CubeSat Astronomical Telescopes and Research in the 2020s

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Abstract A 2020s CubeSat astronomical telescope revolution could evolve small space telescopes from their current nascent state, to becoming a major contributor to astronomical research, similar to the evolution of small ground telescopes. The same inclusive community of practice facilitated process that resulted in small ground telescopes becoming full research partners could be emulated in the development of small space telescopes. The ground-breaking ASTERIA, SPARCS, and CUTE CubeSat telescopes are pointing the way. Four programs could enhance this evolutionary process:

(1) developing a CubeSat autonomous telescope constellation for astronomical research, (2) advancing CubeSat telescope technology, (3) encouraging CubeSat telescope one-offs, kits, and commercial ventures, and (4) nurturing an inclusive and supportive CubeSat telescope community of practice. By the end of the decade, CubeSat telescopes could open up the direct use of space telescopes for astronomical research to a large number of professional astronomers, citizen scientists, and students.

I. On the Verge of a CubeSat Astronomy Revolution

In ground-based astronomical research, a few large, computer-controlled mountaintop telescopes, such as the 100-inch Hooker telescope on Mt. Wilson, the 200-inch Hale telescope on Mt. Palomar, and the twin 10-meter Keck telescopes on Mauna Kea employ their considerable photon gathering capabilities to observe faint objects or spread their generous light out into high resolution spectra. Professional astronomers and their graduate students use these and other large mountaintop telescopes around the globe for their research.

Many thousands of much smaller, computer-controlled telescopes equipped with CCD cameras are located at schools and backyards throughout the world. Thousands of citizen scientists, as well as many undergraduate and high school students, are using these telescopes for their research. What small telescopes lack in photon capture they make up for by their sheer numbers.

Over the years, large and small telescopes, and the paid and volunteer researchers who use them, have learned to work together in a synergistic and balanced manner, supporting each other and dividing up the work. Some dimensions of this synergy are:

- Large telescopes are designed to observe fainter targets; small telescopes are responsible for observations of brighter targets.
- Large telescopes are over-subscribed, hence often limited to “snapshot” observations; small telescopes can provide long-duration, continuous time-series observations.
- Large telescopes are few and far between; small telescopes are widely and densely scattered across the Earth. Thus, small telescopes, spanning the globe, can keep targets of interest under 24-hour surveillance, passing them from one telescope to the next as the Earth rotates and the weather changes.

There are a few large telescopes in space: Hubble, Chandra, and Spitzer immediately come to mind. However, until 2003 there were no small space telescopes, the counterparts to the many small ground telescopes, and even today there are less than a dozen small astronomical telescopes in space. However, small satellites, built to meet “CubeSat” standardized launch and interface requirements, have encouraged the manufacture of a number of off-the-shelf, miniature, and affordable subsystems. These advances have made the development of low-cost CubeSat space telescopes possible. As noted in the title of a paper by Evgenya Shkolnik (2018), “We are on the verge of a CubeSat astronomy revolution.”

We suggest below, how small, low cost CubeSat astronomical telescopes could, in the 2020s, supply a missing link in space research, just as small ground telescopes already have for ground-based research. This could open the door of astronomical space research to many more professional astronomers and their graduate students, not to mention thousands of undergraduate and high school students and citizen scientists. This would benefit the entire astronomical research community by providing plentiful observations at many wavelengths to complement observations by large space telescopes as well as both large and small ground telescopes.

II. Small Telescope Development and Research within Communities of Practice

This section describes how, over the past several decades, three complementary, inclusive communities of practice have advanced the development and use of small ground research telescopes. Section III describes how, over the coming decade, a similar, inclusive community of practice, drawing on the knowledge and lessons learned with small ground telescopes and the first small space telescopes, could advance the future development and use of CubeSat space telescopes.

