Using Plot Tool 3.19 to Generate Graphical Representations of the Historical Measurement Data

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Abstract: The Plot Tool (Version 3.19) is an Excel utility that generates Cartesian plots of the measurement history of any double star using the Datarequest text file supplied by the WDS at the U. S. Naval Observatory. This powerful tool allows a double star researcher to better detect short arc binaries and linear cases much better than standard data mining methods or trusting that a star one has selected for research is starting to show a trend in the data.

1. Introduction

As an editor for this journal, I review dozens of manuscripts every year. Most of their authors present their data in graphical formats, which is (to my visual way of seeing the world) the clearest way to show patterns and relationships in data (even though that can sometimes be misleading, owing to the brain's tendency to see patterns where none actually exist, a phenomenon known as "pareidolia").

I usually see graphs where the author is trying to show a trend or pattern in the observational data, and often a graph like this is presented:

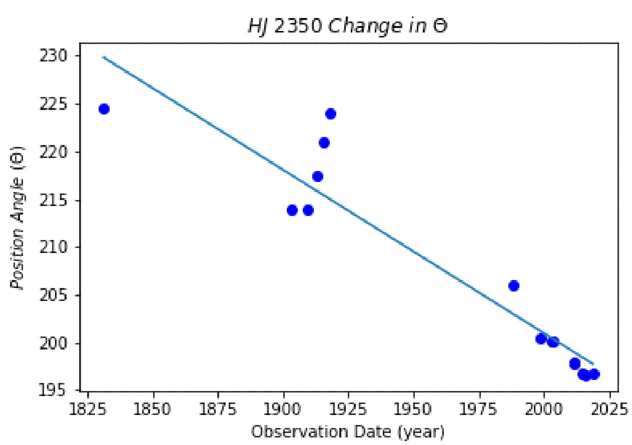

Figure 1: Typical "Change over time" plot

Just exactly what does a plot like this tell us? Not as much as some people think. We can see that over time, theta is decreasing. But so what? Over time, every double star will show a change in theta (although it may take centuries to show up). The slope of the line is not very helpful in telling us anything useful about this pair either.

A better plot would be to show the measurements as recorded in a "Datarequest.txt" file that one can obtain from the WDS. This shows how the stars appear to move relative to each other over time and this can let true trends begin to surface—a short arc in the case of a gravitationally-bound pair in a mutual orbit, or a straight line in the case of two unrelated stars that happen to lie close to each other along our line of sight but are in fact not binary at all.

So how to generate such a plot?

2. A Tool Five Years in the Making

Five years ago, I decided to generate plots of the measurements of double stars and requested (eventually) some 8,000 sets of data from Dr. Brian Mason at the U. S. Naval Observatory (the curators of the Washington Double Star catalog, or WDS for short). The first attempt at generating plots was somewhat crude but helpful in detecting "short arc binaries" (or SABs), stars of immense interest to astronomers as they are probably in an orbit about their barycenter, but for which no solution has yet been proposed. Such pairs should rise to the top of any observing agen-

Received April 9, 2020.

da if one wants to collect useful data on a system.

Similarly, when the plot showed the data lying along a straight line (more or less), we have what is called a linear (or LIN) case. Such cases can be one of two types: (1) the stars are not related at all and are just passing by each other along the plane of the sky and hence are of no interest to us as tools to determine orbits, or (2) the stars are in a very large orbit that is nearly edge-on and thus the points may be interpreted as a LIN case where in fact we may have an orbital case with such a slight amount of arcing that we cannot detect any arc yet. Hypothetically, it should be possible in such cases to determine the rate of change in position over a set time interval (such as a decade, or 50 years, or a century) and see if the points fall along a regular time cadence. If they do, the pair is more than likely LIN in nature. But if the points start bunching up (or spreading out) over time, we may be seeing orbital velocity changes projected onto the plane of the sky. I say "hypothetically" because I have not yet been able to make this checking tool work. But in theory, it should. And there is always the dead giveaway when a "LIN" case suddenly reverses direction and starts to move 180° from its recent motion. Now we know we are dealing with a SAB but without the arc.

Like most Excel spreadsheet programmers, I am notoriously bad on documenting what I do, often embedding notes in some of the cells that contain important steps while keeping the screen as clean as possible. (Excel Notes are indicated by a tiny red triangle in the upper right corner of a cell that has notes attached to it.) As a computer professor once told me, "Real programmers don't document!" He was kidding (I think), but there is a hefty dose of truth in that statement!

3. Structure and Functions in the Plot Tool 3.19 spreadsheet

You may a copy of the Plot Tool 3.19.xlsx by clicking this link: http://www.jdso.org. This action will take you to the JDSO server where a copy of Plot Tool 3.19.xlsx awaits your download underneath this article.

General Structure

There are three pages (or "sheets") in the workbook. I will not take the time here to explain complex Excel functions and processes. If you are not very adept at Excel, you can still use Plot Tool 3.19, but don't expect me to tutor you on the intricacies of Excel. It is a powerful and complex program and it has taken me 15 years to master it—or at least become proficient with it.

The first sheet is called "Instructions." I highly suggest you read that sheet as it will tell you how to use the Plot Tool (as will this paper).

The second sheet is called "Data Plot." This is the page where Excel graphs all the data in the Datarequest.txt file you request from Brian Mason at the U. S. Naval Observatory.

To obtain data on any double star in the WDS, send an email to Brian Mason (brian.d.mason@navy.mil). In the message header, put "Datarequest". In the body of the email, type the WDS number of the star. For example, the WDS number of HJ 2010 is 01027+4742. So you would type that number in the body of your email. I suggest you also add your name and some tag line about your research program (for example, I used "Richard Harshaw / Cave Creek, Arizona / Brilliant Sky Observatory"). Dr. Mason and I know each other well now so when he gets an email from me, he knows who I am, but he may not know you until you have contributed several measurements to the WDS.

Dr. Mason is very good at getting a reply to you quickly—usually within 24 hours, but don't panic if it takes longer than that as he is also an observer and from time to time travels to major observatories for observing runs and is not readily available.

If you want data on more than one star, list the WDS numbers in your email, one WDS number per line. There is no limit to how many files you may request but bear in mind that the reply may run into several megabytes. For large requests, Dr. Mason may compress the data into a "TAR ball" (a compression utility popular with UNIX systems) and send it to you. TAR extraction utilities are available for free on the internet. A 1 MB TAR ball may expand to 15 or 20 MB or more.

The third page of the workbook is called "Datarequest.txt" and this is the sheet where you will dump the data text file Dr. Mason sends you.

Handling the Datarequest.txt File

Datarequest.txt files can be very small or very huge, depending on the double star and how much it has been observed. Whatever the size, you will want to look it over before importing it into The Plot Tool.

Most people try to use the Windows Notepad program. I don't advise that. Notepad makes a mess of line breaks and page formatting, and it is easy to get confused with it. The same can be said of Notepad++, a third-party improvement on Notepad.

The folks at the WDS use a UNIX program called Gedit. You can download it for free at this web site (https://gedit.en.softonic.com/). (Be sure to use this website. There are many clones and knockoffs of Gedit out there and I cannot vouch for them. I can vouch for Gedit.) Gedit runs just fine in any Windows environment. I suggest after you download and install it that you play with it a little to get used to how it works.

