

Computer-aided star pattern recognition with *astrometry.net*: In-flight support of telescope operations on SOFIA

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ABSTRACT

SOFIA is an airborne observatory, operating a gyroscopically stabilized telescope with an effective aperture of 2.5 m on-board a modified Boeing 747SP. Its primary objective is to conduct observations at mid- to far-infrared wavelengths. When SOFIA opens its door to the night sky, the initial telescope pointing is estimated from the aircraft's position and heading as well as the telescope's attitude relative to the aircraft. This initial pointing estimate needs to be corrected using stars that are manually identified in tracking camera images; telescope pointing also needs to be verified and refined at the beginning of each flight leg.

We report about the implementation of the *astrometry.net* package on the telescope operator workstations on-board SOFIA. This package provides a very robust, reliable and fast algorithm for blind astrometric image calibration. Using images from SOFIA's Wide Field Imager, we are able to display an almost instant, continuous feedback of calculated right ascension, declination and field rotation in the GUI for the telescope operator. The computer-aided recognition of star patterns will support telescope pointing calibrations in the future, further increasing the efficiency of the observatory. We also discuss other current and future use cases of the *astrometry.net* package in the SOFIA project and at the German SOFIA Institute (DSI).

Keywords: SOFIA, telescope pointing, astrometry, pattern recognition, plate solving, blind astrometric calibration, data reduction, operations

1. INTRODUCTION

Plans to utilize computer-aided star pattern recognition to support telescope pointing calibrations on SOFIA have been discussed for a long time,¹ but their implementation was problematic. First, the algorithm needs to be absolutely robust. For example, one concern at flight altitude is the much increased exposure to cosmic rays causing spurious sources. Second, any new software needs to be embedded into existing observatory systems. SOFIA's Mission Communications and Control System (MCCS) is responsible for a large variety of the observatory's functions; the supervisory control of the telescope is one of its primary tasks. The MCCS workstations on-board SOFIA that allow monitoring and access of all subsystems are running Solaris 10 and display a graphical user interface (GUI) to the MCCS written in Java. For many years, it appeared that a custom and lengthy software development would be necessary to implement a robust, fail-safe pattern recognition algorithm, as no existing tool seemed to be easily implementable. As a consequence, much like on SOFIA's predecessor, the Kuiper Airborne Observatory (KAO), telescope pointing calibration remained a manual task. On the KAO, it was the task of the tracker operator to compare tracker images with star charts to adjust telescope pointing, and to make sure that the telescope kept tracking on the target of interest, which was often not visible at the wavelength range of the tracking camera. While the tracker subsystem on SOFIA allows for various fully automated

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tracking modes once desired guide stars have been selected in the field of a tracking camera, the recognition of star patterns for pointing calibrations still remains a manual task of the telescope operators.

With the development of the *astrometry.net* package, fully autonomous star pattern recognition has become the standard practice in astrometric data reduction. By now, *astrometry.net* finds wide use both in the professional (f.e. LSST, Palomar Transient Factory, DeepSky) and the amateur community (f.e. *AstroImageJ*) and has a large user base. Refining telescope pointing with *astrometry.net* already finds widespread use among the control of smaller telescopes (e.g. using local setups provided by *AstroTortilla* or *ansvr*, or by using the nova.astrometry.net web service). After the code had demonstrated its superb reliability and robustness also at DSI, calibrating a large variety of image data in recent years - some of it deliberately selected to contain severe artifacts - we revisited the idea to implement *astrometry.net* as an automated tool for star pattern recognition on SOFIA. Our aim was to solve images from SOFIA's Wide Field Imager (WFI) with negligible wait time to support the telescope operator with "live" information on telescope pointing in equatorial coordinates, assisting with pointing calibration. As the *astrometry.net* code does not require any guess on pointing, we were able to implement it as a stand-alone tool without interfacing any MCCS housekeeping data. The *astrometry.net* package was explicitly developed to run without any human intervention, is distributed as open source under the GNU General Public License and was developed on Linux. Having portability in mind, its main code is written in ANSI C and relies on POSIX standards. All these characteristics made it the perfect choice for the problem at hand, although some hurdles had to be overcome to compile it on the MCCS Solaris workstations.

2. TELESCOPE POINTING ON SOFIA

Although being mounted on a moving platform, the SOFIA telescope is pointed in absolute equatorial coordinates (right ascension, declination). The attitude of the Telescope Assembly (TA) is measured using three fiber optic gyroscopes in an inertial reference frame (IRF). The MCCS on-board SOFIA relates measurements from inertial coordinates to equatorial coordinates (ERF) using avionics data (aircraft location, attitude) and a number of reference stars, aside of being responsible for a variety of other tasks.

2.1 SOFIA's Target Acquisition and Tracking Cameras

SOFIA has three cameras for target acquisition and tracking with complementing, co-aligned field of views, sensitive to standard visible wavelengths ($\approx 0.4 - 1.0 \mu\text{m}$). The Focal Plane Imager (FPI, 0.145° field of view) receives visible light from SOFIA's telescope via a dichroic tertiary mirror and is the standard tracking camera during observations, offering the highest resolution and centroid accuracy. The Fine Field Imager (FFI, 1.12°) acts as a backup in case a guide star is not available in the field of the FPI, or an extended object such as a comet with a large coma is observed. The FFI would also act as the primary tracking camera if a fully-reflective tertiary is installed. The Wide Field Imager (WFI, 6°) provides context data on the sky to verify telescope pointing and to monitor field rotation. Both the FFI and the WFI have separate optics and are mounted on the head ring of the telescope metering structure, where they are exposed to stratospheric conditions. All three imagers have filter wheels, carrying f.e. neutral density filters to enable tracking on very bright sources.

The properties of the imagers are summarized in Table 1. Originally, all three tracking cameras employed uncooled TH7888A CCDs with a peak quantum efficiency of $\approx 18\%$. While quantum efficiency of modern back-illuminated CCDs exceeds 90% , advances in chip design enable significantly reduced dark current at any given temperature. The dramatic benefits from a state-of-the-art, cooled, back-illuminated sensor triggered the upgrade of the FPI with an Andor iXon DU-888 camera in early 2013, now known as the FPI⁺, boosting its sensitivity by a factor of $\approx 100\times$. Upgrades of the WFI and FFI are currently in preparation,²⁻⁴ which includes their optics. Both upgrades will employ a modified, ruggedized version of the Andor iXon DU-888 that has been developed for stratospheric conditions and successfully thermal-vacuum tested; to avoid thermal emission at the head ring, the coolers of both cameras will only be used during ground tests. The upgrade of the FFI optics is motivated by its severe defocus while cooling down during the first 2 - 3 h in flight, only being focused as it reaches thermal equilibrium. During this time, no reliable centroids can be calculated for tracking. The new FFI⁺ will employ an athermal Riccardi-Honders f/2.2 design with an increased aperture of 300 mm. Its sensitivity will be boosted by about four stellar magnitudes. The WFI optics will be upgraded as the back focal length of the current Petzval lens is too short to be reused on the new camera, and its off-axis image quality is

Table 1. Properties of SOFIA's Target Acquisition and Tracking Cameras. An upgrade of the WFI and FFI is currently in preparation, which will significantly boost their sensitivity.

