

# PhAst: An IDL Astronomical Image Viewer Optimized for Astrometry of Near Earth Objects

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**ABSTRACT.** We present PHAST, a new IDL astronomical image viewer, based on the existing ATV application, which has been optimized for astrometry of Near Earth Objects (NEOs). After describing the features of PHAST, we describe how PHAST enabled the recovery of the Virtual Impactor (VI) 2011AX22 and the Potentially Hazardous Asteroid (PHA) 2008OX1. The recovery of 2011AX22 led to a large improvement in the time of perihelion passage and in the semimajor axis and eccentricity of its orbit. The distance of closest approach in May 2055 was moved away from Earth to  $>1$  lunar distance. As a result of the orbital improvement made possible by the successful recovery, NEODyS downgraded 2011AX22 from a VI to a PHA, having ruled out the chance of an Earth impact this century. The recovery of 2008OX1 extended its observational arc to 1303 days—more than 2.5 orbital revolutions. It was confirmed to be a PHA and its orbit was improved sufficiently to permit prediction of its sky position to within  $1''$  over an interval of 10 years into the future. We discuss the astrometric and photometric performance of PHAST and then conclude by briefly describing future enhancements to the application.

*Online material:* color figures

## 1. INTRODUCTION

Asteroid researchers typically discover a Near Earth Object (NEO) when it is near its brightest illumination, which usually occurs near opposition. Observational details of newly discovered NEO candidates are sent to the International Astronomical Union (IAU) Minor Planet Center<sup>2</sup> (MPC) at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, for further analysis and verification. The MPC checks the orbit of the NEO candidate against orbits of known moving objects in

its extensive database. If a linkage cannot be made to a previously known moving object and it is possible to fit an orbit with a perihelion distance of less than 1.3 AU, then the MPC posts the object on its Confirmation Page website<sup>3</sup> for further observation. When additional observations (generally obtained within a few nights of discovery) enable the MPC to estimate an orbit with sufficient accuracy, they assign a designation to the object.

The MPC, NASA's Jet Propulsion Laboratory (JPL), and the Near Earth Object Dynamic Site<sup>4</sup> (NEODyS) each perform independent orbit computations for every NEO. The calculations

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<sup>2</sup>The IAU Minor Planet Center website is <http://www.minorplanetcenter.org/iau/mpc.html>.

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<sup>3</sup>The MPC Confirmation Page website is <http://www.minorplanetcenter.org/iau/NEO/ToConfirm.html>.

<sup>4</sup>The Near Earth Object Dynamic Site website is <http://newton.dm.unipi.it/neodyS/>.

draw large numbers of possible orbits (“virtual asteroids”) through the available observation data points in order to estimate the errors of the computed orbits. The virtual asteroid that represents the least-squares fit to the data points is called the “line of variations”, as other orbits drawn using the errors tend to vary about this central line (Milani et al. 2005). If the predicted orbit passes within 0.05 AU of the Earth’s orbit, the object is declared to be a Potentially Hazardous Asteroid (PHA). If at least one of the virtual asteroids intersects the Earth’s orbit, the object is declared to be a Virtual Impactor (VI). VIs and PHAs, by virtue of their close approaches to the Earth’s orbit, are potentially the most dangerous NEOs, and therefore merit special attention.

After discovery and designation, VIs and PHAs are often not observed again as attention is diverted to newly discovered objects. Once observations end, the uncertainty in sky position (ephemeris error) of a new NEO begins to grow with time due to the uncertainty of its orbital elements. As these errors are growing, the NEO generally fades rapidly in brightness as a function of the distance from the Earth and the Earth–NEO–Sun angle. VIs and PHAs can lose a full magnitude of brightness in a matter of days to weeks. While these objects may initially have  $V$  magnitudes between 19 and 21 mag, they can easily fade by as much as 2 mag when observed 50–80 days later.

If VIs and PHAs go unobserved for a long enough period, the ephemeris errors can grow to the point that, as a practical matter, they can no longer be found on the sky using narrow-field telescopes. Once a NEO is unrecoverable by telescopes with conventional fields of view, it may be rediscovered by an asteroid survey project at a future favorable opposition and linked by the MPC to observational data of a previously designated object. The ephemeris of a rediscovered NEO is generally based on observations from multiple orbits, and, in most cases, the ephemeris errors are sufficiently small that the NEO can be easily recovered in the future by asteroid researchers.

The deliberate recovery of a VI or PHA after it has been unobserved for a long period of time (e.g., one orbital period after discovery) is an observationally challenging task. Since NEOs seldom return to a favorable opposition soon after discovery, many VI or PHA recovery candidates will be at the limit of detectibility of 2-meter-class telescopes. The accumulation of ephemeris errors over time typically means that several fields-of-view on the sky (tiles) may need to be searched in order to find the object.

