecated’ by the IAU; we propose that this unit is not used.

2.2 Notation of units

The interested reader is strongly advised to consult (1); we simply list a few specific remarks which are relevant in the light of Gaia:

- The angular units degree, arcminute, arcsecond may be abbreviated as 'deg', 'arcmin', 'arcsec' or denoted by the conventional symbols $^\circ\ '\ ''$.
- Submultiples of the arcsecond are denoted by 'mas' (10^{-3} arcseconds, 1 milli-arcsecond) and 'μas' (10^{-6} arcseconds, 1 micro-arcsecond). In an ASCII environment 'μas' is allowed to degenerate into 'muas'.
- The unit of a Julian year is denoted as 'year', in line with (1), §5.1.1. In theory, some confusion could arise when using 'y' instead of 'year'. For instance the SI unit 'Gy' (Gray, for absorbed radiation dose) could be mis-interpreted as 10^9 years. To add to this confusion, we note that the ('temporarily accepted') radiation unit 'rad' (not to be confused with radian) is defined as 'cGy', i.e., centi-Gray. Although in the context of Gaia, confusion in this area is generally not expected, the unit 'year' shall either be spelled out explicitly, or be abbreviated as 'a', following ISO and Section 8.1 in (1).
- The use of the phrase/unit 'micron' to denote μm is not allowed; this unit should be denoted as 'μm' (or as 'micrometer' in full or 'mum' in abbreviation in an ASCII-environment).
- Note the distinction between a bit (b) and a byte (B, meaning eight bits). Thus: 1 kb denotes one kilobit (10^3 bit) and 1 kB denotes one kilobyte (10^3 byte).
- Note the distinction between binary and decimal prefixes. For example, one kilobit (kb) denotes $10^3 = 1000$ bit but one kibibit (Kib) denotes $2^{10} = 1024$ bit. The prefix kilobinary, or kibi or Ki, means 2^{10}. More examples of binary prefixes, e.g. Mi=$2^{20} \sim 10^6$, Gi=$2^{30} \sim 10^9$ and a complete list can be found at `http://physics.nist.gov/cuu/Units/binary.html`.

3 Time Coordinates

The unit of time has universally been set to the SI second in the preceding section. This, however, is not sufficient to specify the usage and presentation of time coordinates. There are two main reasons for that:
1) There is no natural zero point for time.
2) Different physical time scales have to be considered in a relativistic framework (all using the SI second as unit, of course).

This section has been significantly revised compared to issue 6. The previous conventions have been kept, but there are significant additions which have turned up since 2007. Most significantly, the usage of Unix time and of OBMT has been added.

3.1 Basic Consensus

1. The basic time coordinate for all scientific Gaia data processing will be TCB (Barycentric Coordinate Time), i.e. the coordinate time of the Barycentric Celestial Reference System (BCRS).

2. The representation of this time coordinate will, as far as possible, be in terms of nanoseconds since J2010.0 (TCB).

3. TCB will also be the time coordinate underlying the final Gaia Catalogue data.

4. The practical representation of the timing of on-board events (Gaia's scientific observations in particular), and of data processing events on ground will be the on-board mission timeline (OBMT) and Unix time, respectively.

5. Specific conventions hold for the time tagging of epoch astrometry and epoch photometry (Section 3.8).

The meaning of the terms in these statements will be explained in the remainder of the present section; more details on the BCRS will be given in Section 4.

3.2 Notations for Time Coordinates

There are basically three standardized and unambiguous notations for the presentation of specific instants of time which are accepted for usage in the Gaia project. To these we add a fourth, Gaia-specific representation according to item 2 in Section 3.1. There are a lot of other time formats around, but they are either ambiguous, not readily sortable, or just superfluous and unnecessarily complicating practical work. The three accepted ones are:

1. The CCSDS/ISO 8601 convention for date/time character strings ((22)). It has the form:

   YYYY-MM-DDThh:mm:ss[.ssss...], e.g. 2003-05-26T14:45:56.12345

   Here 'YYYY' means the four digits of the year, 'MM' the two digits of the month, 'DD' the two digits of the day within the month — all in Gregorian calender counting. The symbols 'hh', 'mm', 'ss' analogously denote the two digits of hour, minute and second, respectively. The hyphens, the 'T' and the colons are fixed, compulsory separators. The brackets are not to be included in the string. They indicate that the part within them is optional. It consists of the decimal point (compulsory) and an arbitray number (≥ 1) of decimal digits specifying the fraction of the second. The three dots indicate the arbitrariness of the number of such digits. In the Gaia context the shorthand name of the underlying physical time scale will usually have to be appended in parentheses after the decimal digits, see Section 3.3.

2. The Julian Date. It has the form:

   JD nnnnnnn.d[ddd...], e.g. JD 2443144.5003725

   Here ‘JD’ is a format indicator, ‘nnnnnnn’ means the conventional 7-digit running Julian day numbering, the dot is a decimal point, and d[ddd...] as before indicates an arbitrary number (≥ 1) of decimal digits specifying the fraction of the day. Note that by definition the Julian Date has decimal fraction ‘.5’ when the CCSDS/ISO string ends as ‘T00:00:00’. Note furthermore that the Julian Date is always given with the decimal dot and with at least one decimal digit after the dot (contrary to the CCSDS/ISO string, which may end at the integer second). In the Gaia context the shorthand name of the underlying physical time scale will always have to be appended in parentheses after the decimal digits, see Section 3.3.

   The relation between the CCSDS/ISO string and the Julian Date can most easily be specified by an (arbitrary) example date. We choose:

   1 January 1977 0^h 0^m 0^s = 1977-01-01T00:00:00 = JD 2443144.5

3. Julian years. This notation has the form:

   Jnnnn[.dddd...], e.g. J1991.25

   Here ‘J’ is a format indicator, ‘nnnn’ means the 4 digits of the integer Julian year numbering, the dot is a decimal point, and [.dddd...]’ as before indicates an arbitrary number (≥ 0) of decimal digits specifying the fraction of the year. Note that the Julian year is *not* always given with the decimal dot and with at least one decimal digit after the dot (contrary to the Julian Date). Note furthermore that there is no blank character between the ‘J’ and the digits ‘nnnn’ (contrary to the Julian Date where there is one). In the Gaia context the shorthand name of the underlying physical time scale will usually have to be appended in parentheses after the decimal digits, see Section 3.3.

   The relation between Julian years and the CCSDS/ISO string or the Julian Date can most easily be specified by an (arbitrary) example date, keeping in mind that the length of the Julian year by definition is exactly 365.25 days. We choose an astronomical standard date:

   J2000 = J2000.0 = JD 2451545.0 = 2000-01-01T12:00:00

To these we add the already mentioned Gaia-specific representation:

4. Nanoseconds since J2010.0:

   No specific format is defined for this time representation.

   Time data in nanoseconds since J2010.0 will be used internally in all Gaia data processing environments whenever possible. Since one year has about 3 10^{16} nanoseconds and since the Gaia mission will possibly operate till about 2024, the nanosecond counter will run up to more than 10^{16}. This cannot be represented in a 32-bit integer, nor to full precision in an 8-byte float variable. Internally, in programs and databases, the quantity can be accomodated by a 64-bit integer (Java type 'long') or by two 8-byte floating-point variables (two variables of Java type 'double'). Both ways have been in practical use in prototype Gaia data reduction softwares. In the second version the first floating-point variable carries the (exact!) number of integer days, while the second one carries the fraction of the day in units of seconds (which will not be quite exact to the nanosecond, but almost so).

The representation for data exchange purposes is defined in the MDB[1] Interface Control Document (40).

Note that a numerical precision issue as mentioned in item 4. above similarly holds for the Julian Date and Julian year time format: In both cases a single 8-byte floating-point variable can represent the time to millisecond precision only.

For practical reasons the Gaia community uses other time representations (i.e. in addition to the four specified above), e.g. to accomodate the telemetry format chosen for the practical representation of the on-board time derived from Gaia's master clock (Section 3.7, and of Unix time (Section 3.6. However, the four standardized representations above should be used whenever possible.

As a last item on the issue of the representation of time coordinates we explicitly ban two inappropriate notations that are frequently used in astronomy: Usage of JED (Julian Ephemeris Date) and MJD (Modified Julian Date) is not allowed for Gaia. — JED is an unclear and obsolete synonym for JD (TT). The main reason to avoid MJD is the fact that different existing versions of "MJD" have created much confusion in the past. MJD has (at least!) been used to denote JD-2400000.5, JD-2400000.0 and JD-2440000.0, where especially the first two are very dangerous. MJD has been formally banned by the IAU recently.

Just for the convenience of astronomers, it should perhaps also be mentioned that the spaceflight community (specifically ESOC) uses two special notations for the ISO time character string (item 1 above): The integer-days part is often replaced by "doy" plus an integer number between 1 and 366; this is the "day of year", counted from January 1 as "doy 1". And the time coordinate UTC is often denoted as "z" (pronounced as 'zulu').

3.3 Different Physical Time Scales

In short, different physical time scales arise because of the (special-relativistic) time dilation of moving clocks (sometimes called kinematic time dilation), and because of the (general-relativistic) time dilation of clocks subjected to a gravitational potential (gravitational time dilation). It is not the intention of the present document to explain and discuss the physical

[1] MDB = Gaia Main Database

meaning of the various conventional timescales in use in astronomy. The interested reader may find more information in (17).

In the context of Gaia the following time scales may in principle play a role:

- TT, Terrestrial Time (formerly TDT, Terrestrial Dynamical Time), a scaled version of TCG (see next item); TT is very close to the proper time of a clock on the geoid.
- TCG, Geocentric Coordinate Time, the coordinate time of the Geocentric Celestial Reference System (GCRS, see Section 4.2.2). TCG should not be relevant for Gaia.
- TAI, International Atomic Time, a technical realisation of TT using a globally distributed set of atomic clocks; nominally TT=TAI+32.184 s.
- UTC, Coordinated Universal Time, the same technical realisation of TT, but including integer leap seconds; by definition TAI=UTC+10 s+leap seconds (note: the offset between TAI and UTC was already 10s when the leap seconds were introduced in 1972; for example as of Jan 2009, there were 24 leap seconds, but the offset between TAI and UTC was already 34 s); i.e. nominally TT=UTC+32.184 s+10 s+leap seconds. The official source giving UTC-TAI is the International Earth Rotation Service, see https://hpiers.obspm.fr/iers/bul/bulc/Leap_Second.dat
- TCB, Barycentric Coordinate Time, the coordinate time of the BCRS.
- TDB, Barycentric Dynamical Time, obsolete; a conventional linear function of TCB according to its IAU 2006 re-definition. It is the alternative (secondary) time coordinate — used by ESOC's flight dynamics department — in the Gaia-relevant solar-system ephemerides of the INPOP series. DPAC should never see TDB.
- T_G, 'Temps de Gaia', the proper time of Gaia's master clock; it is discussed in (47) in detail. See also Section 3.5.1.
- OBT, On-board Time, the reading of freely running on-board atomic clock . (notation from (18); the notation ST'' used in (2) is considered less suitable and shall thus not be used).
- OBMT, On-Board Mission Timeline, a modified version of OBT which ensures strict monotony (while OBT itself may possibly be reset during the mission). It is described in Section 3.7

The multitude of time scales makes it necessary to clearly specify which one is meant whenever a time coordinate is given. Thus it is requested that, whenever there is any danger of ambiguity, the shorthand name of the specific time scale is added (in parentheses) to the time string, Julian Date or Julian year. It is recommended to do this *always*.

Accordingly, for data processing interfaces containing time coordinates, the underlying physical time scale must be clearly identified in the definition/documentation.

Thus a complete time coordinate would read, e.g.

1977-01-01T00:00:00 (TAI) = JD 2443144.5 (TAI)

Convention: Among the time coordinates listed above, TCB will be the time scale to be used in the scientific treatment of Gaia data and for the Gaia Data Releases[2]. OBMT is the natural pseudo-time scale with which to label the Gaia raw observations and most intermediate DPAC data. UTC is the time coordinate used by the ESA ground segment to label the telemetry. All others will hopefully not appear at all.[3]
Special conventions hold for the time tagging of epoch astrometry and epoch photometry (see Section 3.8 below).

Implementation: The time transformations and their GaiaTools implementation are described in a lot of details in the three technical notes (47), (48) and (49). They are implemented in a general Java framework called `BasicTimeTransformations`. The additional Java class `GaiaTime` can only transform between TCB and OBMT.

> *In the IAU 1994 Resolution C7 (see e.g. IAU Bulletin 74) the above-mentioned standard epoch J2000.0 is defined explicitly as a time moment in TT, and the Julian century is defined as 36525 days of TT. This seemed to imply that a Julian day is 86400 SI seconds of TT and a Julian year is 365.25 Julian days of TT. An IAU 2006 decision allows that JD and Julian years can be used with any other timescale as well (TCB, UTC, ...), but that the timescale must be explicitly specified.*

3.4 Spacetime Events versus 'Moments of Time'

This short tutorial section is intended to avoid possibly harmful misunderstandings by non-physicists. Everyday experience suggests that there is something like a "physical moment of time", which can be expressed numerically as TT, TCB etc. This would make life easy, but in General Relativity (i.e. in the real physical world) there are no physical moments of time. Instead, there are only 4-dimensional 'events' in spacetime. These always have four coordinates: one time coordinate and three spatial ones. One and the same event could in principle be expressed numerically in an (infinite) variety of 4-dimensional reference systems. In particular this means that if we mean some arbitrary event, we must also specify its spatial position in order to be able to transform between, say, TCB of that event and TT of that event.

[2] It was decided that the solar-system task of DPAC will provide UTC in addition to TCB to label scientific data, just in order to facilitate life for some end-users (including the Minor Planet Center).

[3] T_G is used as intermediate time scale internally in the relativistic modelling software REMAT for the high-accuracy time transformation (HATT).

The spatial locations for all spacetime events relevant for Gaia will either be the location of Gaia, or some point (ground station antenna) on the surface of the Earth. So, in practice, the Gaia project will need transformations between TT (represented by UTC) and TCB at the ground stations, and between OBMT and TCB at the location of the Gaia spacecraft. These transformations are dependent on the masses and orbits of the bodies in the solar-system (represented by some tabulated solar-system ephemeris) and on the Gaia orbit within the solar system. So at least the latter transformation cannot be determined in advance! For details see (47).

> *In practice, an approximation to the transformation OBMT –> TCB [at Gaia] or T_G –> TCB [at Gaia] can be computed once the barycentric orbit of Gaia is known to some precision. An impression of how this transformation could look like (using a rather simple formula) can be seen in (36).*

It should furthermore be noted that TCB does not correspond to the proper time at the barycenter of the solar system. This is a widespread misunderstanding among astronomers. Nor does it correspond to the proper time of any other body or location in the solar system[4]. TCB at the surface of the Earth differs from TAI by a large offset (in the order of 1 minute), small periodic variations (in the order of 1 msec and smaller) and — most importantly — by a different mean rate: It runs faster by about 0.5 s per year.

3.5 Reference Epoch

It appears useful to define a Gaia-specific reference epoch for the practical presentation of times. In the Hipparcos project, the community continually was faced with studies/results that used a different time origin for plots of instrument parameters, light curves of variable stars, attitude parameters and so on. With Gaia the same problem can be expected: different people might adopt some adopted nominal launch date, or some nominal operations start date, or the beginning of a particular year, etc.

Following a suggestion by M. Perryman it is therefore proposed:

- Whenever it seems appropriate to list, or plot, or tabulate (...) times with respect to some specific time origin (‘reference epoch’), the epoch J2010.0 shall invariably be used.
- Whenever this convention is utilized, it shall be explicitly stated in the labelling of the time axis of a plot, or in the header of a table, or in the legend of a list (...), e.g. as ‘time - J2010.0’.

[4] TCB is equivalent to the proper time experienced by a hypothetical clock at rest in a coordinate frame co-moving with the barycentre of the solar system, but outside its gravity well, therefore not influenced by the gravitational time dilation caused by the Sun and the other bodies in the Solar system.

- If this convention is to be used in a high-precision context, the relevant physical time scale shall be explicitly specified, e.g. as 'UTC - J2010.0(UTC)'.
- If the time unit is to be directly included in the label (e.g. for lack of space), short-hands in the form of 'days since J2010.0' or 'seconds since J2010.0(TCB)' etc. can be used.

Note: J2010.0 = JD 2455197.5 = 2010-01-01T00:00:00

Attention: This is at a non-integer day offset from J2000.0 !

3.5.1 The zeropoint of T_G, Gaia's proper time

The definition of T_G as the proper time of Gaia's on-board clock leaves its zeropoint undefined. We herewith define this zeropoint by setting:

T_G = TCB [at Gaia] = $T_{G.zero}$ = TCB$_{zero}$

for some specific instant of time $T_{G.zero}$= TCB$_{zero}$ close to the start of the scientific operations of Gaia. The square brackets above indicate the (quite obvious) necessity to use TCB at the spatial location of Gaia for this definition.

The reference instant $T_{G.zero}$= TCB$_{zero}$ was defined as JD 2457023.5 TCB and was included in the Gaia Parameters Database.

3.6 Practical Time Scale for Data Processing Events: Unix time

In addition to TCB, T_G (see above) and OBMT (see below) to measure events at the spacecraft, we need a time scale to timestamp events in the processing pipeline on Earth (more specifically, at the Data Processing Centers).

For example, DPAC data items like:
`SolutionIdMeta.generationTime`, `SolutionIdMeta.solutionEndTime`, `InputDataUsed.generationTime` require ground-based timestamps. These timestamps relate to processing events and are therefore independent of spacecraft events.

Up to the year 2015, and unofficially, a Unix-based timescale corresponding to the number of milliseconds since 1970-01-01T00:00:00z (see `https://en.wikipedia.org/wiki/Unix_time`) has been employed for the majority of these situations. Following discussions between U. Bastian, A. Brown and H. Siddiqui in early September 2015, the DPAC Chairman (A. Brown) approved introducing this timescale officially within DPAC (See Jira issue C3ACT-148).

Note:

1. The Unix time does not take into account leap seconds and is therefore continuous.

2. Software will usually make use of the Java method System.currentTimeMillis() to perform the timestamping. This would in turn make use of the internal system clock of the hardware in question, and thus variations across internal clocks of machines could introduce small errors in the timestamping. This is expected to be small, and each DPC should ensure that such variations are indeed small, by making use of NTP servers for synchronization, etc. (see `https://en.wikipedia.org/wiki/Network_Time_Protocol`).

