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Astrometric measurements from digitized Carte du Ciel plates

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Abstract

We present the results of our pilot study to derive accurate positions of stars from the old photographic glass plates of the Carte du Ciel survey by using a commercial digital camera as a digitizing instrument. The plates have a field of view of 2°×2°. We use the Tycho-2 stars and the Gaia TGAS (Tycho-Gaia Astrometric Solution) stars as external astrometric reference stars. The image distortions caused by the camera plus lens combination are constant and they can be determined and removed, unlike in the case of flatbed scanners, which have been previously used for digitizing Carte du Ciel plates. However, we find that the astrometric accuracy is equally good with or without removing the camera distortions. We can reach a value of 0.15”-0.18” for astrometric uncertainty when using external reference stars. This applies to an image with a size of 1.7°×1.1°, positioned at the center of a Carte du Ciel plate and not including a corner of a plate. For images which contain a corner of a plate, the external astrometric uncertainty is ~0.2”. The obtained internal astrometric uncertainty, that is, the deviation of the positions of all the common stars within the overlapping images of a single plate, when processing the overlapping images simultaneously, is ~0.06”. For overlapping images which are processed individually, the standard deviation of the differences of the positions of the common stars is ~0.13”. We find that sometimes for images which include a corner of a Carte du Ciel plate, using stars from Tycho-2 catalog instead of Gaia catalog as reference stars for astrometry, gives lower scatter in astrometric solution. This effect is probably caused by dim stars within the strongly elongated and large stellar profiles at the corners of the plates. The final goal of this project is to search for long-period double stars by comparing the ~100 year old stellar coordinates, measured from the Carte du Ciel plates, with the expected epoch-transformed coordinates based on the very accurate coordinates and proper motions measured by the Gaia satellite.

Carte du Ciel

Carte du Ciel was a massive international project, initiated in the late 19th century, to take images of the whole sky and to derive positions and magnitudes of stars down to a magnitude limit of about 14 mag. Due to the vast amount of manual data reduction required, the Carte du Ciel survey was never fully finished. However, a related photographic survey called Astrographic Catalogue (or Astrographic Chart), with a lower limiting magnitude of about 11 mag, was finished. The data of this survey has been combined with the results from ESA's Hipparcos space astrometry satellite to derive proper motions for about 2.5 million stars.

The plates of our study were taken at the Observatory of the University of Helsinki, around the year 1900. The declination range of Helsinki was 40-46 degrees. There are in total of about 1600 glass plates in Helsinki, but in this project, we process about 10 plates and validate the functionality of our method.

† Deceased August 28, 2017

The optical system in the Carte du Ciel telescopes is aplanatic doublet objective. A description of the optical system in the Carte du Ciel telescopes is given by Jones ([1]): '*A further advance was the development of a prototype aplanatic doublet objective of 16 cm aperture corrected for blue light where the photographic plates of those days were most sensitive. The aplanatic design corrects both coma and spherical aberration. Images with coma look like little comets and are unusable for photographic astrometry. For faint stars, only the nucleus registers, but images of bright stars are pulled towards the tail by an amount dependent on the brightness of the star. The Henrys' design does exhibit some astigmatism and field curvature, but these aberrations are symmetrical and have no deleterious effect on astrometry (Weimer 1985 [2]).*'

Instrumentation

The glass plates have a total size of 16x16 cm, while the area covered by photographic emulsion is 13x13 cm. The scale of all the Carte du Ciel plates is 1 arcminute per millimeter.

For digitizing we use the digital camera Canon EOS 5Ds, having 8736×5856 image pixels, together with a Canon 100mm macro lens. We take four partly overlapping images of each plate, so that the shorter side of the image sensor covers half the width of a plate. The central parts of a plate are thus imaged twice. The pixel size is about 13cm/11626≈11µm, corresponding to a nominal resolution of about 0.7 arcsec/pixel (true resolution is probably somewhat worse).

The digital cameras for consumer market, such as Canon EOS 5Ds, have a low-pass filter (so called anti-alias filter) in front of the sensor. The filter prevents Moire effect in images by effectively smoothing the images slightly. We need to have the best possible resolution, therefore JTW Astronomy (http://www.jtwastronomy.com) has removed the anti-aliasing filters and all the other optics and replaced them with thinner optically polished glass with IR-shortpass filter (1/20 λ surface quality with 0.5% reflectivity BBAR coating). This also required a small movement of the detector array to accommodate to the change of the optical path. According to our tests, the automatic focusing works correctly after the filter modification, which means that there is no need for a tedious manual focusing.

When digitizing a plate, the camera is attached to a Kaiser Reproduction Stand RS1/RA1 5510. The glass plates are lit from below by a LED illuminated light table, Artograph LightPad A930 (Fig. 1). There will be a self-made stand for the plates so that they are not lying on the light table. This will prevent scratches on the plates and visibility of dust particles between plate and light table. With a digital camera, it is fast and easy to take a mean value of say, 4 exposures, thus improving the signal-to-noise ratio, especially at the cores of the stars which are the darkest parts of the image.

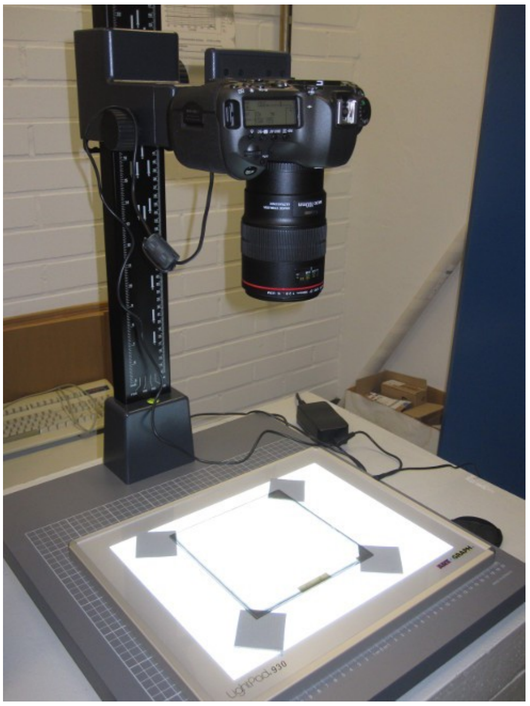


Figure 1. The repro stand, camera, and light box.

Gaia Data Release 1 (DR1)

In our project we utilize position and proper motion values of stars given in the first data release of Gaia, the Gaia DR1. The derivation of proper motion and parallax values after only about one year of Gaia observations was made possible by a joint Tycho-Gaia Astrometric Solution (TGAS) [3]. Figure 2 shows a subsection of stars in TGAS, within Declination 35°─50°, plotted in equatorial coordinates. To have the highest density of reference stars for our Cart du Ciel plates, we have digitized plates which are in the R.A. range of 19h─22h.

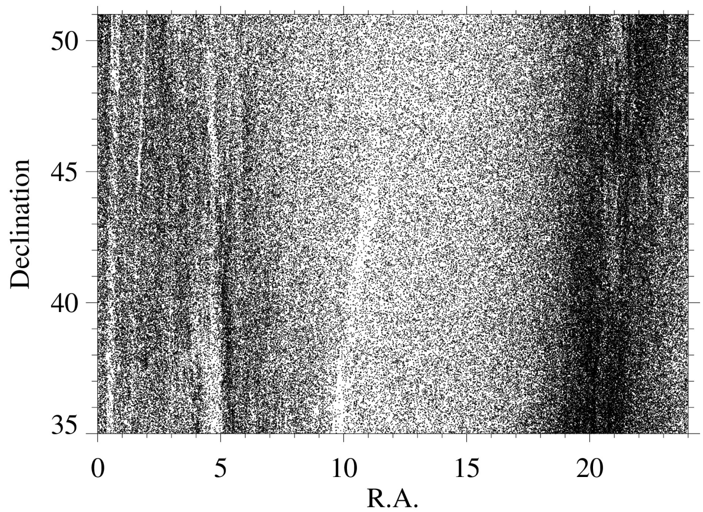


Figure 2.The stars in the 'Tycho-Gaia Astrometric Solution' catalog.

Data processing

The full process is the following:

1) Images are saved in a 14-bit RAW format on a hard disk. In this format, the pixel values *should* be unprocessed (be careful here, these are cameras for consumer market and thus they may process the data in an un-documented way).

2) RAW images are converted into FITS format using cr2fits.py Python script (http://github.com/eaydin/cr2fits), which is based on dcraw program (http://www.cybercom.net/~dcoffin/dcraw). All subsequent data analysis is done in FITS-format.

3) In RAW format, an image has a strong check-board pattern due to the Bayer filter mosaic, which is a color filter array for arranging red/green/blue color filters on a square grid of photosensors. In practice, each 2x2 sub-array of the camera sensor has one pixel for red, one pixel for blue and two pixels for green light (Fig. 3). Usually these three colors are interpolated to obtain a color image. However, we are not interested in colors. We have investigated two ways to remove the Bayer pattern. Firstly, we can use the built-in interpolation options of the dcraw software. In this case, the 'missing' pixels of each color are interpolated, and we get full images for each of the three colors, red, green and blue. The final image is then obtained by taking a suitably weighted mean of the three images. In principle, there is some loss of information in the interpolation process. However, the effect of interpolation on the positions of stars is expected to be minimal because the stars are well sampled with our ~0.7”/pixel resolution. Secondly, we can read the RAW data without any built-in interpolation within dcraw. Then, we derive median values of red, green and blue pixels over the whole image, and each color is scaled so that median value over each color becomes the same. These two methods give practically the same results.

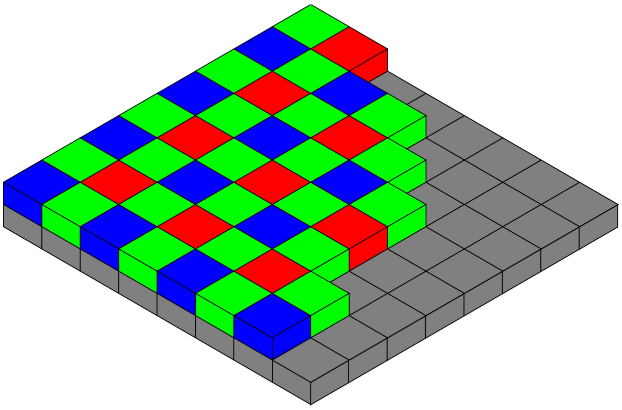


Figure 3. The Bayer color filter pattern of typical digital camera.

4) An example of image data is shown in Fig. 4, after the image has been scaled so that stars are bright (not dark as in glass plates). The photographically superimposed vertical and horizontal réseau grid lines are visible, and one of the stars is located on a grid line.

