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Design and Evaluation of a 3D Printed Filar Micrometer

Emily M. Rull

One of my favorite parts of studying the night sky is that I know that my heritage in astronomy is full of men and women who have devoted themselves to the study of things that are just out of reach. It may seem futile to some, but as we know from our astronomical ancestors, you can learn a lot from what you cannot touch.

I would like to dedicate this thesis to everyone in my life who helps me to see my Creator as He is: much closer than the stars.

ACKNOWLEDGEMENTS

I would like to thank the Pence-Boyce Research Board for providing me the opportunity to pursue research in the summer of 2017. Funding from the Pence-Boyce Summer Research Opportunity made it possible for the foundation of this project to be completed at that time.

This project would have been impossible without Dr. Stephen Case. His mentorship, inspiration, and encouragement have been vital throughout every step of the process. Throughout the project, Professors Amanda Luby and Joseph Makarewicz have provided much-needed aid in programming and running the 3D printers used in this project. Advice from Dr. Beth Schurman and Dr. Dan Sharda has greatly improved the written quality of this thesis.

ABSTRACT

Background

Double stars are celestial objects that allow for calculating the mass of stars by assessing their orbits. Stellar mass affects every current model of stellar evolution, but the most accurate double star orbits can take decades to record. Due to the long-term nature of such observations and lack of groundbreaking research in double star studies, professional astronomers are no longer focused on making these measurements, so amateur astronomers can pick up where professionals have left off. Amateurs can only do this if they can get the equipment that they need at prices they can afford. A personally-manufactured filar micrometer could fill this need. Astronomers use a filar micrometer paired with a telescope to take visual double star measurements. Unfortunately, current commercial filar micrometers are cost prohibitive for most amateur astronomers. This project sought to design, 3D print, test, and calibrate a filar micrometer that amateur astronomers could produce cost effectively.

Methods

Creo Parametric 3.0 and a ProJet MJP 3600 Series 3D printer were used to design and print the filar micrometer. A Fowler 1-2" digital counter micrometer, 54-gauge Nichrome 80 wire, and a 6" Orion SkyQuest Dobsonian telescope were used with the printed filar micrometer to take measurements. The measurements were of the separation between components of an artificial double star created by flashlights reflected in a bearing ball. These measurements were used to calibrate the filar micrometer and find the preliminary accuracy of the filar micrometer.

Results

Twenty-one measurements were taken of three different arrangements of the artificial double star. The average calibration calculated from this data is 1.44E-4 inches per arcsecond. Measurements of the 24 Coronae Borealis simulated star (with a separation of 20.14 arcseconds) produced a seventeen percent error with an average measured separation of 16.74 arcseconds.

Conclusion

Though there is no firm standard, according to multiple sources a professional-quality filar micrometer should be capable of precision to one tenth of an arcsecond when measuring close double stars or one arcsecond for wider double stars. The filar micrometer produced in this project is capable (by design) of precision to seven tenths of an arcsecond. This means that it cannot reach the accuracy of the very few professional filar micrometers available for resale when measuring close double stars. However, at a tenth of the cost of the professionally-produced version, it is an affordable amateur filar micrometer. Since these are preliminary values for the calibration and accuracy of the produced filar micrometer, future data collection in these areas will lead to a better view of the true calibration value and accuracy possible for this filar micrometer.

Keywords: filar micrometer, double stars, 3D printing, amateur astronomy

INTRODUCTION

Double Stars

Astronomers search for sources of data in their investigation of the cosmos. The study of exoplanets supports theories about solar systems; studying gravitational waves is changing the way astronomers search for dark matter; and double stars offer a direct means for gathering data about the mass of stars.

Double stars are systems of two or more stars that are gravitationally bound and orbit each other. Many observable double stars have measurable orbits around the system's center of gravity (Argyle, 2012, p. 5). The mass of the component stars and their distance from each other are factors that affect the orbit, which can be calculated by measuring the separation and position angle between the stars over the period of their orbit. The period of a double star can vary anywhere between a few hours and several millennia (Argyle, 2012, p. 8). Plotting the orbit of double stars from the measurements collected makes it possible to calculate the masses of the stars. Using the orbits of gravitationally bound double stars remains the only direct method of calculating the mass of stars (Mullaney, 2005, p. 25). Since mass is the largest contributing factor to the life and death of a star, this direct data on stellar masses increases the reliability of models of stellar evolution, structure, and movements.

In order to accurately document double star orbits, careful and frequent measurements must be made of the position angle and separation of the pair. When observing a double star, the position angle (θ) is measured as the angle in degrees between the north point in the telescope's field of view and the line observed which connects the primary star to the fainter companion star **(Figure 1).** The separation (ϱ) is the observed separation between the primary star and its companion measured in arcseconds (Worley, 1961, p. 74; Argyle, 2012, p. 2).

