Astrometry from CCD Images

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Abstract

Astrometry is used to measure properties of celestial objects such as their position on the sky, their movement and their velocities. In this experiment, we used a charged coupled device(CCD). The CCD used mapped the sky on 2D plane. Observations were made using the Dunlap Institute Telescope located in New Mexico, United States. The object of interest for this experiment is 30 Urania which is an asteroid. We will measure the plate constants of the CCD using a data collection of stars field in order to correct for the sheerness of the CCD pixels and then we apply it to the data from 30 Urania over the course of three nights to measure the velocity of this asteroid.

1 Introduction

Nowadays, we are able to use computers to do astrometry in order to obtain position and motion of objects in the sky. In this experiment, we identify centroids of the stellar sources and use these centroids to compare and match with the stars found from USNO-B1.0 catalog. Then, we use least square fitting in order to find six constants named plate constants of the CCD which is responsible for the sheer and disorientation of the CCD pixels. We finally use SAOImage DS9 software to detect the asteroid 30 Urania and using these plate constants we figure out the position of the asteroid in celestial coordinates and use these data to calculate the velocity and proper motion of this asteroid through the sky.

2 Experimental Procedure

2.1 Equipment

We used the Dunlap Institute Telescope(DIT) which is a 50-cm robotic telescope dedicated to search for optical counterparts of gamma-ray bursts. The telescope was located at New Mexico on Mt. Joy(32:54:10 N +105:31:46 W). The telescope is equipped with a 4096×4096 pixel CCD array and the resultant field of view is approximately 36×36 arc minutes. Pixel size of this CCD is 9μ. This CCD operated in binning mode to collect the data. Binning is useful since it reduces the size of the resultant FITS file and reduces the effect of read-out noise. For 2×2 binning the resultant array is 2048×2048 pixels.

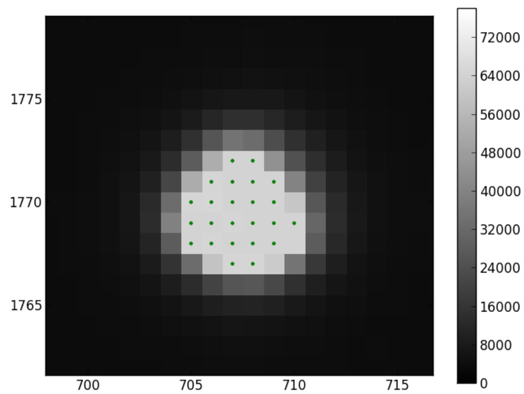
3 Analysis

3.1 CCD Calibration

In order to have good images from the CCD we need to calibrate it. A good image is one that is dark subtracted and divided by flat frames. Therefore, in order to use the data from the CCD, we subtracted the dark data from the actual data. Dark data was taken with the same exposure time as the actual data while the shutter was closed. Dark current is produced due to the noise in the CCD and it might come from the thermal energy of the electrons; therefore, CCDs are kept in cool places in order to reduce the noise. We also divide the dark subtracted data by the flat frames. Flats are morning and evening twilight sky images that are used to normalize the image. Another factor to consider are the bias frames, which are zero second exposures that provide a measure of digital offset when the signal is zero. Here, the bias is assumed to be zero for this long exposure with DIT.

3.2 Detection of Stars

Next step is to find the stars from the CCD image of NGC7331 taken with DIT. The way we did it was to write a python program to check all of the pixels and find the ones that have intensity higher than a specific number, which for me was higher than 20000 ADU. It considered each pixel and then compared it with the pixel on the left, right, bottom and top of it and if it had higher intensity, considered it as a maxima point.This way the program found all of the maxima points; however, there was a problem. For the larger stars, the code put more than one dot on the object since the object consisted of more than one pixel and the code put dots on each of the pixels of the star. Therefore, we need to find the centroids of these maxima points in order for the code to only point to the centroid of the stars and to put only one dot on each star. In order to calculate the centroids, we modified the code so that now it only takes the maxima points and considers a small box around each of the stars and for the maxima points in the specified box finds the centroids. This way we would only have one dot pointing to each star instead of a few. This is shown in figure 1. Figure 2 shows the star centroid, which is only one dot assigned to the star unlike the maxima points that a few points were assigned to each star depending on their intensities.