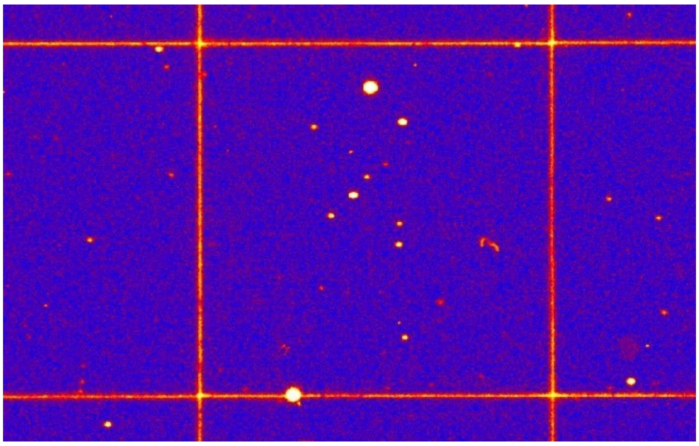


Figure 4. An example of a part of a Carte du Ciel plate. The réseau grid lines are visible.

Before searching for stars in the image, the image has to be heavily smoothed to derive the background value at each pixel. Before smoothing, the grid lines have to be removed, in an automatic way. Our procedure is the following:

- Suppose we want to remove the lines running along the y-direction. We take mean values over each column, obtaining the shapes of the grid lines with a very good signal-to-noise ratio, shown in Fig. 5. The derivative of the vector in Fig.5 is shown in Fig. 6.

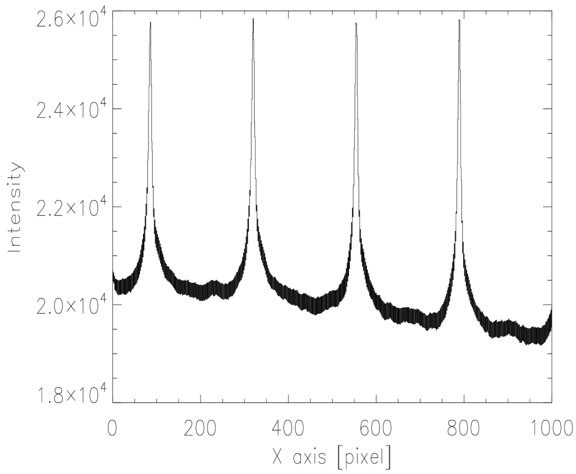


Figure 5. An example of four of the grid lines, after taking a mean along y-axis of an image. The grid lines are seen with a very high signal-to-noise ratio.

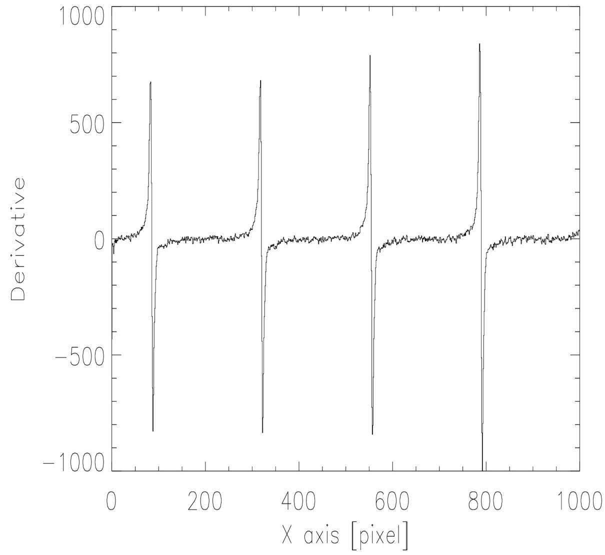


Figure 6. The derivative of the vector in Fig. 5. The positions of the abrupt changes of derivative give the positions of the grid lines.

Finding the positions of the peaks is then finding the regions where derivative changes from large positive values to large negative values. We then linearly interpolate the pixels located +/-7 pixels around the position of the peak. The same is then done for grid lines running along the x-axis. This is a robust method because it does not depend on the absolute value of intensity. The image after removing the grid lines is shown in Fig. 7.

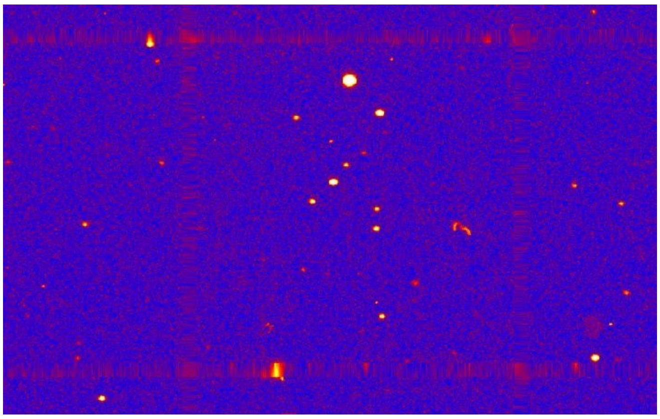


Figure 7. The same as Fig. 4, but the grid lines have been removed by interpolating over the grid lines.

At the same time when removing the grid lines, we make a flag-image, indicating which pixels are interpolated and thus not used in further data analysis. The flagged area is typically about 12% of the total image area. The removal of grid lines is implemented with a Python script.

5) The approximate center coordinates of each plate can be read from a sticker on a plate. Then, a preliminary astrometry for an image can be derived by using the astrometry.net service, including SIP (Simple Imaging Polynomial) distortion factors [4]. The epoch of the reference star catalog used by astrometry.net is around 2000, not around 1900, the epoch of the plates. However, this is not a problem because the purpose of this stage is just to get a preliminary astrometry which SCAMP can successfully use as a starting point in the refinement of the astrometry. Later, we will install the astrometry.net software in a local computer so that the whole process can be run locally.

6) We use SExtractor (http://www.astromatic.net) program to search for the stars and to derive their position and flux. The configuration file of SExtractor is given in Appendix A. The removal of the grid lines produces discontinuity in the image data which SExtractor sometimes detects as false sources. However, the false sources are easy to discard by discarding all the sources which are within the flagged areas. An example of a background map derived by Sextractor is shown in Fig. 8b.

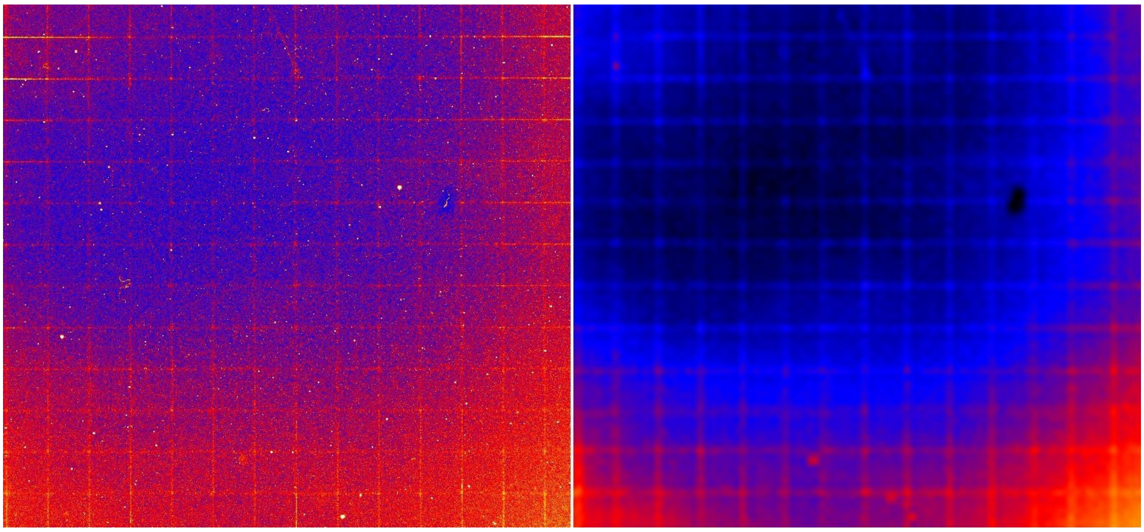


*Figure 8. Panel **a** (left) shows a central part of a Carte du Ciel plate, after the grid lines have been mostly removed. Panel **b** (right) shows a smoothed version of panel **a**. The smoothed version is used as a background image when SExtractor is searching for the stars in the image.*

SExtractor uses an iterative process to determine the position of a source on a digital image, and the process works equally well for circular (stars) or elliptical objects (galaxies). This is particularly important in the case of Carte du Ciel plates where the stars at the corners of the plates are strongly elongated due to astigmatism caused by the telescope (see Figure 15).

A histogram of the uncertainties of the pixel positions of the sources, as determined by SExtractor for one of our images, in shown in Fig. 9. A majority of stars have an uncertainty of less than about 0.15 arcsec.

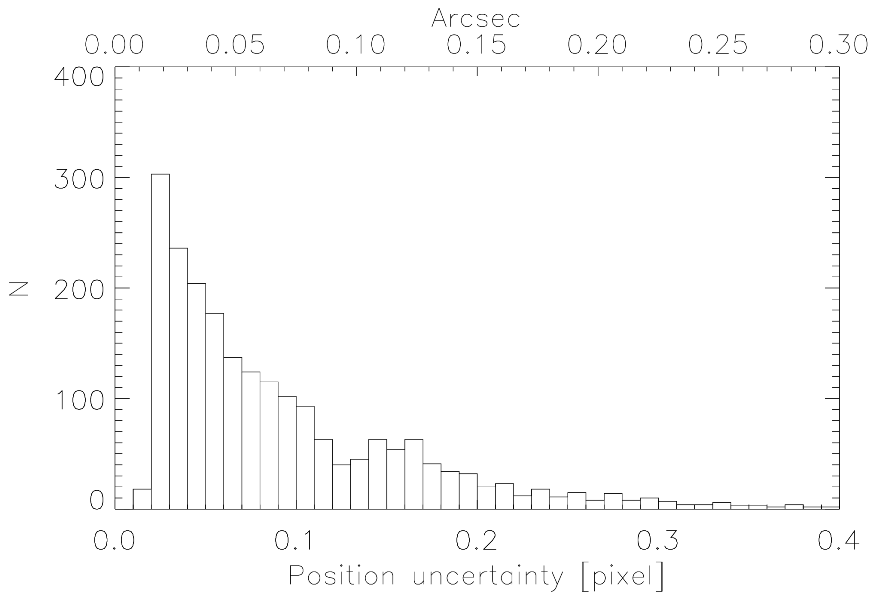


Figure 9. An example of a histogram of uncertainties of pixel positions of stars as given by SExtractor.

7) The final astrometry of a Carte du Ciel plate has to be derived by using a reference catalog of stars where the proper motions of stars have been applied to calculate the positions of stars at the epoch of the plate, around 1900. For this purpose we use both the Tycho-2 catalog and Gaia TGAS (Tycho-Gaia Astrometric Solution) catalog and compare their properties.