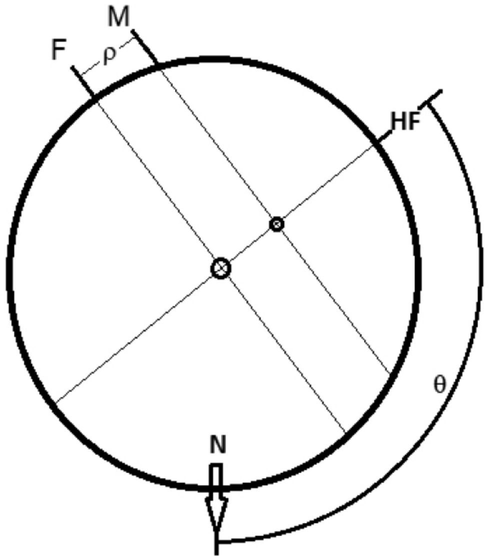

Figure 1: Measuring double stars with a filar micrometer. HF is the horizontal fixed wire of the filar micrometer. F is the vertical fixed wire. M is the vertical moveable wire. N is north in the field of view. θ represents the position angle of the double star. ϱ represents the separation of the double star. The primary star is at the intersection of F and HF. The component star is at the intersection of M and HF.

Star Catalogs

There are many star catalogs that focus on specific kinds of stars. The Washington Double Star Catalog (WDS) is a resource that can be used to find the location and expected separation and position angle of specific double star pairs. The WDS is maintained by the United States Naval Observatory and is updated nightly. A list within the WDS consists of neglected double stars, which are characterized as double star pairs that have not been measured in twenty years and have a separation greater than three arcseconds (Washington Double Star Catalog, 2013). Neglected double stars offer the opportunity to collect data on double stars that have very few recorded observations and can provide new data to stellar mass calculations. Since these stars often have very few recorded measurements, they are targets that amateur astronomers can focus on observing in order to expand orbit and mass catalogs to include data on these neglected stars.

Filar Micrometer

Tracking the orbits of double stars to strengthen the reliability of stellar mass calculations is an important aspect of astronomy that is currently receiving little attention. Since stellar evolution relies more heavily on stellar mass than any other characteristic, stellar mass data collections are some of the most important catalogs of astronomical parameters to maintain. Using instruments like the filar micrometer can allow amateurs to contribute to the study of double stars if the instruments are accessible to those who would use them.

In the early years of telescopic astronomy, there was very little interest in double stars. In order to investigate stellar parallax, William Herschel began observing double stars. Before this time, astronomers paid little attention to the most striking double stars in the sky because they did not understand what the celestial objects revealed (Argyle, 1986, p. 1). In 1803, Herschel published his paper outlining the existence, motion, and measurements of double stars which brought the significance of the double stars in the sky to the attention of astronomers (p. 2).

The filar micrometer has historically been the most commonly used instrument for visually determining position angle and separation by the observational astronomers studying double stars. The filar micrometer was designed and initially used in the early seventeenth century (Argyle, 2012, p. 169). John Herschel noted that the filar micrometer can also be used to make "micrometric measures of planetary diameters, solar spots, distance or elongations of satellites, lunar topography" and more (as cited in Case, 2014, p. 366). Since the early 1800s when William Herschel used his homemade filar micrometer to measure these newly-discovered double stars, many other astronomers followed his example using similar methods (Argyle, 1986, p.2).

Eventually, the most common use for the instrument became measuring double stars in order to plot their orbits (Argyle, 2012, p. 169). However, with the advent of photographic methods, making direct observations with filar micrometers fell out of use. A double star expert noted that in 1986, there were only three professional astronomers who continued to carry out visual observations of double stars with filar micrometers (p. 6). In the years since, research does not indicate any new professionals taking on visual measurements. This means that the number of professionals engaged in these measurements and the professional need for filar micrometers is dwindling. Yet this does not mean there is not still important data to be gleaned from double stars, and this neglect on the part of professional astronomers is actually an opportunity for amateur observers to once again make important contributions in astronomy. For this work to occur, there must be affordable filar micrometers available for amateurs to use.

A filar micrometer fits into a telescope behind the eyepiece. The instrument consists of three wires. Positioned vertically across the field of view are two wires: one is fixed and the other able to slide across the field of view. The third wire is fixed in place perpendicular to the two vertical wires (Byrne, Beesley, and Dunsby, p. 181). The crosshair created by the fixed wires provides a target for one of the double star components. The other component is positioned on the cross created by the moving vertical and fixed horizontal wires. **Figure 1** illustrates this positioning. The measurement made with the filar micrometer must be converted from inches read by the micrometer to arcseconds using the calibration value calculated for the filar micrometer and telescope (Greaney, 2012, p. 350). In this project, the calibration value of the filar micrometer has been calculated as 1.44E-4 inches per arcsecond of separation. Once the separation is recorded, the angle between the stars can be read from a protractor at the base of the instrument.

Filar micrometers declined in use in the 1900s as astronomers moved from observing and taking measurements while standing behind a telescope to using photography and computer software to make the same measurements from digital images. Double stars with a separation larger than approximately ten arcseconds can be easily measured using photographic methods, if the observer has access to the high precision cameras, mounts, and software necessary to measure in this way. In addition, interest in the observation and measurement of double stars has waned due to the long span of time, sometimes extending to decades or centuries, required to follow the complete orbits of many pairs. Since filar micrometers became less popular in the twentieth century, they are difficult to find and expensive to manufacture, which is evident in the fact that Argyle referenced only two manufacturers in 2012 (p. 181). Before closing in 2013, Van Slyke Instruments in Colorado charged between $2,500 and $3,000 for their instruments (p. 406). As of 2018, there are no current manufacturers of filar micrometers.