	Current Imagers			After Upgrade	
	WFI	FFI	FPI ⁺	WFI ⁺	FFI ⁺
Optics	Petzval Lens	Schmidt-Cassegrain & Reducer	Cassegrain (SOFIA TA) & Reducer	Telephoto Lens	Riccardi-Honders
Aperture (mm)	68	254	2526	42.5	300
Focal Ratio	f/2.0	f/2.8	f/2.1	f/2.0	f/2.2
Field Size (arcmin)	362	67	8.7	550	69
Plate Scale (arcsec/pixel)	21.23	3.94	0.51 ^a	32.26	4.04
Sensitivity (mag)	9.8	11.2	> 16	12.8 ^b	15 ^b

^a The FPI⁺ plate scale varies as the M2 of the SOFIA TA is moved to achieve various focus positions; the FPI⁺ is focused separately via movable tilted mirrors in its "delay line assembly".

^b Expected sensitivity based on modeling.²

rather poor. DSI identified an off-the-shelf Canon CN-E 85 mm T1.3 L F telephoto lens as a promising candidate for the upgrade after extensive thermal-vacuum testing; this lens shall be used stepped down to f/2.0. The WFI's sensitivity is expected to increase by about three stellar magnitudes.

2.2 Telescope Pointing Calibration

After SOFIA opens its cavity door to the night sky, the MCCA derives a blind pointing estimate in equatorial coordinates with an accuracy of about 1°; i.e. the desired target is usually not positioned in the field of the FPI⁺ or FFI. This pointing estimate is calculated from GPS measurements of aircraft latitude, longitude and time, avionics information on aircraft heading, and inertial gyroscope measurements of telescope attitude. Based on this pointing estimate, markers for a number of field stars are displayed on a MCCA GUI image overlay on real-time images from the three tracking cameras, misplaced from the true star positions. Lists of stars that determine which markers are displayed in the vicinity of each target are prepared individually before each flight. Their pattern allows the telescope operator to recognize the field in the three tracking cameras and to manually associate two stars in an image with their corresponding markers. To do this, the telescope operator marks an identified star by drawing a box on the GUI image overlay using a computer mouse, and selects the corresponding catalog identifier from a drop down menu. This allows a correlation of image data with catalog data in equatorial coordinates to determine telescope pointing. Typically, the initial pointing calibration is done using a WFI image - also given the defocus of the current FFI optics early in flight - and then verified and refined in the FPI⁺ for best accuracy, provided that at least two stars are visible in the field. Once telescope pointing is established, the science instrument boresight (corresponding to some pixel coordinate in the FPI⁺) is positioned on the infrared source of interest, which is often not visible itself in FPI⁺ images. Continuous centroid measurements of selected guide stars in FPI⁺ or FFI images are then used for "tracking", i.e. to periodically compensate drift of the gyroscope's inertial measurement. For a more detailed summary on telescope pointing and tracking on SOFIA, see e.g. Temi et al. (2014).⁵ An overview on the observatory can be found in Young et al. (2012).⁶

Even with lots of training, experience and preparation before a flight, manual pattern recognition can be challenging and time consuming, especially in crowded fields, i.e. towards the galactic plane. During periods without optical tracking (i.e. aircraft heading changes between flight legs for different astronomical targets), gyro drift deteriorates the telescope pointing estimate, requiring verification and calibration at the beginning of each flight leg. Although manual pointing calibration is usually performed quickly, any human interaction requires time and leaves room for error. As autonomous star pattern recognition has become standard practice in astrometric data reduction, an automated system could transform valuable minutes of flight time into observing time.

3. ASTROMETRY.NET

3.1 The Algorithm

The algorithm behind *astrometry.net* was developed by D. Lang in his PhD thesis;⁷ a comprehensive summary and discussion of the code⁸ can be found in Lang et al. (2010).⁹ A typical run of the `solve-field` command consists of the following steps:

1. Robust source detection and centroid calculation (via a Gaussian fit).
2. Generating geometric hash codes that describe the relative positions of subsets of four bright stars (“quads”), invariant of scale and rotation.
3. Search for similar hash codes (considering positional noise of measured centroids) in a pre-computed catalog index (hash table); each match forms a hypothesis on sky location.
4. Test each hypothesis based on other expected stars in the field in a Bayesian decision process, rejecting all false matches and accepting the true match once found.

Astrometric calibration is done entirely “blind” without any a-priori information other than image data; i.e. no information on image scale or orientation is required to solve an image reliably. Obviously, a search through the pre-computed catalog index will speed up f.e. if the plate scale of the image can be constrained. The Bayesian decision model is designed to fail instead of producing a false result. Pattern matching is robust against missing or spurious source detections, as the position of other extracted sources is checked to align with other known stars in the area of the matched quad. A field should typically contain more than ≈ 20 sources, as the Bayesian decision process requires sufficient evidence to verify an hypothesis. However, our tests showed that the code also works reliably on fields with less than 20 stars.

SOFIA’s WFI has a large field that always contains a sufficient number of bright stars and is therefore ideal for an application of *astrometry.net*. As the code’s own, simple, but robust source extraction worked very well for our application, we had no reason to replace it. The user could run the `solve-field` command instead with a list of previously extracted x, y positions of star centroids to apply only the core pattern matching algorithm, or alternatively, use a local setup of *SExtractor*¹⁰ for source extraction. By default, we use an image downsampling factor of 2 (Parameter `-z 2`). The code’s source extractor applies a Gaussian fit with a standard deviation of 1 pixel as a “matched filter”, based on the assumption that the point spread function (PSF) can be approximated in that way. Effectively, it measures the center of a star image by looking at a 3x3 box around its peak value. Experience shows that this assumed PSF is quite narrow. By downsampling the image by a factor of 2, the assumed PSF size is effectively doubled, which appears to be more realistic. Another positive effect of image downsampling is that it smooths over saturated pixels. That is why downsampling by a factor of 2 is the default in the *astrometry.net* web service, and is widely recommended to be set as a default value.

