Ground Based Testing of the GAIA Filters

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Abstract.

We summarise the case for ground based testing of the GAIA filter system. Two scenarios are evaluated; firstly, that ground based testing be part of the (ongoing) filter design effort, and secondly that the filters be tested on real stars from the ground after they have been finalised. We conclude that the filter design effort would benefit more efficiently and directly from good flux calibrated spectra for representative stars of many types, rather than an immediate and concerted ground based photometric effort. Ground based observations after the filter design has been frozen is highly recommended. We review an initial study of the tolerances needed on the filter central wavelengths and bandwidths in manufacture, assuming millimagnitude photometry. Further work is needed in this area.

1. Why Ground Test?

A very large number of filter systems have been designed in the past for stellar photometry, with over 200 being listed by the Asiago group, see Fiorucci and Munari (2002). Filter systems are always designed within the framework of the best existing knowledge of the spectra of the target objects, and the GAIA filter design effort is no exception. With GAIA, the various proposed filter sets are being tested for the most part against libraries of synthetic and to a lesser extent against actual observed stellar spectra. The number of available stellar spectra with the required resolution (about 5 Å or less) and wavelength coverage ($\lambda\lambda 3400 - 10\,000$ Å) is of order of only a few hundred, and includes mostly normal (disk) stars and a few peculiar stars. The filter development and evaluation is therefore very dependent on synthetic spectra.

The simplest method to test any proposed system is to construct the filters and go out and observe real stars. Rounding up the usual suspects, one would typically observe open clusters, globular clusters, the Magellanic clouds, high stellar density fields at the Galactic center, high reddening fields, subdwarfs, evolved stars, M stars, peculiar stars, various variables such as cepheids and RR Lyrae stars, and white dwarfs as well as the good old main sequence and giant branch members of the disk, thick disk, bulge and halo.

Using CCDs, tens of thousands of stars can then be examined with the system; in clusters, the constraint of isometallicity (or near isometallicity) means that the system can be tested over an appropriate range of stellar temperature and luminosity, just as the final system will have to perform.

If there are problems in the system, then direct observations will reveal them. In 1999, we (E. Høg, J. Knude, C. Flynn) felt that this was sufficient reason to attempt a ground based program of observations which would firstly test an initial GAIA filter proposal, followed by any necessary modifications to the system, with a possible second ground-testing round of observations, before the final filter design would be frozen about mid-2005.

The disadvantages of ground based testing are clear. Firstly, the effort required to obtain observations over a wide range of object types with a set of order 10 filters, including the observing, calibration and photometric reductions for a system without pre-existing standard stars, is formidable. Secondly, any problems which emerge in the proposed filter system must then be resolved, and this is very likely to be with respect to the spectra (synthetic or real) which were used to design the system in the first place.

2. Two Proposals

Testing the GAIA filter system as we would like with ground-based observations requires a special concerted program, and could not be carried out within the scope of in-house resources either in Copenhagen or Turku. However, the telescope and instruments available at the Nordic Optical Telescope (NOT) on La Palma and the Danish/ESO 1.5 m telescope at la Silla appeared excellent tools for the task. The NOT will soon get an optical reducer, giving a field of $6' \times 6'$, while ALFOSC at the Danish/ESO 1.5 m has a field of $13' \times 13'$. Both instruments would thus allow very large numbers of stars to be observed efficiently.

An important addition to the filter set would be the Strömgren β filter, since this would help greatly in breaking of the degeneracy between temperature, reddening and metallicity. The GAIA filter set would then be tested without the β filter, since it is too narrow to fly on the mission. A clear difficulty is that the proposed filter set might use filters which cannot be used from the ground because of atmospheric constraints, such is in the UV or near telluric lines.

The proposals to test the filters should address Galactic structure as well. We therefore proposed to undertake (V. Vansevičius, private communication)

- Deep meridian slices of the Galaxy in selected areas at various latitudes. $10-20$ carefully selected areas observed along the Milky

Way meridian together with available Near Infrared surveys will ensure considerable improvement of the Galaxy model, thin-thick disk evolution understanding, and measurement virtually of every type of stars expected in GAIA mission.

- Investigation of a sample of open clusters $(10 - 20)$ with different ages, metallicity, extinction. Homogeneity (or better to say clumpiness) of the extinction, variable extinction law and binary problems could be successfully addressed via observation of the representative sample of open clusters.
- Investigation of the Magellanic Clouds via a deep photometric survey. The clouds are perhaps the best available polygon for testing GAIA capability of classification of the giant stars (with well known distances) in crowded fields as it will be numerously available in GAIA project at low Galactic latitudes up to 10 kpc distances, moreover, investigation of Magellanic Clouds evolutionary status is a task very tightly related to Galaxy evolution and GAIA mission.

