Measurements of STI 941 from the Palomar Observatory Sky Surveys, Gaia DR1, and New CCD Images

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Abstract: We report and compare seven new measurements of position angle and separation of the double star WDS 20023+6515 (STI 941) from images obtained from the Palomar Observatory Sky Surveys POSS I (1953) and POSS II (1991, 1994), calculated from position data provided by Gaia DR1, and from analysis of new CCD images. Trends in separation and position angle change are difficult to determine due to the possible inaccuracy of the earliest measurements. There is no indication of an elliptical orbit. Analysis of the proper motions suggests that STI 941 can be classed a Similar Proper Motion pair. Analysis of parallax is inconclusive due to high parallax error.

Introduction

WDS 20023+6515 (STI 941) was chosen from the Washington Double Star (WDS) catalog for research after meeting a set of criteria: the candidate system should be visible by an iTelescope imaging system high enough in the sky to minimize atmospheric effects on image quality; have a possibility of being a physical binary; have a separation angle greater than 5 arc seconds so as to obtain clear separation of the pair in CCD images; and have system components with apparent magnitudes of 12 or brighter with a difference in visual magnitude of less than 3 to help avoid overexposure or blooming in CCD images. STI 941 met these criteria.

STI 941 is a double star in the constellation Draco. Its most recent reported values from 2013 are a position angle of 96.4° and 11.722" of separation. The magnitudes of STI 941's primary and secondary components are listed in the WDS as 11.08 and 13.2 respectively. No spectral type data is available for either component.

STI 941 was discovered and first measured by Dutch Vatican Observatory astronomer John (Johan) W. Stein in 1894 while photographing and cataloging stars in the "Vatican Zone" (+55 to +65 declination) for the Paris Observatory's *Astrographic Catalog* (Daley 2006). This first measurement is reported in the WDS as a data reduction of the original Vatican plates by the *Astrographic Catalog 2000* (Urban et al., 1998). There was another Vatican measurement in 1913 superseded and corrected by the *Astrographic Catalog 2000's* data reduction, so it is not included in analysis. The double then went unmeasured for 86 years until 1999 with a measurement obtained from the Two Micron All-Sky Survey (2MASS). Another measurement from 2003 was obtained from the comprehensive *USNO CCD Astrographic Catalog* project (Zacharias et al., 2013), for a total of four recorded measurements of position angle and separation (not including the superseded observation).

This project attempts to acquire both new position and separation data for STI 941 and provide measurements to fill in the gap of missing data that exists from 1913 to 1999. It does so by measuring STI 941 from archived Palomar Observatory Sky Survey (POSS I and POSS II) images, calculating measurements from new coordinate data provided by Gaia DR1, and obtaining measurements from new CCD images. Evidence of STI 941 being a physical binary is also explored.

Equipment and Procedures

Measurement of Digitized Sky Survey Images

STI 941 was measured from Digitized Sky Survey (DSS) images to fill the 86-year gap in observations between 1894 and 2003. These images are based on photographic data from POSS I and POSS II plates imaged in 1953, 1991, and 1994 by Cal Tech's and Palomar Observatory's 48-inch Oschin Schmidt Telescope (Figure 1). POSS II used better photographic plates after the Oschin Schmidt telescope received an upgrade of an achromatic corrector and a provision for au-

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Figure 1. Interior view of the dome and the 48-inch Schmidt telescope, circa 1960 (Photo Credit: Palomar Observatory).

toguiding. The photographic plates were later digitized at a plate scale of 1.1"/pixel by the Palomar Observatory - Space Telescope Science Institute Digital Sky Survey (DSS), which is sufficient resolution to obtain reasonable measurements. The DSS images were obtained using the desktop version of Aladin Sky Atlas in a manner similar to Richard Harshaw's (2013) method of obtaining archive images from VizieR.

A list of images containing STI 941 were obtained in Aladin Sky Atlas by using the menu items "File => Load astronomical image=> Aladin image server." The ID "WDS 20023+6515" was entered into the Target textbox, the default format "FITS" was selected, and the SUBMIT button was clicked. This provided a list of archive images containing the target (Figure 2). Fortunately, there were images taken during the period that no measurements of STI 941 are recorded. The 1953 POSS I O plate was imaged in the blue waveband. The 1991 POSS II J plate was also imaged in the blue waveband and the 1991 POSS II F plate was imaged in the red waveband. The 1994 POSS II N plate was imaged in the near infrared waveband.

The centroids of STI 941 A and B in the digitized POSS photographic plates were not detectable by Aladin (or Mira Pro x64), so Aladin's "Auto Distance Measurer" tool could not be used. Measurements of STI 941's theta and rho values were obtained in Aladin using a procedure described by Harshaw (2013).

Figure 2. The Aladin Image Server showing list of images containing STI 941.

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Aladin's "pixel" tool was used to enhance the images by adjusting the range of visible pixels, and then Aladin's "draw" tool was used to manually mark the center of each star, using the diffraction spikes as a guide when possible. The "dist" tool was then used to measure the position and separation angle of STI 941 ten times for each image (Figure 3). The mean, standard deviation, and standard error of the mean of the measurements was calculated in Excel for the theta and rho obtained from each digitized plate. The Julian epoch of each measurement was calculated from the Julian date of each plate using Equation 1 (Greaney, 2012).

$$\text{Julian epoch} = J2000 + \frac{JD - 2451545}{365.25} \qquad [1]$$

Harshaw (2013) suggests grading the star image quality of the plates on a five-point scale ranging from "Excellent (crisp images, little background noise) to Very Poor (fuzzy images, bloated stars, merging of star images, background noise, etc.)." This is to assist "orbit computers of the future" in judging the quality of each measurement, allowing them to weight the measurements in their calculations. Each POSS plate's star image quality was graded using the following scale borrowed from Harshaw: 1 = Excellent; 2 = Good; 3 = Medium; 4 = Poor; 5 = Very Poor (see Table 4).