> *Communities of practice are formed by people who engage in a process of collective learning in a shared domain of human endeavor: a tribe learning to survive, a band of artists seeking new forms of expression, a group of engineers working on similar problems, a clique of pupils defining their identity in the school, a network of surgeons exploring novel techniques, a gathering of first-time managers helping each other cope. In a nutshell: Communities of practice are groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly (Wenger-Trayner et al. 2015).*

Small Telescope and Instrument Developments within Communities of Practice

Less than a half-century ago, most astronomical research was conducted by professional astronomers and their graduate students on relatively large mountaintop telescopes. Five key technical developments have allowed small, low-land telescopes, and the professional astronomers, students, and citizen scientists who use them, to become useful partners in astronomical research.

These developments were:

- Mass production of affordable Schmidt-Cassegrain telescopes (SCTs)
- Fully autonomous microcomputer-controlled robotic telescopes and observatories
- Affordable CCD cameras and powerful user-friendly PCs and analysis software
- High-speed, low-cost data transfer across the Internet
- Local arrays and global networks of robotic telescopes
- Incorporation of the key features of large mountaintop research telescopes into the manufacture of small research telescopes (redefining what was “small” in the process)

These five key developments are described below. Please note how often volunteer communities of citizen scientists and engineers led the way.

The spherical primary mirrors of Schmidt-Cassegrain telescopes (SCTs) are easy to make with very short focal ratios that result in compact telescopes. However, a large amount of spherical aberration has to be removed with a thin refractive corrector plate with a complex fourth-order curve. Tom Johnson figured out how to make these corrector plates at low cost by vacuum bending a piece of flat glass against a “reverse master” and then grinding and polishing the top of the glass flat. When the vacuum was released, the corrector plate sprang into the correct positive shape. By the 1970s, Tom’s company, Celestron, was mass producing the classic orange-tube SCT that revolutionized small-telescope astronomy (Pickiel & Johnson, 2010).

In the early 1980s, Louis Boyd and Russell Genet used 8-bit/64K RAM microcomputers at the Fairborn Observatory to totally automate telescopes equipped with photoelectric photometers

(Boyd, Genet, & Hall, 1986). From the outset, their telescopes were autonomous, including dynamic decisions on what objects should be observed, when they should be observed, and whether the observations were of acceptable quality or needed to be repeated (Trueblood & Genet, 1985). Their first totally autonomous observations were made in 1983. In 1985 the Fairborn Observatory's robotic telescopes were relocated to Mt. Hopkins in southern Arizona.

Several key robotic innovations were devised at the Fairborn Observatory (Genet et al., 1987). To monitor the autonomous observatory, a computer-generated report summarizing what each telescope and the observatory had done the previous night was sent out via phone line.

Michael Seeds (1992) managed the Fairborn Observatory's "Rent-a-Star" program. For $3.00 USD per photometric sequence of 66 exposures, anyone could obtain a three-color observation. This may be the "grandfather" of today's vibrant commercial robotic "telescope farms" that provide remote-access imaging, astrometry, and photometry to thousands of users.

Two workshops on automated photometric precision were organized by Genet (Young et al., 1991) and attended by a number of astronomers, including William Borucki, who thought that automated high-precision photometry could be used to observe exoplanet transits. High precision photometers were designed by Boyd and installed on an array of four 0.75-meter telescopes at the Fairborn Observatory.

Phone lines (9600-baud) were utilized to provide the first remote access to a robotic observatory. New requests for observations made during the day were automatically added to the observational program and observed that night. Observational results were returned via modem the following morning.

To monitor observational quality, system-check observations were automatically inserted into observational sequences. Gregory Henry (1999) devised software that analyzed past and current system-check observations to detect any unwanted changes or trends that might warrant human attention. These procedures, still in use today, have resulted in light curves with a yearly precision of 0.1-0.2 millimags, a precision that has been maintained for over 25 years.

