A robotic observatory in the city

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The University of St. Thomas (UST) Observatory is an educational facility integrated into UST's undergraduate curriculum as well as the curriculum of several local schools. Three characteristics combine to make the observatory unique. First, the telescope is tied directly to the support structure of a four-story parking ramp instead of an isolated pier. Second, the facility can be operated remotely over an Internet connection and is capable of performing observations without a human operator. Third, the facility is located on campus in the heart of a metropolitan area where light pollution is severe. Our tests indicate that, despite the lack of an isolated pier, vibrations from the ramp do not degrade the image quality at the telescope. The remote capability facilitates long and frequent observing sessions and allows others to use the facility without traveling to UST. Even with the high background due to city lights, the sensitivity and photometric accuracy of the system are sufficient to fulfill our pedagogical goals and to perform a variety of scientific investigations. In this paper, we outline our educational mission, provide a detailed description of the observatory, and discuss its performance characteristics.
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I. INTRODUCTION

Institutional access to high-quality astronomical equipment can have a significant impact on astronomy and physics education.[1,2] The University of Iowa, a pioneer in this area, operates the Iowa Robotic Telescope Project,[1] a remotely accessible robotic observatory that is tightly integrated into their undergraduate curriculum. Traditionally, access to facilities like the one at Iowa have been limited to institutions with the necessary monetary resources and technical expertise to build, maintain, and utilize such equipment. However, recent developments in sophisticated astronomical equipment and observatory control software have brought robotic observatories within reach of a much broader audience. Robotic observatories have a distinct advantage in that many institutions can share the cost of construction and operation of the facility. An example of shared access is the MicroObservatory,[2] a network of automated small telescopes used in middle and high school classrooms throughout the United States. The MicroObservatory has provided significant gains in student conceptual understanding in mathematics and the physical sciences.

While the remote viewing capacity of the Iowa Robotic Telescope and the MicroObservatory is clearly an asset, our experience suggests that students are motivated by the physical presence of a telescope. When students visit the facility and control the telescope directly, they gain an appreciation for the data acquisition process. But at the same time, remote access allows students to gather more data than is practical with visits to the observatory. Because students in remote classrooms can access the facility in real time, local schools can enjoy observing sessions without the need to travel. Our decision to build a remotely accessible on-campus robotic observatory was motivated by the desire to blend the advantages of an easily accessible observatory with those of a remote facility.

When building an observatory, several important details should be taken into consideration in order to achieve the best scientific performance. First, the pier supporting the telescope must be rigid and free from image-degrading vibrations and should, therefore, be mechanically isolated from the surrounding structure. Second, the observatory site should be away from the light pollution associated with metropolitan areas. Third, the climate at the observatory site should provide a large proportion of clear nights and the atmosphere should be dry and still.

The UST observatory breaks most of these rules. It is installed on the upper deck of a four-story parking ramp with the telescope pier tied directly to the ramp support structure. The ramp itself is located in the heart of St. Paul, Minnesota, where light pollution is severe and the weather is often poor.

Despite its apparent shortcomings, the observatory performs very well (Sec. IV) and is fully capable of fulfilling our pedagogical goals (Sec. II) as well as making a variety of scientific measurements. The on-campus location and remote observing capability are key to the facility's success. It is used by students in our introductory course, student researchers, and students at other local schools and community colleges. Nearly, all of the hardware and software were purchased off the shelf at a modest cost, which means that high-quality automated observatories have come of age and are now within the reach of many small institutions.

II. EDUCATIONAL MISSION

The primary role of our observatory is education. Our aim is to facilitate an understanding of and an appreciation for the process of modern scientific investigation as well as the role critical thinking plays in uncovering nature's mysteries. To accomplish this, our observatory programs actively engage participants in the process of discovery. Participants pose scientifically valid questions and actively employ scientific methods to find the answers. Observatory program users are diverse and include UST science and non-science students, education majors, primary and secondary teachers, and interested members of the community.

A. Observational laboratory design

One of our primary goals has been to integrate the observatory into the laboratory component of our introductory astronomy course. This course is aimed primarily at non-technical majors seeking to fulfill the UST core requirement of a physical science with a laboratory. Historically, most of the laboratory exercises were either strictly pencil and paper or based on simulated observations, as is typical of many introductory astronomy courses. Neither we nor the students found them satisfying so we rebuilt the observational portion of our course. The new exercises are designed to mimic professional observational astronomy by leading the student through the design, data acquisition, and data analysis phases of an investigation. A typical experiment takes place over two laboratory periods. The first period is devoted to exploring and understanding an experimental question followed by the development of a data acquisition plan. The second period is devoted to data analysis and reporting experimental results.

