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Phase Retrieval to Monitor HST Focus: I. WFC3 UVIS Software Implementation

Sami-Matias Niemi†, Matthew Lallo, George Hartig & Colin Cox
Space Telescope Science Institute
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Abstract

A monthly focus monitoring of the Hubble Space Telescope (HST) is performed via the Phase Retrieval technique. This has recently relied on Advanced Camera for Surveys (ACS) Wide Field Camera (WFC) data. Due to the installation of Wide Field Camera 3 (WFC3) on board the HST as a part of Servicing Mission 4, a new camera suitable for the monthly focus monitoring has become available. This document briefly describes the Phase Retrieval technique used for the focus monitoring, and outlines the implementation of the WFC3 UVIS channel into the existing software package called FITPSF. This implementation required not only major code changes, but also accurate geometric distortion solutions, charge diffusion kernels, and the properties of the camera optics to be included. Testing of the new software is also described. This showed that unlike ACS, the WFC3 UVIS channel shows a field dependent 3^{rd} order spherical Zernike polynomial. Even so, WFC3 UVIS channel data are well-suited for the focus monitoring and result in a smaller scatter between focus values of different stars than ACS data. This is likely due to a better point spread function (PSF) sampling in the WFC3 UVIS channel, but also due to the relatively large charge transfer inefficiency present in ACS.

1. Introduction

The monthly focus monitoring program of the HST has always been performed with cameras capable of high-resolution imaging. In the early phase of the mission the focus

†niemi@stsci.edu

monitoring was performed using Wide Field Planetary Camera 2 (WFPC2), while after the installation of Advanced Camera for Surveys (ACS) its high-resolution channel was often favoured. The high-resolution camera (HRC) of ACS was well-suited for the focus monitoring because of its small pixel scale and it provided robust results. Unfortunately the failure of ACS disabled the HRC forcing other alternatives to be sought.

The wide field camera (WFC) of ACS shows geometric distortion (Anderson 2007). Existence of such distortion is not helpful when performing Phase Retrieval and accurate PSF fitting, however, it can be taken into account during the process, thus, WFC of ACS is also suitable for focus monitoring. However, the constantly degrading charge transfer efficiency in ACS (Mutchler and Sirianni 2005; Massey et al. 2010) is causing the PSF of ACS WFC to become more and more asymmetric leading to various problems when Phase Retrieval is applied.

During the Servicing Mission 4 (SM4) of the Hubble Space Telescope (HST) in May 2009 a new camera was installed on board the HST. Wide Field Camera 3 (WFC3) is a wide field imager, whose wavelength coverage ranges from ultra-violet to near-infrared. A reasonably small pixel scale ($0.03962''\mathrm{pix}^{-1}$; at 500 nm the full width at half maximum is 1.675 pixels) of the UVIS channel together with a high sensitivity and a large selection of filters makes it well-suited for Phase Retrieval techniques and for focus monitoring. It was therefore highly desirable that analysis capability for the WFC3 UVIS channel would be implemented in the existing HST focus monitoring software FITPSF described in Section 2.2 below. This would also enable an independent confocality check by allowing a focus difference between the WFC3 UVIS and ACS WFC channels to be determined.

2. Phase Retrieval

Phase Retrieval is a technique which is being used for the focus monitoring of the HST, and it concerns finding a solution to the phase problem. Briefly, Phase Retrieval consists in finding the phase that for a measured amplitude satisfies a given set of constraints.

A point spread function (PSF) for an optical system is determined by the amplitude and phase of the (approximately) spherical wavefront as it converges on the point of focus. The amplitude $A(u, v)$ measures the intensity of the wavefront at each point (u, v) on the sphere and is usually approximately uniform across the entire pupil, except where it is obscured by objects in the light path such as the secondary mirror and its support structures such as spiders and mirror pads. The phase $\Phi(u, v)$ measures the deviation of the wavefront from a sphere; a perfectly focused wavefront has zero phase error. If we assume that the wavefront is not strongly curved over the pupil, then PSF $P(x, y)$ can be written

$$P(x, y) = \left| \int \int A(u, v) e^{i2\pi(ux+vy+\Phi(u,v))} \right|^2 \mathrm{d}u\mathrm{d}v \quad . \tag{1}$$

The PSF is therefore the square of the amplitude of the Fourier transform of the complex pupil function.

For the focus monitoring purposes Phase Retrieval can be considered as the process of trying to recover the wavefront error $\Phi(u, v)$ given a measurement of the PSF. In practice, finding the focus consists of fitting a model PSF to data by varying the model parameters. Ultimately we require a mathematical connection between the model parameters and the optical aberrations to recover the focus.

2.1. Zernike Polynomials

The Zernike polynomials are a set of orthogonal polynomials that arise in the expansion of a wavefront function for optical systems with circular pupils (e.g. Wang and Silva 1980; Hu et al. 1989; Molodij and Rousset 1997). Hence, they can be used to describe aberrations within a circular aperture of an optical system and are also normalizable over an annular pupil, as HST. Furthermore, they are related to the classical aberrations and thus provide a convenient mathematical expression of the aberration content in a wave front. Zernike polynomials have been used to examine, e.g., distortions in the HST mirror surface (Fienup et al. 1993; Krist and Burrows 1995).