7a) Tycho-2 catalog is available at ftp://cdsarc.u-strasbg.fr/pub/cats/I/259. The epoch transformation has been done as described in the section '1.5.5. Epoch transformation: Rigorous treatment' in the document http://www.rssd.esa.int/SA/HIPPARCOS/docs/vol1_all.pdf. Rigorous treatment is required because the time span is so large, about 100 years. For a rigorous treatment of error propagation (that is, uncertainty of the coordinates at epoch ~1900 for the reference stars) one should know the correlation coefficients between the astrometric parameters in the Tycho catalog, such as Right Ascension, proper motion, parallax etc. However, the correlations are not given in the Tycho-2 catalog referred above. The correlations are given in the Tycho-1 catalog *tyc_main.dat* available at ftp://cdsarc.u-strasbg.fr/pub/cats/I/239. But then, this catalog has less stars and the uncertainties of proper motions are larger than in the Tycho-2 catalog. Therefore we use solely the Tycho-2 catalog. Figure 10 shows the histogram of uncertainties of Right Ascension and Declination, at epoch 1900, for the Tycho-2 reference stars which are in the Helsinki region of the Carte du Ciel survey. The uncertainties have been derived using a 'simplified treatment', equation [1.5.22] in the above mentioned Hipparcos document. In practice, we find that the difference between using a 'rigorous treatment' and a 'simplified treatment' when calculating the uncertainties of the positions of stars at epoch around 1900 is insignificant compared to the expected astrometric accuracy of the Carte du Ciel plates.

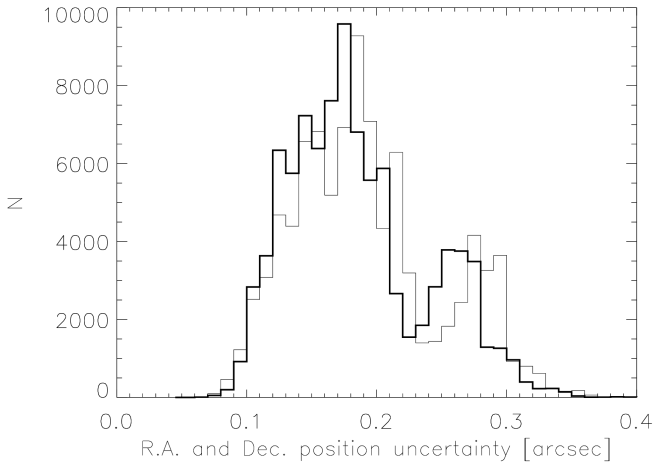


Figure 10. Histogram of uncertainty of Right Ascension (thin line) and Declination (thick line) for the Tycho-2 reference stars, after transforming the positions into epoch 1900. The data set consists of all stars which are in the Helsinki section of the Carte du Ciel survey.

7b) The Gaia TGAS catalog is available at http://gea.esac.esa.int/archive. TGAS catalog includes all the correlation coefficients which are needed for a rigorous treatment of error propagation. Similarly to Fig. 10 above, Fig.11 shows coordinate uncertainty of stars in the TGAS catalog at epoch 1900. The peak values of the histograms corresponds to an uncertainty which is about two times lower than for Tycho-2 data, and furthermore the tails of the histograms are much cleaner for Gaia data.

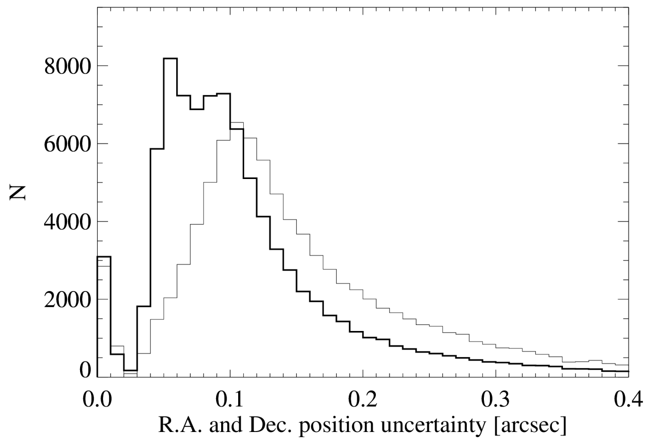


Figure 11. Histogram of uncertainty of Right Ascension (thin line) and Declination (thick line) for the Gaia TGAS reference stars, after transforming the positions into epoch 1900. The data set consists of all stars which are in the Helsinki section of the Carte du Ciel survey.

8) To compute the astrometric projection parameters for the digitized plates, using the Tycho-2 or Gaia TGAS stars transformed to the epoch of a plate as the reference stars, we use SCAMP (www.astromatic.net). It derives a polynomial distortion model for an image by minimizing a weighted quadratic sum of differences in positions between the stars in the plates and the reference stars. We use either 3rd or 4th order polynomials. SCAMP wants to have the reference star cataloque in LDAC (Leiden Data Analysis Center) format. We transform the catalog from ASCII format to LDAC format using the LDAC tools of the THELI (https://www.astro.uni-bonn.de/theli) package, see
https://marvinweb.astro.uni-bonn.de/data_products/THELIWWW/LDAC/LDAC_basics.html

Triple exposures

The Carte du Ciel plates along odd declinations were exposed three times. Each exposure time was 30 minutes, and the pointing of the telescope was moved by about 10 arcsec between the exposures. Thus, there are three images of each star, forming an equilateral triangle, a so called asterism (see Fig. 12). The motivation for triple exposures was that then it is possible to distinguish stars from plate defects and asteroids.

Triple exposures have some nuisances compared to single exposure plates. Firstly, the single star images in an asterism start to merge together when a star is brighter than about 10 mag. Secondly, there is a photographic adjacency effect within an asterism, called Kostinsky effect. It makes the stars in an asterism to appear further away from each other than what they actually are. Thirdly, the asterisms of closely located stars are overlapping. However, good astrometric results are achievable from triple exposure plates, as shown by e.g. Ortiz-Gil et al. (1997 [5]). We fit the asterisms with three overlapping elliptical Gaussians with a saturation parameter (Dick et al. 1993 [6]). The width and height of all the three Gaussians are expected to be equal. We perform the fit with a Python script which is listed in Appendix E. An example of a fit is shown in Fig. 12. The standard deviations of the fitted positions of the elliptical Gaussians are about 0.04 pixel.

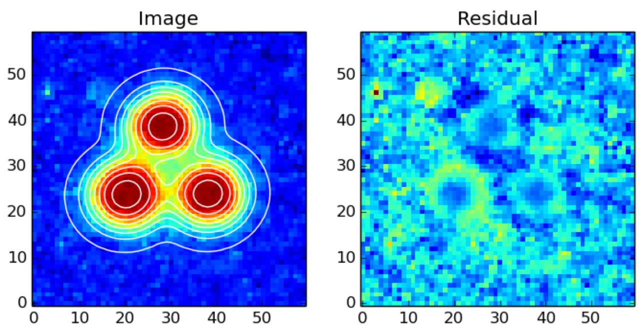


Figure 12. An example of a fit to an asterism on a triple exposure plate. The left panel shows an asterism together with a fit overplotted as contour lines. The right panel shows the residuals of the fit.

Camera + lens distortions

After private discussion with Hervé Bouy, who has a lot of experience with SCAMP, it has become clear that it is recommended to remove the distortions caused by our camera+lens combination. The reason is the following: SCAMP derives the distortions of an instrument in two steps. First it uses the external catalogue to derive the first order solution including the pixel scale and orientation (angle) of the image. Then it uses the 'overlapping plates' method to derive the high order distortions of the instrument. However, in the case of Carte du Ciel plates, we have some, but not enough overlapping plates, and thus SCAMP will only be able to derive a solution relying on the astrometric catalogue. Untill now, the external catalogues (e.g. Tycho-2) have had a relatively poor accuracy for proper motions, and thus the plate distortions computed by SCAMP have not been of high quality. It is true that Gaia will give us more accurate values for proper motions, but also in that case it is a good practice to remove the camera+lens distortions. Then there are only plate distortions left which SCAMP needs to derive.

The camera+lens distortions are constant, thus the distortions need to be determined only once. The procedure for removing the distortions is the following:
i) Make a fake, random stellar field and print it on a paper. Also, make a corresponding star catalog in a format that SCAMP can read.
ii) Take about 20 overlapping images of the field in a dither pattern, that is, move the paper slightly between the exposures.
iii) Use SExtractor to derive the positions of the artificial stars.
iv) Use SCAMP to derive the distortions for each image, based on the positions derived in the previous step, and take a mean value of the distortion parameters. An example of a header file produced by SCAMP, giving the distortion parameters, is given in Appendix D. SCAMP uses PV*i_j* keywords to store the distortion-polynomial coefficients.
v) Use Swarp (http://www.astromatic.net) program to correct the images for camera+lens distortions. This is accomplished simply by setting all the PV*i_j* keywords to zero in the output image.

Figure 13 shows the 1D reference astrometric errors for one of the images of the artificial star field. There are typically around 1800 artificial stars in each image. Although the 'star images' on a paper, printed with a laser printer, are not perfect circles, the large number of stars ensures that the distortion caused by camera+lens can be determined. Note that the uppermost plot in Fig. 13 shows a periodic error, a feature which is visible in every image of the artificial star field. This is most probably caused by uneven movement of a paper and/or laser unit inside the laser printer during printing.

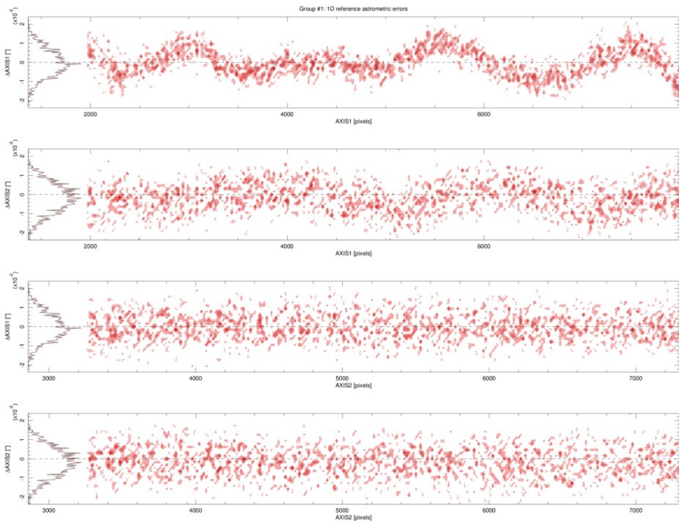


Figure 13. One-dimensional reference astrometric errors for one of the images of the artificial star field.

Figure 14 shows examples of distortion maps for an artifical stellar field and for an image of a Carte du Ciel plate. The general shapes and absolute values of distortion, ~0.2%, are similar, which suggests that the distortions seen on images of Carte du Ciel plates are dominated by distortions caused by our camera+lens combination.