Trueblood, Crawford, and Lebofsky have used the Kitt Peak National Observatory (KPNO) 2.1-m telescope since Semester 2008B to obtain astrometric follow-up data on NEOs, and since Semester 2009B to extend the observed orbital arcs of recently discovered VIs and PHAs. By observing VIs and PHAs as much as 50–80 days after discovery, the astrometric observations provided by Trueblood’s team enables the MPC to compute better

ephemerides based on a longer arc of the NEO’s orbit. Sometimes these follow-up observations enable the MPC to demote the VI or PHA designation of a NEO.

The NEO observing community is small. There is no common set of observation software tools to simplify the process of identifying new NEO candidates, the reacquisition of known NEOs, and the determination of precise astrometry of these moving objects.

Trueblood and collaborators have used a combination of a commercial software tool and a software tool developed for/by members of the amateur astronomical community who have been involved in astrometric follow-up of NEOs and photometric (light curve) studies of asteroids. MaxIm DL,<sup>5</sup> a general-purpose camera control and image processing tool, was used to calibrate CCD images by subtracting bias and processing with a flat field. Astrometrica<sup>6</sup> was used to solve the images for a FITS<sup>7</sup> (Flexible Image Transport System, Wells et al. [1981]) WCS<sup>8</sup> (World Coordinate System, Greisen & Calabretta [2002]; Calabretta & Greisen [2002]), register multiple images of the same NEO, and blink the images for visual identification of the NEO targets. Astrometrica was also used to place the astrometric and photometric measurements of the NEOs in the reporting format required by the MPC.

The combination of Maxim DL and Astrometrica, while effective, was determined to be less than optimal for the real-time reduction of NEO observations at the KPNO 2.1-m console room. Tracking at nonsidereal rates on a moving target is a productive technique to increase the signal-to-noise ratio (SNR) that can be achieved with faint targets. The resulting elongation of field stars became a major impediment to the continued use of Astrometrica, both in centroiding field stars for the astrometric solution and in its photometry based on a circular point-spread function (PSF). A NEO observational software tool was desired that would eliminate these constraints placed on observation technique and, ideally, would allow NEO observers access to the source code so that new features could be added as required. An open-source astronomical image viewer that could be enhanced with state-of-the-art photometry and astrometry analysis codes was needed.

Aaron Barth (University of California, Irvine) has developed an interactive display software tool for astronomical images written in IDL,<sup>9</sup> called ATV<sup>10</sup> (Barth 2001). ATV has many display and photometry functions similar to those of the popular

<sup>5</sup> MaxIm DL can be purchased from Diffraction Limited at 201-100 Craig Henry Drive, Ottawa, ON K2G 5W3, Canada.

<sup>6</sup> Astrometrica can be purchased at <http://www.astrometrica.at/>.

<sup>7</sup> The website of the FITS Support Office at NASA/GSFC is <http://fits.gsfc.nasa.gov/>.

<sup>8</sup> The FITS WCS website at NASA/GFSC is [http://fits.gsfc.nasa.gov/fits\\_wcs.html](http://fits.gsfc.nasa.gov/fits_wcs.html).

<sup>9</sup> IDL can be purchased from Exelis, Inc. at 1650 Tysons Boulevard, Suite 1700, McLean, VA 22102.

<sup>10</sup> The website for ATV is <http://www.physics.uci.edu/~barth/atv/about.html>.

SAOImage DS9<sup>11</sup> (Joye & Mandel 2003) astronomical data visualization application; it can be run from the IDL command line or be called by another IDL procedure. Mighell determined that ATV could provide an excellent starting point for the development of an IDL-based astronomical image viewer optimized for NEO astrometry. Mighell, Trueblood, and Crawford selected Rehnberg as a 2011 KPNO REU (Research Experiences for Undergraduates) summer intern. During the summer of 2011, Rehnberg worked at the headquarters of the National Optical Astronomy Observatory in Tucson, Arizona and developed the PHAST (*Photometry/Astrometry*) astronomical image viewer, based on ATV and enhanced to do CCD image calibration and perform state-of-the-art stellar photometry and astrometry using the software packages SExtractor (Bertin & Arnouts 1996), SCAMP (Bertin 2006), and missFITS (Marmo & Bertin 2008).

PHAST was first used to reduce NEO Arc Extension program CCD observations obtained during an observing run at the KPNO 2.1-m telescope in October 2011. The PHAST results were compared with those from previously used and proven tools. Rehnberg joined Trueblood and Crawford for an observing run in late November 2011, during which PHAST was used in real time to reduce data at the telescope. Since then, PHAST has been used exclusively by Trueblood and collaborators for all subsequent observing runs.

This article describes PHAST, which is an IDL astronomical image viewer that is optimized for the determination of astrometry of NEOs. The source code and documentation for PHAST is publicly available on a website at NOAO.<sup>12</sup> The next section describes some of the features of the PHAST software tool. PHAST was used to produce astrometry of NEOs based on KPNO 2.1-m CCD observations; these results, described in § 3, were submitted and published by the MPC. The article concludes in § 4 with a brief discussion of future enhancements to the capabilities of PHAST.