Index files are built from “quads” of bright stars, uniformly covering the sky and selected based on a healpix grid^{9*}. To be able to search for quads at different scales, a number of index files are generated at different healpix grid scales (see Sec. 4.2). As index files are built from the brightest stars available in any given sky cell, the code also looks for the brightest sources extracted from the image to form quads.

A few practical things should be kept in mind applying the algorithm: First, the code assumes square pixels. SOFIA’s imagers as well as most modern CCD and CMOS cameras fulfill this requirement. Second, a bright, but saturated star should not be removed from the list of detected sources as this would remove a key pattern information. The pattern matching algorithm is able to deal well with the positional error of the saturated star’s centroid. Our tests show that the positional noise introduced by a saturated star has an extremely small effect on the calculated image center position (see next section). Third, the epoch of the image is not considered for the solution; the pattern is recognized solely based on geometric information from a catalog in the respective epoch (in our case, J2000.0; c.f. Sec. 4.2). *Astrometry.net* aims at a robust pattern recognition, not at an astrometric calibration of the highest accuracy. A high precision plate solve reduces the observed position at the epoch of the

*<http://astrometry.net/doc/build-index.html>

observation to the epoch of the catalog and corrects for precession, nutation, stellar aberration, light deflection of the Sun's gravity, parallax, refraction and proper motion of stars. All these effects are not considered in *astrometry.net*, but matching the pattern in the catalog epoch J2000.0 provides a very good estimate of pointing in J2000.0 coordinates, more than enough to calibrate telescope pointing spot-on. Several other tools are available to refine the astrometric calibration of an image^{1,11,12} for high precision astrometric measurements, but those tools require a good guess about pointing and scale, fine tuning of several parameters, and are not as robust.

3.2 Performance Tests

Aside of using *astrometry.net* for about three years for various tasks on our ground-based telescope ATUS (see Sec. 6.3), we extensively tested and confirmed the reliability of the algorithm by calibrating archived WFI and FFI data obtained on SOFIA on various nights, and data from various other sources. A dataset particularly hard to calibrate was obtained during the Quadrantids 2008 MAC mission[†] on January 3, 2008, intended to observe the Quadrantid meteor shower with a large number of cameras and slitless spectrographs through the windows of a Gulfstream GV aircraft. We obtained about ≈ 8 h of image data with two SBIG ST-10XME cameras, one equipped with a 28 mm lens ($19.7^\circ \times 28.7^\circ$ FOV), the other equipped with a 50 mm lens and a low resolution transmission grating ($11.0^\circ \times 16.2^\circ$ FOV). As the cameras were loosely mounted to the aircraft's windows, their images showed all kind of artifacts due to turbulence, aircraft vibrations, periodic roll due to autopilot control, heading corrections (all leading to blurred, elongated or streaked stars) and window reflections (if there was need for light in the cabin), but also artifacts introduced from the sky (large scale aurora, city lights in the lower part of the image, illuminated clouds and haze, meteors) and a much larger number of cosmic ray hits due to flight altitude (estimated to be about $13 - 15\times$ higher than at ground level¹). Despite of the immense amount of artifacts and spurious sources, both data sets (≈ 6000 images in total) solved quickly without a single false positive. Images from the camera with the transmission grating solved based on zero order star images. Performing such a successful astrometric calibration on images that we previously thought would be impossible to solve contributed to the decision to move forward with an implementation of *astrometry.net* on SOFIA.

To analyze the performance of the algorithm further and to understand which impact each of the various parameters of `solve-field` has on run time, we acquired series using the ATUS wide field imager (5.63° FOV, c.f. Sec. 6.3) and using the WFI⁺ test setup (Andor iXon DU-888 with a Canon CN-E 85 mm T1.3 L F lens)¹³ with an exposure time of 1 s and without tracking, i.e. with a fixed camera alignment. During the WFI⁺ image series, we also logged precise GPS time stamps in the FITS header of each image with an accuracy of better than 1 ms, based on a TTL trigger signal from the camera to a GPS device at the start of each exposure.

Table 2 gives an example how various parameters influence run time of `solve-field`, processing a WFI⁺ image. These estimates made clear that the code was able to run fast enough without any modification to solve almost every WFI⁺ image (typically having an exposure time of 1 – 2 s, plus readout). Note that the actual time to recognize a pattern is much less. Significant overhead is caused by image preprocessing and a “FITS file sanitizer” script, both written in Python, as well as source extraction. The FITS file sanitizer can be disabled if the user can make sure that standard-conform FITS files are processed. Aside of that, the `solve-field` command spends almost half of its run time on a WFI⁺ image preparing plots of the extracted sources, of the accepted (matched) quad hypothesis, and of an overlay with constellations and other objects of choice in the field. We can easily discard these plots for telescope pointing calibration. In contrast, specifying a pointing guess (RA, Dec) has almost no impact on run time at WFI⁺ image scales. Limiting plate scale has a more notable effect and can be easily done for the SOFIA imagers. The impact of this parameter on run time becomes much more important towards smaller field sizes (i.e. FFI and FPI⁺); the same applies also for a pointing guess.

We cannot measure the accuracy of the calculated image center coordinate directly (i.e. the deviation from its true value), but we can derive indirect and relative estimates. To assess the accuracy of a WFI⁺ plate solve, we took two approaches:

First, we estimated the root mean square (RMS) position deviation between the matched stars' catalog positions and their centroid position, transformed from image coordinates to equatorial coordinates based on the found solution. The RMS stellar position deviation was between 5 – 6 arcsec over a subset of 300 WFI⁺ images,

[†]<http://quadrantid.seti.org/>

Table 2. Exemplary evaluation how different parameters impact run time of the `solve-field` command. In this example, WFI⁺ images (9.17° FOV) have been solved using the full Tycho-2 index as provided by the *astrometry.net* project (354 MB, scale 7 – 19, c.f. Sec. 4.2); the `INPARALLEL` flag was enabled. The impact of each parameter was tested individually. Provided run times are averaged over solving 300 images from a series individually (not in batch mode). Test platform was a 2013 Macbook Pro with 2.6 GHz Intel Core i7 CPU, 16 GB RAM and a solid-state drive, running *astrometry.net* v0.44.