3.7 Practical Time Scale for On-board Events and Gaia Data: OBMT

3.7.1 OBT (not OBMT)

All timing information on the Gaia observations is ultimately derived from OBT, the On-Board Time, which is generated by a high-precision Rubidium atomic clock. OBT is a discrete integer counter with which the science telemetry, i.e. the star packets (SPs) and auxiliary science data (ASD) are labelled. The resolution ("step" or "unit") of this counter is 50 nanoseconds, corresponding to the 20 MHz basic frequency of the on-board clock distribution unit (CDU).

OBT is not a strictly physical time coordinate. But, being derived from an atomic clock on board Gaia, it is at any time very close to a linear function of the proper time (in the sense of General Relativity) on board of Gaia.[5] In other words, it is very close to a scaled and offset version of Gaia's proper time, i.e. of T_G. Furthermore, despite its low resolution of 50 ns, it has a very high inherent precision and consistency (about a nanosecond per hour, or about 20 nanoseconds over a whole day, or better than 10^{-13}).

3.7.2 OBMT

In November 2008, the DPAC agreed to use a modified version of OBT as the technical time coordinate and as "datation label" for all intermediate data in the Gaia data reduction. It is named OBMT, On-Board Mission Timeline. It is completely defined and explained in BAS-030, (42). Parts of the present section are copied from the introduction of that document.

Why a *modified* version of OBT? Firstly, because OBT may (at least in principle) experience overflows and resets (a reset has actually occurred in the early mission!). Therefore OBT itself is not usable as unique "datation label". Secondly, the resolution of 50 ns is insufficient for astrometric purposes.

[5] Actually, the scale is slightly time-dependent, i.e. the function is slightly non-linear. This is due to the natural property of atomic clocks called "frequency drift".

Why not label the intermediate science data with a physical time coordinate (e.g. TCB or T_G) right away? Because any physical time coordinate on board Gaia must necessarily be derived from OBT by a calibration process. However, such a calibration may change — which means: improve! — even months or years after the initial data treatment, because it necessarily involves imprecisely known quantities (e.g. Gaia's orbit in the solar system, and ground-station time delays) as well as scientific judgement (e.g. how to model the on-board atomic clock, and how to compute the light-travel time delays). Such changes would imply a delicate versioning control to avoid inconsistencies in the data interpretation. On the contrary, labelling all intermediate data with a never-changing "datation label" will avoid any possible confusion or inconsistency in a very straightforward way. This reasoning was presented in more detail to the DPAC Executive and to a SOC/IDT/FL coordination meeting by U. Bastian in the fall of 2008, see http://gaia.esac.esa.int/dpacsvn/DPAC/meetings/DPACE/DPACEM07/BAS-DPACE-07-time-coordinates.ppt.

Any physical (astronomical) interpretation of the Gaia observations will of course need reference to a truly physical time coordinate. This is needed for the proper access to the Gaia orbit file and solar-system ephemerides, and for the comparison of Gaia photometry with ground-based variable-star data, for instance. Also, all published Gaia mission products (final and intermediate) must of course be labelled with a physical time coordinate.

For this purpose, there will at any time be a best-effort time calibration, linking OBMT to physical time coordinates like TCB and T_G. It will be produced by the SOC/CU1, using concepts and software provided by the CU3 working group REMAT. To its users it will be an easy-to-use black box. It will be versioned, but any version of it will produce internally correct and consistent results.

OBMT, like other time representations within DPAC, has a resolution of 1 nanosecond. For practical reasons, there will also be a reduced-resolution version of OBMT, with a resolution of 50 nanoseconds. This is called OBMT50.

For the sake of human readability and mnemonic convenience, an additional, very special time unit is introduced[6] for the representation of OBMT: "revolutions", abbreviated "rev". One revolution corresponds to 6 hours of OBMT, i.e. the nominal rotation period of Gaia. Strictly, it is OBMT(nanoseconds) divided by (10^9*6*3600). This unit is very useful especially in graphical representations of most data products derived from Gaia telemetry, as any effects recurring with the rotational period of Gaia will appear in intervals of (very nearly) 1 revolution.

3.7.3 The basic definition

The definition of OBMT by necessity must be linked to the time intervals between successive OBT overflows or resets, respectively. Let us for brevity call these time intervals "OBT sec-

[6] Decided by the DPACE on its 31st telecon, April 5, 2013.

tions".

Here is the formal definition of OBMT and OBMT50:

- OBMT and OBMT50 each are represented by a Java `long integer` variable.
- Within each OBT section, OBMT50 differs from OBT by a strictly constant integer offset. This offset will be set by SOC/MIT and publicly recorded in a dedicated MDB table.
- For all times, OBMT differs from OBMT50 simply by a factor of 50.
- OBMT and OBMT50 by definition must be strictly monotonous wrt. physical time on board, but they can have positive jumps at times of OBT resets and overflows, i.e. across the boundaries of OBT sections.

More details and explanations on the definition of OBMT and the basic aspects of its practical creation and handling by the MOC Interface Task of CU1/SOC are given in BAS-030, (42). The general DPAC reader needs only know and understand Sections 1 to 3 of (42). The rest of that document is relevant only for the CU1/MIT and CU3/REMAT groups.

> *The concept (and name) of OBMT was initially introduced in (43) for the purpose of defining the Transit Identifier. In addition, (44) describes the detailed assignment of OBMT values (from window datation items in the telemetry) to e.g. individual CCD samples, and the derivation of the time-like astrometric centroid locations* `smObservingTime` *and* `afObservingTime` *in the* `AstroElementary` *records.*

3.7.4 Some Additional Background

This subsection does not contain information needed for the usage of the conventions above. It is for illustration and additional understanding only.

On board of Gaia the absolute time in some conventional physical time scale does not need to be known to high precision. The only uses of absolute time on board concern the Nominal Scanning Law (it has a time-like argument) and maybe the calculation of stellar aberration for the star tracker. A millisecond or so is amply sufficient. For all other on-board purposes, OBT is just a counter of the master clock.

For the scientific usage of the Gaia data, however, OBT needs to be represented in terms of an absolute physical time coordinate, TCB. The needed precision varies with the scientific application. It ranges from a microsecond for the investigation of some general-relativistic aspects, to a millisecond for the astrometry of solar-system objects (the apparent motion of a minor planet typically is of the order of 10–50 μas per millisecond), to 0.1 seconds for photometry and variability studies (email from L. Eyer of 2006-10-09, considering the time resolution of 4 s of any photometric measurement by Gaia), and to one minute for stellar astrometry (the quickest known star in the sky moves by 2 μas per minute).

The relative time precision that is needed on board is of the order of 10 ns, since 17 ns correspond to 1μas of scan on the sky. This is the stability of the TDI clock required to make Gaia's astrometry possible.

The 20 MHz master clock signal of Gaia must be divided (and perhaps multiplied) to give other, secondary time signals (loosely called 'clocks') driving all sorts of processes on board. One example is the TDI clock giving one 'tick' (clock stroke) every 982.8 μs=19656 master clock periods, i.e. at about 1.02 kHz. For some of these secondary clocks there will be counters generated within the DPAC processing chain.

Note that the sequence of TDI lines from the Gaia CCDs constitutes a special kind of time coordinate, representing OBT or OBMT in units of TDI clock strokes. The running counter k of this time coordinate will be called 'along-scan pixel coordinate' and carefully discussed in Section 6. Considered as a consistent integer counter, k will run up to the order of 10^{11} over the mission lifetime.

The practical representation of the OBMT counter (in nanoseconds) will not fit into a single integer variable for the whole mission, as it will run up to the order of $3\,10^{17}$ in ten years. At 20 MHz it will run to the order of 10^{15}. Even at a resolution of only 1 TDI period (about 1 ms) it would run to the order of 10^{11}.

3.8 Time tagging of epoch astrometry and epoch photometry

Two different schemes will be used for the time tagging of epoch data in Gaia Data Releases:

- For solar-system objects, the times for both the epoch astrometry and the epoch photometry will be provided as TCB at Gaia, i.e. as the actual TCB coordinate of the effective observation time at the spacecraft (but, as mentioned before, UTC will additionally be given as purely ancillary information in this case).
- For sources outside the solar system, the time tagging for the epoch photometry will be TCB at the solar system barycentre, i.e. the time at which the wavefront(s) observed by Gaia pass(es) the spatial origin of the BCRS.
- However, the epoch astrometry for sources outside the solar system will time-tagged by TCB at Gaia.

In all three cases, the precision shall be the best possible, e.g. no approximations shall be applied for the barycentric light-travel time correction, nor for the geometric position of the observed object, nor for the transformation from OBMT to TCB at Gaia. The gating of CCDs shall be taken into account in the computation of the individual effective observation times (i.e. halfway between the start and the end of the exposure time on the specific CCD during the transit of the observed celestial object).

The above decisions were taken by the DPACE Telecon no. 60, June 16, 2017 (the minutes of the telecon are in GAIA-CD-MN-LEI-AB-084-1), after discussions via email and Jira issue C9DM-278. It should be added that

- the same rules shall hold for epoch data from the RVS (epoch radial velocities and possibly epoch astrophysical parameters)

The convention given above does not mean an unnecessary and unjustified inconsistency in DPAC output data, but it is inherent to the matter. Firstly, given the smallness of the possible errors due to changing assumptions on the relevant star position, it would be perfectly unreasonable to bother stellar astronomers with the processing of Gaia orbit files to get consistent light curves for their objects. It is a big and well justified convenience to them that we do the barycentric correction for them. Secondly, for solar-system objects it would be just wrong to try and do any correction of the observation time from Gaia-centric to any other place in the solar system. For a newly discovered SSO, the position along the line of sight is undefined; so you don't know how to correct at all. This also holds for the majority of already discovered objects (that have no reasonable orbit yet). For many others, the orbit will still be too badly known to do a sound correction. Even an uncertainty of only 300 km (this is not bad for present-day standard orbits) in the assumed SSO position along the line-of-sight would typically give a 150 mas astrometric error (300km/3au) and a 1msec timing error (300km/c). Thirdly, SSO people are used to the need of taking the observer's location precisely into account. So, contrary to stellar astronomers, they know the problem and have the means for correct treatment.

4 Reference Systems and Reference Frames

A number of different coordinate systems are needed for the description of different aspects of the spacecraft, the instrument and the measurements, and equally for the description of the universe to be observed. They will be described in this section.

Before going into the definition of individual systems and their practical representations, a few general, tutorial remarks should be given. This is the purpose of the following Section 4.1

4.1 General Remarks on Reference Systems and Reference Frames

Present-day terminology distinguishes between reference systems and reference frames. In short, a reference system gives a more or less ideal, abstract definition of a coordinate system, while a reference frame is a practical realisation of such a system.

Astronomical reference systems and reference frames play two very different roles:
1) They are used to represent actual measurements made by real instruments in a standardized, uniform way that is independent of the specific instrument and circumstances: The direction of light rays measured by Gaia somewhere on its orbit will ultimately be represented by coordinates (α and δ) in the barycentric International Celestial Reference System (ICRS) — or rather in a practical realisation of it, the International Celestial Reference Frame (ICRF).
2) They are used to represent the paths of celestial bodies (artificial or natural) through the solar system: The orbits of Gaia and Earth around the sun will be represented in a barycentric reference frame whose axes are (nominally) the same as those of the ICRF.

At the precision level reached by the Gaia measurements it is mandatory that the applied astronomical reference systems are fully relativistic, i.e. 4-dimensional[7] and in accordance with General Relativity. The choice of such systems is also made necessary by IAU conventions, to which the Gaia project will adhere.

In addition to astronomical reference systems there are mechanical (spacecraft or payload) reference systems. These are used to describe the locations and orientations of hardware parts of the actual Gaia spacecraft and payload. As before, they may come in two flavours, namely as abstract definitions and as practical realisations. However, this distinction is less fundamental here than in the case of astronomical systems.

The mechanical reference systems are spatially Euclidean, as there is, of course, no noticeable space curvature over the few meters that the spacecraft extends within the relativistic universe. The natural time coordinate would be proper time of the spacecraft, but in practical usage the mechanical reference systems will be just three-dimensional.

> *Comment by S. Klioner: This is acceptable from the relativistic point of view because there are no physical "events" to be described in the mechanical reference system(s) which need to be time-tagged with high precision. The mechanical systems will be used only to describe essentially time-independent lengths.*

A synoptic diagram giving an overview over the various reference systems and their mutual relations is given in Fig. 1.

[7] Three are spatial dimensions; the fourth (or more frequently 'zeroth') dimension, time, has been discussed in Section 3

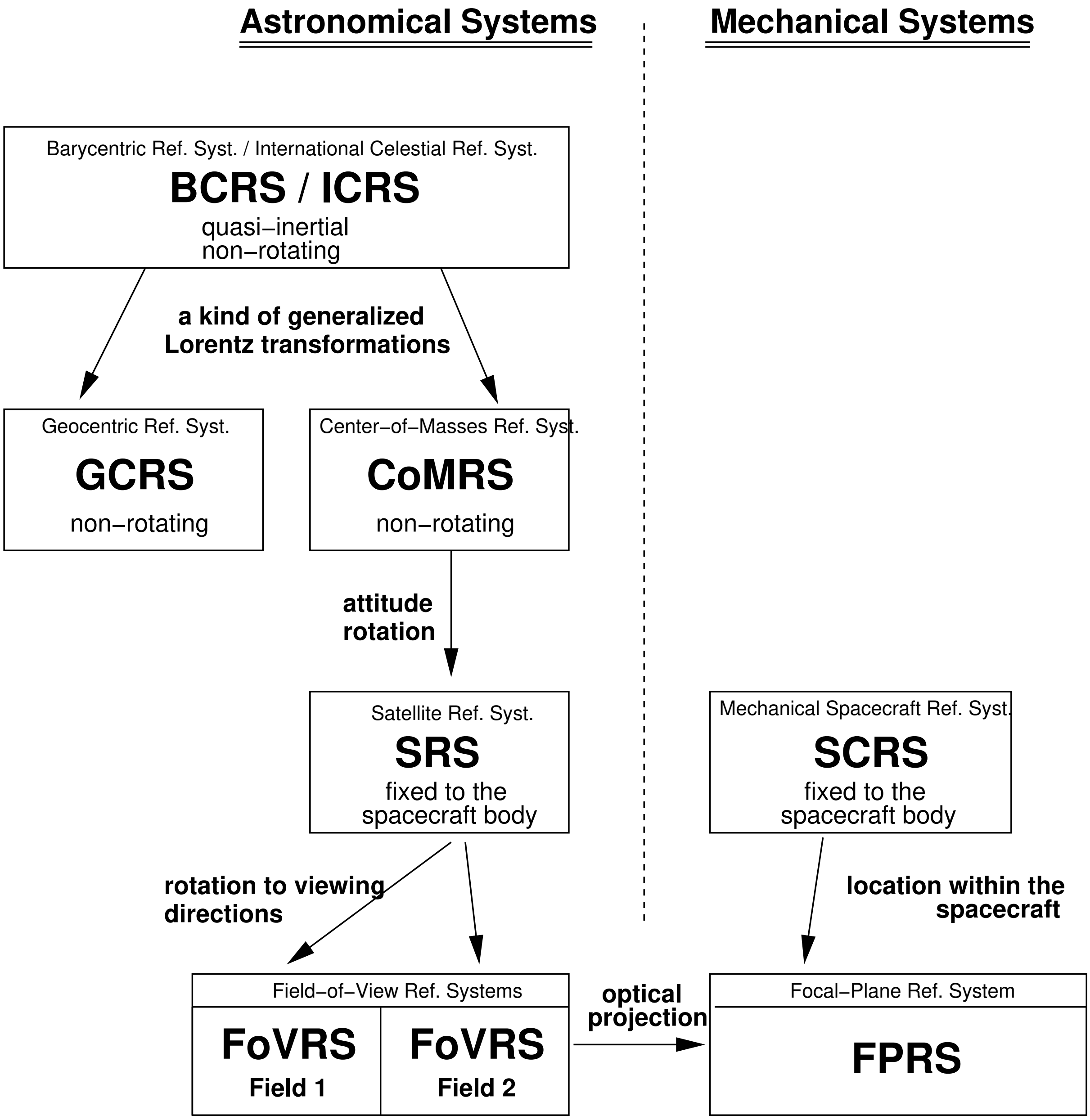

Figure 1: Schematic overview of the reference systems defined in Section 4

4.2 Astronomical Reference Systems

4.2.1 The International Celestial Reference System (ICRS) and the BCRS

The ICRS is the primary reference for astronomical coordinates. All other astronomical systems in this document are derivatives of the ICRS.

4.2.1.1 ICRS, Definition .

Star positions, or more generally, directions in the astronomical sense, are given in the International Celestial Reference System (ICRS). The spherical longitude and latitude coordinates are called right ascension (α) and declination (δ). The fundamental plane ($\delta = 0$) and the zero point ($\alpha = 0$, $\delta = 0$) of the ICRS nominally match the Earth's equatorial plane and the direction to the dynamical spring equinox at the beginning of the year J2000, respectively. This is the historical reason why α and δ are called equatorial coordinates. But strictly (see below) their definition carries no reference whatsoever to the actual orientation of the Earth's orbit or rotation axis.

The ICRS defines the spatial orientation of a more general, fully relativistic 4-dimensional reference system, the Barycentric Celestial Reference System (BCRS), as defined by the IAU in 1991 and extended in 2000. The official form of the definitions can be found in (3). The complete post-Newtonian metric and other formulae are summarized in (12).

The spatial origin of the BCRS is the solar-system barycentre. Its time coordinate is the Barycentric Coordinate Time (TCB). Its full metric will be used in the Gaia data reduction, but its details are not necessary for the present document. They are described in (12). More explanations can be found in (15).

The BCRS/ICRS by definition is supposed to constitute a quasi-inertial and rotation-free reference system. It is defined to be nonrotating with respect to distant extragalactic objects. Since the BCRS is constructed under the assumption that the solar system is isolated, any rotational and translational non-inertiality of the BCRS comes only from the tiny galactic forces acting on the solar system. From the point of view of the practical realization of the ICRS its rotational and translational non-inertiality can be additionally due to the uncertainty of the associated reference frame (see below). [8]

4.2.1.2 ICRS, Reference Frame (ICRF) .

The practical realisation of the BCRS/ICRS, called ICRF, consists of two parts:

1) A set of distant radio sources defining the spatial orientation, viz. the International Celestial Reference Frame (ICRF). The primary practical realisation is a set of a few thousand extragalactic sources observed with radio VLBI. Further details can be found in (4). The actual list of objects is given in (6). A secondary practical realisation is the Hipparcos Catalogue (7) of

[8] The points are (1) the rotational noninertiality of the BCRS is known and amounts to about 1 muas per century (geodetic precession due to the Galaxy), (2) the barycenter is defined by the ephemerides which always have some errors and also do not take into account many (partially unknown) minor bodies changing the position of the barycenter significantly.