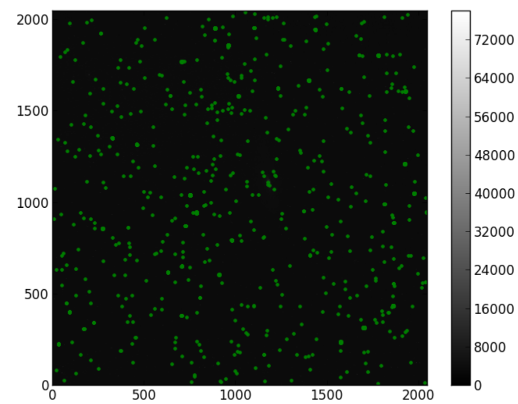


Figure 1: The image on the right shows the maxima points that correspond to the pixels that have intensities higher than 20000 ADU. The image on the left is a random zoomed in part of the right hand side plot in order to show that some of the dots shown on the right image are actually more than one dot. Therefore, we need to find the centroids in order to eliminate the extra dots for one star and only assign one dot to each star.

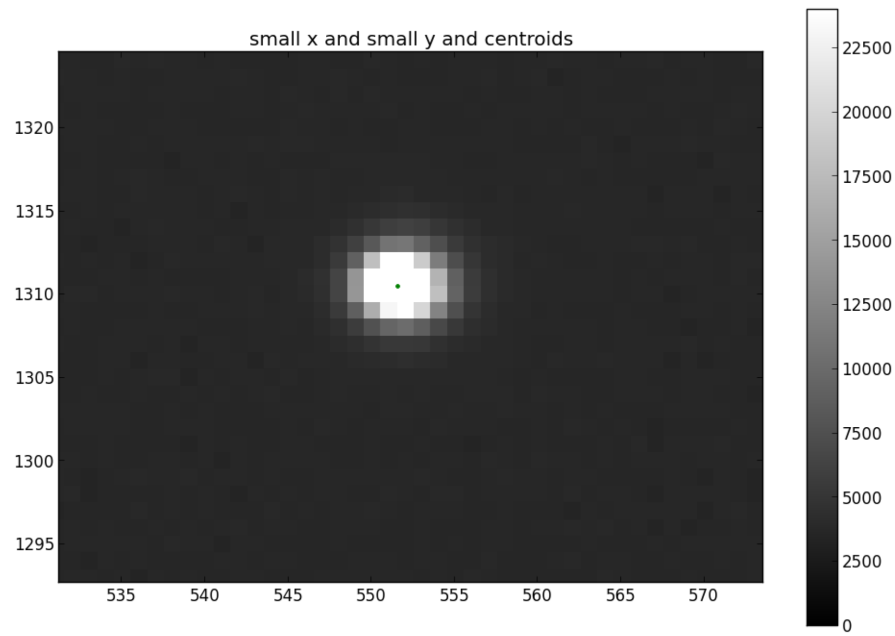


Figure 2: Centroids of the Stars on CCD. This figure shows the centroid of the stars and assigns only one dot to each star unlike the maxima points which a few dots were assigned to each star. The colorer shows the intensity of the plot with black pixels having zero intensity.

3.3 Matching Stars and Standard Coordinates

We need to see if the centroids we found are actually stars; therefore, we used our centroids with an image of NGC7331 from USNO-B1.0 Catalog which is the US Naval Observatory. The USNO-B1.0 catalog lists positions, proper motions and magnitudes in various optical bands over the entire sky. The data are from scans of photographic plates from the Palomar 48-inch Schmidth taken during the last 50 years. This catalog provides all-sky coverage down about magnitude 21 and astrometric accuracy of 0.2 arc second at J2000 and is adequate for the purpose of this experiment. Figure 2 shows NGC7331 from USNO catalog.