## 2. FEATURES OF PhAst

When working with NEO observations, one frequently needs to analyze more than three images simultaneously and in any desired order. Although ATV provides basic support for blinking up to three images, generally only one image can be stored in memory at a time. PHAST has added an image stack to the ATV image viewer. Multiple images can be stored simultaneously in the memory of the PHAST application, which allows users to quickly select any single image to be displayed. The entire image stack can be animated in various ways, allowing the user to easily view an entire observation sequence. All

brightness/contrast adjustments are retained when switching between images.

Minor changes throughout the ATV code have been implemented to exploit the flexibility of the image stack. The circular aperture photometry tool of ATV can now perform photometry on an entire sequence of images with each result being written to a common file. It is now possible to import (read) an entire directory of images at once rather than importing many single images individually.

The graphical user interface (GUI) for ATV does not make optimal use of modern computer displays, which typically have aspect ratios wider than the 4:3 ratio used in many older computer monitors. PHAST has moved the buttons and widgets of the ATV GUI to the left side of its display (see Fig. 1). When the ATV display window is expanded by the user, all of the expanded space is devoted to displaying a larger portion of the image. Controls for the blinking and animation processes can be easily exposed; this is a very useful feature in the analysis of observations of NEOs and other Solar System objects. Configuration files can be used to allow the user to implement a custom configuration of the buttons and widgets in the PHAST GUI.

Figure 1 shows the default PHAST configuration, which has six widgets. On top are the full-field and current region preview images. A compass rose is overlaid on the full-field image to show the orientation of the image on the sky. This image can be used to quickly pan around large images. The current region image is a magnified version of the region immediately surrounding the mouse cursor. The second widget allows the user to navigate the image stack, with buttons for moving forward and backwards, and a drop-down list for jumping to a particular image. WCS-based image alignment can also be enabled from this panel. The third widget displays the current position and brightness of the mouse cursor position, given in both device units and a standardized coordinate system (if a WCS solution is present). The fourth widget contains buttons for the most commonly used image manipulations. This includes zoom and color inversion. A drop-down list allows the selection of various modes for using the mouse. All four of these widgets appear in all PHAST display configurations.

The blink control widget provides controls for animating the image stack. These include blink speed, pattern, and on/off toggle. Clicking the “Blink Control” button will minimize this widget. The star overlay widget starts minimized. If a WCS solution is present, this widget can be used to overlay the positions and catalog names of stars in the image. It also allows the user to search for a particular star by its catalog name. This second class of widgets focuses on specific tasks and are therefore optional. They can be easily disabled through the configuration file.

Less frequently used options can be accessed through the menu bar at the top of the application. The most important category is the “Pipeline” menu, which allows the user to begin individual or batch processing of images. The remainder of the screen is devoted to image display. PHAST places an emphasis on displaying as

<sup>11</sup> The website for SAOImage DS9 is <http://hea-www.harvard.edu/RD/ds9/>.

<sup>12</sup> Source code and documentation for PhAst is available at <http://www.noao.edu/staff/mighell/phast/>.