Measurements from Gaia DR1

The European Space Agency's (ESA) space observatory *Gaia* was launched in 2013. One of its main goals is to determine the position, parallax, and annual proper motion of approximately 1 billion stars. The first data release, Gaia DR1 is based upon observations made between 25 July 2014 and 16 September 2015 and was made available to the public on September 13, 2016. The first part of Gaia DR1 consists of an astrometric data set which contains the positions, parallaxes, and mean proper motions for about 2 million of the brightest stars in common with the Hipparcos and Tycho-2 catalogues (the primary astrometric data set) and the positions for an additional 1.1 billion sources (the secondary astrometric data set). The positions and proper motions in the astrometric data set are given at reference epoch J2015.0; individual epoch observations will be released only with the final catalogue (Gaia Collaboration et al. 2016). The coordinates of STI 941 are included in DR1 and were obtained using Aladin (Table 1). Excel was used to convert the data to radians.

Bob Buchheim (2012) provides trigonometic equations for calculating the rho and theta of two stars given their right ascension (α) and declination (δ) coordinates (Equations 2 and 3). α_1 and δ_1 are the RA and Dec of the primary star in radians; α_2 and δ_2 are the RA and Dec of the secondary star in radians. $\Delta\alpha$ is the differ-

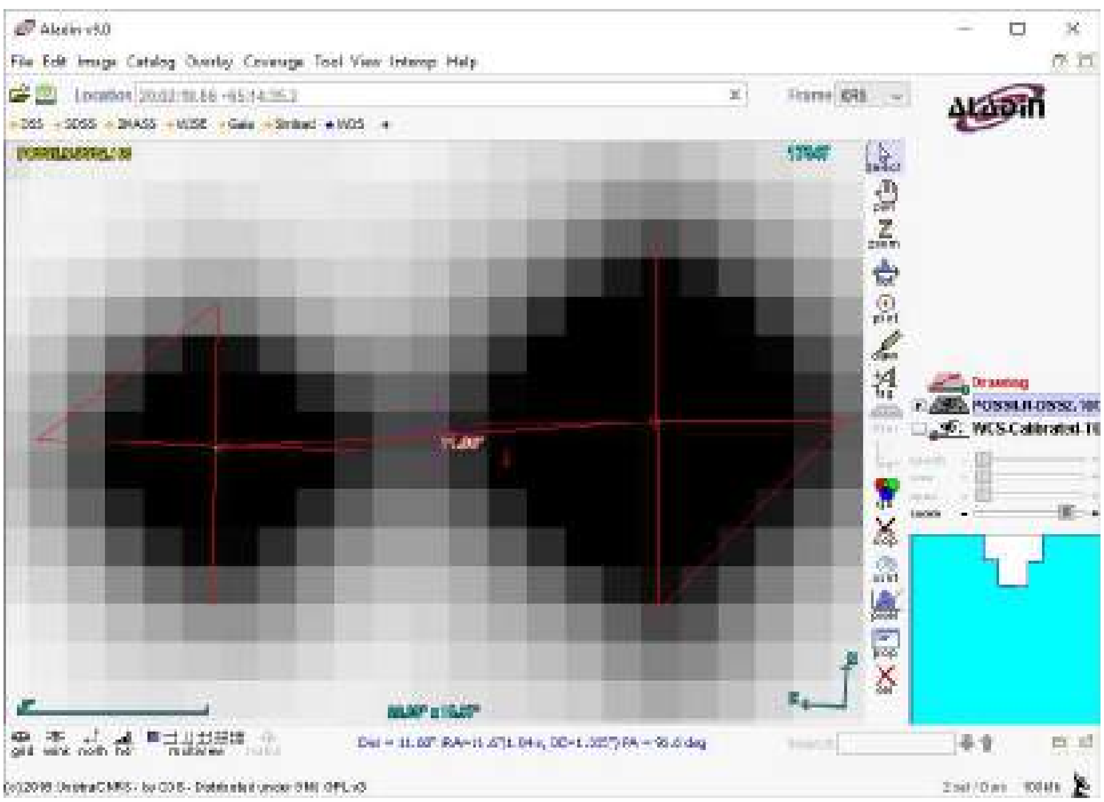

Figure 3. An example of measuring with Aladin's "dist" tool.

Table 1. STI 941 A and B Coordinates at Epoch J2015.0 from Gaia DR1

	RA	Std. Error	Dec	Std Error
STI 941A				
Degrees	300.5742341607	0.205 mas	+65.2433157553	0.430 mas
Radians	5.24601003	9.93868E-10	+1.138710675	2.0847E-09
STI 941B				
Degrees	300.5819499070	0.066 mas	+65.2429561458	0.089 mas
Radians	5.24614470	3.19977E-10	+1.138704398	4.31484E-10

ence between the RA of the secondary and primary ($\alpha_2 - \alpha_1$). These are simplified "small angle" approximations of spherical trigonometry equations suitable for use only when the differences in radians between the right ascensions and declinations of the two stars are both much less than 1 radian ($|\alpha_2 - \alpha_1| << 1$ and $|\delta_2 - \delta_1| << 1$).

$$\rho = \sqrt{(\Delta\alpha\cos\delta_1)^2 + (\delta_2 - \delta_1)^2} \text{ (radians)} \quad [2]$$

$$\theta = \arctan\left(\frac{\Delta\alpha\cos\delta_1}{\delta_2 - \delta_1}\right) \text{ (radians)} \quad [3]$$

An adjustment must be made to θ based on the quadrant to obtain the correct value for the position angle θ, as shown in Table 2.