The filter set itself costs of order 50 000 Euros, while travel and salary costs amount to 140 000 Euros over a three year period. The filter manufacture and delivery time is of order three months. Some thirty nights of dark observing time would be required in the first phase observations alone (i.e. before modifying the filters and re-observing). Similar programs to study the Strömvil system have applied for and obtained observing time allocations of this order of magnitude, so we felt that the time for GAIA testing could be obtained via normal time assignment applications, rather than by special allocation of time for long term programs.

Two applications have been made unsuccessfully to national funding bodies in 2000 and 2001 by us. With a mid-2005 deadline for the freezing of the filter design, ground based testing is now (mid-2001) clearly limited by time constraints. We believe that spectrophotometry is now the best way to proceed in testing the filter designs for GAIA.

3. Spectrophotometry

The disadvantage of testing the filters by taking CCD images of various stellar fields is that any problems which emerge can only be corrected by reference to spectra. These spectra may well be synthetic, in which case the input physics of the computations might also plausibly be blamed in addition to the filter specification. Real spectra are to be preferred, but for filter development they must be flux calibrated, cover the full range of wavelength accessible by GAIA, and have rather high resolution. At present, only about 200 spectra with the resolution (2 Å or smaller) and good spectral coverage ($\lambda\lambda < 3400 -> 9500$ Å) exist. These were obtained by the STELIB collaboration at the Jacobus Kaptein 1 meter telescope in the north and the Siding Springs 2.3 m telescope in the south. Extensive information on the stars observed and the spectra is available from their web site at http://webast.ast.obs-mip.fr/stelib/. It contains dwarf and giants stars of O, B, A, F, G, K and M spectral types and a handful of white dwarfs, Wolf-Rayet stars and subdwarfs. The driving science behind obtaining these spectra was for galaxy population synthesis studies, but they are clearly of very great utility for filter designers too.

The major effort would now seem to be that we obtain more flux calibrated spectra for the full range of metallicity, reddening, effective temperature and luminosity we expect to encounter down to 20th magnitude with GAIA. Ambitious estimates of the number of spectra required are of order a few thousand, but it is probably not realistic to hope to observe this number before mid-2005. The immediate priority is to produce a list of crucial regions in the colour-magnitude diagram for which requisite spectra are clearly lacking altogether or are too few, and searching for telescope and instrument combinations on mid-size telescopes at which the spectra might be obtained. The stellar group at Tartu Observatory has expressed an interest in the observational effort needed (I. Kolka, private communication).

An alternative option is the FEROS system at the ESO 1.5 meter telescope. FEROS has a resolution of $R = 50\,000$ and covers the whole spectral range from 3700 Å to 9000 Å in a single shot. Although it is a fibre instrument, the fibres are 2.5 arcseconds in diameter, so that relative fluxes may be possible (L. Pasquini, private communication).

4. Filter Tolerances

An important issue raised by Kazlauskas et al. (2002), is the tolerances on the GAIA filters. Their studies have shown that an error in the manufacturing in the central wavelength of 20 Å in the filter has a very serious impact on the derived astrophysics of the stars, with errors in particular in log g or [Fe/H] of as much as 0.5 dex.

“Optida” is a company in Vilnius which manufactures interference filters. Present techniques mean that large format filters (e.g. 5×5 cm) can be routinely produced with deviations from the target central wavelength of not more than 20 Å. At increased cost filters can be produced for which the deviations are not more than 10 Å. Similar tolerances apply to the bandwidth of the filter; i.e. the typical bandwidth error in manufacture is 20 Å but 10 Å can be obtained at increased cost. The transmission profiles after manufacture can be routinely measured to an accuracy of 5 Å.

An important point is that the error $\Delta\lambda_{\rm c}$ in the target central wavelength $\lambda_{\rm c}$ is a slowly varying function of position on the filter, changing on the scale of a few mm to cm. Hence $\Delta\lambda_{\rm c}$ can be accurately measured as a function of position on the filter. Since all stars will cross the filter from one side to the other, what matters is the integrated central wavelength error across the filter.

Kazlauskas et al. (2002) have shown that the flux through a filter with a central wavelength error $\Delta\lambda_{\rm c}$ can be corrected to $\Delta\lambda_{\rm c} = 0$, by using the information in all the filters (i.e. by an iteration procedure in which all bands are used). For filters with a tolerance in the central wavelength/bandwidth of 20 Å, correcting to millimagnitude photometry is difficult, but under the constraint that one is solving for the value of $\Delta\lambda_{\rm c}$. If this is known already, say from tracings of the filters made after manufacture, the correction is much better. In order to obtain millimagnitude level photometry their studies nevertheless show that at least 10 Å filter tolerances are required.

The long term stability of the central wavelength and bandwidth of interference filters in space is also of high interest for a 5 year mission. Space Telescope's experience in this regard is being sought.

References

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