Set Parameters	Run Time
1 None, except downsampling for source extraction (<code>-z 2</code>) and enforcing WCS reference point at image center (<code>--crpix-center</code>)	4.65 s
2 Provide RA, Dec estimate and search radius (<code>-3 <hh:mm:ss> -4 <dd:mm:ss> -5 <deg></code>)	4.41 s
3 Constrain parity (<code>-8 <pos/neg></code>)	4.22 s
4 Constrain plate scale with 5% margin around known value (<code>-L <scale> -H <scale> -u app</code>)	4.05 s
5 Disable plots and output files (<code>-p -R none -S none -M none -B none -N none -U none</code>)	2.25 s
6 Disable the “FITS file sanitizer” Python script (<code>-2</code>)	2.22 s
No 4, 5 & 6 together	1.10 s

running `solve-field` with a standard distortion polynomial order (“tweak-order”) of 2; this equals about $\frac{1}{5}$ th to $\frac{1}{6}$ th of the WFI⁺ plate scale. As expected, raising the degree of the distortion polynomial decreases the RMS deviation, but a higher polynomial order might not be a physically accurate model of distortion anymore. The order of the distortion polynomial indirectly affects the estimated center coordinate. However, we assume that the accuracy of the image center coordinate is better than the estimated RMS derivation, as f.e. off-axis stars should show higher positional deviations due to field distortion than on-axis stars. This assumption was confirmed during tests in the Systems Integration Laboratory (SIL) at NASA Ames and on-sky (c.f. Sec. 4.3) as pointing calibrations based on a WFI⁺ solution placed markers on the outer rim of star images in the FPI⁺. Note that the PSF on SOFIA at visible wavelengths is limited to $\approx 3.5 - 5$ arcsec due to shear layer seeing over the cavity;⁵ this means a WFI⁺ solution allows pointing calibration with an accuracy of about 2 – 3 arcsec. We also tested the impact of saturated stars on the accuracy of a solution: We manually removed saturated stars from the extracted source lists (the code is robust against missing source detections given that enough context data is in the field), and compared the RMS stellar position deviation between the solutions that included and that excluded saturated stars. The RMS differed by less than 1 arcsec.

Second, using the logged GPS time stamps of two consecutive images, we calculated how far the image center coordinate should have moved due to the Earth’s rotation, and subtracted the difference between *astrometry.net*’s center coordinate estimates in both images. The result fluctuates around zero with a standard deviation of 1.13 arcsec, i.e. less than $\frac{1}{25}$ th of a pixel, a value that is well within the centroids’ positional uncertainty. This demonstrates that pointing estimates done by *astrometry.net* are very consistent.

4. IMPLEMENTATION ON SOFIA

4.1 Porting the Code to Solaris 10

Six workstations on-board SOFIA provide a graphical user interface (GUI) to the MCCS for control and monitoring: Two workstations for telescope operators (Figure 1), one for the mission director, one for the flight planner and two for education and public outreach purposes. These workstations are running Solaris 10 Release 8/11 on an x64 platform (little endian[‡]). As the workstations are mainly used for displaying the Java-based GUI to the MCCS and have sufficient resources left to run *astrometry.net*, it was decided to install and run the package locally on every workstation. If the user decides to plate solve an image, the latest exposure from the tracking camera gets written into a FITS file before `solve-field` is called.

[‡]Note that the index files offered by the *astrometry.net* project are built for little endian architectures; on a big endian architecture such as SPARC, the index files would need to be rebuilt.

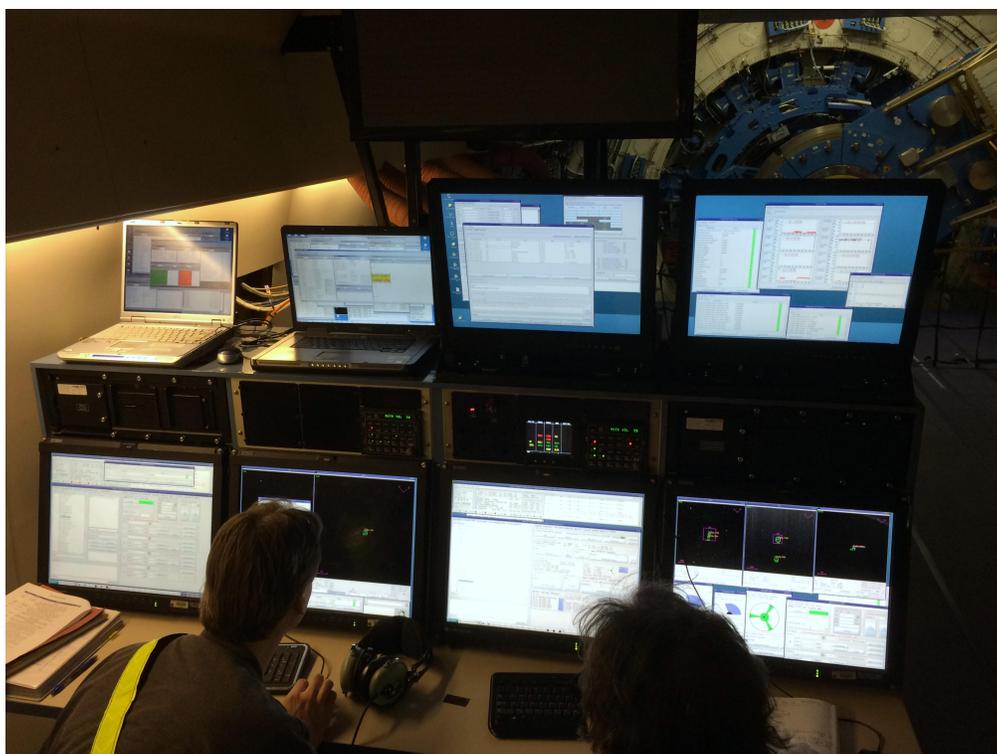


Figure 1. The two MCCS workstations for the telescope operators on-board SOFIA, during ground tests of the *astrometry.net* implementation on March 28, 2016. The pressure bulkhead with the SOFIA telescope can be seen in the background.

We had previously compiled the *astrometry.net* source code on Ubuntu 14.04 LTS and 10.04 LTS, on macOS, and in a Cygwin environment on Windows 7. The *astrometry.net* website and Google group reports about successful installations on FreeBSD and other Linux distributions such as RedHat, RHEL, Fedora and CentOS. Unfortunately, compiling the source code on Solaris 10 was not as straight-forward as initially thought. For testing and development purposes, a virtual machine (VM) of Oracle Solaris 10 Release 1/13 was setup on a Windows 7 64 bit host machine using Oracle VM VirtualBox. This was straight forward as a VM template for Solaris 10 is readily available for download from Oracle for development purposes.

