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# Ground-Based Observations for Gaia : 2010 status

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reference: GAIA-CD-PR-LAB-CS-009-1  
issue: D  
revision: 0  
date: 2010-12-22  
status: Draft

## Abstract

This document presents the status of the ground-based observing programs organized to obtain the mandatory auxiliary data for the Gaia processing. After four years of activities, a good fraction of the auxiliary data has been obtained, from various instruments. We give here a report on what has been done and what is still needed.

## Document History

Issue	Revision	Date	Author	Comment
D	3	2010-12-22	CS	GS and GC inputs
D	2	2010-12-13	CS	Cosmetics
D	1	2010-11-09	GS	Added CU6 calibration requirements to the Ecliptic Pole Catalogue section and filled in Science Alerts Validation
D	0	2010-10-26	CS	Creation

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## 1 Introduction

The Gaia data processing requires auxiliary data for several purposes such as the photometric and spectroscopic calibrations and the test, training or validation of some parts of the processing. Some observational programmes have started as early as 2006 in order to obtain these mandatory data. Four years later, a good fraction of the auxiliary data has been obtained, from various instruments. We describe here, for each category of DPAC needs, the rationale of the corresponding observing programme, the instruments used, the data already obtained and the observations still to be done in the coming years, and eventually during the operations. The calibration plan may evolve later, once we receive the commissioning results in 2013.

## 2 Gaia flux calibration

Gaia G-band magnitudes and BP/RP spectra and integrated magnitudes will be calibrated, within a few percent, in flux. The flux calibration of RVS data is presently under discussion. The calibration model designed for BP/RP spectra requires a large grid ( $\sim 200$ – $300$ ) of high-quality flux tables of spectrophotometric standard stars (SPSS), covering a range of spectral types, and the whole Gaia wavelength range (330–1050 nm). The candidate *Primary* (the ground based calibrators) and *Secondary* (the actual Gaia grid) SPSS are described in Altavilla et al. (2008) and Altavilla et al. (2010), respectively, including 7 SPSS in the Ecliptic Poles regions. The existing sets of SPSS are much smaller than required, and homogeneity is essential, so a large observational campaign has started four years ago.

The survey strategy is based on relative photometry, to check for short term (1–2 hours) and long term (3 yrs) variability, absolute photometry to provide the zeropoint of flux tables, and on absolute or relative spectrophotometry to provide the correct spectral shape. We rely on six different telescopes and instruments, two in the Southern hemisphere (EFOSC2@NTT, ROSS@REM, La Silla) and four in the Northern one (DoLoRes@TNG, La Palma; CAFOS@2.2m, Calar Alto; BFOSC@1.5m, Loiano; LaRuca@1.5m, San Pedro Martir). In total, we have obtained approximately 245 observing nights at these telescopes starting in 2007, through more than 45 proposals (only 3 of which were rejected), at a rate of 50–60 observing nights in visitor mode per year, plus 20–30 nights in service mode. The observations are 70–75% complete as far as absolute photometry, spectroscopy, and short-term variability are concerned, with an estimated end of survey around the end of 2011, or beginning of 2012. The long term variability monitoring is 40% complete and we estimate to complete it in 2013–2014.

To ensure maximum homogeneity in data acquisition and treatment, strict observing and data reduction protocols are enforced, as well as an *Instrument Familiarization Plan* (IFP) that will characterize the instruments (shutter times, linearity, calibration frames stability, and so on) and find procedures to remove various instrument fingerprints ( $2^{nd}$  order contamination, lamp flexures, fringing, CCD cosmetics) in the most accurate way. The IFP and data reduction protocols are being presently finalized, after an intense phase of testing of different procedures. End-to-end test reductions prove that we can easily meet the DPAC constraints (a few percent in flux) and calibrate our SPSS spectra to  $\simeq 1\%$  relative flux accuracy (with respect to Vega and the three CALSPEC pillars), over most of the considered wavelength range. Routine mode reductions have started, we have pre-reduced approximately half of the collected imaging frames, which are also quality checked. Aperture photometry started (10% of the collected frames), and we have short-term variability light-curves for a few tens of our SPSS. For spectroscopy, pre-reductions are proceeding, with 20% of the collected frames extracted and wavelength calibrated, while the following analysis steps are under finalization.

More information on the ground based observations for the flux calibration can be found at our local Wiki pages: [http://yoda.bo.astro.it/wiki/index.php/Main\\_Page](http://yoda.bo.astro.it/wiki/index.php/Main_Page) (credentials: guest and gubana). Our local raw and reduced data archive can also be reached from the Wiki pages.

