

Validation of the data received from the Gaia satellite

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Abstract: The main goal is to develop efficient tools to help validating the data received daily from the Gaia satellite. In order to do so, we study the main data processes and their outputs and build three different tools called *ExtendedStats*, *FLIdtValidation* and *AutoAlarms*.

I. THE GAIA MISSION

The Gaia satellite was launched from the French Guiana on December 19, 2013. It is a mission of the European Space Agency (ESA) which aims to determine the position, proper motions and parallaxes of more than one billion stars and other objects with unprecedented accuracy, as well as their photometry and spectroscopy. Currently, the satellite is orbiting the second Lagrange point L2 (placed 1.5 million kilometers from the Earth in the anti-Sun direction and co-rotating with the Earth around the Sun) and has been in nominal operations since July 2014. At the end of the mission, around 2022, the most accurate 3D map of our galaxy is expected.

II. DATA PROCESSING

As it is represented in Fig. 1, once the data is downloaded from the spacecraft, it goes through a series of three daily data processes called Mission Operations Center (MOC) Interface Task (MIT), Initial Data Treatment (IDT) and First Look (FL). The MOC Interface Task receives RAPID files from the MOC and sends them as PacketGroups to IDT. The Initial Data Treatment orders the telemetry data into tables (called xxxxObservation [8]) and generates preliminary astrometric, photometric and spectroscopic data for all the sources detected as well as an initial determination of the attitude of the satellite. All the data is stored in a database, and the raw and the intermediate data are used in First Look to monitor almost in real-time the on-board detectors and see if any correction on them is necessary.

After these three processes, all the data is stored into the main database. Every six months during the length of the mission, an iterative process called IDU uses all the raw data up to that moment and the latest calibrations to recalculate all the parameters and redetermine the catalogue produced by IDT.

Several algorithms have been developed to extract all the physical information from the Gaia data: the Astrometric Global Iterative Solution (AGIS) will deter-

mine positions and velocities, the Photometric Pipeline (Photpipe) will determine the photometric solutions of the sources observed, and CU6 is a Coordination Unit (CU) working on the spectra and radial velocities.

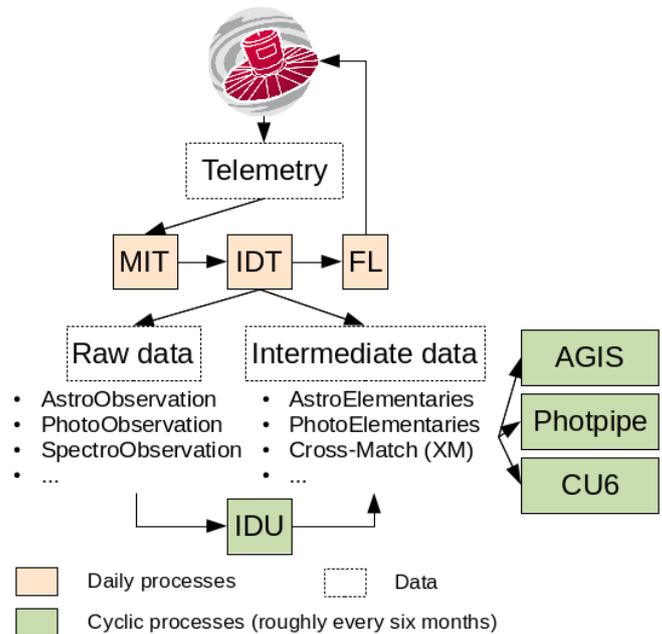


FIG. 1: Scheme of the main processes used to create the astrometric and photometric catalogue from the Gaia data. The coloured boxes represent different processes, being the colour an indication of how often they are performed, and the dashed boxes represent different types of data.

A. Initial Data Treatment (IDT)

The Initial Data Treatment runs three main tasks. The first one is to reconstruct and rearrange the raw data into tables so it can be used in the various CUs (called xxxxObservation). The second one is the initial determination of the astrometric and photometric parameters (stored in tables called xxxxElementary [9]) as well as an initial determination of the attitude of the satellite (OGA1). This is the so called intermediate data which is later used in FL, AGIS and Photpipe. The third task is to create the catalogue by cross-matching the observations against an

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on-ground source catalogue and producing a `Match` table, linking transits (detections) and sources, adding new sources when needed. The cross-match (XM) is triggered roughly once a day.

