

# Automatic Alignment of Multi-Temporal Images of Planetary Nebulae Using Local Optimization

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## ABSTRACT

Automatic alignment of time-separated astronomical images have historically proven to be difficult. The main reason for this difficulty is the amount of sporadic and unpredictable noise associated with astronomical images. A few examples of these effects are: image distortion due to optics, cosmic ray hits, transient background sources (super novae) and various artifact sources associated with the CCD imager itself. In this paper a new automated image registration method is introduced for aligning two time-separated images while minimizing the inherent errors and unpredictabilities. Using local optimization, the two images are aligned when the root mean square of the difference between the two images is minimized. The dataset consists of images of galactic planetary nebulae acquired by the Hubble Space Telescope. The aligned centroids inferred by the suggested method agree with the results from previously aligned images by inspection with high confidence. It is also demonstrated that this method is robust, sufficient, does not require extensive user input and it is highly sensitive to minor adjustments.

## 1. INTRODUCTION

Image registration is the practice of overlaying two or more images and aligning them based on various criteria.<sup>1</sup> Image registration or representation of images in one common coordinate system is commonplace in any field of remote sensing.<sup>2</sup> Registration in these fields tends to be relatively simple since the basis of comparison are common, and static reference points. In medicine, images of CT scans, X-rays and MRIs are registered and overlaid for a comprehensive presentation and complete diagnosis. Image registration is also used in Earth observation, image mosaicking and image super resolution.<sup>3</sup>

Almost all image registration techniques consist of the detection of features in the trial image, finding the corresponding features in the reference image, producing a mapping transformation, performing necessary transformations and matching.<sup>3</sup> The above-mentioned process is relatively easy to do as the two images have features that are dependably static and common. For example, if two different remotely sensed satellite images of a city are to be overlaid, the common feature can be a river or an intersection. If a common feature is not present then the registration procedure is much more difficult and in some cases, impossible.

In this paper a method of registering images without the presence of a robust common feature is explained. The two images are of the same astrophysical object but are acquired at different times. It is crucial to align the images as accurately as possible for analysis, as the smallest mis-alignment will have serious repercussions in the measured quantity and the scientific interpretations. Accurate distance information can be extracted from the aligned images. This tends to agree with previously published results while possessing smaller uncertainties. In other words distances are determined with higher confidence.

The data being analyzed was acquired using the Wide Field Camera for Survey 2 on the Hubble Space Telescope. The objects of interest are 16 planetary nebula in our galaxy. Planetary nebulae (PN) are an expanding, glowing shell of ionized gas and plasma ejected from certain types of stars late in their lives.<sup>4</sup> Since the images were captured using the same instrument, it is assumed that the field of view and the angular resolution of the two corresponding images are similar and the only mis-alignment is translational and rotational for each set of images.

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First, the reason for the necessity of perfectly aligning the images of the PN is outlined. Then, the registration method is described and the results from the method is presented and compared with the results determined by inspection. Finally, the impact of mis-alignment on interpretation of the data is shown and a brief discussion is held. Results from one of the objects in the sample -NGC6543- are presented wherever a demonstration is needed, otherwise the entire sample is referred to.

## 2. MOTIVATION

Planetary nebulae are the ejecta of the gaseous outer layers of stars of  $\sim 0.8$ -8 times the mass of our sun during the asymptotic giant branch.<sup>5</sup> In this stage of the star's life, the imbalances within the star force it to shed some of its excess weight in order to achieve an equilibrium in the form of a white dwarf star. The gas ejecta will move away from the central star at speeds of a few kilometers per second<sup>6</sup> and it will become part of the surroundings and will eventually be consumed in the formation of other stars. There are approximately 2-5 PN being formed in our galaxy every year. Many interesting physical properties (mass, luminosity, radius, etc.) of this class of stars can be studied and understood if an accurate measurement of their distances was available. Properties such as the exact rate of white dwarf creation in the galaxy and the connection between the stars' thermal pulses (or internal nuclear fusion) to the dynamical time-scales of multiple halos of gas ejected in the PN phase, can help in understanding the stellar life-cycles.

In general, distances are poorly determined in astronomy, if at all. Trigonometric parallaxes have been used to determine distances to objects that are in the vicinity of the solar system, and only a handful of PN have their distances determined by this method.<sup>7</sup> Statistical distance estimation methods have been used to deduce PN distance as well. These methods make assumptions about the intrinsic properties of the object in question and based on the astronomical observations, calculate a distance to that object.<sup>7</sup> Therefore, it is sufficient to say that the distances derived using the statistical methods can not be trusted to be very accurate. Both trigonometric parallaxes and statistical distance determination have errors  $\geq 50\%$ . In some cases the error can be as large as  $\sim 200\%$ .