Porting *astrometry.net* to Solaris 10 revealed some minor POSIX nonconformities of system function calls, and some incompatibilities of the Solaris 10 operating system to other main stream Linux & Unix distributions in terms of system header files, missing symbol definitions, missing functions, and different syntax and functionality of standard shell tools. All findings lead to various minor source code improvements that have been incorporated in *astrometry.net* release v0.65 to make platform portability to less common Unix-like operation systems even more robust. The *astrometry.net* package requires a number of other packages that are readily available on current Linux operating systems. In contrast, Oracle's support of free and open source software in Solaris 10 is extremely limited; none of the software packages that are necessary to run *astrometry.net* can be obtained directly through Oracle. The community-driven software repository "OpenCSW"[§] was an immense help to find most required packages. It provides precompiled binary packages and source packages in the Solaris-native SVR4 format for many popular open source software projects. This was essential, as porting all prerequisite packages required by *astrometry.net* to Solaris would have been a major undertaking. From OpenCSW, we installed a number of GNU (*gmake*, *gawk*, *gcc4core*, *gcc4gfortran*) and other open source software packages (*swig*, *netpbm*, *libnetpbm_dev*, *libcairo2*, *libcairo_dev*, *python27*, *python27_dev*, *py-numpy*, *py-pip*, *fontconfig*), including their dependent packages, that were required to build and run the code with full functionality (i.e. plotting

[§]<http://www.opencsw.org>

capability, image preprocessing for source extraction in Python, *Netpbm* for source extraction). Note that all packages related to *Netpbm*, *Cairo* and Python are used by auxiliary functions, not by the core solver for pattern recognition. We decided to install *astrometry.net* with full functionality on the MCCS workstations; this might allow various other uses in the future (e.g. use of the plotting capabilities) and avoided creating a “SOFIA specific” subrelease, f.e. by attempting to replace source extraction. In addition, we manually compiled three other required packages: The *CFITSIO* library (NASA’s standard library for reading and writing FITS files), the freeware version of the “file” command known from Linux and FreeBSD operating systems (due to syntax and output incompatibilities of Solaris’ own file command) and the *PyFITS* v3.3.0 library (its successor *astropy* can be used as well). In addition to installing all prerequisites, a number of Solaris 10-specific changes to a few Makefiles had to be made, as much as resolving a name conflict of two data type definitions in the *astrometry.net* code with definitions in Solaris’ system header files not common on other Unix- or Linux-platforms. The whole procedure to compile the package on Solaris 10 is summarized in a technical report.¹⁴

After finishing, documenting and verifying all required steps to compile the code in the VM, the *astrometry.net* package was recompiled on a Solaris developer workstation with similar hardware as the MCCS workstations, and successfully tested in the SIL. Eventually, an installation DVD including all prerequisites, binaries and catalog files (described in the next section) was prepared, tested, and deployed for installation on all workstations on-board SOFIA.

4.2 Catalog Selection

To solve an image, we are using index files (hash tables) that are based on the Tycho-2 catalog. The structure of the index files used on SOFIA is explained in Table 3. Tycho-2 is assessed to be 99% complete down to $V = 11$ mag, and 90% complete down to $V = 11.5$ mag[¶]; it contains about 2.5 million stars. It is also the most accurate catalog that is currently available (6 mas astrometric standard error up to $V = 9$ mag, 60 mas general accuracy), only to be superseded by the first GAIA data release later this year. Although our initial goal was to solve WFI images, it became immediately clear that the Tycho-2 catalog is also the perfect choice for solving FFI images as the catalog’s limiting magnitude (or “depth”) is well matched to the sensitivity of both tracking cameras. The *astrometry.net* project publicly distributes index files that have been generated from the Tycho-2 catalog^{||} on scales no. 19 – 7 (c.f. Table 3), i.e. down to 22 arcmin quad size. On smaller scales, “quads” can no longer be built in the entire sky, as certain areas are sparse of Tycho-2 stars. The code that has been used to build the Tycho-2 indices from the original catalog is distributed with the *astrometry.net* package and allows the user to build custom index files.

There is no formal requirement which quad scales need to be searched to solve an image, but usually, a lower scale of 15 – 20% of the respective field size is recommended. Check marks in Table 3 indicate which Tycho-2 index files are searched during a plate solve of a WFI, a FFI, and prospectively, a WFI+ image. The searched index files cover 11.5% – 100% of the WFI’s field, and 23.8% – 100% of the FFI’s field. For the FFI, we have built an additional index on scale no. 6 to cover quads down to 16 arcmin in size. As the sky becomes sparse of Tycho-2 stars at this scale, a number of sky patches (healpix grid cells) of 16×16 arcmin² size exist that do not contain a single Tycho-2 star ($\approx 6\%$ of the entire sky), while only $\approx 10\%$ of the cells contain 10 or more Tycho-2 stars from which a large number of quads can be comfortably built. In $\approx 86\%$ of the cells, at least one quad could be found that can be used for pattern matching. Therefore, we concluded that adding an index of scale no. 6 still contributes meaningful pattern information to most FFI fields, but it does not add searchable features “all-sky” anymore. Due to the distribution of Tycho-2 stars in the sky, it is not meaningful to generate indices at even smaller scales, as sky coverage of catalog quads would be even less. The only solution to have a better coverage of searchable features at smaller scales would be to increase the FFI’s sensitivity, which will be achieved with the imager upgrade.

For the WFI, we found that most images solve already based on a quad found in the index with scale no. 13, indexing quads about half of the WFI’s field size; the solver almost never searches indices containing smaller quads. This is likely due to the large field size and good distribution of Tycho-2 stars on WFI field scales. For the FFI, we see successful solves based on indices no. 9 – 7, the later indexing quads about 32.7% of the FFI’s field

[¶]<http://cdsarc.u-strasbg.fr/viz-bin/Cat?I/259>

^{||}<http://data.astrometry.net/4100/>

Table 3. Index files generated from the Tycho-2 catalog that are required to solve WFI, FFI and future WFI⁺ images, including the scale of “quads” they contain, the scale number used internally by the code for the given range, and file size of each index file.