In order to keep track of the process and be able to identify each piece of data, different numerical identifications are determined on this first stage of data processing. The first one, and most important, is determined from on-board data and it is called *transitId*. This identification is unique for each given detection. The second one corresponds to which source of the catalogue the transit has been linked to (if it creates a new source then a new one is produced), and it is called *sourceId*. And the third one codes the technical information of the IDT process used and it is called *IDT solutionId*.

In every IDT job several tables are produced. Besides the tables containing the raw and intermediate data, specially relevant are those tables containing the result of the cross-match and the result of the attitude and coordinates first computation (called `Match`, `Oga1` and `DetectionRecord` respectively). The XM job links every transit to the adequate sources of the catalogue within a certain radius and decides to which one the transit actually corresponds, so the `Match` table links all the identifiers associated to a detection: its *transitId*, the *IDT solutionId* and its designated *sourceId*. The `Oga1` table contains a refined first on-ground determination made from the IOGA (Initial On-Ground Attitude) output, which is the initial attitude determination made by IDT from the raw attitude data from the satellite. The `DetectionRecord` table contains the result of the first coordinates determination made by IDT (detections are identified by both its *transitId* as well as its *IDT solutionId*).

B. First Look (FL)

The First Look system is a near real time monitoring system of the on-board instruments. It uses the raw and intermediate data to perform a statistical analysis on a daily basis and verify if a set of situations are happening or not. In the case where anything on the instruments is wrong, an urgent petition for a change is raised to the MOC. It is an important part of the data processing as it proposes changes that may avoid further errors.

Besides this monitoring, it also recomputes several parameters of the transits processed in the last 24 hours by IDT, such as the coordinates and the attitude of the satellite (stored in tables called `Oga2` and `PrimarySource/SecondarySource` respectively). As a FL run does not always coincide with an IDT run, the reprocessed data is associated with a *solutionId* which codes the version of FL software used among other technical data. This FL *solutionId* identifier is not the same one as that given by IDT, so a table called `InputDataUsed` is used to store which IDT *solutionId* are used to compute a certain FL run and which FL *solutionId* they have associated.

III. STATISTICAL ANALYSIS

The validation tools developed had to be optimized to work with huge amounts of data as they were designed to run over at least one IDT run, which contains around 22 hours of transits (about 40 million detections on average). Because of the large volume of data, only statistical analysis can be performed on a daily basis.

The robust scatter estimator (RSE) is a dispersion estimator described in [4] and [6] as

$$RSE = 0.390152 * (P_{90} - P_{10})$$

where P_{90} and P_{10} are the 90th and 10th percentiles respectively, and the constant has been chosen to make RSE equal to the standard deviation for a Gaussian distribution.

As it is discussed in [6], the median and the RSE are recommended as the robust estimators of the centre of an array of data and of the sample standard deviations respectively. Despite of this, the analysis included in the tools described here includes the determination of the minimum and the maximum, the computation of the mean and the median as central estimators, and the computation of the standard deviation and the RSE. It was decided to compute also the mean and the standard deviation so their similarity to the median and RSE could be verified.

IV. VALIDATION TOOLS

A. ExtendedStats

The first tool developed in this work, **ExtendedStats**, is the one most similar to what had already been developed. It is implemented inside the IDT system and it is used off-line to verify that the data streaming, reception and processing is being done correctly. This tool has been designed to perform a statistical analysis over all the transits processed on an IDT run and produces a set of histograms. It analyses all the parameters (both scientific and technical) included in the following tables:

- (i) Raw data: `AstroObservation`, `PhotoObservation` and `SpectroObservation`
- (ii) Intermediate data: `AstroElementary` and `PhotoElementary`

In Fig. 2 and 3 we show two examples of the histograms produced with this tool for every transit in an `AstroObservation` table with 440 thousand entries. The first one corresponds to a histogram of the object type flag, which is set on the satellite according to what the on-board software thinks a certain transit is. The second one corresponds to a histogram of the flags raised on-board during the acquisition of the transits.

