

## The Double Star Speckle Interferometry Observation and Reduction Process

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**Abstract** The process of planning for, obtaining, and reducing speckle interferometry observations can be broken down into three major phases: pre-run, during-the-run, and post-run. Establishing formats for a target list, run log, and reduction program facilitates a smooth flow of data that minimizes human work and errors.

### Introduction

Lists of double star observational candidates are maintained by various astronomers in formats they have devised that work for them. They may maintain a single master list, or perhaps more than one list—a different list for each observational program. Astronomers often make their observations on the same telescope year after year. For any specific run, their master list or lists may be pared down to match the run constraints in terms of RA, Dec, etc., thus providing them with a run list. If there are multiple master lists, they may be combined prior to trimming, to yield a single run list. Some but not all of the candidates on the pared-down run list will then be observed during the run. After the run, the data is reduced, often with a custom program written by the astronomer.

The situation being considered here is a somewhat different (and specialized) situation than the normal situation for single astronomers. The observational process discussed below would typically involve multiple astronomers, multiple at-the-telescope observers, and observations on different telescopes at different times. The observational results are widely shared and relatively easy-to-use and well-documented “public” reduction and analysis techniques are vital. Due to the variety of observational programs and participants (including beginning students), a somewhat standardized, well documented observational process that specifies file formats and provides well-documented software should aid efficiency and accessibility.

What is presented below is a work in progress. A seven-night run at Kitt Peak National Observatory required that a standardized format be generated on rather short notice. That said, it should form a starting point for more refined processes for similar runs and perhaps help with the formulation of a fully automated speckle interferometry observation and reduction process.

A computerized Scheduler is a requirement for automated observations. The input to a Scheduler is the Run List of potential targets. The Scheduler decides, based on a set of decision rules, what specific target is to be observed next by an automated telescope. This set of decision rules can be somewhat complex as it has to consider closeness to the meridian to minimize air mass, spatial nearness to other targets to minimize slew times, azimuthal location if observed at a domed observatory to minimize long dome rotations, scientific priority of the target, past observations of the target, any special observational needs such as repeated observations for calibration, changes in the overall observing program in case of major weather or equipment problems, etc.

In the process described below, the Run Master is the human Scheduler, and the decision on what to observe next during a run is made by the Run Master based on the sorted contents of the Target List. The advantage of a *Run List* is that, if properly generated, it can reduce the scope of the decisions the Run

Master needs to make, although some human assessment would still be required as decisions would have to be made on what should and should not be observed as one fell behind in the “meridian window.” The Run Master would also need to note on the *Run List* what had been observed so it would not be needlessly re-observed on following nights unless that was what was desired.

The binary star speckle interferometry observational process can be broken down into three major phases: Pre-Run, During-the-Run, and Post-Run. Each phase is described briefly below. Two separate documents provide suggested file formats and describe a speckle interferometry reduction program, PlateSolve3 (PS3), written by David Rowe.

Four principles have guided the development of the speckle interferometry observation and reduction process. They are: (1) minimizing human entries, (2) separate flows for target information and image data (FITS cubes), (3) minimizing data carry through in the reduction program, and (4) aiming for eventual full automation. Each principle is described briefly below:

- (1) In organizing the data flow and specifying file formats, attention has been paid to minimizing human entries, especially in terms of copying information from one format to another. Such minimization reduces human-induced errors. This minimization required working backwards from the required inputs for the reduction program, PS3, to the Run Log, and finally to the Target List. This is not to suggest that humans (or computers) do not need to add data as they go through the process from beginning to end (they do), just that inputs should not have to be repeated and formats should be specified such that they can directly feed into the reduction program.
- (2) While the Andor EMCCD cameras used in some of our runs automatically place considerable camera-related information into the FITS headers, we have chosen not to add any outside human- or machine-entered data into the FITS headers, relying instead on a separate flow of information via spreadsheets.
- (3) The third organizing principle was minimizing data “carry through” in the reduction program. The reduction program, PS3, is intended for general use, both manual one-FITS-cube-at-a-time operation as well as semi-automatic operation on an entire file of FITS cubes. By only acting on the minimum required inputs, placing these at the beginning of each row in the input, and ignoring everything beyond these columns, the reduction program minimizes constraints on users. This does require, however, that the PS3 output needs to be merged with other data to provide the final results.
- (4) Besides serving human-operated telescopes and cameras, it is the aim of this speckle interferometry observation and reduction process to achieve total automation, given the appropriate telescopes and cameras.

There are six files with specified formats. Movement from one file to another is made easier to the extent possible by insisting that the parameters in the files have the same names and definitions, are in the same column order on spreadsheets, and are grouped together in intelligent ways. The six files are: (1) Target List, (2) Run Log, (3) FITS Cubes, (4) PS3 Out File, (5) Final Results, and (6) Reference Stars.