118 000 stars[9], soon to be replaced by ICRF-3 and Gaia-CRF2. Both the primary and the secondary realisations give two-dimensional celestial coordinates of the observed objects (in the case of Hipparcos and Gaia as function of time).

2) An ephemeris giving the three-dimensional spatial coordinates of solar-system bodies as function of a time coordinate.

The present precision of the VLBI frame (ICRF-3) is typically better than 0.1 mas for the individual sources. Altogether they define the directions of the coordinate axes at a level of about 0.02 mas. The Hipparcos precision for individual sources is of the order of 1 mas (in 1991) and 30 mas (in 2020), respectively. Altogether they define the directions of the coordinate axes (with respect to the primary VLBI frame) to about 0.5 mas (in 1991) and 4 mas (in 2020). The time dependence results from the uncertainty of the proper motions for individual sources and from the uncertainty of the global rotation rate of the system, respectively. Details can be found in (7), Vol.3, Ch.18.

4.2.1.3 ICRS, Celestial Coordinates .

The location (or, in more relativistic terms, the trajectory or 'world line') of a physical body in the BCRS is given by three spatial coordinates and a time coordinate. In astronomy, the direction to a body can usually be measured much more precisely than its distance. Thus it is useful to split the spatial coordinates into two angular ones and a distance. This, in other words, means to represent the location of the body by a unit vector (the coordinate direction to the body) and its length. The angular coordinates by convention are the spherical longitude and latitude, called right ascension (α) and declination (δ).

The unit vectors along the principal directions of the BCRS/ICRS are denoted **X, Y, Z**, with **Z** pointing towards $\delta = +90°$, the ICRS north pole, **X** towards ($\alpha = 0,\ \delta = 0$) and $\mathbf{Y} = \mathbf{Z} \times \mathbf{X}$. Thus the system **X, Y, Z** is right-handed. A general unit vector **u** has direction cosines X, Y, Z, such that

$$\mathbf{u} = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z} \tag{1}$$

with $X^2 + Y^2 + Z^2 = 1$, and

$$X = \cos\alpha\cos\delta \tag{2}$$
$$Y = \sin\alpha\cos\delta \tag{3}$$
$$Z = \sin\delta \tag{4}$$

There is no physical unit associated with the cartesian coordinates (X, Y, Z). The angular coordinates (α, δ) will be given either in radians, or else in degrees, arcminutes and arcseconds.

[9] More precisely, IAU in (3), Resolution B1.2, specifies that the 'Hipparcos Celestial Reference Frame' (HCRF) will exclude those Hipparcos stars flagged as astrometrically peculiar or suspicious.

Practical considerations will lead to radians for computational purposes (e.g. subroutine call parameters, data base entries etc.), while printed presentations will frequently use degrees, arcminutes and arcseconds. No strict convention needs to be set here, because there is no real danger of confusion.

The ICRS coordinates are illustrated in Fig. 2.

The natural time coordinate to be used along with celestial ICRS coordinates is TCB. TCB can be transformed to and from other relevant time coordinates — TT, TAI, TDB, UTC — by standard procedures. Some of these are exact by definition, others contain integrals of orbits in the solar system, relativistic effects etc. and thus are both non-trivial and subject to uncertainties, with the precision of these transformations gradually increasing due to better ephemerides and general physical knowledge.

The primary quantity to be measured in astrometry is the direction of light rays. This quantity also can be expressed in the ICRS by spherical longitude and latitude coordinates (α) and (δ), or else by cartesian unit vectors. Conceptually, however, it should not be mixed up with the BCRS coordinates of the corresponding body from which the light ray originated. Light rays are curved, and the observed direction of a light ray depends on the point of observation and on the motion of the observer.

4.2.1.4 ICRS, Ephemeris Coordinates .

The primary practical realisation is given by the "INPOP" series of ephemerides of the IMCCE (Paris). The presently (2020) valid version is INPOP 10e, see (39). The INPOP seies nominally implements the BCRS, with TCB as time coordinate. It gives three-dimensional spatial coordinates of natural solar-system bodies as function of TCB. The origin of these coordinates is in the solar-system barycentre. The orientation of the coordinate axes is nominally given by the ICRS. The physical length unit associated with the spatial coordinates is the astronomical unit, strictly defined by the IAU via an exactly fixed number of SI meters (IAU resolution 2012-B2).

Since there will never be a danger of confusion with celestial coordinates, ephemeris coordinates can also be denoted X, Y, Z.

> *The Gaia orbit files delivered by ESOC are based on the IMCCE ephemeris INPOP 10e. These files deviate from the above conventions in two ways: The spatial coordinates are 'geocentric'; they are the difference between the fitted BCRS coordinates of Gaia and of the Earth's center of mass. The time coordinate is taken from the TDB version of INPOP. Transformations to TCB and genuine BCRS coordinates are provided by the GaiaTools library.*

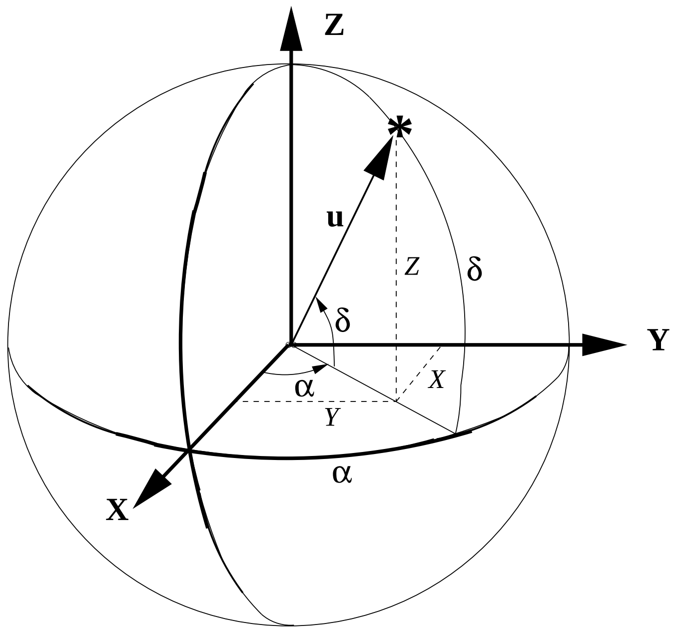

Figure 2: Illustrative sketch of the celestial sphere indicating the ICRS spherical coordinates (α, δ) and direction cosines (X, Y, Z) of a unit vector **u** towards a star (upper right), with the origin of (α, δ) at front left and the ICRS north pole towards the top.

4.2.2 The Geocentric Celestial Reference System (GCRS)

In certain fields of science (geodesy, geophysics etc.) this reference system is the natural one. It is also of importance for parts of astronomy, since most astronomical observations are made with instruments moving with the Earth. Also, spacecraft orbits (ephemerides) are frequently described in geocentric terms.

The GCRS plays no role in the Gaia data reduction. Nevertheless, for completeness it will be briefly described here. Note that the above-mentioned geocentric presentation of the Gaia orbit files is strictly in the BCRS, not in the GCRS.

4.2.2.1 GCRS, Definition .

The GCRS is defined by the BCRS/ICRS and the coordinate transformations given in the IAU Resolution B1.3 (2000), as given and explained in (3) and (12).

The spatial origin of the GCRS is the barycentre of the Earth. Its time coordinate is the Geocentric Coordinate Time (TCG). By definition, TCG is close to TT, but not identical. The differences are irrelevant for most purposes. The GCRS is defined by the IAU as kinematically non-rotating with respect to the BCRS.

> *S. Klioner comments: By this definition, the GCRS is not an inertial system. The orbit of the Earth around the sun causes variable aberration of light, varying coordinate velocities of observed celestial bodies etc. Furthermore, the kinematically-nonrotating nature of GCRS implies that no traces of geodetic precession can be seen in the GCRS positions of remote sources (stars). The price for this nice property in that some "artificial" Coriolis force appears in the dynamical equations of motion of test particles modelled in the GCRS. This relativistic Coriolis force for the Earth satellites is given e.g. in Chapter 10 of the IERS Conventions 2000, which are available from the following URL:* `http://iers-conventions.obspm.fr/`*, which can be found through* `https://www.iers.org/IERS/EN/Organization/ProductCentres/ConventionsCentre/conventions.html`.

4.2.2.2 GCRS, Reference Frame .

A kind of realization of the GCRS can be obtained by applying the formal BCRS-GCRS transformations on any realization of the BCRS (e.g. the INPOP Ephemeris). More practical realizations are the coordinates (as functions of time) of certain satellites (Lageos, or GPS/NAVSTAR) or of observing sites on the Earth (plus, in this case, a model for the rotational motion of the Earth about its own barycentre).[10]

4.2.2.3 GCRS, Celestial Coordinates .

Celestial Coordinates in the GCRS do not play a role for Gaia.

4.2.2.4 GCRS, Ephemeris Coordinates .

Ephemeris coordinates are given by practical ephemerides, as for the BCRS. Details of the relativistic coordinate transformations between BCRS and GCRS can be found in (12).

[10] Such a model is provided by the International Earth Rotation Service, under the name of Earth Orientation Parameters (EOP). However, it will not be used directly for the Gaia operations and data reduction (implicitly it will, of course, due to the ground stations being located on the rotating Earth; but this is treated by the ground segment internally). The interested reader will find details in (11).

Sources at distances further than about 100 pc cannot be described in the GCRS at all, since the GCRS is not (and cannot in a relativistically consistent way be) defined so far from the geocenter. This is one of the reasons why celestial coordinates of remote (astronomical) objects will not play a role in the GCRS.

4.2.3 The Center-of-Mass Reference System (CoMRS)

The CoMRS is a non-rotating system that moves with the Gaia spacecraft. In the terminology of (13) it is the proper system of Gaia. In the terminology of (14) (Sections 9.2.1 and 9.3.3) it is the local rest frame of the Gaia instrument.[11] The significance of this system is expressed by the fact that the *measurable* angle $\psi_{1,2}$ between the light rays from two different sources at the Gaia spacecraft is simply given by the Euclidean product of their cartesian direction vectors (unit vectors) $\mathbf{u_1}, \mathbf{u_2}$ — if these are expressed in the CoMRS:

$$\cos\psi_{1,2} = \mathbf{u_1} \cdot \mathbf{u_2} \tag{5}$$

In other words: This is the natural system in which to describe the measurements made by Gaia.

4.2.3.1 CoMRS, Definition .

The CoMRS is not defined explicitly by any resolutions of the IAU or other institutions. However, it must be defined fully relativistically. A rigorous relativistic definition of the CoMRS and a detailed discussion of its properties can be found in (38) and references therein.

The CoMRS is defined to be kinematically non-rotating with respect to the ICRS/BCRS. Its spatial origin is the center of mass of the Gaia satellite. For events at the origin (i.e. at the center of mass of Gaia, the only location of interest with respect to the Gaia data reductions) the time coordinate of the CoMRS exactly coincides with the proper time at the center of mass of the satellite. The latter is called T_G (see Section 3.3). Its practical realisation, called On-board Time (OBT), is produced by an atomic clock on board.

Note that, by this definition, the CoMRS is not an inertial reference system. The orbit of the spacecraft around the sun causes variable aberration of light, varying coordinate velocities of observed celestial bodies etc.

> *Physically the CoMRS is an analogue of the GCRS, the differences being that the origin is Gaia instead of the Earth and that the gravitational potential of the satellite itself is ignored since it is negligible. The time coordinate of the CoMRS is a coordinate time in analogy to TCG.*

[11] Note that the CoMRS is called 'satellite reference system' in (14). We deviate from that naming for the sake of clarity; see also Section 4.2.4

4.2.3.2 CoMRS, Reference Frame .

Analogous considerations to Section 4.2.2.2 hold here. The practical realisation of the CoMRS will be some realization of the BCRS, plus the BCRS-CoMRS transformations as defined in (38). A practical realisation of the CoMRS must thus include a representation of the Gaia orbit in the BCRS. Note that, since the CoMRS is defined as non-rotating with respect to the BCRS, the rotational motions of the Gaia spacecraft are treated separately; see Section 4.2.4.

4.2.3.3 CoMRS, Celestial Coordinates .

Coordinate directions to celestial bodies and coordinate directions of light rays are defined and denoted as for the ICRS. For a given astronomical source the coordinate directions of light rays differ from the ICRS coordinate direction to the same source in a way that is discussed in Section 4.2.3.6 below.

4.2.3.4 CoMRS, Ephemeris Coordinates .

Ephemeris coordinates in the CoMRS will probably not play any role for Gaia. If they should, analogous consideration to Section 4.2.2.4 would hold.

4.2.3.5 CoMRS, Transformation ICRS $\rightarrow$ CoMRS .

The transformation of the ICRS coordinate direction towards a source into the CoMRS coordinate direction of a light ray coming from that source (and vice versa) is one of the central topics of the Gaia astrometric data reduction. In astrometric terms it is the computation of proper directions (in technical Gaia documents it frequently appears under the heading of 'astrometric modelling'). A summary description is given in Section 5.2 of (20). The details have been subject of intense study by the REMAT Group. They are not a subject of the present document. The results have been coined into standard DPAC software routines within the GaiaTools library.

4.2.3.6 CoMRS, Kinematically Nonrotating Reference Systems .

In principle there are several "natural" choices of the orientation of a local reference system with respect to the ICRS/BCRS being a global one. One choice which is used by the IAU conventions and for the Gaia project is to define the local reference systems to be kinematically nonrotating with respect to the BCRS. The exact mathematical meaning of this can be found in the literature (e.g. in (12)).

From the practical point of view such a choice guarantees that the proper direction vector in the CoMRS of a light ray coming from any given astronomical source shall differ from the ICRS/BCRS proper direction vector toward the source only by the effects of:

- parallactic displacement due to the spatial offset between the solar-system barycentre and the Gaia spacecraft
- light travel time effects due to the spatial offset between the solar-system barycentre and the Gaia spacecraft
- light-bending due to the gravitational effects of the heavy bodies in the solar system
- aberration of light due to the Lorentz transformation from zero barycentric velocity to the actual barycentric orbital velocity of Gaia

In a very loose, Newtonian sense this means that the spatial coordinate axes of the CoMRS point "in the same directions" as those of the BCRS/ICRS. [12]

4.2.3.7 CoMRS, Comment on the Definition of its Zero Point .

There have been discussions whether the — hardly accessible — centre of mass of the Gaia spacecraft should be replaced by some practical fiducial point inside the spacecraft. One of the arguments was that the centre of mass will even *move* with respect to the fixed hardware parts of the spacecraft (due to outgassing, consumption of fuel etc.).

The spatial offset of the centre of mass from *any* reasonably selected hardware point inside the spacecraft is at most 1 meter, the differential velocity (due to the spacecraft rotation) then is at most 0.3 millimeters per second. Both these offsets are irrelevant for all astrometric aspects at the 1 μas level.[13]

On the other hand, the satellite ephemeris is the central item in defining the co-moving reference system. That ephemeris will surely be modelled in terms of a point mass moving under the gravitational influence of the heavy solar-system bodies. It is strictly the center of mass of Gaia that moves in this way. Thus, for 'aesthetic' reasons, and without any practical consequences, we choose that point as the origin.

[12] We should point out here that this loose phrase should not be mixed up with the mathematically clear notion of parallel vectors which is used in General Relativity. The axes of the BCRS and the CoMRS or GCRS are not related to each other by parallel transport in the mathematical sense.

[13] Even these unrealistically large numbers would give a parallax of only 1.3 μas at 1 au distance, and an aberration difference of 0.2 μas in certain directions.

To be very clear: The precise location of the origin inside the spacecraft is of no relevance in astronomical contexts. In purely technical contexts, and for the description of hardware parts of Gaia, some readily accessible fiducial point(s) will indeed be chosen as coordinate origins (see Section 4.3.1).

4.2.4 The Scanning Reference System (SRS)

In the previous section we introduced a system co-moving with Gaia. Now we are going to introduce a system co-moving and co-rotating with the body of the Gaia spacecraft, the Scanning Reference System (SRS). [14] It is mainly used to define the satellite attitude. It is an intermediate system between the CoMRS (Section 4.2.3) and the Field-of-View Reference Systems (Section 4.2.5).

4.2.4.1 SRS, Definition .

The SRS is rigidly connected to the body of the Gaia spacecraft (which in turn is assumed to be a rigid body). The origin of the system is at the center of mass of Gaia. The natural time coordinate is the proper time of the spacecraft, see Section 4.2.3.1.

This abstract definition is made specific by requesting that the principal axes **x, y, z** of the SRS (see Section 4.2.4.2 and Fig. 3) are nominally aligned parallel to the $+\mathbf{Z}_s$, $+\mathbf{Y}_s$ and $-\mathbf{X}_s$ axes of the Mechanical Spacecraft Reference System (SCRS, see Section 4.3.1 and Fig. 4). The precise meaning of this "alignment" with the SCRS axes can only be given along with the definition of the Field-of-View Reference Systems in Section 4.2.5 below.

4.2.4.2 SRS, Celestial Coordinates .

Celestial coordinates in the SRS differ from those in the CoMRS *only* by a Euclidean rotation, given by the attitude of the satellite, see Section 4.2.4.3. They are expressed by cartesian unit vectors.[15]

The unit vectors along the principal axes are called **x, y, z**, see Fig. 3. The **z** axis is the nominal rotation axis of the satellite; with the direction towards the sun being at an angle of 45 degrees from the **z** axis during Gaia operations. The **x** axis is in the plane of the two Astro viewing

[14] Note that this system had been called Satellite Reference System up to issue 3 of the present document. We changed that naming for the sake of clarity and uniqueness, see also Section 4.2.3

[15] Occasionally, angular coordinates in the SRS are used as well. They are called instrument angles, and denoted as ϕ and ζ. They are closely related to the field angles η and ζ which will be defined in Section 4.2.5 for the Field-of-View Reference Systems: ζ is identical in the two systems, and ϕ differs from η exactly by plus or minus half of Gaia's nominal basic angle γ.

directions (i.e. the two projections of the optical axis of Gaia's telescope onto the sky), half a basic angle ($\gamma/2$, i.e. 53.25°) away from each of them. The **y** axis is also in the plane of the two viewing directions such that the system **x, y, z** is right-handed. A general unit vector **u** in the SRS has direction cosines x, y, z, such that

$$\mathbf{u} = x\mathbf{x} + y\mathbf{y} + z\mathbf{z} \tag{6}$$

with $x^2 + y^2 + z^2 = 1$.