Despite their rarity, these instruments remain useful for taking measurements of resolvable star pairs with close orbits or stars that have very unequal magnitudes. For this type of pair, photographs and computers have difficulty determining the separation because of the way starlight from each component interferes and makes the images unclear (Buchheim, 2007, p. 254). Measuring close doubles remains of interest to amateur astronomers because their tight orbits likely have extremely short periods (decades instead of centuries) and thus present targets the orbits of which could be observed over entire revolutions (Mullaney, 2005, p. 8). Most double stars take many years to travel through their orbit and thus require just as long to produce a reliable mass calculation from measurements taken at regular intervals throughout the orbit.

Since other areas of astronomy take much less time to make advances, this is an area of astronomy that has been almost entirely neglected by professionals. This means that amateurs can make significant contributions to the index of stellar masses if they have reasonable access to equipment such as a filar micrometer.

Amateur Astronomers and Filar Micrometers

As commercial filar micrometers are often cost-prohibitive for amateur astronomers looking to study double stars, some have turned to their own resources to produce their own filar micrometers. Each of the amateurs discussed below designed and manufactured their instruments solely for their own use rather than for distribution. Amateur manufacturers Polman (1977) and Robertson (1985) have worked with machined metals and the traditional micrometer screws to produce instruments whose manufacturing cost is far less than half of their retail value. The Robertson filar micrometer was completed at a cost of $46 since he used scrap aluminum and did not have to pay for labor because he completed the work himself (Robertson, 1985, p. 359). An amateur astronomer in California built a filar micrometer that employed a vernier micrometer, similar to the one used in this project, as the primary measuring tool (Byrne, Beesley, and Dunsby, 1984, p. 182). A fourth amateur carried out a project very similar to this in 1999, but with aluminum workings in combination with a vernier micrometer (De Villier, 1999, p.164). The materials and method of measurement chosen by each of these amateurs has been outlined in Table 1 alongside the cost and accuracy of the instruments.

This project is unique when compared to these previous designs in that it made use of 3D printers to produce the primary components of the filar micrometer. This allows the micrometer components to be easily reproduced in the future by any other interested party with access to a 3D printer. Since its conception in the 1980s, 3D printing is most commonly used for small scale production of prototypes in the design process (Lipson, 2010, p.30). In 2012, almost half of the 3D printers sold were purchased for consumer rather than commercial use (p. 34). This means that over the last ten years, 3D printers have become more available to the general public than ever before.

Despite the low cost of personally-produced filar micrometers, these improvised instruments are a valuable tool for gaining experience using the equipment and understanding the measurement of double stars. Authors Polman and Robertson acknowledge the imperfect nature of their "homemade" filar micrometers by reporting margins of error in their measurements of approximately ten percent (translating to 0.1 arcseconds when measuring the closest double stars), which is equal to the error allowed in professional measurements (Polman, 1977, p. 396; Robertson, 1985, p. 360). Neither claims to have a professional quality filar micrometer from their personal design and manufacturing process, but they have made instruments similar to the expensive equipment of professionals accessible to the amateur community.

TABLE 1
Comparative Information on Amateur Filar Micrometers

Astronomer	Polman	Robertson	Byrne, Beesley, and Dunsby	De Villier	Rull
Year	1977	1985	1984	1999	2017
Material	Aluminum and Brass	Brass	*	Aluminum	Plastic
Cost	*	$46	*	*	$235
Percent Error	10%	*	<10%	2%	17%
Measuring Tool	Micrometer Screw	Micrometer Screw	Vernier Micrometer	Vernier Micrometer	Vernier Micrometer

** Data not reported*

Professionally Produced Filar Micrometers

As with any measuring tool, filar micrometers have a tolerance by professional standards when it comes to an acceptable margin of error in measurements. Tanguay, in his article for Sky & Telescope in 1999, outlines acceptable margins of error:

> For pairs in the 1.0-arcsecond separation range, measurements of separation should not differ more than about ±10 percent and position angle not more than about ±5.0° from the published values. For wider pairs that span around 100 arcseconds, your separation measurements should not vary more than about ±1 percent and position-angle measurements not more than about ±0.5° from the WDS [Washington Double Star Catalog] values (p.120).

This means that in order for the filar micrometer to be of a professional standard specific to close double stars, it must be accurate to 0.1 arcseconds. In order for it to be of a professional standard specific to wider stars, it must be accurate to one arcsecond.

The Fowler 1-2" Digital Counter Micrometer, the primary measuring component in this design, is precise to the ten thousandth of an inch, which (according to the calibration value found in this project) is equal to 0.7 arcseconds in separation with respect to this filar micrometer setup. This value will change if there is a change in telescope, filar micrometer, or eyepiece. This means that the filar micrometer produced in this project is not quite up to professional standards with respect to the closest double stars but is capable (in principle) of professional data collection for wider double stars. The accuracy of the filar micrometer also depends heavily on the accuracy made possible by the skill of the operator. Since a precision of 0.7 arcseconds is possible by design of the filar micrometer, it is the limiting factor in terms of the accuracy of the filar micrometer. The amateur astronomers mentioned above all reported margins of error much lower than those reported in this project. One of the likely contributors to that discrepancy is the fact that the amateurs referenced above were all visual observers of double stars before they began work with their filar micrometer, whereas I had minimal experience working with telescopes and observing double stars before the project began.