The Run Log and Target List files are identical in format. However, there are two distinct differences between these files. One difference is that more run-specific values have been entered by the Run Master into the Run Log during the run than are contained in the Target List. For instance, the Run Master enters FITS Cube numbers (the camera sequence number) of both double star targets and single reference stars and the filter ID.

The other difference is that while the Target List contains all possible targets that could potentially be observed, one per row, the Run Log contains what was actually observed, both Targets and single reference stars, one FITS Cube per row. The double star rows are in exactly the same format as the rows in the Target List, and in fact the rows are simply copied out as they are observed. The Run Master fills in the empty cells in the row with the camera sequence numbers, etc. The single star rows, however, only contain the single star ID, camera sequence number, and the filter ID.

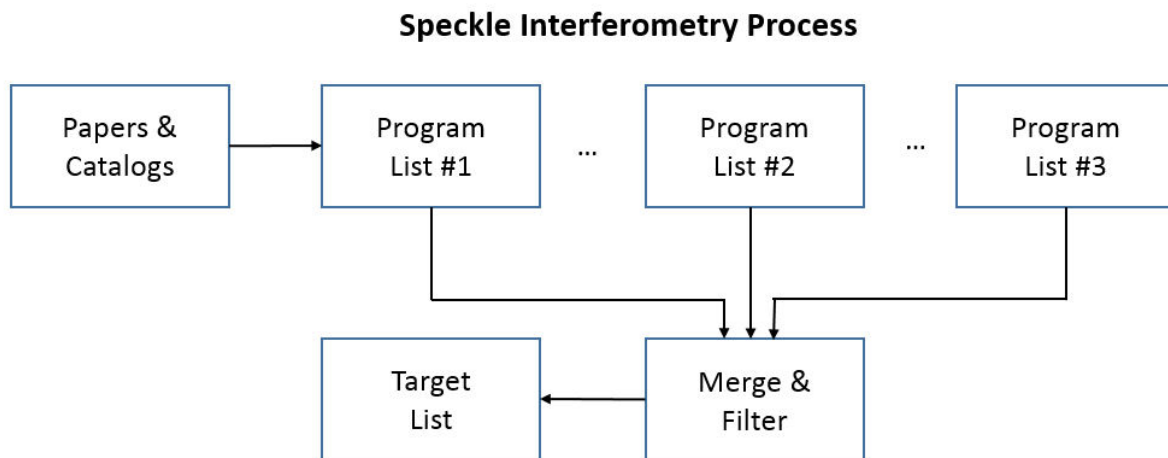
If a target is observed several times in a row on one night, or on several different nights, it will appear multiple times in the Run Log at different places in the log, while it will only appear once in the Target List.

The FITS Cubes file is simply the raw observational data file of FITS cubes. It can be transformed to a preprocessed file where the Fourier transforms have been taken of all the frames (typically a thousand or so) and averaged. Preprocessing reduces the file size by roughly the number of frames in a FITS cube, or roughly a thousand. Once preprocessed, this much smaller file is easy to handle and distribute. It is vital, however, to maintain the raw data, as one never knows what reduction techniques might be applied to the raw observational data in the future.

The PS3 Out File is the reduced observations (with position angle, separation, and delta magnitude), along with reduction parameter settings and any comments by the reducer. The Final Results file merges data from the Run Log and the PS3 Out File to provide final results.

### Pre-Run

The objective of the pre-run phase is to develop a Target List for a specific observational run. The pre-run process is shown in Fig. 1. Candidate target lists are developed by searching catalogs such as the Washington Double Star Catalog, the Sixth Orbit Catalog, the Fourth Interferometric Catalog, etc., for suitable targets for a specific scientific research program. Past papers in a given research area often provides target suggestions.



**Figure 1.** Pre-run major functions.

The various program lists are then merged in preparation for a run on a specific telescope. If the Program Lists are in different formats, merging may require manual intervention. Thus there is merit in employing a uniform format across various Program Lists. On the other hand, some research programs may have important parameters unique to an observational program (such as the period and other orbital parameters for known binaries). One approach to maintaining uniformity with diversity is to standardize a limited number of columns on the “left” of the spreadsheet lists, thus allowing uniform filtering and sorting, while leaving the remaining columns to be free form and thus vary from one program to the next.

Once the program lists are merged, then the observational constraints for the specific run can be applied to filter out unsuitable candidates. Such constraints typically include a range of RA and Dec coordinates, as well as upper and lower limits for separation, delta magnitude, and brightness. Typically, target lists should contain somewhat more targets than could possibly be observed even if the weather was clear for the entire run and the equipment operated perfectly.