A method of determining accurate distance to these objects, expansion parallax, is explained in detail by Hajian, Terzian and Bignell 1993.<sup>8</sup> In short, if one PN is observed at a given time (epoch1) and observed again after some time has elapsed (epoch2), a noticeable change should be observed in the expanding shell around the central star, (Figure 1). The time difference needs to be on the order of a few years to be able to see any noticeable expansion of the ejecta. Using this property, an angular expansion rate can be determined. A distance to the PN can be determined when the Doppler expansion velocity of an object is divided by its angular expansion rate. The accuracy of the calculated distance depends solely on how precisely the two images have been aligned.

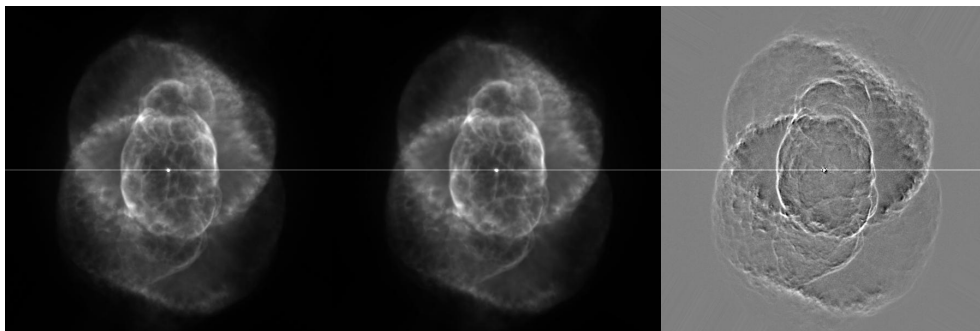


Figure 1. Image of NGC6543: epoch2 - 2008 (left), epoch1 - 1994 (center) and the residual image after negating the two epochs (right). The images of the two epochs have been aligned using the method described in this paper.

## 3. THE REGISTRATION METHOD

The method of local optimization used here is simple yet elegant. Local optimization is not practiced often and most of the literature focuses on global optimization in order to register images.<sup>9</sup> In this study, the images are acquired using the same camera on board the Hubble Space Telescope, so the intrinsic variations due to the instrument are constant. The

two images are also processed and reduced via similar algorithms which would remove any foreground object, perform a background subtraction, and remove any impurities in the image (such as cosmic ray hits, and any other instrument aberrations). Essentially, the images from different epochs would have a similar background value and all the unnecessary objects in the images would be removed. Keeping this in mind, and given the two images are properly aligned (translation and rotation), the background value in the subtracted (residual) image should be very close to zero.

Operating on the basis that the above-mentioned assumptions are correct, the registration was performed through an automated, iterative process, similar to the one described in Sawhney and Kumar 1999.<sup>10</sup> It is designed to operate without any user intervention. An initial x-y coordinate for the centroid of the epoch2 image was guessed and overlaid onto epoch1 based on the guessed coordinates. The two images were then negated and 16 equal sized apertures were clipped from the residual image, the central 150 pixel radius of the image which contains the central star and most of the structure of the planetary nebula itself were avoided, the root mean square (RMS) of each of the 16 apertures were determined and the average was recorded. This process was repeated while systematically changing the x-y coordinates for the centroid. When a range of  $\pm 3$  pixels around the initial guessed x-y centroid was covered, the centroid that corresponded to the minimum RMS average of the apertures was chosen to be the most accurate centroid. As a result, the translational off-set of the two images was determined. The process described here is very similar to the entropy minimization process proposed in Maes *et al.* 1997,<sup>11</sup> in which the goodness of registration is determined based on the minimization of the randomness of energy in the image. The rotational off-set was determined through an identical iterative process by pivoting epoch2 image around the newly found centroid and minimizing the average RMS.

#### 4. RESULTS AND DISCUSSION

The results (image centroids) determined using the registration technique are presented here and compared with the centroids found by inspection. As previously mentioned, the specific case of NGC6543 will be presented as an example. After, the impact of a minute mis-alignment of the two epochs on the distance and its confidence interval is shown.