Calibration of a Filar Micrometer

Proper calibration of a filar micrometer is vital to making the most accurate measurements possible. The separation observed with the telescope is measured in tiny fractions of an inch in the filar micrometer. In order for the linear measurements in inches to translate properly to the subtended angle of separation between the stars in arcseconds, an accurate calibration value must be calculated. To determine this calibration, a known subtended angle of separation must be measured to find the equivalent linear measurement in inches (as measured by the Fowler micrometer).

Paul Couteau describes a method of practicing double star observations utilizing an artificial double star that offers a simple method of calibration (p. 89). Using two flashlights reflected on a bearing ball more than one hundred meters away, the astronomer can create an artificial double star with a predetermined separation of components **(Figure 2)**. A telescope can then be used to observe the artificial double and take measurements with the filar micrometer to calibrate the instrument. This simulation is useful because the astronomer can carry out these observations during daylight or cloudy weather and does not need to be concerned with the diurnal motion of the stars. This method of observation does not allow for simulations of position angle.

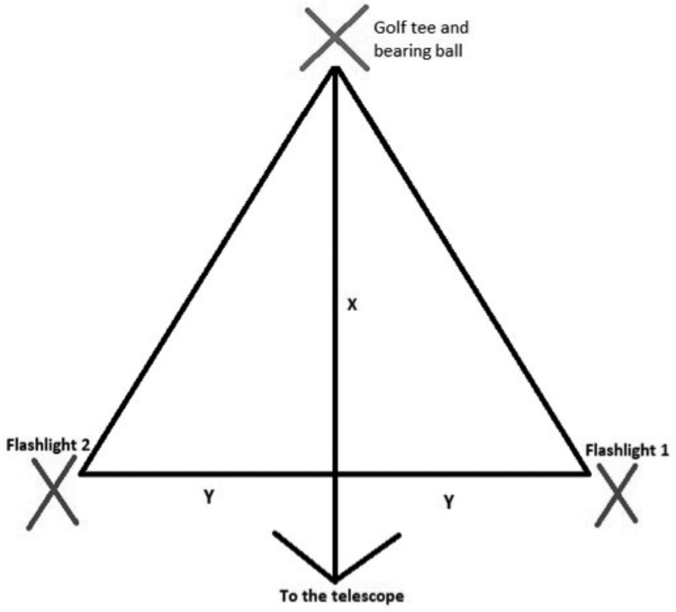

Figure 2: Artificial double star arrangement to calibrate the filar micrometer. The x and y parameters are changed depending on the desired separation. The flashlights used are directed toward the bearing ball in this arrangement. The bearing ball then reflects the light from the flashlights to the observer at the telescope.

This project sought to design and 3D print a filar micrometer that amateur astronomers could produce cost effectively. To evaluate the effectiveness of the filar micrometer, data was collected for calibration and analysis of accuracy. Paul Couteau's method of calibration was selected because of the season and climate in which the measurements would need to take place.

METHODS

The 3D printed components of the filar micrometer were designed using Creo Parametric 3.0. **Figure 3** shows the complete CAD model in an assembly file. The 3D-modeled parts of the filar micrometer are the front plate, slide, slide casing, and position angle circle. The front plate, slide, and position angle circle are all approximately one tenth of an inch thick, and the slide casing's thickness is nearly two tenths of an inch. All four components have a hole for the sightline between the telescope's mirrors and the eyepiece. The designed components were printed with a ProJet MJP 3600 Series 3D printer out of Visijet M3 plastic. Drawings of each component can be found in the appendix. A Fowler 1-2" Digital Counter micrometer, which is a type of vernier micrometer, was selected to work with the filar micrometer design. To be sure that the wires were thin enough to be observed through the eyepiece, 54-gauge Nichrome 80 wire was selected. In order for the wires to be visible in the field of view of the telescope, an LED circuit was assembled and fixed to the front plate of the filar micrometer. The positioning of the LED illuminated the wires to make them visible against the dark field of view.