Single reference stars need to be assigned to each target double. One way of doing this is to develop an all-sky “catalog” of single reference stars within an appropriate magnitude range. For any given double star target, a selection “aid” could then display the possible single reference stars within some specified radius, and an appropriate star selected. Alternatively, this selection process could be fully automated. For targets that have small separations, are observed at high air mass, or are otherwise “difficult” targets (large delta magnitude, faint, etc.), it will be important to select a nearby reference star and observe it

immediately before or after the double star. On the other hand, for “easy” targets, the reference star will not need to be so close in space and time. Thus one reference star might be observed just once and provide the reference for a number of sufficiently close double stars. This would increase observational efficiency by reducing the number of unnecessary reference star observations.

Target lists should include instructions on how many times a target is to be observed within a single night, and for how many nights. For instance, a few well-known binaries might be observed several times a night on each night of a run to help establish within- and between-night observational precision.

We have found it useful, prior to the run, to sort the Target List into RA bands where the width of each band is two hours in RA. Within each band, the targets are then sorted in Dec, with high Dec targets at the top and low or negative Dec targets at the bottom. These RA bands can all be on the same overall spreadsheet as individual pages, with the western-most RA band at the first page in the spreadsheet and the eastern-most as the last page in the spreadsheet. Over a time period of a couple of hours, one observes targets within one RA band, knowing that targets will rarely be more than one hour away from the meridian and thus have minimal air mass. Roughly every two hours, one moves on to the next RA band. This procedure can be modified somewhat if one wants to extend RA coverage by picking up somewhat high air-mass targets in the west in the early evening and similar targets in the east in the early morning.

Target lists can also be supplemented with information extracted from catalogs as well as graphical plots of past observations, calculated orbits, etc. For instance, for lists containing known binaries, the plots of the binaries can be placed in the same folder that also contains the Target List spreadsheet with the plots linked to the Target List spreadsheet. This way, while considering the Target List during a run, one can view a plot with a click of the mouse and the visual display can help determine whether the target should be observed or not. If the target is observed, then the plot will help determine if quick-look results match what was expected.

As mentioned in the Introduction, to minimize human entries and allow direct reduction without reformatting, it is necessary that the required reduction entries be placed in the left-most columns of every target row. Work can be minimized if this requirement is also applied (working backwards) to the individual program lists, although this is not an absolute requirement.

### **During-the-Run**

Telescopes at major observatories are not usually equipped for speckle interferometry, so observers bring and operate their own systems. Some telescopes have staff operators, while others are operated by the using astronomers themselves. Speckle interferometry is fast-paced, and while it is possible for a single person to operate the telescope, speckle camera, and select targets and maintain an observing log, a team of three observers is ideal. Having relief replacements, especially for long, multi-night winter runs, is highly desirable. It is helpful to have enough observers on hand so data can be reduced during the observations and their quality assessed. Suggested team assignments/titles are: Run Master, Camera Operator, Telescope Operator, and Quick-Look Analyst (see Figure 2).

As targets are observed, the information from the Target List is carried through and combined with additional information to form the Run Log. The Run Log is a chronological record of what actually happened during the run. Although the Run Log carries through the information from the Target List, it differs from the Target List in four ways:

- (1) Not all targets on the Target List will be observed, so those not observed are not carried through to the Run Log. Poor weather and many other factors can affect how many targets are actually observed.
- (2) Some targets are observed more than once on a given night, and may be observed more than one night, weather and other circumstances permitting. Thus what starts out as a single row on the Target List, with instructions on the desired number of repeated observations/night and number of nights, can end up as many rows on the Run Log, each associated with a specific double star FITS cube.
- (3) While each target on the Target List includes information (in its row) on the single reference star that should be observed, it would not make sense to make this a separate row on the Target List and, in any event, several double star targets may share the same single reference star.

On the other hand, each row in the Run Log needs to correspond to an observation, i.e. a FITS Cube. So, as reference stars are observed, they need to become rows in the Run Log, along with the corresponding camera sequence # that ties a Run Log row to a specific FITS Cube. The rows for a given target star may not be contiguous, depending on the sequence of its observations.

- (4) Additional information is obtained during the run that was not available prior to the run on the Target List but needs to be incorporated in the Run Log. Specifically, the camera sequence # (FITS Cube) associated with each target observation, and, if multiple filters are being employed, the filter(s) used in the observation need to be included.

The Target List itself can be modified during the run to show which targets have been observed on which nights (and how many times they were observed during the night—almost always observations taken one right after the other). We have found that a handy way to do this is to have narrow columns in the Target List, one for each night of observations. As targets are observed, the Run Master simply enters the number of times the target was observed (most often, just a “1”) for that night. As the run progresses, it is easy for the Run Master to glance at these columns and determine if the target has been observed sufficiently or not. If the weather turns bad during a run, the Run Master may elect to only observe very high priority targets. Knowing at a glance what has already been observed can aid this decision process.

