

Astronomy Education Review

2013, AER, 12(1), 010204, <http://dx.doi.org/10.3847/AER2013009>

Exploring the Hidden Structure of Astronomical Images: A “Pixelated” View of Solar System and Deep Space Features!

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Received: 04/12/13, Accepted: 08/17/13, Published: 09/12/13

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Abstract

We describe activities created to help student participants in Project ITEAMS (Innovative Technology-Enabled Astronomy for Middle Schools) develop a deeper understanding of picture elements (pixels), image creation, and analysis of the recorded data. ITEAMS is an out-of-school time (OST) program funded by the National Science Foundation (NSF) with the goal of inspiring grades 5–8 students to pursue ICT (Information and Communications Technology) and STEM (science, technology, engineering, and mathematics) careers and increasing their 21st century work skills. ITEAMS students access our department’s MicroObservatory, online telescopes from home and school to request solar system and deep space images taken during the nighttime hours, and then receive an email the next morning notifying them their requested images are available for retrieval. Once retrieved, students use the project software to process the images. We found image processing became more meaningful when students developed some understanding of what a pixel is, what causes different saturation levels of the pixels, and the nature of the data stored in the pixels. We developed a set of hands-on explorations for students to investigate pixels, sensors, and data transmission. Anecdotal evidence suggests students increased their understanding of the nature of pixels, the underlying technology, how the data are transmitted, and a better sense of how processing astronomical images changes the way data are represented but does not change the data itself.

1. INTRODUCTION

Nearly all of today’s middle and high school students have seen pictures where the “checkerboard-like” squares of individual pixels become evident, a phenomenon common with enlarged images on computer screens, cameras, cell phones, and more (Note-1). Yet what these pixels, or pixel elements, represent or how they occur is not widely understood. This issue emerged for us when working with students taking part in our project ITEAMS (Innovative Technology-Enabled Astronomy for Middle Schools). ITEAMS is an out-of-school time (OST) program funded by the National Science Foundation (08-33378) to the Science Education Department (SED) at the Harvard College Observatory (HCO) (Note-2). Central to ITEAMS are the SED’s online, robotic MicroObservatory telescopes, currently located in AZ and MA (Note-3). The need to provide more information about pixels became apparent with the first cohort of ITEAMS participants. Students download and begin to

process requested images no later than the second meeting. Our introductory image processing software includes a tool to determine linear sizes of objects in pixels. Placing a cursor over any part of an image reveals the “pixel value”—the quantity of measured light—of a single pixel plus its y and x coordinates in the field. Students can also change the dynamic range of an image, using a sliding scale to set and identify minimum and maximum pixel values for reference points. When a student greatly enlarges an image, the individual pixels are prominently displayed. We realized the students were immediately confronted with both the term “pixel” itself and the “pixilated” visualizations on the computer screen that were central to the activities, but where they had little if any insight into what the pixels represented or the embedded technology. Additionally, we realized the need to address the common misconceptions about the capabilities and limits of modern technological tools, plus the strong belief that images can be resolved infinitely. We describe below our efforts to create investigations to help students develop deeper understanding of both the nature of pixels and the information they contain.

2. THE NATIONAL PERSPECTIVE

The twofold goal in ITEAMS is to inspire students to pursue and persist in ICT and STEM career pathways using astronomy as an entrée and to increase their 21st century technological skills. We especially target girls and underserved minority youth. The background for these needs has been extensively documented in the literature on the national imperative for STEM and the value of OST programming and is not a focus of this article. We note here only a word about the value of astronomy as the entrée for engaging more students in ICT or STEM. In one of our most recent online surveys conducted to gauge the interest in ITEAMS, about 90% of the nearly 350 OST or formal classroom educators responding reported strong or very strong interest in astronomy as a way to engage students. This mirrors the pattern we saw in ITEAMS. While it was one of many OST options in each of the participating schools, a majority of the students chose to stay involved for two or three years.

