# History of the UCAC Astrograph

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February 2012

The telescope used for the United States Naval Observatory CCD Astrograph Catalog (UCAC) project was originally a twin astrograph built by Boller & Chivens in 1970. This earlier version of the telescope, known as the USNO Twin Astrograph, used two 8-inch lenses (one designed for the yellow spectral band pass and the other for the blue) and took 8-inch by 10-inch glass photographic plates [1]. The Twin Astrograph was used in the first half of the 1980's to take plates from Washington DC to form the northern part (+90° to −18° declination) of what was intended to be the full-sky Twin Astrographic Catalog (TAC) [2]. In 1986, the telescope was then moved to the USNO station in New Zealand[1] to take plates of the southern hemisphere sky. Due to problems with the telescope and budgetary issues, the southern part of TAC was never completed. Instead, the telescope was used to observe selected fields around quasars to assist in the tie of the optical to the radio reference frame [3,4]. In this process about 1/3 of the southern sky was covered to a limiting magnitude of about R = 14. These observations were later also used to improve the proper motions of UCAC [5]. The telescope was moved back to Washington in 1990 and put in storage.

While the astrograph was still in New Zealand, there were plans to make a number of upgrades to the way the focus was set and to use a new 5-element lens designed for the red spectral band pass; this would eliminate the need to take two photographic plates for each field. The University of Arizona was contracted to build the lens. Although the project in New Zealand was cancelled before the red lens could be delivered, the contract for the lens could not be cancelled and the lens arrived at USNO in 1992. Steve Gauss, head of the Astrometry Department at that time, wanted the new lens tested before accepting it and asked Ted Rafferty to do it. Rafferty suggested the best method would be to set up the astrograph in Washington and take 8 inch by 10 inch photograph plates of a star field to test the performance of the new lens. The dome used for the northern hemisphere TAC had not been used since the astrograph was sent to New Zealand, so it was available. Gauss agreed to test the red lens on the astrograph and to install it back in the TAC dome.

The test results using photographic plates showed the new red lens was excellent and it was apparent that a new project should be done with the telescope. A decision had to be made whether the project should be done using photographic plates or a CCD. Up until that time, the CCD chips were too small to include enough reference stars to determine accurate positions, but a 4K by 4K CCD with 9 micron pixels was soon to become available. Also, ESA was to release its Tycho Catalog in 1997, which would provide the necessary increase in density of reference stars. A test camera using a Kodak 1K by 1.5K CCD chip was ordered that had the same pixel size and characteristics as the 4K by 4K chip. The test CCD camera was mounted on one of the plate holders for the astrograph, so we could easily switch from taking plates to taking CCD images during the same night. The control computer was set up in a small shed next to the telescope dome. During the early testing sessions,

[1] the Black Birch Astrometric Observatory, located outside the city of Blenheim on the northern end of the South Island

the telescope was not yet automated, so one person would need to be at the computer and another out in the dome with the telescope, which was usually Norbert Zacharais at the computer and Ted Rafferty out with the telescope. After some changes were implemented by Rafferty inside the dome, an exposure was taken. Rafferty would then run around the corner and stick his head into the control room asking "how does it look?", while Norbert Zacharias would always reply "still reading out", since it took over a minute to read and display the small (by modern standards) image. At the end of the night a 50 yard network cable had to be rolled out between the control room and a nearby building to download the observing data to a workstation to do reductions and to backup the images. After that the cable had to be rolled back up again; otherwise it likely would have been chewed on by the deer on the USNO grounds. After a few test runs, it was clear the CCD results were much better than those from the photographic plates, and plans to use plates were abandoned [6,7].

A team made up of Norbert and Marion Zacharias, Marvin Germain, Ellis Holdenried, and Ted Rafferty started working on getting the astrograph ready for a pole-to-pole astrometric survey, to be called the USNO CCD Astrograph Catalog (UCAC) [8,9]. The team received support from the Instrument Shop (particularly John Pohlman and Gary Wieder), the department's electronic technician, Charles Carpenter, and Lars Winter of the Hamburg Observatory. The Zacharias's mainly focused on getting the necessary software ready for astrometric reductions of the CCD exposures, with Lars Winter also playing an important role in that effort. Germain designed the electronics for the telescope controls, and Germain and Holdenried wrote the necessary interface software. Rafferty mainly worked with the Instrument Shop on the mechanical parts of the telescope. From time to time, Steve Gauss helped with the computer interface. Some input was also provided by Christian deVegt of the Hamburg Observatory in Germany.