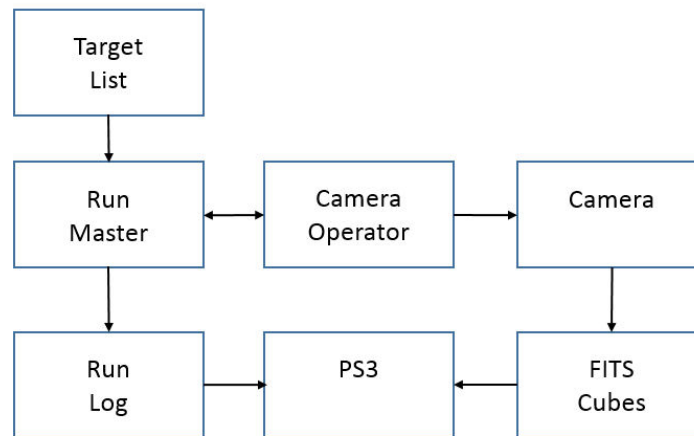


Figure 2. During-the-run major functions.

After selecting the next target to be observed from the Target List, the Run Master informs the Telescope Operator of the target, with precise coordinates often stored in advance in the telescope’s queue. The target is then acquired and passed on to the Camera Operator, who may fine-center the telescope pointing, adjust the camera settings (integration time, gain setting, number of frames, and filter), and start the integrations.

At this point, the Camera Operator informs the Run Master of the FITS cube sequence # so the Run Master can enter the FITS cube sequence # in the Run Log. If more than one filter is used, the Run Master enters the filter ID in the Run Log. Great care must be taken to assure that each and every FITS Cube has a unique sequence number that is entered in the Run Log for the observed target. Finally, the Run Master checks off the appropriate row on the Target List that an observation was made on this night. The Run Master then selects the next target.

During the run, it is prudent to reduce some of the observations as a check on quality. Although at this point, calibration constants may not be well known, “quick look” reductions can still assess the quality of the observations. To make quick looks truly “quick,” it is helpful if the Run Log and FITS Cubes can be directly fed into the reduction program, PS3, without any modification.

Finally, it might be noted that during the run it may be convenient to use PS3 to preprocess the FITS Cubes, as this reduces the file size by a factor of roughly 1000 and also reduces reduction time.

Although the original unprocessed FITS Cubes should be retained, preprocessed FITS Cubes can be easily replicated and dispersed among the observers or even placed on line, thereby assuring that the data from the run will not be accidentally lost.

### Post-Run

After the run, the data is reduced. The Run Log contains critical information on each target, and has the FITS Cube sequence numbers that tie the appropriate FITS Cubes to the targets and reference stars. The post-run major functions are shown in Figure 3.

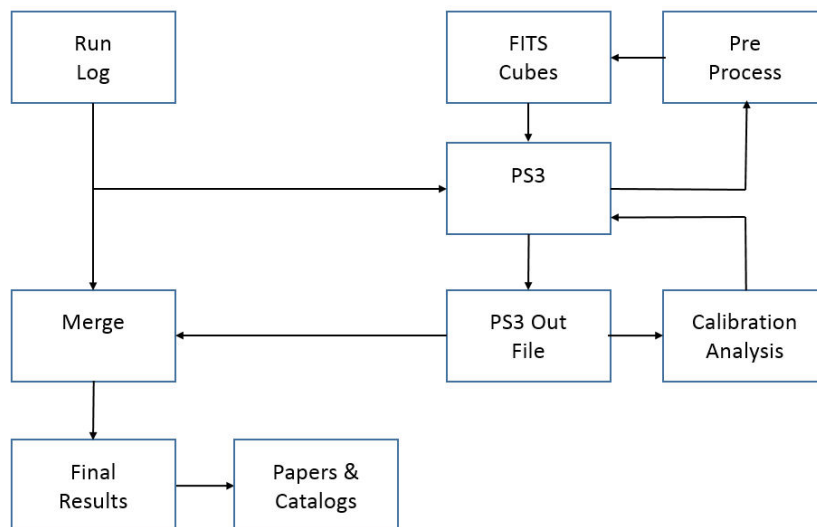


Figure 3. Post-run major functions.

The FITS Cubes file can be quite sizeable. On longer runs it can exceed a terabyte. PlateSolve3 (PS3) has a Pre Process feature that obtains a Fourier transform of each image in a FITS Cube and averages the results. This not only greatly increases the S/N, but reduces the file size by a factor of 1000 or more. While preprocessing can be time consuming, it is an entirely automatic process and can be completed before data reduction proper begins.

The PS3 In File actually only requires and utilizes eight parameters for each target in the Run Log. These parameters must be contained in the first eight columns of the Run Log PS3 In File. Any other columns are ignored, thus the requirement to merge these ignored columns in the Run Log with the PS3 Out File to obtain the Final Results.

The PS3 Reduction is typically done in two iterations. In the first iteration, only observations intended to calibrate the camera angle and pixel scale are reduced. These observations may be of calibration binaries, clusters, drifts, slit masks, or known telescope movements. Analyses of these observations yield the camera angle,  $\Delta$ , and the pixel scale,  $E$ . These calibration values are then used in the subsequent reduction of the entire data set.