The nominal rotation of Gaia is positive about the positive **z** axis. The **y** axis thus precedes the **x** axis on the sky by 90 degrees. A given star is first seen in the field no. 1 (preceding field), and 106.5° later in the field no. 2 (following field).

Note that during nominal operations the sun by definition has a positive z coordinate in the SRS.

4.2.4.3 SRS, Attitude: The Transformation CoMRS → SRS .

The attitude of the satellite is the orientation of the SRS with respect to the CoMRS (i.e. essentially with respect to the ICRS). It is expressed by the attitude matrix **A**, an orthonormal 3×3 matrix, as function of time. The matrix contains 9 scalar values of which only three are independent. Each line of the matrix contains the equatorial (CoMRS) direction cosines of one of the Scanning System's principal axes. Conversely, the columns of the matrix contain the direction cosines of the CoMRS (ICRS) principal axes expressed in the SRS. Symbolically:

$$\mathbf{A} = \begin{pmatrix} \mathbf{x}^T \\ \mathbf{y}^T \\ \mathbf{z}^T \end{pmatrix}_{ICRS} = (\mathbf{XYZ})_{SRS} \tag{7}$$

where the T denotes the transpose of a vector.

Multiplying **A** with any vector **u** given in CoMRS (ICRS) coordinates produces the representation of that vector in the SRS:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{\mathbf{u}} = \mathbf{A} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\mathbf{u}} \tag{8}$$

Note that for the trivial attitude matrix (three times '1' in the diagonal and zero elsewhere) the **x, y, z** axes are parallel to **X, Y, Z**.[16]

Instead of the rotation matrix **A** any other conventional mathematical representation of a three-dimensional rotation can be used, e.g. any set of Euler angles or Tait-Bryan angles, or quaternions. For reasons explained in (19) the choice for the Gaia data reductions will be quaternions.

[16] This, by the way, will never happen for Gaia during nominal operations.

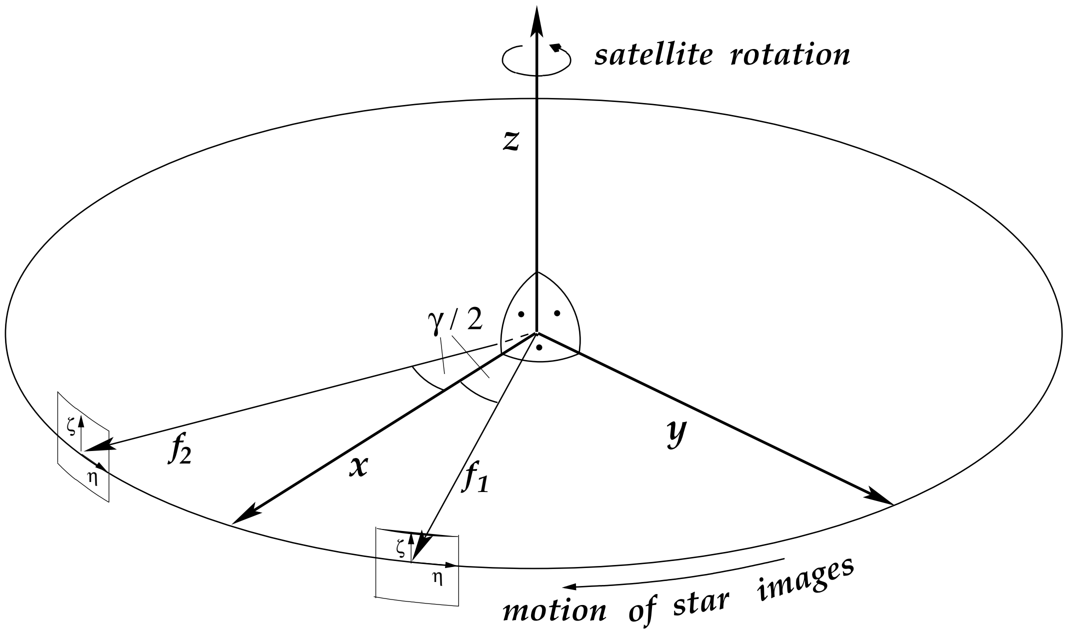

Figure 3: The Scanning Reference System (SRS), the Gaia viewing directions and the Field-of-View Reference Systems (FoVRS). The angles between the two viewing directions are not drawn to scale. The black dots near the centre denote 90° angles (marked by the arcs). The big ellipse indicates the instantaneous scan great circle on the celestial sphere. The small rectangles indicate the fields on the sky; the small arrows show the orientation of the field angles. The principal axes **f** of the FoVRS point towards the centre of each field of view. The **w** and **z** axes (not labelled in the diagram) point parallel to the η and ζ axes, respectively. The direction to the sun is always at an angle of 45 degrees from the positive z axis.

A quaternion **q** is a vector of four scalar quantities (q_1, q_2, q_3, q_4), the Euler symmetric parameters. It is equivalent to the attitude matrix and connected with it through

$$\mathbf{A(q)} = \begin{bmatrix} q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 - q_2q_4) \\ 2(q_1q_2 - q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & 2(q_2q_3 + q_1q_4) \\ 2(q_1q_3 + q_2q_4) & 2(q_2q_3 - q_1q_4) & -q_1^2 - q_2^2 + q_3^2 + q_4^2 \end{bmatrix} \quad (9)$$

under the constraint that $q_1^2 + q_2^2 + q_3^2 + q_4^2 = 1$. For more explanations and more formulae see (19) and (45).

4.2.4.4 SRS, Practical Realisation .

The practical realisation of the SRS mainly consists of a model for the attitude as function of time (apart from the ICRF and the barycentric spacecraft orbit defining the CoMRS, of course). There are several such models:

- The nominal attitude, sometimes also called nominal scanning law (NSL). This represents the pre-launch plan for the scanning of the sky during the mission. The real attitude during the mission is allowed to deviate from the nominal one by 1 arcmin (3σ). The nominal scanning law has some free parameters to be chosen after launch. Several choices of these parameters have actually been chosen for various segments of the real Gaia mission. More such segments will follow.
- The real-time attitude, also called on-board attitude. This is a model of the real attitude which is determined by the attitude control system on board for the purpose of autonomous real-time operations. It is a good approximation of the real attitude at the level of 20 arcsec (3σ).
- The high-precision scientific attitude, reconstructed on ground from the measurements performed by the Gaia instruments. This will ultimately be an approximation of the real attitude at the level of a few times 10μas.

The scientific attitude is represented by quaternions, which in turn are represented as function of time by a set of four B-splines, each of them corresponding to one of the four Euler symmetric parameters. For more details see (20), Section 5.3.

In actual fact, and for purely practical reasons, there are three levels of scientific on-ground attitude (OGA) reconstructions within DPAC, with increasing precision and accuracy: OGA1, produced by the Initial Data Treatment (IDT) process; OGA2, produced by the First Look (FL) process; finally the definitive OGA3, produced by the Astrometric Global Iterative Solution (AGIS) process. Descriptions of each can be found in the relevant process documentations, respectively.

4.2.5 The Field-of-View Reference Systems (FoVRS)

There are two Field-of-View Reference Systems, one for each sky field seen by Gaia. Both systems are simply rotated versions of the SRS. They are defined for convenience of the modelling of the observations and instruments. Their advantage over the SRS in this respect will become apparent in Section 4.4. The angular celestial coordinates in the FoVRS are called field angles; cartesian unit vector components are called field coordinates.

4.2.5.1 FoVRS, Definition .

This definition had to be changed significantly as of issue 6 of the present document with respect to previous versions. The reasons for this change are given in (35). The decision to implement a re-definition of the SRS and FoVRS was taken by the Gaia Science Team at its 18th meeting.

The FoVRS are, like the SRS, rigidly connected to the body of the Gaia spacecraft (which in turn is assumed to be a rigid body). The origins of the systems are at the center of mass of Gaia. Their natural time coordinate is the proper time of the spacecraft, see Section 4.2.3.1.

The difference to the SRS is a rotation around the z axis such that in each of the two systems the first of the principal coordinate axes points along the viewing direction (roughly the projection of the optical axis onto the sky) for the respective field of view.

More precisely, the viewing directions, and thus the origins of the field coordinates (and field angles) are defined to (nominally) coincide with the optical projections of specific points on the focal-plane assembly (see Section 4.3.3 and Fig. 6) onto the celestial sphere. The naively obvious choice, namely to use the two projections of the origin of the focal-plane coordinates as the origins of the two FoVRS, is impossible for reasons given in (35).

We therefore define (see Fig. 6 for an illustration):

The origin of the field coordinates for FoV 1 (the preceding field of view, representing light collected by telescope number 1) is the nominal projection onto the celestial sphere of the point on the focal plane having the focal-plane coordinates **Xfpa**=-37.5 mm (across-scan coordinate, see Fig. 6) and **Yfpa**=0.0 mm (along-scan coordinate). This point is indicated by the lower white dot close to the center of Fig. 6.

The origin of the field coordinates for FoV 2 (the following field of view, representing light collected by telescope number 2) is the nominal projection onto the celestial sphere of the point on the focal plane having the focal-plane coordinates **Xfpa**=+37.5 mm (across-scan coordinate, see Fig. 6) and **Yfpa**=0.0 mm (along-scan coordinate). This point is indicated by the upper white dot close to the center of Fig. 6.

These two statements are strictly equivalent to saying that the origins of the field coordinates are nominally projected onto the points **Xfpa**=-37.5 mm, **Yfpa**=0.0 mm (FoV 1) and **Xfpa**=+37.5 mm, **Yfpa**=0.0 mm (FoV 2) on the focal-plane assembly.

These two statements are also roughly equivalent to saying that the origin of the focal-plane coordinates (the red dot close to the center of Fig. 6) is projected to across-scan field coordinates of -37.5 mm/35 m (FoV 1) and +37.5 mm/35 m (FoV 2), where 35 m is the nominal focal length of the telescopes. The word "roughly" in the previous sentence indicates that the precise value depends on the details of the optical projection (viz. the optical distortion and the actual focal length), and that this sentence can therefore not be used as a formal definition of the FoVRS.

The actual operational definition of the field coordinate origins in the course of the scientific data reduction is a part of the astrometric calibration processing.[17] It is not a matter of convention, and thus not a subject of the present document. Nevertheless the basic ideas will be explained in Section 4.4.

4.2.5.2 FoVRS, Celestial Coordinates .

Celestial coordinates in each of the FoVRS differ from those in the SRS *only* by a fixed nominal Euclidean rotation about the **z** axis. The rotation angles are defined by the two nominal viewing directions of Gaia's two telescopes (see below). **This statement, along with the values for the rotations given in the next subsection, constitutes the completion of the SRS definition, which had to be postponed in Section 4.2.4.1.**

The celestial coordinates in the FoVRS are expressed by field angles η, ζ (spherical longitude and latitude coordinates) or by field coordinates f, w, z (direction cosines of cartesian unit vectors). An illustration is given in Fig. 3.

The unit vectors along the principal axes are called **f, w, z**. The **z** axis still is the nominal rotation axis of the satellite. Thus it can be denoted by the same symbol as the SRS **z** axis, with no danger of confusion. The **f** axis ('f' being a mnemonic for 'focal direction') points along the viewing direction (i.e. the projection of the respective optical axis onto the sky). The **w** axis is defined by $\mathbf{w} = \mathbf{z} \times \mathbf{f}$, such that the system **f, w, z** is right-handed. A general unit vector **u** in any FoVRS has direction cosines f, w, z, such that

$$\mathbf{u} = f\mathbf{f} + w\mathbf{w} + z\mathbf{z} \tag{10}$$

with $f^2 + w^2 + z^2 = 1$.

The relations between field angles and field coordinates are analogous to those between equatorial (ICRS) coordinates and the respective cartesian direction cosines (see Section 4.2.1.3).

Please note:

1. There are two sets of FoVRS (one for each field of view), with the origins of the field coordinates w, z (and field angles η, ζ) nominally being on the optical axes of each of Gaia's telescopes.

[17] The actual definition of the field angle origin(s) will be created by the normalization conditions used in the calibration processing. So it will depend on the actual locations of the CCDs on the real (hardware) focal plane(s). And not just by a few μas or mas!

2. The two field coordinate origins (roughly the optical axes of the two Gaia telescopes) are not projected onto the same point of the focal-plane assembly.

3. During nominal operations the sun by definition has a positive field angle ζ and positive z coordinate in both FoVRS.

4. The star images move towards negative field angle η and towards negative w coordinate if Gaia rotates in the nominal sense.

5. The instrument angles ϕ and ζ which were briefly mentioned in Section 4.2.4.2 already can now be fully defined with respect to the field angles, see next paragraph.

4.2.5.3 FoVRS, Transformation SRS → FoVRS .

The rotation from the SRS to either of the FoVRS is expressed by a fixed nominal rotation matrix $\mathbf{R}_\psi$ (different for each FoVRS). Each line of the matrix contains the SRS direction cosines of one of the FoVRS's principal axes. Conversely, the columns of the matrix contain the direction cosines of the SRS principal axes expressed in the FoVRS. Symbolically:

$$\mathbf{R}_\psi = \begin{pmatrix} \mathbf{f}^T \\ \mathbf{w}^T \\ \mathbf{z}^T \end{pmatrix}_{SRS} = (\mathbf{xyz})_{FoVRS} \quad (11)$$

where the T denotes the transpose of a vector.

Multiplying $\mathbf{R}$ with any vector $\mathbf{u}$ given in SRS coordinates produces the representation of that vector in the FoVRS:

$$\begin{pmatrix} f \\ w \\ z \end{pmatrix}_{\mathbf{u}} = \mathbf{R}_\psi \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{\mathbf{u}} \quad (12)$$

Since $\mathbf{R}_\psi$ contains only a rotation around the $\mathbf{z}$ axis, the transformation has a simple form when written explicitly. Both matrices $\mathbf{R}_\psi$ have the form

$$\mathbf{R}_\psi = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (13)$$

where ψ is the rotation angle around the $\mathbf{z}$ axis. This angle is given by

- $\psi = +\gamma/2 = +53.25°$ for FoV 1
- $\psi = -\gamma/2 = -53.25°$ for FoV 2

Note that these values are fixed nominal ones which are given by the nominal Gaia instrument design.

Thus the FoVRS axes **z** are all strictly identical to the third axis of the SRS, and

$$\mathbf{f} = \mathbf{x}\cos\psi + \mathbf{y}\sin\psi \tag{14}$$
$$\mathbf{w} = \mathbf{y}\cos\psi - \mathbf{x}\sin\psi \tag{15}$$

and the field coordinates are related to the SRS coordinates by the simple equations

$$f = x\cos\psi + y\sin\psi; \quad x = f\cos\psi - w\sin\psi \tag{16}$$
$$w = y\cos\psi - x\sin\psi; \quad y = w\cos\psi + f\sin\psi \tag{17}$$
$$z = z \tag{18}$$

Finally, the relation between the along-scan field angles (FoVRS) and the along-scan instrument angle (SRS) is

$$\eta_{(FoV1)} = \phi - \gamma/2 \tag{19}$$
$$\eta_{(FoV2)} = \phi + \gamma/2 \tag{20}$$

while the across-scan field angles z and the across-scan instrument angle z are strictly identical, which allows to use the same symbol (z) for them.

4.2.5.4 FoVRS, Practical Realisation .

The practical realisation consists of just the two fixed nominal rotation matrices $\mathbf{R}_\psi$.

4.2.5.5 FoVRS, Remark on Notations .

We have not defined separate notations for the axes, field coordinates and field angles for the two different FoVRS; the circumstances will always make clear which of the two systems is dealt with. In a programming environment whenever both FoVRS are treated at the same time they must of course be distingushed by suitable naming extensions.

4.2.6 The Reference Great-Circle Systems (RGCS)

The needs of the astrometric First Look task led to the introduction of still another sort of astronomical reference system, the Reference Great-Circle systems (RGCS). Such coordinate systems will also be useful for other purposes, e.g. the investigation and presentation of attitude disturbances, and for the comparison of intermediate results from the Astrometric Global Iterative Solution (AGIS) with alternative global astrometric solution methods, such as the Global Spherical Reconstruction (GSR). A complete but very compact definition of the RGCS is given in the paragraph below.

A reference great-circle (RGC) is defined by its pole, precisely by its ICRS coordinates $\alpha_\wp$ (right ascension) and $\delta_\wp$ (declination)[18]. The RGC coordinates υ and r are defined as longitude and latitude coordinates in a spherical coordinate system determined by this pole. The zero-point of the longitude coordinate υ is the ascending intersection of the RGC equator with the ICRS equator. The RGC coordinates υ and r are called (RGC) abscissa and (RGC) ordinate, respectively. Note that υ is not a latin 'v', but a greek `\upsilon`.

The representation of the RGCS by a rotation matrix relative to the ICRS — rather than by its pole in the ICRS — can be found as Eqs. 1.7a and 1.7b on pages 16/17 in (41). Those equations give the elements of the rotation matrix as function of the pole coordinates. Instead of a matrix, the corresponding quaternion can equally well be used to define the RGCS.

> *The actual One-Day Astrometric Solution (ODAS) software of the First Look task deviates from this definition. It defines the RGCS by a (more or less arbitrarily selected) attitude quaternion which closely corresponds to the actual attitude of Gaia in the middle of the fitted time interval (of order of 1 day). In this way, the zero-point of the longitude coordinate υ usually does not coincide with the ascending intersection of the RGC equator with the ICRS equator. Instead it can be anywhere along the RGC equator.*

4.3 Mechanical Reference Systems

The general purpose of mechanical reference systems, and the basic difference to astronomical systems is explained in Section 4.1.

4.3.1 Mechanical Spacecraft Reference System (SCRS)

The SCRS is the mechanical equivalent to the SRS. Both the SRS and the SCRS are rigidly connected to the body of the Gaia spacecraft. It has, alas, not been possible to have the corresponding axes oriented and named in harmony between the SRS and the SCRS. Separate traditions on the astronomical and engineering sides had already been too deeply embedded in too many documents and brains when work on the present document was started. The most critical point was that in engineering tradition the 'x' axis of a spacecraft points along the long axis

[18] The subscript $\wp$ is a calligraphic 'P' which is occasionally used in mathematical contexts; its LaTeX code is `\wp`.

of the launcher vehicle, in the direction of motion during launch (i.e. vertically upwards on the launch pad), while in the astronomical tradition the rotation axis of an astrometric satellite has always been called z'. The solution of this problem, after careful discussion with all concerned parties, is as follows: For astronomical coordinate systems the astronomers' tradition is to be used, for mechanical coordinate systems the engineers' tradition is to be used. This solution has fully been implemented in this version of the present document, aiming at consistency with the Gaia Mission Requirements Document (25).

