A New Technique for Measuring Absolute Proper Motions with HST: Using Background Galaxies as Positional References

S. Tony Sohn, Jay Anderson, & Roeland P. van der Marel

Abstract. Over the past few years, it has been demonstrated that HST is well suited for high accuracy astrometric sciences. For example, HST's imagers have been used to measure relative proper motions of stars for deriving the internal dynamics of globular clusters. Absolute proper motions have also been measured in several studies but so far, most of them relied on a single reference object, a quasi-stellar object (QSO) within the field. In this work, we present a new way of measuring proper motions of stars. Instead of relying on background QSOs, we developed a technique that uses numerous background galaxies as positional references. We discuss this technique in detail and demonstrate how well we are able to measure proper motions of stars. Our new method can in principle be applied to any existing multi-epoch HST data and opens up a possibility to measure accurate transverse motions for galaxies out to a few Mpc.

1. Introduction

Thanks to the excellent resolving power of HST, high precision astrometric science is now a well-established field. For example, HST's imaging cameras have been used to measure the relative motions of stars for studying the internal dynamics of Galactic globular clusters (e.g., McLaughlin et al. 2006; Anderson & van der Marel 2010).

The current onboard imagers of HST (e.g., ACS and WFC3) are capable of measuring relative positions of stellar sources to better than 0.5 mas. However, the absolute astrometric accuracy of HST itself is limited by the quality of the Guide Star Catalog (∼0.2 arcsec for GSC2.3). Nevertheless, it is possible to measure very accurate absolute proper motions (PMs) of stars by measuring their displacement over time relative to stationary background references sources in the same field.

What are considered good background reference sources? Conventionally, quasi-stellar objects (QSOs) have served as excellent reference sources due to their star-like appearance and luminous nature (see e.g., Piatek et al. 2002; Kalirai et al. 2006). However, using QSOs has the disadvantage that they must be spectroscopically identified in advance, and that the number density of known bright QSOs are limited (but rapidly increasing with new surveys). For the small field of view of HST imagers, these limits require the observer to deliberately image a QSO in the field in at least two different epochs to measure the absolute PM of stars around them. Background galaxies, on the other hand, are abundant and on average homogeneously distributed over the sky. A glance at any HST image shows that there are many galaxies in its background. In addition, thanks to the exquisite spatial resolution, HST can distinguish galaxies from stars down to a level where galaxies become numerous. It is clear that if the positions of these background galaxies can be reliably measured, they can serve as excellent local positional references and stars could then be measured directly against them. Examples of such approach are demonstrated by Bedin et al. (2005) and Kalirai et al. (2007) on measuring absolute PMs of two stellar clusters, but
the galaxy samples used as reference objects were limited to the ones that are very compact and point-like.

In this article, we introduce a new technique for measuring absolute PMs of stars in the field using background galaxies as reference points. The core of our technique lies in determining positions of galaxies using a template-fitting method. This allows us to measure not only compact galaxies but also extended ones with great precision. We discuss the details of our measurements and provide estimates on the uncertainties.

2. Measuring Absolute Proper Motions

Measuring absolute PMs involves measuring the displacement between the position for a target object at one epoch and its position at another epoch with respect to stationary reference objects. In this section, we discuss the details on how we obtain PM measurements. We assume that we are working on a deep and well-dithered set of first epoch data that will be used to (1) construct the reference image and to (2) build templates of the background galaxies, and a less deep set of second epoch data taken with the same imager as the first epoch. Exposure times are assumed to be nearly identical for all individual images including the second epoch ones. The majority of stars found in this field would belong to a co-moving stellar system (e.g., halo stars of M31 or Local Group dwarf galaxies) and our goal will be to measure the bulk motion of those stars over time.
2.1. Overview

Our technique starts with the construction of a median-combined master frame based on all individual exposures of a field. This co-addition is similar to MultiDrizzle but better optimized for astrometry. Since the observations were well-dithered, we supersample the image by a factor of 2 to enhance the spatial resolution of our master image. The supersampling ensures that aliasing effects are minimized when building the galaxy templates via interpolation. An automatic detection scheme is then run on the master frame to identify and classify sources into stars and galaxies. For the stars in the field, we adopt their positions determined from fitting library PSFs and use those to derive transformation relations that tie each individual exposure to the master frame. The transformations are derived for both first and second epochs. Because most of the stars in the field will have moved towards the same direction on the sky in the second epoch, the way we have set up the transformations will allow us to measure the displacement of galaxies with respect to a fixed stellar moving reference frame. In the course of deriving such transformations between the master and individual frames, we adopt the available distortion solutions (e.g., Anderson & King 2004) and use six-parameter linear transformations to correct for any time-dependent linear skew variations (Anderson 2007).