### 3 Radial velocity standard stars for the RVS

The RVS being an integral field spectrograph with no entrance slit and no on-board wavelength calibration source, the wavelength scale and radial velocity (RV) zero-point have to be derived from already known reference objects, stars and asteroids. For this purpose, a stellar grid is being built, consisting of  $\sim 1000$  FGK stars in the magnitude range  $6 < V < 11$ , with an homogeneous distribution on the sky. The RV standard stars have to be stable in radial velocity at the 300 m/s level, to match the 1 km/s precision expected from their future RVS measurements, with no drift until the end of the mission (2017). A preliminary list of 1420 candidates has been established from recent RV catalogues, complemented with IAU radial velocity standards in the appropriate magnitude range, as described in Crifo et al. (2010). Each candidate has to be observed at least twice before launch in order to ascertain its stability.

The observing programme is currently on-going on three echelle spectrographs, the french SOPHIE at OHP and NARVAL at the Pic du Midi Observatory for the North, and CORALIE on the Swiss Euler telescope at La Silla for the South. Relevant observations have also been retrieved from the ELODIE and HARPS archives. Asteroids are systematically observed during the runs. Since their motion is known from solar system ephemerides with an accuracy of 1 m/s, they are used to set-up our observations on different instruments on a common scale. As of October 2010, a total of 4109 measurements is available for 1334 stars, performed with NARVAL (98 measurements), CORALIE (688), SOPHIE (976), ELODIE (1057) and HARPS (1290). Preliminary results show that  $\sim 8\%$  of the candidates exhibit RV variations and should be rejected as RV standard stars. Nearly 50 nights have been allocated on SOPHIE since 2006, 12 on NARVAL and 9 on CORALIE. The pre-launch programme is expected to be completed in 2011. All the selected RV standard star candidates will have to be re-observed once after launch, to check their long term stability.

As part of the Ecliptic Poles catalogues (see next section), 34 stars brighter than  $V=11.5$  and selected in the Tycho-2 catalogue in a one degree radius field around the Northern Ecliptic Pole are being observed on NARVAL. They will be used to assess the RV measurements during the commissioning phase. This is a short observing programme, 30 hours over 2 years, requiring 3 measurements per star for a rough characterisation of their properties and variability. It is also foreseen to observe a selection of stars hotter than F5 to test a possible bias in RV determination, related to the spectral type. These observations will be done on NARVAL which include the RVS range 847-874 nm. NARVAL spectra are also used to compare RV determinations with the RVS characteristics (spectral range and resolution) to that obtained at higher resolution in the full optical range.

## 4 The Ecliptic Poles catalogues

Reference fields are being created for the commissioning phase of Gaia to assess its performance and to provide the initial calibration. During this early phase, Gaia will adopt a peculiar scanning law differing from its routine mode, covering the two ecliptic poles every six hours. Building the Ecliptic Pole (EP) catalogues is a CU3 task, but the other CUs are also involved. Several observing campaigns have been conducted to secure the astrometric, photometric, and spectroscopic measurements. Imaging has been completed at CFHT and La Silla T2.2 (MPIA-time) and a spectroscopic follow up program of the Southern EP field has been started, using ESO-FLAMES (GIRAFFE & UVES). This data set will be used to calibrate the Gaia high resolution spectroscopy, i.e. the determination of radial velocities, atmospheric parameters, and abundances. This FLAMES programme is not yet completed due to allocation difficulties and should continue in 2011.

CU3 and CU5 will simultaneously model LSF/PSF and radiation damage throughout the mission because astrometry and photometry are very sensitive to changes in both LSF/PSF and radiation damage. Because RVS spectra are less sensitive to changes in LSF/PSF, CU6 are considering a plan to define a relatively un-radiation damaged AL LSF during the commissioning phase of Gaia using the narrow lines of giant stars in the Ecliptic Pole Scanning Law (EPSL). As only the EPs are guaranteed to be seen by Gaia during the EPSL, it is prudent to check that these small fields of view contain appropriate CU6 calibration stars. The majority of the observed ESO-FLAMES South Ecliptic Pole (SEP) spectra are fainter ( $V > 12$ ) than CU6 calibration requirements ( $G_{RVS} < 10$ ). The EP Catalogue database will include literature data including Radial Velocity Experiment (RAVE) spectra and parameters. Voss & Bastian (2007) suggested a special field centred on the SEP could be observed by the Radial Velocity Experiment (RAVE). The number of RAVE SEP stars already observed and expected to be observed in the future will be assessed and, if required, the possibility of supplementary RAVE observations of a special field centred on the SEP will be investigated.