Knapp (2016) provides a method used to calculate the errors for the calculated RA and Dec, shown in equations 4 and 5. dRA and dDEC are the averages of the Gaia DR1 RA and Dec errors.

$$\rho_{error} = \sqrt{dRA^2 + dDEC^2} \quad [4]$$

$$\theta_{error} = \arctan\left(\frac{\rho_{error}}{\rho}\right) \quad [5]$$

The equations were transferred to an Excel spreadsheet, theta and rho were calculated in radians, the errors were calculated, and then all results were converted to degrees and arc seconds when appropriate.

Measurements from New CCD Images

The iTelescope network of remotely operated telescopes was used to acquire CCD images of STI 941. The first iTelescope system used was T7, located at the AstroCamp Observatory in Nerpio, Spain. It is a 17" Corrected Dall-Kirkham (CDK) with a focal ratio of f/6.8, equipped with an SBIG STL11000M monochrome camera (Figure 4). The field of view of T7 is 28x42 arcminutes with 0.63″/pixel resolution. This telescope provided a large enough aperture to acquire high quality images of the 13th magnitude star in one of the systems we chose. The second iTelescope system used, T18, is also located at AstroCamp Observatory. T18 is a 12" CDK with a focal ratio of f/7.9 and equipped with an SBIG STXL-6303E camera (Figure 5). T18's field of view is 37.41' x 24.94' with 0.73"/pixel resolution. Both telescopes have a wide selection of filters available for use. These telescope systems in Spain were used because of their suitable capabilities and the good weather available at the time of the observations.

In addition, a Celestron 11" Schmidt Cassegrain telescope with a focal ratio of f/10 owned and operated by Allen Priest was used (see Figure 6 for a similar telescope). This system included an Orion Starshoot Pro 6 megapixel one-shot-color CCD camera for imaging. Utilizing a Starizona flat-field corrector, this system images at 0.83″/pixel at a focal length of 2100mm. An ASI290 monochrome camera was used for autoguiding. The imaging with this system was carried out at Tierra Del Sol, the dark sky site operated by the San Diego Astronomy Association (SDAA).

Initially, seven images of STI 941 (one image is shown in Figure 7) were taken over five nights in July, 2016. Due to demand affecting telescope availability, it was not possible to reserve time or schedule an imaging

Table 2. Theta Adjustment Based on Quadrant

Sign of α_2-α_1	Sign of δ_2-δ_1	Quadrant	Position Angle θ (in radians)
$+ (>0)$	$+ (>0)$	I	$\theta = \Theta$
$+(>0)$	$-(<0)$	II	$\theta = \pi + \Theta$
$-(<0)$	$-(<0)$	III	$\theta = \pi + \Theta$
$-(<0)$	$+ (>0)$	IV	$\theta = 2\pi + \Theta$

Figure 4. T7 17" PlaneWave f/6.8 CDK Astrograph with SBIG STL11000M CCD in Nerpio, Spain.

Figure 5. T18 12" PlaneWave f/7.9 CDK Astrograph with SBIG STXL-6303E CCD in Nerpio, Spain.

plan with iTelescope. Consequently, STI 941 was imaged with T7 and T18 using iTelescope's quick "Single Image" functionality in-between scheduled imaging runs. In addition, Allen Priest acquired images with his Celestron C-11 from the SDAA dark sky observing site in Tierra del Sol, CA. On November 1, 2016, eight more images of STI 941 were taken with iTelescope's T7 using a luminance filter. The specifics of the image acquisitions are listed in Table 3.

The acquired CCD images were calibrated for rotation and pixel scale. Pinpoint Astrometry, a plug-in for Maxim DL software, was used to obtain a plate solution for most of the images by locating many stars in the image and comparing their positions against the *Fourth U.S. Naval Observatory CCD Astrograph Catalogue* (UCAC4). This procedure is necessary to determine the exact pixel scale and rotation angle of the image. The information is added to the FITS header for the image which is then saved for further processing in other software tools. Two images could not be plate solved by Pinpoint Astrometry, so the website Astrometry.net was used for calibration. Images were uploaded to Astrometry.net, which then calibrated the images using their own algorithm and the USNO-B and Tycho2 catalogs. Astrometry.net then provided a calibrated version of the image for download. One of these plate solving processes was performed on every image.

Each plate-solved image was then opened with Mira Pro x64, a software product from Mirametrics, Inc. This software enables many different analytic measurements of the stars in the image including absolute position in RA and Dec, separation in arc seconds, and rela-

Figure 6. Celestron C-11 Telescope similar to that used in Tierra Del Sol near San Diego, CA.

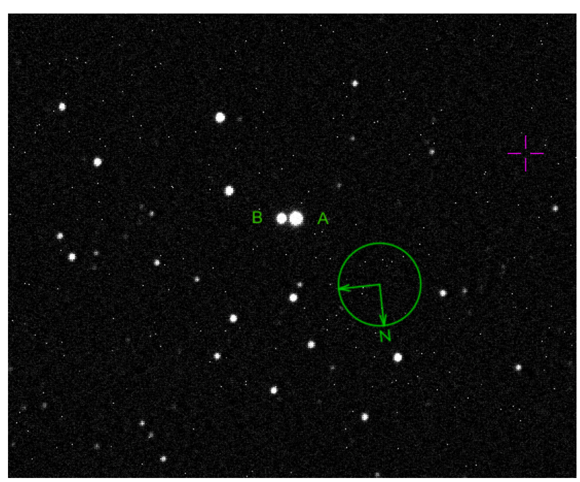

Figure 7. Sample image of STI 941 with components labeled.