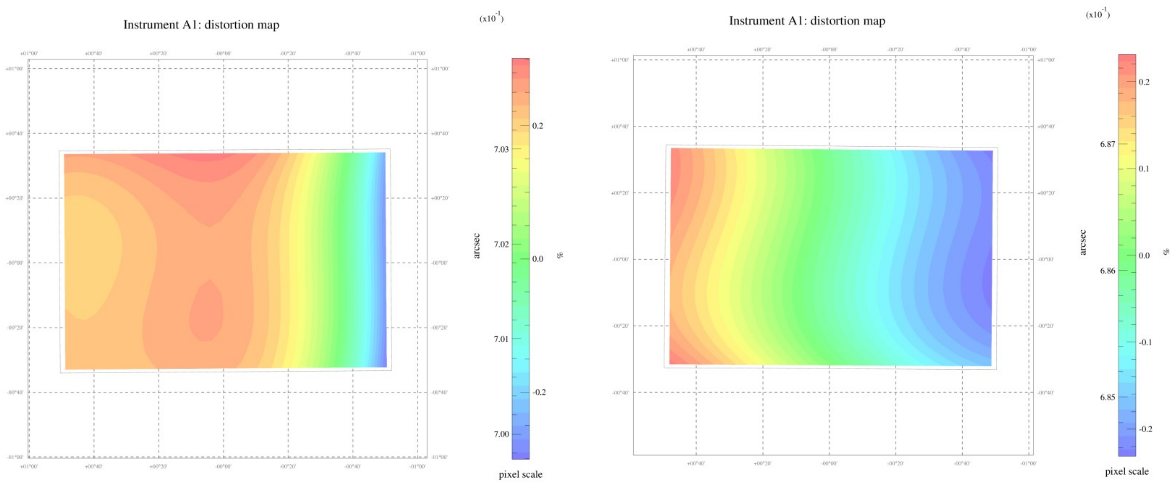


Figure 14. The distortion maps for an artificial stellar field (left panel) and for an image of a Carte du Ciel plate (right panel). Note the general similarity between the maps.

Results

Figure 15 shows stellar profiles and sizes of a typical star at the center and corner of a Carte du Ciel plate. The large diameters, between 10”-20”, mean that buried within the stellar profiles there may be dimmer, unseen stars which move the photo-center of the star seen on a plate away from its expected position. This effect is more serious at the corners of the plates because the stellar profiles are larger there.

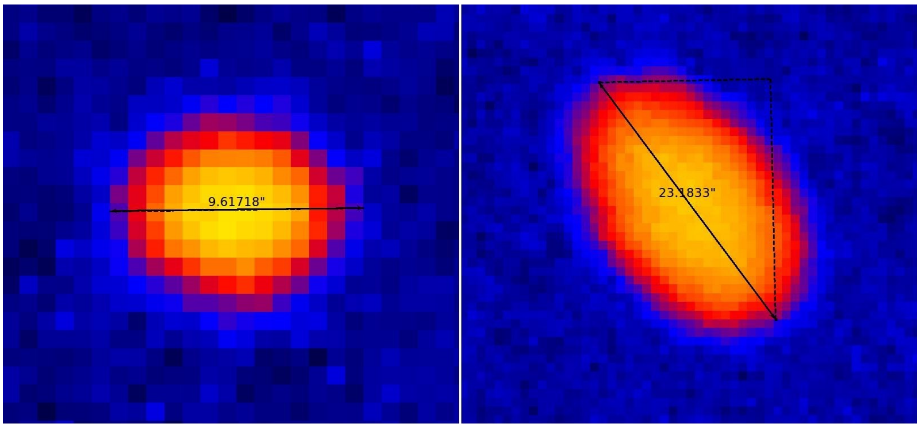


Figure 15.Typical stellar profiles at a center (left panel) and corner (right panel) of a Carte du Ciel plate.

Figure 16 shows the plate distortions for an image at the center of a Carte du Ciel plate, before and after the distortions caused by camera+lens combination have been removed. The distortions have decreased from about ±0.2% to about ±0.015%. Furthermore, the distortions in the latter case have a shape which is in general as expected for an astronomical telescope (largest pixel scale coinciding with the optical axis of the telescope). Note that this example is based on just one image of an artificial stellar field, while a proper determination of camera+lens distortions requires an average over several distortion maps of an artificial stellar field.

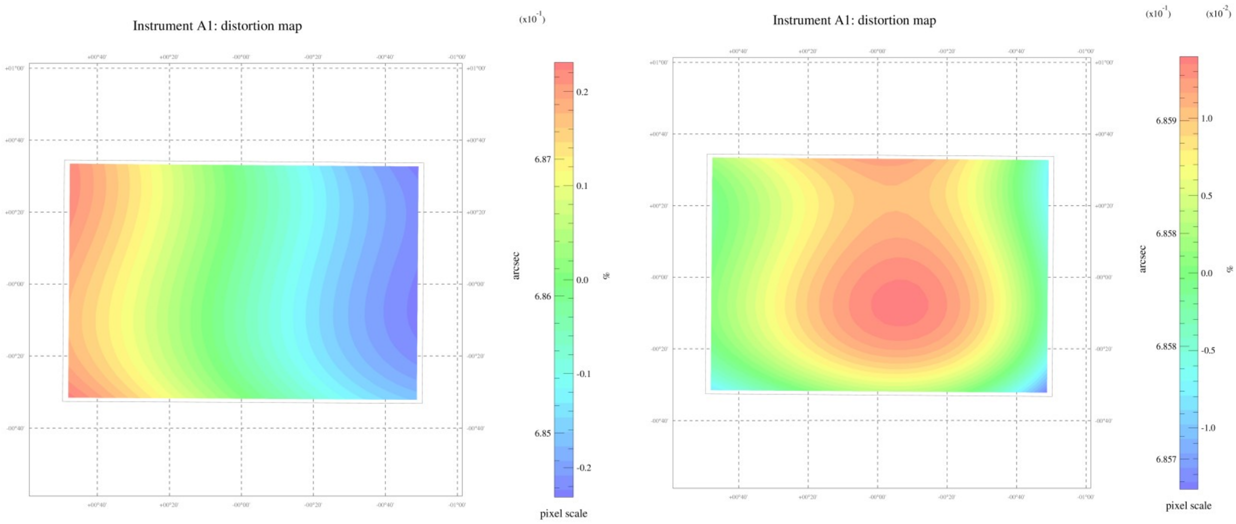


Figure 16. An example of distortions of a central part of a Carte du Ciel plate before (left) and after (right) correcting for the distortions caused by our camera+lens combination.

We have digitized plates with different setups, but we present here two different cases:
i) Two images of a Carte du Ciel plate, the other one at the center of a plate, and the other one at the corner of a plate. The whole plate is not covered. In this case we have determined the distortions caused by the camera+lens combination. The pixel scale is 0.69”/pixel.
ii) Four overlapping images of a Carte du Ciel plate, covering the whole plate. In this case we have not determined the distortions caused by the camera+lens combination. The pixel scale is 0.68”/pixel.

In both cases the digitized plate is Carte du Ciel plate #892, which has approximate coordinates R.A.=21h10m, Dec.=44°. In the following we discuss about external and internal errors (or statistics) of the astrometric solutions computed by SCAMP. The external errors are computed from the comparisons of astrometric positions of the Carte du Ciel stars with the reference stars. The internal errors are computed from the differences of astrometric positions of sources inside the overlapping images of a single plate.

The results of astrometric solution by SCAMP are best visualized by the following pictures (the sentences in apostrophe are directly from the SCAMP manual).

i) Two images of a Carte du Ciel plate

The purpose of this case is to compare the obtained accuracy of astrometry of an image which does not include any corner of a plate with an image which includes a corner of a plate. Figure 17 is for the image at the center of a plate, showing as green diamonds those stars which we detect on a Carte du Ciel plate and which are also in the Gaia TGAS reference star catalog, and thus are used for astrometric solution. Red boxes are stars which we detect on a Carte du Ciel plate and which are also in the Gaia TGAS reference star catalog, but are not used for astrometric solution, because they are either flagged as bad by Sextractor or they are outliers in the fitting of astrometry. The small dots are stars which are only in the Carte Du Ciel plate. There are 157 reference stars which are used to derive the astrometry and distortion of the image. This gives a surface density of ~84 reference stars per square degree. There are regions with sizes up to about 20' which do not have any reference star.

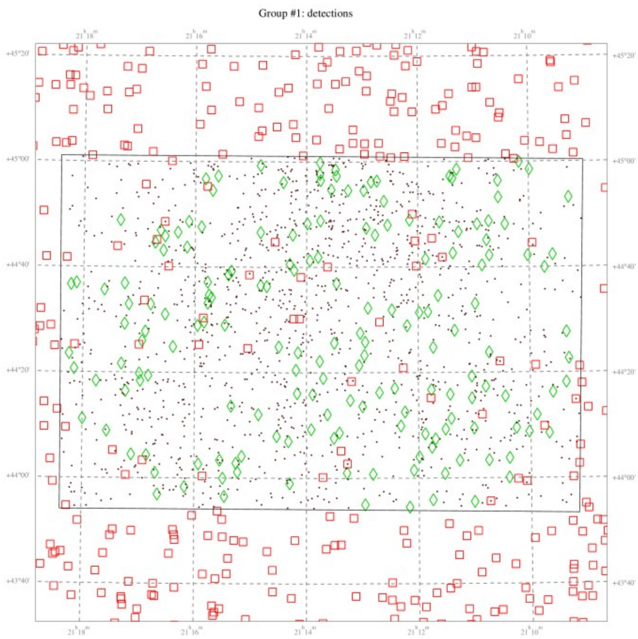


Figure 17. Carte du Ciel and reference stars on an image of a plate. Stars which are only on our image of a Carte du Ciel plate (black dots), stars which are both on our image of a Carte du Ciel plate and in the Gaia TGAS catalog and which are thus used for astrometric solution (green objects), stars which are in the Gaia catalog but not used for astrometric solution by SCAMP (red objects).The borders of the image are shown.

Figure 18 gives a 'scatter plot showing the 1-dimensional differences between detection coordinates and coordinates of the associated astrometric reference stars as a function of position along each reprojected axis.' The scatter is evenly distributed around zero, which indicates that the chosen degree of distortion polynomials is sufficient to modell the distortions of the image.

Figure 18. One-dimensional external reference astrometric errors.