For CU7, EROS II is at present the only available catalogue of variable stars containing the Gaia Southern EP-field (SEP). The catalogue covers about 80% of the SEP with multiband light curves for roughly 15 Classical Cepheids and more than a hundred RR Lyrae stars in that area. Observations by OGLE IV are planned to monitor the variable stars of the entire SEP field, as also is doing the near infrared ( $YJK_s$ ) ESO public survey VISTA Magellanic Clouds (VMC). While the  $K_s$  time-series photometry being obtained by VMC is already available to CU7 members who are also directly involved in the survey, it will be evaluated whether there is need of requesting time at ESO to obtain time-series visual photometry with the 2.2m ESO/MPI WIFI to cover the missing part of the Gaia SEP-field in case the OGLE IV data will not be available.

## 5 Ground-Based Optical Tracking (GBOT)

The position and motion of the Gaia satellite needs to be known far better than in the case of other missions. Effects, such as astronomical aberration caused by the finite velocity of light, and gravitational deflection of light by the major planets, significantly affect the proper directions of the stars, and therefore need to be accounted for. For parallax measurements of small solar system bodies the baseline is no longer small with respect to the distance, which also leads to a need to know Gaia's exact position. Therefore the usual method of using one tracking station to communicate with Gaia and to track its position is not good enough. This demanding task will be accomplished using ground based optical observations of the satellite. For this it is necessary to negotiate observation programs at suitable observing facilities, to initiate test campaigns and to prepare the routine observations and data reductions. Observed topocentric Gaia positions will be delivered to the ESOC flight dynamics department. Activities started in early 2008.

The daily ground-based optical tracking of the satellite is being prepared by making tests with astrometric observations of WMAP (located at L2 and with a magnitude similar to Gaia's), Planck, Herschel and asteroids. Negotiations have begun to build the network of small telescopes that will perform a regular tracking over the five years of the mission.

## 6 Gaia Science Alerts validation

The ground-based science verification of Gaia Science (CU4 SSOs, CU5 flux, CU6 RVS) Alerts is the responsibility of DPAC and will be co-ordinated by GBOG. The ground-based follow-up of Gaia Science Alerts will not be co-ordinated by DPAC but by various science communities (which include DPAC members).

### 6.1 CU4 : Follow-Up Network for the Solar System Objects

The observation of Solar System Objects (SSO) by Gaia will be constrained by a scanning law. Several detections of interesting objects may be done with no possibility of further observations. These objects will then require complementary ground-based observations after an alert based on the Gaia detection. Among them, previously unknown Near-Earth Objects, fast moving towards the Earth or going away from it could be found. Several objects discovered by Gaia can also be Inner-Earth Objects, since the spacecraft's observations can take place at small solar elongations. In order to achieve the goal of following interesting targets soon after their first detection in space, a dedicated network is organized, the Gaia Follow-Up Network for SSO (FUN-SSO). This task is performed in the frame the DPAC-CU4, devoted to data processing of specific objects. The goal of the network will be to improve the knowledge of the orbit of poorly observed targets by astrometric observations on alert. This activity will be coordinated by a central node interacting with the Gaia data reduction pipeline all along the mission. A



workshop in Paris has been organized in November 2010 in order to promote the coordination of the network of observing stations already identified or to get in touch with possibly new stations. The participants have been invited to present their equipment, instruments, observing sites and to express their needs and interest. During appropriate discussion sessions, procedures for observation, data policy, and other issues common to all the observers were agreed.

## 6.2 CU5: Flux Alerts

“The main aim of the Science Alerts Verification Phase (SAVP) is to verify the robustness of the issued alerts and confirm them with the dedicated network of follow-up telescopes operating in the Target of Opportunity (ToO) mode. The verification observations should be carried both photometrically (imaging) and spectroscopically in order to, e.g. confirm the presence of the detected new object, or to confirm or fine-tune the classification of the alert. Verification Phase should reveal all necessary adjustments which has to be done to the detection and classification algorithms to assure the best and the most robust performance later on.”