We now have the position of the observed stars from the CCD in pixel x and y and in right ascension and declination from the USNO-B1.0 Catalog. The USNO-B1.0 coordinates are on the celestial sphere, whereas the stars in the CCD image are on a plane, which is the projection of the celestial sphere. Therefore, we need to compare the stars we found with the ones in the catalog. As a result, we need to have a common coordinate system and in order to do so, we need to transform the celestial sphere coordinates of the catalog into plane

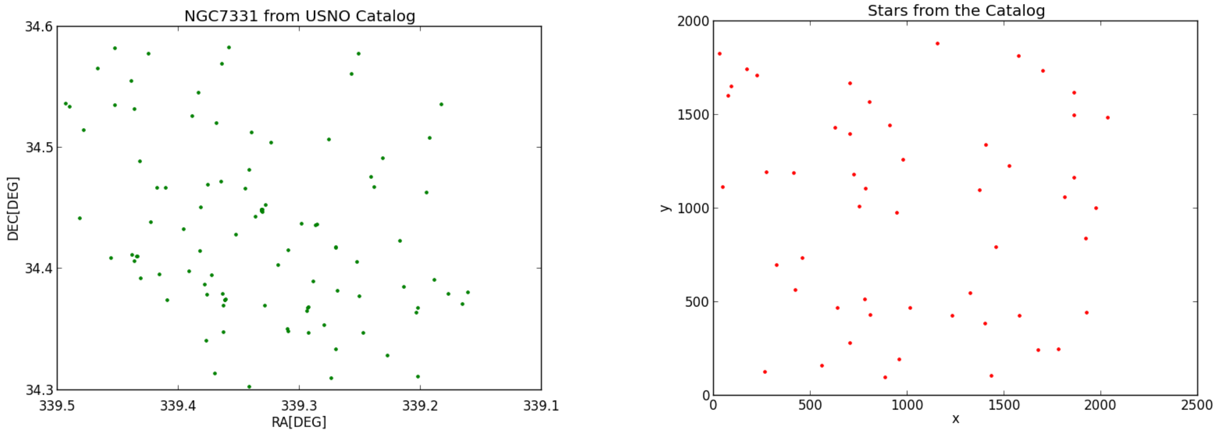


Figure 3: Right.The catalog position of USNO-B1.0 catalog stars within 30 $\times$ 30 arc minute square field centred at the positions of NGC7331(RA = 339°.325 ; DEC = 34°.444 at apoch J2000) in sky co-ordinates. Only stars with magnitude greater than 13 are plotted. Left. The position of catalog stars in x and y pixels

coordinates, in other words, into pixels. The transformation formulae are given below:

$$X = -\frac{\cos\delta\sin(\alpha-\alpha_0)}{\cos\delta_0\cos\delta\cos(\alpha-\alpha_0)+\sin(\delta)\sin\delta_0} \tag{1}$$

$$Y = -\frac{\sin\delta_0\cos\delta\cos(\alpha-\alpha_0)-\cos\delta_0\sin\delta}{\cos\delta_0\cos\delta\cos(\alpha-\alpha_0)+\sin\delta\sin\delta_0} \tag{2}$$

The values of α_0 and δ_0 are given in the usno catalog. The values we used for α_0 and δ_0 are 5.922338484329758 radians and 0.60115442016539133 radians, respectively. The conversion from (X, Y) coordinates to pixel coordinates (x,y) is straightforward. If f is the focal length of the camera and p is the pixel size, then for an ideal camera we have:

$$x = f(\frac{X}{p}) + x_0 \tag{3}$$

$$y = f(\frac{Y}{p}) + y_0 \tag{4}$$

However, we know that the CCD is not ideal which means that the focal length of the imaging system might not be constant over the field, there might be anamorphic magnification($f_x \neq f_y$) or the CCD might not be oriented in an ideal way(the X-axis might not lie along the declination small circle.) Here we considered the CCD to be ideal as a first guess. f=3435 mm and p=0.018 because of the binning of the pixel points. One way to match the stars from the catalog with the ones we found from CCD is to consider a box with a certain radius(we used 15 pixels) and find the difference between the points from catalog and the centroid points we found and take the two stars with the smallest distance to be match up of each other. The result of this is shown in figure 4. As it is seen, the stars from USNO catalog almost perfectly match up with the centroids found from the CCD. In general the Ccd is not ideal so we need to take into consideration the effect of a non-ideal CCD. Therefore,the relation between (x,y) coordinates with (X, Y) becomes:

$$x = \frac{f}{p}(X \sin\theta - Y \cos\theta) + x_0$$

(5)

$$y = \frac{f}{p}(X \cos\theta - Y \sin\theta) + y_0$$

(6)