We want to perform more than one experiment per semester, but because we have only one observatory and many students, multiple observatory visits are impractical. We have overcome this limitation by employing two data acquisition models. The first involves an observatory visit where groups of four students operate the telescope in real time and learn how an observatory functions. Group members assume the roles of telescope operator, camera operator, recorder, and staff scientist. The staff scientist leads the group through the observing plan; the telescope operator points the telescope and acquires a target; the camera operator takes images; and the recorder writes the details in the observing log. After taking a few images of a given target, the roles rotate allowing everyone to perform each task. The second model involves unattended queue-based observing. Students submit their observing plans to a queue at the end of the first laboratory period and retrieve their data for analysis at the beginning of the second.

During their observatory visit, students image a galaxy through a set of color filters. In the subsequent laboratory, they create color images from raw data, study galaxy types and classification schemes, and classify their galaxy. The queue-based exercises will be drawn from among several seasonal experiments. Examples of queue-based exercises are: determining the mass of Jupiter using a time series of observations of its moons; determining the distance to and age of a star cluster by constructing an HR-diagram; and measuring the properties of transiting extra-solar planets. The Jupiter experiment is currently in use, while the star cluster and extra-solar planet experiments are in development.

We are also actively integrating the observatory into the curriculum of several local schools. Cretin-Derham Hall (CDH), a local high school, currently uses both the galaxy classification and the mass of Jupiter experiments in their year-long astronomy course. Building on the success of the CDH program, we are working with a consortium of local schools including CDH, the University of Minnesota, North Hennepin Community College, Normandale Community College, and Metropolitan State University to develop several additional laboratory exercises. The robotic nature of our observatory will allow these schools to implement the exercises via either queued or live remote observing over the Internet. Given the proximity of the facility, students from these schools can easily visit the telescope for an in-person observing experience, as CDH has done once per term since the program began.

B. Impact beyond the classroom/training future scientists

Beyond the direct impact that it has in the classroom, the observatory provides an excellent training ground for future scientists and engineers. Each semester, we employ a group of four student workers who are responsible for day-to-day observatory operations, helping other students make observations, and assisting with public events. These student workers gain valuable hands-on experience in the maintenance and operation of the facility. This experience facilitates their transition into a research role where they use their knowledge in collaborative research with a faculty member. In addition to acquiring technical ability, observatory workers gain leadership skills as they guide others through observations and engage the public as experts. The process is transformative as the students take ownership and responsibility for the observatory.

Early on, at several key points during the design, installation and configuration stages, student/faculty collaborative projects involved a partnership with the UST school of engineering. For example, engineering students developed a procedure to properly align the telescope mount with the Earth's polar axis. Another engineering student designed and built an embedded controller to automate control of the security lights on the upper deck of the parking ramp. As the observatory matured, we began grooming the observatory student workers for astronomical research projects. Several of the students spent time during the summer of 2011 learning the basics of astronomical image processing. Leveraging this knowledge, they are currently in the early data acquisition stages of an exoplanet study and we are planning a variable star study in the near future.

C. Public events

Because it is located in a metropolitan area, the observatory generates significant public interest. Public events are very well attended and managing them requires careful planning. A typical event begins with a 20- to 30-min presentation followed by a tour of the observatory and an observing session. Although the observatory capacity is only 15 people, with careful planning we can accommodate groups of up to 45.

After the presentation, attendees are divided into groups of 15. The first group is sent to the observatory, while the remaining groups chat with staff or watch an astronomy-related film in the auditorium. Ten minutes later, the second group is sent to the observatory and the process is repeated until the auditorium is empty. On the upper deck of the parking ramp, staff members provide guided night sky tours using small telescopes. Next, attendees tour the observatory dome to see the main telescope and its mount and watch as the system automatically acquires and images a target. Ten minutes later, the group enters the control room to see the software that controls the observatory, watches as the system acquires and images a target, and views the final image on a 36 in. monitor.

III. THE OBSERVATORY

Constructing a robotic observatory is fundamentally different today than it was even a decade ago. Development and growth in the amateur hardware market have brought high-quality astronomy equipment within reach of small institutions and serious amateurs. A basic system containing a high-quality 16- to 24-in. telescope, a science-grade CCD camera with filters, and a precision computer-controlled mount can be assembled for the price of a luxury car. The necessary control software to fully automate an entire observatory is available off the shelf. Although technical expertise is required to set up, operate, and maintain the system,

Table I. List of all hardware in the system with current retail prices.

