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**Gaia Follow-up Network for Solar System Objects  
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## Foreword

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This workshop was dedicated to the setting-up of a follow-up network for the Solar System Objects observed by the Gaia mission. After several years for getting in touch with candidate observers in many different countries, it was an important step aiming at accompanying this space astrometry mission all along its five year observation period. This workshop allowed us to know more on the status of the project, to propose a work flow for the processing of alerts, to get precise information on the observing sites and their specificities, to organize discussions and try to answer to some questions, to meet each other, to have fruitful exchanges and to simply reinforce the international collaboration. But most of all it was the opportunity to make this network active, and to foresee further actions. These proceedings provide a large overview of the communications and will be a reference document for the setting up and operation of the Gaia-FUN-SSO network. However, some open questions remains. Among them, the number of alerts is probably one of the most important unknowns, since it determines the work load to be carried on by the network, both by the central node and by the observing sites. Another important question appeared and could not be solved: the needs of funding for some observing sites. During the period of time before the launch of Gaia, we hope to get answers to these points.

We would like to thank all the participants to this fruitful meeting.

Paolo TANGA & William THUILLOT  
Co-chair of the Gaia-FUN-SSO workshop

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# Astrometry Correction for Chromatic Refraction

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## Introduction

Since the index of refraction of air depends on wavelength, light from a star will be refracted into a spectrum as it passes through the Earth's atmosphere. The direction of the refraction is toward the zenith, with blue light refracted more than red. Consequently, stars of different spectral types will experience differing degrees of atmospheric refraction, which is referred to “chromatic” or “colour” refraction (CR). As far as the amount of refraction increases with the zenith distance, so does CR. As a result, CR will be a source of systematic error, if it is neglected.

Until very recently, catalogs of stellar positions have not been corrected for CR, since it was considered unimportant with respect to other sources of error in these catalogs. This situation has radically changed with the release of the Hipparcos and Tycho-2 stellar catalogs. If the goal for positional accuracy is less than 100 mas and include observations taken at moderate to large zenith distances, corrections for CR might be needed in the astrometric reductions.

## 1. Short Review of Monochromatic Refraction

In a pure sense, atmospheric refraction should be calculated theoretically by tracing the path of light through the Earth's atmosphere, wherein the refraction will be just the difference in the directions of the light before it enters the atmosphere and as seen at the telescope. In order to make this tracing, detailed knowledge of the atmospheric temperature, pressure, and water vapor is needed along this path. This aerological data can be obtained from radiosonde, radar, and lidar measurements on a nightly basis. Because of the high costs involved, it was considered impractical decades years ago. However the situation changed: one can easily get access to the numerical mesoscale weather modeling, e.g. <http://www.wrf-model.org>, and use it for your own predictions, even if you have not recorded necessary data at the particular observing site.

Alternately, a model for the atmosphere can be assumed, and the aerological data assumed from it. The US Standard Atmosphere (1976) is often chosen. Also, refraction can be determined in a very straightforward manner, requiring only knowledge of the meteorological conditions (ambient temperature, atmospheric pressure, and water vapor) recorded at the observing site with each observation. Besides being very simple (only analytic expressions are used) and fast, this approach is also very accurate for zenith distances under  $75^\circ$ .

## 2. Practical Considerations

The Association Internationale de Géodesie (<http://www.iugg.org>) has recommended new equations for the precise calculation of the continuum component of phase refractive and group indices of air. They cover a wide range of wavelength from 300 nm to 1690 nm and atmospheric conditions at least  $-40^\circ$  to  $+100^\circ\text{C}$ , 80 to 120 kPa, and 0 to 100% relative humidity that are relevant to both laboratory measurements and surveying. There are experimental limits to the determination of phase refractive index with a limit uncertainty

about  $10^{-8}$ , such as  $0.01^\circ\text{C}$  for measuring temperature, 3 Pa for pressure, 0.4% for relative humidity, 100 ppm for  $\text{CO}_2$  content (Ciddor, 1996 & Ciddor, 2002).