3. THE ITEAMS PROJECT

ITEAMS is part of an NSF workforce development program for grades 5–8 students. Building on the widespread, intrinsic interest in astronomy, technology, and robotics, we created ITEAMS to inspire students to pursue and persist in ICT and STEM career pathways and increase their 21st century work skills. We believed that providing unlimited access to the MicroObservatory telescopes would interest students in either field. Over the last decade, there has been a significant increase in the use of robotic telescopes by professional and amateur astronomers, as well as by college and pre-college students. MicroObservatory, designed and developed in the late 1980s by scientists and engineers at the HCO, is one of the first initiatives giving students access to robotic telescopes.

The MicroObservatory network is a free, online system that permits multiple users simultaneous access to the robotic telescopes. Its research grade telescopes were specifically built for educational purposes, whereas other systems restrict the amount of time designated to education. We believe it is the only automated telescope system designed for novice learners. It has a 15-year history of building reliability, reaching and engaging larger audiences, and serving as an entry point for students of all ages to readily acquire and process research grade data. Most, if not all other robotic telescope systems are inherently limited in their ability to accommodate large numbers of users, especially novices. The limiting factors include the specialized knowledge required to select appropriate targets and the restriction permitting only one user at a time. Since the MicroObservatory telescopes are optimized for educational use and require no previous experience, parents or caregivers also find them readily accessible. The telescope portal most used, Observing With NASA (OWN) (<http://mo-www.cfa.harvard.edu/OWN/index.html>) has specialized software that automatically permits users to know what objects might be visible at some point that night. This allows even first-time observers to request and receive current image data without depending on a telescope operator or other expert, nor wait extended periods of time to receive requested images. An observer can select exposure time for target objects and a choice of filters. The system automatically pools all observers' requests. If there are a hundred individual requests for a single target object that night, the MicroObservatory system optimizes observing resources by taking a single image of the target object that is then available for all who requested it. More robotic telescopes are now coming online, but nearly all, if not all require sophisticated software and expert assistance in operating the instruments. Since its inception MicroObservatory has been the centerpiece for six projects and in April 2010 registered the 500 000th image taken with the telescopes.

Each of the past four years we worked with as many as 150 students from five Eastern Massachusetts schools who used the MicroObservatory telescopes and a complementary curriculum. Students controlled the robotic telescopes during or after school, entering target coordinates for solar system or deep space objects, exposure times, and filter choices. The selected images were available next morning for downloading and processing. We also included explorations in modeling, determining size and scale, light and color, and a range of other activities to investigate the technology of image acquisition, transmission, and processing. There are both academic and non-academic partners, including: Harvard University's Earth and Planetary Sciences Department; the Amateur Telescope Makers of Boston (one of the oldest and largest amateur astronomy clubs in the nation); and the Retirees' School Volunteers Association (supported by Raytheon Corporation, and whose retired engineer members annually contribute more than 5000 h of volunteer service to area schools).

4. THE TELESCOPES AND TECHNICAL SPECIFICATIONS

MicroObservatory is a network of five compact, internet-enabled robotic telescopes. Currently the telescopes are in Cambridge, MA (where the network's staff and support facilities are located) and at the Smithsonian Astrophysical Observatory's Fred Lawrence Whipple Observatory in Amado, AZ. Each telescope (see Figure 1) has two co-aligned optical systems. The primary or main telescope is an original Maksutov design, with a six-inch spherical primary mirror and a slightly smaller corrective lens, resulting in a $f/3.6$ ratio with an effective focal length of 560 mm. The finder or secondary optical system uses a 28 mm $f/4.5$ focal length wide-field photographic lens to form an image on a second CCD. This system also gives a 650 pixel by 500 pixel image, but with a field of view that is 12° wide and 9° high. Observing requests of the Sun can only be done by request since an externally mounted solar filter must be manually installed in advance by project staff.

5. IMAGE PROCESSING

ITEAMS students receive emails each morning informing them that the images requested the previous afternoon or night are posted on the MicroObservatory Image Directory and available for retrieval (images are stored on the Directory for 1 month after they are taken). The same images are also freely available online to anyone visiting the network's website. There are several options for retrieving image data. We recommend that students access the FITS (Flexible Image Transport System, the standard data format in the astronomical community) formatted images and move them to their desktops. Following they download the free MicroObservatory image



Figure 1. MicroObservatory Telescope at Mt. Hopkins, AZ

processing software and drag their FITS images onto the opening screen. The images are then ready for processing and analyzing (Note-4).