The PS3 Out File contains the information provided in the first eight columns of the Run log, the PS3 “solutions” in terms of camera angles, separations, and delta magnitudes, as well as supporting information on the settings of various solution parameters. The PS3 Out File may also contain comments from the Reducer such as “triple star noted” or “suspect reduction” etc.

The final PS3 Out File is then Merged with data from the Run Log to generate the Final Results file. The Results File can then be placed on line and various users can access their portion of the results. After further analysis, the observations appear in published papers or IAU Commission 27 circulars, and eventually in the various catalogs, thus completing the overall process.

## Content of the Spreadsheets

### Introduction

The formats for the spreadsheets (or their .csv file equivalents) in the double star speckle interferometry observation and reduction process were established by starting with the essentially “firm requirement” for specific spreadsheet (.csv) inputs to the PlateSolve3 (PS3) reduction program and working backwards to the Run Log spreadsheet and then to the Target List spreadsheet. Once this was done in terms of required information on these spreadsheets, then further “propagation” backwards to the Program Lists could be made. Similarly, one can start with the information in the Run Log and PS3 Out File and merge and select and/or arrange so as to form the Final Results.

While the above was how the contents were established, the contents and order of the individual parameters in the columns in the Target List and Run Log are identical, the only difference in the two spreadsheets being that some of the cells in the Run Log, such as camera sequence numbers, have to be filled in during the run. Given below is the content in column order.

### Required PS3 InFile First Column's Content

For double stars, the required Run Log .csv file content is established in a forthright manner. The first seven columns of each row in the Run Log must contain the following information:

*T* – If the Target is a “D” (for double), then PS3 will process this file, otherwise it will be ignored. This allows the Run Log spreadsheet to have rows, for instance, for single stars used for deconvolution, slit mask, or drift calibrations, etc., with codes assigned to these other cases. Single reference stars have been assigned an “S”.

*DSFN* – Double star (FITS cube) file name. This required information will be provided by the Camera Operator when starting a FITS Cube observation and will be entered into the Run Log by the Run Master. Our plan at this point is to have the FITS Cube filename be the camera sequence number.

*RSFN* – Reference star (FITS) cube file name. As above, this required information will also be provided by the Camera Operator when starting a FITS Cube observation and entered into the Run Log by the Run Master. Our plan at this point is to also have the single star FITS Cube filename just be the camera sequence number.

*ThetaC* – Calculated (input) estimated, predicted, or last catalog reported double star position angle. This information is used by PS3 to place a “predicted position” of the double star on the autocorellogram. This prediction can then be compared with the automatic solution provided by PS3. If the two are close, one simply accepts the automatic solution and moves on to the next double star. If the predicted position is close to an obvious solution that the automatic solution process somehow missed, then one overrides the automatic solution and readily provides the correct solution. There are other cases where the correct solution is not obvious and this would normally be noted in the “comments” section of the PS3 Out File. The point is that ThetaC is helpful but not critical to the process. Thus it does not have to be a highly accurate value nor, in fact, does it even have to be entered, although a blank cell must be included in the .csv file.

*RhoC* – Calculated (input), estimated, predicted, or last catalog reported double star separation.

*Delta* – Camera Angle (degrees). Delta is the camera orientation angle with respect to the sky. Until the calibration data is reduced and analyzed, Delta (and E, below) will not be known with precision. However they can be estimated beforehand and the Delta and E values entered in all the cells in these two columns in the Run Log in advance. When the camera is installed on the telescope, the goal is to have a camera angle of 0° so 0 can be the initially assigned camera angle.

*E* – Pixel scale (arc seconds / pixel). E can be estimated based on the telescope's focal length and camera chip's pixel size. Alternatively, if the same camera has been previously used on the same telescope, then the earlier pixel scale can be used.

*Filter* – A single letter code identifying the filter. For the Johnson-Cousins system, the filter code is B, V, R, or I (and possibly Y), while for Sloan it is b, g, r, I, or z. If other filters are used, an identifier can be devised (such as H for H-alpha).

In addition to the “mandatory” information in the Run Log required as an input by PS3, additional information for double stars may be supplied.

*Comment* – Any comment the Run Master deems appropriate to enter that might help in subsequent analysis and interpretation of the observational results. At a minimum, the date and time when observations began and ended for each night during the run should be recorded. Recording weather comments would be appropriate, as well as any equipment problems, etc.

*Date and Time* – Also, while the date and time each FITS Cube is initiated is contained in the FITS headers, and can also (optionally) be automatically included in the FITS Cube file name, it is important to also enter this information into the Run Log to help assure that a firm tie exists between the targets and FITS cubes. To enter the date in a cell in the Run Log, click on the date cell and hit *control*; and then click on the time cell and hit *control shift*. The clocks on the PCs that will record or handle data should be set to correct date/time (check time zone!).