Therefore, we can form a matrix multiplication where X=$(X, Y, 1)$, x=$(x, y, 1)$:

x=TX where

$$T = \begin{pmatrix} (\frac{f}{p})a_{11} & (\frac{f}{p})a_{12} & x_0 \\ (\frac{f}{p})a_{21} & (\frac{f}{p})a_{22} & y_0 \\ 0 & 0 & 1 \end{pmatrix} \tag{7}$$

Thus, there are six unknowns, known as plate constants which we can find using linear least square. The constant a_{ij} refer to the scale, shear and orientation of the image, and x_0 and y_0 are pointing offsets in pixels. In order to find the solution to the least-square we can form the equation a=Bc, where for x we have:

$$a = \begin{pmatrix} x_1 \\ x_2 \\ x_N \end{pmatrix} \tag{8}$$

$$B = \begin{pmatrix} (\frac{f}{p})X_1 & (\frac{f}{p})Y_1 & 1 \\ (\frac{f}{p})X_2 & (\frac{f}{p})Y_2 & 1 \\ \vdots & \vdots & \vdots \\ (\frac{f}{p})X_N & (\frac{f}{p})Y_N & 1 \end{pmatrix}, c = \begin{pmatrix} a_{11} & a_{12} & x_0 \end{pmatrix} \tag{9}$$

We also have a similar equation for y which gives the other three unknowns. Finally, the elements of matrix c can be found by applying the B transpose and B inverse matrices. We then get: c=$(B^T B)^-1 B^T a$. In the initial matching of the stars from the catalog with the stars from the CCD, we can see that some of the stars are off from the other ones, as it is shown in figure . However, after removing the points that are off, we get smaller residuals, as shown in figure .

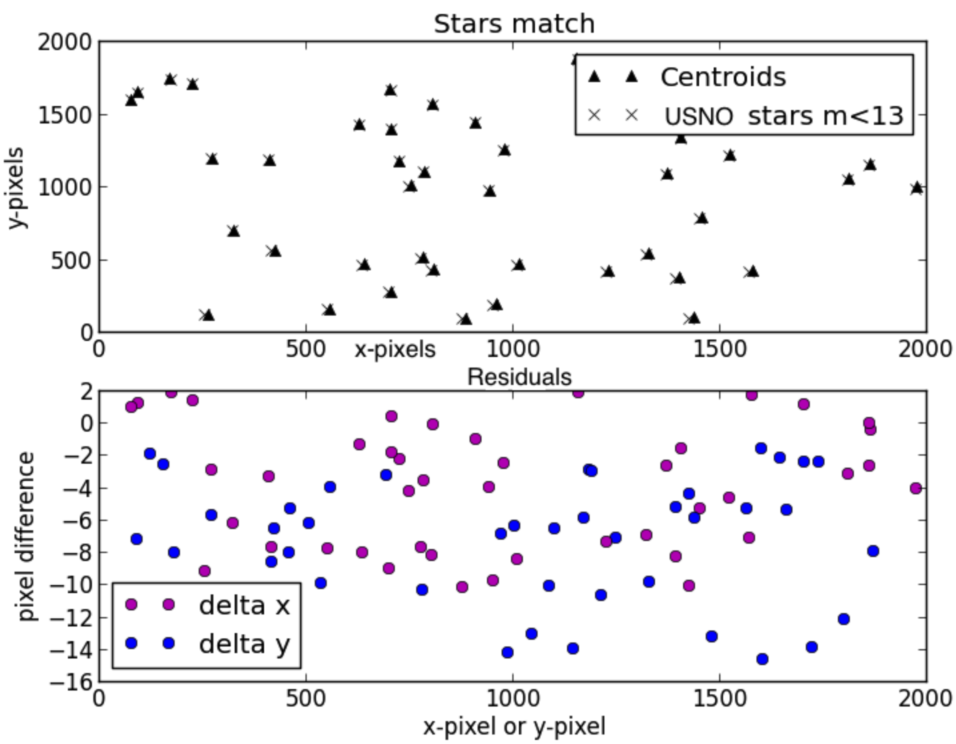


Figure 4: Stars from catalog and from CCS matching, and their residuals. A few points in the residuals are off so the range of residuals is a bit high, running from -16 to 2.