For each individual galaxy, we create a template from the master frame that takes into account the galaxy morphology, the PSF, and the pixel binning. This template is used to measure the accurate position of galaxies (which will be discussed below in detail) in each exposure. Once we derive the positions of galaxies in each frame, we take the average of those positions for each epoch [i.e., $(\bar{X}, \bar{Y})_1$ for epoch 1 and $(\bar{X}, \bar{Y})_2$ for epoch 2], calculate the difference between the positions, and divide them by the time baseline $(\Delta T)$ to calculate the proper motions in each X and Y. The final measured reflex displacement of each individual galaxy implies a PM of the stars in the field equal to

$$
\mu(X, Y) = -\frac{(\bar{X}, \bar{Y})_2 - (\bar{X}, \bar{Y})_1}{\Delta T}.
$$

In principle, one can use the position of galaxies for deriving the transformations that relate individual frames to the master frame and directly measure the stellar motion as has been done by Mahmud & Anderson (2008). However, positions of stars are much reliably measured than those of galaxies, and to reduce the uncertainties, the optimal way to define the transformations are by using the numerous stars in the field. We show the diagram illustrating the overall process discussed above in Fig 1.

2.2. Measuring Positions of Galaxies: GSF-Fitting Method

The master frame we created is used to construct a template for each galaxy that gives us an idea on how the galaxy’s flux is expected to be distributed among the pixels in the pixel grid of each individual exposure as a function of our assumed center for that galaxy. This template is then fit to the observed pixels to determine the position for the galaxy, just as an effective point spread function (ePSF) is used to derive the position of stars (Anderson & King 2000). Since our galaxy templates are similar to the concept of ePSF, they will be denoted by galaxy spread functions (GSFs).

An important question one might ask at this point would be what exactly the definition of a position of galaxy is. For stars, positions are relatively well defined since they are point sources by nature. However, for galaxies, the definition of position is arbitrary – a galaxy may be intrinsically asymmetric, have less pronounced peak than stars, or even have multiple peaks. Fortunately, the definition of position is not crucial because of the following reason. Our galaxy templates can be built around any point of reference as long as there is flux that belongs to the galaxy. For the sake of minimizing the uncertainties associated with determining the positions (described below), the best point of reference would of course be
where it provides the highest signal-to-noise ratio. Hence, we adopted the galaxy’s brightest pixel in the master image as its point of reference. This provides us with a handle for each galaxy. Consequently, when we measure a position of a galaxy in an image, we are simply finding the location of this handle in each individual exposure.

Once we have positions of the handles in the master frame, we locate the predicted positions of them in each individual exposure using the transformation relations derived in the earlier stage. Since the center of the template corresponds to the handle for the galaxy, we find the position for the galaxy in the exposure by finding the location within the exposure’s pixel grid that corresponds to the center of the template. To do this, we take the 5 × 5 pixels centered on the galaxy’s brightest pixel in the exposure. We then resample the master frame about this center and construct the galaxy templates. The template is moved right, left, up, and down in order to better fit the exposure in increments of 1/100 pixel. At each trial offset, we evaluate the template at the location of each of the 25 pixels (using bicubic interpolation to interpolate the finely sampled template) and compare it with the observed pixel values. This gives us a $\chi^2$-type quality-of-fit estimate for each trial location. We find the minimum of this surface and associate the location of the template center in the individual image with the location of the handle in the master frame. Fig 2 illustrates the process of the GSF-fitting method.
Figure 3: Examples of the uncertainties obtained using the GSF-fitting method. Two panels are shown in this figure, and for each panel the first column shows the thumbnail image of each galaxy, the second column shows the 3-dimensional surface plot for better showing profile, the third column shows the distribution of $\Delta X$ and $\Delta Y$ measurements (where $\Delta$ denotes the difference between the average and individual measured positions), and the fourth column shows the RMS of the distribution in $X$ and $Y$. In each panel, the galaxies are ordered in decreasing surface brightness from top to bottom.