It was decided to use original motors and electronics for the Boller & Chivens mount and add the necessary hardware and electronics to allow the telescope to be controlled by a computer. Although the original motors and electronics were 25 years old at the time and replacement parts were no longer available, there was no time and money to upgrade them all.

The plan was to get the astrograph working in Washington DC before shipping it to Cerro Tololo International Observatory (CTIO) in Chile to observe the southern hemisphere. Ken Seidelmann was involved in working out a memorandum of understanding between USNO and CTIO. CTIO had a dome housing a 16-inch reflector they were currently not using where the astrograph could be put. The dome would be a tight fit for the astrograph, but the drawings of the dome that CTIO sent showed it should fit.

Progress was slowed when Germain left Washington to work on USNO's NPOI in Flagstaff and Holdenried had to take over programming the telescope controls. There was also a problem that the telescope controls would often crash, causing the computer to reboot. The source of this problem was never determined while the astrograph was in Washington. The 4K by 4K CCD camera also had a few problems. For example, the computer would sometimes timeout while reading out the CCD chip. Steve Gauss worked on the problem and found that the images from the camera were being scanned by a virus checker on the PC being used. Once the virus checker was removed the problems reading out the chip almost disappeared. A more significant problem involved the Charge Transfer Efficiency (CTE) of the CCD chip. Although of high cosmetic quality, our 16 million pixel detector with a single readout register had poor CTE. This caused the images of the stars to be smeared as a function of distance from the readout register and magnitude of the stars, leading to a coma-like effect degrading the observed positions of the stars. This was about the worst problem one could have for astrometry. It was seriously considered to cancel the project or at least to delay it until a better detector could be obtained. However, it was decided to move forward, with the plan to take out most of the effect in software later on. It was also found that altering the operating temperature would somewhat mitigate the problem. The camera was built to operate at $-30°$ C, but if the operating temperature was raised to about $-18°$ C the CTE effect was reduced to a more manageable level; however this was at the expense of a higher dark current, which prevented taking exposures longer than about 200 seconds.

By the latter part of 1997, arrangements were completed with CTIO and the astrograph was packed up for shipment to Chile. Norbert and Marion Zacharias arranged to stay in Chile to oversee operations of the astrograph and they departed for CTIO in December of 1997. Holdenried, Wieder, and Rafferty left for CTIO in early January, 1998.

The dome had to be lifted off to allow the astrograph to be lifted in. Within three days the telescope was put together and it was discovered it would hit a dome motor when pointed far north of the zenith. Rafferty discussed with Oscar Saa, the CTIO site manager, what options were available and decided the easiest solution would be to raise the dome by 17 inches. Saa had his people build a wooden ring for this purpose, which they built and installed in just three days.

Other than the problem with the dome, getting the telescope operational went very smoothly. Norbert and Marion Zacharias stayed at CTIO for a year and a half to observe, work on the reduction pipeline, improve the observing procedures, and train the Chilean telescope operators. The operations manual kept expanding and even a year into the program situations or error conditions came up which had not experienced before and solutions had to be tested and documented.

Holdenried and Rafferty would go down to CTIO from time to time to do maintenance on the telescope control software and hardware. Since the plan was to link the star positions determined by the astrograph to the International Celestial Reference Frame (ICRF), observations of those quasars were needed, which were made using the CTIO 0.9m reflector. At the same time those fields were covered with the astrograph with multiple exposures and utilizing East-West flip of the telescope to provide well calibrated reference stars for the deep CCD images of the 0.9m telescope at the same epoch, avoiding issues with unknown proper motions of medium bright link stars. These radio-optical reference frame (RORF) observations were carried out about 3 to 4 times per year following the general UCAC survey coverage on the sky [10,11].