The Zernike polynomials can be divided into odd and even polynomials and are invariant in form with respect to rotations of axes about the center of the pupil. They can be conveniently written in polar coordinates as products of angular functions and radial polynomials. Thus, the polynomials $Z_j(\mathbf{x})$ normalized on the telescope aperture are defined in polar coordinates (ρ, θ) by

$$Z_j^m(\rho,\theta) = \sqrt{n+1} \times \begin{cases} R_n^m(\rho)\sqrt{2}\cos(m\theta) & \text{if } j \text{ is odd and } m \neq 0 \\ R_n^m(\rho)\sqrt{2}\sin(m\theta) & \text{if } j \text{ is even and } m \neq 0 \\ R_n^0(\rho) & m = 0 \end{cases}, \tag{2}$$

where

$$R_n^m(\rho) = \sum_{s=0}^{\frac{n-m}{2}} \frac{(-1)^s (n-s)!}{s!(\frac{n+m}{2}-s)!(\frac{n-m}{2}-s)!}\rho^{n-2s} \quad . \tag{3}$$

Now n is the radial degree of the jth polynomial and m is its azimuthal frequency. The visualization of Zernike polynomials, which can aid in understanding their nature, is shown in Figure 1, while the low-order Zernike polynomials are defined in Table 1. For the HST the most strongly varying aberration is the focus, described here by Zernike polynomial Z_2^0.

2.2. FITPSF Software

In 1997 John Krist and Christopher Burrows wrote a parametric Phase Retrieval software package called FITPSF that is suitable for HST focus monitoring (Krist and Burrows

Table 1: Low-order Zernike polynomials.

Zernike Term	Aberration
Z_0^0	Piston
Z_1^{-1}	Y-tilt
Z_1^1	X-tilt
Z_2^{-2}	Y-Astigmatism
Z_2^2	X-Astigmatism
Z_2^0	Focus
Z_3^{-1}	Y-coma
Z_3^1	X-coma
Z_4^0	Spherical
Z_3^{-3}	Y-clover
Z_3^3	X-clover
Z_4^{-2}	Y-spherical astigmatism
Z_4^2	X-spherical astigmatism
Z_4^{-4}	Y-ashtray
Z_4^4	X-ashtray

1997). FITPSF is an Interactive Data Language (IDL) program that can be used to determine aberrations in optical systems by measuring point spread function (PSF) images. This program uses the known characteristics of an optical system of a chosen camera such as obscuration pattern, focal ratio, pixel size, etc. to generate model PSFs and compares the models with the observed PSFs, iteratively adjusting the aberration content as described by Zernike polynomials, for the best fit. The software and its application to HST data are described in Krist and Burrows (1995) and will not be repeated here.

As noted in the introduction, some HST cameras like ACS and WFC3 show geometric distortion, which complicates the Phase Retrieval process. To take into account this complication the Phase Retrieval algorithm of FITPSF performs a distortion to the model that it fits to the measured image data, which are uncorrected. This permits fitting of e.g. the charge diffusion, which is symmetric in detector space, in addition to the optically symmetric (e.g. focus, 3$^{\mathrm{rd}}$-order spherical, and jitter) terms which are distorted due to the detector tilt with respect to the chief ray.

The user's guide of FITPSF (Krist and Burrows 1997) describes how the software can be run, we therefore refer the interested readers to it. Appendix D of the user's guide briefly describes what is required when adding a new camera to the FITPSF software. This text was used as a reference, however, we found it to be incomplete as it lists only the absolute minimum that is required when adding a new camera. In case of the WFC3 UVIS channel, we found that several routines, not listed in the Appendix D of the user's guide, had to be modified to enable the usage of WFC3 data in FITPSF.

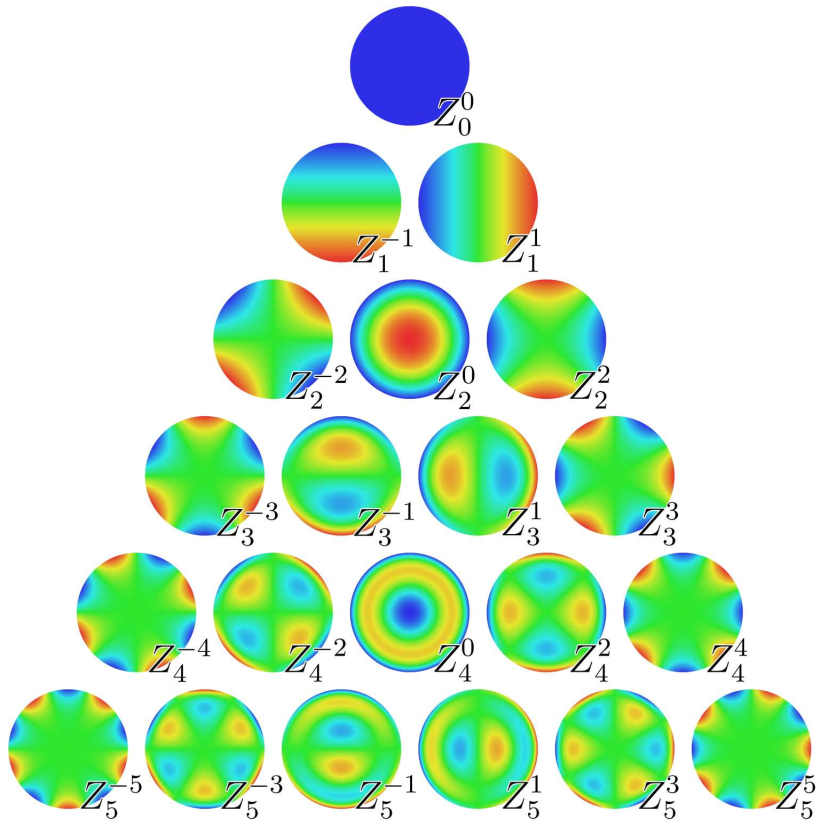

Fig. 1.— Selected Zernike polynomials in the unit disk. For definitions, see Table 1. Courtesy of Wikipedia.