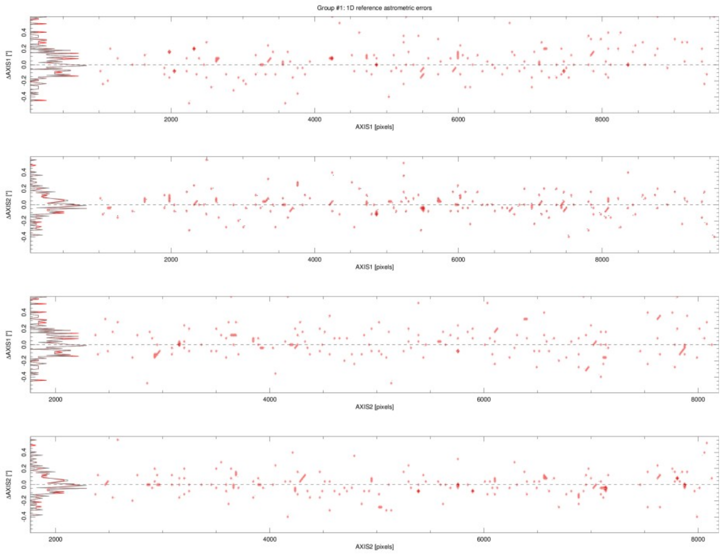


Figure 19 shows a '2-dimensional scatter plot showing the differences between detection coordinates and coordinates of the associated astrometric reference star.' The dashed box shows the size of a single pixel. The majority of stars are located within a single pixel from their modelled position. This accuracy should be compared with typical stellar profiles shown in Fig. 15 above.

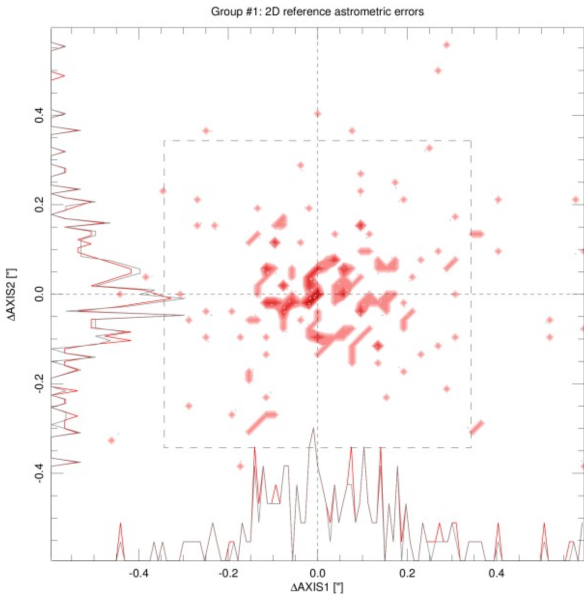


Figure 19. Two-dimensional external reference astrometric errors. The dashed box shows the size of a single pixel.

As an example of the obtained astrometric accuracy, we present results using both Tycho-2 and Gaia TGAS stars as reference stars, and both with and without correcting for camera+lens distortions. We have two images, one at the center of the plate, the other at the corner, with sizes of about 1.7°×1.1°. We use a degree of 4 for the distortion polynomial groups. Tables 1 and 2 give the external astrometric statistics when using Tycho-2 and Gaia TGAS reference stars, respectively. The dAXIS1/2 parameters give the width of the distribution of the distances between the cataloged positions of reference stars and the modelled positions of the corresponding stars on a Carte du Ciel plate, along the two axes of the image, as was shown graphically in Fig. 18 above. The chi-squared value of the fit is given by χ2.

Two conclusions can be drawn from Tables 1 and 2:
i) The achieved astrometric accuracy is better over an image which is centered at the center of a Carte du Ciel plate and not including the corners of a plate, than over an image which includes a corner of a plate. This is valid both for Tycho-2 and Gaia TGAS reference stars.
ii) Over an image which is centered at the center of a Carte du Ciel plate and not including a corner of a plate, using Gaia TGAS reference stars gives slightly better astrometric accuracy. Over an image which includes also a corner of a plate, using Tycho-2 reference stars gives better astrometric accuracy.

	No camera distortion correction	With camera distortion correction
Center	dAXIS1/2=0.193”/0.180”, χ2=0.56	dAXIS1/2=0.194”/0.180”, χ2=0.56
Corner	dAXIS1/2=0.255”/0.226”, χ2=1.2	dAXIS1/2=0.236”/0.225”, χ2=0.97

Table 1. Astrometric statistics for Tycho-2 reference stars.

	No camera distortion correction	With camera distortion correction
Center	dAXIS1/2=0.179”/0.145”, χ2=0.91	dAXIS1/2=0.180”/0.145”, χ2=0.89
Corner	dAXIS1/2=0.268”/0.271”, χ2=2.6	dAXIS1/2=0.264”/0.263”, χ2=2.6

Table 2. Astrometric statistics for Gaia TGAS reference stars.

ii) Four overlapping images of a Carte du Ciel plate

The purpose of this is to study what is the internal accuracy of positions of stars for partly overlapping images. We also study if fitting astrometry in sub-fields of an image improves accuracy of astrometry.

The four overlapping images are shown in Fig. 20. The blue symbols are stars which are common in the overlapping images. The external astrometric errors for each of the four images are given in Table 3, either using Tycho-2 or Gaia TGAS stars as reference stars. The astrometric uncertainty is lower in the case of Gaia TGAS reference stars.

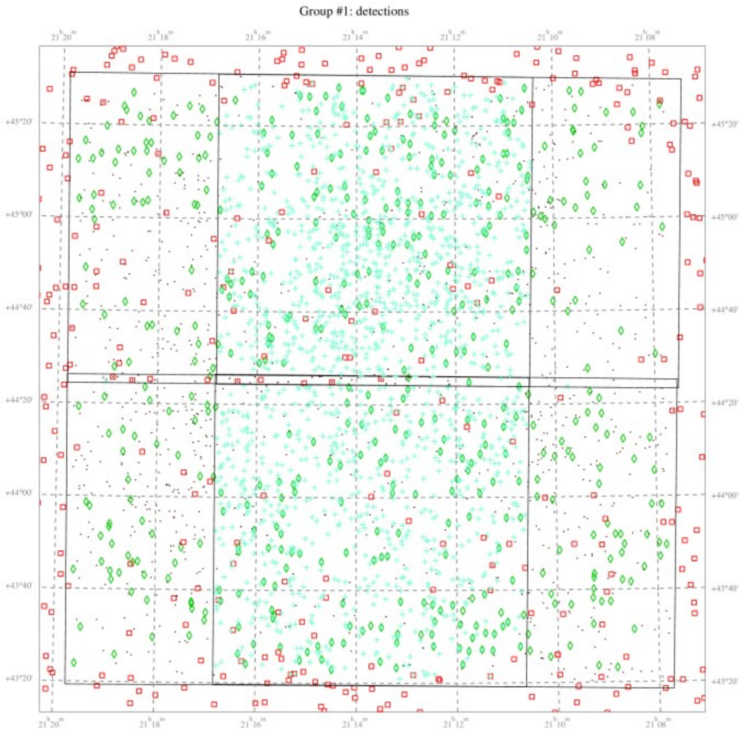


Figure 20. The borders of the four partly overlapping images which cover a single Carte du Ciel plate. The blue symbols are stars which are common in the overlapping areas.

Image	Tycho-2, dAXIS 1/2 [”]	Gaia-TGAS, dAXIS 1/2 [”]
corner-1	0.234 / 0.223	0.235 / 0.229
corner-2	0.195 / 0.230	0.140 / 0.185
corner-3	0.406 / 0.210	0.344 / 0.193
corner-4	0.334 / 0.188	0.318 / 0.150

Table 3. Astrometric statistics for each of the four images of Fig. 20, using either Tycho-2 or Gaia TGAS reference stars.

We have then divided each of the four images into two sub-images along the middle column of the images, and fitted astrometry for each of the sub-image. There are typically about 80 reference stars in each sub-image, which is about the minimum number of stars for a decent astrometric solution by SCAMP. Therefore we use a degree of 3 for the distortion polynomial groups. The results are shown in Table 4, separately for Tycho-2 and Gaia TGAS reference stars. By comparing Tables 3 and 4 we conclude that i) the obtained astrometric uncertainty is lower in sub-fields, and ii) also in sub-fields, using Gaia TGAS reference stars gives lower astrometric uncertainty than using Tycho-2 stars. The mean value of external astrometric errors (dAXIS1/2 in Table 4) is ~0.21” for Gaia TGAS reference stars.

Sub-image	Tycho-2, dAXIS 1/2 [”]	Gaia-TGAS, dAXIS 1/2 [”]
corner-1-sub-A	0.157 / 0.222	0.137 / 0.200
corner-1-sub-B	0.280 / 0.189	0.378 / 0.230
corner-2-sub-A	0.188 / 0.224	0.137 / 0.155
corner-2-sub-B	0.160 / 0.208	0.138 / 0.198
corner-3-sub-A	0.319 / 0.218	0.269 / 0.211
corner-3-sub-B	0.343 / 0.199	0.311 / 0.168
corner-4-sub-A	0.322 / 0.178	0.277 / 0.154
corner-4-sub-B	0.192 / 0.191	0.230 / 0.137

Table 4. Astrometric statistics for each of the four images of Fig. 20 and Table 3 after dividing each image into two sub-images (sub-A and sub-B).

We have run Samp by giving simultaneously all the partly overlapping images of Fig. 20 as input images. SCAMP can then compute internal astrometric errors for all the stars which are within the overlapping areas, not just for reference stars. A 2-dimensional plot of the internal astrometric errors is shown in Fig. 21. The standard deviation of the distribution is ~0.06” along Right Ascension and Declination. One can see that the distribution along Right Ascension (AXIS1) is somewhat skewed. The reason for this is unknown.

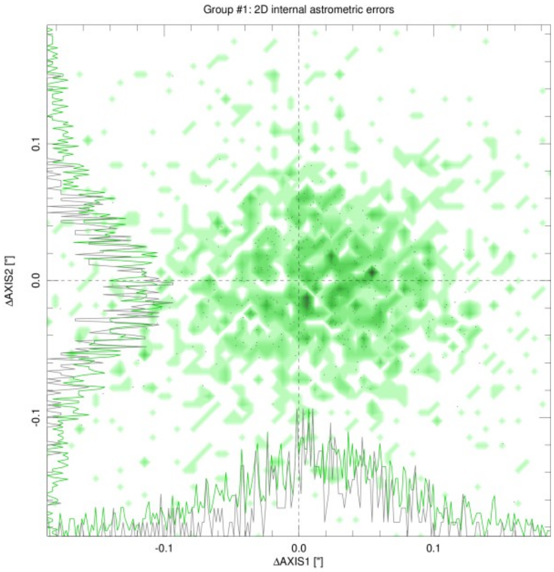
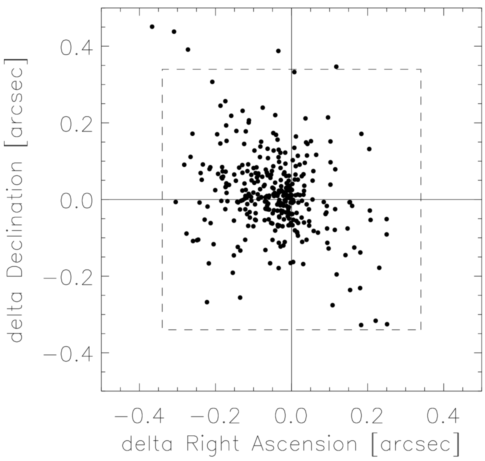


Figure 21. The internal astrometric errors for the four overlapping images of Fig 20.