When I receive datarequests from Dr. Mason, I

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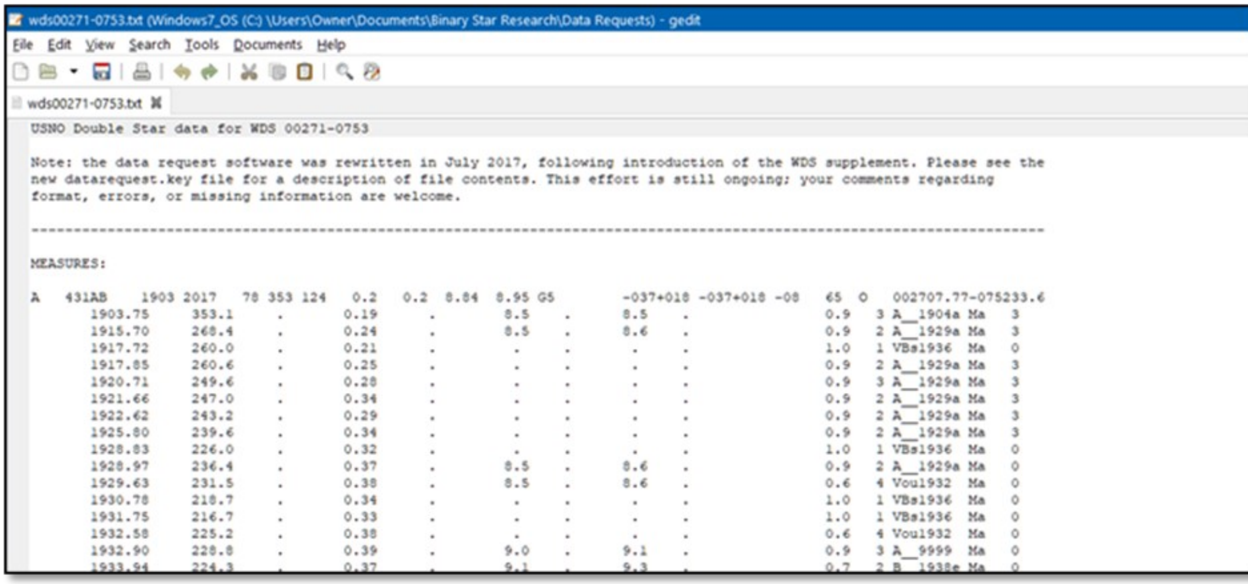

```
wds00271-0753.txt (Windows7_OS (C:) \Users\Owner\Documents\Binary Star Research\Data Requests) - gedit
File Edit View Search Tools Documents Help
wds00271-0753.txt

USNO Double Star data for WDS 00271-0753

Note: the data request software was rewritten in July 2017, following introduction of the WDS supplement. Please see the
new datarequest.key file for a description of file contents. This effort is still ongoing; your comments regarding
format, errors, or missing information are welcome.

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MEASURES:

A   431AB    1903 2017   78 353 124   0.2   0.2  8.84  8.95 G5        -037+018 -037+018 -08   65  0   002707.77-075233.6
       1903.75     353.1     .       0.19     .        8.5    .     8.5    .                 0.9   3 A__1904a Ma   3
       1915.70     268.4     .       0.24     .        8.5    .     8.6    .                 0.9   2 A__1929a Ma   3
       1917.72     260.0     .       0.21     .         .     .      .     .                 1.0   1 VBs1936  Ma   0
       1917.85     260.6     .       0.25     .         .     .      .     .                 0.9   2 A__1929a Ma   3
       1920.71     249.6     .       0.28     .         .     .      .     .                 0.9   3 A__1929a Ma   3
       1921.66     247.0     .       0.34     .         .     .      .     .                 0.9   2 A__1929a Ma   3
       1922.62     243.2     .       0.29     .         .     .      .     .                 0.9   2 A__1929a Ma   3
       1925.80     239.6     .       0.34     .         .     .      .     .                 0.9   2 A__1929a Ma   3
       1928.83     226.0     .       0.32     .         .     .      .     .                 1.0   1 VBs1936  Ma   0
       1928.97     236.4     .       0.37     .        8.5    .     8.6    .                 0.9   2 A__1929a Ma   0
       1929.63     231.5     .       0.38     .        8.5    .     8.6    .                 0.6   4 Vou1932  Ma   0
       1930.78     218.7     .       0.34     .         .     .      .     .                 1.0   1 VBs1936  Ma   0
       1931.75     216.7     .       0.33     .         .     .      .     .                 1.0   1 VBs1936  Ma   0
       1932.58     225.2     .       0.38     .         .     .      .     .                 0.6   4 Vou1932  Ma   0
       1932.90     228.8     .       0.39     .        9.0    .     9.1    .                 0.9   3 A__9999  Ma   0
       1933.94     224.3     .       0.37     .        9.1    .     9.3    .                 0.7   2 B__1938e Ma   0
```

Figure 2: A Datarequest.txt file displayed in Gedit.

have my Outlook program save them into a special file folder under my Binary Stars file folder. I named this folder, surprisingly, Datarequests.

I then open Gedit and navigate to the Datarequests file folder and find the file(s) I want to work with. (You can open multiple files at once with Gedit.)

Figure 2 is a typical Datarequest.txt file as opened in Gedit.

This shows the top portion only of the file (this one is large). Note the WDS number at the very top of the file and the Discoverer Code (A 431 AB) just below the entry "Measures". I will leave it to the reader to figure out the format of the datarequest.txt file from the key that Dr. Mason always sends with every datarequest. Get to know how to read this file. It can make your life as a double star astronomer so much more productive.

Before we can dump this text file into the Plot Tool, we need to edit it. You will want to scan through the file and look for any lines with either a missing value for θ, a mission value for ρ, or both. There are none of these in Figure 2, but Figure 3 is one from another datarequest file.

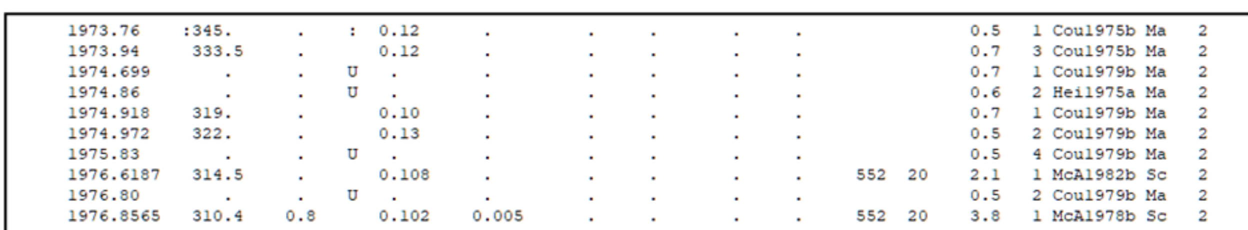
Here we see that there are missing values for θ and/or ρ in 1974.699, 1974.86, 1975.83 and 1976.80. If we import these null value records into Plot Tool, it will not display the data correctly. So you must DELETE any record with a null value in either q or r.

Finally, be sure to remove any record flagged by the WDS as not reliable. These records will have a capital X at the right end, between the method (here, Ma, Sc, etc.) and the number (2, etc.), which is the number of nights the pair was observed. Any record with an X between the method and nights should also be DELETED.

Once all the null records and X flags have been deleted, select the entire file (in Windows, use CTRL+A) and then go to the Plot Tool "Datarequest.txt" page and paste it there (Windows, CTRL+V).

You may then close the text file (and I suggest you save it when you do).

For the examples in this paper, I will be using WDS 02157+2503 (aka COU 79).



```
1973.76     :345.      .    :  0.12      .          .     .       .     .                 0.5   1 Cou1975b Ma    2
1973.94      333.5     .       0.12      .          .     .       .     .                 0.7   3 Cou1975b Ma    2
1974.699       .       .    U   .        .          .     .       .     .                 0.7   1 Cou1979b Ma    2
1974.86        .       .    U   .        .          .     .       .     .                 0.6   2 Heil975a Ma    2
1974.918     319.      .       0.10      .          .     .       .     .                 0.7   1 Cou1979b Ma    2
1974.972     322.      .       0.13      .          .     .       .     .                 0.5   2 Cou1979b Ma    2
1975.83        .       .    U   .        .          .     .       .     .                 0.5   4 Cou1979b Ma    2
1976.6187    314.5     .       0.108     .          .     .       .     .    552   20     2.1   1 McA1982b Sc    2
1976.80        .       .    U   .        .          .     .       .     .                 0.5   2 Cou1979b Ma    2
1976.8565    310.4    0.8      0.102    0.005       .     .       .     .    552   20     3.8   1 McA1978b Sc    2
1976.9219    308.3    0.2      0.102    0.001                                552   20     3.8   1 McA1979a Sc    2
```

Figure 3: Datarequest showing Null Values in Theta and/or Rho

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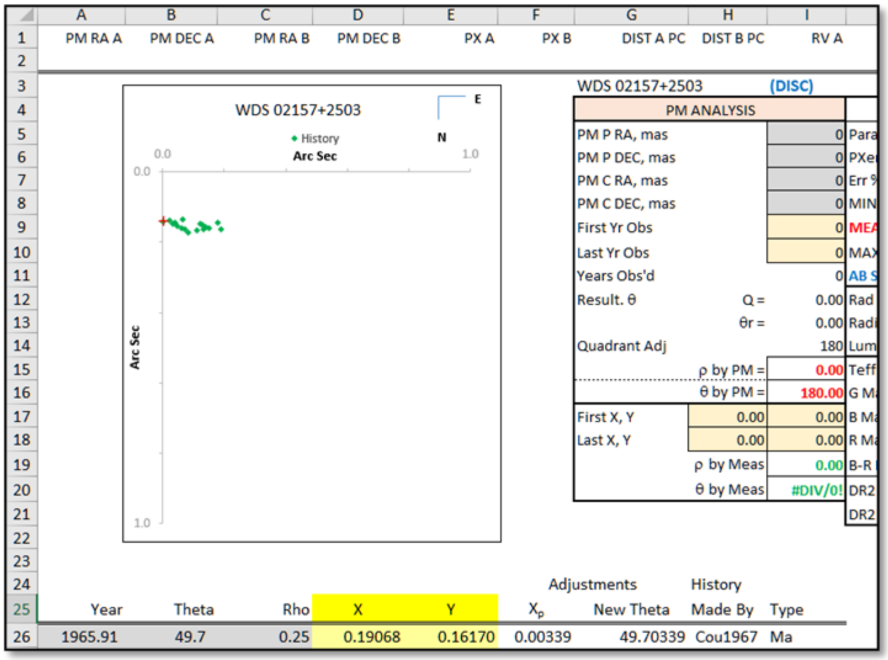

Figure 4: Unprocessed Data Plot page.

