

Locating Double Stars in the UCAC with the WDS Catalog and CCD Parameters

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Double star orbits are determined to aid navigation and communications, but are often compiled from limited observations. The identification of double stars in the USNO CCD Astrograph Catalog (UCAC) provides a means to discover new double stars and improve orbital information for known double stars. Several artifacts remained in the pixel data after the UCAC2 release, including the presence of a bright streak along the x -axis of bright stars resulting from a shutter problem, and the presence of cosmic ray events on individual CCD frames. Starting with a list of already identified potential double stars, these artifacts were detected and potential double stars were flagged for whether they were affected by either artifact. In addition, the Washington Double Star Catalog was matched with potential UCAC double stars. From these identifications, each potential double star was flagged for whether (1) they actually do not exist but were listed due to being on a streak, (2) they are cosmic rays instead, or (3) they are most likely double stars, verified with a Washington Double Star Catalog match if possible. Despite that matches were within 1-15 px of each other, coordinate accuracy could still be improved by using double orbital catalogs and proper motions from the UCAC. Most cosmic ray events and almost all bright streaks were detected successfully, providing a sortable list of double stars that can be used by astronomers to discover new double stars and improve currently known double stars' orbits.

PACS numbers: double stars, astrometry, UCAC

I. INTRODUCTION

The United States Naval Observatory (USNO) Charge-Coupled Device (CCD) Astrograph Catalog (UCAC) is an all-sky survey of stars spanning from the bright 8th magnitude to the faint 16th magnitude where many stars were previously uncataloged¹. Started in 1998, this project has been conducted via digital observations using a 4K CCD camera at the Cerro Tololo Inter-American Observatory (CTIO) and the Naval Observatory Flagstaff Station (NOFS). The primary breakthrough of the UCAC is that star coordinates are accurately determined at 15-70 mas. The first version (UCAC1) and second version (UCAC2) were intermediate releases that kept systematic errors within 10 mas. Even so, the third and final release (UCAC3) is due in late 2008, aiming to handle most other errors and provide final position and motion and matches with other star catalogs.

Double stars comprise the majority of all stars in the Milky Way galaxy. The USNO's Washington Double Star Catalog (WDS) is both an historic resource and modern list of double stars⁴ observed at different times, often over a century. Double stars are of interest to any human or robotic sky observers since their orbital motion creates differences in star positions as seen from Earth or Earth orbit. When double star astronomers accurately resolve double stars' separation and position angle over a period of time, the orbits can be determined, allowing for systematic correction of star catalogs.

The systematic correction of star catalogs is necessary

to provide the most accurate star location. Double stars need to be identified in the UCAC since they move with respect to each other, meaning that their orbits must be determined and used to predict their locations accurately. Such accuracy is necessary for satellite communications and navigation.

To determine potential candidates for double stars in the UCAC, stars in close proximity that matched the criteria for being a double star were identified in the UCAC pixel data processing step. The criteria for this identification were: (1) a sufficient number of pixels, (2) a sufficient elongation, and (3) the presence of a double peak.

The reduction of this list of potential double stars in the UCAC to a list with 80 to 90 percent actual double stars is the main goal of this research. To achieve this, the Washington Double Star Catalog was matched to the UCAC star data to verify the select number of double stars in common between the two star catalogs. Other identified potential double stars in the UCAC were verified using available UCAC detection parameters. In the end, the list of potential UCAC double stars is regenerated with a flag column explaining whether each potential double star is actually a double star. The final product of this work constitutes a list of WDS identifications and of new double star discoveries that can be confirmed by follow-up observations.

One purpose of this research is to use UCAC observations to develop orbital improvements of double stars. The final verified UCAC double stars could be observed at a different time, and then the separation and position

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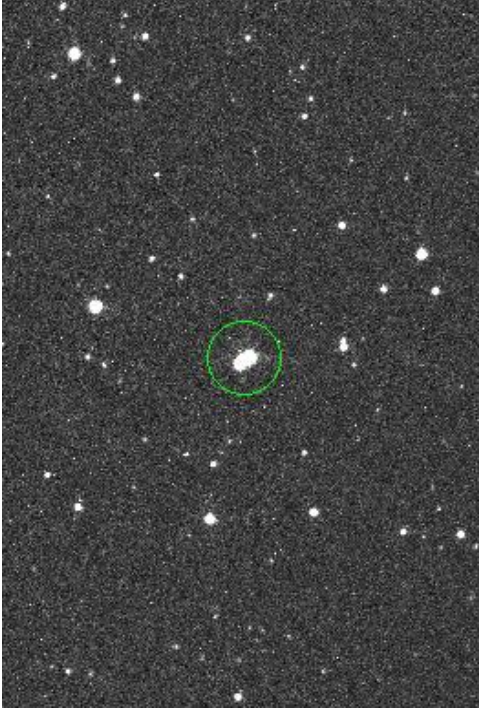