Table 3. CCD Image Acquisition Dates

Date	Telescope	Camera/Filter Type	# of Images
July 2, 2016	T7	Luminance	1
July 2, 2016	T18	Luminance	1
July 3, 2016	C-11 SCT	One-Shot Color	2
July 5, 2016	T18	Ha	1
July 6, 2016	T7	Red	1
July 11, 2016	T18	Luminance	1
Nov 1, 2016	T7	Luminance	8

tive position angles. Using the point and click Distance & Angle function of Mira Pro x64, the position angle and separation of the binary stars were measured. For highest accuracy, the software was set to calculate the centroid of each star selected in the measurement process. The centroid calculation uses the brightness data for many pixels in the star image to calculate a weighted measurement of the star's exact position. This makes it possible for the centroid calculation to pinpoint a star's location within a fraction of a pixel, resulting in very accurate measurements even for the faintest stars. The parameters of this calculation can be adjusted if necessary to account for the size of the stars in the image. If the stars in the image are close together, the radius value of the centroid function can be adjusted to prevent including both stars in one centroid calculation. In some cases, where the star might be overexposed, resulting in blooming, it is possible to disable this centroid measurement and use other methods of pinpointing a star's location. For example, if there are diffraction spikes in the image, these can be used to locate the center of the star. These new CCD images, however, did not contain any diffraction spikes and the centroid measurement functionality was used.

To begin a measurement, the primary component is clicked on first. When the first star is selected, Mira Pro calculates the centroid of the star and synchronizes the start of the measurement from that point. Releasing the mouse button on the second star allows the software to locate that star's centroid position and provide the desired measurement from these centroid positions.

After completion of the position angle and separation measurements, the data were placed into an Excel spreadsheet to calculate the mean, standard deviation, and standard error of the mean for each measurement. The mean of the Julian dates of the observations was calculated and then converted to Besselian epoch using Equation 1.

Each measurement was compared to the data available in the Washington Double Star (WDS) catalog. This comparison allows confirmation that the measurements are being made appropriately and that the new data agrees with previously published data.

Results

POSS I and POSS II Results

Measurements acquired from one POSS I and three POSS II images are shown in Table 4. Each image was measured 10 times in Aladin Sky Atlas, and the mean, standard deviation, and standard error of the mean of the measurements were calculated in Excel. Each plate was graded on quality.

Gaia DR1 Results

Measurements calculated from Gaia DR1 coordinates are shown in Table 5.

Table 4. POSS I and POSS II Image Measurements

Survey	Waveband	Star Image Quality	Nights		θ (degrees)	ρ (arc seconds)	Epoch
POSS I O	Blue	4 (Poor)	1	Mean	96.5	11.60	J1953.609343
				Std Dev	0.35	0.05	
				Std Error	0.11	0.01	
POSS II J	Blue	3 (Medium)	1	Mean	95.9	11.69	J1991.520397
				Std Dev	0.25	0.03	
				Std Error	0.08	0.01	
POSS II F	Red	3 (Medium)	1	Mean	97.9	11.61	J1991.591373
				Std Dev	0.28	0.06	
				Std Error	0.09	0.02	
POSS II N	Near IR	3 (Medium)	1	Mean	95.9	11.53	J1994.458202
				Std Dev	0.41	0.03	
				Std Error	0.14	0.01	

Table 5. Gaia DR1 Calculated Measurements

θ	$θ_{error}$	ρ	$ρ_{error}$	Epoch
96.3506931	2.28092×10^{-5}	11.70374338	2.25885×10^{-11}	J2015.0

theta values in degrees, rho values in arc seconds

New CCD Images Results

Measurements were taken from the seven CCD images acquired over five nights in July, 2016 and combined into one observation. The eight images taken on one night in November 2016 are presented as a separate observation. The mean, standard deviation, and standard error of the mean for the separation distance in arc seconds and the position angle in degrees for both observations were calculated. These are shown in Table 6.

Discussion

POSS I and POSS II Images

Image POSS I O has significant merging between the two stars (as shown in Figure 8) which increased the difficulty of finding the stars' centroids. The other images had merging to a lesser extent. Measuring the angles required locating the centroids of each star. Since Aladin Sky Atlas could not detect the centroids of the stars, they were determined by the authors manually, which added a small subjective element to the measuring. Measurement of POSS II F gave a theta value 1.4° greater than POSS I O, and 2° greater than that obtained from POSS II J and N. It is possible that this plate had an alignment error.

Gaia DR1 Observation

While the Gaia DR1 measurement has the potential to be the most accurate of all measurements presented, there is no specific epoch associated with it. All of the Gaia DR1 data is presented with a uniform epoch of 2015.0. In general, individual epoch observations will be released only with the final catalog. While it is not now possible to know the exact epoch represented by the calculated observation, it is possible to compare it with the historical measurements.

New CCD Image Observations

There are two new CCD image observations: B2016.5107, averaged from measurements of seven images taken over five nights with three different imaging systems using a combination of different filters; and B2016.8374, averaged from measurements of eight images taken in one night with iTelescope's T7 system and a luminance filter. Consequently, B2016.8374 is considered a higher quality observation and compares favorably to the Gaia DR1 observation with a difference of only .01° of position and .03" of separation.