3. Implementing WFC3 UVIS Channel into FITPSF

The implementation of the WFC3 UVIS channel into the existing FITPSF software was started in October 2009 by identifying all code changes that were (likely to be) required. We started with the assumption that the UVIS channel can be modeled based on how the ACS Wide Field Camera had been implemented (Krist, private communication 2009). Based on ground testing (Cox, private communication 2009) and Servicing Mission Orbital Verification (SMOV) results (Kozhurina-Platais et al. 2009) it is clear that WFC3 suffers from mild field-dependent geometric distortion that should be taken into account when fitting PSFs. Therefore, ACS provided a natural starting point for the WFC3 UVIS implementation, even though ACS is located further from the center of the focal plane.

After identifying all likely changes we divided them into three categories: interface, optical, and detector related changes. A few small interface related changes, that were required, were identified; these include, for example, adding WFC3 UVIS channel to the list of cameras in the user interface. Optics related changes that were required include, for example, setting the focal ratio of the WFC3 UVIS camera, the geometric distortion coefficients and creating a correct pupil image. The detector related changes we identified include, for example, the pixel scale and charge diffusion kernels. Implementing all the characteristics of the WFC3 UVIS channel required several existing IDL routines to be modified, while a few new ones had to be written. In the following sections we describe in detail all the changes that were made to FITPSF to enable phase retrieval on data obtained with the WFC3 UVIS channel.

3.1. Properties of WFC3 UVIS Channel

The FITPSF files that were modified in the course of implementing the WFC3 UVIS channel into the existing FITPSF software are listed in Appendix A.1. In this Section we describe all the changes made to each file in detail for future reference. The code changes are presented in the order they were categorized.

The code changes were started by modifying the graphical user interface (GUI) described in wfit.pro. The WFC3 UVIS 1 and 2 detectors were included in the GUI, while other obsolete options, such as WFPC2 and ACSHRC, were commented out to clarify the GUI. The GUI was also streamlined so that the most often used options, i.e. ACS and WFC3, are easily accessible. The way the FITPSF program displays images to a user was also modified. The image re-binning, given in selectpsf.pro, was changed to take advantage of large monitors readily available nowadays. The software now displays ACS and WFC3 images using 2×2 binning rather than the 4×4 binning applied previously. This makes it easier for the user to select a star for fitting as centering of the cursor on top of the star is more accurate.

As noted earlier, Phase Retrieval fits a model PSF to data, thus, an initial PSF model is required. To generate a model PSF for the UVIS channel, a suitable pupil image must be produced. A pupil image of the WFC3 UVIS channel can be generated with the in-built tools used for the other cameras. However, due to the ~ 45 degree rotation of WFC3 with respect to the focal plane coordinate system $(v2, v3)$ an additional rotation compared to ACS is required. For this a new file named drawwfc3.pro was created, which holds a procedure called DrawWFC3. This procedure draws an optical telescope assembly (OTA) pupil image by including the obscuration of the secondary mirror and the spider arms as well as the primary mirror pads. To orient the pupil image correctly a rotation of -133.2° is required (see Fig. 3 upper left image). The rotated pupil image can now be used to generate an idealistic model PSF by taking a Fourier transform of the image.

A realistic model PSF needs to take into account, not only the pupil image, but also the polishing errors of the HST mirrors (see also Hartig 2008, 2009). This can be achieved with the HST zonal error phase maps also known as the mirror maps. The mirror maps, like the pupil image, have to be oriented correctly. Additionally, the secondary mirror map must be shifted for a given field position. To position and orient the mirror maps correctly for the WFC3 UVIS channel we adopted the $v2$ and $v3$ reference coordinate system and apply a rotation of 46.8 degrees in mirrormap.pro. Note that this is exactly the same rotation as applied for the pupil image ($180° - 133.2° = 46.8°$).

After a realistic model PSF has been generated, this model must be mapped to the detector space of the given instrument. We therefore identified the default pixel size and focal ratio for the WFC3 UVIS channel: 15.0 μm and 31.0, respectively, and included these into getscale.pro. In case of ACS and WFC3, as both require the geometric distortion to be taken into account in the model PSF, the default pixel scale is superseded by a proper pixel scale variable. For WFC3 we set the proper pixel scale to $0.03962/''$ in init_wfc3.pro. This file holds all information related to the instrument's location in the focal plane (in $v2, v3$ reference coordinates) as well as the geometric distortion coefficients (for detailed information see Cox 2008). Initially we included coefficients that were derived in October 2009, but in March 2010 the coefficients were updated to the latest values.

We also had to set two other scales that are optics related, namely the oversampling and the pupil magnification, which are defined in scale.pro. The oversampling can be used to calculate an optimally sampled PSF using the critical pixel size. Note, however, that we set the oversampling to unity for the UVIS channel, as the pupil magnification is being used to change the sampling of the PSF. To increase the default sampling of a model PSF we adopt 1.2^{-1} as our pupil magnification (Krist, private communication 2009), in agreement with the value adopted for ACS.

