GAIA DATA REDUCTION TASKS FOR DOUBLE AND MULTIPLE STARS

Frédéric Arenou[*1], **Staffan Söderhjelm**[*2]

[1]Observatoire de Paris, GEPI / CNRS UMR 8111, 92195 Meudon cedex, France
[2]Lund Observatory, Box 43, SE-221 00 Lund, Sweden

ABSTRACT

As a result of the different instruments on-board Gaia and their various spatial or time resolutions, millions of Double and Multiple Stars (DMS) will be detected, of almost every kind. Accordingly, the data processing of DMS will undoubtedly be complex. This processing can be described in broad categories: resolved doubles and multiple stars, astrometric, spectroscopic, photometric or eclipsing binaries and classification task; in total, not less than 32 algorithms may be needed, which also call for adapted simulations.

Key words: Binaries; Multiple Stars; Gaia; Data processing.

1. DMS TASKS

The global data reduction of the huge amount of Gaia data will represent a challenge for the astronomical community. Considering now non-single stars, a major supplementary reduction process needs to be accounted for, as already experienced on a much lesser scale with e.g., the Hipparcos data reductions. On the other hand, this complexity is needed to obtain all that can be brought by the study of duplicity in stellar and galactic physics: masses, radii, luminosities and separations contribute to the knowledge of stellar structure, stellar formation, galactic potential, chemical evolution, etc.

The DMS algorithms which are foreseen are indicated in the following section, and summarised in Table 1. A more detailed description, with associated Work Packages, can be found in Arenou & Söderhjelm (2003). This document, regularly updated thanks to the contribution of the DMS community, can be found on the Gaia Double and Multiple Stars Working Group web site[1].

Besides the general classification of the DMS, mainly depending on the instrument with which they are detected and managed, there are many other differences between the algorithms. Some algorithms will have to take into account a binary motion; several algorithms may be seen as a first implementation of a given task, and will include other algorithms in a second step; some will use the data of one instrument only, requiring an in-depth knowledge of this instrument, whereas others need an overall view only of all instruments.

The complexity of the algorithms is also variable and cannot be described in detail here. However, it is clear that both the variability of the sky, of the observation characteristics and of the data reduction processes have to be accounted for. Robustness will then have to be implemented to cope with all what can and will happen: cosmic rays, varying background, imperfect calibrations, uneven epoch observations, etc.

Although *very* uncertain at this stage, the CPU load will depend on the complexity of the algorithm but also on the type and number of data that it has to manage: whether the algorithm needs the final astrometric parameters of each star only, the centroid at each transit, or all the samples observed at all transits for all stars, requires an increasing number of operations. This has to be multiplied by the tremendous numbers of binaries which should be analysed (see Figure 1 and Söderhjelm 2004), requiring large optimisations for some algorithms (e.g., those doing the detection of duplicity), while the positive detections may be tackled by other tasks using more complex algorithms, but applied on a much smaller number of systems.

It should be stressed that the description which is given here does not represent the final list of algorithms which will be applied for the data reduction. Rather it allows to initiate the work and to estimate the needed resources. One interesting challenge is the interlink of the various algorithms, with an increased duplicity detection probability by combination of individual algorithm results, and different run modes depending on the kind of available measurements and parameters.

2. DESCRIPTION

Seven main tasks are described below, each being distributed in several algorithms. One main task, not described here, is the dedicated simulation of the various DMS categories: non-interacting binaries, multiples,

[*] On behalf of the Gaia Double and Multiple Stars Working Group
[1] http://wwwhip.obspm.fr/gaia/DMS

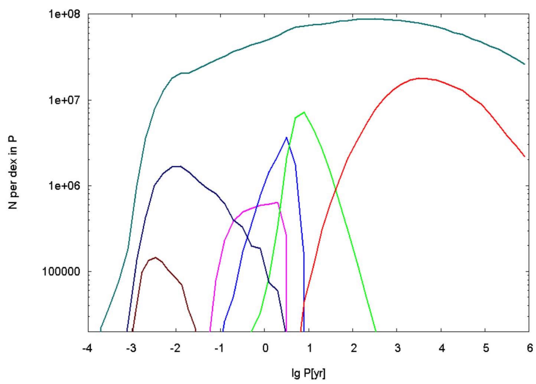

Figure 1. Simulated numbers of all DMS (overall curve) and resulting main solutions obtained per dex of orbital period, as a function of period. From left to right: spectroscopic orbits encompassing eclipsing binaries, joined astro+spectro orbits, astrometric binaries, acceleration solutions, resolved binaries. The overlaps, giving a better detection, imply joined solutions which improve the orbital parameters and the astrometry.

variables, or close binaries.