Historical Data

Historical data for STI 941 was obtained from the US Naval Observatory. STI 941 has five previously published observations (Table 7). There are two observations listed for 1913.68, however, the first of the two is by the Vatican Observatory from the *Astrographic Catalog*, *Appendix 3* (1926, 1930) and is coded in the WDS as being "...superseded by later reductions of the same data," in this case for the *Astrographic Catalog 2000* (Urban, et al., 1998). Consequently, the first of the two 1913 observations has been eliminated from analysis, leaving four observations from 1894 to 2003. There is a large gap in reported measurements between the years 1913 and 1999

Table 8 shows the historical data from the WDS combined with the new data from measurement of POSS I and POSS II images, calculated values from Gaia DR1 coordinate data, and CCD imaging.

An XY plot of all observations is shown in Figure 9, with STI 941A at coordinate 0,0. There is no discernable curve to the plot. A zoomed-in representation of the data is shown in Figure 10. The values of theta plotted over time are shown in Figure 11 and the values of rho plotted over time are shown in Figure 12. In all four figures, the POSS data points are represented by squares (■), the Gaia DR1 data points by diamonds (◆), and the new CCD image data points by triangles (▲).

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Table 6. CCD Image Results for STI 941

WDS ID	Disc.	Nights	Images		θ (degrees)	ρ (arc seconds)	Epoch
20023+6515	STI 941	5	7	Mean	96.56	11.63	J2016.509045
				Std Dev	0.51	0.11	
				Std Error	0.19	0.04	
		1	8	Mean	96.36	11.73	J2016.835792
				Std Dev	0.04	0.03	
				Std Error	0.01	0.01	

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Table 7. Historical Measurements of STI 941

Epoch	Observer	θ (degrees)	ρ (arc seconds)	Notes
1894.78	WFC1998	98.7	12.172	Vatican Observatory. Photographic, with astrograph. Reduced from the Astrographic Catalog
1913.68	*Vat1926*	*100.9*	*11.6*	Vatican Observatory. Photographic, with astrograph. Superseded in the WDS by later reduction of the same data
1913.68	WFC1998	100.6	11.612	Photographic, with astrograph. Reduced from the Astro-graphic Catalog plates.
1999.42	TMA2003	96.5	11.66	2MASS
2003.7	UC_2013b	96.4	11.722	UCAC4

Table 8. All Observations of STI 941 (new observations)*

Epoch	θ (degrees)	ρ (a.s.)	Notes
1894.78	98.7	12.172	Vatican Observatory
1913.68	*100.9*	*11.61*	*Vatican Observatory, superseded*
1913.68	100.6	11.612	Vatican Observatory
J1953.609343	96.5	11.60	POSS I O*
J1991.520397	95.9	11.69	POSS II J*
J1991.591373	97.9	11.61	POSS II F*
J1994.458202	95.9	11.53	POSS II N*
1999.42	96.5	11.66	2MASS
2003.7	96.4	11.722	UCAC4
J2015.0	96.35	11.70	Gaia DR1*
J2016.509045	96.56	11.63	CCD Imaging*
J2016.835792	96.36	11.73	CCD Imaging*

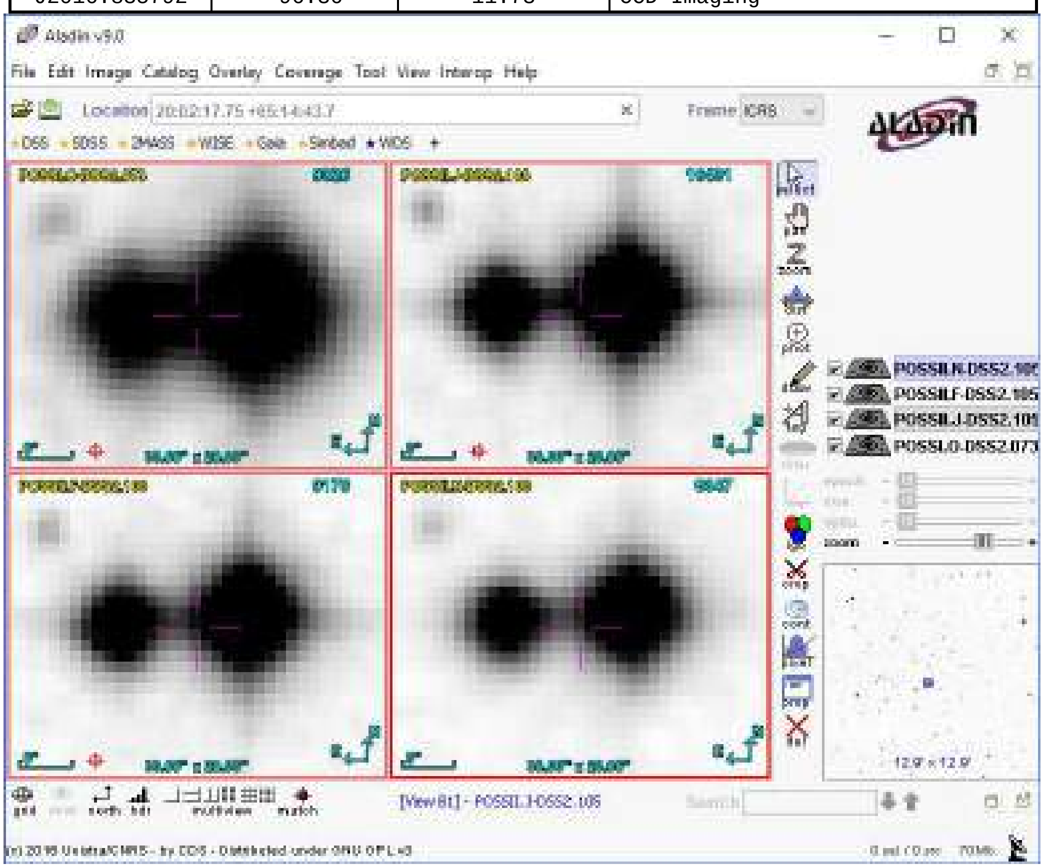

Figure 8. POSS I and POSS II images of STI 941.