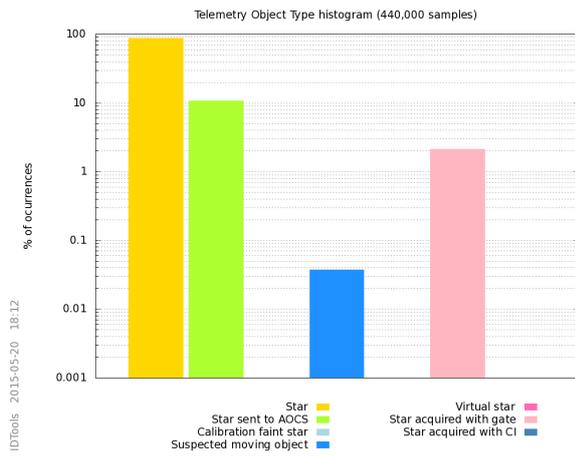


FIG. 2: Example of one of the plots produced by our **ExtendedStats** tool. It is a histogram of the Object Type flag (set on-board) for every transit in a 440000 AstroObservation table.

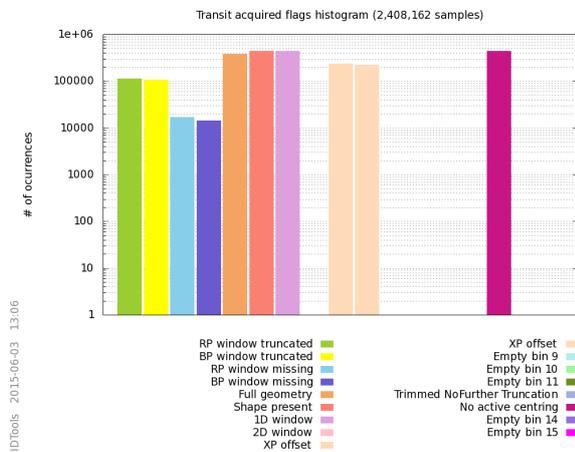


FIG. 3: Example of one of the plots produced by our **ExtendedStats** tool. It is a histogram of the flags raised on-board during the acquisition of every transit in a 440000 AstroObservation table.

B. FIIdtValidation

The **FIIdtValidation** tool was designed to compare the outputs from an IDT run against the outputs of the FL process. The FL algorithms are the first ones in the Gaia data processing able to reach microarcsecond-level astrometry, so we can use the FL outputs as a reliable reference against which we can check the quality of the IDT daily outputs. In order to do so, we implemented an algorithm to compare the coordinates and the attitudes computed by the two data processes.

The most difficult part of designing this tool was to decide which tables were needed and how to load them in an easy and quick way so that the program would not take too long to run. The final design for the data loading is represented in Fig. 4 and consists of the following

steps:

- (i) Through the configuration of the program, we have to define the IDT *solutionId* referring to the cross-match (XM) of the run we want to study.
- (ii) Using the IDT XM *solutionId*, the software loads the **InputDataUsed**, looks for all the FL *solutionId* linked to the specified IDT XM *solutionId* and stores them in a list called *flSolIdList*.
- (iii) Using the list *flSolIdList*, the software loads all the entries from the **PrimarySource** or **SecondarySource** table (corresponding to high priority or low priority transits) linked to the FL *solutionId* in the list.
- (iv) It loads, from the **Match** table, all the transits with the IDT XM *solutionId* and whose *sourceIds* appear on the **PrimarySource/SecondarySource** already loaded. Only the *transitIds* of the detections loaded are stored into a list called *transitIdList*.
- (v) Using the list *transitIdList*, the software loads all the entries from the **DetectionRecord** table, and stores only the *transitId*, the *solutionId*, the G_{mag} and the coordinates α and δ computed by IDT.
- (vi) It loads all the **Oga1** entries corresponding to that IDT run interval time.
- (vii) It loads all the **Oga2** entries corresponding to all the FL *solutionIds*.

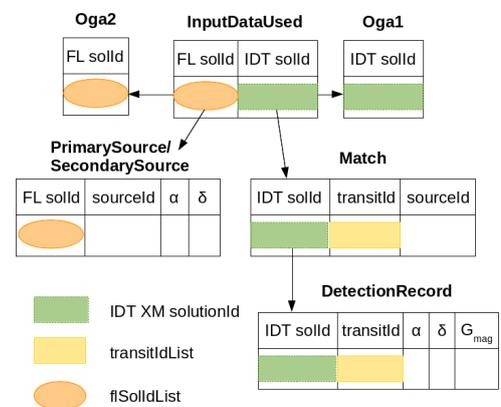


FIG. 4: Scheme of the data selection and loading for our **FIIdtValidation Tools**. The green box represents the given IDT cross-match *solutionId* from which all the data is selected.