For single stars, only *T* (an *S*), *RSFN*, and *Filter* from above are required. The other columns may be left blank except for:

*Single star identifier* – SSID This will normally be the Hipparcos (HIP) number or SAO number of the single star, and will identify what specific single star observation is to be assigned during reduction to each double star. Several double stars can share the same single star, although the converse is not allowed.

### Target List/Run Log Content

For the KP2 run, candidates for the run will be submitted as Program Lists (Excel spreadsheets) where each row is a double star or single reference star to be observed. There will be mandatory entries and optional entries as described below. Missing or unknown information can be signified with an XXX.

*Research Program* – Three character identifier of the overall science research program. There may be several researchers from different institutions participating in the same overall research program. Examples include short arc binaries (SAB), large delta mag (LDM) binaries, common proper motion (CPM) pairs, etc.

*Requestor Code* – Three character identifier of the researcher who is requesting the observation. If a code has already been assigned for first author references in the WDS, please use this code (such as Hor for Elliot Horch, Los for Florent Losse, etc.). If this is more of an institutional request, a three letter (all CAPS) code (similar to those in the WDS) could be used instead.

*Target Classification Code* – A three character classification code which can be unique to a given research program, that provides information on the object. For instance, “known” binaries have been given codes such as KBO (known bad orbit), KSP (known string of pearls), KNS (known no previous speckle observations), etc. There is a beginning of a classification system for short arc binary candidates. The *Target Classification Code* allows the KPI results to be partitioned according to characteristics of the target. Known binaries have been classified based on a visual inspection of the orbital plots of their past observations provided by the US Naval Observatory in their *Sixth Catalog of Orbits of Visual Binary Stars*. This classification scheme was originally developed by R. Genet and E. Weise and has been further refined. “K” was for “Known” to be a binary.

KBO Bad Orbit  
 KCB Calibration Binary  
 KFO Fair Orbit  
 KFS Few Speckles  
 KFM Fast Moving  
 KNP No Points (on plot)  
 KNS No Speckles  
 KSP String of Pearls  
 KVC Very Close  
 KVF Very Fast



Many of the targets are not known to be binaries but, based on their short arcs, are binary candidates. We have not yet developed a classification scheme for short arc targets but may adopt or modify one developed by Richard Harshaw: SAX Short Arc X (binary candidate with X to be defined in the future).

*Individual Double Star Information 1* – In the case of known binaries, this is the Grade. Other information could be displayed in the case of short arc binaries or common motion pairs, etc.

*Individual Double Star Information 2* – In the case of known binaries, this is the Period. Other information could be displayed in the case of short arc binaries or common motion pairs, etc.

*Within night repetitions M* – Number of times to observe per night (assumed in a row). Often more than one data cube if a calibration binary or a difficult (faint, large delta mag, high air mass) target.

*Number of nights N* – How many nights should object be observed? Calibration binaries, for instance, might want to be observed on several nights. Also, in general, there can be some merit in observing on two different nights. For instance, a triple star “discovery” may actually just be a transient asteroid or satellite.

*Night of Observation* – Columns, one for each night of the run, where the number of observations actually made on that night are entered by the Run Master. This can be compared with the number of requested observations to assess whether or not additional observations are warranted.

The remaining columns are an exact copy of the target double star from the WDS catalog. It is expected that this will be a straight cut and paste without any alteration. Almost all targets will have WDS entries. For those that do not, similar information should be supplied.

*2000 Coordinates (WDS number)*

*Discoverer & Number*

*Components*

*Date (first)*

*Date (last)*

*Number of Observations*

*Position Angle (first)*

*Position Angle (last)*

*Separation (first)*

*Separation (last)*

*Magnitude of First Component*

*Magnitude of Second Component*

*Spectral Type (Primary/Secondary)*

*Primary Proper Motion (RA)*

*Primary Proper Motion (Dec)*

*Secondary Proper Motion (RA)*

*Secondary Proper Motion (Dec)*

*Durchmusterung Number*

*Notes 1*

*Notes 2*

*Notes 3*

*Notes 4*

*2000 arc second coordinates*

### Target List and Run Log Spreadsheet Examples

Shown below is a Target List example in two parts. The first part (on the left of the spreadsheet) is the “custom” columns that require inputs either when the Target List is created or entry by the Run Master during the run. In the example below, the blank columns in the Target List are filled in later by the Run Master after a row in the Target List is pasted into the Run Log. Note the **green x's** checked off on the right. These are the nights that these double stars were observed. The Run Master made these entries in the Target List as they were observed. Thus on Wednesday night, the last night of this run, the Run Master will know on which nights the double star has already been observed (as an aid to deciding what to observe next).