##### 4.1 Registration

Figure 2 shows the convergence of the x-y centroid and the rotation of epoch2 image with respect to epoch1 of NGC6543. The background RMS of the residual image is minimized when the images are offset by (-0.42, 1.35) and rotated by  $0.09^\circ$  with respect to each other.

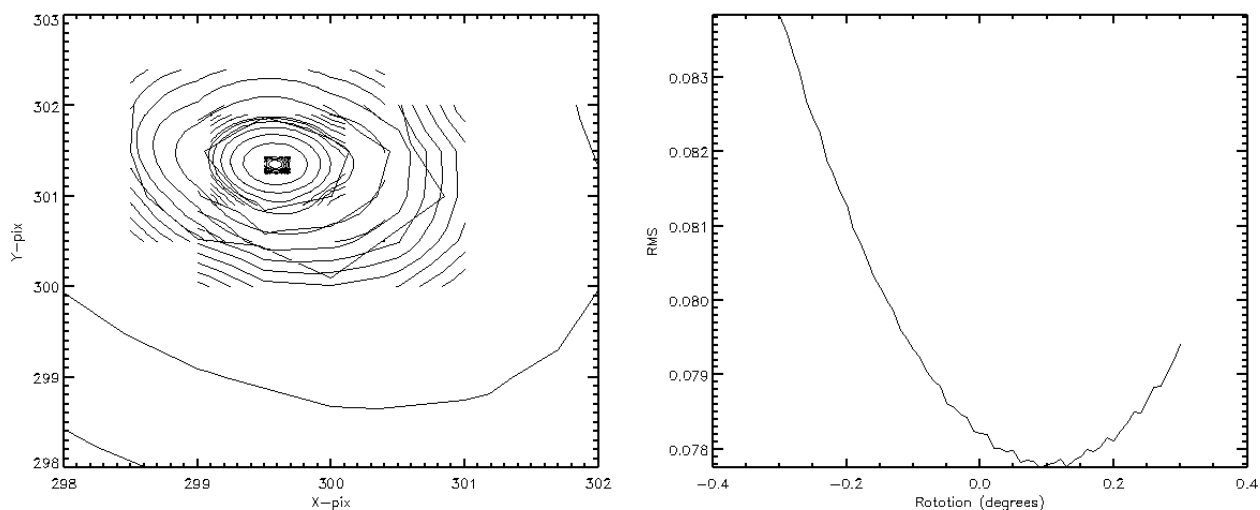


Figure 2. A contour plot of background RMS with changing x-y centroids (left), and the convergence of the rotation of the images with respect to each other (right).

This procedure was repeated for the other 15 PN in this study and their respective x-y centroids and rotation angles were determined similar to NGC6543. For all PN, the x-y centroids was also evaluated by inspection before the registration

software was developed. Previously, it was believed that registering the images by inspection was the only method of achieving acceptable results. Table 1 summarizes the x-y centroids evaluated using the automated registration (code) and determined by inspection (manual). It is worth noting that the centroids found via each method do not seem to display any major discrepancies, meaning that the values are off-set in the same direction.

Table 1. Registered centroids of epoch2 with respect to epoch1 using the code and evaluated by eye.

PN	(x,y) <sub>code</sub>	(x,y) <sub>manual</sub>
BD30	(299.49, 300.5)	(299.5, 300.45)
IC418	(299.62, 299.44)	(299.7, 299.35)
IC2448	(299.48, 299.6)	(299.5, 299.6)
J900	(300.47, 299.74)	(300.5, 299.8)
NGC2392	(300.17, 301.6)	(300.25, 301.3)
NGC3918	(299.71, 300.81)	(299.8, 301.05)
NGC5852	(300.46, 299.41)	(300.4, 299.3)
NGC6326	(299.58, 299.5)	(299.85, 299.5)
NGC6543	(299.58, 301.35)	(299.75, 301.55)
NGC6578	(300.35, 300.44)	(300.15, 300.2)
NGC6741	(300.2, 302.11)	(300.0, 302.1)
NGC6751	(301.37, 300.32)	(301.3, 300.05)
NGC6826	(400.51, 400.46)	(400.45, 400.25)
NGC6891	(299.63, 299.63)	(299.9, 299.7)
NGC7026	(399.42, 398.55)	(399.35, 398.85)
NGC7354	(399.5, 398.5)	(399.95, 398.85)

Figure 3 shows the x-y centroids of epoch2 of the 16 PN, normalized to the centroid of their respective epoch2. On average, the centroids determined by inspection agree well with their corresponding centroids evaluated by the method discussed in this paper. They are in some cases different by larger than one sigma, this phenomena is attributed to the fact that during inspection by eye, no rotational misalignment was assumed. This means that all the PN centroids were fixed at  $\theta$  equal to zero. Using the method implemented in this study, it quickly becomes apparent that this is not a correct assumption and that all epoch2 images are rotationally mis-aligned, however small the rotation may be. Also, with the error associated with each of these measurements, the difference in the measurements determined by inspection is less than 5% of the measurements evaluated by the code, therefore there is a very good agreement between the two methods.