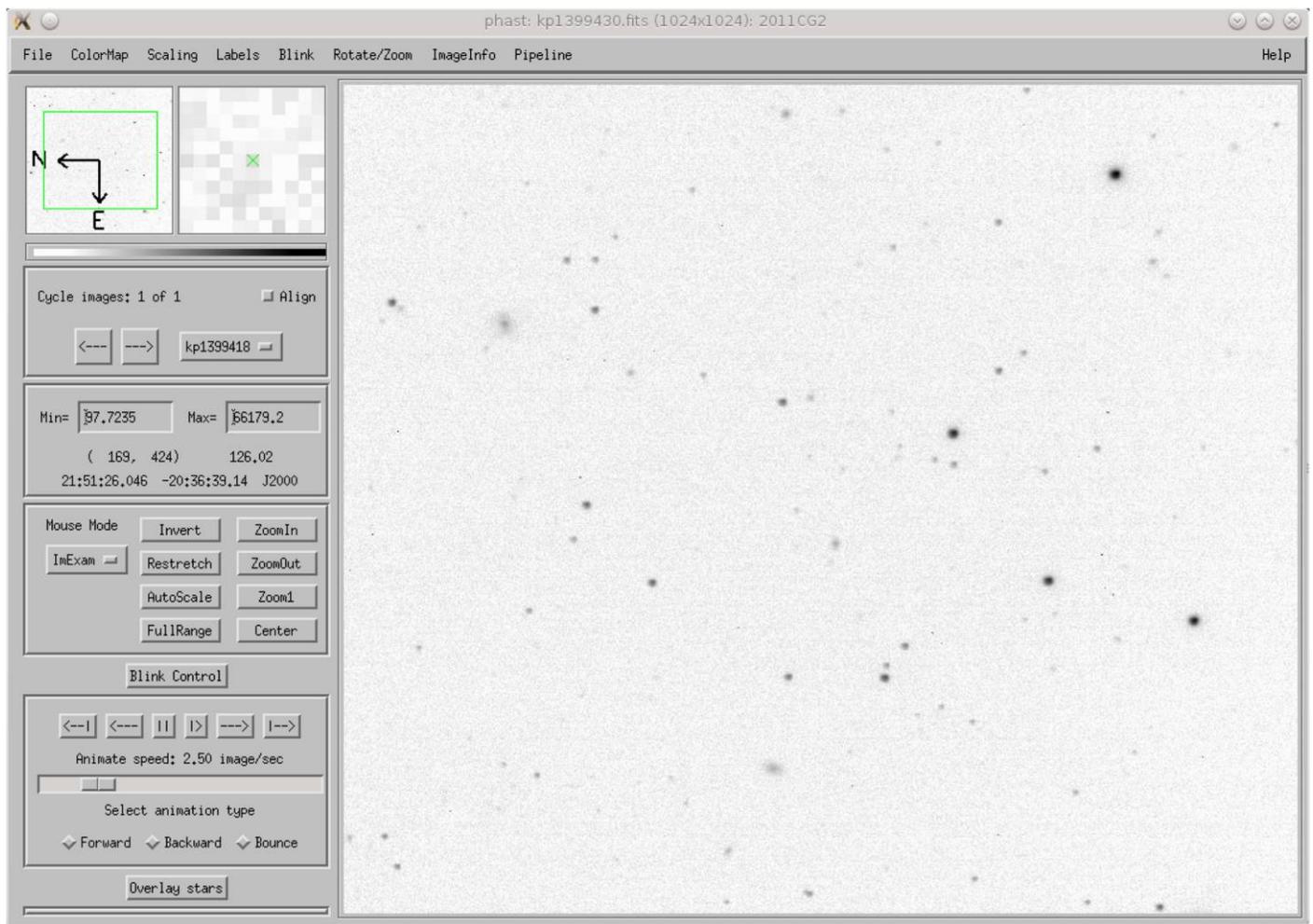


FIG. 1.—PhAst as it appears on startup with an image loaded. A negative lookup table was used to emphasize faint features in the image. See the electronic edition of the *PASP* for a color version of this figure.

much of an image as possible. As the application window is expanded, only the image region of PHAST is increased.

PHAST adds a number of new features to the original ATV framework which significantly extend its usefulness beyond a simple astronomical image viewer. These features enable NEO observers to do real-time calibration and reduction of CCD observations.

PHAST can calibrate raw astronomical CCD images with user-designated flat, dark, and bias frames. Overscan regions on raw CCD images can be used and then removed from the calibrated CCD images. Calibration can be applied to either a single image or to an entire directory of files.

PHAST can determine an astrometric solution for a given astronomical observation of a stellar field. The application provides a front-end interface to the astronomical software packages SExtractor, SCAMP, and missFITS which are maintained independently by Bertin and collaborators. To determine the astrometric solution of an image, SExtractor is used for source extraction. SExtractor generates a catalog of all of the

image's sources (stars, galaxies, etc.) and the pixel coordinates of each. SCAMP is used to match this catalog to known sources in a standard reference catalog; this generates the astrometric solution. SCAMP generates a linear solution for the image and missFITS is used to write the solution to the FITS header of the output file. Once an image has a WCS, PHAST can take advantage of it in a number of ways described below.

PHAST has kept the ATV functionality to interactively display the right ascension and declination of a location in the image marked by the graphics cursor. These coordinates can be transformed to a number of different systems (J2000, B1950, galactic, ecliptic). PHAST can query the online USNO-B1.0 catalog (Monet et al. 2003) and, using the WCS, can overlay the names and positions of all field stars given in that catalog (see Fig. 2). The user can also search for a particular star in the given field; this is convenient for those doing photometry on particular stars within the field of view. If a moving object was being tracked during a series of exposures, the WCS of the images