Please note that in early issues of the present document — up to issue 2.0 — the SCRS had been named MRS, with names and orientations for the axes different from the agreed ones given below.

4.3.1.1 SCRS, Definition .

The SCRS is defined by a zero point $\mathbf{C}_s$ inside the satellite body, and by the coordinate axes $\mathbf{X}_s, \mathbf{Y}_s$ and $\mathbf{Z}_s$ with associated SCRS coordinates X_s, Y_s and Z_s. Their orientation with respect to the satellite body is different from those of the SRS axes with similar names! The SCRS is sketched in Fig. 4. For clarity, Fig. 5 schematically shows the Gaia spacecraft mounted inside the launch vehicle, motivating the choice of the $\mathbf{X}_s$ axis.

Here is the complete definition of the SCRS:

- SCRS coordinates are three-dimensional cartesian coordinates measured in units of millimeters.
- The $-\mathbf{X}_s$ axis (*negative* axis!) points along the nominal rotation axis of the spacecraft, with the direction towards the sun being at an angle of 45 degrees from the $-\mathbf{X}_s$ axis during Gaia operations.
- The $+\mathbf{Z}_s$ axis lies in the plane of the two viewing directions of the telescope, half a basic angle ($\gamma/2$, i.e. 53.25°) away from each of them.
- The $+\mathbf{Y}_s$ axis also is in the plane of the two viewing directions such that the system $\mathbf{X}_s$**,** $\mathbf{Y}_s$**,** $\mathbf{Z}_s$ is right-handed.
- The zero point $\mathbf{C}_s$ is at the center of the circular satellite interface with the launch vehicle adapter, in the separation plane.

The conceptual differences between the SRS and the SCRS are the following:

- The spatial origin of the SCRS is defined by an easily accessible and invariant fiducial point in the spacecraft body. It will not be the center of mass.

- Similarly, the directions of the coordinate axes are fixed by some easily accessible and invariant fiducial points or hardware parts in the spacecraft (rather than along the optical axes).
- There is a specific length scale for all coordinates, viz. millimeters.
- The natural time coordinate would be proper time of the spacecraft, but in practical usage the SCRS will be just three-dimensional.

4.3.1.2 SCRS, Practical Realisation .

The fiducial points defining the SCRS have been specified by industry. There is no particular preference from astronomical considerations. The fiducial points need not be at the zero point, nor on the primary axes. The only requirement is that they shall be well defined and easily accessible.

The practical realisation of the SCRS will not play a role in the scientific data reduction (apart from setting nominal reference values and possibly initial values for some calibration processes).

4.3.2 Unit Coordinate Systems (UCS)

Individual hardware units within the spacecraft may warrant their own internal coordinate systems. Following the Gaia Mission Requirements Document (25), these will generically be defined as follows:

- A unit coordinate system (C_u, X_u, Y_u, Z_u) will be fixed relative to the unit geometry.
- It shall be a right-handed orthogonal coordinate system defined by a zero point (origin) C_u and three spatial coordinates X_u, Y_u, Z_u.
- One of the attachment holes of the unit will be chosen as reference hole, which shall be identified by an engraved letter “R” on the unit.
- The zero point (origin) C_u shall be located at the center of the reference hole, at the level of the mounting interface plane.
- The X_u axis shall be perpendicular to the mounting interface plane, pointing positively towards (into) the unit.
- The Y_u, Z_y axes shall be oriented such that (most of) the unit will be included inside the $+Y_u/+Z_u$ quadrant of the mounting interface plane. Moreover, if the unit has a rectangular shape, the Y_u, Z_y axes shall be parallel to the unit edges.

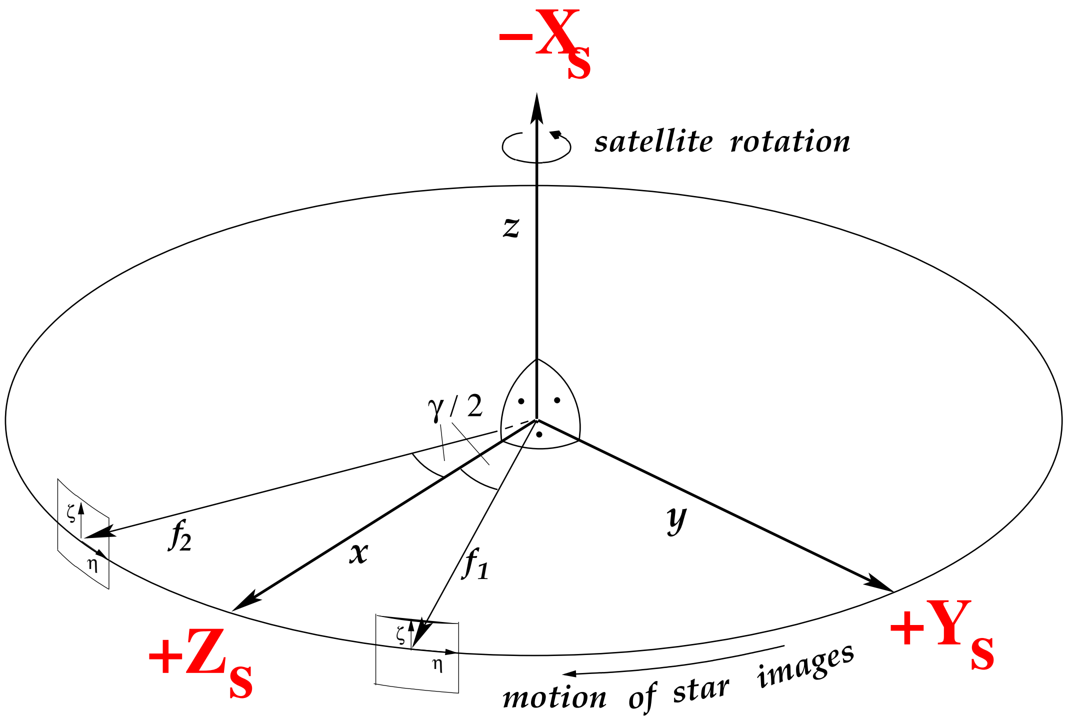

Figure 4: The Spacecraft Reference System, SCRS. Same as Fig. 3, but with the principal axes of the SCRS added in bold red.

4.3.3 Focal-Plane Reference System (FPRS)

The FPRS is defined to describe the locations of the individual CCDs on the FPA as well as other properties of the FPA.

Previous versions of the present document had used the original industrial coordinate system for the Astro focal plane ((9), p. 10), extending that (incomplete) definition by some missing items in a consistent way. With the change to the Gaia-3 design we have a more complete industrial definition (originally from (34), Part 1 “Proposed Spacecraft Design and Development Approach”, Chapter 7 “Payload Module Design”, Section ‘Optical Design”). It is consistent with the definition used in the previous versions of the present document. It is presented in the following. It has been implemented in the Gaia Parameters Database from issue 2.2 onwards.

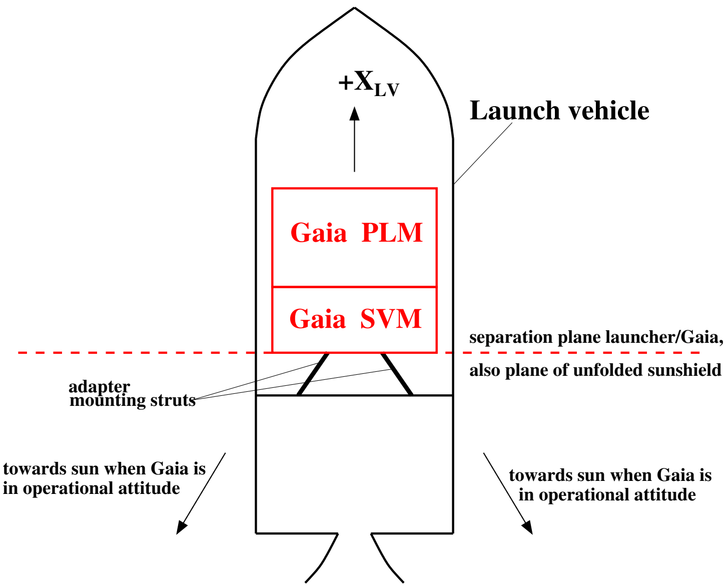

Figure 5: Sketch of the Gaia spacecraft mounted inside the launch vehicle, defining the positive X_{LV} axis of the launch vehicle's coordinate system and thus of the Spacecraft Reference System.

4.3.3.1 FPA Coordinates: Definition .

Fig. 6 shows a sketch of the Gaia FPA. The FPRS is defined by the FPA axes $\mathbf{Xfpa}$, $\mathbf{Yfpa}$ and $\mathbf{Zfpa}$ with associated FPA coordinates $Xfpa, Yfpa$ and $Zfpa$. Their orientation is indicated at top left in Fig. 6. Their origin is defined to be near the mechanical and optical center of the FPA. Here is the complete definition[19]:

- FPA coordinates are three-dimensional cartesian coordinates measured in units of millimeters.
- The origin of the FPA coordinates is in the centre of the (fictitious) gap between lines 220 and 221 on the CCDs of the strip AF7 (see Fig. 6 for the meaning of a strip and Section 5.1 for the meaning of a line) and in the (fictitious) gap between the two central pixel columns of the CCDs in the AF row no.4 (again see Fig. 6 for the meaning of a row and Section 5.1 for the meaning of a column), on the nominal plane of the CCDs' illuminated silicon surface. This location is indicated by the red dot in Fig. 6.
- The positive $\mathbf{Xfpa}$ axis lies in the nominal plane of the CCDs' illuminated silicon surface. It points into the nominal cross-scan direction, towards CCD row no.7.
- The positive $\mathbf{Yfpa}$ axis lies in the nominal plane of the CCDs' illuminated silicon

[19]The numerical values in this definition have substantially changes from issue 6 of the present document. That issue had been based on preliminary documentation from industry

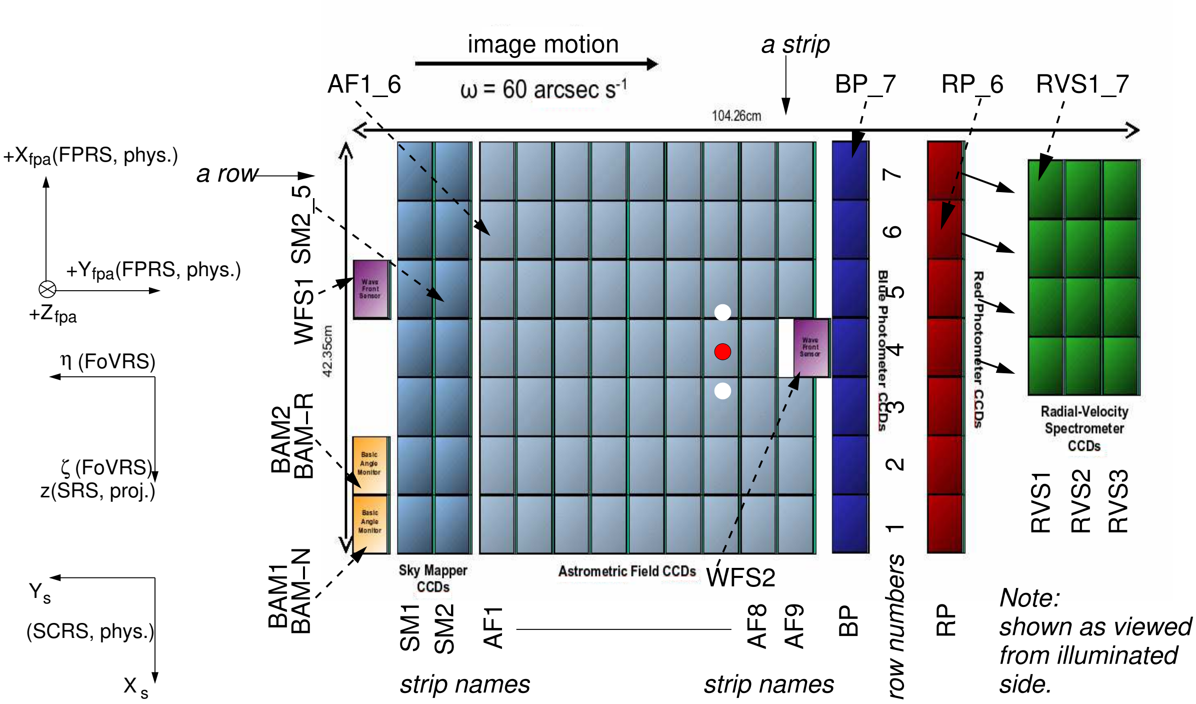

Figure 6: The Focal-Plane Reference System (FPRS), including some additional notations concerning the FoVRS, the CCDs and the FPA. The coordinate arrows at left indicate only the orientations of the FPRS axes (**Xfpa, Yfpa, Zfpa**), not their origin. The **Zfpa** axis (crossed circle) is to be seen as pointing into the paper, i.e. from the illuminated side into the FPA substrate. The origin of the FPRS is indicated by the red dot in the centre of the picture (on the AF7_4 CCD). It is precisely defined in the text (its location in the plot does somewhat deviate from that definition). The two white dots above and below the red dot (on the AF7_5 and AF7_3 CCDs) indicate the projections of the origins of the two FoVRS onto the focal-plane assembly. The lower dot represents FoV 1 (light from telescope 1), the upper dot represents FoV 2 (light from telescope 2).

surface. It points into the nominal along-scan direction, towards the CCD strips of the RVS, i.e. in the direction of star image motion across the CCDs.

- The positive **Zfpa** axis is perpendicular to the nominal plane of the CCDs' illuminated silicon surface. It points down into the CCD and FPA substrates, i.e. in the direction of the light rays.

Note that the origin is not in the centre of a CCD, but farther from the read-out register. The centre of the CCD would be close to line 4500/2=2250 instead of line 220. The "two central pixel columns" of a CCD are understood as columns 1966/2+13=996 and 997 in the sense of the pixel numbering scheme of Section 5.3.

4.3.3.2 FPA Coordinates: Practical Realisation .

The practical realisation of the FPRS was given by industry in the form of relative positions and rotations (measured on the completed device before launch) of the individual CCD chips with respect to the nominal origin and orientation. It needs not be detailed further in the present document.

4.4 Geometric Calibration: The Connection between FoVRS and FPRS

At this place the reader might expect a presentation of the transformation from the FoVRS to the FPRS, in other words: of the optical projection from the sky onto the focal plane. The detailed form of this projection for the actual mission would then be what is called the geometric calibration of the Gaia instrument(s). This is not included here, for two main reasons.

Firstly, the geometric calibration is not a transformation of reference systems like e.g. SRS→FoVRS etc., but a matter of research and modelling. Even the choice of an analytical parameterisation for it is far from trivial. Well, there is an ideal, nominal transformation: Gnomonic projection about the optical axis. But at the level of precision needed for Gaia this one will be so far from reality that it is not worth to be discussed.

Secondly — and more importantly! — that optical projection will never be known. It is not observable. What Gaia delivers is not image locations in physical space on the focal planes (in units of millimeters, say), but image locations in a pixel data space.

Thus the geometric calibration actually needed for Gaia will model a transformation not from FoVRS to FPRS, but from FoVRS to Gaia's data space. That space will be discussed extensively in Section 6. The geometric calibration thus is a subject of the astrometric modelling of the Gaia data. As such it is a subject of research and parameter adjustment (in the framework of the AGIS, i.e. the global iterative solution), not a subject of the present document.

The above comments strictly hold for the SM and AF, i.e. for the undispersed images. For the BP, RP and RVS the geometric calibration is even more complex, since the transformation from the FoVRS onto the focal plane is strongly dependent on wavelength. Again, it will never be known, exactly as for the AF and SM.

5 CCD-related Terminology and Conventions

A lot of confusion and misunderstandings can be produced by incorrect, inappropriate, or just inconsistent usage of CCD-related terminology. This is why we in the following specify a consistent set of conventions and notations to be used for Gaia. Many of them are not Gaia-specific but common industrial or astronomical terms.

5.1 Basic CCD Terminology

This subsection follows (32) and a clarifying email by J. de Bruijne of 4 Aug, 2006.

There is a German proverb saying ‘a single picture can tell more than a thousand words’. In this spirit much of the CCD-related terminology is defined in Fig. 7, which is largely self-explaining.

Here are very short explanations of the individual terms and details visible in Fig. 7:

- A ‘pixel’ (shorthand for ‘picture element’) is the elementary charge generation and storage element in the light-sensitive area of the CCD.
- A ‘column’ is the set of all pixels having the same across-scan coordinate (i.e. a one-dimensional pixel array extending along scan).
- A ‘line’ is the set of all pixels having the same along-scan coordinate (i.e. a one-dimensional pixel array extending across scan).
- The ‘summing register’ (SR, also called ‘summing well’) is a special pixel line following the light-sensitive pixels. It is used to combine (add) the charges from several lines into one. Summing registers are present in all Gaia CCDs.
- The ‘read-out register’ (ROR, also called ‘serial register’) is the special pixel line which is used to transfer the accumulated charges from the CCD chip into the read-out amplifier (and thus further into the further amplification and digitisation electronics).
- The ‘read-out amplifier’ (ROA) is the electronic circuit at the end of the read-out register where the registration and pre-amplification of the photoelectric charges takes place.
- ‘Pre-scan pixels’ are a number of additional pixels in the read-out register line which are not fed with photoelectric charges but nevertheless are read out at the ROA (before the pixels of the light-sensitive area). They are used to determine the so-called bias (offset voltage), dark current and noise of the read-out electronics. There are 15 of them in the Gaia CCDs, but only 14 will be used in Gaia operations.
- ‘Post-scan pixels’ also are a number of additional pixels in the read-out register line which are not fed with photoelectric charges but nevertheless can be read out at the ROA (after the pixels of the light-sensitive area). In addition to the uses of pre-scan pixels they also determine the dark current associated with the transfer through the ROR (expected to the negligible for Gaia). There are 132 post-scan pixels in the Gaia CCDs, according to (37).