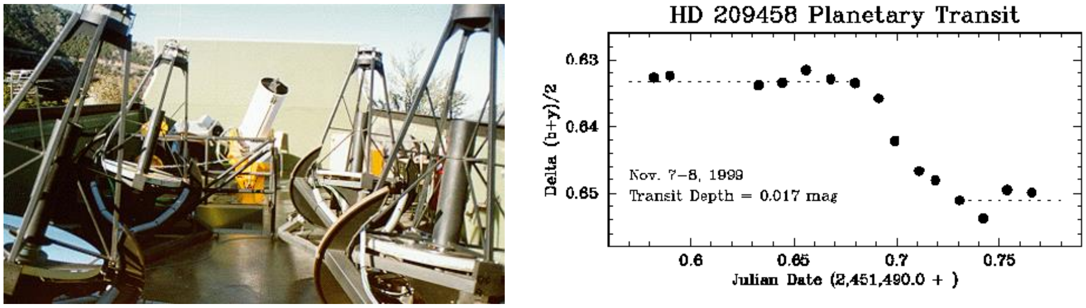
The development and use of autonomous robotic telescopes at the Fairborn Observatory were due, in large part, to a supportive community of practice—the International Amateur-Professional Photoelectric Photometry (IAPPP) Association. Founded in 1980, the IAPPP featured a quarterly journal, annual conferences with proceedings published as books, and a visit each year to the growing number of robotic telescopes at the Fairborn Observatory on Mt. Hopkins.

By the end of the 1980s, the advantages of autonomous robotic telescopes and observatories had become clear:

- Lower operating costs because there were no observers to be paid
- Lower maintenance costs because telescopes were not disturbed by human observers or technicians changing instruments
- Placement of the telescopes at good weather sites even if they were very remote
- Anonymous computer operation, which was faster and less error prone than humans in selecting targets, controlling telescopes and instruments, and recording observations

The 1989 book, *Robotic Observatories* (Genet & Hayes, 1989) suggested that in the future, local arrays and global networks of identical telescopes would be scientifically productive, larger aperture telescopes could be automated, and observations could be made remotely in real time. It was also suggested that robotic telescopes could be placed into Low Earth Orbit (LEO), on the contemplated International Space Station, and on the moon in polar lunar craters (Genet et al. 1994).

William Borucki and Russell Genet (1992) suggested that a global network of small robotic ground telescopes equipped with high-precision photometers could detect exoplanet transits. A 0.8-meter telescope at the Fairborn Observatory detected an exoplanet transit in 1999 (Henry et al. 2000) as did David Charbonneau at different observatory (Charbonneau et al. 2000).



Left: Autonomous robotic telescopes at the Fairborn Observatory on Mt. Hopkins in the late 1980s. Right: Exoplanet transit obtained by Gregory Henry with the Fairborn Observatory's 0.8-meter robotic telescope. Only the first part of the transit was caught before the star set in the west.

CCD cameras entered professional astronomy in the 1980s, but they were large and expensive. Small, affordable CCD camera kits were developed by Richard Berry (Berry et al. 1994) and were soon commercially produced by Alan Holmes at the Santa Barbara Instrument Group. The trio of computer-controlled SCTs, affordable CCD cameras, and powerful PCs for data reduction and analysis all came together in the late 1990s to form the core equipment for small-telescope research.

Networks of modest-aperture telescopes are vital for understanding time-varying phenomenon (supernovae, exoplanet transits, variable stars, tumbling asteroids, etc.). The current premier network is the Las Cumbres Observatory (LCO), a global network of 22 robotic telescopes (0.4, 1.0, and 2.0-meters) at seven sites around the planet that work together as a single instrument, overcoming the adverse effects of the Earth's rotation and inclement weather. Wayne Rosing's team of engineers and scientists labored for over a decade to complete the LCO (Brown et al. 2013). LCO's moto: Many eyes, one vision.

Left: Las Cumbres Observatory (LCO) 2.0- and 1.0-meter telescopes at Siding Spring Observatory in Australia. Right: Map showing the location of LCO's 2.0-, 1.0-, and 0.4-meter telescopes.

The Alt-Az Initiative is a community of practice of (primarily) volunteer engineers and amateur astronomers who love telescopes. A major goal of the Initiative (and hence its name) has been to capture the key features of the many large altitude-azimuth (alt-az) mountaintop telescopes that they visited and replicate them in much smaller telescopes produced in quantity at low cost. A "pilot" 0.45-m telescope—the Cal Poly 18—that incorporated many of these key features was built by two student teams at California Polytechnic State University and the members of the Alt-Az Initiative (Genet et al. 2010).