After all the GUI and optical characteristics related changes were implemented, we were left with the detector-related changes. All Charged-Couple Devices (CCDs) suffer, to some extent, from charge diffusion (e.g. Dale et al. 1993). We therefore implemented wavelength dependent charge diffusion (CD) kernels in computepsf.pro to model the CD in the WFC3 UVIS detectors 1 and 2 (see also Hartig 2008). Three different kernels at wavelengths 4000, 6000, and 8000Å are currently being used; for any given wavelength a linear interpolation of these kernels is used. The kernel values were provided by G. Hartig in October 2009. In the process of PSF modeling and fitting, the CD kernels are used to convolve the model PSF. In addition to convolution with the CD kernel FITPSF also fits a Gaussian blur, also symmetric in detector space, which may represent variations in the CD over field, such as seen in ACS by Krist (2003).

3.2. Additional Changes to the FITPSF Software

Several additional code changes to the FITPSF software were done, and are identified here for completeness. These changes either fixed old bugs, introduced new functionalities or enabled the usage of WFC3 data. Many of these changes are related to reading in WFC3 FITS files or identifying the Zernike polynomials that are being either fit, fixed or ignored during the fitting process.

The FITPSF software contains a routine in mkfocuslist.pro that can be used for a given instrument to generate a list of FITS files that are suitable for FITPSF. A new part that handles the WFC3 FITS files had to be included to make it possible to generate a list of WFC3 images. The FITPSF software uses two different IDL routines, selectpsf.pro and getpsf.pro, to read in data from FITS files. A new part that handles FITS files produced by the UVIS channel had to be included into both files. The selectpsf.pro displays each image in a file list and allows the user to select a star and a background box, and mark bad pixels. As the IDL routine cannot re-bin the image unless both x and y dimensions are even, the top row of each image has to be ignored (WFC3 full frame images are $(x, y) = (4096, 2051)$). We chose to ignore the top row to avoid any problems with the detector coordinates. After selecting a PSF star its location on the detector together with a bad pixel table is saved and used by getpsf.pro to read only a given number of pixels around the PSF star. This procedure will also use the bad pixel flags to mask out unwanted pixels by setting their value to 10^{36}.

The fitting routine of FITPSF is controlled by an input file. These input files can be created using a routine in mkfocusin.pro. This routine relies on template files that had to be created for WFC3 UVIS 1 and 2 detector separately. These templates include all appropriate Zernike polynomials and a control letter, which defines whether a given polynomial is being fitted, has been fixed or is being ignored. A fully functional input file for WFC3 UVIS 1 is given in Appendix A.2. When FITPSF is run it will use readin.pro to read the given input file. To enable Phase Retrieval on data obtained with the WFC3 UVIS channel, reading in the input file correctly had to be implemented as well. Due to the tedious nature of the readin.pro several changes were required that were not only related to reading in the input files, but also to the usage of the mirror maps.

As the FITPSF software relies on a C extension for the geometric distortion calculations a new file named init_distortwfc3.pro had to be created that allows the parent program to call the C implementation. This new file was modeled after the equivalent ACS file; the only changes made were related to the common IDL variables that are instrument specific.

Small changes were also made to the main fitting routine described in crvefit.pro. As the computing power has increased significantly during the last 15 years, the fitting criteria were tightened slightly to provide more accurate fits. The maximum number of iterations were increased from 20 to 100, while the difference limit between consequent iterations were lowered from 0.0033 to 0.00025. Neither of these changes made a substantial impact on the functionality of the FITPSF nor the results it produces, albeit a small increase in accuracy should be achieved.

Changes were required to the focusresults.pro file as well to enable the results of the UVIS channel fits and focus determinations to be shown. The majority of the routine was rewritten, not only to enable displaying of the WFC3 results, but also to provide extra output. This routine was changed so that it now also saves the results to a file for later use. All Zernike polynomials implemented in the FITPSF software are also being included to this file to help the WFC3 team to improve the TinyTim[1] software, which was found to produce somewhat inaccurate PSF models.

3.3. Bug Fixes

In January 2010 a bug (brother of the infamous y2k bug) was identified in catfits.pro. The bug originated from the fact that this file uses the DATE-OBS header keyword when generating file lists in a way that the "if" statement required the year to start either with 199 or with 200. The criterion was changed to look for either 19 or 20, as no harm is done by relaxing the criteria. This change enables the usage of data taken after 2009.

While implementing the WFC3 UVIS channel into the FITPSF a bug was identified in readin.pro. In this procedure the HST focal plane offsets for each camera are being defined to be used later to calculate appropriate mirror map shifts. It was noticed that for all cameras except for the ACS WFC detector 1 the mirror map shifts were given in arcminutes, while for the ACS WFC1 these were given in arcseconds. Because of the limited earlier use of ACS WFC for phase retrieval, this bug was never identified, even though ACS WFC detectors 1 and 2 were being treated differently, which could have lead to a large scatter between the measurements of the two detectors and possible error in focus values. The bug was fixed in September 2009.

4. Testing

4.1. Data

During the course of implementing the WFC3 UVIS channel into the FITPSF software several tests were carried out. The comprehensive testing was performed between October 2009 and February 2010 and used data from the focus monitoring program (proposal 11788, P.I. Lallo). Data taken during visits $2-9$ were processed using the default pipeline. Flat fielded (_flt) data products were used for the analysis. On average about 10 stars per chip per visit were fit resulting in about 160 focus measurements and fitted PSF models and Zernike polynomial values.