- ‘Over-scan pixels’ serve a similar purpose as post-scan pixels. They are, however, not related to any physical feature of the CCD. They are produced by giving the ROR more read-out steps than it contains physical pixels. They give the same information as post-scan pixels.
- ‘Under-scan pixels’: not applicable to Gaia.
- The ‘time delay integration’ mode (abbreviated TDI mode, also called drift-scan mode) consists of gradually shifting the photoelectric charges from “left” to “right” — and eventually into the read-out register — to follow moving optical images over the light-sensitive area.
- The ‘charge injection structure’ (CIS, formerly sometimes called ‘charge injection device’) is a device preceding the light-sensitive area in which non-photoelectric charges can be inserted into the TDI-transported charge flow. It is used to counter the effects of so-called charge traps on the image quality.
- ‘Gates’ (also called ‘TDI gates’, not shown in Fig. 7) are special lines within the light-sensitive area. If activated they act like summing registers, holding up charges, i.e. preventing them from moving along scan in spite of the TDI clocking. This causes a collapse (summing-up) of the already accumulated TDI images into a single line, and the creation of a new “blank” empty space “in front of” this line. In Gaia CCDs, gates are used for the observation of bright stars (during nominal observations) and for the achievement of on-board attitude convergence (during attitude initialization phases).

A few additional comments are necessary:

1. Note that the one-dimensional arrays of CCD pixels are called ‘columns’ (along scan) and ‘lines’ (across scan), respectively, while the one-dimensional arrays of entire chips are called ‘rows’ (along scan) and ‘strips’ (across scan), respectively (see Fig. 6). This very useful distinction was introduced in (9).[20]
2. It is a long-standing tradition in the Gaia project to plot the CCDs with the read-out register on the right-hand side, so that the image motion is towards the right. However, this is not sufficient to completely define the orientation of such a plot: It must in addition be specified whether the CCD is seen from the illuminated side or from the substrate side. Figs. 7 and Fig. 6 introduce the standard that FPAs and CCDs should always be plotted as seen from the illuminated side.
3. Note that the illuminated side of the Gaia CCDs is called ‘backside’ in the usual CCD terminology (the Gaia CCDs are thus ‘backside-illuminated’, or ‘back-illuminated CCDs’).

[20] Note that ‘rows’ have been called ‘trails’ for a short time; but this term should no longer be used

4. Even respecting item 2 above it is still not obvious where the read-out amplifier of a CCD is situated. The CCD manufacturer (E2V) on request confirmed (to A. Short, ESTEC) that it is in the top-right corner of Fig. 7. This is further confirmed by Fig. 4.1-2 of (32).

5. Note that the terms 'across-scan direction' = 'serial direction' and 'along-scan direction' = 'parallel direction' have no sense of orientation, while the terms 'TDI direction' and 'read-out direction' have. The orientations of the 'TDI direction' and of the 'read-out direction' by definition point along the motion of the charges in the light-sensitive area and in the read-out register, respectively.

6. Version 1.0 of the present document had used the term 'charge injection device' (abbreviated CID) for 'charge injection structure'. This has been changed to 'charge injection structure' (CIS) in order to avoid the abbreviation CID which commonly stands for Charge-Integrating Device.

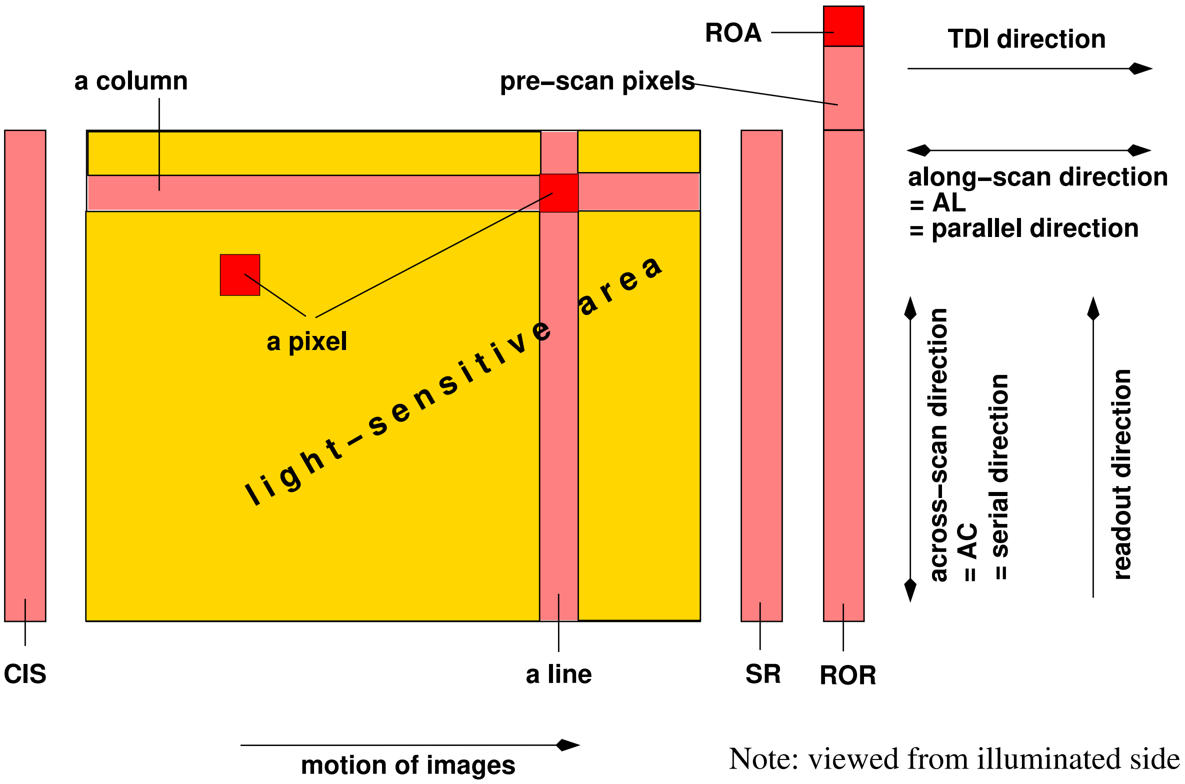

Figure 7: CCD-related notations. All notations and acronyms are explained in the text. Abbreviations in the figure are: SR = summing register, ROR = read-out register, also called serial register, CIS = charge injection structure, ROA = read-out amplifier, TDI = Time Delay Integration. — The location of the ROA at top right has been confirmed by industry.

5.2 Gaia-specific Terminology

This section defines Gaia-specific terms and naming conventions. Some of these terms deserve a bit of explanation, in addition to the formal definition.

5.2.1 Gaia CCD Designations

5.2.1.1 Basic notation .

The designations of the various CCD chips, strips and rows (along with the definition of the terms ‘strip’ and ‘row’) are given in Fig. 6. The scheme follows the Gaia payload module specification document (32). Those CCD designations should be used throughout. The acronyms SM, AF, BP, RP, and RVS used in them denote the ‘instrument modules’ Sky Mapper, Astrometric (Main) Field, Blue Photometer, Red Photometer and Radial-Velocity Spectrograph, respectively. The acronyms BAM and WFS denote the basic-angle measurement and wavefront sensor CCDs.

The general structure of the CCD designations is ‘FFFi_j’, where ‘FFF’ is the 2- to 3-character shorthand for the respective instrument module (SM etc., see preceding paragraph), ‘i’ is the running number of the strip (within instrument module ‘FFF’), and ‘j’ is the running number of the row (again within instrument module ‘FFF’).

This is a compact and convenient notation for text environments. The fact that an underscore character is used here as separator between the strip and the row numbers may be a problem for some computer file names or variable names, because it is not an alphanumerical character[21]. Note also that there is no formal separator between the module and the strip number.

It is therefore agreed that in programming environments the underscore separators can be replaced by a different character (e.g. ‘R’ for ‘row”) as long as no ambiguities arise (the hyphen should be avoided, see below). Also, some character might be used as formal separator between the module and the strip number. A specific implementation of these general rules is found in the Gaia parameters database, (10).

Examples for CCD designations thus are ‘SM1_5’ ‘AF2_4’, ‘RVS3_6’. It is in the spirit of this convention to denote one strip of the AF e.g. as ‘AF7’, and a range of strips e.g. as ‘AF2–7’. Denoting a row in the same spirit is also possible, but leads to somewhat clumsy results like ‘AF1–11_5’. It seems preferable to simply call it ‘AF row no. 5’. All mentioned examples might contain the ‘R’ instead of the underscore.

Warning: *Unfortunately, this convention has not consistently been implemented in DPAC. It*

[21] In previous versions of the present document the separator was a comma rather than an underscore; this has created some other problems.

was created with an implementation in the form of a Java `enumerator` *in mind. In fact a wide variety of strip numberings appears in DPAC softwares and interfaces, so that special care needs constantly to be taken in order to avoid errors.*

The originally targetted Java `enumerator` *actually exists in GaiaTools, in the Java class* `gaia.cu1.tools.satellite.definitions.CCD_STRIP`*, and it is used in many places. It is defined as: BAM_WFS, SM1, SM2, AF1, AF2, AF3, AF4, AF5, AF6, AF7, AF8, AF9_WFS, BP, RP, RVS1, RVS2, RVS3. This is in agreement with the above convention.*

In that Java class there is the standard method `get(int ordinal)`*, the JavaDoc of which states [0-16] as the valid range. This is the usual way an* `enumerator` *works, and it means BAM_WFS=0, AF1=3 and RVS3=16. However, in that same class there also is a method to deal with the "strip number": in this case, the range goes from 1 to 17, and it means BAM_WFS=1, AF1=4 and RVS3=17.*

Furthermore, in the `AstroElementary` *interface, the BAM_WFS strip does not appear, and the SM1 and SM2 strips are combined into one (because only one of the two SM strips can ever contain data belonging to a particular star transit). Thus the array index of AF1 is 1 in this case, while SM1&SM2 get index 0.*

In summary: There is a lot of variation. The strip AF1, for instance, can take indices all the way from 1 to 4; only its "name" AF1 is unambiguous.

5.2.1.2 Extended 2-digit notations .

In many circumstances connected with individual CCDs it is necessary to distinguish the two fields of view (FoV), e.g. in the astrometric and photometric calibration. A convenient way to do this was created by the former Solar-System Working Group. It is consistent with the basic notation given in the previous section, and can also be easily adapted to programming environments. It is therefore accepted as an extension to the basic scheme.

The idea is to use two digits for the strip index, i.e. 'FFFki_j', where 'k' is the field-of-view index, '1' or '2'. Thus, e.g. CCD 'AF1_6' for FoV no. 2 becomes 'AF21_6'.

> *There is another variation of the basic notation, also utilizing the 2-digit pseudo-strip numbering, which rests on the same idea as the that in the* `AstroElementary` *format mentioned above: The distinction between the two FoVs leaves only one active SM in each FoV. This allows to logically assign AF strip no. zero to the SM. Thus, e.g. CCD 'SM1_6' for FoV no. 1 becomes 'AF10_6', and CCD 'SM2_6' for FoV no. 2 becomes 'AF20_6'. This may be useful in programming environ-*

ments but should not be used in text environments (where quick reading may occasionally lead to confusion).

5.2.2 Samples

Neither ICRS coordinates nor field coordinates of celestial objects, nor their magnitudes are directly observable by Gaia. The primary signal of Gaia are streams of charge pixels ('samples') produced by the TDI operation of the detector chips. The primary astrometric observable thus is the location of a stellar image within one such stream of samples. The primary photometric observable is the total amount of photo-electric charge in the set of samples constituting a particular stellar image.

Note that samples are not physical entities on a CCD chip, but data items in the output data stream from a CCD. Usually there is no real danger of confusion between these two concepts, but a clear distinction can be made (whenever necessary) by calling them 'samples' and 'physical pixels', respectively.

A sample may contain the sum of the photo-electric charges from several physical pixels on the CCD. There are two basic possibilities for adding ('binning') the charges from several pixels into one sample: on-chip binning and numerical binning. The former operates on the CCD chip itself, combining the physical charges before read-out, amplification and digitisation. The latter operates in the instrument computer, simply adding the digitised numerical values representing the original charges.

- On-chip binning: The summing register (SR in Fig. 7) allows to add the charges from several (n=1, 2, 3,..) adjacent pixels along scan, i.e. to combine charges being transported along the same CCD column during the TDI clocking. The charges are fed to the read-out register and read out only after the desired number of TDI lines has been accumulated.
  The read-out amplifier analogously allows to add several pixels from the read-out register, i.e. to combine charges being transported in the same line (or set of lines if $n > 1$) during the TDI clocking. The charges are added into the capacitor of the read-out amplifier and then actually measured only after the desired number of columns has been accumulated.
  The resulting combined charges are called '1-d samples' if $n = 1$ and '2-d samples' if $n > 1$.
  On-chip binning reduces both the primary data rate on board (thus also the telemetry rate) and, most importantly, the read-out noise in the raw signal.
- Numerical binning: Numerical binning is more flexible than on-chip binning. However it can neither reduce the primary data rate on board nor the read-out noise in the raw signal.

The concept of samples is illustrated in Fig. 8.

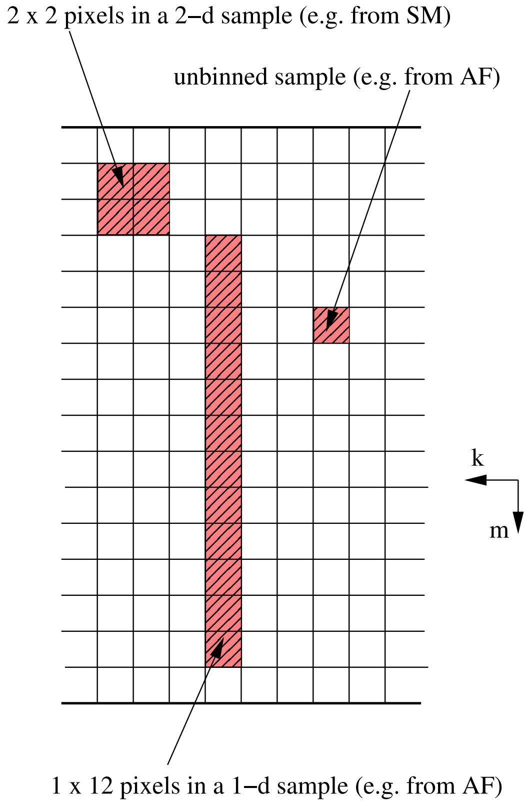

Figure 8: Samples: The small white squares denote individual TDI pixels, the orange rectangles illustrate various forms of samples. The remarks in parentheses refer to the currently foreseen sampling strategy. The arrows labelled ‘k’ and ‘m’ will be explained in Section 6.

5.2.3 Windows and Patches

The total stream of samples that the Gaia CCDs could in principle produce is much too big to be treated by the instrument computer, let alone to be telemetered to the ground entirely. But it mostly contains dark, empty sky. Therefore it is both necessary and useful to select specific cut-outs containing actual stellar images of that stream for inclusion into the telemetry data stream sent to the ground. Such cut-outs are called ‘windows’. A window by definition is a rectangular subarray[22] of the stream of samples produced by a specific CCD and selected from that stream to represent a specific optical image of some celestial source. The samples in a window can be non-uniform, i.e. they may combine different numbers of pixels across scan (in the so-called truncated or paved windows). Along scan they necessarily are uniform.

The unwanted samples containing dark, empty sky can be avoided in two different ways: They can either be skipped in the read-out amplifier already (i.e. the charge is flushed electronically

[22] There may actually be windows that are not simple rectangles, but this is an irrelevant detail at the moment.

without being read and digitised) or else be deleted from the memory of the instrument computer later on. Both ways are used by Gaia. The latter reduces only the telemetry stream while the former directly reduces the data rate load on the instrument computer — and indirectly even the read-out noise in the remaining samples.

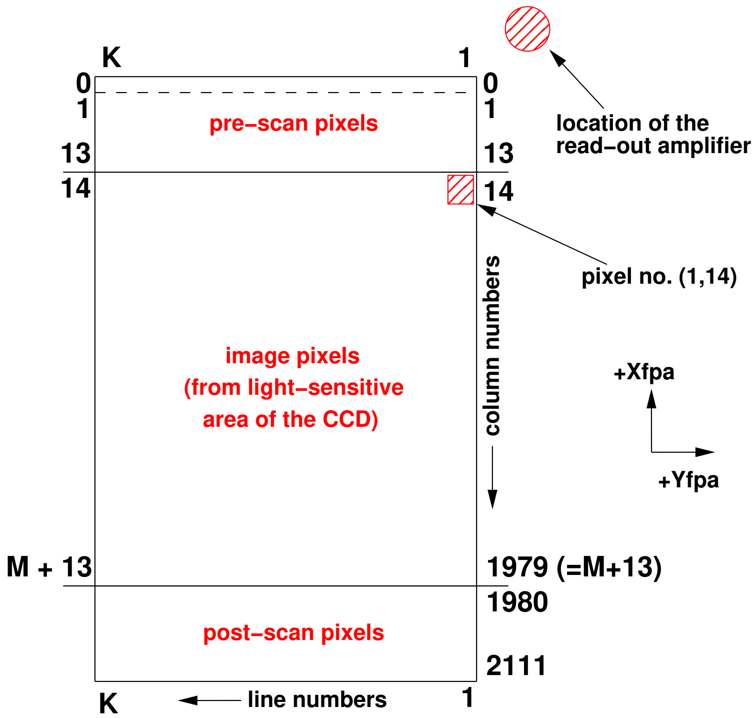

Figure 9: Schematic view of the pixel numbering, for a CCD assumed to have M columns, K lines and 14 pre-scan pixels. Note that this picture is neither a true map of the CCD surface nor a map of the data structure, but a mixture of both: On one hand, pre-scan pixels are physically present only close to the read-out amplifier, still they may appear in every line of data pixels. On the other hand, there is nothing like a 'location of the read-out amplifier' in the data space.
The location of the read-out amplifier and the orientation of the **Xfpa and Yfpa** axes are as in Fig. 6.

The complete specification of all sorts of windows for the various Gaia instruments is not a subject of the present document, but of the so-called sampling strategy, the details of which can be found in (24) and (23) or later versions. The basic concept of a window, however, is independent of such details. It is illustrated in Fig. 10.

A 'patch' is a one-dimensional along-scan subarray of adjacent and identical samples belonging to a window, i.e. the set of all samples having the same across-scan coordinate. For a rectangular window all patches have the same size.

The size of a window is conventionally given in units of samples, with the along-scan size named first. Thus a '12*6 window' consists of 72 samples, composed of 6 patches with 12 samples each.

5.2.4 Further Gaia-specific terms

The ‘TDI period’ is the time interval in which the charges on the light-sensitive part of a CCD are transported by one pixel (more precisely: by one line) along scan. It is the inverse of the TDI clocking frequency (which is also called TDI rate, occasionally). Several misleading and ambiguous names for the TDI period have been used in the past (including ‘TDI time’, ‘pixel time’ and ‘exposure time’). They are to be avoided. The TDI period has been denoted τ in various documents. In the Gaia Parameter Database it is denoted CCD_TDIPeriod.