Range of skymark diameter		Scale	File size	WFI	FFI	WFI ⁺
arcmin	deg	No.	MB			
480 – 680	8.00 – 11.33	16	0.39			✓
340 – 480	5.67 – 8.00	15	0.71	✓		✓
240 – 340	4.00 – 5.67	14	1.32	✓		✓
170 – 240	2.83 – 4.00	13	2.61	✓		✓
120 – 170	2.00 – 2.83	12	5.05	✓		✓
85 – 120	1.42 – 2.00	11	9.73	✓		✓
60 – 85	1.00 – 1.42	10	23.72	✓	✓	✓
42 – 60	0.70 – 1.00	9	47.47	✓	✓	
30 – 42	0.50 – 0.70	8	90.17		✓	
22 – 30	0.37 – 0.50	7	157.35		✓	
16 – 22	0.27 – 0.37	6 ¹	219.56		✓	
Amount to search (MB)				90.60	538.27	43.53

¹ Built to amend the publicly distributed Tycho-2 index files, using the `build-astrometry-index` program distributed with the package. See text for details.

size. Depending on the image, smaller features are required for pattern recognition, as Tycho-2 stars are not as homogeneously distributed among the sky anymore on FFI field scales. The solver did not utilize the additional index file at scale no. 6 in our tests with FFI images; we included it nonetheless to meet the recommended lower index scale that should be available for searches. Given the small size of the index files of interest, all of them can be loaded into memory and then checked in parallel for features^{**}, further speeding up pattern recognition.

4.3 Extension to the FFI and Results

Tests of *astrometry.net* in the SIL and during a ground-based test campaign on SOFIA in Palmdale (“line ops”) end of March 2016 demonstrated that telescope pointing can be calibrated with sufficient accuracy based on a solved WFI image. Given that the current WFI and FFI are uncooled and were running at about 20°C that night, image quality was much degraded compared to images taken at temperatures in the stratosphere; WFI images solved successfully nonetheless. The solution obtained with the WFI is accurate enough to mark known stars directly in the much higher resolved FFI⁺ field, placing markers already on the rim or inside of stars seen in the FFI⁺. Areas of interest (AOIs) defined to monitor guide stars are well positioned in FFI⁺ images to such accuracy that they can be immediately centered on the star’s centroid, allowing a very quick refinement of the pointing based on FFI⁺ image data. Run time of a `solve-field` command on the MCCS workstations is below 2 s for a WFI image.

Having demonstrated its capabilities in the WFI, it was decided to extend *astrometry.net*’s plate solving to the FFI right away.¹⁵ Tests showed that a “blind” calibration of a FFI image, only constraining plate scale, is only slightly slower compared to solving a WFI image blind. As the resolution of the FFI is about 5× higher than of the WFI, it would obviously be the preferred imager for pattern recognition: The derived pointing estimate would be even more accurate, as centroid positions of stars can be measured more accurately.

However, as previously explained, the FFI is badly defocused in the first 2 – 3 h in flight while it cools down to stratospheric temperatures. During this time, stars are so much out of focus that they appear as small

^{**}To search index files in parallel, the `INPARALLEL` flag in `astrometry.cfg` needs to be set. Note that `solve-field` currently only obeys a given CPU time out limit specified by `-1 <seconds>` if the `INPARALLEL` flag is activated.

“donuts” and can not be used for tracking. We retrieved a number of such defocused FFI images taken early in flight from the archive and solved them successfully with *astrometry.net*. As long as enough sources can be extracted in the field, the FFI’s defocus appears to be no issue for pattern matching, illustrating once again the great robustness of the algorithm. Downsampling the image by a factor of 2 as explained in Sec. 3.1 also seems to provide sufficient binning to derive centroid positions from “donuts” that are sufficiently accurate for pattern recognition. However, defocus reduces the sensitivity of the FFI, reducing the number of available sources. Also, the reduced centroid accuracy obtained from a defocused image likely propagates into the accuracy of the image center coordinate estimate, compensating the FFI’s advantage in resolution.

While the WFI is normally running with a fixed exposure time during the entire flight, the FFI is occasionally used for tracking on a guide star. Doing so, exposure times are adjusted towards the brightness of the chosen guide star. If the guide star is too bright, a neutral density filter is used. Both measures also reduce the number of recorded sources in the image.

Being in focus and operated with nominal exposure times, the current FFI records a sufficient number of stars to allow for a successful pattern recognition with *astrometry.net*. However, due to its defocus issue and occasional use for tracking, a sufficient number of field stars can not be guaranteed at all times. In such a (very rare) situation, pattern recognition could in principle fail. In contrast, the WFI will always see enough stars to guarantee successful pattern recognition. To ensure a 100% availability of the tool, we decided to solve images from both tracking cameras recursively, at least until they are upgraded. To reduce run time, we are using the solution obtained from the WFI to solve the FFI image with a search radius of slightly more than half of the FFI’s field diagonal. Should the FFI be operating under conditions that would not allow to record a sufficient number of stars to recognize their pattern, we fall back on the WFI solution after `solve-field` times out after 6 seconds. If the FFI solution is successful, it supersedes the WFI solution to calibrate telescope pointing.

The MCCS GUI was extended with a new panel illustrated in Figure 2 to provide access to *astrometry.net*’s image calibration. By default, a WFI image is plate solved every 60 s. The GUI displays right ascension, declination and rotation of field as obtained from the latest solution. In addition to the ‘continuous mode’, the telescope operator can choose to solve a WFI image at any time, and execute a pointing calibration (“`coord.correct`”) based on the latest result. In the same manner, a recursive WFI-FFI plate solve can be executed at any time and used to calibrate telescope pointing.

5. FUTURE WORK

The availability of *astrometry.net* offers some interesting perspectives for SOFIA. It appears quite straight forward to extend plate solving capabilities towards the FFI⁺; successful solving would be limited to fields that contain a sufficient number of stars to recognize their pattern. To solve such a small field, an index down to a quad scale of at least 2.0 arcmin (scale no. 0) is required, resulting in a much larger index size. To solve the field as fast as possible and to reduce index size, the index should be optimized towards the FFI⁺’s limiting magnitude. UCAC4, the 4th USNO CCD Astrograph Catalog, appears as a good choice as its depth (complete down to $R \approx 16.3$) is well matched to the limiting magnitude of the FFI⁺.