Original images retrieved have no pixels with a value below the minimum displayed and none above the maximum displayed value. For an image with a maximum pixel value of 800, there are no pixels with greater light saturation. Generally, the first processing step is to adjust the brightness and contrast of the black and white images, as many unprocessed images, especially those of deep-space objects, appear completely black with only a few white points (initially students interpret this to be a faulty image without value). The “Adjust Image” tool in the software pull-down menu window displays numerically the minimum and maximum pixel values of images, or respectively, the lowest and highest pixel values. There is a button to raise the minimum and lower the maximum range either linearly or logarithmically (relative to the mean brightness value). In effect both options narrow the intensity range so that all the pixels with values outside a mathematically determined range are re-displayed as either black (pixel value = zero) or white (pixel value = 4095). This narrower range contains the critical data for the target object, allowing one to better change the brightness and contrast of the images, alter the image quality, or highlight image features of interest. With practice the students learn how to represent the same data in different ways to emphasize hidden details or unseen structures. The students also discover there are limits to what evidence can be drawn from the image data. In some ITEAMS activities, they determine the angular, proportional, and actual sizes of features and the objects working from the linear size measured in pixels. A zoomed-in image is highly pixilated. While it is useful for measurements, the quality of an enlarged image has limited use for the other processes. There are also other image-processing options. One can invert the image color (e.g., displaying white as black, and vice versa) or colorize images. Working with three separate images of the same object taken with the red, green, and blue filters, the students can combine these images into a full color picture (see Figure 2).

The measuring tool to find linear pixel dimensions allows students to determine a number of physical characteristics of features or objects. We have students measure the pixel dimension of a moon crater and that of the Moon itself to compare their relative sizes. Given the actual diameter of the Moon it is possible to determine the diameter of the crater. More experienced ITEAMS students use MicroObservatory images combined with classroom activities to determine the distances to the Moon, other solar system objects, and deep-space structures. Figure 3 below is a partially processed image (taken 7 August 2012 at Mt. Hopkins, AZ) of the Waning Gibbous Moon shown with the measuring tool line indicating the approximate Moon diameter to be 354 pixels (or 1770 arc seconds, which is equal to about 29.5 arc minutes).

ITEAMS students envisioned every MicroObservatory image as a two-dimensional array of squares (like a checkerboard). Images are 650 pixels wide and 500 pixels wide, consisting of 325 000 individual pixels. Each pixel represents a unique location in the image with specific coordinates, and is assigned a grayscale number, between 0 and 4095, representing the level of darkness or brightness respectively for that part of the image. The fact that a pixel cannot be divided infinitely nor contain limitless data is not intuitive, and is difficult for students



Figure 2. MicroObservatory Image of M-42 (Orion Nebula)