Equipment	Manufacturer	Model	Price
Telescope	PlaneWave Instruments (Ref. 3)	CDK 17	$22,000
Camera	SBIG (Ref. 4)	STL 11000	$6,500
Filter Wheel	SBIG	FW8-STL	$1,000
Photometry Filters	Astrodon (Ref. 5)	UVBRI Set	$1,500
Imaging Filters	Astrodon	LRGB Set	$900
Narrow Band Filters	Astrodon	H α, S II, and O III Set	$1,000
Telescope Mount	Astro-Physics (Ref. 6)	GTO 3600PE	$27,000
Dome	Ash Manufacturing Company (Ref. 7)	5 m Ash-Dome	$37,000
Dome Automation Kit	ACE (Ref. 8)	SmartDome	$15,000
Weather Station	Diffraction Limited (Ref. 9)	Boltwood Cloud Sensor II	$1,700
Pier	Custom fabrication	Custom made steel pier	$2,500
Control computer	Dell	Precision T5500	$1,800
Total cost			**$117,900**

there is no longer any need for institutions to invest in costly software and hardware development to create a working robotic observatory.

A. Facilities

The observatory building is divided into an equipment room where the telescope is mounted and a control room where the observers work. The separation between the rooms is critical as the heated control room allows year-round access to the facility, which is particularly important during cold Minnesota winters. In the equipment room, a raised platform surrounds the telescope pier allowing visitors and workers to access the telescope and dome. A desktop-to-ceiling window separates the rooms and allows observers and visitors to watch the telescope from a comfortable location. An L-shaped desk in the control room holds monitors displaying the interfaces for all of the observatory equipment. A large wall-mounted monitor displays images as they are taken by the telescope and is also used to display video, web pages, and other media. Several comfortable chairs around the periphery of the control room offer a place for visitors to watch the action.

The wall monitor plays a central role for public night visitors. Because the telescope does not have a permanently mounted eyepiece, visitors are unable to view celestial objects directly. Instead, the monitor displays images from the telescope. Initial concerns that the lack of an eyepiece would be disappointing to visitors were unfounded. In practice, visitors find the view provided by the monitor satisfying and exciting. Because the camera is much more sensitive than the eye, deep sky objects that are difficult to see through the eyepiece are easily visible on the monitor. Often, when viewing faint objects through the eyepiece of the telescope, one is never quite sure if one is seeing the intended object; but using the monitor leaves little doubt. Even when it is cloudy outside, visitors can view previously acquired images, learn about image processing, see the telescope move, and engage in a question and answer period about a variety of topics.

Table II. List of critical system specifications.

Parameter	Value
Aperture	17 in (432 mm)
Focal length	115.7 in (2939 mm)
Focal ratio	F/6.8
Detector size	4008 $\times$ 2672 pixels, 36 $\times$ 24.7 mm
Plate scale	0.63 arcsec/pixel
Field of view	0.70 $\times$ 0.47 deg

B. Hardware

The telescope, a CDK-17 from PlaneWave Instruments, is an innovative corrected Dall-Kirkham design. At half the price of the Ritchey-Chrétien design, the CDK-17 offers excellent imaging performance. The optics consist of an ellipsoidal primary mirror and a spherical secondary mirror. A lens couplet between the secondary mirror and the focal plane removes spherical aberrations and flattens the focal plane providing sharp focus over a wide field of view. The mount, a 3600GTOPE from Astro-Physics, provides a very stable imaging platform and has capacity for more instrumentation. A high-precision encoder on the right ascension axis reduces periodic tracking errors to under 1 arcsec. The large-format camera and eight-position filter wheel provide a great degree of imaging flexibility, and the wide field of view allows us to image large star clusters and nebulae in a

Fig. 1. A schematic view of the support structure underneath the telescope pier. The pier is attached to a crossbeam between two concrete columns extending to the building foundation. This structure shields the telescope from oscillations in the parking deck.