A stringent test for the accuracy and repeatability of astrometry is to compare the positions of stars on two partly overlapping images of a single plate. After solving the astrometry with SCAMP, using Gaia TGAS stars at the epoch of the plate as reference stars, we insert the obtained distortion parameters (PV*i_j* keywords) into the header of the FITS image. We then run SExtractor again, to get the positions of all sources in the framework of the astrometric solution computed by SCAMP.

As an example, we have compared the positions of the stars in the images corner-1-sub-A and corner-2-sub-B of Table 4. A plot of the coordinate differences is shown in Fig. 22. The standard deviations of the distributions along Right Ascension and Declination are 0.14” and 0.12”, respectively. These low values give us confidence that the fitted astrometry in each image is reliable. The sources with the largest deviations in the positions are predominantly weak stars or artifacts. Similarly to the Fig. 21 above, one can see that the distribution is skewed along Right Ascension.

Figure 22. The differences of the coordinates of the common stars in the partly overlapping images corner-1-sub-A and corner-2-sub-B (Table 4). The dashed box shows the size of a single pixel.



Discussion

Figure 9 gives a mean uncertainty of about 0.08 pixel, that is about 0.06 arcsec, for the position of a star on a digital image of a Carte du Ciel plate. Figure 11 gives a typical uncertainty of about 0.1 arcsec for the coordinate of a Gaia TGAS reference star which has been transformed into epoch 1900. These two uncertainties are unrelated, thus a crude estimate for the total uncertainty of a coordinate of a star on a Carte du Ciel plate, without any effects by plate distortions, is expected to be about 0.12 arcsec. That is lower, as expected, than the external astrometric uncertainty given by SCAMP, at minimum about 0.15”-0.18” for an image without any corner of a Carte du Ciel plate, or about 0.21” for an image which includes a corner of a Carte du Ciel plate.

As suggested by Tables 1-4, sometimes the astrometric uncertainty is larger, by up to a factor of two, along Right Ascension (dAXIS1) than along Declination (dAXIS2). This may be related to the skewed distribution of internal astrometric errors along Right Ascension as shown in Fig. 21. The difference between dAXIS1 and dAXIS2 may be caused simply by small-number statistics of reference stars used to fit the astrometry. Another explanation is that it is caused by small errors in the clock drive during an exposure. However, clock drive errors should have the same effect for every image of a single Carte du Ciel plate. In addition, none of the images show stellar profiles which are elongated along Right Ascension.

We sometimes see that for an image which contains a corner of a plate, better astrometric accuracy can be obtained when using Tycho-2 reference stars instead of Gaia TGAS reference stars. This has to stem from the fact that proper motions in Tycho-2 catalog are heavily based on old photographic images. Thus, the proper motions of those stars in the Tycho-2 catalog which are in the Helsinki's region of the Carte du Ciel survey are based on the section of the Astrographic Catalogue survey which was realised at Helsinki. If those Astrographic Catalogue plates were taken at the same coordinates as the plates of the Carte du Ciel survey, the same stars have the same biases in both of the surveys. We believe that the most important bias is that within the large, elongated stellar profiles there are dimmer, unseen stars which move the photo-center of the star seen on a plate. Then, this bias affected the positions of the stars, derived from the plates by hand with a measuring machine, and the erroneous positions affected the proper motions in the Tycho-2 catalog. Thus, the astrometry of a Carte du Ciel plate, especially at the corners, can be better fitted using Tycho-2 reference stars than Gaia reference stars. However, this explanation requires that SExtractor, the program used to derive the star positions on our digital images, is affected by the distortions in the same way than the measuring machines that were used to measure visually star positions on glass plates. This requires further investigation.

Currently, none of the available digital cameras on market has enough pixels so that a whole Carte du Ciel plate could be imaged at once with good enough resolution (arcsecond per pixel). Therefore, one has to digitize a plate by taking several, preferably partly overlapping, images. Because the positioning of a plate during imaging has to be done manually, the process has to be simple so that one can digitize hundreds of plates within a reasonable time. In practice, a 2 by 2 mosaic is the largest mosaic which is easily handled. One way to do the imaging is the one shown in Fig. 20. It remains to be studied which method gives better results; smaller pixel scale and thus less overlapping between images, or larger pixel scale and thus more overlapping between images.

Vicente et al. [7] have digitized Carte du Ciel plates with a flatbed scanner. Analysis of such data requires complicated techniques to correct for the large and non-constant distortions introduced by a scanner. They give a value of 0.2” for mean positional uncertainty. To compare the positional accuracy obtained by Vicente et al. with our results, we need to quote their values for 'reference star residuals of Carte du Ciel catalogue based on a comparison with the Tycho-2 positions at the epoch of the plates', 0.22” and 0.24” along right ascension and declination, respectively (their Fig. 8). We can reach somewhat better residual, ~0.21”, without any corrections for the data outside SCAMP, which models the plate distortions. Thus we believe that our data, produced with a digital camera, is more accurate, but also more reliable than data produced with a scanner because our data is free of complicated data analysis which may introduce artifacts to the data.

Acknowledgements. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

In Memoriam: Tapio Markkanen passed away on August 28, 2017. He had a central role in initiating this project. In his report from a group meeting ”Call for Participation in Plate Archive Digitization and Preservation” (Babelsberg, Germany, 2009) he pointed out the importance of comparing the coordinates and magnitudes of stars on the Carte du Ciel plates with the coordinates and magnitudes measured by the Gaia satellite. Tapio's wide knowledge of history of astronomy, including the Carte du Ciel survey, was essential for this project.

References

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Appendix A. The configuration parameters for SExtractor.

```
# Default configuration file for SExtractor 2.19.5
# EB 2014-03-19
#

#-------------------------------- Catalog ------------------------------------

CATALOG_NAME     cduc-1-NoGrid.resamp-WCS.ldac   # name of the output catalog
FLAG_IMAGE       cduc-1-flag.resamp.fits

CATALOG_TYPE     FITS_LDAC   # NONE,ASCII,ASCII_HEAD, ASCII_SKYCAT,
                             # ASCII_VOTABLE, FITS_1.0 or FITS_LDAC

PARAMETERS_NAME  default.param  # name of the file containing catalog contents

#------------------------------- Extraction ----------------------------------

DETECT_TYPE      CCD            # CCD (linear) or PHOTO (with gamma correction)
DETECT_MINAREA   9              # min. # of pixels above threshold
DETECT_MAXAREA   2500           # max. # of pixels above threshold (0=unlimited)
THRESH_TYPE      RELATIVE       # threshold type: RELATIVE (in sigmas)
                                # or ABSOLUTE (in ADUs)
DETECT_THRESH    3.0            # <sigmas> or <threshold>,<ZP> in mag.arcsec-2
ANALYSIS_THRESH  3.0            # <sigmas> or <threshold>,<ZP> in mag.arcsec-2

FILTER           Y              # apply filter for detection (Y or N)?
FILTER_NAME      gauss_5.0_9x9.conv   # name of the file containing the filter

FILTER_THRESH                   # Threshold[s] for retina filtering

DEBLEND_NTHRESH  32             # Number of deblending sub-thresholds
DEBLEND_MINCONT  0.005          # Minimum contrast parameter for deblending

CLEAN            Y              # Clean spurious detections? (Y or N)?
CLEAN_PARAM      1.0            # Cleaning efficiency

MASK_TYPE        CORRECT        # type of detection MASKing: can be one of
                                # NONE, BLANK or CORRECT

#-------------------------------- WEIGHTing ----------------------------------

WEIGHT_TYPE      NONE           # type of WEIGHTing: NONE, BACKGROUND,
                                # MAP_RMS, MAP_VAR or MAP_WEIGHT
RESCALE_WEIGHTS  Y              # Rescale input weights/variances (Y/N)?
WEIGHT_IMAGE     weight.fits    # weight-map filename
WEIGHT_GAIN      Y              # modulate gain (E/ADU) with weights? (Y/N)
WEIGHT_THRESH                   # weight threshold[s] for bad pixels

#-------------------------------- FLAGging -----------------------------------
```

```
FLAG_TYPE       OR          # flag pixel combination: OR, AND, MIN, MAX
                            # or MOST

#------------------------------ Photometry -----------------------------------

PHOT_APERTURES   5           # MAG_APER aperture diameter(s) in pixels
PHOT_AUTOPARAMS  1.5, 1.5      # MAG_AUTO parameters: <Kron_fact>,<min_radius>
PHOT_PETROPARAMS 2.0, 3.5      # MAG_PETRO parameters: <Petrosian_fact>,
                            # <min_radius>
PHOT_AUTOAPERS   0.0,0.0       # <estimation>,<measurement> minimum apertures
                            # for MAG_AUTO and MAG_PETRO
PHOT_FLUXFRAC    0.5          # flux fraction[s] used for FLUX_RADIUS

SATUR_LEVEL      500000.0       # level (in ADUs) at which arises saturation
SATUR_KEY       SATURATE       # keyword for saturation level (in ADUs)

MAG_ZEROPOINT    0.0          # magnitude zero-point
MAG_GAMMA       1.0          # gamma of emulsion (for photographic scans)
GAIN            1.0          # detector gain in e-/ADU
GAIN_KEY        GAIN         # keyword for detector gain in e-/ADU
PIXEL_SCALE       1.0          # size of pixel in arcsec (0=use FITS WCS info)

#------------------------- Star/Galaxy Separation ----------------------------

SEEING_FWHM      10.0          # stellar FWHM in arcsec
STARNNW_NAME     default.nnw    # Neural-Network_Weight table filename

#------------------------------ Background -----------------------------------

BACK_TYPE       AUTO          # AUTO or MANUAL
BACK_VALUE       0.0          # Default background value in MANUAL mode
BACK_SIZE       64           # Background mesh: <size> or <width>,<height>
BACK_FILTERSIZE  1            # Background filter: <size> or <width>,<height>

BACKPHOTO_TYPE   GLOBAL        # can be GLOBAL or LOCAL
BACKPHOTO_THICK  24           # thickness of the background LOCAL annulus
BACK_FILTTHRESH  0.0          # Threshold above which the background-
                            # map filter operates

#------------------------------ Check Image ----------------------------------

CHECKIMAGE_TYPE   OBJECTS      # can be NONE, BACKGROUND,
BACKGROUND_RMS,
                            # MINIBACKGROUND, MINIBACK_RMS, -BACKGROUND,
                            # FILTERED, OBJECTS, -OBJECTS, SEGMENTATION,
                            # or APERTURES
CHECKIMAGE_NAME  check.fits     # Filename for the check-image

#--------------------- Memory (change with caution!) -------------------------

MEMORY_OBJSTACK  6000         # number of objects in stack
```

```
MEMORY_PIXSTACK  600000        # number of pixels in stack
MEMORY_BUFSIZE   2048          # number of lines in buffer

#------------------------------- ASSOCiation ---------------------------------

ASSOC_NAME       sky.list       # name of the ASCII file to ASSOCiate
ASSOC_DATA       2,3,4          # columns of the data to replicate (0=all)
ASSOC_PARAMS     2,3,4          # columns of xpos,ypos[,mag]
ASSOCCOORD_TYPE  PIXEL          # ASSOC coordinates: PIXEL or WORLD
ASSOC_RADIUS     2.0            # cross-matching radius (pixels)
ASSOC_TYPE       NEAREST        # ASSOCiation method: FIRST, NEAREST, MEAN,
                                # MAG_MEAN, SUM, MAG_SUM, MIN or MAX
ASSOCSELEC_TYPE  MATCHED        # ASSOC selection type: ALL, MATCHED or
-MATCHED

#----------------------------- Miscellaneous ---------------------------------

VERBOSE_TYPE     FULL           # can be QUIET, NORMAL or FULL
HEADER_SUFFIX    .head          # Filename extension for additional headers
WRITE_XML        N              # Write XML file (Y/N)?
XML_NAME         sex.xml        # Filename for XML output
XSL_URL          file:///usr/share/sextractor/sextractor.xsl
                                # Filename for XSL style-sheet
NTHREADS         1              # 1 single thread

FITS_UNSIGNED    N              # Treat FITS integer values as unsigned (Y/N)?
INTERP_MAXXLAG   16             # Max. lag along X for 0-weight interpolation
INTERP_MAXYLAG   16             # Max. lag along Y for 0-weight interpolation
INTERP_TYPE      ALL            # Interpolation type: NONE, VAR_ONLY or ALL

#--------------------------- Experimental Stuff -----------------------------

PSF_NAME         default.psf    # File containing the PSF model
PSF_NMAX         1              # Max.number of PSFs fitted simultaneously
PATTERN_TYPE     RINGS-HARMONIC # can RINGS-QUADPOLE, RINGS-OCTOPOLE,
                                # RINGS-HARMONICS or GAUSS-LAGUERRE
SOM_NAME         default.som    # File containing Self-Organizing Map weights
```