The focus of the UCAC astrograph was done automatically using a four-hole Hartmann screen. The telescope would point to a nearby bright star, and close the Hartmann screen over the front of the lens. A motor would adjust the focus so it was somewhat off where the best focus was assumed to be. The setting of the focus was determined using a linear Sony encoder. A short exposure would be taken and the focus would be moved a little closer to the assumed best focus for another short exposure. The focus would then be moved to the other side of the assumed best focus and two exposures taken at two different settings of the focus. The distances between star images created by the Hartmann screen varied linearly as a function of the focus setting, so doing a least square solution of the separations and focus settings yielded the best focus setting, which the focus of the telescope would then be set to. This process was done automatically under computer control and it took about five minutes to make a focus determination in this way with extremely accurate result. Only one pair of holes was required for a focus determination while the second pair of holes, orthogonal to the first pair and with slightly different spacing, served as a consistency check.

Four computers were used for the UCAC program [12]. There was a single board computer (SBC) used to operate the functions of the telescope and mount. The SBC was located in an electronics rack out in the dome next to the mount. A PC, running Windows 95, was used to send commands to the SBC and operate the CCD camera. After an exposure was taken by the CCD camera, the image was transferred over to an HP workstation, where a “quick-look” reduction pipeline would run to provide feedback to the observer within a minute. The workstation also did the final raw data reductions on the night’s worth of data the next day and the backup of images onto two 8mm tapes running in parallel for about 2 hours. A second PC was used to backup the images onto CD’s (later DVD’s). The early writable CDs cost about $10 each and ran at a whopping 1x speed, which allowed the backup of the previous night’s data (about 4 CDs) to be completed by the observer during the next night.

The yellow lens was used as the guide scope with an SBIG ST4 auto guider. The ST4 was mounted on an X/Y slide so it could be moved to different parts of the field. For each field we were going to image with the 4K camera, we knew the position of the brighter stars to be used as guide stars. When a field was selected, the position of the ST4 was moved using the X/Y slide, which was motorized and had encoders on both axes. If the star was not located in the center of view of the ST4, the telescope would be moved so it was centered. Using this method, the telescope could be pointed with an accuracy of about 30 arcseconds. This was all done automatically and ensured that the fields taken with the 4K camera had the desired overlap with the fields around it.

At the beginning of a shift the observer would check on the completion of the daily reductions and run some code which generated an observing list based on the entire observing history performed so far. The night would start with the telescope operator opening the dome and turning on all the equipment. Once it was dark enough, the operator would manually point the telescope at a known bright star using an eyepiece on the guide scope and sync the RA and Dec counters to this known pointing. A focus determination was then made and observing the program fields could start. The telescope would point to the desired field, the ST4 was positioned with the X/Y slide, the guide star was centered in the ST4 and the auto guiding was started. Two exposures were taken of each field. One exposure was long (100, 125, or 150 seconds, depending on the sky conditions) that reached around 16th magnitude. The other exposure was a factor of five shorter than the long exposure. It took about 17 seconds to read out the CCD chip and a few seconds more to FTP the image over to the workstation. While the next exposure was being made, the workstation would check the previous exposure and display a one line summery of the results of the previous dozen exposures. These reductions included a match to the Tycho reference stars and information was listed about mean background level and noise, number of stars detected, how round the star images were, the average full width at half maximum (FWHM) of the star profiles and limiting and saturation magnitude. The telescope operator would monitor these lines as they came out for each exposure and could tell if the guiding was good (from the roundness of the star images), if the temperature–dependent focus needed to be reset (from the FWHM), or if clouds or haze were moving in (from the background level and magnitudes).

The focus was measured about 5 to 10 times a night, with more frequent measurements made at the start of the night (fewer measurements were needed in the second half of the night, when the temperature typically stabilized). The fields to be selected were observed automatically, with the observer interrupting the auto-mode only if a new focus was needed, the exposure time needed to be changed, a special field needed observing, or a problem came up. A few times a night the direct memory access readout of the CCD would fail and the exposure would be repeated automatically. About once a night the Windows OS would hang up and a re-start of the control PC was needed. Sometimes a reboot of the SBC was needed. When everything was running normally, which was often the case, the telescope operator had little to do except to watch the data displayed on the workstation. At those times the observer could attend to the second PC to make backups onto CDs and monitor the weather.