FIG. 1: An example double star in the UCAC.

angle measurements by the observer and the measurements in the UCAC could be used to determine a precise orbit. In this manner, the identification of double stars in the UCAC is similar to the identification of minor planets², in that a key objective is to improve the orbits of objects we recognize in space.

II. VERIFICATION METHODS

The initial detections of potential double stars was contaminated with artifacts of various kinds. For one, when an unusually bright star of high amplitude was encountered, the shutter's failure to close produced a bright streak that amplified the background noise to seem like a line of clustered stars, many of which were then misclassified as double stars due to their great amplitude and elongation from the streak. To eliminate these systematically erroneous data from the final list of double stars in the UCAC, the streaks were tracked. This was done quite precisely comparing to the handling of other artifacts.

Another significant artifact is the presence of cosmic rays in the UCAC frames. These extraterrestrial bright bursts of energy are highly elongated and are found in most UCAC frames, though undesired. As cosmic rays travel at high velocities through space, they are likely not to be found on any two frames at the same location. These objects can be removed from the catalog of stars by simply comparing its presence on one frame at a particular location to that same location on other frames.

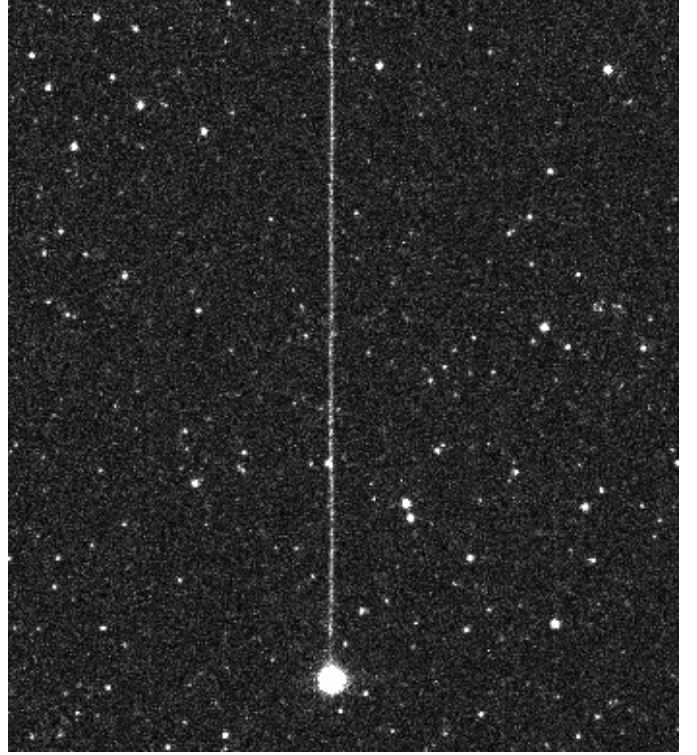


FIG. 2: One of the more pronounced bright streaks caused by a shutter problem. [A rare phenomenon in the UCAC, this bright streak on frame 073869 creates false double star detections along the streak which are identified using the source of the streak.]

An attempt to detect cosmic ray events is made here.

A. Detecting Streaks

Streaks were identified by finding bright stars, using star amplitude as the measure of brightness. When the threshold star amplitude of 5000 ADU is exceeded, a sub-iteration is run to search through all the stars that are affected by that bright star. All stars directly above the bright star are quarantined to test for streak interference.

In addition, any star with a high integrated intensity, or flux Φ , that lies directly above or directly below the bright star is also quarantined. In other words, the rectangle's range of y -values is limited to the values only above the star should the star being looked at in the range have a low integrated intensity.