What the Data Plot Page Tells Us

First, I note that the Plot (Figure 4) is showing only a handful of the 220+ data points. What is going on?

The plot is just showing the data that fits within the parameters I programmed into Excel. We need to customize this plot. To do so, begin by clicking anywhere inside the plot frame. Small "selection" circles will appear on the border. Now click on any of the green data points. When you do, Excel draws a rectangle around the data used for the plot. You can see this as a lightly darker shading and border around the numbers in columns D and E (labeled X and Y here). Scroll down the page and see that the rectangle stops on line 42. But we have data all the way down to row 243. We need to expand the data selection. To do so, you can either drag the bottom left corner of each column's rectangle down to row 243 or you can manually type in the addresses of the cells. The easiest way is to drag the border with the mouse. If you decide to manually type in the cell address, you need to click on the green points then select the Chart Design tab and then click the Select Data button. You will get a screen that should look like Figure 5.

For now, you can clear the box for Cou1975 (by

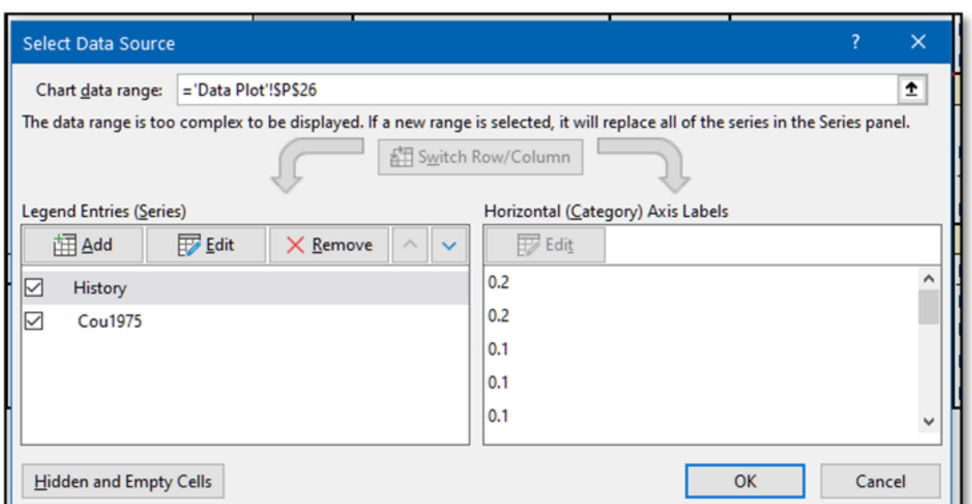

Figure 5: Editing the Data Selection.

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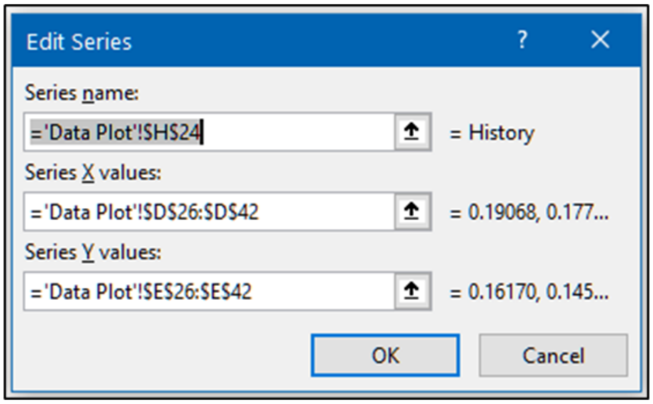

Figure 6: The Data Range edit screen.

clicking on the checkbox). This label is provided to allow the user to enter his or her own data point and have it displayed with a different data icon in a different color.

Select the History set (it is already highlighted) by clicking on it and then Ok. You will see the pop-up window shown in Figure 6.

We want to extend the data selection in columns D and E to row 243. So you should click with the mouse just to the right of $42. Then backspace twice and type "243." Do this for both the Series X Values and Series Y Values windows. Then click Ok twice. See Figure 7.

Does THAT change the plot!

We obviously are dealing with an orbit. But note how small the plot is, and we have a lot of unused space. We can (and should) expand the axis scales.

When generating a plot with the Plot Tool, I strongly suggest you make both axes the same size (in terms of arc seconds). Nothing will get a manuscript returned to you faster than two different axis scales!

To change the axis scales, note that a value of 0.5 arc seconds would easily contain the entire orbit. To change the axis scales, double-click on the horizontal axis. The axis editing dialog box appears, Figure 8.

Let's make the Minimum -0.5 and the Maximum 0.5. Let's also change the Major unit to 0.25 and the Minor unit to 0.10.

Do the same for the vertical axis.

That is much better! See Figure 9. (In fact, we might have even been able to zoom in to -0.3 and 0.3 minima and maxima and changed the major subdivision to 0.1 and minor to 0.05 and gotten an even tighter zoom.

Cardinal rule for plotting data: always be sure each axis is the same size in terms of arc seconds and linear length (centimeters). If this is not done, the plot may be skewed and lead you to a conclusion that is not warranted.

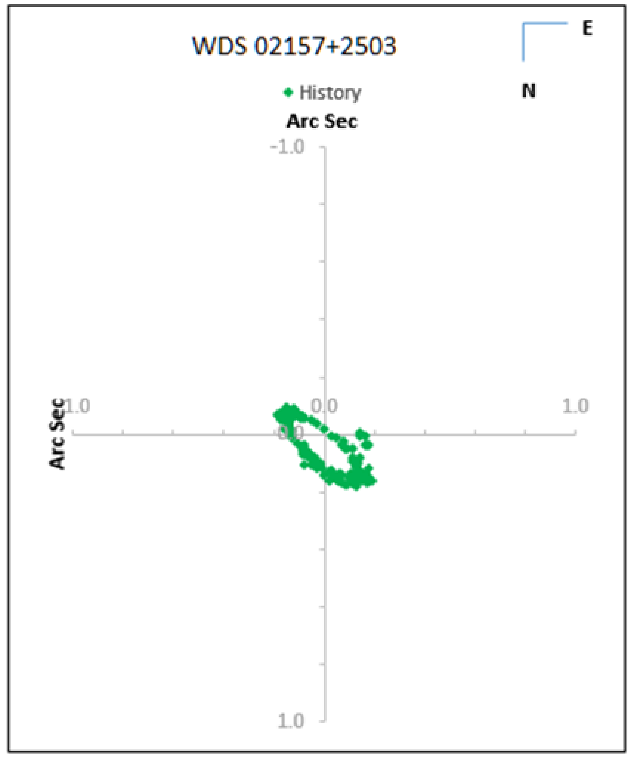

Figure 7: The Updated Data Plot.

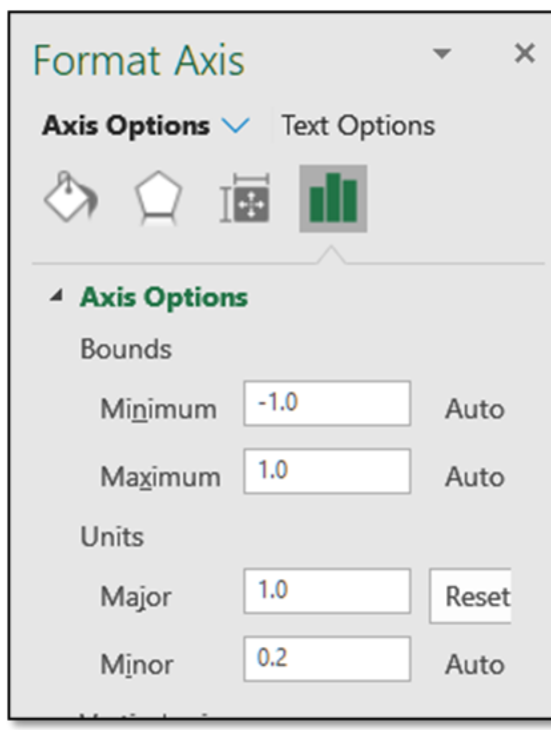

Figure 8: The Axis format dialog.