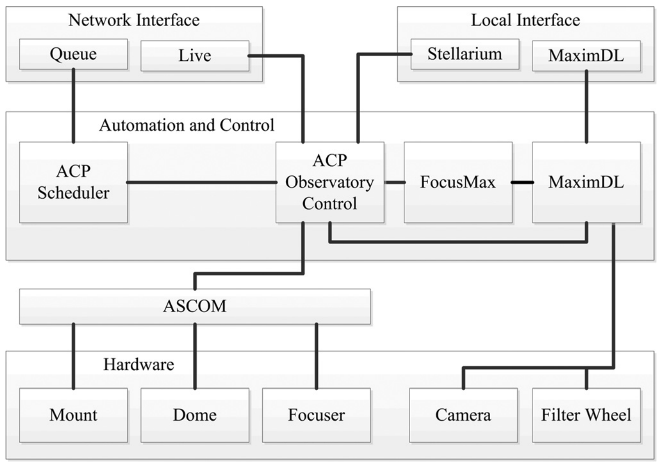

Fig. 2. Block diagram of the observatory software systems.

single exposure. The filter wheel holds both a color-balanced LRGB filter set and a subset of UVBRI photometry filters, allowing easy transitions between astrophotography and photometry projects in a single observing session. Table I lists the major hardware components installed in the observatory along with their retail price at the time of publication. Table II lists some key technical specifications of the telescope-camera combination.

C. The pier

Although a parking ramp is not an ideal location for an observatory, when we were given access to the space we plunged ahead anyway. Knowing that other parking ramp observatories are plagued with vibration problems,[10] we looked for ways to reduce them in our installation. The vibrations in the ramp are due to oscillations in the deck surface and are greatest away from the columns and crossbeams that support the deck. Poured as a continuous unit, the deck and crossbeams are attached to the main support columns of the structure. The column and crossbeam structure in the original design could not support the concrete observatory. Therefore, two additional concrete support columns extending to the ramp foundation were added. The resulting six-column structure substitutes for a traditional pier and reduces the deck oscillations. We located the telescope midway along a short crossbeam at the center of the cage formed by the columns and crossbeams, as illustrated in Fig. 1. The 16-in. diameter, 80-in. tall steel column that holds up the mount is attached to a large $3 \times 3 \times 2$ ft.^{3} concrete mass tied directly to the crossbeam. The observatory floor floats on foam and does not directly touch the concrete mass. As demonstrated in Sec. IV, the pier performs surprisingly well, and deck oscillations have not been a problem.

D. Software

The software system is illustrated in Fig. 2. At the lowest software level, the ASCOM platform[11] provides an application programming interface (API) to the observatory hardware. ASCOM is a freely available platform based on a driver model. Hardware manufacturers are encouraged to provide an ASCOM-compliant driver with their equipment allowing software developers to create device-independent control software. For the end user, this model makes changing observatory hardware as painless as changing a printer.

At the intermediate level sits the centerpiece of the control system: ACP Observatory Control by DC3-Dreams.[12] ACP Observatory Control is a sophisticated software system that, in conjunction with the ASCOM platform, automates all aspects of observatory operation. It acquires images through MAXIMDL,[13] synchronizes the telescope and the dome, auto-focuses the telescope through FOCUSMAX,[14] calculates automated plate solutions for acquired images, performs automated dynamic pointing corrections, and executes pre-written observing plans. When coupled with ACP Scheduler,[12] the observatory can perform unattended queue-based observing, automatically waking up at dusk, executing observing plans all night, and closing down at dawn.

There are three primary ways in which users interact with the system: from the control room, live remote control through a web browser, or via the observing queue. From the control room, users can control the telescope using a planetarium program such as the freely available STELLARIUM[15] and take images using MAXIMDL's user interface. Telescope pointing commands from STELLARIUM are routed through ACP Observatory Control to ensure that pointing corrections are applied and that the dome is synchronized. Alternately, ACP Observatory Control provides a web interface allowing real-time remote control of the observatory through a web browser. Lastly, ACP SCHEDULER also provides a web interface allowing users to remotely add observing plans to the queue for execution at a later time. This combination of observing modes provides a tremendous amount of flexibility and allows us to use the observatory in a variety of different ways. Table III lists the system software along with vendors and retail prices at the time of publication.

IV. PERFORMANCE

We characterized the performance of the observatory in three areas: stability against vibrations, limiting magnitude,

Table III. List of major software in the system with current retail prices.