Appendix B. The configuration parameters for SCAMP.

```
# Default configuration file for SCAMP 2.0.4
# EB 2014-07-09
#

#---------------------------- Field grouping ---------------------------------

FGROUP_RADIUS          10.0            # Max dist (deg) between field groups

#---------------------------- Reference catalogs ------------------------------

REF_SERVER         cocat1.u-strasbg.fr # Internet addresses of catalog servers
ASTREF_CATALOG       FILE             # NONE, FILE, USNO-A1,USNO-A2,USNO-B1,
                                      # GSC-1.3,GSC-2.2,GSC-2.3,
                                      # TYCHO-2, UCAC-1,UCAC-2,UCAC-3,UCAC-4,
                                      # NOMAD-1, PPMX, CMC-14, 2MASS, DENIS-3,
                                      # SDSS-R3,SDSS-R5,SDSS-R6,SDSS-R7,
                                      # SDSS-R8, SDSS-R9

ASTREFCAT_NAME       /home/kimmo/CduC/Gaia_1900_Hesa_ldac.cat
# ASTREFCAT_NAME         StellarField_ldac.cat

ASTREFCENT_KEYS      alpha, delta
ASTREFERR_KEYS       e_alpha, e_delta
ASTREFMAG_KEY        Mag
ASTREFMAGERR_KEY     e_Mag
# ASTREFOBSDATE_KEY      MJD-OBS        # Local ref.cat. obs. date parameter

ASTREF_BAND           DEFAULT        # Photom. band for astr.ref.magnitudes
                                      # or DEFAULT, BLUEST, or REDDEST
ASTREFMAG_LIMITS       -99.0,99.0      # Select magnitude range in ASTREF_BAND
SAVE_REFCATALOG        N              # Save ref catalogs in FITS-LDAC format?
REFOUT_CATPATH         .              # Save path for reference catalogs


#--------------------------- Merged output catalogs ---------------------------

MERGEDOUTCAT_TYPE      ASCII_HEAD          # NONE, ASCII_HEAD, ASCII,
FITS_LDAC
MERGEDOUTCAT_NAME      merged.cat      # Merged output catalog filename

#--------------------------- Full output catalogs ---------------------------

FULLOUTCAT_TYPE       ASCII_HEAD          # NONE, ASCII_HEAD, ASCII, FITS_LDAC
FULLOUTCAT_NAME       full-plate-1.cat       # Full output catalog filename

#---------------------------- Pattern matching ------------------------------

MATCH                Y              # Do pattern-matching (Y/N) ?
MATCH_NMAX           0              # Max.number of detections for MATCHing
                                      # (0=auto)
```

PIXSCALE_MAXERR 2.0 # Max scale-factor uncertainty
POSANGLE_MAXERR 45.0 # Max position-angle uncertainty (deg)
POSITION_MAXERR 40.0 # Max positional uncertainty (arcmin)
MATCH_RESOL 0 # Matching resolution (arcsec); 0=auto
MATCH_FLIPPED N # Allow matching with flipped axes?
MOSAIC_TYPE UNCHANGED # UNCHANGED, SAME_CRVAL,
SHARE_PROJAXIS,
FIX_FOCALPLANE or LOOSE

#---------------------------- Cross-identification ----------------------------

CROSSID_RADIUS 2.0 # Cross-id initial radius (arcsec)

#---------------------------- Astrometric solution ----------------------------

SOLVE_ASTROM Y # Compute astrometric solution (Y/N) ?
PROJECTION_TYPE SAME # SAME, TPV or TAN
ASTRINSTRU_KEY FILTER,QRUNID # FITS keyword(s) defining the astrom
STABILITY_TYPE INSTRUMENT # EXPOSURE, PRE-DISTORTED or INSTRUMENT
CENTROID_KEYS XWIN_IMAGE,YWIN_IMAGE # Cat. parameters for centroiding
CENTROIDERR_KEYS ERRAWIN_IMAGE,ERRBWIN_IMAGE,ERRTHETAWIN_IMAGE
Cat. params for centroid err ellipse
DISTORT_KEYS XWIN_IMAGE,YWIN_IMAGE # Cat. parameters or FITS keywords
DISTORT_GROUPS 1,1 # Polynom group for each context key
DISTORT_DEGREES 4 # Polynom degree for each group
ASTRCLIP_NSIGMA 3.0

COMPUTE_PROPERMOTIONS N
INCLUDE_ASTREFCATALOG N # Include ref.cat in prop.motions (Y/N)?

ASTREF_WEIGHT 1.0

#---------------------------- Photometric solution ----------------------------

SOLVE_PHOTOM N # Compute photometric solution (Y/N) ?
MAGZERO_OUT 0.0 # Magnitude zero-point(s) in output
MAGZERO_INTERR 0.01 # Internal mag.zero-point accuracy
MAGZERO_REFERR 0.03 # Photom.field mag.zero-point accuracy
PHOTINSTRU_KEY FILTER # FITS keyword(s) defining the photom.
MAGZERO_KEY PHOT_C # FITS keyword for the mag zero-point
EXPOTIME_KEY EXPTIME # FITS keyword for the exposure time (s)
AIRMASS_KEY AIRMASS # FITS keyword for the airmass
EXTINCT_KEY PHOT_K # FITS keyword for the extinction coeff
PHOTOMFLAG_KEY PHOTFLAG # FITS keyword for the photometry flag
PHOTFLUX_KEY FLUX_AUTO # ISOAREA_IMAGE # Catalog param. for the flux
measurement
PHOTFLUXERR_KEY FLUXERR_AUTO # Catalog parameter for the flux error

#------------------------------- Check-plots ----------------------------------

CHECKPLOT_DEV PSC # NULL, XWIN, TK, PS, PSC, XFIG, PNG,
JPEG, AQT, PDF or SVG

```
CHECKPLOT_TYPE
FGROUPS,DISTORTION,ASTR_INTERROR2D,ASTR_INTERROR1D,ASTR_REFERROR2D,
ASTR_REFERROR1D,ASTR_CHI2,PHOT_ERROR
CHECKPLOT_NAME
fgroups,distort,astr_interror2d,astr_interror1d,astr_referror2d,astr_referror1d,astr_chi2,psphot_error
# Check-plot filename(s)

#------------------------------ Miscellaneous ---------------------------------

SN_THRESHOLDS       3.0, 100.0    # S/N thresholds (in sigmas) for all and
                                  # high-SN sample
FWHM_THRESHOLDS     0.0,100.0     # FWHM thresholds (in pixels) for sources

FLAGS_MASK          255           # Rejection mask on SEx FLAGS
# WEIGHTFLAGS_MASK    0x00ff        # Rejection mask on SEx FLAGS_WEIGHT
IMAFLAGS_MASK       255           # Rejection mask on SEx IMAFLAGS_ISO

AHEADER_SUFFIX      .ahead        # Filename extension for additional
                                  # INPUT headers
AHEADER_GLOBAL      scamp.ahead
HEADER_SUFFIX       .head         # Filename extension for OUTPUT headers
VERBOSE_TYPE        NORMAL        # QUIET, NORMAL, LOG or FULL
WRITE_XML           Y             # Write XML file (Y/N)?
XML_NAME            scamp.xml     # Filename for XML output
NTHREADS            0             # Number of simultaneous threads for
                                  # the SMP version of SCAMP
                                  # 0 = automatic
```