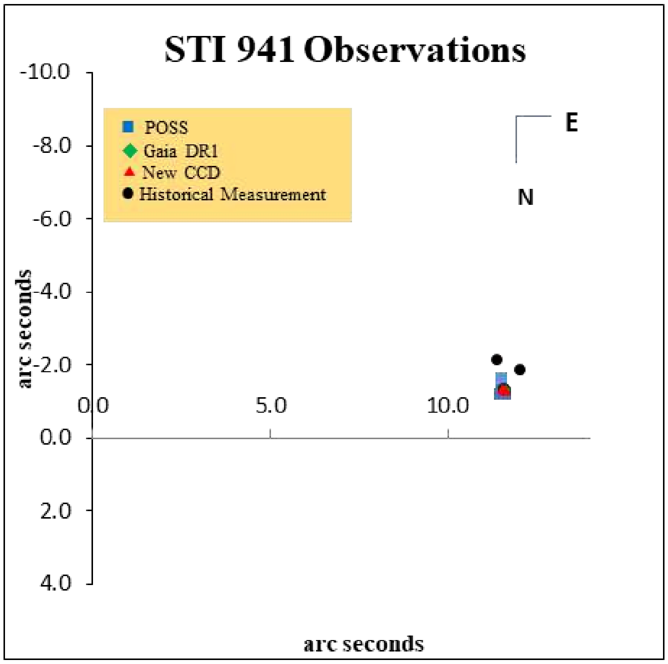

Figure 9. XY plot of all STI 941 observations. STI 941A is located at (0,0).

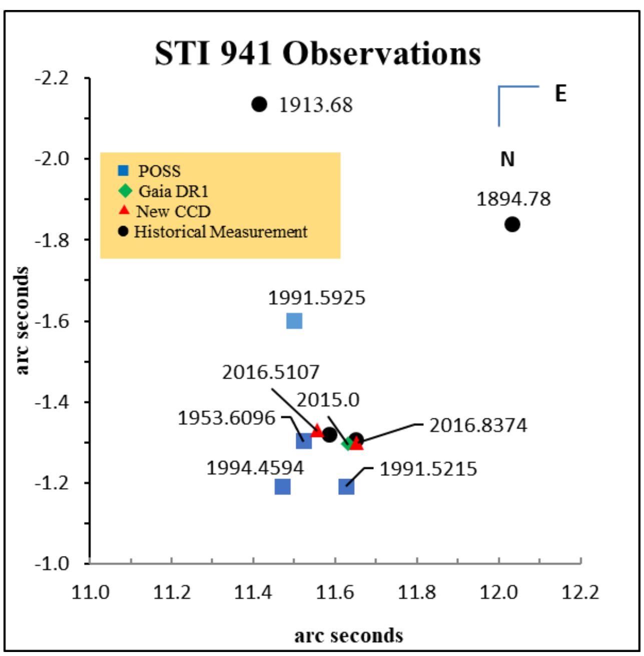

Figure 10. Zoomed-in view of all STI 941 observations. STI 941A is located at (0,0).

From Figure 11 and Figure 12, it is apparent that there have been no notable changes in position or separation angle from 1953 to the present, except for the theta measurement from POSS II F in 1991. From 1999 to 2016 the values for theta have been steady with a range of only 0.2°. Over the same period, rho has a range of only 0.1". Changes in value of the earlier POSS rho and theta measurements could be due to the quality of the scanned plates and the measurement technique.

This brings into question the accuracy of the Vatican Observatory measurements of 1894 and 1913. It is interesting to note that the 1913 position angle measurement is 1.9° greater than the earliest 1894 observation, and at least 4° greater than any future observation excluding the 1991 POSS II F manual measurement. The Vatican Observatory's Carte du Ciel astrograph captured images on 5-inch (130 mm) square blue sensitive glass plates covering 2 x 2 degrees of sky that when color-corrected for blue provided extremely sharp images (Daley, 2006). The plate scale of the images was 1 mm per minute of arc. It is possible that a minor error could have been introduced at some point during image capture, plate reduction, or digital scanning.

If it is assumed that no actual change has occurred to the theta and rho of STI 941 over time (and it has not been established that this is the case) and any deviations from the mean of the observations are due to errors, then it is possible to look for outliers in the data. One simple method for identifying a potential outlier is to use the Interquartile Range Rule. With this rule, any data point more than 1.5 interquartile ranges below the first or above the third, or upper, quartile is a potential outlier. The interquartile range for theta is 1.62° with an upper quartile of 97.92°. 1.5 interquartiles above 97.92 is 100.35°. Although it is less than three standard deviations from the mean (<101.41°), under the Interquartile Range Rule the Vatican's observation of 100.6° could be considered an outlier. The interquartile range for rho is 0.102" with an upper quartile of 11.71". 1.5 interquartiles above 11.71 is 11.87". Consequently, the Vatican Observatory's 1894 rho observation of 12.172" could also be considered an outlier. 12.172" is also very close to three standard deviations from the mean (12.20"). It might be best to assign much less weight to the Vatican Observatory data in calculations.