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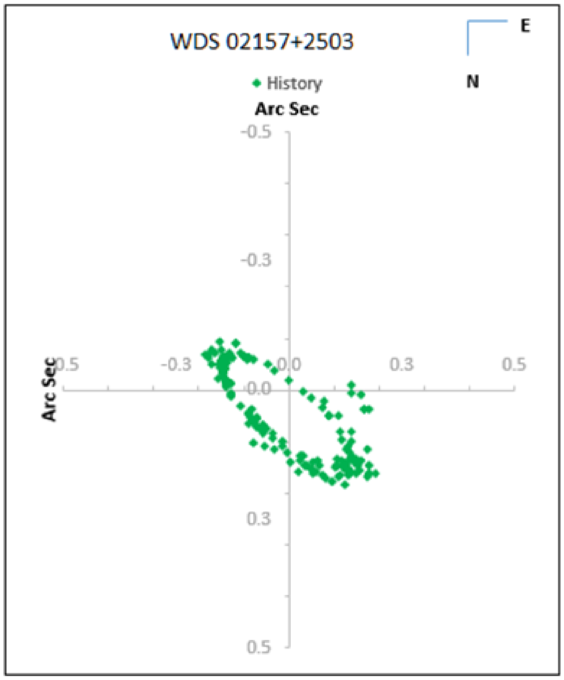

Figure 9: Resized Data Plot.

How the Plot Tool Generates the X-Y Graph

To convert the measurements for θ and ρ in the WDS into Cartesian coordinates so they can be plotted in an X-Y space, we need to apply two simple transforms to the values for θ and ρ.

To convert θ to a Cartesian point, we multiply the value for θ by this transform:

$$\text{Transform 1: } X = \rho\cos(\theta)$$

And to convert ρ to a Cartesian point, we multiply ρ by this transform:

$$\text{Transform 2: } Y = \rho\sin(\theta)$$

This is straightforward enough. However, things are not always that easy in astronomy, and this is one area where it is not easy. That is because the earth wobbles on its axis, like a spinning top on a table (a phenomenon called “precession”). The entire cycle takes around 26,000 years, but it does mean that the true north (“celestial north”) is a constantly moving target. From day to day, year to year, it is not much of a change. But after a century or more, it can begin to make a serious difference in measurements.

Why? Because a measurement made, say, in 1821 was made when celestial north was a few arc minutes away from where it is today, and all readings of θ by that astronomer that night must be adjusted for our current epoch in order to get a true reading on the position angle in today’s terms.

The transformation that does this adjustment is a bit complicated and is openly stated on The Plot Tool, Data Plot page, in the area bounded from cell S3 to Z13. Essentially, we must convert the star’s position in RA (right ascension) and DEC (declination) into degrees of RA and DEC (no conversion needed for the DEC, of course). We also need to know the year of the original measurement and the current year so the computer will know how much to adjust the shift in the celestial pole.

That computation then feeds into the cells in columns F and G, which can be viewed by any curious user if you want to investigate the math involved.

I am indebted to William Hartkopf (retired U. S. Naval Observatory astronomer) for this algorithm.

For wide pairs, the change in θ from 1821 (or any other earlier year) to the present is hardly noticeable, but for very close pairs (pairs under 2" in separation), the change in the plots can be substantial. As Dr. Hartkopf explained to me, when an astronomer chooses to attempt to solve an orbit for a pair, they must first correct for precession because otherwise, the solution will be off by what could be a significant amount. The Plot Tool makes those changes for you automatically. The plot displayed is one that has been corrected for precession.

The Other Data Manipulations on The Plot Tool

I will explain the setup of the other data manipulation routines in the Plot Tool using a plot of ES 1083 (WDS 09013+4843). Figure 10 is the upper left portion of the Data Plot page.

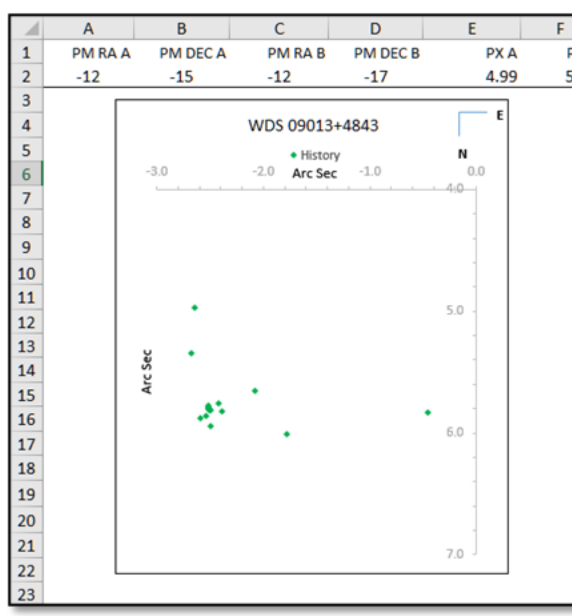

Figure 10: Plot of ES 1083.

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The data seem to be somewhat haphazard and random.

To get the data handling routines to work, you will need to import data from Gaia DR2. You can either do this on-line (using such services as VizieR), or you can download the file "`WDSGaiaDR2 Ver3B.xlsx`" from the JDSO website. This is an extraction of the WDS from DR2 created by Dave Rowe of PlaneWave Instruments that I use almost daily. It is a large file—some 41.2 MB!

To use the Excel extraction from DR2, you need to have the Plot Tool open and on the Data Plot page with the Datarequest.txt file already read into it. Then you need to place the cursor in cell A2.

Next, jump over to the DR2 extraction (ALT+TAB works, or use the keyboard Windows button) and do a search on the star you need. You can search by either the WDS number (best) or discoverer code (tricky). The tricky part about using the discoverer code is to remember that the WDS uses a 7-place alphanumeric string for the discover code. A star like STF1783 is a no-brainer, but something like Bu47 is a bit trickier. You would need to add 3 spaces after the u in Bu to find the star. So you would need to search for Bu_ _ _47 (where the _ characters are spaces).

Once you find the star you need, move the cursor to column E. Simultaneously hold down the SHIFT key and press the RIGHT ARROW key until you highlight everything over to column AB. With all those cells highlighted (shaded light gray), issue the Copy command (I use CTRL+C) and then jump back over to the Plot Tool, Data Plot page. With the cursor in A2, paste the data (CTRL+V) into the Plot Tool.

Before you mess up and accidentally overwrite your Plot Tool file with a star, rename the Plot Tool to the star you are researching.

Figure 11 is part of the lines 1 and 2 from the Plot Tool for ES 1083, Gaia DR2 import.

Several things should be obvious from even a casual glance at this data. First, note in cells A2 through D2 that the proper motion values for these two stars are almost the same. This makes this pair what we call a "common proper motion" (CPM) pair. While this can be an important indicator that the stars may be physically interacting, it is not a sufficient condition to insure this by itself. We need other data to help us build the case.

That other data comes in several forms. Notice the data in cells E2 and F2, the parallax values. They are almost identical, suggesting the stars are at very nearly the same distance. (In this case, the difference of 0.02 milliarcseconds is not enough to worry about. These two stars are, for all practical purposes, at the same distance.) This bodes well for a physical pair!

This case also shows, however, the lower limits of parallax reliability. I find that parallaxes below 5 milliarcseconds are not to be taken as carved in stone. Granted, Gaia DR2 is the best data we have ever accumulated on the stars, but at parallaxes below 5 mas, we are straining the instruments for every bit of their accuracy. If you had a pair with parallaxes, say of 1.62 and 1.88 mas, they may or may not be at approximately the same distance. It would be best to say that the data is inconclusive.

If two stars are gravitationally bound, their radial velocities (cells I2 and J2) should not be too different. Differences greater than that suggested by the system escape velocity could mean that the stars are moving so fast that they can escape each other's gravitational pull and hence stop being a binary (or they were never a binary to begin with). (Rica, 2011)

Figure 12 is where the main data for confirming a pair's likelihood of being physical is handled in the Plot Tool.

There are six numbered zones in this part of the Plot Tool that I will now discuss in some detail.

Zone 1

Here, Plot Tool does a proper motion analysis on the pair. Note that it reads the PM factors for both RA and DEC for each star from row 2. The First Yr Obs is automatically copied from the Datatext file, but since we don't know how many measures each pair has, the Last Yr Obs cell will not contain data until you type it in. Just scroll down to the last row of measurements to get the year to enter here.

Zone 2

Plot Tool then computes how many years have elapsed between the first and last observations and then computes what the motion of the pair SHOULD have projected on the sky during that time. This is displayed in Zone 2. The numbers in red indicate the expected displacement (ρ) and the position angle of that displace-

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	PM RA A	PM DEC A	PM RA B	PM DEC B	PX A	PX B	DIST A PC	DIST B PC	RV A	RV B	RAD A	RAD B	LUM A	LUM B
2	-12	-15	-12	-17	4.99	5.01	200.40	199.60	13.35	12.54	1.19	1.23	1.71	1.92

Figure 11: Part of a DR2 data import.