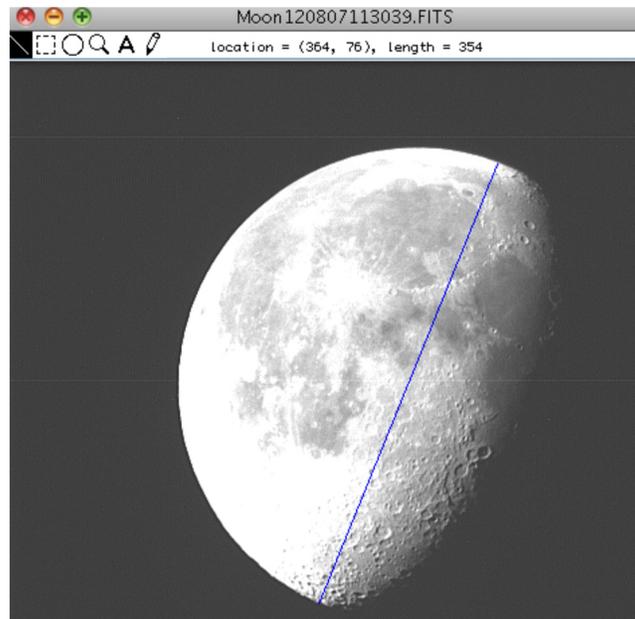


Figure 3. MicroObservatory Image of the Waning Gibbous Moon

to accept. The model we use to address this difficulty is that of painting by numbers, where each pixel receives a numerical value for the light saturation captured by the digital detector (i.e., its pixel value). What is important for students to understand is that altering the grayscale or color of an image does not alter the data embedded in each pixel. Rather, they are displaying the image data differently by re-assigning a different grayscale or color to the pixels. The meaning of this numerical data is best understood using the photon model for light behavior; teachers can choose if and when to introduce it to their students. Generally it is beyond the scope of our ITEAMS program to discuss the electronic aspects of the MicroObservatory telescopes' CCD light sensor, although as described below, we created activities to uncover why the numbers assigned pixels differ from one to another.

6. STUDENT UNDERSTANDING OF PIXELS

While a large body of literature exists about student understanding of light and color, writings on common ideas about pixels are sparse and almost exclusively related to photography. If students have wondered at all about pixels it is likely related to the shape, especially if they have seen the composition of magnified newsprint. We believed it was important for students to come to understand information in a pixel is fixed, representing a specific location and brightness value in an image. While possible to represent that information in a variety of ways and transmit it to others, the information itself cannot be altered.

7. “PENNIES FROM ABOVE” AND “PAINT BY NUMBERS”

We developed activities to investigate pixels after showing some students the components inside a telescope—the mirror, lenses, filters and filter wheel, the CCD sensor, the motors, the circuit board, wiring, and more. Many questions followed: How do you control the telescope from your computer? How does an image get from the telescope to a computer screen? What do the numbers for each pixel mean? Subsequently, we created activities to model how the image of a celestial object taken with a telescope hundreds of miles distant ends up on one's computer screen, using a systems approach (i.e., command, transmission, tracking target objects, capturing the light, etc.).

7.1. “Pennies From Above”

Finding a simple way to model how the telescope's CCD sensor captures photons was a challenge. Astronomers commonly use the analogy that a telescope is like a water bucket that collects “droplets of light” (photons). While imperfect, it is a good starting point if one envisions the CCD as an array of tiny buckets. We dropped objects (dried beans, coins, etc.) from different heights into a variety of containers (small paper or plastic cups,

bowls, etc.), arranged in grids. We chose to use the bottom of pressed paper egg cartons (not plastic or Styrofoam types) for the model pixels and pennies for photons. We arranged three egg cartons—each carton has two rows of six cups—into a six-by-six grid. We found the optimum number of pennies was between 50 and 75, and the optimum drop height about 50 to 70 cm. What worked best was to gently “pour” the pennies into one hand, letting them fall through the spaces between outstretched fingers. The number of pennies in each cup is recorded on a grid once all have been dropped. There are potential misconceptions: all photons are equivalent (inferred since all pennies are essentially the same), or the CCD sensor is uniformly sensitive (the CCD used in the telescopes is most sensitive in the red to near infrared, and less so with increasing energy levels of photons). But our pilot testing did confirm that dropping and counting the pennies in individual egg cups gave fuller meaning to the pixel value in the images.

7.2. “Paint by Numbers”

Encoding the data (i.e., the number of pennies in each cup) to be sent elsewhere for replication was the next challenge. Starting from a simple grid with the number of pennies in each egg cup, teams devised a means to “send” its results to another team, but not in picture or graphic form. Students used colors, letters, and symbols as well as numbers to represent the data. What transpired was a new representation of the same data, a “paint by numbers” result based on encoded data. We did not label the y and x axes of the grids in the worksheets, leaving those designations to the students. What became clear—and not always anticipated by students—was the data could not be decoded unless the recipients knew the code used to create the new representation. The whole process models in part how the telescope’s sensor captures data (photons) and transmits the data for storage or display.