Software	Developer	Description	Price
ASCOM PLATFORM 6 (Ref. 11)	The ASCOM Initiative	Astronomy driver layer	Free
ACP (Ref. 12)	DC-3 Dreams	Observatory control program	$2,000
ACP SCHEDULER (Ref. 12)	DC-3 Dreams	Queue based observation scheduler	$900
MAXIMDL (Ref. 13)	Diffraction Limited	Imaging and data analysis	$670
FOCUSMAX (Ref. 14)	Larry Weber & Steve Brady	Auto focus	Free
STELLARIUM (Ref. 15)		Planetarium software	Free
Total cost			**$3,570**

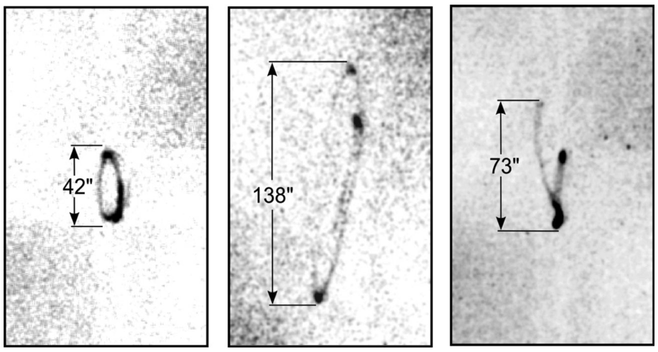

Fig. 3. A sample of 1 s images taken through a tripod-mounted telescope located on the parking deck outside of the observatory building. During imaging, we jumped on the deck to create vibrations. Displacement of a bright star in the image ranged from just under 1 arcmin to over 2 arcmin. In images taken through the CDK-17 in the observatory, stellar profiles range from 2.5 to 3.5 arcsec full width at half maximum even with light traffic on the ramp.

and photometric accuracy. We then compared our results with simultaneous measurements made from the Macalester College observatory. The Macalester observatory is located less than a mile away from the UST observatory and houses a 16 in. telescope mounted on a traditional isolated pier. The temporal and geographic coincidence of the observations ensures that both data sets were taken under identical atmospheric conditions. The two instrumental setups are similar with the exception of the pier. We show that our installation is robust against vibrations from the ramp and that our overall performance is as good as the performance of a traditional installation of similar size and location.

A. Mechanical stability

Attaching the telescope pier directly to the parking structure raises questions regarding the mechanical stability of the telescope. As described in Sec. III C, the telescope is mounted on a crossbeam to minimize deck oscillations. We illustrate the stability of the mount in two ways: first, by measuring the magnitude of deck oscillations away from the observatory building, and second, by comparing the full width at half maximum (FWHM) of stellar profiles in images from the UST telescope with those taken at Macalester.

We measured the magnitude of the vibrations using a CCD-equipped 12-in. Meade LX-200 mounted on a sturdy tripod on the parking deck away from the observatory building. With the telescope tracking at the sidereal rate and pointed at a bright star, we took a series of 1 s images while jumping on the deck to create vibrations. The three panels in Fig. 3 are characteristic of the results. Displacement of the source in the image ranges from just under 1 arcmin to over 2 arcmin. In images taken through the CDK-17 in the observatory building, stars appear symmetric and do not display the extreme displacement observed in the LX-200 images, even with light automobile traffic on the ramp. In Table V, we compare the full width at half maximum (FWHM) of stellar profiles in images from the UST observatory with those from the Macalester observatory taken at the same time. We find that the UST observatory compares favorably with the Macalester observatory. We also find that the FWHM of stellar profiles does not increase significantly with jumping or light traffic on the ramp, as illustrated in Fig. 4.

Fig. 4. Image of the Great Orion Nebula from the UST Observatory in downtown St. Paul. All data for the image were acquired by UST students and final image processing was performed by co-author Gerry Ruch. Total exposure time is approximately 15 min per filter for a total exposure time of 1 h. Stars in the image are symmetric with a FWHM of approximately 2.5 arcsec. The spatial resolution and color detail in the image suggest that the system will perform well for a wide variety of projects.

B. Limiting magnitude

Because the observatory is located in a large metropolitan area, light pollution is a major concern. The high background due to scattered light from the surrounding city limits the faintness of objects observable by the telescope. The limiting magnitude is defined as the magnitude of the dimmest star achieving a signal-to-noise ratio of 3 in a 1 min exposure. We measured the limiting magnitude of the UST and Macalester telescopes by taking simultaneous observations of a field of Landolt standards.[16] Table IV lists the standard stars

Table IV. Landolt standard sources used in measuring the limiting magnitude and photometric accuracy of the UST and Macalester observatories.