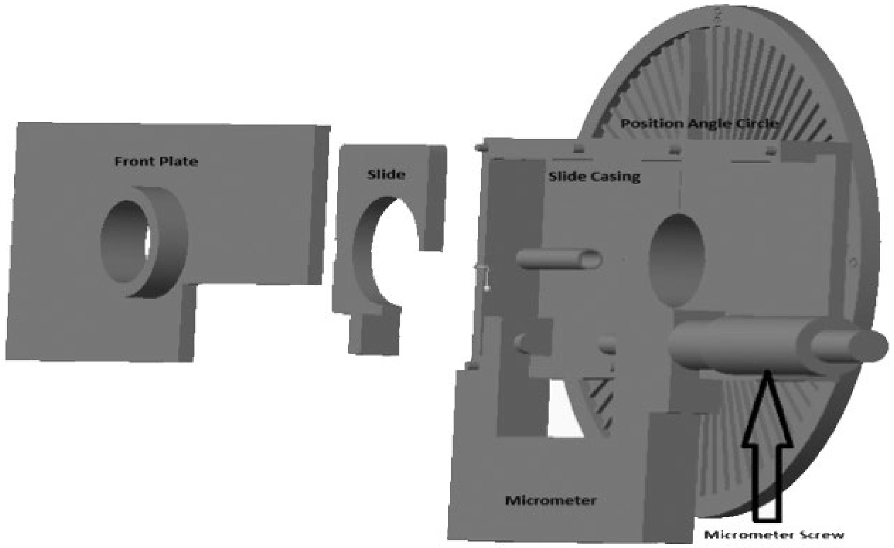

Figure 3: Assembly file of the filar micrometer produced in Creo Parametric 3.0. The front plate carries the eyepiece and the LED circuit. The slide carries the moving wire and is moved by the micrometer spindle. The micrometer is a Fowler 1-2" digital counter micrometer. The slide casing has a tube for the spring, grooves for the fixed wires, and gaps for the slide and the micrometer. The position angle is the reference used to measure the position angle of the double star when the horizontal fixed thread has been placed along the line between the primary and component stars.

Since eyepieces generally enclose their own focal plane, a 16.3-millimeter Criterion eyepiece was disassembled and fitted specifically to this filar micrometer to achieve the necessary placement of the wires within the telescope's focal plane. Disassembly of the eyepiece decreased its diameter to 0.96 inches, so the front plate of the filar micrometer was designed with a 0.97-inch hole so that the Criterion eyepiece would fit tightly. The six-inch Dobsonian-mounted reflecting telescope used with this project is an Orion Skyquest telescope.

A measurement made with the filar micrometer required that the horizontal fixed wire be positioned so that it bisected both stars. The moveable wire is moved on the slide using the spindle of the Fowler micrometer (as labeled in **Figure 4**) to position the wire first on the primary star, then on the secondary star, making note of each position on the Fowler micrometer. The difference between these positions is equal to the separation between the stars in inches. The Fowler micrometer used in this project has been designed to measure distances in inches, so the raw measurements are in inches.

The calibration of the filar micrometer was accomplished using Paul Couteau's artificial double star to simulate double stars of known separation. Figure 2 displays the layout of the bearing ball and flashlights used to find the separation simulated by the artificial star. Calibration of the filar micrometer in this research utilized simulations of three wider double star pairs: 16 Cygni (39.75 arcseconds), 24 Coronae Borealis (20.14 arcseconds) and Delta Orionis (52.42 arcseconds). According to the professional standards referenced above, we would hope for an error of ten percent or less. These stars were selected from a list of calibration pairs that have not changed in separation in recent history. This selection makes it possible to observe the simulated pairs for measurement before turning the telescope to the real pairs for comparison.

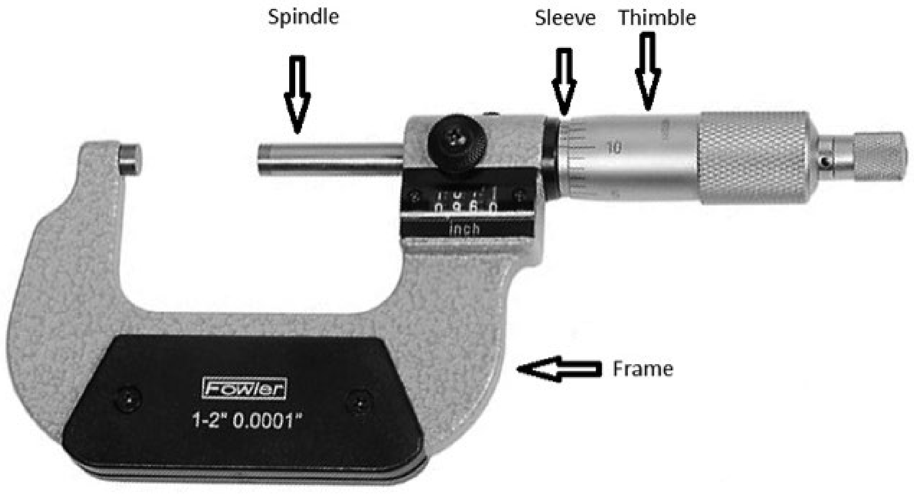

Figure 4: The Fowler 1-2" digital micrometer. The spindle remains in contact with the slide and enables measurement of the location of the moveable wire. The sleeve increases the precision of the micrometer to the ten thousandth of an inch. The thimble is rotated to move the spindle linearly. The frame fits into the slide casing which keeps it in a consistent location.