With the anticipated upgrade of the WFI and FFI in 2017, the current implementation of *astrometry.net* will be revisited. For the WFI⁺ (c.f. Table 1), the Tycho-2 index files still provide the optimal database for pattern matching, while the amount of indices that need to be searched can be further reduced given the increased field size (c.f. Table 3). For the FFI⁺; a deeper catalog than Tycho-2 should be used to provide sufficient pattern context information, matching the increased sensitivity of the imager. Again, an index based on the UCAC4 catalog, at features scales appropriate for the FFI⁺ field, appears to be a good choice. As the camera controllers for the new FFI⁺ and WFI⁺ will be running on Ubuntu Linux, it would then be possible to run *astrometry.net* directly on each camera controller and provide relevant results of a plate solve via housekeeping data, instead of running `solve-field` on each MCCS workstation individually.

Index files based on the UCAC4 catalog have been created¹⁶ and successfully tested with FFI⁺ images. However, it came to our attention that UCAC4 contains spurious sources caused by “streak stars”, present in a 30° radius around the galactic center^{††}, and by diffraction spikes. Filtering such spurious entries based on the

^{††}http://www.ap-i.net/skychart/en/news/ucac4_streak

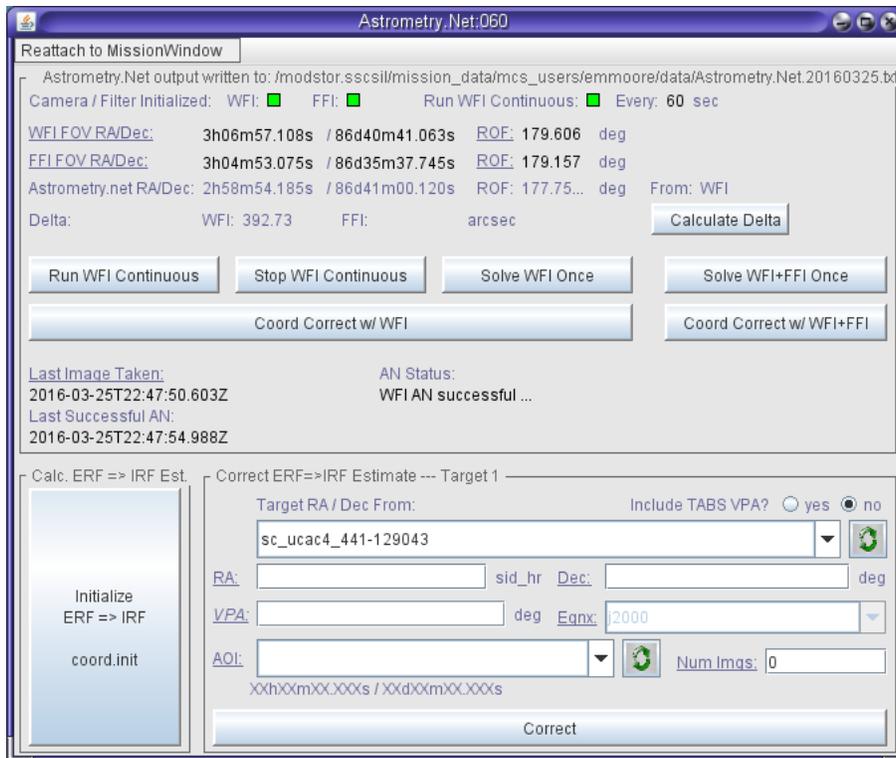


Figure 2. The new MCCS GUI panel, offering the telescope operator to solve WFI and FFI images with *astrometry.net*.

“object type” flag is not possible, as sources flagged as spurious (“2”) were often relabeled by a higher value, indicating other issues like a problematic proper motion solution. For the generation of the USNO-B1.0 index files* that the nova.astrometry.net web service is using, the USNO-B1.0 catalog was “cleaned” of spurious entries caused by diffraction spikes and reflection halos using computer vision techniques^{17††}. A similar “clean-up” of the UCAC4 catalog might be required. Alternatively, a magnitude-limited subset of the cleaned USNO-B1.0 catalog, tuned respectively for the limiting magnitude of the FFI⁺ and FPI⁺, could find use for plate solving images from both tracking cameras in the future.

Unwanted reflections in the SOFIA telescope assembly can cause a variety of ghost images; an example of a prominent ghost due to a very bright star nearby can be seen in the solved image in Figure 3, Sec. 6.2. Some ghost images, primarily those caused by internal reflections on the dichroic tertiary mirror, appear as a regular star in the field and could therefore be mistakenly selected as a guide star; this needs to be avoided as tracking on a ghost would be compromised. The *astrometry.net* solution could immediately allow identification of all “real” sources in an image by marking them in an overlay plot, isolating possible ghost images or moving targets such as asteroids that should not be selected for tracking.

The installation of the upgraded tracking cameras and their alignment with the optical axis of the SOFIA telescope will certainly benefit from an astrometric image calibration that can be conducted ad-hoc on the sky. Solving images taken simultaneously by all three cameras allows to study temperature induced flexure in alignment, as temperatures vary greatly between conditions on the ground in Palmdale and in the stratosphere. Verification of long term imager alignment stability would be easily possible, too.

At this moment, we are using the *astrometry.net* package “as is”; this was a pragmatic and practical solution, but is not optimal in terms of run time. Some code optimizations would allow to speed up pattern recognition;

*Index files that have been generated from USNO-B1.0 are available from the *astrometry.net* project upon request under special licensing terms.

††<http://astrometry.net/cleanusnob/>

while improvements could be marginal for WFI images, they could become more important towards FPI⁺ images. Image preprocessing could be accelerated being implemented with C code instead of using the Python interpreter. Modularity of the current code dictates f.e. to write an x, y list of extracted sources to disk, which is then read again by the core solver; other temporary files are written to the /tmp folder which could be avoided as well. Instead of reading a FITS file from disk, the code could use an image that is already in memory, applying a seamless integration of source extraction and avoiding unnecessary I/O to a disk drive. Although subsequent calls of `solve-field` make use of index files that have already been cached in memory, the `solve-field` process is currently terminated after each image. Once started, it could be kept idling instead of terminating, waiting for the next image in memory.

6. OTHER USE CASES

Besides of being a new tool supporting telescope pointing calibration on SOFIA, the *astrometry.net* package has a number of use cases at DSI. We deployed several setups of *astrometry.net* v0.67 running in a Cygwin environment on Windows 7¹⁸ or natively on macOS and Ubuntu.