Appendix C. The configuration parameters for Swarp.

```
# Default configuration file for SWarp 2.19.1
# EB 2013-11-23
#
#---------------------------------- Output ----------------------------------
IMAGEOUT_NAME         coadd.fits      # Output filename
WEIGHTOUT_NAME        coadd.weight.fits # Output weight-map filename

HEADER_ONLY           N               # Only a header as an output file (Y/N)?
HEADER_SUFFIX         .head           # Filename extension for additional headers

#------------------------------- Input Weights --------------------------------

WEIGHT_TYPE           NONE            # BACKGROUND,MAP_RMS,MAP_VARIANCE
                      # or MAP_WEIGHT
WEIGHT_SUFFIX         .weight.fits    # Suffix to use for weight-maps
WEIGHT_IMAGE                          # Weightmap filename if suffix not used
                      # (all or for each weight-map)

#------------------------------- Co-addition ----------------------------------

COMBINE               Y               # Combine resampled images (Y/N)?
COMBINE_TYPE          MEDIAN          # MEDIAN,AVERAGE,MIN,MAX,WEIGHTED,CHI2
                      # or SUM

#-------------------------------- Astrometry ----------------------------------

CELESTIAL_TYPE        EQUATORIAL      # NATIVE, PIXEL, EQUATORIAL,
                      # GALACTIC,ECLIPTIC, or SUPERGALACTIC
PROJECTION_TYPE       TAN             # Any WCS projection code or NONE
PROJECTION_ERR        0.001           # Maximum projection error (in output
                      # pixels), or 0 for no approximation
CENTER_TYPE           ALL             # MANUAL, ALL or MOST
CENTER        00:00:00.0, +00:00:00.0 # Coordinates of the image center
PIXELSCALE_TYPE       FIT             # MANUAL,FIT,MIN,MAX or MEDIAN
PIXEL_SCALE           0.7             # Pixel scale
IMAGE_SIZE            9000,6000       # Image size (0 = AUTOMATIC)

#-------------------------------- Resampling ----------------------------------

RESAMPLE              Y               # Resample input images (Y/N)?
RESAMPLE_DIR          .               # Directory path for resampled images
RESAMPLE_SUFFIX       .resamp.fits    # filename extension for resampled images

RESAMPLING_TYPE       LANCZOS3        # NEAREST,BILINEAR,LANCZOS2,LANCZOS3
                      # or LANCZOS4 (1 per axis)
OVERSAMPLING          0               # Oversampling in each dimension
                      # (0 = automatic)
INTERPOLATE           N               # Interpolate bad input pixels (Y/N)?
                      # (all or for each image)
```

```
FSCALASTRO_TYPE       FIXED         # NONE,FIXED, or VARIABLE
FSCALE_KEYWORD        FLXSCALE      # FITS keyword for the multiplicative
                                    # factor applied to each input image
FSCALE_DEFAULT        1.0           # Default FSCALE value if not in header

GAIN_KEYWORD          GAIN          # FITS keyword for effect. gain (e-/ADU)
GAIN_DEFAULT          0.0           # Default gain if no FITS keyword found

#--------------------------- Background subtraction ---------------------------

SUBTRACT_BACK         N             # Subtraction sky background (Y/N)?
                                    # (all or for each image)

BACK_TYPE             AUTO          # AUTO or MANUAL
                                    # (all or for each image)
BACK_DEFAULT          0.0           # Default background value in MANUAL
                                    # (all or for each image)
BACK_SIZE             128           # Background mesh size (pixels)
                                    # (all or for each image)
BACK_FILTERSIZE       3             # Background map filter range (meshes)
                                    # (all or for each image)

#------------------------------ Memory management -----------------------------

VMEM_DIR              .             # Directory path for swap files
VMEM_MAX              2047          # Maximum amount of virtual memory (MB)
MEM_MAX               256           # Maximum amount of usable RAM (MB)
COMBINE_BUFSIZE       256           # RAM dedicated to co-addition(MB)

#------------------------------ Miscellaneous ---------------------------------

DELETE_TMPFILES       Y             # Delete temporary resampled FITS files
                                    # (Y/N)?
COPY_KEYWORDS         OBJECT        # List of FITS keywords to propagate
                                    # from the input to the output headers
WRITE_FILEINFO        N             # Write information about each input
                                    # file in the output image header?
WRITE_XML             Y             # Write XML file (Y/N)?
XML_NAME              swarp.xml     # Filename for XML output
VERBOSE_TYPE          NORMAL        # QUIET,NORMAL or FULL

NTHREADS              0             # Number of simultaneous threads for
                                    # the SMP version of SWarp
                                    # 0 = automatic
```

Appendix D. An example of a header file produced by SCAMP.

```
HISTORY   Astrometric solution by SCAMP version 2.0.4 (2016-05-11)
COMMENT   (c) 2010-2013 IAP/CNRS/UPMC
COMMENT
EQUINOX =        2000.00000000 / Mean equinox
RADESYS = 'ICRS    '           / Astrometric system
CTYPE1  = 'RA---TAN'           / WCS projection type for this axis
CTYPE2  = 'DEC--TAN'           / WCS projection type for this axis
CUNIT1  = 'deg     '           / Axis unit
CUNIT2  = 'deg     '           / Axis unit
CRVAL1  =   9.210773210248E-04 / World coordinate on this axis
CRVAL2  =   1.113289610851E-04 / World coordinate on this axis
CRPIX1  =   4.300000000000E+03 / Reference pixel on this axis
CRPIX2  =   2.900000000000E+03 / Reference pixel on this axis
CD1_1   =  -2.442920305476E-06 / Linear projection matrix
CD1_2   =   9.543673356062E-09 / Linear projection matrix
CD2_1   =   9.543673356062E-09 / Linear projection matrix
CD2_2   =   2.442920305476E-06 / Linear projection matrix
PV1_0   =  -3.149556166061E-05 / Projection distortion parameter
PV1_1   =   1.001363443070E+00 / Projection distortion parameter
PV1_2   =   5.782679748151E-04 / Projection distortion parameter
PV1_4   =   1.549290027844E-01 / Projection distortion parameter
PV1_5   =   5.337351248089E-03 / Projection distortion parameter
PV1_6   =  -5.521191068008E-02 / Projection distortion parameter
PV1_7   =  -1.787180497903E+01 / Projection distortion parameter
PV1_8   =  -4.148942877694E-01 / Projection distortion parameter
PV1_9   =   4.302321311170E+00 / Projection distortion parameter
PV1_10  =  -2.054224335468E+00 / Projection distortion parameter
PV1_12  =  -4.403186808508E+02 / Projection distortion parameter
PV1_13  =  -1.808880329688E+02 / Projection distortion parameter
PV1_14  =   1.750056911542E+02 / Projection distortion parameter
PV1_15  =   1.822039155587E+01 / Projection distortion parameter
PV1_16  =   2.523598576524E+02 / Projection distortion parameter
PV2_0   =  -3.614688487793E-06 / Projection distortion parameter
PV2_1   =   9.985580826347E-01 / Projection distortion parameter
PV2_2   =   1.368453738566E-04 / Projection distortion parameter
PV2_4   =   2.791165516159E-02 / Projection distortion parameter
PV2_5   =   1.720180659194E-01 / Projection distortion parameter
PV2_6   =   5.605328337602E-03 / Projection distortion parameter
PV2_7   =   3.692447331287E+00 / Projection distortion parameter
PV2_8   =   1.269181068185E+00 / Projection distortion parameter
PV2_9   =   1.844375368566E+00 / Projection distortion parameter
PV2_10  =  -2.965965583546E+00 / Projection distortion parameter
PV2_12  =  -4.754555223815E+02 / Projection distortion parameter
PV2_13  =  -3.737787758783E+01 / Projection distortion parameter
PV2_14  =  -4.651741037542E+01 / Projection distortion parameter
PV2_15  =  -1.055196351254E+02 / Projection distortion parameter
PV2_16  =  -2.692672327631E+02 / Projection distortion parameter
FGROUPNO=                    1 / SCAMP field group label
ASTIRMS1=   6.654594326021E-07 / Astrom. dispersion RMS (intern., high S/N)
ASTIRMS2=   3.485937935371E-07 / Astrom. dispersion RMS (intern., high S/N)
```

```
ASTRRMS1=   2.136776979259E-06 / Astrom. dispersion RMS (ref., high S/N)
ASTRRMS2=   2.066185903942E-06 / Astrom. dispersion RMS (ref., high S/N)
ASTINST =                    1 / SCAMP astrometric instrument label
FLXSCALE=   0.000000000000E+00 / SCAMP relative flux scale
MAGZEROP=           0.00000000 / SCAMP zero-point
PHOTIRMS=           0.07715588 / mag dispersion RMS (internal, high S/N)
PHOTINST=                    1 / SCAMP photometric instrument label
PHOTLINK=                    F / True if linked to a photometric field
END
```

Appendix E. The Python script used to fit an asterism of a triple exposure plate with the sum of three elliptical Gaussian.

```
from astropy.io import fits
import scipy.optimize as opt
import matplotlib.pyplot as plt
import numpy as np

hdulist = fits.open('plate-1.fits')
data = hdulist[0].data

ys = 2824
xs = 5592
sub = data[ys:ys+60,xs:xs+60]
ydata = sub.ravel()

#define model function and pass independent variables x and y as a list
def TripleGaussian((x,y), amplitude, sigma_x, sigma_y, s, t, xc1, xc2, xc3, yc1, yc2, yc3,
background):
    gauss1 = np.exp( -0.5 * ( (1.0/(1.0-t**2)) * ( ((x-xc1)/sigma_x)**2 + ((y-yc1)/sigma_y)**2 - \
    2.0 * t * ( ((x-xc1)/sigma_x) * ((y-yc1)/sigma_y) ) ) )**s )
    gauss2 = np.exp( -0.5 * ( (1.0/(1.0-t**2)) * ( ((x-xc2)/sigma_x)**2 + ((y-yc2)/sigma_y)**2 - \
    2.0 * t * ( ((x-xc2)/sigma_x) * ((y-yc2)/sigma_y) ) ) )**s )
    gauss3 = np.exp( -0.5 * ( (1.0/(1.0-t**2)) * ( ((x-xc3)/sigma_x)**2 + ((y-yc3)/sigma_y)**2 - \
    2.0 * t * ( ((x-xc3)/sigma_x) * ((y-yc3)/sigma_y) ) ) )**s )
    g = background + amplitude*(gauss1 + gauss2 + gauss3)
    return g.ravel()

# Create x and y indices
x = np.linspace(0, 59, 60)
y = np.linspace(0, 59, 60)
x,y = np.meshgrid(x, y)
xdata = np.vstack((x.ravel(),y.ravel()))

initial_guess = (50000.0, 5.0, 5.0, 1.0, 0.1, 25, 25, 40, 21, 41, 30, 15000.0)

# make the fit
param_bounds = ([ 10.0,  1.0,  1.0, 0.01, 0.0, 15, 15, 30, 10, 30, 20,   1.0],
                [1.0E6, 20.0, 20.0, 10.0, 0.9, 35, 35, 50, 30, 50, 40, 1.0E6])

popt, pcov = opt.curve_fit( TripleGaussian, xdata, ydata, p0 = initial_guess,
     bounds = param_bounds )

data_fitted = TripleGaussian((x, y), *popt)

# lasketaan parametrien virheet pcov taulukosta
perr = np.sqrt(np.diag(pcov))
print 'Parametrit ovat amplitude, sigma_x, sigma_y, s, t, xc1, xc2, xc3, yc1, yc2, yc3, background.'
print 'Niidet arvot ovat:'
print popt
print 'ja niiden virheet (one standard deviation) ovat:'
```

```
print perr

plt.subplot(1, 2, 1)
plt.imshow(sub, origin='lower', interpolation='nearest')
plt.title("Image")
plt.contour(x, y, data_fitted.reshape(60, 60), 8, colors='w')
plt.subplot(1, 2, 2)
plt.imshow(sub - data_fitted.reshape(60, 60), origin='lower', interpolation='nearest')
plt.title("Residual")
plt.show()
```