This tool has two different parts: the coordinates analysis and the attitude comparison. The first one consists in a thorough analysis, transit by transit, of the coordinates determined by IDT and FL and requires as inputs the *transitId* and the **DetectionRecord**, either the **PrimarySource** or the **SecondarySource**, and the **Oga1** tables. It computes the deviation of the IDT coordinates using the

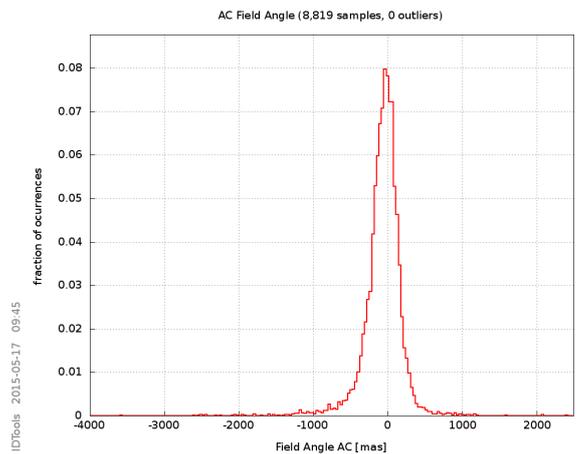
FL coordinates as the reference. Among other parameters, it computes the distance between the coordinates as $d = |\hat{\rho}_{FL} - \hat{\rho}_{IDT}|$, where $\hat{\rho}_{FL}$ is the unit vector in spherical coordinates of the FL coordinates (the same for $\hat{\rho}_{IDT}$), as well as the field angles AC and AL. The field angles are defined as the projection on the across-scan and the along-scan direction of the angle between the detection and a reference axis defined on the spacecraft. All the parameters computed are stored as histograms for an easier visual analysis. In Fig. 5 we present an example of the histograms produced for the field angles in the across and the along scan directions corresponding to the difference between the IDT and FL coordinates. It can be seen that the distributions are well centred in zero and the dispersion is rather small. Note that this analysis reveals that IDT is correctly determining the sky coordinates of most of the transits with a sub-miliarcsecond accuracy. Note, however, that some value can go up to -2500 mas (in the case of Fig. 5 (a)). All values should be contained inside the XM radius ($r_{XM} = 2$ arcsec), so this out-of-range values indicate that something strange is happening.

The attitude comparison uses the same algorithm as the one implemented in IDT and used to compare deviations between the raw attitude, IOGA, Oga1 and the Nominal Scanning Law (NSL), as described in [4]. It takes as inputs only Oga1 and Oga2 tables referring to the same Obmt (On-Board Mission Timeline) time interval, and stores as outputs histograms as a function of the number of occurrences and as a function of time of the rotation deviation of Eta, Zeta1 and Zeta2. These parameters are the projection on the along and across scan directions (for field of view 1 and 2) of the attitude residuals and are obtained from comparing the difference of two quaternions, computed as the rotation of the three axes. In Fig. 6 there is an example of the histograms produced for the rotation deviation of Eta and Zeta1.

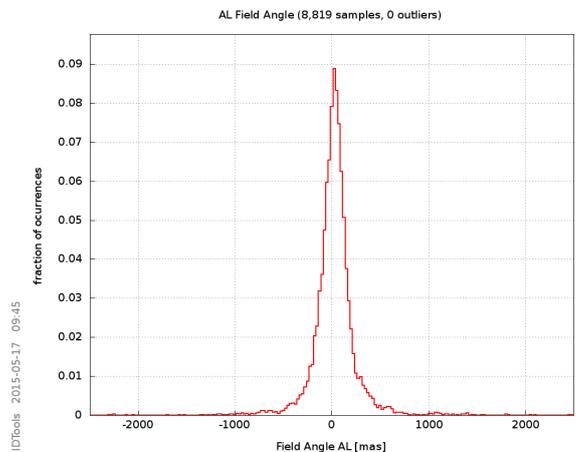
C. AutoAlarms

As described in [7], all the validation outputs from IDT are uploaded to a webpage called IDTMon so that anyone inside the Gaia project can access them and check how is the data reception and processing going.

Some of the validation outputs, such as the basic statistics, the attitude diagnostics or the cross-match monitoring, are daily revised by the ESAC and UB teams to see if there is something wrong. This is a time consuming process since it requires to check a lot of tables and plots in detail and to compare them with previous results to see if there has been any major variation. In order to do this evaluation easier, the **AutoAlarms** system has been designed to automatically check a series of predetermined parameters and to raise an alarm if any of them is not behaving like expected. This tool will be used daily in the last version of IDT that will be installed in ESAC in June 2015.