“Verification Phase could last for about 3 months and is planned to take place after around 3-6 months after receiving the first Gaia data to assure there is enough historical data available for most of the objects. Some areas (close to the nodes of the scanning pattern) will have enough observations accumulated to allow for early start of the alerting pipeline. In principle, some pre-launch preparations could take place in the areas of very dense Gaia observations. It includes gathering all useful information about the objects in these regions both from existing catalogues and with new observations. The information includes, among the others, variability classification and spectral type classification.”

“The Science Alerts Verification Phase will be conducted mainly under umbrella of GBOG (Ground Based Observations for Gaia), however we encourage other groups of astronomers to join this effort as early as possible. Early involvement in the alerts observations can result in establishing a good connection with Gaia alerts stream when they become fully public.” ([http://www.ast.cam.ac.uk/research/gsaug/index.php/Verification\\_phase](http://www.ast.cam.ac.uk/research/gsaug/index.php/Verification_phase))

In October 2010, CU5 issued a White Book on the status of flux alerts (<http://www.ast.cam.ac.uk/research/gsaug/index.php/Workshop2010:main>) but the ground-based science verification of flux alerts has not yet been planned.

## 6.3 CU6: RVS Alerts

The CU5 verification timescales also apply to CU6. The RVS Science Alerts work package is being started in December 2010 and so, like CU5, the ground-based science verification of RVS alerts has not yet been planned but there may be considerable overlap with the flux alert verification if both systems alert on the same transient phenomena.

## 7 VLBI program for the reference frame alignment

Gaia will permit to construct a dense optical QSO-based celestial reference frame. For consistency between optical and radio positions, it will be important to align the Gaia frame and the fundamental celestial reference frame, measured with VLBI (Very Long Baseline Interferometry), with the highest accuracy. Bourda et al. (2008) showed that only 10% of the ICRF (International Celestial Reference Frame) sources were suitable to establish this link (70 sources), either because they are not bright enough at optical wavelengths or because they have significant extended radio emission which precludes reaching the highest astrometric accuracy. In order to improve the situation, a multi-step VLBI survey is on-going in order to find additional suitable radio sources for aligning the two frames. The sample consists of 447 sources, typically 20 times weaker than the ICRF sources, which have been selected by cross-correlating optical and radio catalogs. The observing strategy adopted by Bourda et al. (2010) is based on three steps over several years to detect and image the sources, and then measure accurate positions for the relevant ones.

Based on the initial observations carried out in June and October 2007 with the EVN (European VLBI Network), during two 48-hours experiments, an excellent detection rate of 89% was found: 398 sources were detected at both S- and X-bands.

The second step was targeted at imaging the sources previously detected, using the global VLBI network (EVN+VLBA; Very Long Baseline Array), in order to identify the most point-like sources and therefore the most suitable ones for the alignment: (i) a pilot imaging experiment was carried out in March 2008, during 48-hours, to image 105 sources from the detected sample. As a result, all sources could be imaged at both bands, and we showed that about 50% of them were point-like sources (47 sources); (ii) another imaging experiment was carried out in March 2010 (97 sources), during 48-hours; (iii) while the rest of the sources (196 sources) will be observed in November 2010 and probably beginning 2011.

Finally, the astrometry dedicated observations for the most point-like sources of the sample will begin in 2011.

## 8 Network in support to the variable star pipeline

The variability processing of CU7 mainly uses available catalogues such as the Hipparcos, OGLE II-III and EROS I-II catalogues for variable stars to develop and test algorithms for the classification and characterization of variable stars. Both the Hipparcos and EROS II catalogues have been ingested into the CU7 database in Geneva and are currently being used for testing the CU7 software. However, observation of particular classes of objects may be needed to validate specific algorithms being developed within the CU7. To this purpose one of the GBOG activity in CU7 has been the organization of a network of telescopes (from 8 to 200 cm in size)

spread on about 9-10 different sites mainly over Europe. A number of observing programs for CU7 have been started. These include following period changes in selected sample of Classical Cepheids; taking spectra of bright Galactic Miras in the wavelength region covered by the RVS, with the 2m Coude spectrograph at the Ondrejov Observatory (CU7 network); obtaining photometry of short-period variables with the 1.2 Belgian Mercator telescope in Canary Islands (CU7 network). Observations of DT Lyn, a bright B subdwarf were obtained for this latter program in December 2009 and March 2010 and several known frequencies were identified in the de-trended dataset thus demonstrating that this telescope can be used for the verification of Gaia short period candidate variables. Time-series  $K_s$ -band photometry of RR Lyrae stars and Cepheids in the Gaia SEP calibrating field, obtained as part of the VISTA VMC survey (observations completed on October 2010) was combined with visual-band light curves from EROS II. The data are being used to check the period search, mode classification, and Fourier parameter definition algorithms developed within the CU7 RR Lyrae and Cepheids workpackages, and to build multiband PL relations of RR Lyrae stars and Cepheids which are used to develop an automatic way to detect and reject outliers and misclassified objects.