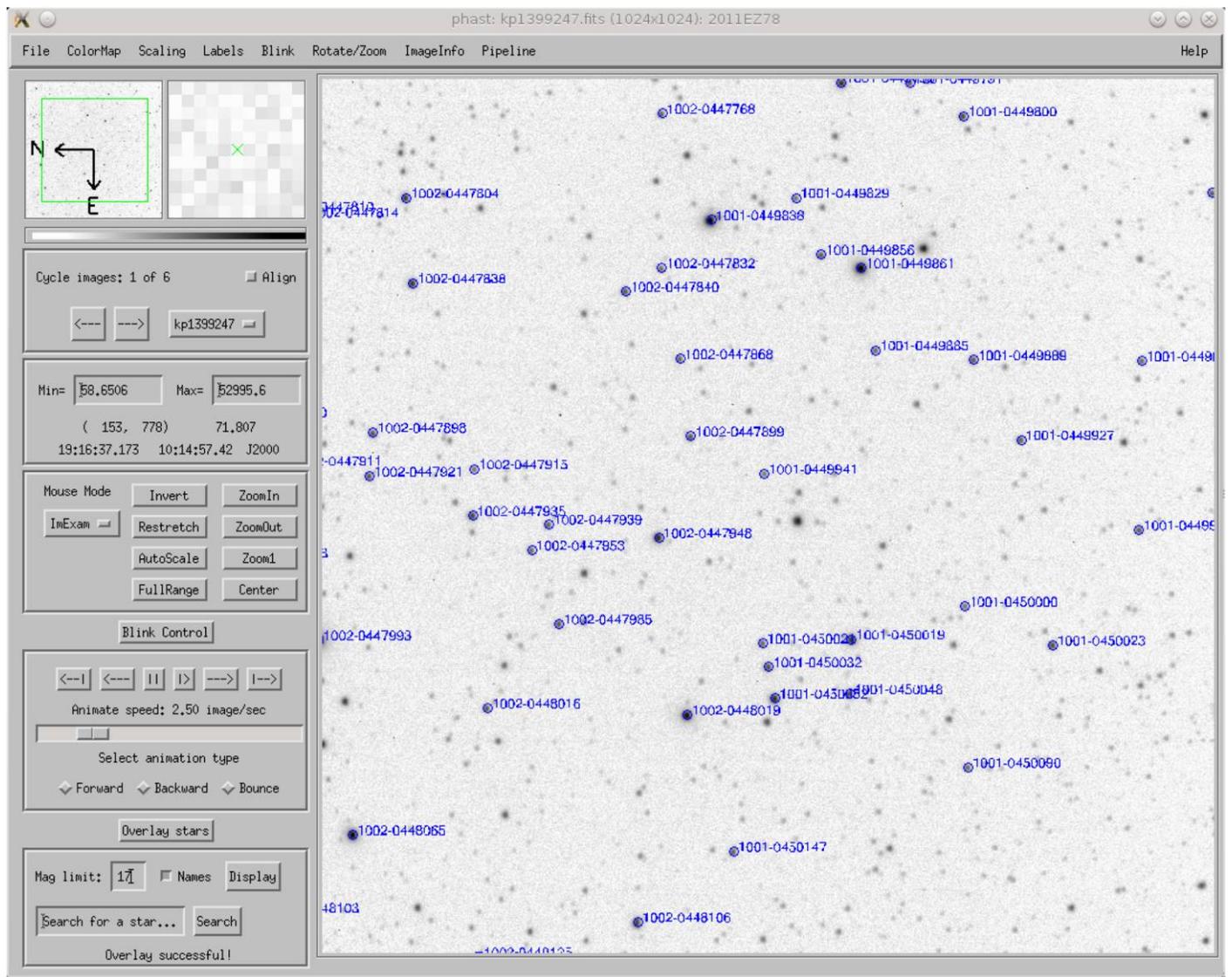


FIG. 2.—PhAst with an image loaded and USNO-B1.0 catalog stars ( $\leq 17$  mag); names are overlaid on top the image. Note the “Overlay Stars” toolbox present on the bottom of the left pane. See the electronic edition of the *PASP* for a color version of this figure.

can be used to align the images, thus freezing the motion of everything but the object of interest.

PHAST can also take a calibrated image with an astrometric solution and compute its photometric zero-point. This calculation is performed by matching each star in the image, as measured by SExtractor, with its corresponding USNO-B1.0 catalog star. Once the photometric zero-point value is written to the FITS header, subsequent use of PHAST’s photometry module will report standardized photometric measurements on the photographic  $R$  magnitude system.

For NEO research, PHAST can prepare an object report for the IAU Minor Planet Center (MPC). MPC reporting requires that an image is calibrated with an astrometric solution and a photometric zero-point. MPC-compliant astrometry reports can be generated using PHAST, which then can sent by the ob-

servers to the MPC directly from the telescope console room during a night of NEO observations (see Fig. 3).

### 3. RESULTS

#### 3.1. Recovery of VI 2011AX22 and PHA 2008OX1

Trueblood, Crawford, and Rehnberg used the KPNO 2.1-m telescope on 2011 November 21–22 to do long-term follow-up observations of NEOs as part of the NEO Arc Extension program of Trueblood and collaborators. They used the CFIM CCD camera with T2KB CCD which together have a  $10.2' \times 9.4'$  unvignetted field of view that is adequate to perform routine astrometric follow-up and arc extension observations. A clear filter (Schott glass BK7) was used in order to maximize the detection of light from the NEO. Four or more exposures were