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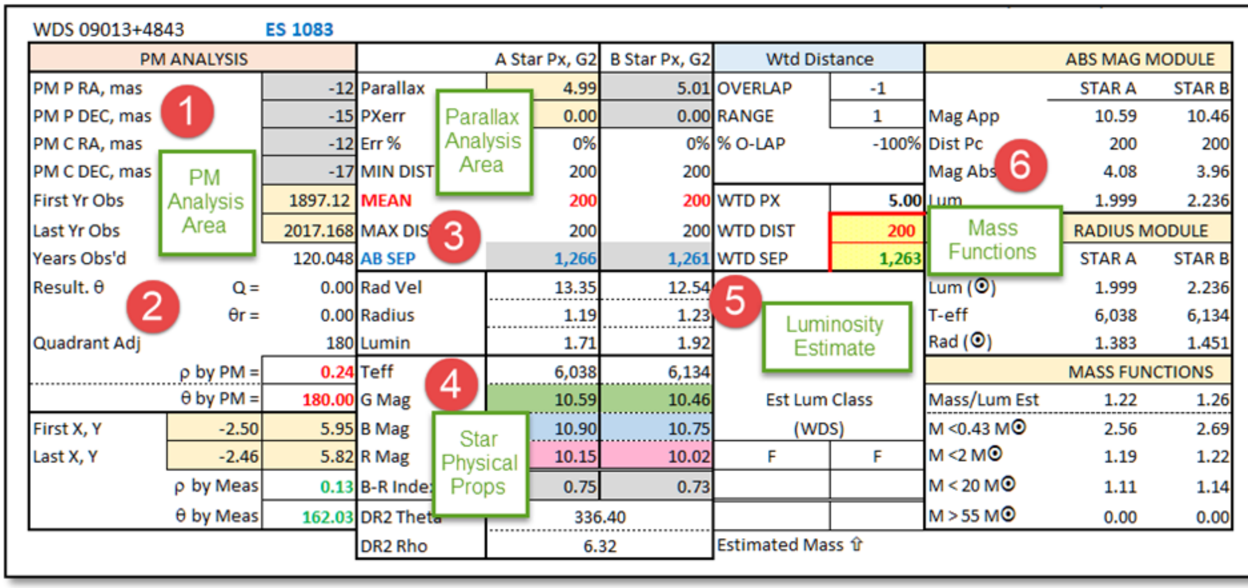

Figure 12: DR2 Analysis in the Plot Tool.

ment (θ). If the proper motion data is accurate, we should see something close to this motion and direction based on actual measurements.

That is where the next section comes in. Plot Tool reads the First X, Y from the datarequest file, but the Last X, Y data must be input manually. Just scroll down to the end of the datarequest file and enter the values for X and Y as shown in columns D and E.

Plot Tool then computes the measured θ and ρ from the measurements. If the values in green come in close to the values in red in this section, that is a good indication that the proper motion data is probably accurate and that the proper motion data can account for the motion of the system over time. This may (or may not) mean the pair is physical, but it is a good indicator that this is certainly a possibility. It is when the values in red and green differ greatly that one must suspect that the pair is not physical.

But there is a caveat. If the red and green numbers in Zone 2 are significantly different, it could be because (a) the proper motion data is invalid, or (b) either the first or last measurement is inaccurate, or both. Case (b) will apply in many cases where the first measurements were made prior to 1850, when measurement was done by filar micrometers illuminated by candles or ring micrometers and stop watches.

Zone 3

Plot Tool analyzes the parallax data in Zone 3. It reads the parallax values from row 2. The cells PXerr are where the parallax error estimate goes. When Mr. Rowe created the Gaia DR2 WDS extraction, he did not think including the error estimates was essential, but I believe it is. To get the error estimates, you will need to access the double star through a service like VizieR and call up the DR2 catalog, enter the coordinates, and select the correct star from the list of stars returned by the query. It may add 5 minutes to your analysis, but it can help confirm (or dispel) a pair being physical or not.

The MIN DIST, MEAN, and MAX DIST values are merely the minimum distance based on the parallax plus the error estimate, the parallax without error estimate, and the parallax less the error estimate.

The AB SEP numbers (in blue) are estimates of the minimum separation between the two stars. I say minimum because we have no idea yet of the orientation of the pair's orbit to earth (or if it even has an orbit), so the projected separation is merely the hypotenuse of a much more complex trig problem. Knowing that the Sixth Orbit Catalog has very few pairs where the actual separation exceeds 2,000 or so astronomical units (AU) is helpful, but not an ironclad guarantee of physicality. Mathematical modeling of double stars shows that in some cases a pair can be separated by up to 380,000 AU and more (Knapp, 2020).

To the right of the Parallax Zone (zone 3) is a section headed "Wtd Distance." This is where Plot Tool projects the distance to the pair using a weighting method. The "Wtd Px" cell computes a "median" parallax based on the relative weights of the parallaxes, with the parallax with the smaller error estimate having a higher weight than the other parallax. The formula is open to review if you want to see it. Place the cursor in cell N9

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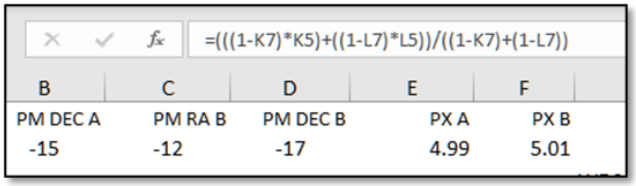
=(((1-K7)*K5)+((1-L7)*L5))/((1-K7)+(1-L7))

B	C	D	E	F
PM DEC A	PM RA B	PM DEC B	PX A	PX B
-15	-12	-17	4.99	5.01

Figure 13: The Parallax Weighting Formula.

and read the formula in the formula bar at the top of Excel (Figure 13).

Once the weighted parallax is computed, Plot Tool can then determine the distance to the pair assuming that the weighted parallax is close to the actual parallax. Note that if you do not look up and enter the parallax error estimates from Gaia's DR2, the weighted parallax will be the same as the mean parallax.

I suggest that any parallax of under 5 mas (milliarcseconds) should be taken with a healthy dose of skepticism for reasons already stated.

The Overlap cell (N4) expresses how much overlap may be between the two stars when their parallaxes are different. Figure 14 is an example of overlap.

The DR2 data for the double star HJ 2687 would suggest different distances to the stars (218 and 227 parsecs respectively, making them some 9 parsecs apart—far too wide to be a gravitationally bound binary, but perhaps still being a physical pair). But the parallax error estimates suggest that the primary star could be anywhere from 188 to 261 parsecs away while the companion could be 227 to 261 parsecs. There is an obvious overlap as shown in Figure 14, but there is also a pretty large area to the left of the overlap zone where the primary star could be at a much greater distance from companion. So we cannot say with certainty that the two stars are physical, let alone binary.

The Overlap Range is the amount of overlap between the two error lines. (In Figure 14, that would be 261-227 = 34 parsecs). The "% of O-Lap" would then be 34 parsecs divided by the total distance spread of 261 parsecs less 188 parsecs (which is 73 parsecs). So the "% of O-Lap" would be 34 / 73 = 47%. This means that slightly less than half the total range of possible distances is where both stars could be close enough to be gravitationally bound.

Zone 4

Zone 4 captures the relevant physical data about the pair—radial velocities, radii, luminosities, Teff, and the G, R and B magnitudes. The B-R index is computed by Plot Tool. This section is for convenience's sake and has no direct bearing on the calculations of distance and proper motion.

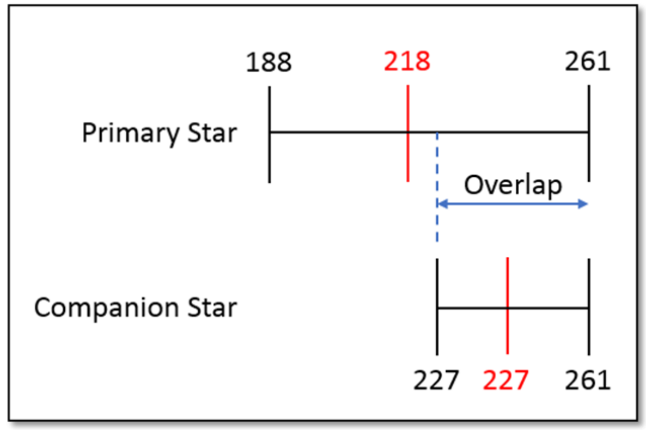

Figure 14: Graphical representation of parallax overlap (IHJ2687 as the example)

Zone 5

Zone 5 is where Plot Tool estimates the spectral class of the stars (cells M18 and N18). The letter classification is based purely on the T_{eff} value. Cells M19 and N19 are where you can type in the spectral class (including the luminosity class) from the WDS. Cells M20 and N20 are where you can enter an estimate of the masses of the two stars. This in turn is based on the outputs of Zone 6.