All focus results derived from WFC3 UVIS data were always compared against the focus measurements derived from ACS WFC data for consistency. During SMOV, the confocality of WFC3 and ACS was actively maximized (described by Lallo, in prep). However, the accuracy with which this was achieved remained somewhat uncertain at ~ 1 μm OTA secondary mirror despace level. So the absolute focus values derived using ACS WFC data

[1] `http://www.stecf.org/instruments/TinyTim/`

should not be used for direct comparison, but only as a guideline. Due to breathing (for a detailed discussion, see Di Nino et al. 2008), the most robust comparison between the two instruments is achieved when the exposures that had been taken at the same time are compared. Unfortunately the visits $2-11$ of the focus monitoring program only took two full frame exposures with the UVIS channels, which bracketed the first ACS WFC exposure. The full frame UVIS exposures allowed the study of field-dependency of the Zernike terms. However, as this did not provide the best measure for the confocality, we updated the program in March 2010. Due to the long time required on the cameras' buffer dumps, the updated program is limited to eight UVIS subarray and four full frame ACS WFC exposures per visit.

4.2. Fixing Zernike Terms

The early state of testing was performed by fitting all the used Zernike polynomials. This lead to a concern that fitting the higher order polynomials, especially the spherical terms, but also so-called clover, "ashtray" and spherical astigmatism (see Table 1 for definitions), could have led to less than robust focus determinations. However, tests carried out after fixing the high-order Zernike polynomials, showed that the focus measurements change only little; in general $< 0.01\mu$m (in the units of the despace of the secondary mirror). Fitting the high-order polynomials was necessary to help to fix some of these terms in the future.

Values for the Zernike polynomials, fitted during the initial testing, are presented in Table 2. Note that some terms show significant scatter due to the field-dependency of these terms. We therefore chose not to fix, for example, the 3^{rd} order spherical term, like in case of ACS. The 3^{rd} order spherical term shows a strong field-dependency in the case of the WFC3 UVIS channel that is present in both detectors[2]. The values for the Zernike polynomials we chose to fix, identified in Table 2 by 'Y' in the last column (see also Appendix A.2), were derived by fitting a Gaussian to the distribution and finding the center of it. Examples of fitted clover values are given in Figure 2.

4.3. Deriving Focus Values

Figure 3 shows an example of a modeled PSF in comparison to observed data. The figure displays the best PSF model for a single star from the focus monitoring program visit 38 data. The residuals (left lower image) are small and on the level of noise. The horizontal and vertical cross sections also show that the differences between the observed (solid line) and modeled (hatched line) PSFs are small. The largest differences are seen in the wings of the PSFs where noise becomes significant.

[2]This field-dependency is inherent in the optical design of WFC3.

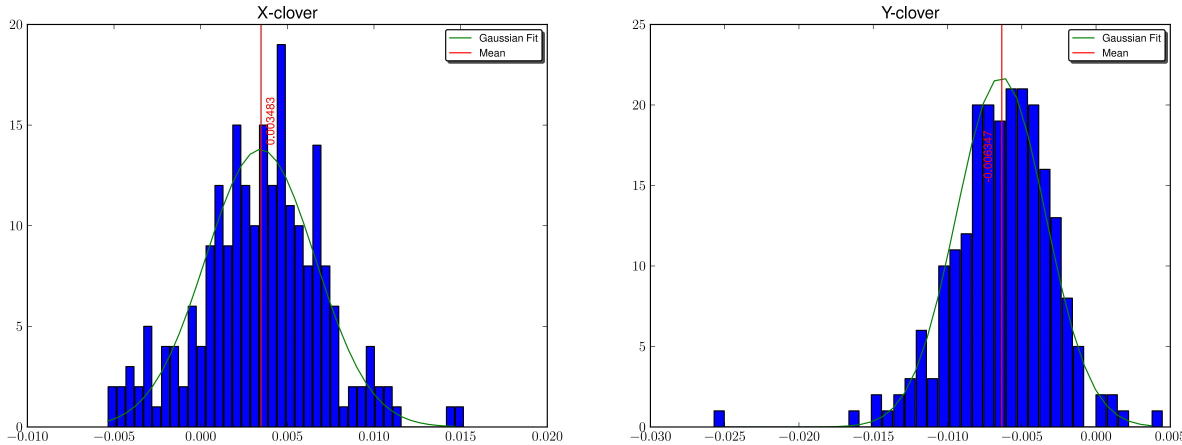

Fig. 2.— Distributions of two high-order Zernike polynomials, namely X and Y-clover, after about 160 PSFs have been fitted using the new version of FITPSF. The red vertical line shows the mean of the distribution while the green curve shows a Gaussian fit to the data.

Table 2: Averages, medians and standard deviations of Zernike polynomials after the initial testing phase. Zernike terms identified with 'N' at the last column are continued to being fit after the initial testing was completed.