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COD 695
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OBS M. Trueblood, L. Lebofsky, R. Crawford
MEA R. Crawford, M. Rehnberg
TEL 2.1-m f/7.7 Ritchey-Chretien + CCD
ACK MPCReport file updated
AC2 mtrueblood@noao.edu
NET USNO-B1.0
COM Based on work partially supported by NASA SMD NEO Observation Program
  C061001 C2012 02 19.24400 9 59 21.94 +15 43 30.1      22.1 R      695
  C061001 C2012 02 19.25437 9 59 19.60 +15 43 41.5      22.8 R      695
  C061001 C2012 02 20.37154 9 54 59.61 +16  4 34.5      23.7 r      695
  C061001 C2012 02 20.38156 9 54 57.05 +16  4 45.7      23.7 r      695
----- end -----

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FIG. 3.—An example of a Minor Planet Center report generated by PhAst. This raw ASCII text file can be attached to an email for submission to the MPC.

typically obtained so that at least three images would show the NEO's motion across the sky without blending with field stars or being corrupted by detector defects. The CCD images were transferred to the data reduction computer in real time, and then PHAST was used to calibrate, register, and visually inspect multiple observations by blinking the aligned images. Astrometry was submitted to the MPC, extending the arcs of 1 VI and 4 PHAs discovered earlier in 2011 and observing one PHA recovery candidate after more than 9 years without observation.

Trueblood, Crawford, and Lebofsky used the KPNO 2.1-m telescope on 2012 February 17–19 to do long-term follow-up observations of NEOs as part of the NEO Arc Extension program with an emphasis for this run on NEO recovery. They used the same instrumentation setup and analysis methods that were used in the November run described above.

PHAST was used to calibrate and reduce all of the recovery images taken of the VI 2011AX22 (see Fig. 4) and the PHA 2008OX1. Images were taken while tracking the NEOs for 12 minutes (2011AX22) and 4 minutes (2008OX1) at non-sideral rates on the moving target. After each readout was completed, the image was immediately transferred from the KPNO instrument control computer to the data reduction computer running PHAST. PHAST calibrated the images with biases and flats, and then used SExtractor to generate object lists and SCAMP to solve for the WCS of each image. PHAST then determined the photometric zeropoints of the images to permit photometry. SExtractor's ability to measure elongated objects using elliptical apertures is central to PHAST's capability to reduce images of this kind. PHAST was used to align the multiple images astrometrically and to blink them in the visual search for the moving target.

VI 2011AX22 was detected provisionally on two images on each of two nights. Astrometric and photometric measurements were made using PHAST by pointing and clicking the mouse on the identified target. The object was followed (unsuccessfully,

given sky conditions) for the remainder of its visibility on those nights, with a sequence of 12-minute images.

PHA 2008OX1 posed the need to search the sky with 9 overlapping fields of view (sky tiles) with a cumulative 70% chance of containing the object. Each sky tile was imaged deeply once while tracking on the moving target. While the observing team moved to image the next tile, PHAST was used to reduce the deep image and to examine it for a candidate target detection based on the expected circular PSF (a consequence of tracking on the moving target) at a magnitude consistent with ephemeris predictions. When such a candidate was found in the seventh tile, the observers returned to that position and obtained three additional images of the field. PHAST was used to align and blink the images to conclusively identify the target, to measure the target's astrometric position and its magnitude in the images, and to prepare a formatted report for submittal to MPC.

In the NEO Arc Extension program, data is routinely submitted to the MPC during the night as targets are detected and measured. Given the difficulty of NEO recovery during this particular observing run, complete analysis and submittal of data were delayed to permit a detailed assessment of the data a few days later. The detection images were remeasured using PHAST and the resulting sky positions were compared critically to the ephemeris uncertainty analysis provided by NEODYs. The detection of VI 2011AX22 was confirmed at a position near the nominal prediction and lying within the three standard deviation ( $3\sigma$ ) uncertainty ellipse on the line of variations. The detection of 2008OX1 was confirmed at a position in the seventh tile, far from the nominal position, and lying close to (but outside) the  $3\sigma$  uncertainty ellipse for the nominal position. The data were submitted to MPC, which confirmed the recoveries through independent analysis, and were accepted. Some of the observing parameters for these NEO recovery observations are given in Table 1.

The recovery of 2011AX22 led to a large improvement in the time of perihelion passage and in the semimajor axis and the