The Cal Poly 18 prototype was followed by commercial production of 0.7- and 1.0-m advanced technology telescopes by PlaneWave Instruments (Rowe et al. 2010). These telescopes feature a compact alt-az configuration, two Nasmyth ports that allow instruments of almost any weight to be place on either port without having to rebalance the telescope, a direct drive control system (that eliminates all belts, pulleys, and gears, and provides high precision pointing and tracking as well as very fast slewing), and low thermal expansion, lightweight mirrors in a corrected Dall-Kirkham (CDK) configuration. CDK optics, which preform every bit as well as corrected Ritchey-Chretien optics, have spherical secondary mirrors which are much easier to align and make (hence they are lower in cost).

Many key features of large mountaintop research telescope, such as alt-az mounts, dual Nasmyth foci, direct drives, and advanced optics, that were captured by the Alt-Az Initiative community of practice have been incorporated in production-line telescopes built by PlaneWave Instruments. Left: 0.7-meter telescope at the Great Basin Observatory. Right: the 1.0-meter telescope and undergraduate student researchers at the College of the Desert.

Small Telescope Research within Communities of Practice

Citizen scientist researchers may be the biggest users of small telescopes. Members of the American Association of Variable Star observers have contributed observations to data bases for over a century. There are many other active organizations whose members contribute their observations, such as the Center for Backyard Astrophysics (cataclysmic variables) and the International Occultation Timing Association (occultations of stars by asteroids). Suggestions for observations are often made by the professional astronomers who then use the data provided by the citizen scientists.

The Astronomy Research Seminar, with more than 150 published papers coauthored by some 500 students to its credit, have amply demonstrated that undergraduate and high school student teams can, in a single semester or less, complete modest astronomical research projects in the same manner as professional teams. Each student team writes a research proposal, submits it for approval, manages their own research, obtains and analyzes original data (often from a remote robotic telescope), writes a team paper, obtains an external review of their paper, submits their paper for publication to an appropriate journal, and gives a public presentation. Students are supported by a community of experienced researchers and by InStAR, the Institute for Student Astronomical Research (Genet et al. 2016, Freed et al. 2017, and www.in4star.org).

Astronomy Research Seminar student teams: Left: A Waipahu High School Early College team that used a remote Las Cumbres Observatory telescope for their research. Right: Student teams at The Evergreen State College interact with a remote Seminar instructor, InStAR President Rachel Freed.

III. CubeSat Astronomical Telescopes in the 2020s

CubeSat Telescope Development Today

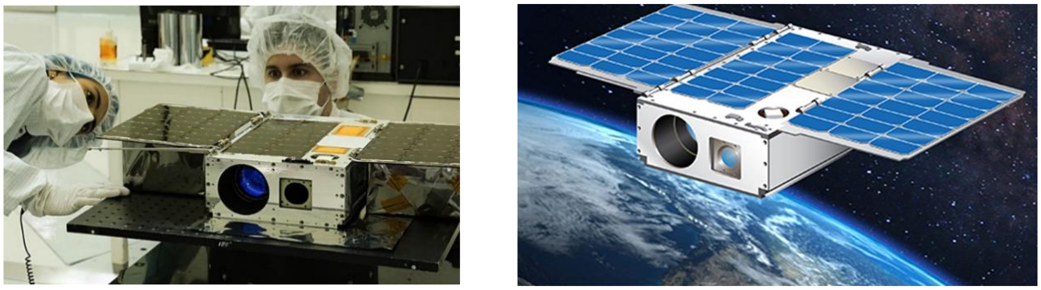
Until 2003, all space telescopes were physically large because miniaturized components had not yet been developed. In addition, it was expensive to place large, heavy telescopes in orbit. Then the MOST (Microvariability and Oscillations of Stars) telescope was launched in 2003 (Walker et al. 2003). It was relatively small (15 cm aperture, 60x60x24 cm) and weighed 54 kg. It was dedicated to asteroseismology, the study of stellar oscillations. A decade later (launched in 2013), the BRITE (BRIght Target Explorer) telescopes were even smaller (3 cm aperture, 20x20x20 cm size and 7 kg). This constellation of five nanosatellites has been investigating the stellar structure and evolution of the brightest stars in the sky (Handler et al. 2016).