Zone 6

Zone 6 is where Plot Tool does some calculations of absolute magnitude and hence an indicator of the luminosity class and mass estimates based on DR2's distance estimate, T_{eff} and luminosity. If we know the apparent magnitude (how bright the star looks to us) and the distance, we can compute the absolute magnitude (how bright the star is at a standard distance of 10 parsecs). From this information, we can compute the luminosity in cells P9 and Q9. Note that the luminosity values from these calculations may or may not agree with the DR2 luminosity reported in cells K14 and L14.

The Radius Module section estimates the physical sizes of the stars based on their Teff values and luminosity. The result is an estimate of the star's radius in terms of the Sun.

The Mass Functions area estimates the stellar mass based on the mass/luminosity ratio where empirical data suggests that a star's luminosity is proportional to the star's mass to the power (1/3.5).

Figure 15 shows the estimated mass based on the

$$Mass = \left({L}/{n} \right)^x$$

relationship that a star's luminosity is related to its mass along the relationship

where L is luminosity, n is a divisor based on empirical

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Rad (☉)	1.383	1.451
MASS FUNCTIONS		
Mass/Lum Est	1.22	1.26
M <0.43 M☉	2.56	2.69
M <2 M☉	1.19	1.22
M < 20 M☉	1.11	1.14
M > 55 M☉	0.00	0.00

Figure 15: Mass function section.

Mass range	*n*	*x*
< 0.43 solar	0.23	1/2.3
< 2 solar	1	1/4
< 20 solar	1.4	1/3.5
Over 55 solar	32,000	1

Table 1. Values of n and x for the Mass-Luminosity relationship

studies of stars, and *x* is an exponent also derived from those empirical studies. Table 1 are the divisors and exponents.

Note that the mass derived from this process is an approximate estimate only. The only certain way to obtain stellar masses is to solve a binary orbit and know the distance to the pair. The data in the table above is derived from the pioneering work of Jakob Karl Ernst Halm and applies only to Main Sequence stars. (See this web site for a decent treatment of these factors: https://www.1728.org/masslum.htm).

Using our example of ES 1083, with predicted mass/luminosity ratios of 1.22 and 1.26, I would probably place these two stars at about 2 solar masses each. Given their slightly larger sizes and F spectral classes, we might assign them to the Main Sequence, so they would be late FV and FV classes respectively, possible F9V types.

4. A Useful Tool: Excel's Trend Lines

Once you have plotted the data for a pair, you can look at the plot to determine if you see a pattern in the data. (But be careful! The human mind is very good at creating patterns where there are none.)

Most of the time, a plot of data from the WDS will be like the one I have been using in this paper— ES 1083. The data will display a random smattering of points, not unlike the pattern of pellets from a shotgun shot at some distance from a target.

But other times, you will get plots that show tantalizing hints of a possible pattern. I am referring to two types of pattern in particular: a short arc (an arc being a segment of an ellipse, which is the projection of a 3-dimensionsal orbit onto a 2-dimensional sky) and a line (the points lie along a line of some length). Obviously, an arc suggests an orbit is involved, even if it has not yet been solved. Any short arc binary (SAB) pair should receive priority in any observing program as we need to gather more data to enable someone to someday derive an orbit.

The linear cases (LINs) are a little tougher. Sometimes, the linear pattern may be only a few arc seconds in length. Is this a true linear case (suggesting an optical pair of stars), or are we seeing a very small piece of a large nearly edge-on orbit? (Such cases could masquerade as linear examples.) But if the pathway is long (several arc seconds), and is strongly linear, it is likely (but not guaranteed) that the pair is, in fact, a linear (optical) case.

Let's examine a case of a SAB plot. In Figure 16

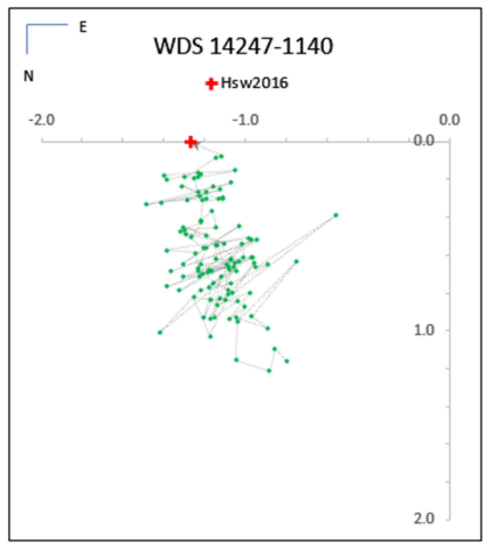

Figure 16: Plot of WDS 14247-1140.

we have the Plot Tool depiction of WDS 14247-1140 (STF1837).

I have superimposed over the data an Excel line that connects the data in chronological order. (Later you will see how this handy feature can sometimes show what looks like a LIN or SAB case to be random noise in the data.)

You can see a definite curvature to the data trend. Figure 17 is the same plot without the chronological line connecting the data. It is much harder to detect a pattern here!

And Figure 18 is the same plot with an Excel trend line (in this case, a polynomial line) and it's R^2 value.

(You can ask Excel to draw a trend line by right clicking on any data point and selecting "Add Trend-

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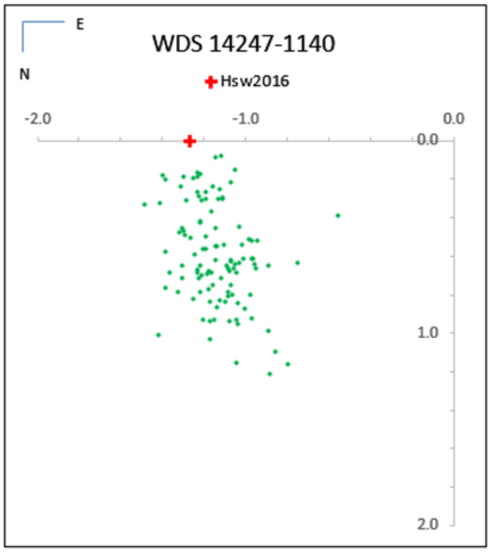

Figure 17: WDS 14247-1140 without the chronological connector.

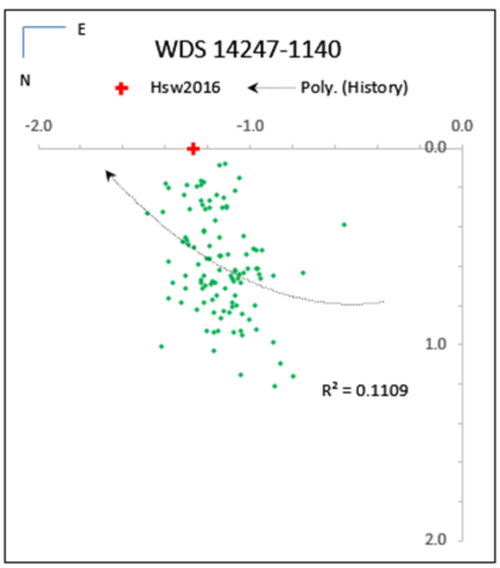

Figure 18: WDS 14247-1140 with an Excel polynomial trend line.

line" from the fly-out menu. When that option is chosen, you have control over how the trend line is displayed. I chose the polynomial trend function because orbits follow ellipses which are polynomial equations.) The R^2 value of 0.1109 is not very strong. This number represents how well the data fit the trend line. A value of 1.0000 means there is a perfect correlation between the data and the trend line. A value of 0.0000 means absolutely no correlation exists. (For comparison, a linear trend for this pair has a lower R^2 value, 0.1055.)

This case could use some weighting, and I will come back to that later in this paper.

Let's now consider a linear case (one that, surprisingly, does not yet have a solution). Figure 19 is the plot for WDS 00167+4104 (FAB 2 AB). In this case, I

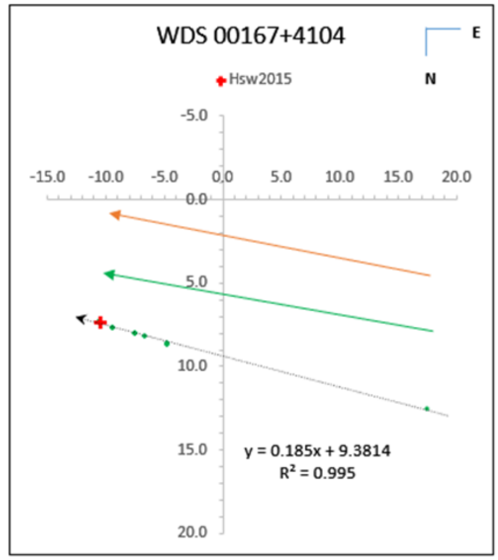

Figure 19: Plot of WDS 00157+4104.

have also included the equation of the line as well as two vector arrows, one orange and one green.