Quantity	Average	Median	Standard Deviation	Fixed [Y/N]
X-coma	−0.0056	−0.0067	0.0062	N
Y-coma	0.0016	0.0010	0.0054	N
X-astigmatism	−0.0031	−0.0018	0.0166	N
Y-astigmatism	0.0090	0.0091	0.0130	N
3^{rd} order Spherical	−0.0109	−0.0113	0.0057	N
X-clover	0.0035	0.0036	0.0035	Y
Y-clover	−0.0063	−0.0062	0.0035	Y
X-ashtray	0.0052	0.0042	0.0069	Y
Y-ashtray	−0.0066	−0.0063	0.0058	Y

Figures 4 and 5 show two examples of the focus monitoring program focus measurements. Figure 4 shows the focus measurements from visit 2, which executed in August 2009, while Fig. 5 shows the measurements from visit 37, which executed in May 2010. The visit 2 results are breathing model corrected, while the visit 37 results show the directly measured values without any model corrections. The large scatter visible in both figures shows the intrinsic scatter in the Phase Retrieval technique when the PSF is only modestly sampled. ACS shows larger scatter, especially in Fig. 5. This is likely due to the poorer sampling of the PSF, but can also be, at least partially, due to the relatively large charge transfer inefficiency (CTI) in ACS, which will make the PSF more asymmetric than would be optically induced.

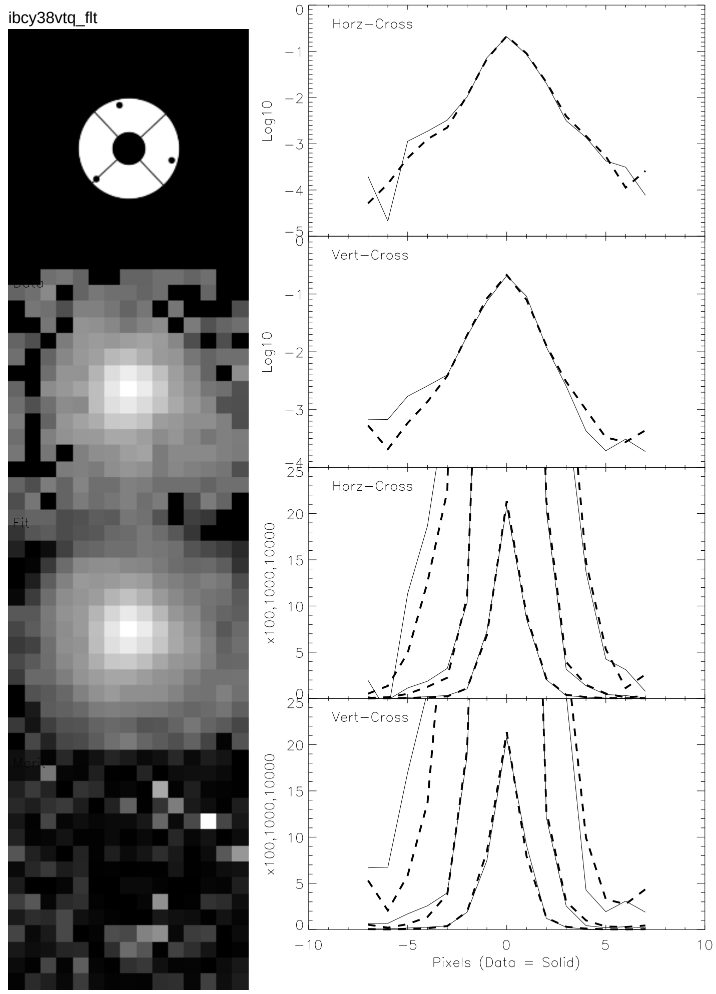

Fig. 3.— An example of a comparison of a modeled PSF and an observed star. On the left; pupil, data, fit, and residual images. On the right; horizontal and vertical cross sections of the PSFs with two different scalings.

With a perfectly sampled PSF, the CTI would not change symmetric Zernike terms like focus; however, because of the less than optimal sampling in ACS WFC, it is likely that an abnormal excess of counts in the PSF wing on one side may change the best fit of the focus term. This shows the in-built weakness of the Phase Retrieval technique: it is not possible to separate completely the optical effects from, e.g., effects caused by imperfect electronics in a CCD.

5. Future Improvements

The current version of the FITPSF software cannot be run in a batch mode. This is an obvious place for an improvement that would allow a large statistical sample of many stars to be fitted. This would make the measured focus values more robust as clear outliers due