In 1999, California Polytechnic State University and Stanford University devised the CubeSat standard. Each “cube” unit (U) in a CubeSat is 10x10x10 cm. A 3U CubeSat, for instance, is 10x10x30 cm. Standardization reduced launching costs and promoted subsystem interchangeability. Recent advances in CubeSat miniaturization technology, combined with NASA-CubeSat launches, have, as mentioned previously, placed us “On the verge of an astronomy CubeSat Revolution.”

ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics), the first CubeSat astronomical telescope, is a small (8.5 cm aperture, 10x20x30 cm, 12 kg) 6U CubeSat space telescope that has high pointing accuracy and precise camera temperature control. Placed in orbit from the International Space station in 2017, it is observing exoplanet transits in visible wavelengths (Smith et al. 2018).

NASA has funded several astrophysics CubeSats. Two funded ultraviolet CubeSat telescopes are currently under development. SPARCS (Star-Planet Activity Research CubeSat) is a 6U imaging astronomical telescope with a planned launch in late 2021. SPARCS will observe low-mass stars in the near- and far-ultraviolet, monitoring flares in these chromospherically active stars (Ardila et al. 2018).

CUTE (Colorado Ultraviolet Transit Experiment) is a near-UV, 6U CubeSat telescope equipped with a spectrograph designed to monitor transiting hot Jupiters to quantify their atmospheric mass loss and magnetic fields (Fleming et al. 2018). CUTE will probe both atomic (Mg and Fe) and molecular (OH) lines for evidence of enhanced transit absorption and search for evidence of early ingress due to bow shocks ahead of the planet's orbital motion.



ASTERIA, the first CubeSat telescope. Launched into low Earth orbit from the International Space Station in 2017, it has been observing exoplanet transits. Left: Two recent college graduates at JPL obtain hands-on experience with ASTERIA. Right: artist's conception of ASTERIA in orbit.

Suggested below are four complementary programs that could, over the coming decade, make a large number of advanced CubeSat telescopes available for research by professional scientists, citizen scientists, and student researchers.

1. CubeSat Autonomous Telescope Constellation

ASTERIA has shown that high-precision, time-series imaging photometry can be accomplished with a 6U CubeSat telescope. The 6U SPARCS telescope is paving the way for ultraviolet time-series photometry, while CUTE is doing the same for ultraviolet spectroscopy.

The objective of this first of four proposed programs will be to extend the pioneering accomplishments of these three CubeSat telescopes to a constellation of CubeSat astronomical telescopes that will serve a large, growing, and diverse community of professional, student, and citizen science researchers. A constellation with a dozen or so telescopes could be in orbit by the end of the decade.

It is vital that, from the start, this constellation should be fully autonomous. As described earlier, dynamic planning and execution, as well as fully automated initial data reduction, were standard from the outset at the Fairborn Observatory. Preset sequences were never generated, and raw data was never sent to users. On-the-fly image quality assessment was added early on, followed by increasingly sophisticated health monitoring.

The Las Cumbres Observatory solved the much more difficult dynamic problem of autonomously handing off multiple targets between telescope as the earth turned or weather intervened. The challenge is to implement these autonomous features in space, where, unlike the ground, the telescopes are on the move and cannot be accessed for maintenance. See “Enabling and Enhancing Astrophysical Observations with Systems Autonomy” (Rashied Amini et al. 2019). The growing fleet of downward-looking Planet Labs CubeSat telescopes could inform upward-looking telescopes about autonomy and efficiently serving a large community. For ideas on a constellation of CubeSat telescopes, see *CubeSat Astronomy Network* (Alex Johnson et. al., 2019).

Besides autonomy, telescope designs should stress evolvability; how, over time, more capable telescopes could be gracefully added to the growing constellation. Designers should also consider how telescopes could be produced in large quantities at low cost while still assuring high reliability. Extensive documentation, videos, and workshops could facilitate telescope use by the many professional, student and citizen scientist researchers who will be using these telescope.