To determine what exactly constitutes being directly above, a tall rectangle is chosen which runs along the x -value of the bright star for all y -values. The width Δx of the rectangle is given in terms of bright star amplitude A :

$$\Delta\hat{x} = a + bA \quad (\text{II.1})$$

$$a = 1.2802 \text{ px} \quad (\text{II.2})$$

$$b = 1.0 \times 10^{-6} \text{ px/ADU} \quad (\text{II.3})$$

$$y_{min} = \begin{cases} 0 \text{ px} & \text{if } \Phi \geq 8.7198 \times 10^3, \\ 2047 \text{ px} & \text{if } \Phi < 8.7198 \times 10^3. \end{cases} \quad (\text{II.4})$$

$$y_{max} = 4094 \text{ px} \quad (\text{II.5})$$

The most appropriate Δx for each amplitude is best modeled by a linear fit. A representative sample of UCAC frames was used to calculate constants a and b as used in the linear fit. The linear regression works well as is suggested by the coefficient of determination $R^2 = 0.999$.

By looping through all bright stars and the stars that could be affected by them, the stars possibly affected by a streak are flagged with the letter **S** in the (x, y) coordinate information output.

B. Removing Cosmic Rays

Cosmic rays are readily distinguishable from ordinary stars or star systems in their elongation, leading their surface plots to resemble walls more than the peaks of a star's surface plot. The UCAC measurement parameters were not intended or designed to handle cosmic rays, yet the available expanse of parameters is sufficient to detect cosmic rays with roughly 65 percent reliability.

The current method of detecting cosmic rays is by evaluating that at least one distance-related parameter and at least one brightness-related parameter is satisfied. The distance-related conditions are: (1) the radius of the object is less than 0.7 px, or (2) the separation of the objects is greater than 3 px. The brightness-related conditions are: (1) the amplitude over the background of the object is greater than 100 ADU and the difference between the background of the objects against the UCAC frame's mean background is greater than 6.8298 ADU. These conditions are a compromise since the exact conditions vary from frame to frame.

If any of the above conditions is satisfied, but not at least one from each category, then a flag with the letter **c** is given, meaning that the potential double star should be checked.

Although cosmic ray detection may not be as robust in this phase, they are to be removed for sure when bright, elongated stars are matched between frames to test their recurrence.

C. WDS Catalog Matching

Determining the stars in the UCAC that correspond to WDS Catalog stars is interesting since the WDS celestial

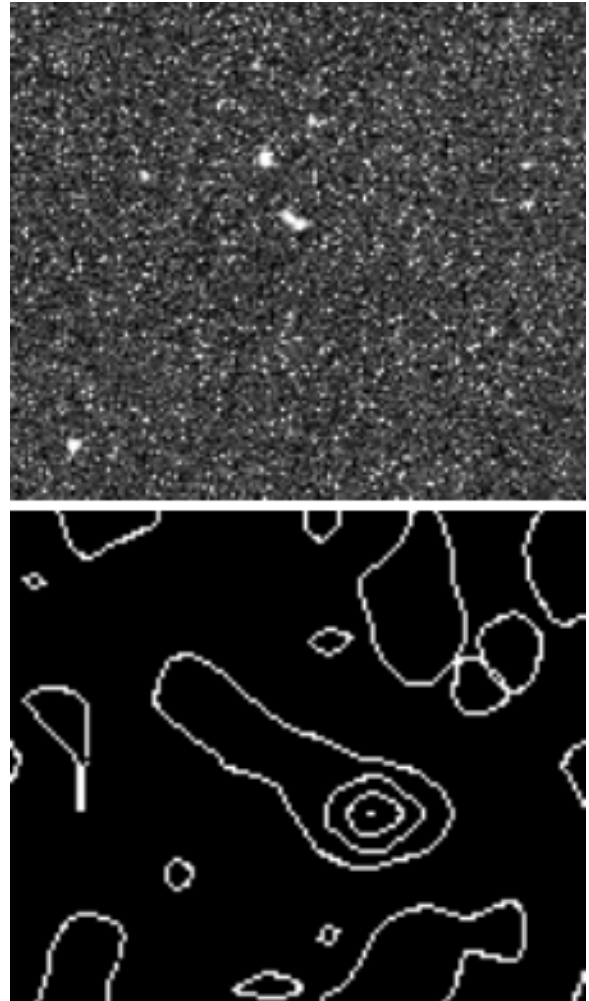


FIG. 3: A cosmic ray event that could be mistook for a double star. [Cosmic rays are not always discernible from a frame image (above), but their contour plots (below) make them clear in their great elongation and single major peak.]