The orange vector is how the pair should have moved over the years if we are considering only the proper motion (which in this case is very large and of very different values). The green vector is the motion given my using the first and last measurements. Note how the two vectors are nearly identical in magnitude and direction. This suggests very strongly that this pair's motion can be explained by the proper motions of the stars alone and that there is no motion due to gravitationally-induced motion as in the case of a binary star. This pair is most likely optical.

[To draw the vectors, use the outputs of Plot Tool, cells I15 and I16 (for the proper motion) and cells I19 and I20 (for the measurements). Select the draw tool in Excel and choose the one-headed arrow. Draw a vector along one of the axes the same length as the values shown in either cell I15 (for proper motion) or I19 (for measurements). To get the angle of orientation, right click on the arrow and select Size and Position, then adjust the rotation to match the position angles of cells I16 or I20. Then drag the arrow to a convenient place on the plot.]

5. Weighting the Data for a Better Analysis

Excel assigns equal weight to every data point, but when analyzing measurement data, astronomers know

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that some measurements are worth more than others, so they must "weight" the data. There is a simple (but cumbersome) workaround for this in Excel.

I weight data using four key factors, similar to the factors suggested by Dr. William Hartkopf [1] of the U S Naval Observatory (retired)—see http://ad.usno.navy.mil/wds/orb6/orb6ephem.html: (1) the separation of the pair compared to the Rayleigh limit of the telescope; (2) the type of measurement made; (3) the observer making the measurement; and (4) how many nights the pair was observed. I will now explain how this method works.

The Rayleigh Limit Factor

How close is the pair compared to the telescope's resolving power? The Rayleigh Limit defines a telescope's theoretical resolving power as a function of its diameter. A larger telescope can resolve smaller angles. For my weighting method, I use the following criteria:

- If the Rayleigh Limit RL is less than ρ: weight of 0.5
- If the RL is between 0.5 and 2.0 ρ: weight of 1.0
- If the RL is between 2.0 and 4.0 ρ: weight of 2
- If the RL is greater than 4.0 ρ: weight of 3

To compute the RL for a telescope, take 5.23 and divide by the objective diameter if it is in inches, or divide 0.138 by the objective if stated in meters.

The Type of Measurement

This refers to the method used by the astronomer, such as filar micrometer, photo, CCD, speckle and so on.

I took 303 known Grade 1 and Grade 2 orbits and ran residuals on every measurement made by every observer. I then analyzed the results for trends and found many. One of them was the type of method used. Certain methods routinely produced *lower* residuals (that is, better measurements) than other methods. I use five weighting levels.

Methods of weight 5 (the most accurate methods) include any satellite method (since the satellite is imaging the stars above the distortions of the atmosphere), all interferometric methods, and all speckle methods.

Weight 4.5 Methods include CCD and photographic imaging.

Weight 4 Includes adaptive optics, electronic imaging, and the Mt. Wilson interferometers.

Weight 3: Micrometers.

Weight 2: Visual interferometers, the Celestron MicroGuide (and Mead Astrometric) eyepiece, and transit circles.

Weight 1: Heliometers, occultations.

The Observer Making the Measurement

By its nature, this is very private and personal data and as such I am not comfortable sharing my findings with the general public. My analysis of the 303 orbits showed that some astronomers were consistently poor in observing quality while others were consistently high. I use a 5 point scale, with 5 getting the greatest weight. Since you don't have access to my data, you can play it safe and assign all observers a default weight of 2.5.

The Nights the Pair Was Observed

This is simply the square root of the number of nights the star was observed. Obviously, an astronomer who reports measures that are an amalgamation of four nights of work is going to have a steadier result than the one who only observes the pair one time.

Normalizing the Weights

Figure 20 is a picture of the normalization routine and weighting process I use when weighting measurements. (Note that this routine is not part of Plot Tool 3.19 but must be added if you want to do weights. I did not include it for the reason I stated earlier about distributing observer weights.)

The first column—Rho/RL—is the ratio of the value of r to the Rayleigh Limit of the telescope. Since all the values are greater than 4, I entered "3" into the Aper Gr column. The Meth Gr column is filled in based on the type of measurement. Obs Gr is a semi-objective assessment of each observer's skills. And the Sqrt N column is merely the square root of the number of nights the star was observed. The "Moment" column is the product of all the weights.

Above the Moment header are three numbers: Max, Min and Range. The Max is the largest moment in the list of measurements. The Min is the minimum moment, and Range is the difference in these two values.

				Max	135		
				Min	33.75		
				Range	101.25	20.25	
Rho/RL	Meth Gr	Obs Gr	Aper Gr	Sqrt N	Moment		Final Wt
		2.5		1	0	0	1
21.56957	5	2.5	3	1	37.5	1.851852	2
21.56957	5	2.5	3	1	37.5	1.851852	2
21.35217	5	2.5	3	1	37.5	1.851852	2
21.35217	5	2.5	3	1	37.5	1.851852	2
99.19565	4.5	2.5	3	1	33.75	1.666667	2
99.19565	4.5	2.5	3	1	33.75	1.666667	2
15.94928	4.5	5	3	2	135	6.666667	7
15.94928	4.5	5	3	2	135	6.666667	7
15.94928	4.5	5	3	2	135	6.666667	7
15.94928	4.5	5	3	2	135	6.666667	7
15.94928	4.5	5	3	2	135	6.666667	7
15.94928	4.5	5	3	2	135	6.666667	7
15.94928	4.5	5	3	2	135	6.666667	7
61.73188	5	5	3	1	75	3.703704	4

Figure 20: The weights normalization process.

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The 20.25 value you see in the example (circled) is the Range divided by a number that is chosen to get the lowest Final Wt value as close to 1 as possible. In this example, Range was divided by 4 to get 20.25.

The Moments are then divided by this recomputed Range to get the numbers to the immediate right of the Moment column. For the Final Wt, I then round the adjusted moment to the nearest integer.

Example: the second measure in the list comes in at 37.5 for the moment, 1.851852 for the adjusted moment, and 2 for the Final Wt.

Once all the weights are finalized, I then go to any weight that comes in below 0.5 and delete it. For the measures that are left, I then go to the line directly below the measure and insert as many blank lines as necessary to get to the Final Wt number. (For a Final Wt of 2, I would insert one line. For a weight of 5, insert 4 blank lines.)

Next, I select the line above the blank line and copy it, then Paste it into the newly formed blank line, but be sure to use the **Paste Special, Values** option. Otherwise, the process will not work.

In this somewhat cumbersome method, Excel now properly assigns weights to each measurement and the R2 value displayed on any plots is very accurate. Of course, the line or curve will also be reshaped to some extent by this procedure.

6. The Value of a Chronological Plot in Weeding Out False Positives

Sometimes, Plot Tool generates a data plot that strongly suggests either a LIN or SAB pattern. Figure 21 is one example of a LIN case. The measurement vector (green arrow) suggests a linear pattern. But is it? Figure 22 is the same plot with the chronological plotting option displayed.

The "appearance" of linearity is due to a few measures being outliers. The first measurement (the farthest outlier) was made by John Herschel in 1829. John's error is significant, but understandable seeing how he was using an early, primitive and very difficult method to determine θ and ρ—a ring micrometer. When you look at the latest data, the points all cluster near one another in a tight pattern, something that is typical of early micrometric measurements. (The sky can distort measurements that much from night to night and observer to observer!)

Figure 23 is an even better example. There is a strong R^2 coefficient and an "obvious" linear pattern, until one looks at the data in chronological order, Figure 24.

What happened to our nice linear plot? It was never there. Instead, the data seems to be one of those

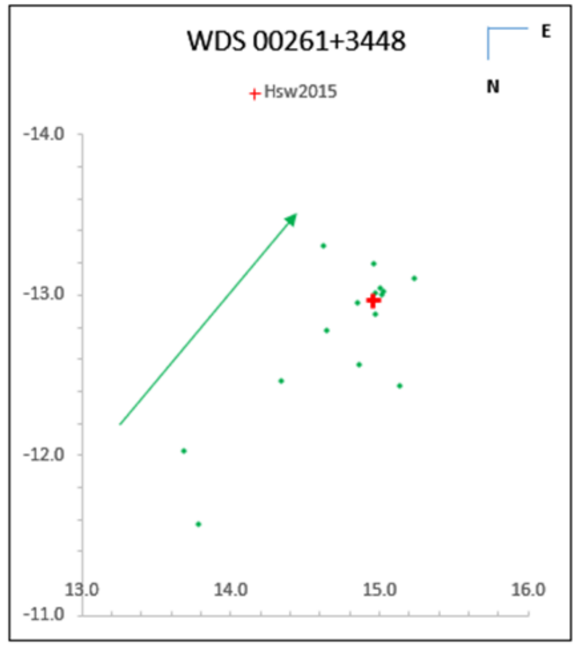

Figure 21: Plot of HJ 622.