The ‘line duration’ is the time interval in which one line of samples enters the read-out register. It differs from the TDI period by the along-scan on-chip binning factor. In the terminology of (30) it is the inverse of the parallel transfer gate clock frequency. In the Gaia Parameter Database the line duration is denoted CCD_LineDuration. It differs between the different Gaia instrument modules (e.g. between SM and AF).

The ‘exposure time’ is the time that the centroid of a star image spends on the light-sensitive area of a CCD. It is essentially the product of the TDI period and the number of light-sensitive lines of the particular CCD. Again, several misleading and ambiguous names for this quantity have been used in the past (including ‘TDI length’, TDI integration period’ and ‘TDI period’). They are to be avoided.

The ‘transit time’ is the along-scan coordinate of an optical image in the data pixel space. To first order it corresponds to the instant of time when the centroid of the image reaches the “trailing edge” of a CCD. This quantity will be discussed in detail in Section 6. In several documents it has been denoted t_{tr}, so that this notation is recommended. More than half a dozen names have been used for this quantity in the past (including ‘x position’, ‘observation time’, ‘datation time’, ‘time of detection’, ‘along-scan position’ etc.). They are to be avoided.

The ‘observation time’ is the effective mean instant of the photon collection for one CCD transit of a star image. To first order it corresponds to the instant of time when the centroid of the image has traversed halfway across the light-sensitive area of a CCD in the along-scan direction. The concept was introduced and denoted t_{obs} by L. Lindegren in (33), Ch. 5.1.2.3. To first order t_{obs} differs from t_{tr} by half an exposure time. Note that unfortunately, and in spite of his notation t_{obs}, Lindegren used the name ‘transit time’ for this quantity, which is to be avoided.

> *At this point a clarification concerning the TDI period might be useful. Quoting an e-mail by Jos de Bruijne of Jan 3, 2007: “The TDI period τ is completely fixed (it is defined as a certain number of clock cycles of the master clock). After launch and cooling down, the true focal lengths of the telescopes will have settled down to their true in-orbit values. Then, during nominal operations, the ACS feedback loop will ensure that the spin rate ω is maintained such that, for the given focal length(s) and the given TDI period, the image smearing is minimal. In short: the TDI rate is fixed, the focal length(s) will be what it (they) will be, and the spin rate is the free parameter that is adjusted to fit the TDI rate and*

the focal length(s)." It may be added that the actual focal lengths (and thus the actual spin rate) shall differ from the nominal ones by about 1.5 10^{-4} at maximum.

5.3 Pixel Numbering Convention

One might consider to define a formal CCD Reference System, but after quite some consideration I can see no practical usage of it. This is why here and in Section 6 a different route is followed. After all, the data from Gaia do not look like CCD frames, but have a different logical structure. Therefore, what is very much needed is a clear and consistent coordinate sytem describing the location of samples, windows and images in the actual Gaia data structure. That system will be defined in Section 6.

If Gaia would read out ordinary CCD frames we would just follow FITS conventions. But things are a bit more complicated, for two main reasons. First, the pre-scan pixels should be incorporated in a consistent way. Second, the TDI mode produces sample arrays that can in no way be mapped to physical pixels on the chips (only to columns). A third complication arises if one wants to create a consistent numbering scheme for both pixels and samples because many different sorts of samples are created by the Gaia CCDs. This will be dealt with in Section 6.

For the sake of clarity and consistency we follow the official Gaia Project pixel numbering convention, as defined in Fig. 4.1-2 of (32). This in particular follows the usual CCD practice by numbering pixels according to the sequence in which they reach the read-out amplifier. Thus the smallest pixel number should reside at top right in Fig. 7. The convention chosen from these considerations is shown in Fig. 9 which is completely self-explaining.

The choice of (1,0) as the label of the "topmost" pre-scan pixel avoids negative numbers. The pixels of the image section of the CCD thus start with (1,14). The end of the first line of image pixels is (1,13+M), where M is the number of columns in the image section of the CCD. Overscan pixels can in a natural way be accomodated beyond that end.

At first sight it seems unnecessarily inconvenient to have the pixel numbering running in the opposite direction of the rows numbering and of the **+Xfpa** *axis. But all possible alternatives are equally awkward. They would either imply numbering of the pixels in reverse read-out sequence or a reversal of the meanwhile well-established numbering of rows and of the focal-plane coordinates.*

Note that for the Gaia CCDs M=1966 and K=4500. Physically there are 15 pre-scan pixels, but the first one is ignored at readout. This leaves 14 actual pre-scan pixels in the data, which are numbered 0–13. The light-sensitive columns of the CCDs are numbered 14–1979.

The above is the official Gaia Project numbering convention. Note that the CCD manufacturer e2v uses a different numbering scheme (light-sensitive columns of the CCDs num-

bered 1–1966). This is unfortunate, and must be kept in mind when using specification and laboratory data from e2v. But this will never appear in the Gaia telemetry or data reductions.

6 Datation of Samples and Windows

This section establishes a kind of reference system in Gaia's data space. A consistent set of coordinates is defined specifying the identity and location of samples, windows and ultimately of star images (centroids) in that data space.

6.1 Pixel Coordinates of an Unbinned Sample

Due to the TDI mode, every Gaia CCD n produces a "ribbon" of samples which is "infinitely" long in scan direction (time) and has a finite width in the perpendicular direction, limited by the number of the pixel columns of the particular CCD. This is illustrated in Fig. 10. Mathematically, the "ribbon" is a rectangular array. Following (14) the identity of a particular sample in the data stream from a given Gaia instrument can be specified by three integer indices which we call the 'pixel coordinates' of the particular sample. If the samples would correspond to single physical TDI pixels the definition would be as follows:

- k, the 'along-scan pixel coordinate' of the sample. In principle this is the running number of the TDI clock stroke at which the sample is read into the read-out register (serial register) of the CCD chip. In essence, the index k enumerates a time sequence. In the actual Gaia data processing it is represented by the OBMT of the on-board instant in which the sample is transferred to the readout register of the relevant CCD (i.e. not actually as an integer index in units of the TDI period). It corresponds to the 'transit time' of the pixel center in the sense of Section 5.2.4. For related information see also Section 6.4.
- m, the 'across-scan pixel coordinate' of the sample. This is the running number of the particular CCD column to which the sample belongs: for the imaging area of the CCD chip, $m = 14, ..., 13 + M$, where M is the total number of columns for the particular CCD and $m = 14$ is defined to be the column closest to the read-out amplifier (see Fig. 9 and Section 5.3).
- n, a designation identifying the particular CCD chip from which the sample was read: $n = 1, ..., N$, where N is the total number of CCD chips on the focal planes. N is of the order of one hundred. The conventional designations of the CCDs are given in Section 5.2.1. In telemetry, the CCD chip index n will most probably be a simple sequential number. But in all other circumstances the more logical

and mnemonic designation scheme should be used, as defined in Section 5.2.1 in connection with Fig. 6.

The implementation of k in terms of OBMT assures its strictly monotonous increase over the mission, and thus its uniqueness. The practical usage in the DPAC data processing system occurs via the unique DPAC transit identifier and the 'AF1 reference acquisition pixel', see Section 7 and the documents cited there.

6.2 Pixel Coordinates of a Binned Sample

In case of binned samples we define the pixel coordinates as follows:

- k_s, the 'along-scan pixel coordinate' of the binned sample. This is the highest along-scan pixel coordinate occurring in the set of pixels contributing to the sample. All other remarks as for k in the preceding section.
- m_s, the 'across-scan pixel coordinate' of the binned sample. This is the highest across-scan pixel coordinate occurring in the set of pixels contributing to the sample. All other remarks as for m in the preceding section.
- n_s, the common CCD designation of all pixels contributing to the sample.

For an illustration the reader may have a look at Fig. 11. The pixel coordinates of the binned sample are the pixel coordinates of the "lower left" pixel contributing to it (instead of "lower left" the term "lower trailing" pixel would perhaps be more telling).

Note that the above definition of k_s and m_s constitutes a reasonable and consistent choice: k_s corresponds to the instant of time when the sample first appears in the Gaia data stream. It is the running number of the TDI clock stroke that initiates the actual readout of the sample. Insofar it is the true analogue of k for an unbinned sample. Similarly, m_s is the running number of the shifting steps in the serial register that initiates the actual registration of the charge in the read-out amplifier.

6.3 Pixel Coordinates of a Window

A window is characterized by the pixel coordinate of the sample in its "top right corner" (compare Figure 10) and by its type. In total it is therefore specified by four indices (compare Section 6.1):

- k_w, the 'along-scan pixel coordinate' of the window. This is the smallest along-scan sample coordinate occurring in the set of samples contributing to the window.
- m_w, the 'across-scan pixel coordinate' of the window. This is the smallest across-scan sample coordinate occurring in the set of samples contributing to the window.
- n_w, the common CCD designation of all samples contributing to the window.
- $type$, characterizes the window type and — in consequence — the numbers, sizes and positions of samples and patches of the window. In actual programming environments, the $type$ will often not be a single data item, and it often will be uniquely implied by the processing context (and in such cases not needed to be given explicitly).

Note again that this definition of k_w and m_w constitutes a reasonable and consistent choice: k_w corresponds to the instant of time when the window first appears in the Gaia data stream. It is the running number of the TDI clock stroke that initiates the readout of the first samples of this window. Analogously, m_w is the running number of the shifting steps in the serial register that initiates the actual registration of the first sample in the read-out amplifier.

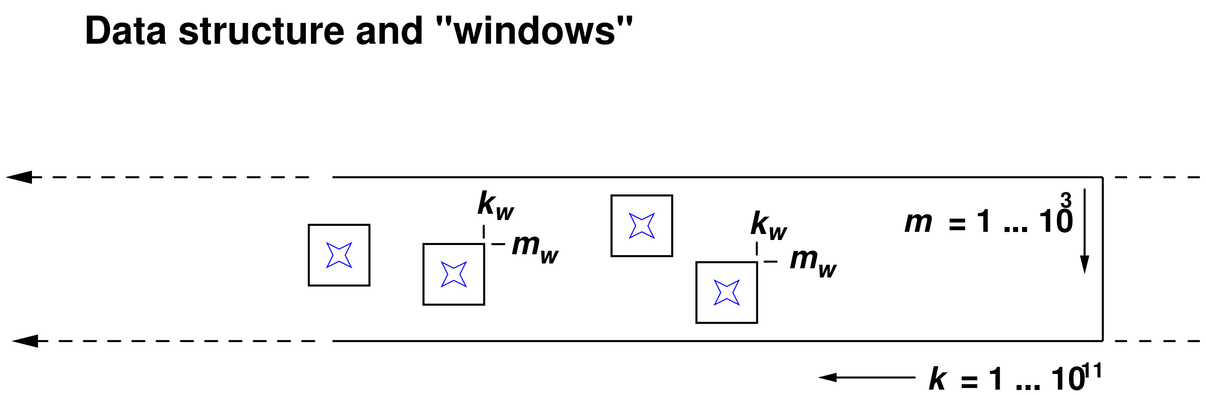

Figure 10: Windows in the stream of samples produced by a CCD. Note that k and m run towards the left and towards the bottom, respectively.

The pixel coordinates of samples and windows are illustrated in Fig. 11.

6.4 Pixel Coordinates of a Star Image

Let us adopt the following notations:

S_{kmn} the photometric signal in the sample identified by pixel coordinates k, m, n.

Δ_k the size of a sample along scan (in units of pixels)

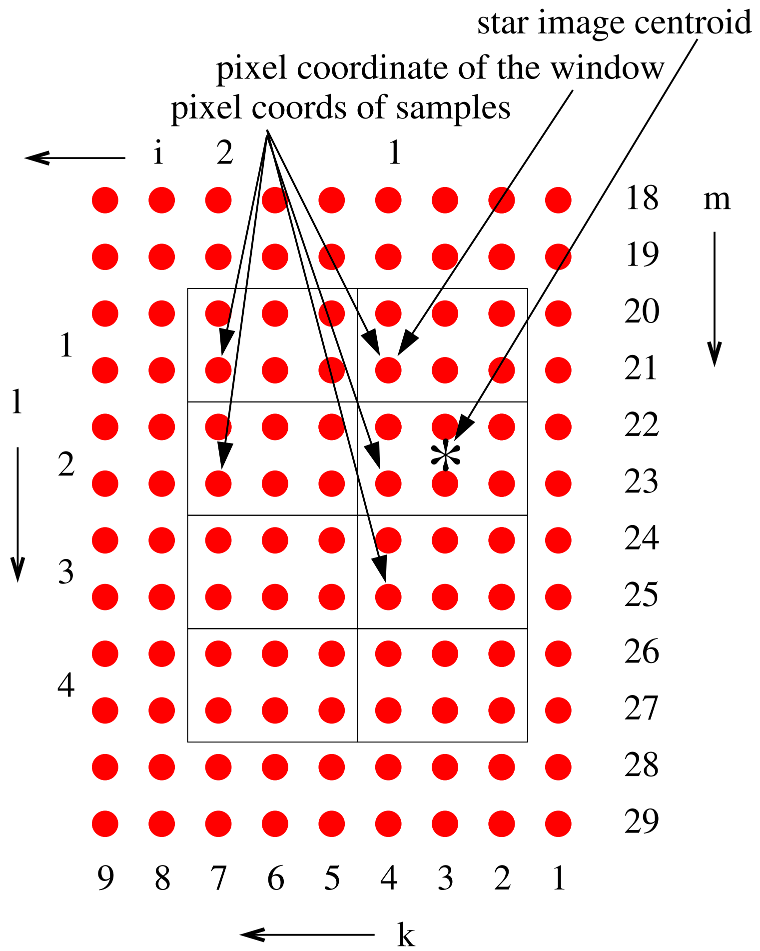

Figure 11: An illustrative example of the pixel coordinates of samples, windows and image centroids. The red dots indicate the integer grid of pixels (or unbinned samples) with pixel coordinates k and m. The thin boxes indicate (3×2)-samples. The sample at top left has pixel coordinates (k_s, m_s)=(7,21), the one immediately below has pixel coordinates (k_s, m_s)=(7,23). The group of eight marked samples may be considered to form a (2×4)-window. The pixel coordinates of that window are (k_w, m_w)=(4,21). Finally the asterisk denotes the centroid of a star image that is centered on sample (k_s, m_s)=(4,23). Note that its pixel coordinates are not (4,23), but (κ, μ)=(3,22.5). The scale at left shows the across-scan sample coordinates l of the various samples within the window. The corresponding along-scan coordinates i are shown at the top.

Δ_m the size of a sample across scan (in units of pixels)

I the size of a window along scan (in units of samples)

L the size of a window across scan (in units of samples)

The location of a star image in a window (or in any set of samples) is determined from the set of S_{kmn} by some sort of centroiding algorithm. The internals of that algorithm are of no relevance presently, nor are its detailed properties. The algorithm used in the on-board data processing for attitude determination differs from that used on ground for the scientific data reductions.

But, of course, the location of the centroid need not be an integer. Let us denote the centroid position by κ (corresponding to along-scan pixel coordinate k) and μ (corresponding to m), and let us call κ and μ the pixel coordinates of the star image. **These are the primary astrometric observables of the non-dispersed Gaia instruments.** The details of their definition and determination are not a subject of the present document. The conceptual and mathematical complexities connected with them, as well as their intricate interplay with the PSF/LSF calibration are described in (50).

The coordinates κ and μ of the image centroids are continuous interpolations of the discrete (integer) sample indices k and m. Following FITS conventions we define that the values of κ and μ are integers when the S_{kmn} are symmetric about some pixel (not sample!) with pixel coordinates (k, m, n). [23]

Since the centroiding algorithm works on nothing but samples, the resulting centroid will first of all be in units of sample indices counting from some corner of the window. In order to have a reasonable and consistent set of coordinates, this has then to be transformed to pixel coordinates, by the following procedure.

Before we can actually proceed to define the pixel coordinates of an image centroid it is thus useful to consider 'sample coordinates' within a window. Consider an $(I \times L)$-window consisting of $(\Delta_k \times \Delta_m)$-samples. Let us label the samples within that window by (purely window-internal) indices (i, l), where $i = 1, ..., I$ and $l = 1, ...L$, in sequence of increasing k_s and m_s, respectively. We may call (i, l) the 'sample coordinates' of samples. Since, as already mentioned, the centroiding algorithm works on nothing but samples, it can first of all produce the centroid location only in terms of a continuous interpolation of sample coordinates (i, l). Let us denote these by (ι, λ).

The pixel coordinates of sample (i, l) are

$$(k_s, m_s) = (k_w + (i - 1)\Delta_k \, , \, m_w + (l - 1)\Delta_m)$$

The pixel coordinates of a star image centered on sample (i, l) are (see Fig. 11!)

$$(\kappa, \mu) = (k_s - (\Delta_k - 1)/2 \, , \, m_s - (\Delta_m - 1)/2)$$

Thus the pixel coordinates of a star image centered on sample (i, l) are

[23] For asymmetric point-spread functions this definition would have to be a bit more complicated, see (50); but this is an irrelevant detail at the moment.

$$\begin{aligned}(\kappa,\mu) &= (k_w + (i-1)\Delta_k - (\Delta_k - 1)/2\,,\, m_w + (l-1)\Delta_m - (\Delta_m - 1)/2) \\ &= (k_w + 1/2 + (i-3/2)\Delta_k\,,\, m_w + 1/2 + (l-3/2)\Delta_m)\end{aligned} \tag{21}$$

And the pixel coordinates of a star image centered on general sample coordinates (ι, λ) analogously are

$$(\kappa,\mu) = (k_w + 1/2 + (\iota-3/2)\Delta_k\,,\, m_w + 1/2 + (\lambda-3/2)\Delta_m) \tag{22}$$

At first sight the above consideration and the resulting formula may seem unnecessarily complicated. But once you have the formula it is nothing to worry about any more. Furthermore, it has two great advantages:
1) A given physical image location on the CCD will lead to the same resulting pixel coordinates regardless of the sample size and window size.
2) The centroiding algorithm does not need to know anything about the sample size and window size (except, of course, if it wants to make use of a known PSF/LSF or a known background; but this is quite a separate matter, unrelated with coordinate definitions).
And why not from the very start reckon in sample coordinates rather than pixel coordinates? Because samples can be positioned in steps of individual pixels, not only in steps corresponding to the sample size. The AF chips, for instance, can produce 1×12-pixels having pixel coordinate $m_s = 24$ as well as $m_s = 25$ or $m_s = 27$.