The equation used to find the simulated separation is shown below, and the distances used in these simulations are provided in Table 2. To collect the artificial double star measurements, a double star was set up and the filar micrometer was used to measure the separation between the stars. The calibration value determined from this data is essentially a conversion factor that makes it possible to compare the measurements made in inches using the filar micrometer to the actual separation of a double star in arcseconds. The bearing ball and flashlights were positioned according to Figure 2 with the bearing ball located on the bearing ball stand. Measurements of position angle were not made because Couteau's artificial double star setup does not simulate position angle. Table 2 represents object distances used to calculate the separation created by the artificial double star set-up using the following equation:

$$s = RL/(hD) \times 10^5$$

where

s is the double star separation in arcseconds
R is the radius of the bearing ball in meters
L is the distance between the flashlights in meters determined by solving for L given all other values
h is the distance from the flashlights to the bearing ball in meters
D is the distance from the telescope's objective lens to the bearing ball in meters

All values were selected with respect to advice from Couteau. For example, he recommends appropriate bearing ball sizes, an acceptable distance from the flashlights to the bearing ball, and a distance from the telescope to the bearing ball. Since the bearing ball was made to precise measurements, we can be confident in all provided decimal values. The distances L, h, and D can be assumed accurate to six thousandths of a meter (approximately half a centimeter). Using significant figure rules, we find that the separation between the simulated stars can realistically only be precise to two significant figures, or to the arcsecond. This is important to consider when comparing this first approximation of calibration and accuracy values to those reported by other amateur filar micrometer producers.

TABLE 2
Values Used In Determination Of Artificial Double Star Separation

Variable	Delta Orionis	16 Cygni	24 Coronae Bernices
s	52.42 [arcseconds]	39.75 [arcseconds]	20.14 [arcseconds]
R	00.0127 [m]	00.0127 [m]	00.0127 [m]
L	01.07 [m]	00.81 [m]	00.41 [m]
h	00.50 [m]	00.50 [m]	00.50 [m]
D	51.80 [m]	51.80 [m]	51.80 [m]

Since the separation of the artificial double star is known (at a particular confidence level), once the micrometer measures the apparent distance between the component stars, the linear separation in inches can be connected to the angular separation in arcseconds. Dividing the distance in inches by the known separation in arcseconds provides the calibration data for the micrometer-telescope-eyepiece apparatus. This calibration data is specific to the telescope, filar micrometer, and eyepiece combination of this project and can be used to interpret measurements of separations in the focal plane of the telescope. Two of the artificial double stars were used to calibrate the device, but the measurements of the third artificial double star were used to develop preliminary data on the accuracy and precision of the tool (Table 3). This method of calibration and accuracy evaluation was selected so that the accuracy data found by evaluating the simulated 24 Coronae Borealis would be independent of its “personal” calibration value.

RESULTS

A total of twenty-one measurements of three artificial double stars were analyzed to produce a conversion factor. 16 Cygni, 24 Coronae Borealis, and Delta Orionis were selected from a list of calibration pairs that do not have any recorded changes in separation. This means that the simulated double star should produce an image very similar to observations of the real stars when observed for measurement. The preliminary calibration found is that one arcsecond of separation measured by the micrometer is equal to 1.44E-4 inches. The average calibrations and percent error reported in Table 3 represent the difference between the location of the primary star and the location of the companion star when observing the artificial double star. The calibration values found for 16 Cygni (1.466E-4 inches per arcsecond) and Delta Orionis (1.64E-4 inches per arcsecond) were averaged and applied to the measurements of 24 Coronae Borealis. This process produced the converted measurements that were taken of 24 Coronae Borealis. Comparing these measurements to the true separation of the simulated double star results in a percent error of 16.88 for measurements of the simulated 24 Coronae Borealis.

TABLE 3
Average Calibration and Accuracy

Star and Type of Data	Value	Standard Deviation
16 Cygni Average Calibration	1.466E-4 inches	1.199E-4
Delta Orionis Average Calibration	1.640E-4 inches	1.970E-4
24 Coronae Borealis Percent Error	16.88 percent	8.263E-4

DISCUSSION

Proof of Concept

This project was a proof-of-concept design of an affordable and easy-to-replicate filar micrometer for amateur astronomers. This filar micrometer can be used to contribute to an area of astronomy that has become neglected by professionals. This 3D printable prototype lowers the barrier of expense and makes the instrument accessible to amateurs. The plans provided in the Appendix make it possible for anyone to build their own copy of the filar micrometer to take double star measurements.

In most cases, 3D printing is less expensive than metal working, and 3D printers are becoming more accessible to the general population through personal purchase and public access locations such as libraries (Lisbon, 2010, p.30). 3D printing this project in plastic was chosen because this method is the most accessible for public use by amateur astronomers who may print the device in the future. In this project, the final cost of the designed filar micrometer and the necessary accessories came to $235, not including a fee to use the printer. Van Slyke Instruments charged between $2500 and $3000 for the same instrument made from aluminum. With such a dramatic difference in price, an amateur astronomer could purchase a 3D printer ($1140), purchase a telescope ($600), print the filar micrometer, and outfit the instrument ($235) for the same cost.

In addition to being inexpensive, the design could be adjusted to another telescope and printed within about a week. Changes to the design could be completed by a user with basic CAD experience in just a few hours, and the printing and preparation for use would take a few more days. Since the design has already been made and needs only minor adjustments to be used with a different telescope, the filar micrometer presented here offers broad application for the amateur astronomer. A new user must only make adjustments to the size of the eyepiece tube and the distance created between the eyepiece and the micrometer wires. These simple changes make this design flexible and easy-to-adapt to the individual needs of a user.