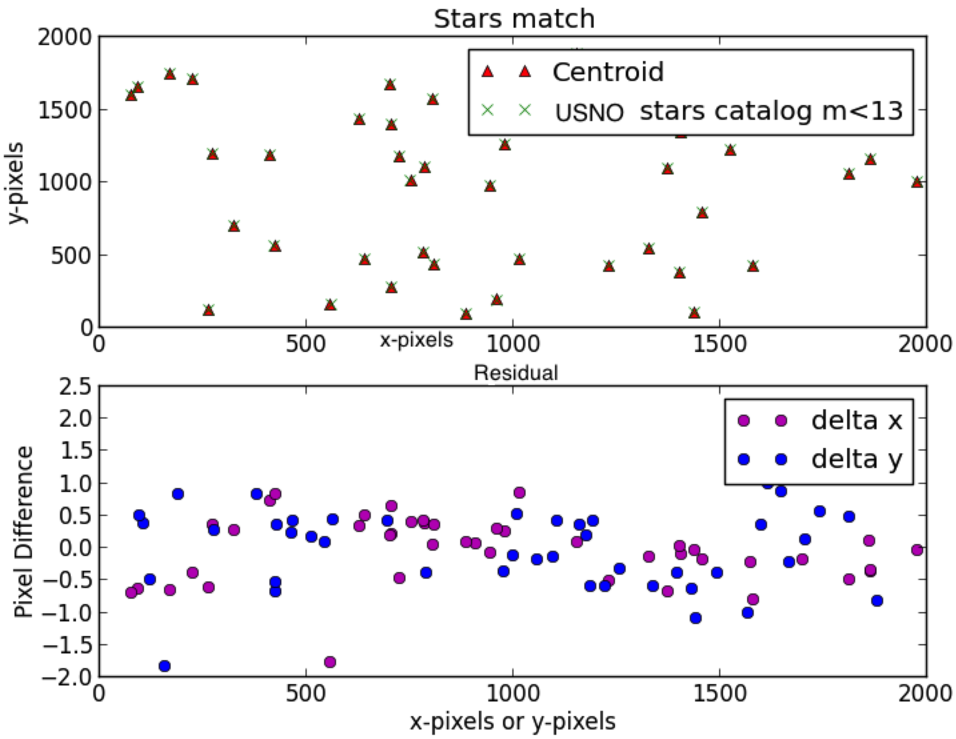


Figure 5: Stars from catalog and from CCS matching, and their residuals. As it is shown, when the residuals which were very off are removed, the residuals is pretty small, which means that the catalog and CCD stars match up almost perfectly. The range of residuals runs from -2 to 1.5

We can also compute the chi squared using the equation below:

$$\chi^2 = (a - Bc)^T (a - Bc) \tag{10}$$

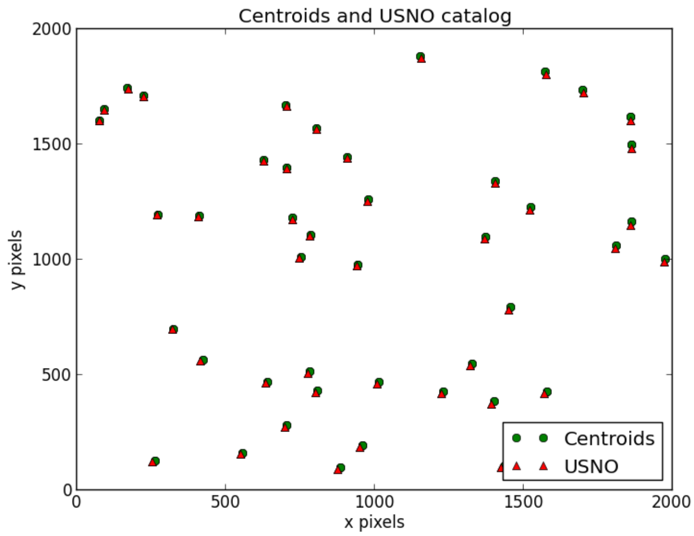


Figure 6: Stars from the USNO-B1.0 catalog and the stars found from the CCD. They almost perfectly match up.