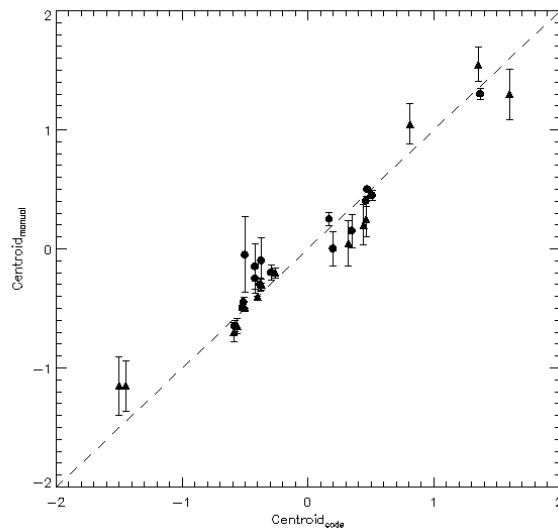


Figure 3. A plot of the x-coordinate (circle) and y-coordinate (triangle) centroid of the sample found by inspection and using the automated registration procedure. The centroids have been normalized to (0,0) for ease of presentation. A line of unity is plotted to demonstrate the correspondence between the two methods.

## 4.2 Distance Precision

As previously discussed, determination of accurate distances is crucial in astronomy. In addition, the distances to PN seem to be very elusive. Distances to 16 PN were determined using the method described earlier. The proper registration of the multi-temporal images is what allows for the most precise distance calculations of these objects. The purpose here is not to determine the most accurate distance to these objects, but to demonstrate that with a reliable registration method the distances can be determined with higher precision.

In order to emphasize the robustness of the registration method introduced in this paper, the distance to NGC6543 was calculated with purposely mis-aligned images. It was assumed that with the most accurately aligned image the most precise distance to this object could be calculated. In an effort to display this point the two images of the different epochs have purposely been registered with slight mis-alignments and the distances with their respective uncertainties were determined. Figure 4 displays the results of this exercise. From the residual image produced using the *ideal* centroid offset for NGC6543, (299.58, 301.35), the distance to this object was measured. Then, each of the x- and y-coordinates of the centroid was adjusted, in steps of 0.5 pixel,  $\pm 2$  pixels around the ideal value while keeping the other coordinate fixed. At each *new* centroid position a residual image was created, and using it, the distance to NGC6543 was measured.