A difficulty that results from using an artificial arrangement such as that described by Paul Couteau is that the calibration value is dependent on the measurements made between a telescope, two flashlights, and a bearing ball. This forces a much larger uncertainty value to be considered with respect to the calibration and accuracy. This challenge is another likely cause of the lower reported accuracy when compared with other amateur filar micrometers. The components of the artificial double star are subject to certainty of only about a quarter of an inch. The lowered level of certainty here decreases the certainty with which we can quote the set separation between the components in the simulated double star. This could result in a higher margin of error as a result of an imprecise simulated separation. This challenge can be overcome by taking measurements of real double stars whose separations are well recorded in order to calculate the necessary calibration value. Since this was not the method selected for this project, the calibration and accuracy values can be considered a first approximation of their values given more extensive use.

The seventeen percent preliminary accuracy and 0.7 arcseconds precision limits the double star separation that an amateur can measure with this filar micrometer. For example, it may provide sufficient measurements of ϰ Bootis at 12.6 arcseconds of separation, but it will do even better measuring 90 Leonis at 63.1 arcseconds of separation because a smaller percentage of the error could be attributed to the filar micrometer itself. The precision of the measurements made of ϰ Bootis would be equal to five percent of the distance being measured compared to 90 Leonis, where the precision is only one percent. So although the closest double stars have the shortest periods, this filar micrometer (at its current precision) may be best used on wider double stars when making measurements to professional standards. I would recommend not using this filar micrometer, as is, to measure stars closer than ten arcseconds if the goal is to make professional-quality measurements.

Design Comparisons and Advantages

It has been calculated that the filar micrometer designed here is capable of precision to 0.7 arcseconds, which results in imprecision in principle but not inherent inaccuracy. This precision could be increased by choosing another method of making the linear measurements such as a more precise vernier micrometer or a micrometer screw. This imprecision is a result of the limitations of the Fowler micrometer selected for this project. Consequently, the designed filar micrometer does not quite meet the professional standard of precision to 0.1 arcseconds (for close double stars) expected from a filar micrometer costing a customer nearly $3000.

Another design for taking measurements with a filar micrometer is to use a micrometer screw rather than a vernier micrometer. The micrometer screw carries out the same function as the micrometer used in this project but without the advantage of a built in numerical display for easier measurement. In order to make a measurement with the micrometer screw, the operator must know how many partial turns of the screw produce the separation between the stars. Micrometer screws have been the prominent tool used in filar micrometers since their invention (Argyle, 1986, p.29). With either of these methods, Becker cites the advantage of using screw mechanisms in micrometers as producing and measuring a small linear displacement using a large rotational displacement which is seen by turning the thimble of the micrometer (as seen in Figure 4) (p. 52). This theory applies similarly to vernier micrometers.

A Fowler micrometer was selected for this project in order to simplify the measurement process and decrease the prerequisite knowledge and skill necessary to make meaningful measurements. It is widely acknowledged that micrometric measurements of a new observer follow a pattern of increasing accuracy for their first few years of observation. Although this research is specific to observers using a micrometer screw filar micrometer, there is no reason to expect observers using a vernier micrometer to experience anything different.

The data obtained by calibration through observation of an artificial double star makes it possible to apply this method not only to practical use as an amateur astronomer but also to pedagogical use in an astronomy lab. In fact, this design has already been shared by personal communication at a recent conference, and will be used by Frank Florian at the TELUS World of Science in Edmonton, Alberta, Canada (F. Florian, personal communication, October 31, 2017).

Future research should continue to enhance the precision of the instrument by either choosing a more precise micrometer that has smaller units of measurement or choosing a different method of measurement that will produce a higher precision than the filar micrometer is capable of at this time. Reverting to a micrometer screw method of determining measurements could be utilized for experimentation to compare measurements from the vernier micrometer and the micrometer screw. Study of these different methods could additionally be useful to amateurs in the future. Collecting additional observational data by measuring either artificial double or real double stars would also increase the observer's accuracy when working with the filar micrometer. These increases in accuracy are realized with continuous use of the filar micrometer by increasing the skill of the operator and the reliability of the measurements.

The filar micrometer designed in this project can be 3D printed for individual amateur astronomers and outfitted for $235. Paul Couteau's method of artificial double stars provided targets of a specified separation to calibrate the filar micrometer and find the conversion value from measured inches to arcseconds of separation. Amateur astronomers will be able to use this design to make micrometric measurements of double stars which can be used to record their orbit and calculate their mass. This important data makes it possible for dedicated amateur astronomer observers to contribute to astrophysical research.

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APPENDIX
Engineering Drawings of 3D Printed Filar Micrometer Parts

Figure A.1
Drawing of final
Front Plate design.