(a) Distribution of the field angle in the across scan direction corresponding to the difference between the IDT and FL coordinates in terms of the fraction of occurrences.

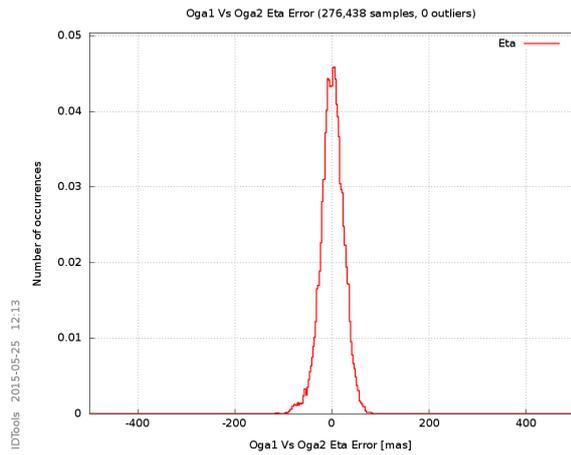


(b) Distribution of the field angle in the along scan direction corresponding to the difference between the IDT and FL coordinates in terms of the fraction of occurrences.

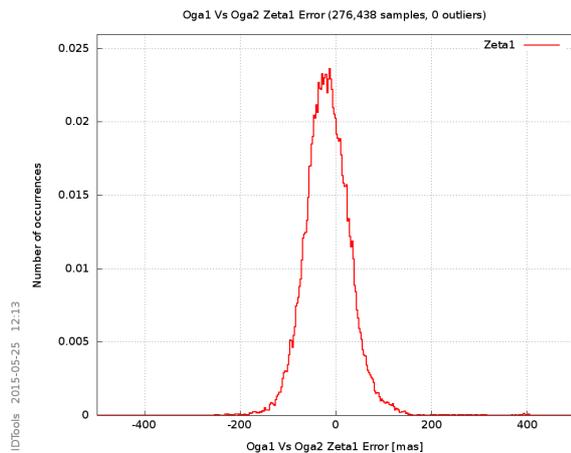
FIG. 5: Example of two of the plots produced by our **FIIdt-Validation** tool on real data from Gaia.

The **AutoAlarms** tool loads some of the files that are later used to build the IDTMon webpage and analyses certain parameters in them. The parameters analysed are both technical and scientific, such as how long do the jobs inside IDT take, or how many detections have been classified as spurious. The analysis can be done by comparing the value of the parameter against a reference defined in the program configuration, or by comparing it against the reference computed by previous results, or by comparing it against the other values for the same parameter (for example, to compare a value between the different CCD strips).

In the first case, the reference may be either a limit (upper or lower) or an absolute value and a certain tolerance (which may be expressed as a percentage or as an absolute value). This case is useful for parameters that are expected to behave always in a certain way. In the second situation, the reference can be computed from



(a) Distribution of the rotation deviation of Eta in terms of the number of occurrences.



(b) Distribution of the rotation deviation of Zeta1 (field of view 1) in terms of the number of occurrences.

FIG. 6: Example of two of the plots produced by our **FIIdt-Validation** tool on real attitude data from Gaia.

the mean or the median of previous results (defining in the properties the method and the number of previous

results used), and the tolerance is defined through properties. This is done for cases when the absolute value of reference may vary from one IDT run to another. Finally, in the third case, a value is compared to the mean or the median of all the values for that parameter (as in the second case, the tolerance is defined through properties). This last case is useful when trying to detect big variations of a parameter studied for different CCD rows.

If in any of these cases a value does not fulfil the condition, an alarm is set with a small explanation and stored into a log file, which will later be uploaded to the IDT-Mon webpage so anyone can see them and investigate why is it being set.

V. CONCLUSIONS

- My work has consisted in writing and testing the code for the **ExtendedStats** starting from the **BasicStats** tools, and on designing, writing and testing the **FIIdtValidation** and **AutoAlarms** tools.
- Developing efficient tools to validate huge amounts of data is a crucial part for the development and operation of projects like Gaia.
- The work done has helped in the evaluation of the data during the commissioning as well as during the operational phase.
- The algorithms developed along this work have been included on the operational software and run on the IDT daily process.

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 - [8] More specifically: AstroObservation, PhotoObservation and SpectroObservation
 - [9] More specifically: AstroElementary and PhotoElementary