The original project plan was for the astrograph to be at CTIO for two years and cover the sky from the South Pole to $-5°$ declination, with Norbert and Marion Zacharias staying at CTIO for that entire period to oversee the project. The operation of the project at CTIO was running so smoothly that the Zacharias's returned to Washington DC after a year and a half, and had the astrograph continue observing for an additional year and a half beyond the planned two years. This allowed the astrograph to observe about as much of the sky as was possible from the CTIO location. When the telescope was shut down on Sept 19 2001 at CTIO, it had complete sky coverage from the South Pole to $+24°$ declination, with some areas of right ascension having coverage to $+32°$ declination. This is about 74% of the entire sky.

While the astrograph was at CTIO, plans were being made as to where it would be located in the northern hemisphere for the northern half of the program. Ideally a location with similar conditions to those in Chile was desirable. Following a suggestion by Dr. deVegt, USNO started looking into making arrangements to move the telescope to Tenerife in the Canary Islands. Most of the details were worked out, but the plan had to be approved by the government of Spain and they delayed making a decision so long that it was decided to look elsewhere, since the observing in Chile were nearly completed.

When it became clear the telescope could not go to the Canary Islands, sites in California (one near Monterey and the other at Lick) were checked. In both cases arrangements looked promising, but once again delays caused those plans to be abandoned. Because time was running out, it was decided to move the astrograph to the USNO station (NOFS) in Flagstaff, Arizona, where it would be much easier to make arrangements. The seasonal weather patterns in Flagstaff meant it would take longer to complete the observing in the northern hemisphere, but no other choice was available. NOFS had recently given away a

16-inch telescope, which freed up a dome that was the correct size for the astrograph. The height of the pier had to be lowered, and John Pohlman and Gary Wieder build and installed a plate on the top of the pier for the astrograph mount to be used at that latitude.

By September 2001, the observing program at CTIO would be completed and the astrograph had to be moved to Flagstaff before the start of winter. The original plan was for the Zacharias's and Rafferty to travel to CTIO on September 13 2001, and for Gary Wieder to follow on September 16th. This would have allowed for calibration observations with the CCD camera rotated 90 degrees on the astrograph for the nights of September 14, 15, and 16. On September 17, disassembly of the telescope and computer systems apart would start, preparing for the larger telescope parts to be lifted from the dome on September 21. Those plans were changed due to the events of September 11, 2001 in New York City and Washington DC. In rescheduling, CTIO informed USNO that the crane to be used to lift our telescope from the dome was scheduled to be at another location on September 23 in support of another project; the crane would have to lift the telescope from the dome on September 21 as planned or be rescheduled for early October.

Wanting to get the telescope to Flagstaff by mid-October to avoid snow at that site, it was decided to hold off on the calibrations until the telescope was in Flagstaff and have the Zacharias's, Holdenried, Wieder, and Rafferty depart for CTIO at the same time on Sept 18. They arrived at CTIO at 1300 on September 19, which gave them 45 hours to have things ready for the crane on the $21^{st}$. Norbert and Marion Zacharias focused on getting the data, system backups, and computer equipment ready for shipment back to the USA, while Wieder and Rafferty worked on dismantling the telescope. Putting in long hours of work each day, they were able to have the telescope ready to be lifted out of the dome on September 21 as scheduled. By late afternoon on September 21, the telescope was packed in its shipping crates, and by mid-morning on September 22, all the computer and electronic equipment was also packed for shipment. Wieder departed CTIO to fly home on the morning of September 22. Norbert and Marion Zacharias, and Rafferty traveled down to La Serena to meet with the three Chilean observers who had worked with the UCAC project during the three and a half years at CTIO. On September 24, the mountain staff of CTIO was gathered and Rafferty presented a USNO plaque to Oscar Saa (the site manager for CTIO) and his staff for their excellent support of our project. Later that afternoon, another USNO plaque was presented to Dr. Malcolm Smith (the head of CTIO) and the La Serena staff of CTIO for their support.