Parallax

If the distance to a double star and the pair's angular separation are known, then the minimum linear separation of the pair can be calculated with trigonometry. An extremely large minimum linear separation could be useful to help rule out the physical binary status of a pair. Gaia DR1 provides the only parallax data for STI

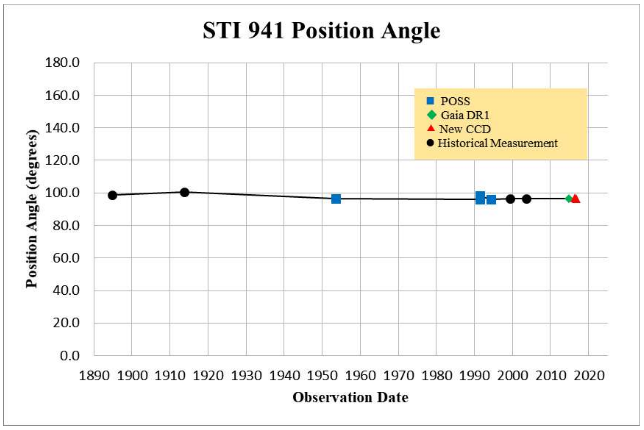

Figure 11. A plot of STI 941 position angle observations over time.

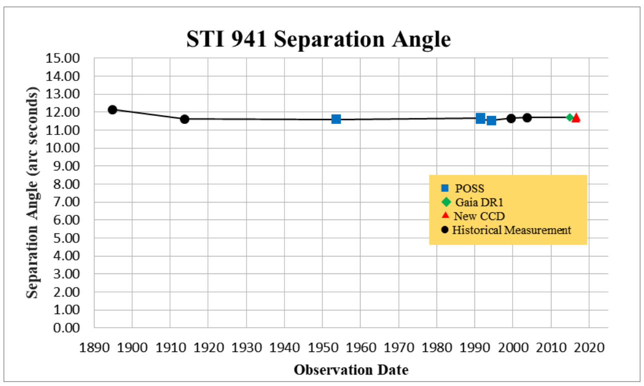

Figure 12. A plot of STI 941 separation angle observation over time.

941A that is not a negative value (Table 9). No parallax data is available for STI 941B. STI 941A has a parallax of 3.57±0.74 mas (which includes an additional Gaia DR1 systematic parallax error of ±0.3 mas). If it were assumed that STI 941A and STI 941B were at the same distance, it could be possible to estimate a minimum linear separation. Unfortunately, the error-to-parallax ratio (0.74/3.57) is 21%, uncomfortably high to calculate a reliable distance to STI 941. Lack of accurate parallax and distance data also rules out use of the distance modulus to estimate absolute magnitudes and possible spectral types of STI 941.

Table 9. Gaia DR1 Parallax Data

	Parallax	Error	Error/ Parallax
STI 941A	3.57	0.74	21%

Is STI 941 a Common Proper Motion Pair?

Stars that are gravitationally bound move through space together; consequently, they should have very similar proper motions vectors. It is possible to determine how different the proper motions of two stars are by computing a proper motion vector for each star, and then comparing the largest of the two vectors to the resultant of their difference. Harshaw (2016) provides classification guidelines: if there is less than 20% difference, they can be considered a Common Proper Motion Pair (CPM); differences between 20%-60% are classed Similar Proper Motion Pairs (SPM), and greater than 60% are classed Different Proper Motion Pairs (DPM).

The only source that has proper motion data for both STI 941 components is UCAC4 (Table 10), and the errors for the B component are very large. As shown, Tycho-2 (with very high errors) and Gaia DR1 only provide proper motion values for the A component. Interestingly, Gaia DR1 gives an RA proper motion value about twice that of previous values. Figure 13 illustrates the proper motion of the pair using data from the three catalogs.

To compare the proper motions of the pair, proper motion vectors for each star are calculated with the following equation:

$$V = \sqrt{pmRA^2 + pmDE^2} \qquad [6]$$

The resultant (R) of the difference of the two vectors is found by:

$$R = \sqrt{\left(pmRA_a - pmRA_b\right)^2 + \left(pmDE_a - pmDE_b\right)^2} \qquad [7]$$

As shown in Table 11, the primary's proper motion vector has a value of 11.86 and the secondary's has a value of 14.39. The resultant of the difference of the vectors is 2.55, which is 18% of the largest vector.

Table 10. Proper Motion for STI 941

Catalog	STI 941A				STI 941B			
	PM RA	PM RA error	PM Dec	PM Dec error	PM RA	PM RA error	PM Dec	PM Dec error
Tycho-2	6.7	2.3	7.4	2.5	--	--	--	--
UCAC4	7.6	0.6	9.1	0.6	9.4	5.0	10.9	1.8
Gaia DR1	14.002	1.308	9.112	1.821	--	--	--	--