2.1. Resolved Doubles

- *Detected binaries*: computes the astrometry, BBP photometry and relative astrometric parameters for any source resolved in the sky mappers. It is assumed that approximate positions and magnitudes are known from 'ASM data handling' or 'Imaging analysis'.

- *Undetected resolved binaries*: the reduction of resolved binaries *a priori* unknown, typically applied to all stars with a poor single star fit. It will need a kind of "grid-search" for the secondary position and in some cases also for the component colours.

- *Orbits of resolved binaries*: the systems from (mostly) 'Undetected resolved binaries' with definitely curved motions, large-size astrometric orbits, or other potentially resolvable orbits are solved with a complete Keplerian model.

- *Imaging analysis*: faint companions to a detected star may not be detected at each transit observation, whereas an imaging analysis of the star environment using all mission data may be profitable to detect perturbing sources. Two different algorithms (drizzle and Tikhonov) are indicated in Table 1.

- *Common proper motion*: companions are searched in a relatively large angular radius around each star, and the proximity of components in phase-space is statistically tested.

- *Variable resolved binaries*: resolved binaries with one or both components variable in light. This can be seen as a complexification of 'Detected binaries' and 'Undetected resolved binaries'.

2.2. Astrometric Binaries

- *Acceleration solutions*: the significance of a curvature of the proper motion of an apparently single star will be computed for most stars. A second or third order term with respect to time may be needed. Output may have to be given to 'Astrometric orbits'.

- *Astrometric orbits*: for any source classified as unresolved double or multiple, this task performs a periodogram analysis of positional residuals and attempts to describe the photocentric motion by a Keplerian orbit.

- *Joined Astro + Spectro orbits*: when a (often uncertain) Keplerian orbit can be applied on either spectroscopic or astrometric data, both data can be used to attempt a joined solution (see Figure 1).

- *Photocentric binaries*: given a colour difference between components, the astrometry in the Broad Band Photometers may reveal components separated by down to a few milliarcseconds. An orbital solution may then be needed.

- *Stochastic labels*: a robust solution for stars with a bad goodness-of-fit, where initial acceleration or orbital solutions are not satisfactory. This may (or may not) correspond to short period binaries, providing an alternative input to 'Joined Astro + Spectro orbits', when applicable.

- *Variable unresolved binaries*: detects the presence of a companion through the variability of one component, and the associated astrometric shift.

2.3. Multiple stars

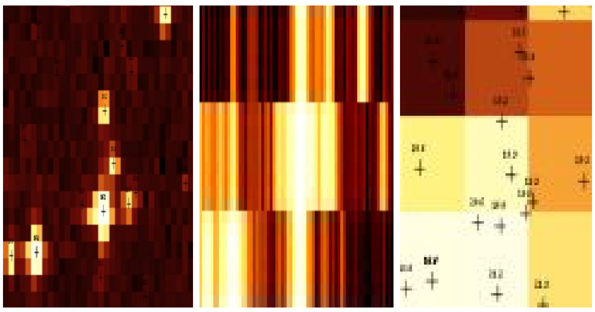

Figure 2. The same multiple system in a high density $3'' \times 4.7''$ field shown with the binning of the Astrometric Sky Mappers (left, $0.088'' \times 0.265''$ samples), the Astrometric Field (middle, $0.044'' \times 1.59''$ samples) and the Spectro Sky Mappers (right, $0.897'' \times 1.345''$ pixels). Crosses indicate the $G < 22$ stars. The various resolutions, underlining the complexity of the data reduction, call for dedicated, yet not independent, algorithms.

- *ASM data handling*: provides improved parameters (especially transverse position), using colour information, PSF and calibrations not available on-board, and is used as a starting point to 'Detected binaries' and 'Detected multiple stars'.