During the 3.5 years at CTIO, there were very few mechanical failures. The shutter on the 4K CCD camera failed three times, a connection in the CCD camera caused problems twice, and the dome rotation motors failed twice. In each case, the CTIO people were able to correct the problems quickly. For some of the problems with the 4K CCD camera, it was arranged for Gary Simms (the president of Speckle Instruments that built the camera) to call Oscar Saa and talk him through solving a problem with the camera.

When the astrograph was at CTIO it was operated by Marion and Norbert Zacharias, three Chileans (Mauricio Martinez, Danilo Castillo, and Sergio Pizarro), and, on a few nights, by Ted Rafferty.

On October 22, 2001 the crates with the telescope as well as Wieder, Holdenried, Marion and Norbert Zacharias and Rafferty arrived at NOFS. On October 24 a crane lifted the telescope and mount into the dome. Unpacking, cleaning and assembling the astrograph equipment went very well, greatly supported by NOFS staff members (B. Canzian, M. Divittorio, A. Rhodes, S. Sell and C. Dahn). Most of the minor problems were related to computer issues. Holdenried made updates to the single board computer and user interface for northern hemisphere operations. On the night of October 26 the polar alignment was performed by Wieder and Rafferty, and on Sunday night, October 28, the 4K camera saw first light from NOFS. On the night of October 31, the first regular fields were observed to continue with the survey. There was only a 42 day break between the last survey observation made at CTIO and the first at NOFS.

As when the astrograph was at CTIO, Norbert Zacharias and Ted Rafferty traveled to NOFS often while the UCAC program was underway to deal with software and hardware issues, and to do maintenance on the telescope. Often we would combine our visits to NOFS with observing runs with the Kitt Peak 0.9m reflector to link the UCAC fields to ICRF sources.

As at CTIO, the astrograph had few serious problems while doing the UCAC program at NOFS. There was a problem with the valve in the 4K CCD camera that caused a very slow leak; this required the camera to be pumped down more often than normal. During one of his visits, Rafferty removed the camera in the early morning and drove down to Tucson, where Spectral Instruments (the maker of the camera) was located to replace the valve. It only took them a few hours to replace the valve and pump down the camera, and Rafferty was able to drive back to Flagstaff the same day and had the camera back on the telescope to continue observing that night.

During the 3.5 years the astrograph was in Flagstaff, it was operated by Trudy Tilleman, Stephanie Potter, Dominic Marcello, and, on a few nights, Norbert Zacharias and Ted Rafferty. The last fields for the UCAC program were taken on the night of May 17, 2004, some calibration fields were taken the following week, and the last 4K camera exposure was obtained on the night of June 9. Handwritten notes by the observers filled 7 volumes, documenting which survey field area or extra observing were covered, noting focus measures, and reporting any problems. All exposures were numbered consecutively throughout the project.

In total the astrograph took 278,185 exposures, including 3,595 taken in 1997 from its testing location in Washington DC. The first light picture at CTIO was taken of the globular cluster 47 Tuc. A single 4K frame covered just over 1 by 1 degree and the 2-fold overlap pattern of fields comprised 85,158 telescope pointings. The astrograph operated in a single bandpass (579–642 nm) with a fixed, built-in filter, which doubled as the camera window. With 2065 mm focal length the scale of the astrograph is just over $100''$/mm which resulted in an observed scale of 0.905 arcsec/pixel with the 9 $\mu$m pixel size. Only a tiny fraction of the 9 degree diameter field of view of the red lens design was utilized in this program due to the then available size of the largest detectors. When the astrograph came to CTIO it was the smallest telescope (except the 50mm H$\alpha$ survey lens) with the largest CCD of all telescopes on the mountain. There were a total of 4 data releases, with the UCAC2 [13] being the most popular so far, providing accurate astrometry for about 48 million stars from the south celestial pole to about $+50°$ declination. The final UCAC4 all-sky catalog (release in June 2012) lists 113 million objects after various re-processing of the data.

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