A few more words on the along-scan pixel coordinate or 'transit time' κ of an image centroid:

It is a very central concept to all of Gaia astrometry. To first order it corresponds to the instant of time when the centroid of the image reaches the "trailing edge" of a CCD. It is basically given as a continuous interpolation of the integer grid of pixel coordinates k, and in practice it is given in OBMT with a resolution of 1 nanosecond, corresponding to 0.06 μas on the sky.

6.5 Datation of BP, RP and RVS Spectra

The datation of BP, RP and RVS spectra is defined by CU5 and CU6 in accordance and analogy to the scheme described above and complemented by the Transit Identifier in Section 7. The concept of pixel coordinates of a star image (centroid, Section 6.4) is not applicable in that simple form, in particular.

7 The DPAC Transit Identifier and DPAC Source Identifiers

7.1 The DPAC Transit Identifier

Gaia's elementary scientific observations are triggered by the autonomous on-board detection of star-like images in the continuous (complete, non-windowed) stream of TDI samples from the SM CCDs. Each such detection creates a complex series of on-board events and a whole set of telemetry items. These events and telemetry data are subsumed under a logical item called 'transit'. On ground, each transit creates an extensive set of raw-data and intermediate-data items in the DPAC data processing chain. For clarity, the term transit is occasionally extended to read 'star transit' or 'FoV transit', the latter being used to clearly distinguish it from a 'CCD transit', meaning the parts of a physical transit event related to one CCD only.

The telemetry items produced by a given transit[24] are highly scattered across the on-board data management scheme, and they may appear in the telemetry stream at widely different times — up several days apart. The corresponding ground processing products similarly are scattered across the DPAC data structures, with some of them being created in multiple versions during the cyclic stages of the DPAC data processing.

These complications necessitate a strict and unique labelling of all the DPAC data items belonging to the same given transit. This purpose is served by the DPAC Transit Identifier, a unique filing key given to each transit. The Transit Identifier is created in the very first scientific data processing step on ground, the Initial Data Treatment (IDT), and it is attached to each and every data item subsequently produced for the given transit in the DPAC processing chain.

7.1.1 Definition

The structure and format of the Transit Identifier is defined in (43); the details of its creation from telemetry data is described in (44). The Transit Identifier is a single Java `long` integer quantity (64 bits). In order to maximise its usefulness — over and above its required uniqueness — it carries the essential parameters of a transit, specifically (for details see (43)):

- OBMT (On-Board Mission Timeline, 42 bits) with a resolution of 204.8s. This is the result of discarding the 10 MSB and the 12 LSB of OBMT50 of the Astrium AF1 'reference sample (see (44)) of the window in AF1.
- FoV (Field of View, 2 bits), as received from the TM, i.e. ranging from 0 to 3.
- CCD Row (3 bits), as received from the TM, i.e. ranging from 1 to 7.

[24] Specifically: up to three Star Packets (SP) and several Auxiliary File records, plus onboard statistics and housekeep data; see e.g. (44).

- Across-scan coordinate (12 bits) of the Astrium AF1 'reference sample, as received from the TM, i.e. ranging from 14 to 1997.

This definition leads to a TransitId of 59 bits, thus fitting in a 64-bit `long` type and leaving the 5 MSB spare. Note that the encoding of FoV and AC coordinate of the AF1 window does not follow the DPAC conventions set out in Figures 3, 11 and 9 above, respectively. Note furthermore that, with the OBMT part being in the uppermost bits used, sorting according to Transit Identifier is a convenient way to sort all DPAC raw and intermediate data by time.

7.1.2 Human-Readable Format

A human-friendly representation of the clumsy `long` integer corresponding to 17 decimal digits is proposed in Section 3 of (43). It disassembles the various logical parts of the Transit Identifier into separate decimal digits. For details see (43).

In short, the format is as follows: RRRRR-MMMMMMMMM-F-C-AAAA, where:

- RRRRR (5 digits) indicates the integer part of the OBMT in units of revolutions
- MMMMMMMMM (9 digits) indicates the remaining fraction the OBMT in units of revolutions
- F (1 digit) is the FOV, from 1 to 4
- C (1 digit) is the CCD Row, from 1 to 7
- AAAA (4 digits) is the AC Coordinate, from 0014 to 1979 pixels .

Thus, for example, Transit Identifier 41001999429850823 becomes 2966-000117720-2-5-1735. Note that — contrary to the original contents of the Transit Identifier itself! — the encoding of FoV and AC pixel numbering in this format **does** follow the DPAC conventions set out in Figures 3 and 9 above, respectively (but still not the convention of the window coordinate set out in Figure 11).

GaiaTools provides the `TransitIdParser.toString()` method to generate this format from a given binary Transit Identifier value. Additionally, an on-line Transit Identifier decoding tool is provided in https://gaia.esac.esa.int/decoder/.

7.2 The DPAC Source Identifier

Initially, the specific physical celestial object recorded in any given FoV transit is anonymous, i.e. unknown, both on board as well as in the the early stages of the scientific ground treatment.

Before any science can be made out of a FoV transit, it is therefore necessary to assign it to a specific celestial object (in Gaia language called ‘source’ to avoid possible mix-up with e.g. Java objects). This is the purpose of the task called cross-matching (or shorter cross-match, abbreviated as XM). To this end, each source must uniguely be labelled by a source identifier (often abbreviated as sourceId).

The function of the cross-matching is to assign transit identifiers and source identifiers. This at first sight trivially looking task is complicated by two facts: i) This assignment will occasionally not be uniquely possible, e.g. by the superposition of the two FoVs on the CCDs, or by close proximity of two sources on the sky. ii) The list of sources (i.e. Gaia’s sky inventory) must be defined from the Gaia observations themselves. The combination of these two complications makes the cross-matching one of the most complex and computationally heavy tasks in all of DPAC. The present section does not describe the cross-matching, but only defines the source identifiers to be created and used by that process (and in consequence by all of DPAC).

The basic concept, the format and contents, and the fundamental rules for the creation and handling of Source Identifiers are described in detail in the document (46) which was approved by DPACE in 2013. The following subsection mainly is an excerpt from that document.

The format and handling of source identifiers is supported in GaiaTools by the Java interface `gaia.cu1.tools.util.SourceIdUtil`.

7.2.1 Definition and Format

In short, the Source Identifier used by DPAC consists of a single Java `long` integer (64 bits), constructed from:

- a HEALPix sky pixel in bits 36-63 (where lsb=1, msb=64), in the following called index number. By definition the smallest HEALPix index number is zero. More details are given in (46), and a short explanation is given below.
- a 3-bit DPC code in bits 33-35 (lsb=1, msb=64). The allowed values are defined in Section 2.6 of (46),
- a 25-bit plus 7-bit sequence number within the HEALPix pixel in bits 1-32 (lsb=1, msb=64), which in turn is split into two parts:
- a 25-bit running number in bits 8-32 (lsb=1, msb=64). The running numbers are defined to be positive, i.e. never zero (except in the case of forced empty windows, see below).
- a 7-bit component number in bits 1-7 (lsb=1, msb=64).

7.2.2 A few short explanations

Healpix: The idea of labelling celestial objects by a sky pixel plus a running number within that pixel is very old; in fact it was first systematically used by Bayer and Flamsteed in the 17th century, where the "pixels" were the traditional constellations. More modern versions are known from e.g. the General Catalogue of Variable Stars, the Hubble Space Telescope's GSC and other star catalogues. The term HEALPix means 'Hierarchical Equal-Area iso-Latitude Pixelisation' (of a sphere). More explanations are given in Sections 2.1 and 2.2 of (46).

Solar-system objects (SSOs) and forced empty windows (also called Virtual Objects, VOs) do not belong to any specific index number (HEALPix). Special formats and rules are defined for the Source Identifiers of such Gaia sources, therefore. They involve negative pseudo-index numbers, and in the case of VOs special running numbers. Details are again defined in (46).

DPC code: In order that the data processing at different DPCs can independently assign source identifiers without creating inconsistencies, a DPC code was added to the source identifier in the year 2011. It is a 3-bit binary code with the possible values DPCE=0, DPCB=1, DPCI=2, DPCC=3. More motivation for this is given in Sections 3.4 and 3.8 of (46).

Component number: Since Gaia source identifiers are primarily assigned on the basis of SM detections (by IDT and IDU). Therefore, by necessity are defined in terms of the resolution properties of the 2-d images of the SM and of the on-board detection algorithm. In other words, a source identifier primarily denotes a certain set of SM detection items on the sky[25]. However, as detailed in Section 4.2 and Section 4.3 of (46), such an item may later split into several distinct astrophysical objects. For this reason the lowest 7 bits of the running number are reserved for the component number. In other words, the true source counter starts on bit 8 only. By definition, the smallest component number (in particular the one for sources which have not split into components at all) will always be zero. Thus, including the lowest seven bits, the smallest sequence number within each HEALPix will actually be 2^7=128.

Component numbers will be needed whenever a Gaia source splits up and separate parameters are determined for more than one physical object contained in it. Components can turn up in all of CU4,5,6,7,8. Examples are the G magnitudes of the constant partners in variability-induced movers (VIMs) from CU4, positions and magnitudes of double-star companions from the Source Environment Analysis (SEA) process (CU5), masses of the components of eclipsing binaries from radial-velocity curves (CU6), diameters and surface brightnesses of eclipsing-binary partners from lightcurves (CU7), effective temperatures of the members of unresolved doubles from multi-colour photometry and/or from RVS spectral classification (CU8).

Up to now (i.e. up to DPAC Processing Cycle 3), none of the above CUs have created specific

[25]For Gaia DR4 and later, this limitation will to some extent be overcome by the enhanced IDU processing in DPAC Processing Cycle 04 and later. But this does not alter the basic principles described here

plans for the creation and management of components. Thus the precise scheme for the assignment of component numbers is not yet a topic of the present document, nor of (46). It is to be defined in a consensus between the relevant CUs. A future issue of the present document should record it, once it is formed and finally agreed.

7.2.3 Human-Readable Format

A human-friendly representation of the clumsy `long` integer corresponding to 19 decimal digits is proposed in Section 2.8 of (46). Like the one for the transit identifier, it disassembles the various logical parts of the Source Identifier into its various logical parts. For details see (46). It differs between normal sources, SSOs and VOs.

For normal sources the format is as follows: HEALPix-DPCnumber-comp, where:

- HEALPix is the index number as defined above, indicated as [N,E,S] for North, Equator or South, followed by [0-3] for the top-level pixel within the N/E/S region, followed by the six-digit hexadecimal number of the region
- DPC is one letter: T,B,I,C,G or E.
- Number is the decimal running number (from 00000001 to 33554432)
- Comp is the decimal component number (from 000 to 127)

This decoding is available, for example, in the DPAC on-line SourceId Decoder at URL https://gaia.esac.esa.int/decoder/.

Some examples from Gaia DR1:
Sirius b is 2947050466531873024, which is decoded as E11CC0D9-B-102434-0
Proxima Centauri is 5853498713160606720, decoded as N22779C2-B-412104-0
Kapteyns Star is 4810594479417465600, decoded as N0585546-B-17462-0

8 Photometry Conventions

8.1 Magnitude Systems

This section briefly explains the various magnitude systems in use in astronomy, and then states the choice taken by DPAC, in agreement with the Gaia Science Team, and meanwhile implemented in the integrated photometry of Gaia Data Releases 1 and 2.

In completely abstract terms, an astronomical magnitude is defined by

$$\text{magnitude} = -2.5 \log \frac{\int F_\nu^{star} \cdot \text{Filter}_\nu \cdot \text{Telescope}_\nu \cdot \text{Detector}_\nu \, \text{d}\nu}{\int F_\nu^{ref} \cdot \text{Filter}_\nu \cdot \text{Telescope}_\nu \cdot \text{Detector}_\nu \, \text{d}\nu} \tag{23}$$

where ν is the frequency of the detected radiation, Filter_ν is the transmission curve (as function of ν) of the filter(s) used, Telescope_ν is the optical transmission of the telescope optics, Detector_ν is the sensitivity curve of the radiation detector, F_ν^{star} is the flux density from the astronomical source under observation, and F_ν^{ref} is the flux density of some reference spectrum which defines the magnitude system. There are basically three different magnitude systems in astronomy, which differ by the reference spectrum F_ν^{ref}:

- 'Johnson-type' magnitudes, also known as 'Vega-type' magnitudes, use an ideal unreddened A0V star (nominally Vega), which by definition has the same magnitude in all wavelength bands, i.e. for all possible functions $\text{Filter}_\nu \cdot \text{Telescope}_\nu \cdot \text{Detector}_\nu$. In consequence all colour indices are zero for this spectrum. This system has been highly successful over the last six decades, in the optical, near IR and near UV. It becomes problematic if extrapolated far into the UV and IR (due to the general shape of an A0 spectrum) and it becomes ill-defined in the far UV (because of the UV variability of actual stars and the lack of good models for A0 spectra). Another problem is caused by the unavoidable differences between individual stars, due to metallicity, rotation etc.
- Therefore the 'AB magnitudes' system has become more and more widespread over the last two decades. It is defined by F_ν^{ref}=3.631 $10^{-23}\,\text{Wm}^{-2}\,\text{Hz}^{-1}$, i.e. by a constant physical flux density. It was originally introduced by Oke and Gunn in 1983 (28) for quasi-monochromatic magnitudes ('spectro-photometry' in the astronomical jargon) as $AB_\nu = -2.5 \log f_\nu - 48.60$ (with f_ν the flux density in cgs units). More information can be found in (29). Gossip says that the acronym 'AB' stands for 'absolute'.
- A third system, 'ST magnitudes', using a constant flux density F_λ in wavelength rather than in frequency units was introduced in the framework of Hubble Space Telescope photometry, but its usage apparently has never spread beyond its originator. So it was not seriously considered for Gaia.

Convention: Gaia/DPAC uses 'Johnson-type' = 'Vega-type' magnitudes for the integrated photometry from AF, BP, RP and RVS.

This decision was proposed by Floor van Leeuwen in 2012, accepted by the DPACE meeting of July 15, 2012, and has been applied for Gaia DR1,2,3 already.

No such convention is adopted for the spectrally resolved photometry products from BP, RP and RVS. These will not be externally calibrated, but will be on an internally and homogeneously flux-calibrated scale (email information from the CU5 leader, Dafydd Evans, of Feb 4, 2020). Methods to transform theoretical model spectra to the internally calibrated BP and RP spectra are planned to be provided to users, however.

A flux calibration is also planned for the RVS spectra; in case of lacking man-power, the RVS spectra may be possibly published as normalised to a pseudo-continuum (emails from CU6 leader, Paola Sartoretti, of May 5, 2020).

8.2 Notations for Gaia Magnitudes

There are no conventions for programming environments. In text environments, however, the integrated magnitudes derived from AF, BP, RP and RVS observations shall be denoted as G, G_{BP}, G_{RP} and G_{RVS}, respectively.

This is what is used in the DR2 papers, and it is in accordance with e.g. the A&A convention in use for UBV photometry.
The DR2 online documentation uses G, $\mathrm{G_{BP}}$, $\mathrm{G_{RP}}$ and $\mathrm{G_{RVS}}$, *i.e. with the G not in math italic. - This is clearly unfortunate. It is foreseen to be homogenized in the future, in particular for the papers and documentation of eDR3 etc.*

8.3 Raw Counts vs. Final Magnitudes

The final (published) G, G_{BP}, G_{RP} magnitudes will be “standard” magnitudes in the sense that each ouput value aims at referring to an exactly defined physical spectral band, i.e. to an exactly defined spectral response function and magnitude zero point. This is what an end user wants.

In actual fact the various CCDs and prisms in use to produce a set of relevant raw data will differ slightly among each other. There will furthermore be variations from column to column, variations over time and possibly differences between the two fields of view. Thus, the transformation of the ‘observed fluxes’ (photo-electron counts summed up over an image) into standard magnitudes will result from a complex calibration process.

The terminology of that process and of the quantities involved in it is not a subject of the present document.

9 Further Conventions and Notations

This section contains a miscellaneous collection of further conventions on different aspects of the mission and the data reductions. The reader may add more to this collection.

9.1 The Gaia Parameter Database

The Gaia Parameter Database, see (10), is to be considered as a standard for DPAC. This concerns notations for the quantities given there, as well as the values for them. Of special interest in this respect is the "nature" section of that database, giving specific values for some physical and astronomical quantities.

9.2 Parallax and π

Historically the (trigonometric annual) parallax has mostly been denoted by the Greek letter π. However, this has frequently led to confusion or inconveniences since that letter is even more commonly used for 3.14159...

Therefore the symbol ϖ has been used for the parallax occasionally. This usage is adopted as convention for Gaia. The LaTeX code for ϖ is `\varpi`.

9.3 Notations for Physical Quantities

A number of physical quantities should always be denoted by the symbols in common use in physics:

c — the speed of light

k — Boltzmann's constant

h — Planck's constant

Suggestions for the extension of this list are welcome.

9.4 Stellar Spectral Classes

Apparently there are no IAU resolutions on this. The MK system is the practical standard. But maybe Gaia itself will change that ...

A widely accepted recent addition to the MK system may be particularly relevant for Gaia: The introduction of the new spectral classes ‘L’ and ‘T’ extending the MK sequence to lower surface temperatures, i.e. beyond class M. More information can be found in (26) and (27).

9.5 Chemical Elements and Ions

The chemical elements are to be denoted by their usual chemical symbols, e.g. ‘O’ for oxygen, ‘Ti’ for titanium and ‘K’ for potassium.

The doubly ionized oxygen ion is to be denoted ‘O^{2+}’ or ‘O^{++}’. The line spectrum produced by it, being the third spectrum of oxygen, is to be denoted ‘O III’.

9.6 Orientation of Sky Plots in Galactic Coordinates

Following a suggestion by J. de Bruijne it is recommended that all-sky plots showing the distribution of some quantity in galactic coordinates should uniformly be oriented in the following way: North up, galactic centre in the centre of the picture, longitude increasing towards the LEFT (this gives a non-inverted view, like looking towards the real sky).

Ronald Drimmel commented that this should by no means be taken as a binding convention, and that *any* plot of the sky should be labelled or explained well enough that its coordinates are unambiguous.

10 Appendices

Appendix A: Ecliptic and Galactic Coordinates

Ecliptic and galactic coordinates are alternate coordinates for the ICRS. They do not represent or constitute a reference system of their own. Formal transformations from the equatorial ICRS coordinates will be given in the documentation of published Gaia mission results.

> *The Gaia online DR1/DR2 documentation already gives a full version to 16 decimal places. A 10-digit version of these transformations — not sufficient to conserve the internal precision of Gaia results, but amply sufficient for all practical use cases of ecliptic and galactic coordinates — is given in Vol. 1, Section 1.5 of (7).*

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