For astrometry in a small field, i.e. differential reductions made with reference objects in the field, these accuracies can be much worse. For accuracies of 10 mas or less in a  $5^\circ$  field in declination, the required accuracies are only  $0.5^\circ\text{C}$  and 1 mm Hg in pressure, the correction for water vapor can be ignored altogether (Stone, 1996).

The previously discussed refraction  $R(\lambda)$  is only for monochromatic light of wavelength  $\lambda$ . As the first approximation for the refraction, the effective wavelength of a passband could be determined and then used to compute the refraction. Unfortunately, the effective wavelength for a given passband is not constant, but rather a variable that depends on the nature of the incoming light.

As discussed in (Stone, 1996), a better method for computing CR consists of calculating a mean refraction  $R_m$  by weighting the individual selective refractions  $R(\lambda)$  with the apparent stellar flux at wavelength  $\lambda$  and averaging across the passband. The mean refraction is given then by

$$R_m = \frac{\int_0^\infty S(\lambda)E(\lambda)A(\lambda)L(\lambda)F(\lambda)D(\lambda)R(\lambda)d\lambda}{\int_0^\infty S(\lambda)E(\lambda)A(\lambda)L(\lambda)F(\lambda)D(\lambda)d\lambda}$$

where  $S(\lambda)$  is the spectral energy distribution for the star being observed;  $E(\lambda)$  is the transmittance of interstellar dust along the line of site;  $A(\lambda)$  is the transmission of the atmosphere at the airmass being observed;  $L(\lambda)$  is the transmittance of the telescope optics;  $F(\lambda)$  is the filter transmission;  $D(\lambda)$  is the quantum efficiency of the detector being used; and  $R(\lambda)$  is the selective refraction discussed above.

For simplicity, a blackbody function could be used for the spectral energy function  $S(\lambda)$ ; however, this can be a poor assumption, if prominent spectral features are present within the passband. These features can reduce or increase the amount of refraction, depending on their prominence and placement within the passband. E.g., a narrow passband centered on about 500 nm will be strongly affected by TiO absorption when observing an M0 star. It would be better to use the spectral energy distribution of the star being observed. If the true distribution is not known, which is usually the case, then a distribution can be chosen that matches the spectral type of the star. Tabulations of spectral energy are given for all spectral types by different authors (Pickles, 1998). The functions  $E(\lambda)$  and  $A(\lambda)$  can be approximated from the tabular data in (Cox, 2000).

For many stars, neither the spectral type nor the color excess are known from spectroscopy. If multiband photometry is available, then a spectral type and color excess can be inferred. If only a color index is known, then a crude spectral type can be determined. A new opportunity arisen with the availability of 2MASS infrared magnitudes, where you can infer an approximate spectral class. When there is neither spectral nor photometric data available, which is often the case, an assumed spectral type and color excess can be adopted, e.g. a spectral type K0 and a color excess of  $E(B-V) = 0.3$  mag. These are working assumptions, bearing in mind the refraction for these stars can be later corrected, should these parameters eventually become known. The relative displacement of star of different classes caused by CR can be assessed from Table 1, according to (Stone, 1996).

**Table 1** – Chromatic refraction in mas at a zenith distance of 45°

Passbands / Spectral types	O	B	A	F	G	K	M
U	101	36	-29	0	8	-4	-42
B	88	58	12	0	-28	-100	-115
V	26	17	12	0	-8	-35	-42
R	22	18	12	0	-6	-21	-35
I	6	5	2	0	-1	-4	-6

The bluer a passband center is, the more pronounced the color refraction will be. This is to be expected considering the selective nature of atmospheric refraction. Furthermore, color refraction is a quasilinear function that decreases with later spectral type.

### Conclusion

The present review shows contemporary possibilities for calculating chromatic refraction. The chromatic refraction can be computed easily if the meteorological conditions are known at the time of observations and taken near the telescope. It is wavelength dependent and should be calculated for each telescope, if the astrometric accuracy better than 100 mas is required.

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