Finally, the CU7 telescope network will contribute to the validation of the Gaia Alerts system (GSA) being developed by CU5. An official LoI from CU7 was given to the CU5 GSA people in November 2009. Telescopes of the CU7 network will take part in a simulation that the GSA is organizing to test the reaction capabilities to triggers currently issued by other alert networks (e.g. Catalina).

## 9 Reference stars for stellar parametrization

The external calibration of the stellar parametrization algorithms developed within CU8 (GSP and ESP) requires to build an extended grid of reference stars, representative of the parameter space. Candidate reference stars are stars which will be observed in good conditions by Gaia ("good conditions" meaning high S/N, no overlap between spectra, etc.), and that will have their astrophysical parameters well known in advance. The strategy of a three level reference grid (benchmarks stars, primary and secondary reference stars) is described in Heiter et al. (2009).

To define the final set of calibrators we need to collect all the necessary data to characterize them in detail and homogeneously. A quantity of high quality data already exist and has been compiled from existing archives and catalogues as explained in Soubiran & Heiter (2010). For some stars new observations are needed and the program benefits of allocated time on the echelle spectrograph NARVAL, which has a resolution of 80000 and covers the full optical range, including the spectral range of RVS.

In addition, the methods of parameter determination need to be improved by improving the stellar atmosphere models used for that purpose. Models using various sources for input data and various approaches for modelling physical processes (such as convection) are being tested on

very high resolution spectra of so-called benchmark stars. For these observations ESO/3.6m/HARPS, TNG/SARG and also TBL/NARVAL are used.

## 10 Spectral Energy Distributions of peculiar stars across the HR diagram

Astrophysical parameters will be determined by the Gaia data processing for a huge number of stars. The common spectrum fitting approach currently adopted by the DPAC consortium is however based on the *ab initio* knowledge of the physical processes taking place in the stellar photospheres in usual circumstances, close to hydrostatic, radiative, and statistical balance. Given the existence of very different sources of opacity, of circumstellar envelopes, and/or the presence of strong magnetic fields, the standard classification methods devised for normal stars might be insufficient. A catalogue of spectrophotometric data is being constructed, covering the wavelength range of Gaia RVS (i.e., 847-874 nm), to improve the available atmosphere models and develop semi-empirical models that will be used for the classification of peculiar stars. NTT+EFOSC2 have been used in 2009 to obtain a total of 586 spectra with two grisms for 99 peculiar stars and reference stars. The reduction procedure includes two steps : extraction and wavelength calibration, plus relative flux calibration. Other relevant data have been gathered from various databases. A catalogue of archived spectra of a large variety of emission line stars is presented in Lobel et al. (2010)

## 11 Taxonomic training for asteroids

The Gaia mission of the ESA is expected to produce a real revolution in asteroid science. Among many goals of the mission there is also the exploitation of the spectroscopic capability of the focal plane instrumentation. On one hand, spectroscopic data will be needed to apply the correct colour-dependent PSF to the analysis of asteroid signals in the focal plane. On the other hand, spectroscopic data *per se* will be used to produce a new taxonomic classification of about 200,000 asteroids (to be compared to the present 3000 asteroid spectra available). For the first time after many years, this classification will be based on data covering a large interval of wavelengths (330–1000nm), including the blue part of the reflectance spectrum.

A program has been defined to collect new asteroid spectroscopic data because in the current phase of modeling of the expected signals it is very important to have at disposal spectroscopic data covering the same wavelength interval, and obtained in the same observing circumstances that will characterize Gaia data. The aim of this program is to scan the different mineralogical classes of asteroids that are commonly admitted by the asteroid community. Each class will be represented by a master spectrum from which a representative population can be generated and hence automatic classification algorithms can be tested. The chosen telescope for these

observations is the TNG with the Do- LoRes spectrometer, since the wavelength coverage is very close to the Gaias one, and includes also blue wavelengths that traditionally have not been observed often. Moreover, the observations are performed near the quadrature phase, in order to be as close as possible to the same configuration of the satellite observations. The observations have been carried out in October 2008 and November 2010.

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