- *Detected multiple stars*: visual multiple stars analysis may then be considered as a subtask of 'Detected binaries', and deals with wide trapezium systems detected in the ASM.
- *Resolved third components*: resolved doubles (AB) from 'Undetected resolved binaries' with remaining poor fit are tested for a third resolved component (C) close to one of the known ones.
- *Acceleration in multiples*: resolved doubles (AB) from 'Detected binaries' or 'Undetected resolved binaries' with too large curvature to be due to the main AB orbital motion are flagged as multiples, but no new solutions are performed.
- *Astrometric and/or R.V. orbits in multiples*: from 'Detected binaries', the astrometry of the resolved components may not be satisfactory. If tested as significant, a Keplerian motion for one of the components is computed.
- *Close trapezium system*: makes the data reduction of a close trapezium system unresolved in the ASM.
- *Variable multiple stars*: this task processes a multiple system with one (or more) variable components, such as e.g., the Orion Trapezium.

2.4. Spectroscopic Binaries

- *Spectrum binaries*: detects a composite spectra and recovers spectroscopic information from each companion, assuming no relative motion. This excludes the case of spectra overlapping with a different star at each transit, which is expected in the galactic plane due to crowding.
- *SB orbits*: tests the duplicity, performs a fast periodogram analysis of the epoch radial velocities, and provides an orbital solution. A 'Joined Astro + Spectro orbits' solution may then be needed.
- *SB2 analysis*: detects the duplicity, provides an orbital solution, and characterises physically the components.

2.5. Photometric Analysis

- *Photometric binaries*: this task should detect a composite flux in MBP and, when possible, contribute to the parametrisation of the two components.
- *Photometric multiple*: detects the presence of multiple components in MBP from the composite flux.

2.6. Eclipsing Binaries

- *Detection of eclipsing binaries*: performs the detection of eclipsing binaries and derive preliminary parameters, such as period. Epoch measurements of AF, BBP and MBP may have to be combined in order to find the periodicity.
- *Light-curve analysis*: performs a refined light curve analysis and derive physical parameters of the system, possibly using the astrometry. When a joint photometric/spectroscopic solution is possible, this task provides input to 'Eclipsing spectroscopic binaries'.
- *Eclipsing spectroscopic binaries*: computes the orbit and all physical parameters (mass, radius) of an eclipsing system, when input from 'Light-curve analysis' and epoch spectroscopic measurements are available.
- *Timing Binaries*: detects the existence of a third companion through the analysis of the light curve minima of eclipsing binaries (or other very regular variables). An acceleration 'Acceleration solutions' or orbital 'Astrometric orbits' input solution may be used jointly for improving the solution.
- *Eclipsing binaries with variable component*: performs a refined light curve analysis for eclipsing binaries with variable components such as cataclysmic or RS CVns stars, and derives physical parameters.
- *Variable eclipsing binaries in multiples*: performs a refined light curve analysis for eclipsing multiples with variable components such as cataclysmic or RS CVn stars, and derives physical parameters.

2.7. Classification

- *Rejection from core processing*: checks whether a source is a single star or not using all significance tests produced by all other algorithms. This would be used for the rejection of the object and its observations from the core processing of single stars.
- *Measurement classification*: in a double or multiple system, the observations coming from one or another instrument, or the various epoch measurements in each instrument, may refer to one, two or more different components (see Figure 2). Each observation should be labelled as a function of the concerned components.

3. CONCLUSION

As should be apparent, the amount of work needed for the data reduction of DMS is challenging and will have to be performed in coordination with several other Gaia Working Groups. Two representative algorithms have been delivered in the current second phase of the Gaia Data Access and Analysis Study (GDAAS), and the remaining tasks call for an early involvement of the community.