coordinates had to be matched to UCAC frames whose (x, y) coordinate data is expressed in pixels. First, all of the stars in a double star system in the WDS Catalog were put into the equatorial coordinates of right ascension α and declination δ . Considering that WDS (α_0, δ_0) coordinates are given only for the primary star, the separation ρ and position angle θ were used for all secondary stars³ to systematically compute the (α, δ) coordinates for all stars in the system:

$$\alpha = \alpha_0 + \Delta\alpha \quad (\text{II.6})$$

$$\delta = \delta_0 + \Delta\delta \quad (\text{II.7})$$

$$\Delta\alpha = \frac{\rho \sin(\theta)}{\cos(\delta)} \quad (\text{II.8})$$

$$\Delta\delta = \rho \cos(\theta) \quad (\text{II.9})$$

These WDS celestial coordinates were matched to the center of each UCAC frame, also given in celestial coordi-

nates. Each frame's field of view is approximately a 1° by 1° on the celestial sphere². This was used in determining frame α width along with a $\cos(\delta)$ factor¹ to compensate for the shrinking of right ascension values towards the celestial poles. The δ frame height is always roughly one degree. From the frame center $(\alpha_{cen}, \delta_{cen})$,

$$\Delta\alpha \cos \delta = 32 \text{ arcmin} \quad (\text{II.10})$$

$$\Delta\delta = 32 \text{ arcmin} \quad (\text{II.11})$$

Furthermore, right ascension values were compared correctly for the entire sphere because 0 h is the same as 24 h in right ascension due to the continuous wrapping around of the domain.

Using the WDS matched to the respective UCAC frames with center $(\alpha_{cen}, \delta_{cen})$, the celestial coordinates (α, δ) of the double stars from the WDS were converted to standard coordinates³ (ξ, η) and then scaled to the correct pixel resolution of 0.905 arcsec/px to provide the corresponding approximate (x, y) coordinates:

$$\xi = \frac{\cos(\delta) \sin(\alpha - \alpha_{cen})}{\sin(\delta_{cen}) \sin(\delta) + \cos(\delta_{cen}) \cos(\delta) \cos(\alpha - \alpha_{cen})} \quad (\text{II.12})$$

$$\eta = \frac{\cos(\delta_{cen}) \sin(\delta) - \sin(\delta_{cen}) \cos(\delta) \cos(\alpha - \alpha_{cen})}{\sin(\delta_{cen}) \sin(\delta) + \cos(\delta_{cen}) \cos(\delta) \cos(\alpha - \alpha_{cen})} \quad (\text{II.13})$$

The orientation of the CCD camera was also factored into the process of converting from equatorial coordinates (α, δ) to standard coordinates (ξ, η) , in that the standard coordinates were flipped until they were correctly oriented with the direction of x and direction of y .

Orientation Flag	x -axis Orientation	y -axis Orientation
WA (default)	East	North
EA	West	South
WB	North	West
EB	South	East

By factoring in the orientation of standard coordinate data and scaling that to go from an angle in radians to pixel coordinates, a fairly precise (x, y) is obtained.

III. IMPROVING COORDINATE ACCURACY

Although the double star coordinates calculated from the Washington Double Star Catalog are precise, the accuracy of the location for a particular date and time can be improved by applying proper motions and orbital information.

After applying the original algorithm used in this paper, proper motions should be applied if a close match to a UCAC double star is found. The calculated position² corrected for time differences in WDS data later to be

compared with raw UCAC data, when observation exposure time (ET) and difference in Universal Time ($\Delta UT = UT_{UCACframe} - UT_{WDS}$) are known, is given by:

$$\alpha = \alpha_{WDS} + \mu_\alpha(\Delta UT + \frac{1}{2}ET) \quad (\text{III.1})$$

$$\delta = \delta_{WDS} + \mu_\delta(\Delta UT + \frac{1}{2}ET) \quad (\text{III.2})$$

The orbital information about double stars, such as the well-documented catalogs on the USNO Double Star CD⁴, are also paramount to obtaining accurate coordinates for a certain time. The compiled observational data of double stars' (ρ, θ) over time in the Sixth Catalog of Orbits of Visual Binary Stars and Catalog of Rectilinear Elements of Visual Double Stars are useful sources to model orbits with.

IV. RESULTS

A file in the software package describes in detail how to run the programs, but the basic order is to run `wdscmp`, `wdsmxy`, and then `xyldss`.

A. UCAC-WDS Match List

Once the WDS coordinates are converted from equatorial coordinates to the UCAC frame's (x, y) coordinate system, the close matches between the WDS and UCAC potential double stars are stored in a file `udsm`. This is an example line from `udsm`.

```
u080367 18591-2609 1859.171 3441.024 1863 3446 12.082 11.080 B
```

In this short file, only the UCAC frame number, WDS identifier, UCAC and WDS (x, y) coordinates, UCAC and WDS separations, and WDS component letter are provided in that order for each double star system's individual star match.