T	DSFN	SSFN	TheC	RhoC	Delta	E	F	Com	Date	Time	SAO#	RPg	RqC	TCC	G	Per	WN	BN	T	F	S	S	M	T	W
D			116.6	0.209	-11.0492	0.01166	i				12345	KBS	Gen	KVS	1	1.7	1	2			x	x	x		
D			356.6	0.201	-11.0492	0.01166	i				54321	KBS	Gen	KVS	2	2.5	1	2							x

Shown below is the second part (on the right of the spreadsheet). It is a straight paste in from the Washington Double Star Catalog (or more exactly, an Excel copy of the WDS Catalog).

WDS	Dis	Comp	First	Last	Nob	PAF	PAL	SF	SL	MagF	MagL	Spec	PPMRA	PPMDec	SPMRA	SPMDec	DM	N	2	3	4	Coord
16555-0820	KUI 75	AB	1934	2009	370	135	81	0.2	0.2	9.73	9.81	M3Ve	-829	-879			-08 4352	N	O			165529.24-082003.1
19121+0254	AST 1		1982	2007	30	224	297	0	0	11.3	13.1	M3.5V	179	-52				N	O	D	P	191213.55+025315.6

Finally, below is an example of the left side of a Run Log spreadsheet (the right side is identical to the Target List as it is the same straight extract from the WDS Catalog, just copied over along with the rest of the row from the Target List to the Run Log). The cells in **blue** were entered by the Run Master. As can be seen for any given observation (row) the Run Master actually does not have to enter much, just the **camera sequence numbers** on the left, and the **date and time** on the right which is a nearly automatic click entry on the spreadsheet as described above.

T	DSFN	SSFN	TheC	RhoC	Delta	E	F	Com	Date	Time	SSID	RPg	RqC	TCC	I1	I2	WN	BN	T	F	S	S	M	T	W
S		<b>234</b>					i		<b>3/31/2014</b>	<b>10:38:45 PM</b>	12345														
D	<b>235</b>	<b>234</b>	116.6	0.209	-11.0492	0.01166	i		<b>3/31/2014</b>	<b>10:43:22 PM</b>	12345	KBS	Gen	KVS	1	1.7	2	1							
D	<b>236</b>	<b>234</b>	116.6	0.209	-11.0492	0.01166	i		<b>3/31/2014</b>	<b>10:47:17 PM</b>	12345	KBS	Gen	KVS	1	1.7	2	1							
S		<b>237</b>					i		<b>3/31/2014</b>	<b>10:53:23 PM</b>	54321														
D	<b>238</b>	<b>237</b>	356.6	0.201	-11.0492	0.01166	i		<b>3/31/2014</b>	<b>10:57:13 PM</b>	54321	KBS	Gen	KVS	2	2.5	1	2							

DSFN and/or SSFN are filled in by the Run Master when informed by the Camera Operator what the camera sequence number is for the double star or the sequence number for the “matching” single star observation. It might be appropriate to always observe the single star first so multiple observations of the double star would fall below the single star observation in the Run Log and the SSFN (camera sequence number for the single star) could just be copied. Every double star observation must have a DSFN and a matching SSFN, while single star observations will only have a SSFN.

F (filter) can be filled in in advance on the Target List if all the observations will be made in the same color band. If not, the Run Master will need to enter the filter values. In the example above, the Run Master did not have any comments (Com).

The first four observations were made on the 14<sup>th</sup> close to midnight, while the last observation was made on the 15<sup>th</sup> just after midnight. Finally, all the observations were made on Monday, M, except the last observation which was made on Tuesday, T.

### PlateSolve 3 Out File Contents and Column Order

The PS3 Out File contents are comma-delimited, one row per output. The column order is always the same, so any “missing” data is filled with a place holder missing data designator, 9999. Conventional order in double star astrometry is angle and then separation ( $\theta$ ,  $\rho$ ). Keeping outputs in this order makes transcriptions, etc., easier. Also a convention in much of astronomy is to call the result “observed” and any pre-observation estimates “calculated.” These calculated values may just be the last reported position in a catalog, or may be calculations from an ephemerides table or orbital formulae, etc.

The classical “observed minus calculated” provides the disagreement between what was measured and what was “expected.” By placing “observed” and “calculated” values side by side, the user can immediately spot deviant results. All observed and “raw” angles are given as values between 0 and 360 degrees. The traditional double star convention is followed with 0° straight down, 90° to the right, 180° at the top, and 270° to the left. In other words, 0° = North, 90° = East, 180° = South, and 270° = West. The only exception to this rule is that CA, the camera orientation angle (which is expected to be near but not exactly 0°) is given as a (normally) small + or – angle. This helps make the math come out properly.

*DSFN* – Double star (FITS cube) file name. Please see above for the standard for file names.

*RSFN* – Reference star (FITS) cube file name. Similar to above.

*F* – Filter standard AAVSO abbreviation: *U, B, V, Rc, Ic, Y, SG, SR, SI, and SZ* for the Johnson-Cousins and Sloan filters. Similar abbreviations may be formed for Stromgren or other filter systems Entered by observer. For Tycho, *T435* and *T505* are abbreviations for its filters, although obviously not used by any Earth-bound observers!