Table 1: Plates constants

Unknowns	x	y
	x	y
a_1	0.9902040	0.006890
a_2	-0.0067157	0.9901437
a_3	1027.717	1031.749

4 Detection of Asteroid

Now that we have the plate constants, we can transform the coordinates of the objects detected on the CCD onto the spherical plane. In other words, we are able to find the right ascension and declination of the asteroid using the plate constant we found in previous parts of this experiment. Therefore, we can measure the position of the asteroid on the sky from different nights and calculate its velocity and proper motion through the sky. Data from Asteroid 30 Urania was taken in 5 almost consecutive nights. We used DS9 program in order to detect the asteroid from the background stars. The way we found the asteroid is that we opened the FITS files in DS9 application and log scaled them so that we can find the stars. Then the way we found the asteroid is that we looked at the pattern of the stars and figured out which bright dot is in one image but not in the others. Therefore, the asteroid is found in all four images. We know the a and y pixel numbers of the position of the asteroid on

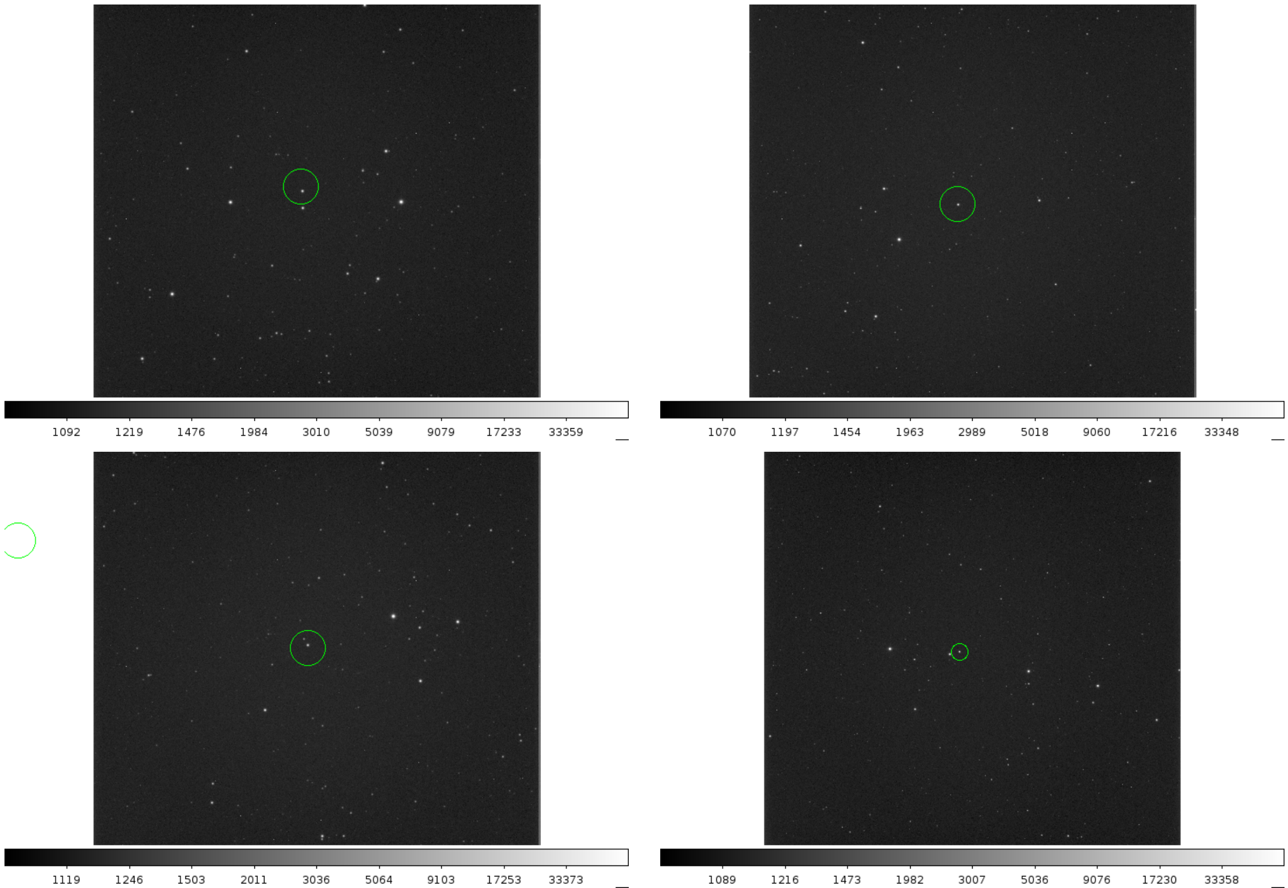


Figure 7: Tracking position of asteroid 30 Urania in the sky. The FITS files were opened using DS9 application. The way of detection of the asteroid was visually by looking at the fixed stars and figuring out which point is moving in the stars plane.

the CCD and using the plate constants we found previously from NGC7331, we converted the pixel numbers to right ascension and declination coordinate. From the position of the asteroid on the sky, we measured the differences in the positions in order to calculate the proper motion. The position results are listed in table 2. In order to find the motion of the asteroid in the sky, we plotted the position of the asteroid during different times and plotted the line of best fit. We can use the plate constants found in section 3.3 to convert the position of the asteroid from pixel into right ascension and declination. To do so , we need to solve the following matrix: X=T^{-1}x The conversion from standard coordinated to celestial coordinated is then given by the following equations:

$$\alpha = tan^{-1}(-\frac{X}{\cos\delta_0 - Y\sin\delta_0}) \tag{11}$$

$$\delta = \sin^{-1}\left(\frac{\sin\delta_0 + Y\cos\delta_0}{(1+X^2+Y^2)^{0.5}}\right) \tag{12}$$

Table 2: Position of asteroid 30 Urania During Different Times

Date	Time	X position	Y position	Right Ascension	Declination
20 Jan 2012	04:28:30	1089.500	977.375	2:57:49.051	+19:14:29.82
21 Jan 2012	04:40:27	1090.375	1039.500	2:58:44.297	+19:16:44.85
23 Jan 2012	05:43:40	1063.130	1008.163	3:00:41.050	+19:21:37.71
24 Jan 2012	04:26:48	1088.602	1038.716	3:01:37.247	+19:24:02.69

Table 3 shows the calculated velocities of the asteroid in declination and right ascension directions, along with their proper motion which is the square root of sum of each of the velocity components squared. If we average the velocities, we end up getting the velocity of the asteroid 30 Urania to be 0.02505 deg/h in declination direction and to be 0.00997 deg/h in the right ascension direction. Therefore, the average proper motion of the asteroid 30 Urania would be 0.02696 deg/h through the sky.

Table 3: Velocities in declination and right ascension direction and the proper motion

Delta Dec(deg)	Delta RA(deg)	Delta time(h)	$\mathrm{V}_dec(deg/h)$	$\mathrm{V}_ra(deg/h)$	Proper Motion(deg/h)
0.562625	0.230191	24.19916667	0.0232497	0.009512	0.02512
1.22025	0.486471	48.22027778	0.025305743	0.010088515	0.0272426
0.6040833	0.23415383	22.71888889	0.026589473	0.01030657	0.0285172

5 Conclusion

In this lab we learned how astrometry works. We learnt how to find objects from a 2D array CCD and how to find the centroids. We also learnt querying data from USNO-B1.0 catalog and we compared the stars from the catalog with the centroid points we found and matched them. We also learnt the conversion between the pixel coordinates and celestial coordinates(right ascension and declination). Using the mentioned techniques, we were able to detect the movement of the asteroid in the sky using the data taken during 4 almost consecutive nights and we measured the velocity of it in both declination and right ascension direction; therefore, we were able to calculate its proper motion through the sky which turned out to be approximately 0.02 degrees per hour.