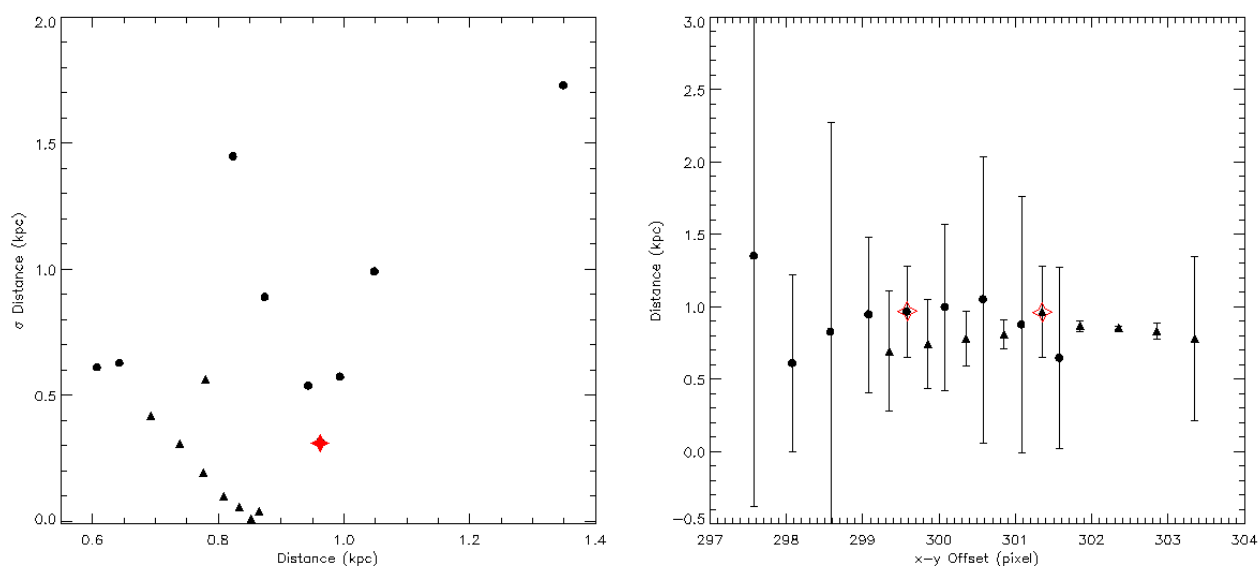


Figure 4. A plot of the error in distance as a function of the estimated distance (left), and distance as a function of x- and y-offset (right). In these two plots, measurements made with respect to the x-coordinates are shown in filled circles, and y-coordinates are shown in filled triangles. In both plots the results of the automatic registration technique have been highlighted with a red star.

Figure 4 shows the spread of distances and their respective uncertainties. The range in distances seems to be about 0.4 kpc from the nominal distance of about  $0.81 \pm 0.11$  (14%) kpc, determined via this method. In the literature, the accepted distance to this object is  $1.0 \pm 0.3$  (30%) kpc.<sup>12</sup> The error in the distance measurement is the stochastic error associated with the flux measurement of the astronomical observations. This is added in quadrature to the errors in Doppler radial velocity measurement. The largest offset from the nominal centroid position results in distances that are more unlike the nominal distance. In astronomical distance scales, hundreds of parsecs can have a grave impact on the inferred physical properties of an object. It is observed that the uncertainties in the distance are much more sensitive to mis-alignment in the x-coordinate. Evidently, distance uncertainty tends to decrease as the y-coordinate of the centroid increases from the nominal value. However, the global minimization of the uncertainty in distances is apparent as the x- and y-coordinates near the nominal centroid.

It is worth noting that the effects of diagonal offsets (changes in x- and y-coordinates together) were not investigated in this study. However, it is safe to assume that the distance and uncertainty in the distance would only be worse than what is shown here. Lastly, it is easy to slightly alter one input (x- or y-coordinate) at a time and investigate the changes in the

output. Nevertheless, it is important to note that all input parameters will need to be changed concurrently in order to find the most optimum registration of the two images.

## 5. SUMMARY

Based on the results shown here, the method suggested and implemented in this paper is a sound, self-contained, closed-loop and non-interactive algorithm for registering and aligning two images of a PN separated in time. It is assumed that the images have been put through a similar reduction process and the mis-alignment, if any, is only due to the translation and rotation of one of the images with respect to the other. Only by initializing this algorithm, the corrected centroid and the rotation angle is determined and the two images are perfectly aligned.

Sixteen PN were the subject of study in this paper. For each set of images of a given nebula, the centroid and rotation was determined using the algorithm introduced in this paper and also determined by inspection. It has been shown that both methods produce comparable results. The impact of slight mis-alignment is also studied in the form of calculating the distance and uncertainty of distance to NGC6543. It has been demonstrated that the distance determination depends very heavily on x-coordinate offset and that minor mis-alignments can largely impact the distance and its uncertainty to the said nebula.

Historically, it was believed that astrophysical images are to be inspected only by eye for applications such as those mentioned in this paper. Therefore, automated procedures to deduce results were not widely trusted and accepted among the scientists in this field. Data analysis by inspection is very time consuming and is subject to numerous shortcomings. The subjectiveness of the person analyzing the data may alter results. The lighting conditions in the room may affect judgment. In some cases, the goodness of alignment is not even apparent to the eye. Any or all of the above can lead to erroneous results being produced, hence different interpretations of the data.

The algorithm designed and implemented here uses the intrinsic properties of the images to determine the goodness of alignment and the best criteria. It is much faster in producing results than the inspection technique, and the results produced are consistent from one test to the next.

As astrophysical datasets become larger, the need for automatic data reduction and analysis tools becomes more pressing. Tools such as the one created in this study need to be created, tested, used, and trusted in order for scientists to be able to provide the best and most accurate analysis of the data at hand, for better interpretations and ultimately, conclusions about our universe.

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