REFERENCES

Arenou, F., Söderhjelm, S., 2003, DMS Work Packages, Gaia technical report DMS-FASS-04

Söderhjelm, S., 2005, ESA SP-576, this volume

*Table 1. Preliminary estimation of the tasks to be performed: (a) Algorithm designation; (b) instruments where the algorithm mostly applies (*CCD: A=AF1-11, B=BBP, M=MBP, R=RVS, *Ast=ASM+AF+BBP); (c) relation with other Working Groups (*WG: *I=ICAP, O=OBD, P=PWG, R=RVS, S=SWG, V=VS); (d) software development complexity (*Cplx*); (e)* **very** *uncertain processing load: data which are used (*Data *from source: O=observations, E=elementary data, P=source parameters), number of stars on which the algorithm is applied, and corresponding total CPU-year normalised to a ≈ Pentium 4 2GHz processor, generally for one iteration; (f) development priority (*Prio*); (g) schedule with respect to GDAAS phase (GP=2, 3 or 4). See Arenou & Söderhjelm (2003) for more details.*

Algorithm	CCD	WG	Cplx	Processing load			Prio	GP
				Data	Stars	CPU-yr		
Resolved doubles								
Detected binaries	A-B		$\star\star\star$	O	10^7	0.5	$\star\star\star$	2
Undetected resolved binaries	A-B		$\star\star\star\star$	O	3×10^8	50	$\star\star\star$	2
Orbits of resolved binaries	A		$\star\star\star$	E	10^5	0.06	$\star$	3
Imaging analysis	AF11	P	$\star\star$	O	10^9	80	$\star\star$	3
	ASM	P	$\star\star$	O	10^9	740	$\star\star$	3
Common proper motion	A		$\star$	P	10^9	$\star$	$\star\star$	4
Variable resolved binaries	A-B	V	$\star\star\star\star$	O		$\star\star$	$\star\star$	3
Astrometric binaries								
Acceleration solutions	A		$\star$	E	10^9	0.1	$\star\star\star$	2
Astrometric orbits	A		$\star\star$	E	3×10^8	170	$\star\star\star$	2
Joined Astro + Spectro orbits	A+R		$\star\star\star$	E	10^7	6	$\star\star\star$	3
Photocentric binaries	B+A	P	$\star\star\star$	E/P	10^7	0.5	$\star\star$	3
Stochastic labels	A+R		$\star\star$	E	10^7	0.01	$\star\star$	3
Variable unresolved binaries	A-B	V	$\star\star\star\star$	E		$\star\star$	$\star$	3
Multiples stars								
ASM data handling	ASM	O	$\star\star$	O	10^9	440	$\star\star\star$	2
Detected multiple stars	Ast		$\star\star\star$	O	10^6	0.5	$\star\star\star$	3
Resolved third components	A-B		$\star\star\star\star$	O	10^7	50	$\star\star$	3
Acceleration in multiples	A-B		$\star\star\star$	O/E		$\star\star$	$\star\star$	3
Astro/RV orbits in multiples	A-B		$\star\star\star\star$	O		$\star\star$	$\star$	3
Close trapezium system	Ast		$\star\star\star\star\star$	O		$\star\star$	$\star$	3
Variable multiple stars	Ast	V	$\star\star\star\star\star$	O		$\star\star$	$\star$	3
Spectroscopic binaries								
Spectrum binaries	R	R	$\star\star\star$	O	2×10^7	0.6	$\star\star$	3
SB orbits	R	R	$\star\star\star$	E	3×10^6	0.2	$\star\star\star$	3
SB2 analysis	R	R	$\star\star\star\star$	O		$\star$	$\star\star\star$	3
Photometric analysis								
Photometric binaries	M	P-I	$\star\star\star$	E		$\star\star$	$\star\star$	3
Photometric multiple	M	P-I	$\star\star\star\star$	E		$\star\star$	$\star$	4
Eclipsing binaries								
Detection of eclipsing B.	all	V	$\star\star\star\star$	E	10^9	$\star\star\star$	$\star\star\star$	3
Light-curve analysis	all	V	$\star\star$	E	2×10^6	$\star\star$	$\star\star$	3
Eclipsing spectroscopic B.	all	R-V	$\star\star\star\star$	E	2×10^5	0.3	$\star\star\star$	3
Timing Binaries	all	V	$\star\star$	E/P		$\star$	$\star$	4
Eclipsing B. with var. comp.	all	V	$\star\star\star\star$	E		$\star\star$	$\star$	3
Var. ecl. B. in multiples	all	V	$\star\star\star\star\star$	E		$\star$	$\star$	3
Classification								
Rejection from core proc.	Ast	I	$\star$	O/E	10^9	$\star$	$\star\star\star$	2
Measurement classification	all	I	$\star\star$	O	4×10^8	$\star\star$	$\star\star$	3