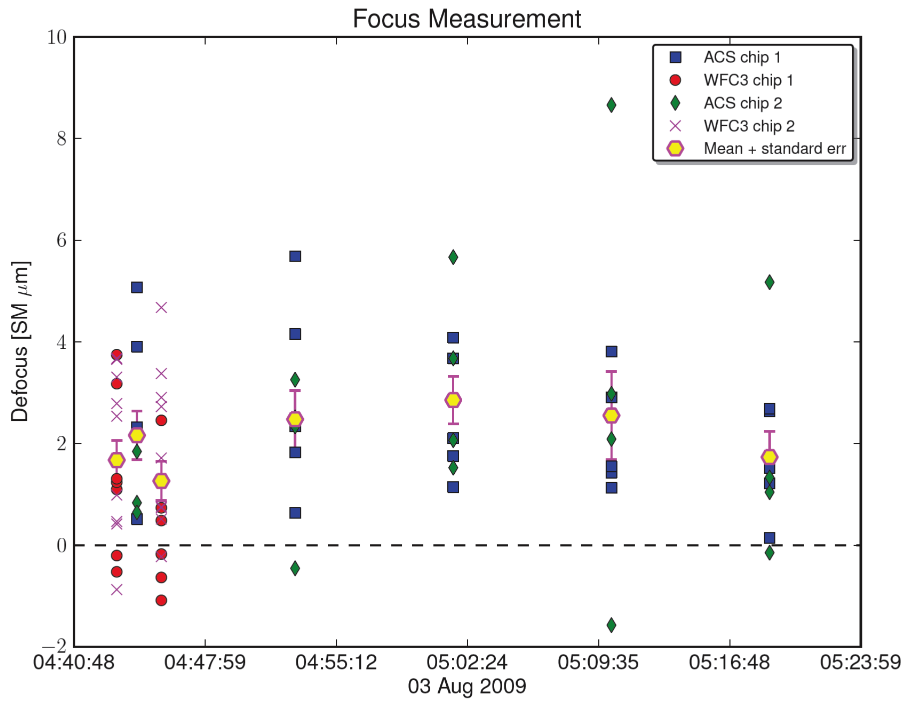

Fig. 4.— Focus measurements of visit 2. Measurements have been corrected with the breathing model described by Di Nino et al. (2008). Only two time stamps of WFC3 UVIS data were available.

to, e.g., bad fits or cosmic ray hits could be excluded using, for example, a sigma clipping technique.

Source Extractor or another source identification algorithm such as “find” of the IDL Astronomy Library could be used to locate stars automatically. Crude photometry could also be done for each star identified. This would allow a signal-to-noise ratio and/or flux measurement errors to be used to exclude stars. Such a scheme would also allow to exclude objects that may be naturally (galaxies) or artificially elongated. The photometry and ellipticity measurements do not have to be extremely accurate, as they would be used only to exclude unsuitable targets, while no further calculations based on these values were performed. This would also enable a check that one does not try to fit any non-point sources.

During the Phase Retrieval process of the PSF fitting, the full width at half maximum (FWHM) values of all stars could be calculated to obtain a crude estimate for the focus position. Even though a FWHM is not only determined by focus, as e.g. the charge diffusion and blur contributes to the width, it would provide a zeroth order estimate for focus. Some other crude estimates for the focus value could also be included for a consistency check. These crude estimates could also be used to double check the goodness-of-fit.

A proper goodness-of-fit estimator should be included to the fitting process and outputted along the Zernike polynomial values and the focus. This would enable users to exclude

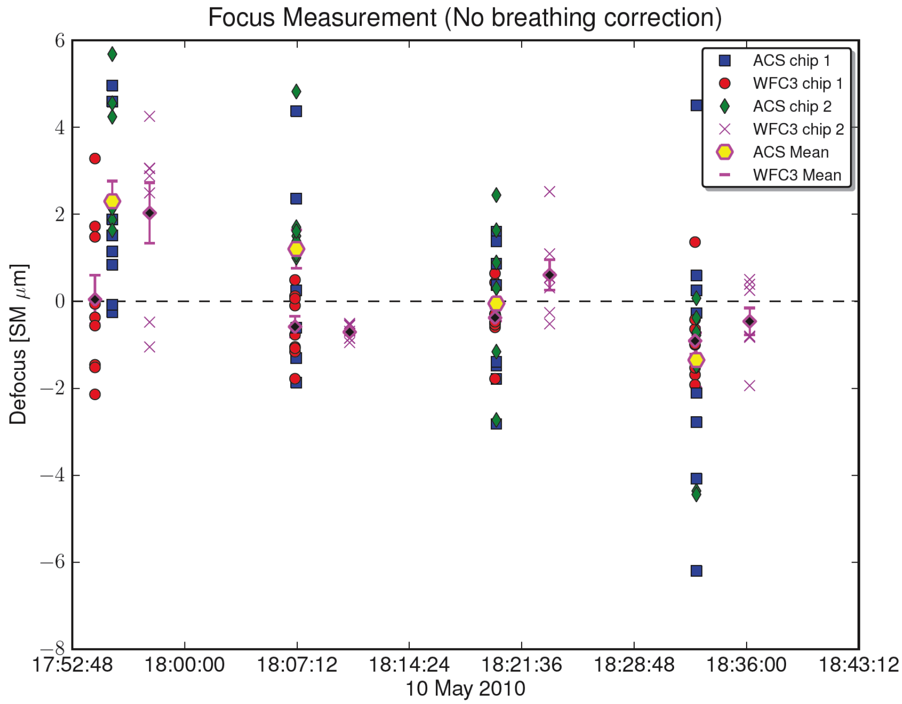

Fig. 5.— Focus measurements of visit 37. These measurements have not been corrected with the breathing model. Note the significantly smaller scatter in WFC3 measurements compared to ACS. This is assumed to be due to the better sampling of the PSF in WFC3, but also the relatively large charge transfer inefficiency present in the ACS CCDs may contribute.

stars for which the PSF fit has not been robust or satisfactory. This would also allow the user to exclude fits that did not converge or converged possibly to a local minima. The current version of the FITPSF software only allows to compare the χ^2 values between different runs, but the absolute value has no real meaning.

The run time of the FITPSF software could be decreased by taking advantage of multi-core processors more effectively. For example, message passing interface (MPI) could be used to enable parallel programming. This could be especially beneficial if a future version of the FITPSF software was run in batch mode. In such case MPI would allow to fit multiple stars simultaneously decreasing the run time directly proportional to the number of available cores.

It would also be highly beneficial to store all previous and future results and Zernike polynomial values into a proper relational database. This would enable an easy access to focus data and a large number of measurements for each star at any given epoch could be stored for a later usage. It would be beneficial to create a few tables to e.g. a MySQL server to hold all the information. This would give instrument team members an easy access to the data that may be highly beneficial if, for example, the field-dependency of the PSF were to be studied in detail.