2. CubeSat Telescope Advanced Technology

As miniaturization advances and launch costs drop, the number of ever more capable CubeSat astronomical telescopes will inevitably increase. Exploring and demonstrating new CubeSat astronomical telescope technologies will be the focus of this second program.

Some of these technology advancements, such as propulsion, should be common to other CubeSat applications. CubeSat propulsion systems could be used for station keeping or extending orbital lifetimes.

Another likely advancement would be increasing the aperture of CubeSat telescopes. This could be done through larger CubeSats (12U or larger) or deployable mirrors (ala the James Web Space Telescope) are a possibility. The AAReST (Autonomous Assembly of a Reconfigurable Space Telescope) program is planning on using multiple CubeSats to demonstrate how this might be accomplished.

A third likely development would be extending wavelength coverage to other wavelengths. CubeSat infrared telescopes should be possible if sufficient vibration-free cooling could be provided in a small enough package, although ESPA-Class spacecraft may be required.

3. CubeSat One-Off Telescopes, Kits, and Commercial Ventures

Instead of purposefully uniform, perhaps even identical telescopes, the third program features a wide spectrum of telescopes. Some of these could be one-off, inventive creations.

Others could be constructed from proven plans or assembled from kits (just parts or preassembled critical subsystems). CubeSat frames and other parts could be produced on 3-D printers. Accompanying the kits would be extensive documentation, training courses, websites and blogs, as well as regional, state, and national clubs and competitions—similar to robotics.

Commercial firms could, similar to Planet Labs’ earth-pointing telescopes, provide outward-pointing telescopes to subscribers for astronomical research. This would be the space-based equivalent of the Fairborn Observatory’s original Rent-a-Star program and the rapidly growing number of commercial ground-based small-telescope “farms” and networks.

These various CubeSat telescopes could be provided with a relatively benign ride to Low Earth Orbit. LEO has the distinct advantage that these telescopes, some which might not work, would naturally deorbit and burn up in a few years, thereby avoiding space clutter.

4. CubeSat Telescope Community of Practice

The transformative development of small ground-based robotic telescopes and networks was achieved through a several-decades-long process of formulating and nurturing a supportive research and development community of practice. Two existing, small ground-based telescope communities of practice have already shown an interest in the development and use of CubeSat astronomical telescopes: the Alt-Az Initiative (engineering development) and InStAR, the Institute for Student Astronomical Research (published student research). These two often work together.

Three CubeSat Astronomy workshops have already been held: at the Society for Astronomical Sciences' 38th annual symposium (June 2018), the 13th annual Alt-Az Initiative workshop (July 2018), and CubeSat Astronomy workshop at California Polytechnic State University (April 2019, that immediately followed the 16th Annual CubeSat Developer's Workshop).

Four new CubeSat Astronomy workshops are in various stages of planning for 2020. They include: *CubeSat Astronomy in the 2020s* (at the American Astronomical Society winter meeting in Honolulu, January 5), *CubeSat Astronomy II* (in April, again at Cal Poly in conjunction with the 17th Annual CubeSat Developer's Workshop), a workshop at NASA Ames Research Center in June, and a session at the 14th annual Alt-Az Initiative workshop in August.

IV. Conclusion

We are on the verge of a CubeSat astronomy telescope revolution. ASTERIA, SPARCS, and CUTE are leading the way. We can emulate, in space, the path pioneered by small ground telescopes where—thanks to their supportive and inclusive communities of practice—a synergistic balance has been achieved between large and small telescopes and paid and unpaid researchers.

By the end of the next decade, a constellation of autonomous, low-cost, production CubeSat telescopes could significantly increase the overall synergy, balance, and cost-effectiveness of astronomical research in space. In addition to expanding the availability of space telescopes to professional astronomers and their graduate students, CubeSat telescopes could open up the direct use of space telescopes to a large number of undergraduate and high school students and citizen scientists.

Everything is in place. The door to the revolution is open. We should grab this moment to walk through it.

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