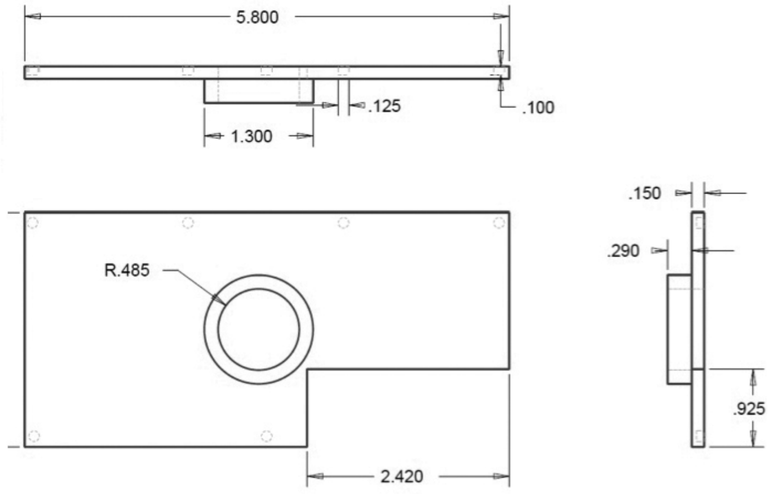
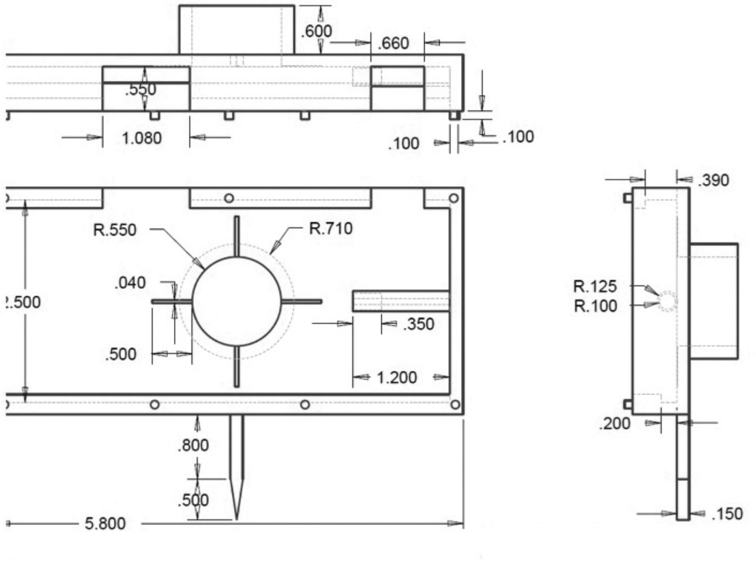


Figure A.2
Drawing of final
Slidecasing design.



APPENDIX

Engineering Drawings of 3D Printed Filar Micrometer Parts

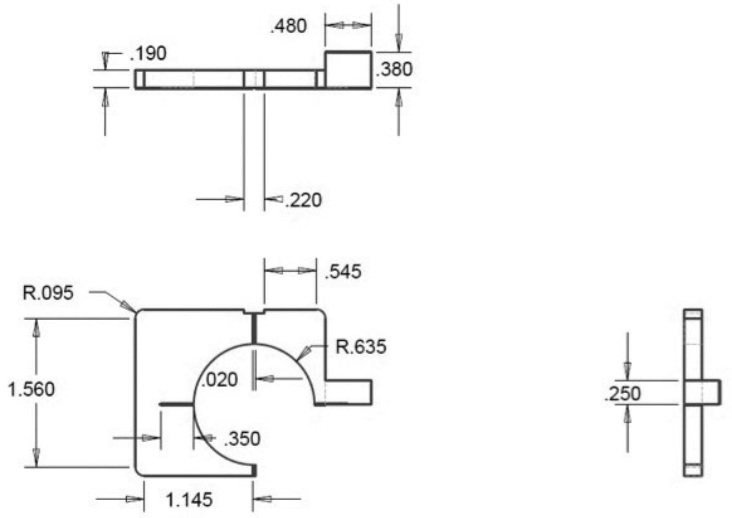


Figure A.3
Drawing of final Slide design.

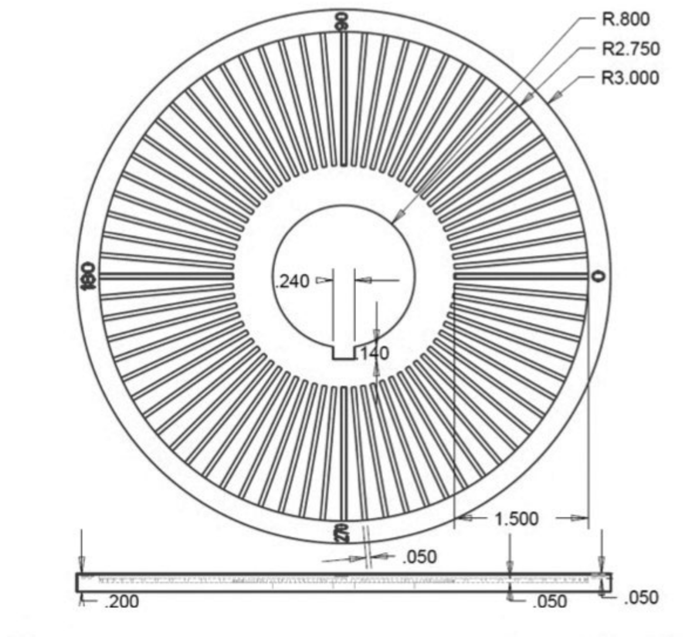


Figure A.4
Drawing of final Position Angle Circle design.