6. Summary and Conclusions

We have briefly described how the monthly focus monitoring of the HST is performed by using the Phase Retrieval technique. The Phase Retrieval consists of finding the phase that for a measured amplitude satisfies a given set of constraints. For the focus monitoring purposes Phase Retrieval can be taken as a process of trying to recover the wavefront error given a measurement of the Point Spread Function (PSF). The Zernike polynomials are a set of orthogonal polynomials that arise in the expansion of a wavefront function for optical systems with circular pupils. Hence, they are related to the classical aberrations and thus provide a convenient mathematical expression of the aberration content in a wavefront.

The main focus of this document was to describe what changes were done to the existing FITPSF software in order to implement an analysis capability for the WFC3 UVIS channel. Prior to any changes to the software, all intended alterations were identified and grouped into three different categories: interface, optics and detector related changes. The graphical user interface changes were found to be trivial, comprising mainly the addition of the WFC3 UVIS channel to the list of available cameras. Also, the way FITPSF displays images to a user was changed to a more user-friendly format that takes advantage of large monitors.

To enable Phase Retrieval on data obtained with the WFC3 UVIS channel, the FITPSF must generate a suitable model PSF. This requires information about the optical characteristics of the camera. The starting point of a PSF model is that a correctly oriented pupil image must be available. Existing tools in the FITPSF software were used to generate a PSF model image for the WFC3 UVIS channel. Also the mirror maps must be oriented and shifted correctly for a given measurement. Other optics related issues implemented include, e.g., the pixel scale and the pupil magnification. The geometric distortion coefficients were also included as FITPSF uses them to distort the model PSF when iteratively fitting the model to the observed PSF by adjusting the Zernike polynomial terms.

Optics is not the only issue that effects the PSF when Charged-Coupled Devices (CCDs) are being used. We implemented three different charge diffusion kernels at three different wavelengths, while the true kernel of a given wavelength is a linear interpolation of the three kernels. This convolution kernel should not be confused with the blur kernel in FITPSF, which is a Gaussian smoothing kernel and usually fitted during the PSF fitting process.

An extensive testing cycle was carried out to confirm that the WFC3 UVIS channel had been implemented correctly. This testing showed that some Zernike polynomials are field-dependent. Especially, the 3^{rd} order spherical, which is fixed for ACS, shows large variations across the field of view. Thus, we chose not to fix its value, but let it be fitted along with coma and astigmatism. The testing also revealed that focus measurements based on WFC3 UVIS data show less scatter than if ACS data are used. This is most likely due to the better sampling of the PSF in WFC3, but also the charge transfer inefficiency, which is relatively large for ACS CCDs, and other detector features may contribute. This shows the intrinsic weakness of Phase Retrieval: effects caused by optics and electronics cannot be easily disentangled.

We have also identified several future improvements that would improve the current software. The highest priority changes include enabling batch mode and storing the focus measurement results into a relational database for an easy access for anyone who may be interested in either the fitted Zernike polynomials or the focus measurements.

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A. Appendix

A.1. Lists of Modified and New Files

Here we list all the files that were modified in course of the implementation of the WFC3 UVIS channel into the existing IDL Phase Retrieval software package named FITPSF. All new files that had to be created are listed below the modified files.

A list of files that had to be modified in order to enable Phase Retrieval on data obtained with WFC3 UVIS channel:

```
catfits.pro
computepsf.pro
computepupil.pro
crvefit.pro
fitpsf.pro
focusresults.pro
getpsfs.pro
getscale.pro
makein.pro
mirrormap.pro
mkfocusin.pro
mkfocuslist.pro
printparams.pro
readin.pro
scale.pro
selectpsf.pro
wfit.pro
```

A list of new files that had to be created when implementing the WFC3 UVIS channel to the FITPSF software:

```
drawwfc3.pro
init_distortwfc3.pro
init_wfc3.pro
```

A.2. WFC3 UVIS Channel Input Parameters

A complete and fully functional input parameter file for WFC3 UVIS detector 1 is listed below. All detector 2 input parameters are the same as for the UVIS 1 except "Camera mode", which should be "WFC3UVIS2". The best parameter values found during the testing process conducted between October 2009 and February 2010 are also given. Note that newer and more accurate values may be available and should be used instead.

An example of the WFC3 UVIS detector 1 input file (wfc3template1.in):

```
     Array dimensions      512
           Wavelength   0.4107
       Fitting method        1
  Merit function power  2.00000
    Merit wing damping  0.00500
           Camera mode    WFC3UVIS1
          Zernike type OBSCURED
Y                  Focus (microns)       0.0010
Y                 X-coma (microns)       0.0000
Y                 Y-coma (microns)       0.0000
Y          X-astigmatism (microns)       0.0000
Y          Y-astigmatism (microns)       0.0000
Y              Spherical (microns)      -0.0110
N               X-clover (microns)       0.0035
N               Y-clover (microns)      -0.0065
I X-spherical astigmatism (microns)       0.0000
I Y-spherical astigmatism (microns)       0.0000
N              X-ashtray (microns)       0.0045
N              Y-Ashtray (microns)      -0.0065
I   Fifth order spherical (microns)       0.0000
Y            Star  1 Background*1e4       0.0000
Y           Star  1 X-tilt (microns)       0.0000
Y           Star  1 Y-tilt (microns)       0.0000
Y                                Blur       0.4500
```