$\theta_c$  – Alternative symbol is *PAC* for Position Angle Calculated. This is the last catalog or predicted (input) double star position angle (PA,  $\theta$ , are abbreviations). This may not always be provided in the input spreadsheet, so we either need to instruct users to include some “no data” code, or need to sense a blank. This estimate would often be the last reported PA, but could be an interpolated value from an orbit ephemeris. This would be up to the spreadsheet user, of course. The main use of this would be to place the cursor in an initial location. This is not a useful input for pure manual operation.

$\theta_o$  – Alternative symbol is *PAO* for Position Angle Observed (output from PS3) double star position angle. This would only have meaning when the user provides the camera angle from some calibration external to the reduction. If not available, the user could enter any number and ignore the results, or enter a camera angle of “0” and the output would be the “uncorrected” camera angle. It should be easy to see if they are off by about 180 or 360. A possible refinement at some point would be to automatically add or subtract 180 or 360 degrees to get closest match between input and output sky position angles. Sky position angle is calculated as frame position angle (always between 0 and 359.999) minus camera orientation angle. We expect the camera orientation to be near 0 (unless like me one places the camera 180 out!), so I think we should ask users to input their camera angle (from their calibration) as a plus or minus value (from north). This should make the math come out right.

$\theta_f$  – Alternative symbol *PAF*, Position Angle Frame. Position angle calculated by PS3 from the centroid pixel locations. Although there are two values (ambiguity), I suggest we only report one. When running automatically, it would be the solution closest to the input sky angle solution. When running manually, it would be the one (of two possibilities) the user selects.

$\rho_c$  – Alternative symbol *SepC*, Separation Calculated (input). The estimated, predicted, or last catalog reported separation. Similar to above for position angle.

$\rho_o$  – Alternative symbol *SepO* Separation Observed (output). Separation calculated by PS3 using plate scale. Also similar to above except the input scale factor, instead of input camera orientation angle, is used for the calculation (a multiplication instead of a subtraction).

$\rho_f$  – Alternative symbol *SepF*, Separation Frame calculation separation in pixels. Similar to above but only one value is available, so do not have to make any decisions, just output.

*CA* – Camera Angle (degrees). Camera orientation angle with respect to the sky.

*PS* – Plate scale ("/pixel).

*AD* – Aperture Diameter (radius in pixels).

*LTP* – Lock to Peak (True/False).

*DCT* – DeConvolution Type: *None 0, Use Reference PSD 1, Subtract Symmetrized PSF 3.*

*DCS* – DeConvolution Strength, usually set at 100%.

*GPR* – Lowpass Radius (pixels). Settings for Gaussian lowpass filter.

*LPU* – Lowpass used (True/False).

*HPR* – Highpass Radius (pixels). Setting for Gaussian highpass filter.

*HPU* – Highpass used (True/False).

*IF* – Interference Filter used (True/False).

*EAR* – Elongation Aspect Ratio (degrees).

*EA* – Elongation Angle (degrees). Angle (that matches elongation aspect ratio).

*RI* – Relative Intensity.

*DMag* – Magnitude Difference. Delta (differential) magnitude calculated by PS3.

*Comm* – User comment. A GUI insert based on user assessment of the solution. We might work (with users) on developing some sort of “standard” assessment language, abbreviations, or rating scales. This might help us move toward automation. If humans can provide quantitative ratings, then perhaps we can correlate the human decisions with calculated parameters to allow the reduction program to make similar ratings.

*DaT* – Date and time output created.

### **Note on Optional Autocorellogram Assessment Code**

The autocorellogram provides a useful visual display of the solution that is automatically saved by PS3 along with each row of the csv output file. PS3, running in the semi-automatic mode used to reduce the KPI data, shows on the autocorellogram both the predicted position angle and separation ( $\rho$  and  $\theta$ ) as well as the automated solution (which can be overridden to provide a manual solution). As an aid to identifying problems with the input data, interpreting results, and refining the automatic solution algorithm in the future, a two-digit *Autocorrelation Assessment Code* has been assigned to each reduced target based on a visual inspection of the autocorellogram.

#### *Prediction*

1. Dead on
2. Close
3. Same general area
4. Uncertain
5. Not on screen
6. Way off

#### *Automatic Solution*

1. Excellent (dead on)
2. Good
3. Poor
4. Missed, but an easy manual solution
5. Solution does not look possible
6. No solution provided, but easy manual solution
7. No solution provided, but possible manual solution

### **Final Results**

The Final Results file could, in its simplest form, simply be a merging of the PS3 Out File and the Run Log. Each PS3 Out File row would have the corresponding row from the Run Log appended to it. A more sophisticated Final Results file might only include selected data and might rearrange its order. A “standardized” Final Results file content and format has not yet been devised.

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