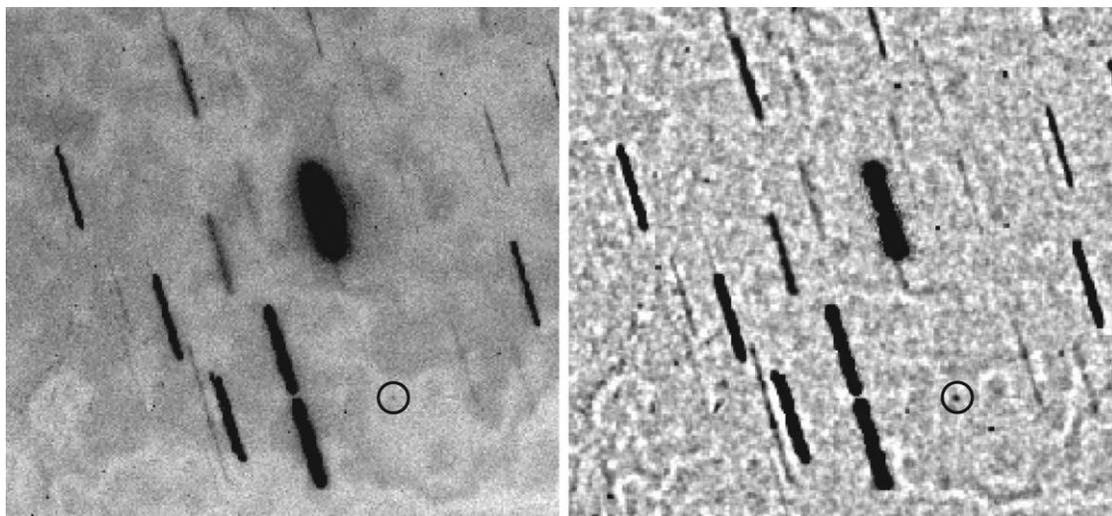


FIG. 4.—Detection image for the Virtual Impactor 2011AX22 (2012 February 18 MST). Field stars are elongated by  $31''$  as a result of tracking the KPNO 2.1-m telescope for 12 minutes at a nonsidereal rate in order to follow the moving target on the sky. The target is seen in the center of the circle on each image. The *left image* is the calibrated CCD image. The *right image* is an unsharp masked version of the left image.

eccentricity of its orbit. The distance of closest approach in May 2055 was moved away from Earth to  $>1$  lunar distance. As a result of the orbital improvement made possible by the successful recovery, NEODyS downgraded 2011AX22 from a VI to a PHA, having ruled out the chance of an Earth impact this century.

The recovery of 2008OX1 extended its observational arc to 1303 days—more than 2.5 orbital revolutions. It was confirmed as a PHA and its orbit was improved sufficiently to permit prediction of its sky position to within  $1''$  over an interval of 10 years into the future.

### 3.2. Astrometric and Photometric Performance

To assess the astrometric performance of PHAST, we examined 302 observations submitted to the MPC from observing runs at KPNO over the period October 2010 through March 2012. All observations were made by Trueblood and collaborators using the KPNO 2.1-m telescope with the CFIM CCD imager for their NEO Arc Extension program. A total of 243 observations of 75 targets were reduced with the previously used software, while 59 observations of 18 targets were reduced

with PHAST since its adoption in October 2011. The observations of astrometric positions and estimated  $V$  magnitude were retrieved from the NEODyS system and screened to remove data submitted by other teams using telescopes at KPNO.

Asteroid astrometry is a relative measurement of sky position in comparison to the positions assigned to reference stars in the image by the selected astrometric catalog. All of the observations were reduced using the USNO-B1.0 catalog, which has been shown to have systematic errors of  $0.1''$  in declination and smaller systematic errors in right ascension (Chesley et al. 2010). Astrometric errors were determined for all observations as being the residual between the observed positions reported to the MPC and the positions estimated in the orbital solutions computed by NEODyS, which are based on the complete observational history of an object.

The bias (average error) in right ascension and declination using PHAST was  $-0''.02$  and  $+0''.14$ , respectively. With the previous software, the bias in right ascension and declination was  $-0''.03$  and  $-0''.12$ , respectively. These biases are consistent with the known astrometric bias of the USNO-B1.0 catalog, which was used for all of the observations. The precision (rms error) using PHAST was  $0''.23$  as compared to  $0''.26$  with the previous software. Although the overall astrometric precision is similar for PHAST and the previous software, a significant improvement in the distribution of total astrometric errors is clearly seen in Fig. 5. With the previous software, 44% of the observations had astrometric precision in the range  $0''.20$  to  $0''.50$ . While the quality of this astrometry was acceptable, the adoption of PHAST has significantly improved the astrometric precision of these NEO observations: 69% of the observations analyzed with PHAST had astrometric errors of  $0''.20$  or less. PHAST does not attempt to correct for the known biases in the reference catalog, which is handled by the orbit computers.

TABLE 1  
NEO RECOVERY OBSERVATIONS REDUCED WITH PHAST

Observing parameter	2011AX22	2009OX1
Classification	VI	PHA
Time since last observed (days)	373	1271
Apparent $V$ magnitude (mag)	22.7	21.7
Exposure time (s)	720	240
Field star elongation ( $''$ )	31	11
Astrometric precision ( $''$ )	1.4	0.5
Photometric precision ( $R$ mag)	0.6	0.4