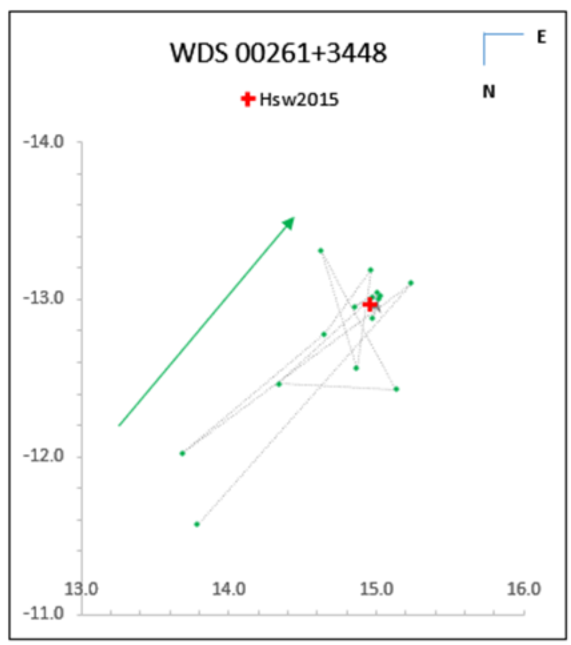

Figure 22: HJ 622 with the data plotted in chronological order.

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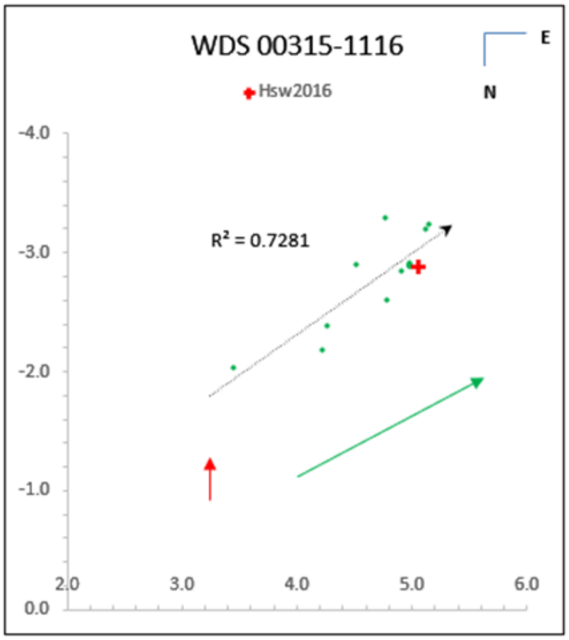

Figure 23: Possible linear case of HJ 1980.

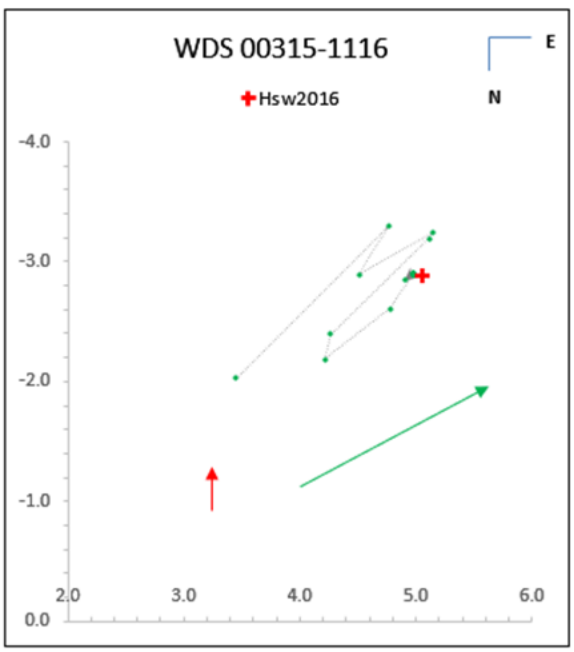

Figure 24: HJ 1980 with chronological data plot.

"random walk" illustrations shown in many statistics textbooks. If anything, there may be a very weak arc going clockwise from upper left to lower right, but that is purely subjective and not admissible in a court of scientific inquiry.

The same thing works for detecting false SAB cases. The polynomial trend line in Figure 25 produces a much better fit at R^2 = 0.7300 than a linear trend with an R^2 value of only 0.3317. So at first glance, we might

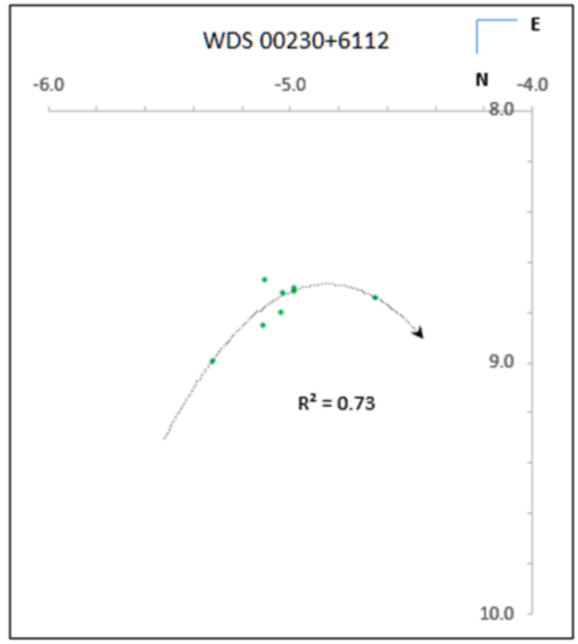

Figure 25: The SAB plot of WDS 00230+6112-- or is it?

conclude we are dealing with a SAB.

But notice how the curve does not wrap around the graph's origin point [(0,0), not shown here but off to the upper right]. All SABs should wrap around the system's origin (the location of the primary star for these plots). So that tells us right off that something is amiss with the trend data from Excel.

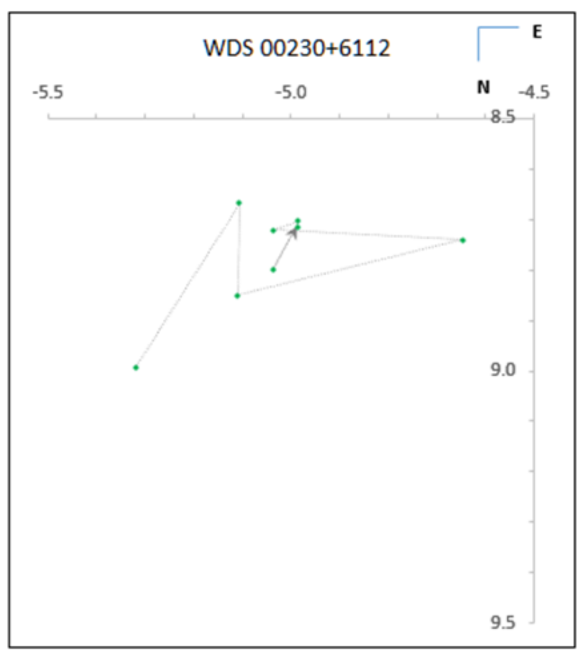

Figure 26: :The same pair with a chronological connection of the data.

In Figure 26, I have asked Excel for a chronological plot of the data and that changes things significantly. That tempting SAB is now gone. No short arc here. Just a random set of noisy observations.

Because of the power of a chronological plot, I almost always suggest that authors submitting papers to the JDSO first generate a chronological plot of the data to see if the trend they say they see is real or not. Our brains are so easily fooled by random information appearing as patterns. (Just think of the constellations of the night sky!)

8. Conclusion

If you want a copy of The Plot Tool 3.19 (for Excel, written in the Office 365 version, but should be readable by any version of Excel from 2007 on), you can download "`Plot Tool 3.19.xlsx`" from the JDSO website. Hopefully, use of this tool will help you see double stars in a new way and find real patterns as opposed to what merely looks like a pattern. You may also download a copy of the WDS Extraction from Gaia DR2 from the JDSO website named in Section 3, The Other Data Manipulations on The Plot Tool subhead.

9. Acknowledgements

The author would like to thank Dr. William Hartkopf of the U. S. Naval Observatory (retired) for his assistance in the precession algorithm in Plot Tool.

The author also wishes to acknowledge the valuable contribution to double star research provided by Mr. David Rowe of PlainWave Instruments for his detailed extraction of the WDS from Gaia DR2.

Finally, heartfelt appreciation goes to Dr. Brian Mason of the U. S. Naval Observatory. His tireless and cheerful response to over 8,000 datarequests generated some big "Tar balls" and led to both of us learning a thing or two about large data transfers.

10. References

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