8. DISCUSSION

Our primary goal is to inspire students to self-identify with ICT and STEM, based on their intrinsic interest in astronomy and modern technology. Interest in astronomy often dissipates for too many of our younger students with little or no access to resources beyond traditional curricula. And while students are very facile in their use of modern technology, it is primarily utilitarian and generally used with superficial understanding of its underlying principles. The astronomical images capturing the public imagination are nearly all the result of CCD technology. This means that with MicroObservatory we have a perfect vehicle for introducing students to some of the central 21st-century skills.

Our findings are anecdotal or impressionistic. Initially, having a new sense of the meaning of the pixel value gave students a better understanding of what happened as they processed images. After completing the penny drop activity most students saw the image grayscale differences as a product of different amounts of light striking different pixels, and analogously, a paint-by-number process. When the minimum and maximum pixel values were given in the original image students came to understand that every pixel had a saturation level within that range. We also discovered the students saw that while every pixel in their telescope images had an assigned value (within a range), not all the egg cups had pennies. This led to discussions about how models are always imperfect, why some photons are captured in every pixel in the telescope’s CCD sensor, or why the sky is black for pixels where some photons are captured.

When the pennies are dropped into the egg cups the results are unpredictable, not unlike taking an image with the telescope, and relates well to the nature of scientific investigation. A common problem for novices using the telescopes is overexposing the whole image. Students came to see this phenomenon as analogous to having an unlimited number of pennies spilling onto every egg cup. A similar phenomenon is “blooming,” an artifact of imaging some dimmer objects in proximity to a brighter object (as, for example, imaging the Galilean moons of Jupiter). Here, the “spike” of light in the image extending vertically above and below bright Jupiter is the result of photons (more precisely, charge) spilling over into the adjacent sensor cells of the CCD, not unlike pennies in an egg cup spilling over into adjacent cups.

There are two options for “colorizing” an image. In one students can choose to represent their grayscale image in hues of single colors (red, green, or blue) or mixed colors, or with the colors inverted, a good example of “painting by numbers.” Students often note it is easier to see craters on the Moon when the image has been

colorized. No matter how one chooses to alter the image appearance, the pixel information or brightness value remains constant, showing students that when astronomers alter an image for effect, the data remains unchanged.

The second multistep option involves working with three separate images of the same object taken with the red, green, and blue filters to create a full color, composite image. Figure 2 above of M-42 is an example of a full color image from three MicroObservatory filtered images, created by a middle-school student. There is an advanced technique to increase the sharpness of images by subtracting the telescope's electronic "noise" using a dark sky image taken with an opaque filter as reference. ITEAMS students are capable of using this advanced technique, but we recommend it be introduced when they are more experienced since it brings in an exception to the "pixel information does not change" rule.

9. CONCLUSION

What started with student questions about our robotic telescopes evolved into a series of activities highlighting the individual components of our systems approach. We only looked at one of those components in this article, that of the CCD sensors and the information stored within the pixels. We found the penny drop activity gave students a new appreciation for what information or data was embedded in the pixelated values in their images. We found as well that when students came to understand it was possible to represent data differently without altering it (that is, represent or "paint" the same data differently), the experience gave them a deeper appreciation of how astronomical images are modified to highlight important features. Moreover, we see that the knowledge and skills ITEAMS students develop are precisely those skills that are readily transferable to 21st-century ICT and STEM careers.

Notes

Note 1: The reasons for the shape of a pixel are beyond the scope of this article.

Note 2: The grant is from the ITEST (Innovative Technology Experiences for Students and Teachers) program. The HCO partners with the Smithsonian Astrophysical Observatory to form the Harvard-Smithsonian Center for Astrophysics (CfA).

Note 3: A portal to MicroObservatory telescopes, Observing with NASA (OWN), is freely open to the public and can be accessed at <http://www.MicroObservatory.org>.

Note 4: Visitors to the MicroObservatory website can access images from the Image Archive Directory, download the free software, and process the images. Tutorials for all of these processes are on the OWN portal's "Tools and Training".

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