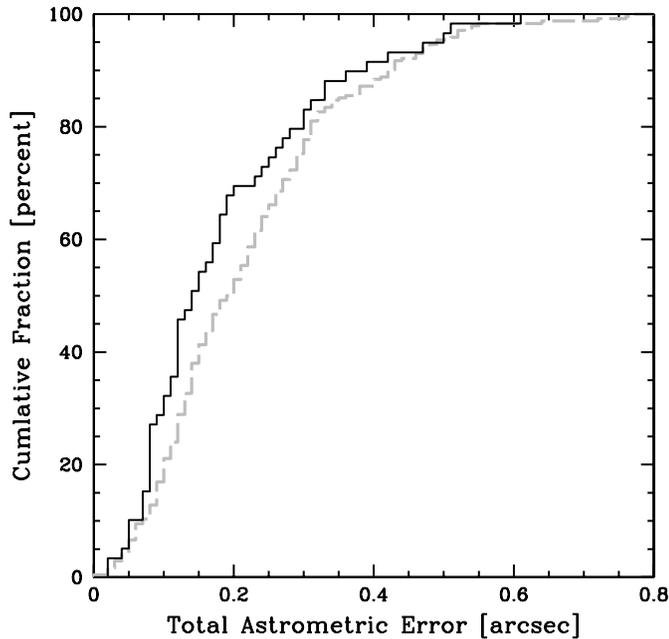


FIG. 5.—The astrometric precision for targets observed with the NEO Arc Extension program when astrometry was determined using PhAST (*black curve*) and ASTROMETRICA (*gray dashed curve*).

The observing team previously used Astrometrica for astrometric and photometric calibration and measurement. While the quality of the measurements made by that program was high, the assumption of a circular Gaussian point-spread function limited the program's ability to accurately reduce images in which field stars were elongated by nonsideral tracking of the moving target on the sky (e.g., see Fig. 4). If the elongation of field stars exceeded the size of the circular aperture used in object detection, stars could be truncated during centroiding, which would adversely affect the quality of the astrometric calibration of the image. SExtractor yielded superior centroiding and flux determination because it uses adaptable elliptical apertures while Astrometrica uses fixed circular apertures. These considerations forced the 2.1-m telescope observers to limit the length of time that moving targets could be followed on the sky in order to limit the elongation of the field stars. This limitation made observations of fainter NEOs very difficult.

Astrometric precision is dependent primarily on the accuracy of centroiding measured objects, the accuracy of the reference astrometric catalog, and the quality of the astrometric solution. Since the USNO-B1.0 catalog was used for all observations, and a linear astrometric solution was fit in both the previous software and in PHAST, we credit the improvement in astrometric precision using PHAST to the better centroiding by SExtractor of the field stars that have been elongated by tracking the telescope at nonsideral tracking to follow the moving target.

The PSF mismatch also adversely affected photometric measurements. The bias (average error) in  $R$  photometry was reduced from 0.06 mag when Astrometrica was used to 0.02 mag when PHAST was used; the accuracy of the photometry was comparable with both reduction packages because the calibration of the photometry was based on the same catalog (USNO-B1.0) which has a photometric accuracy of 0.3 mag (Monet et al. 2003).

#### 4. DISCUSSION

The NEO Arc Extension program seeks to observe a variety of targets, including newly discovered VIs (which may be relatively bright), VIs and PHAs some 50–80 days after discovery (when they may be relatively faint), and upcoming radar targets needing astrometry (which tend to be close to Earth and may be bright). By switching from Astrometrica to PHAST, Trueblood and collaborators can now track moving objects for longer periods of time and reach fainter magnitudes under a wider range of observing conditions. With the previous software, the exposure length was constrained to limit field star elongation to  $\leq 5''$ . VI 2011AX22 was recovered with 12-minute exposures that trailed the field stars by  $31''$  (one-half arcminute). The sixfold increase of exposure time in this case extended the telescope's limiting magnitude by 1 full magnitude and permitted a successful recovery under the adverse sky conditions of the observing nights. The fraction of moving targets observed in the range  $22 \leq R < 23$  mag has nearly doubled (from 12% to 22%) since the adoption of PHAST.

When PHAST uses SCAMP to generate an astrometric solution for an image, SCAMP computes both a linear and a nonlinear solution. The current version of PHAST only uses the linear solution. If the nonlinear solution could be used instead, more accurate point-and-click astrometry could be provided. In cases where image distortion is substantial, such an upgrade to PHAST would greatly increase astrometric accuracy. While PHAST performs only a linear astrometric solution at present, analysis done (with other software) has shown that CCD observations from the 2.1-m telescope are well represented by a linear fit due to the telescope's design and conventional (narrow) field of view.

As the NEO Arc Extension program begins to make greater use of color filter photometry, an effort is underway to enhance PHAST's photometric capabilities. Support for additional reference catalogs is planned, along with a variety of improvements in its photometric methods. These include features to improve performance when operating close to the sky background, improved logic to size the measurement apertures appropriately, and extension of its photometric capabilities beyond that required by the NEO program. Support is planned for features that would make PHAST useful in all-sky photometry, time-series photometry, and in a wider range of filter passbands.

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