Field (Ref. 18)	Name	RA(J2000)	DEC(J2000)	V(mag)	B-V(mag)	V-R(mag)
116	110 229	18:40:45	+00:01:51	13.649	1.910	1.198
	110 230	18:40:51	+00:02:23	14.281	1.084	0.624
	110 232	18:40:52	+00:01:58	12.516	0.729	0.439
	110 233	18:40:52	+00:00:51	12.771	1.281	0.773
130	MARK A2	20:43:54	−10:45:32	14.540	0.666	0.379
	MARK A1	20:43:58	−10:47:11	15.911	0.609	0.367
	MARK A	20:43:59	−10:47:42	13.258	−0.242	−0.115
	MARK A3	20:44:02	−10:45:39	14.818	0.938	0.587

Table V. Results of FWHM, limiting magnitude, and photometric accuracy tests.

Observatory	FWHM (arcsec)	Limiting magnitude(mag)	Photometric accuracy	
			⟨Δmag⟩	Percent flux error
St. Thomas	2.3	17.4	0.02	2.3%
Macalester	3.6	16.9	0.01	1.5%

used for the limiting magnitude and photometric accuracy calculations. All data reduction was performed using IRAF.[17]

Five 12 sec exposures of Landolt field 120 (Ref. 18) were bias-subtracted, dark-subtracted, and co-added to create a single image with an effective exposure time of 1 min. Using the IRAF package *apphot*, we performed aperture photometry and calculated the signal-to-noise ratio (SNR) of each source. We then performed a linear least squares fit to the log of the SNR versus the published magnitude of each source and extrapolated to a SNR of 3. The results are listed in Table V. The UST observatory compares favorably with Macalester, and the limiting magnitude of 17.4 puts a large number of objects within reach of our facility.

C. Photometric accuracy

We measured the accuracy of absolute photometry at the UST and Macalester observatories using the photometric system of Landolt (1992).[16] To perform the experiment, we took five 2 min exposures in each of the standard B, V, and R bandpasses of the two fields of Landolt standards listed in Table IV. All subsequent data reduction was carried out using IRAF. The images were bias-subtracted, dark-subtracted, flat-fielded, and co-added in the standard way to create final images in each bandpass with a total effective exposure time of 10 min. The IRAF task *apphot* was then used to extract raw uncalibrated photometry from the images. Because the spectral response of our system deviates from the Landolt system, we calculated a color correction. Additionally, because we observed the objects through varying column depths of atmosphere (airmass), we corrected for the effects of wavelength-dependent atmospheric extinction. We used the IRAF package *photcal* to calculate both corrections.

To produce the final calibrated magnitudes, we calculated airmass corrections, color corrections, and zero point magnitudes using seven of the eight sources in Table IV. Those values were then used to calculate the V band magnitude of the eighth source. We repeated this procedure for each of the eight sources and computed the mean deviation of our measured magnitudes from those published in Landolt (1992).[16] The mean deviation is listed in Table V for both observatories.

The photometric accuracies of the two facilities compare favorably, with Macalester slightly outperforming the UST facility. We conclude that our ability to perform absolute photometry is sufficient to perform a variety of experiments. Given that our absolute photometric errors are around the two percent level, we assume that our relative photometric errors will be under one percent, a level sufficient to measure extra-solar planet and variable star light curves. The listed absolute photometric errors could likely be improved through more rigorous observations of the standards at a greater range of airmasses and more careful characterization of the instrumental response.

V. CONCLUSIONS

The UST Observatory is a highly successful robotic observatory located at our St. Paul campus assembled from off-the-shelf components. Despite its non-traditional pier and location, its performance has exceeded expectations, and it is more than capable of fulfilling its pedagogical mission. It is integrated into the undergraduate curriculum at St. Thomas as well as other local area schools and is providing exciting public events for the surrounding community. The authors welcome requests for information and questions regarding the observatory and its programs.

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[11]Astronomy Common Object Model (ASCOM) Platform ⟨http://ascom-standards.org/⟩.
[12]DC-3 Dreams observatory control and automation software ⟨http://www.dc3.com⟩.
[13]MaximDL imaging software from Diffraction Limited ⟨http://www.cyanogen.com/maxim_main.php⟩.
[14]FocusMax automated focus program by Larry Weber and Steve Brady ⟨http://users.bsdwebsolutions.com/~larryweber/⟩.
[15]Stellarium planetarium software ⟨http://www.stellarium.org/⟩.
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