all values mas/year

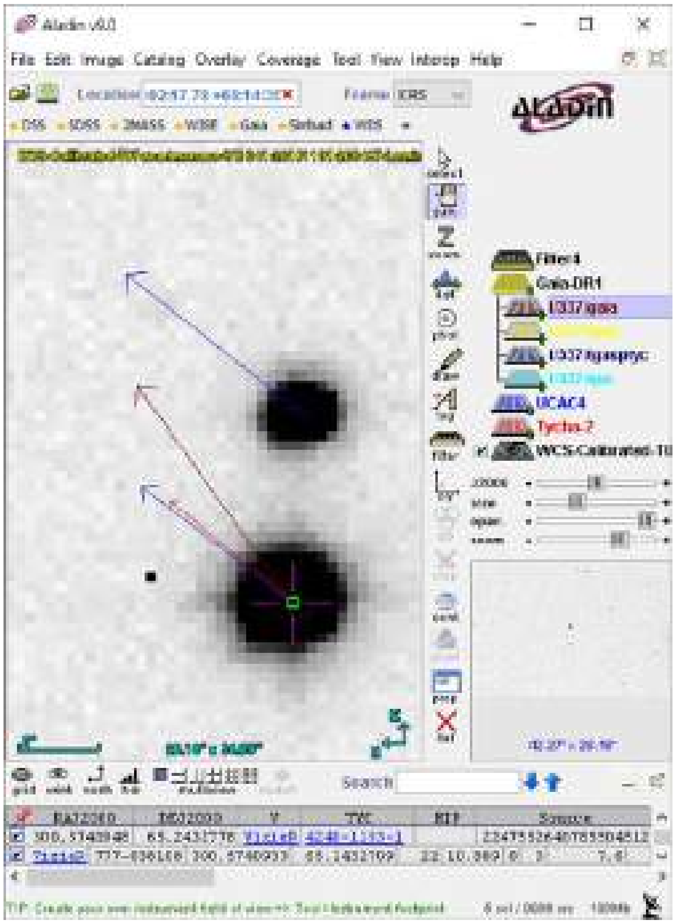

Figure 13. Illustration of proper motions vectors for STI 941 in Aladin Sky Atlas.

While this is low enough to be considered a CPM, only barely. Taking in consideration the very large proper motion error values for the B component, it is probably safer to class STI 941 as a Similar Proper Motion pair, and not a CPM. This can be readdressed when proper motion values are provided for STI 941B in further Gaia data releases.

Table 11. Proper Motion Vectors for STI 941

Component	pmRA	e_pmRA	pmDE	e_pmRA	PM Vector
A	7.6	0.6	9.1	0.6	11.86
B	9.4	5.0	10.9	1.8	14.39
Resultant	2.55				
Ratio of R/Largest PM Vector = 2.55/14.39=0.18					

Conclusions

STI 941 previously had only four reported observations of theta and rho in the WDS, with an 86-year gap between 1913 and 1999. We have added seven new observations; four from measuring digitized POSS I and POSS II plates from 1953 and the 1990s, one by calculation from coordinate data provided by Gaia DR1, and two obtained from measuring new CCD images. All observations were consistent with each other and the historical data. There is no indication of an elliptical orbit in the plot of the secondary's position in relation to the primary. The earliest measurements obtained from the Vatican Observatory deviate suspiciously from the rest of the historical measurements. Current parallax data for STI 941's primary has an error/parallax ratio of 21%, too high to calculate a reliable distance. The proper motions of STI 941 were analyzed and it can be considered a Similar Proper Motion pair until more accurate data, especially for the secondary, is obtained.

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References

Buchheim, B. 2012, "Principles of CCD Double Star Astrometry", *Observing and Measuring Visual Double Stars Second Edition.* Ed. R. W. Argyle, New York, Springer.

Daley, J. A. 2006, "Notes on the Double Stars of Father John W. Stein, S.J.", *Journal of Double Star Observations*, **2**, 134-137.

Gaia Collaboration et al., 2016, Gaia Data Release 1 Documentation Release 1.1. http://gaia.esac.esa.int/documentation/GDR1/

Gaia Collaboration et al. 2016, DATA RELEASE SCENARIO, http://www.cosmos.esa.int/web/gaia/release

Gaia Collaboration et al., 2016, Summary description of Gaia DR1.

Genet, R. M., Johnson, J. M., Buchheim, R., and Harshaw, R., 2015, *Small Telescope Astronomical Research Handbook,* In preparation.

Greaney, M., 2012, "Some Useful Formulae", *Observing and Measuring Visual Double Stars, Second Edition,* Ed. R. W. Argyle, New York: Springer.

Harshaw, R. W. 2016. "CCD Measurements of 141 Proper Motion Stars: The Autumn 2015 Observing Program at the Brilliant Sky Observatory, Part 3",. *Journal of Double Star Observations,* **12**, 394-399.

Harshaw, R. W., 2013, "Using VizieR/Aladin to Measure Neglected Double Stars", *Journal of Double Star Observations,* **9**, 75-87.

Hartkopf, W. I., Mason, B. D., Finch, C. T., Zacharias, N., Wycoff, G. L., and Hsu, D., 2013, "Double Stars in the USNO Astrographic Catalog", *The Astronomical Journal*, 146.76.

Hog E., Fabricius C., Makarov V.V., Urban S., Corbin T., Wycoff G., Bastian U., Schwekendiek P., and Wicenec A., 2000. "The Tycho-2 Catalogue of the 2.5 Million Brightest Stars", *Astronomy & Astrophysics,* **355**, L27.

Hogg, W. D., and Lang, D. 2016. Astrometry.net. http://astrometry.net.

Knapp, W. R. A., 2016, "Measurements of Some VizieR I/330 Objects", *Journal of Double Star Observations*, **12**, 589-594.

Mason, B. and Hartkopf, W. October 2015. *The Washington Double Star Catalog.* Astrometry Department, U.S. Naval Observatory.

Urban, S. E., Corbin, T. E., Wycoff, G. L., Martin, J. C., Jackson, E. S. M., Zacharias, I., and Hall, D. M., 1998, "The AC 2000: The Astrographic Catalogue on the System Defined by the *Hipparcos* Catalogue", *The Astronomical Journal*, **115**, 1212 - 1223.

Zacharias, N. et al., 2013, "The Fourth US Naval Observatory CCD Astrograph Catalog", The Astronomical Journal, 145:14.