When observing pixel data of frames in software such as SAOImage DS9, the `udsm` file is particularly useful in finding double stars manually.

B. UCAC Double Star List

The final result in this research algorithm is a table of double star systems that are identified and matched with UCAC star data in a file `ud`. The beginning and ending columns are the most important, providing the information not calculated before. The first column is the UCAC frame number which a double star system is found on. The third to last column is the separation between stellar components for the double star system, in pixels. The third to last column is the double star system component apparent magnitude difference. The last

column is the newly assigned flag previously discussed. Its meanings are given as:

Flag	Meaning	Process
W	In Washington Double Star Catalog	wdscmp, wdsmtx, and xyldss
d	Almost certainly a double star	xyldss
c	Check that this is not a cosmic	xyldss
C	Most likely is a cosmic ray	xyldss
S	Not a double star, but in streak	xyldss

These classifications are ordered in this table from most double star-like to least double star-like. Replacing the flags with numbers and doing a decreasing numeric sort ordered by that flag column on `ud` could be an effective way to observe new double stars.

The final product which contains these flags may take a whole week of computing time to arrive at. This ultimate output file built via `xyldss`, `udsm`, looks as follows:

```

      1  2 3      1      2      3      4
    frn index nx it      x1      y1      bgr ampl
-----
u040726  168  1 12 3578.979 610.927  32.5 19123.
...
      5      6      7      8      9      10      14
     rad      x2      y2  ampl2 sigx1 sigy1 sigx2
-----
1.646 3578.887 614.799 15590. 0.021 0.024 0.026
...
     15      17      18      19
    sigy2 chisq  mag1  mag2  delr  delm f
-----
0.030 327.67 6.466 6.688 3.873 0.222 S
...
```

A detailed list of format specifications is listed in the actual product's `formats.txt` file.

V. DISCUSSION

The matching of double stars in the UCAC with the WDS Catalog is the most time-consuming part in the algorithm, despite the fact that its contribution to the end result is minimal. There are comparatively fewer

double stars that match exactly with identified potential UCAC double stars. The vast number of double stars in the Washington Double Star Catalog are usually brighter than 12th magnitude, while UCAC stars are usually fainter than 8th magnitude. This leaves a significant range of magnitude overlap between the two catalogs, but not enough to find the entire WDS in the UCAC.

The identification of streaks is highly successful, considering that no example streak identification was found where there actually was no streak. Conversely, no example streak was found where there was no streak identification.

Cosmic rays were not detected to a great degree of accuracy, mainly because the UCAC data was not designed for this. However, around half of the potential UCAC double stars flagged as cosmics are actually cosmics. Only the second batch of star comparisons between frames can accurately determine whether an object is a cosmic ray or not.

VI. CONCLUSIONS

Nearly half a million legit double stars were identified in the UCAC. A statistics program was written to quantify how many of each flag was encountered on each frame.

The discovery of thousands of new double stars must be accompanied by careful observations. Most double stars identified and verified in the UCAC are between magnitudes 9 and 18. While double star astronomers may want to use the ultimate UCAC double star list to find new double stars, the UCAC data on matched double stars can also be better used to improve orbital information.

As the UCAC's (x, y) coordinates are translated to equatorial coordinates (α, δ) , the results of this research can be better realized. Double star astronomers will then be able to point their equatorially mounted telescopes into the exact location of the identified double stars.

¹ Zacharias, N., S. E. Urban, M. I. Zacharias, G. L. Wycoff, D. M. Hall, D. G. Monet, T. J. Rafferty, *The Second US Naval Observatory CCD Astrograph Catalog (UCAC2)*, *The Astronomical Journal* 127 (March 2004), pp. 3043-3059.

² Dutta, S. and N. Zacharias, *UCAC: Minor Planet Identification*, US Naval Observatory, Washington, DC, 2006.

³ Green, R. M., *Spherical Astronomy*, Cambridge University

Press, Cambridge, UK, 1985.

⁴ Mason, B., G. L. Wycoff, W. I. Hartkopf, G. G. Douglass, C. E. Worley, *The 2001 US Naval Observatory Double Star CD-ROM. I. The Washington Double Star Catalog*, *The Astronomical Journal* 122, No. 6 (December 2001), pp. 3466-3471.