2.3. Uncertainties of the Proper Motion Measurements

The random error of PM ($\mu$) in Equation (1) can be expressed as

$$\Delta \mu = \frac{1}{\Delta T} \sqrt{\frac{\sigma^2}{M_1} + \frac{\sigma^2}{M_2}},$$

where $\sigma$ is the RMS scatter and $M$ is the number of exposures per epoch. Because the stars have far better positional accuracies than the galaxies, the RMS scatter $\sigma$ in Equation (2) will be dominated by the uncertainties in our measurements for the galaxy positions. If we assume that the number of exposures in the first epoch is considerably higher than those of the second epoch (e.g., $M_1 = 100$ and $M_2 = 2$; then, $M_1 >> M_2$), the final PM error is simplified as $\Delta \mu = \sigma/\Delta T \sqrt{M}$. The typical RMS positional accuracy $\sigma$ per galaxy and exposure will be similar for the two epochs since both epochs are observed with the same detector. We may then derive $\sigma$ from the repeated measurements of the epoch which has the higher number of exposures (the first epoch in our test case).

In order to estimate the positional uncertainties of our GSF-fitting method with real HST data, we have carried out simulations on a test data set that consists of 108 ACS/WFC images of the “M31 Spheroid” field (Brown et al. 2003) taken with the F606W filter in Dec 2002 and Jan 2003. The master frame was created as described in Section 2.1. To simu-
late individual images, we first replaced the pixel values of the master frame with random deviates drawn from a Poisson distribution with the mean equal to the original counts, and then used the linear transformation relations and distortion solutions to project the noise-added master image onto exposure planes (this latter process is called “blotting back” in MultiDrizzle). Positions of galaxies were derived on each simulated exposure using our GSF-fitting method. We carried out 1,000 simulations and measured the RMS scatter of the distributions for difference in the average and individual positions in $X (\Delta X)$ and $Y (\Delta Y)$.

In Fig 3, we show examples of our results for two different cases: circular galaxies (left panel) and highly-elongated ones (right panel; mostly edge-on spirals). In each panel, the third column shows how consistently the GSF-fitting method found the positions of galaxies among independent simulations, i.e., a narrower scatter indicates that the measured positions are precise whereas a wider scatter implies that the positions are uncertain. The RMS of the distribution in $X$ and $Y$ are displayed in the fourth columns. For the circular shaped galaxies the scatter plots generally show isotropic distributions. Our results indicate that even for galaxies that appear very faint such as the two faintest galaxies in Fig 3, the one-dimensional RMS is $\leq 0.1$ pix ($\sim 5$ mas). In order to compare our GSF-fitting method against classical approaches in finding positions, we have repeated the simulations this time using various centroiding methods (e.g., Gaussian-fitting and derivative search methods) for measuring the positions of galaxies. For nearly all galaxies, the GSF-fitting method provided lower uncertainties. The two faintest galaxies in the left panel of Fig 3, for example, were measured with RMS larger than $\sim 0.3$ pix using the centroiding methods. For the highly-elongated galaxies, we find that the scatter plots show elongated distribution about the average position. Consequently, the RMS is small on one side and significantly larger on the other. This demonstrates that our GSF-fitting method allows even the edge-on galaxies to be used as positional references for stars located along the perpendicular direction of the disk.

2.4. GSF-Fitting Method: Application to Real Data

We finally demonstrate how well the GSF-fitting works on real data. For each galaxy in the four-panel examples of Fig 4, we show an extraction from the individual image, the GSF that gives the minimum residual (see Section 2.2 above), and the actual residual image. We find that for most of the galaxies, the residual images look very clean albeit with some cosmic rays. However, for some of the galaxies, the residual images show under- or over-subtracted features. The most likely cause of these cases is the cosmic rays affecting the inner $5 \times 5$ pixel region of the individual images. We examine the residual images one after another to reject the positions of the galaxies affected by the cosmic rays.

3. Conclusions

We have shown that our GSF-fitting technique for measuring positions of galaxies works very well. We conclude this proceeding by listing the benefits of using background galaxies as positional references:

- Abundance of sources provides an $\sqrt{N}$ advantage in averaging.
- For any given frame, background galaxies are generally found all over the place. By using these objects, we are able to sample the entire detector, thereby reducing the chance to introduce systematic errors caused by local effects.
- Background galaxies are virtually found anywhere in the sky. There are some instances where galaxy groups or clusters are found in the background of a target field, and one will benefit further by using those galaxies in the field.
Figure 4: Four-panel examples showing how well the GSF-fitting method works on real data. For each panel, the first column shows galaxies in each individual image, the second column shows the best-fit GSF, and the third column shows the difference between the first and second columns.

- Finally, for the reasons stated above, there are many potential scientific applications for the Local Group and beyond.

References

Piatek, S. et al. 2002., AJ, 124, 3198