6.1 FPI⁺ Level 3 Data Products

The upgraded Focal Plane Imager (FPI⁺) has been transformed into a Facility Class science instrument and is available to general investigators since Cycle 4.¹⁹ Raw and calibrated data products are available through the SOFIA Data Cycle System (DCS). The flux calibrated Level 3 data products also contain World Coordinate System (WCS) information in the FITS file header, which are added based on the astrometric calibration conducted with *astrometry.net*.

6.2 Multi-Platform GUI

To allow quick astrometric data reduction, a GUI for the `solve-field` command has been developed at DSI on the basis of Python and PyQt4. Figure 3 presents a screenshot of the GUI. It allows quick access to all common parameters, batch mode processing, selection of predefined plate scale limits for commonly solved images, and choice of a desired catalog. It also allows the extraction of RA, Dec values logged in the FITS header (i.e. commanded telescope position) to use them as an initial guess, if available, or to solve the first image of an image series entirely blind and to apply results for plate scale, parity and field center as a constraint to solve the remaining images faster. Although `solve-field` is able to solve every image blind, constraining limits of plate scale and pointing significantly speeds up solving narrow fields. The GUI finds use among DSI's staff on various computers running Windows, macOS and Ubuntu. We plan to install this GUI also on the FPI⁺ science laptop that is used to control the operating parameters of the FPI⁺ during scientific observations on SOFIA.

6.3 ATUS: The 0.6 m Astronomical Telescope of the University of Stuttgart

In collaboration with the University of Stuttgart, DSI is operating the remotely controlled 0.6 m “ATUS” telescope[†]. The combination of a long focal length with a relatively small sensor in our prime camera, again an Andor iXon DU-888 EMCCD camera (1024 × 1024 pixels, 13 μm), leads to a narrow field (about 9.6² arcmin²). *Astrometry.net* plays an essential role for astrometric calibration of data that feeds into our pointing model to correct systematic pointing and tracking errors, caused by instrument flexure, polar misalignment and non-orthogonality between axes. Telescope pointing is routinely verified after a critical slew on a target of interest, i.e. a star to be observed during an occultation. Having used *astrometry.net* to successfully calibrate thousands of such narrow images blind, aside of calibrating large image series taken with the ATUS wide field imager (a FLI ProLine 4720 CCD camera with a Canon 135mm f/2.8 lens focused remotely, having a 5.63° FOV), reinforced our confidence that *astrometry.net* is the right tool for SOFIA. Aside of building a pointing model and supporting regular operations, *astrometry.net* is used for data processing and lab work by students using the telescope. The free software package *AstroImageJ*^{20,21} offers plate solving through the nova.astrometry.net API and through a local nova.astrometry.net server emulation running in Cygwin, enabled by the *ansvr* package[‡] written by A. Galasso. The combination of *AstroImageJ* and *ansvr* is f.e. installed on the lab workstations in Stuttgart that students use to control the telescope and to reduce their acquired data.

[†]<http://www.dsi.uni-stuttgart.de/forschung/atus.html>

[‡]<http://adgsoftware.com/ansvr/>

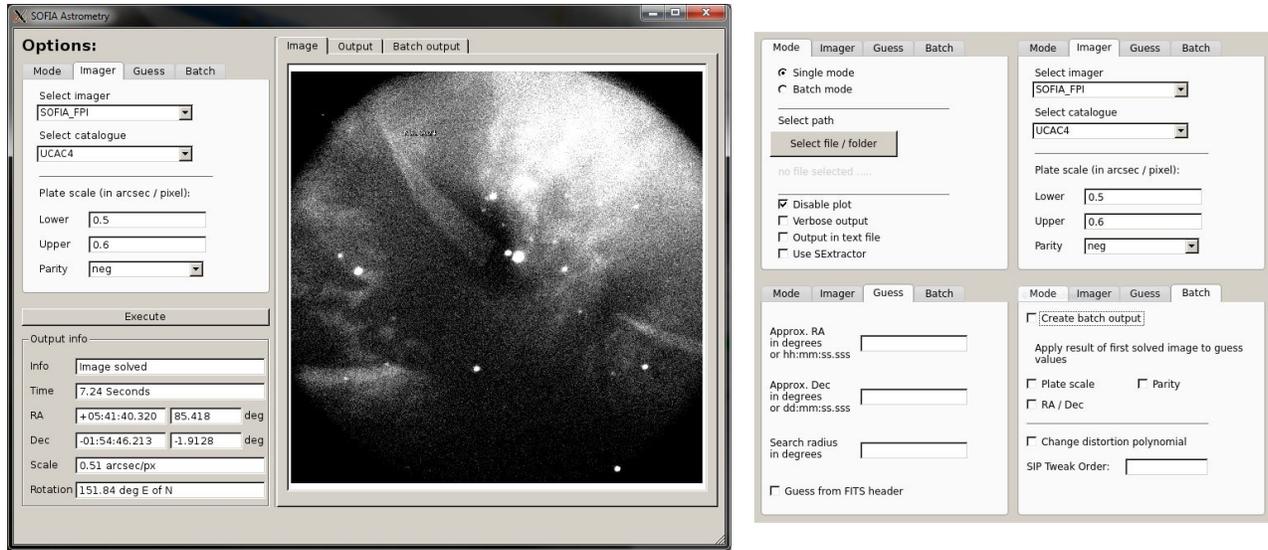


Figure 3. A GUI frontend for `solve-field` developed using Python and PyQt4, running in a Cygwin environment on Windows. The GUI is also used on macOS and Ubuntu.

7. CONCLUSIONS

Automated astrometric image calibration has become a standard practice in astronomy. The open-source project *astrometry.net* has excessively demonstrated its reliability to solve images without any a-priori information, i.e. completely “blind”. Its compatibility to Linux and Unix systems made it an obvious choice for implementation on SOFIA. We successfully ported the code to Solars 10, installed the package on the MCCS workstations on-board SOFIA and added some functionality to the MCCS GUI that allows solving of a WFI and a FFI image. Especially now that SOFIA is in its third Southern Hemisphere deployment, the telescope operator has a tool at hand that he can rely on to quickly calibrate telescope pointing based on Wide Field Imager data, especially in difficult crowded fields. This tool could potentially save a significant number of valuable minutes on every SOFIA flight in favor of collecting more science data, further increasing the efficiency of the observatory. Once the imager update is completed, the much increased sensitivity and improved image quality of the FFI⁺ will likely make it the prime choice for astrometric plate solving with *astrometry.net*. We plan to extend the implementation of *astrometry.net* towards solving FPI⁺ images and potential other use cases; f.e. to provide a tool that helps to identify ghost images.

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