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The Use of Plenoptic Cameras in Astronomy

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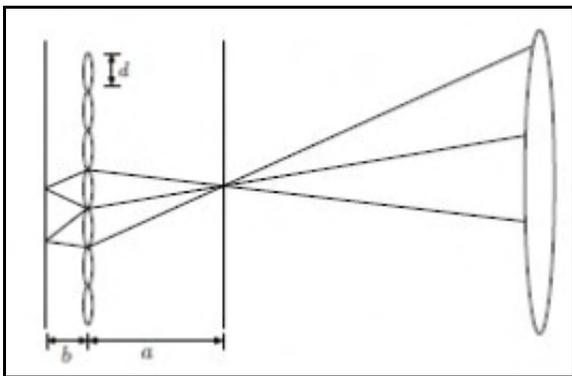Dr. Vincent Wickwar

Physics 4900
Research Project 2017

Abstract

Since light-field imaging cameras are starting to become more in the world today, the question that arises is, "Could these cameras help advance the science when they are used in conjunction with telescopes and microscopes?" With their use in microscopy having been partially settled and no information about their use with telescopes, this experiment was setup to start the ascertainment of the use of light-field imaging cameras with telescopes. With the use of an older plenoptic camera, it was ascertained that a new light-field imaging camera might compare with the conventional digital camera of today.
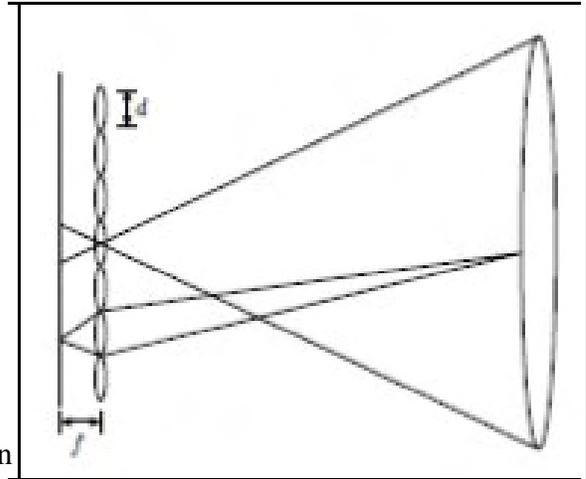
Introduction

There are two types of digital cameras: the standard conventional camera and the light-field imaging or plenoptic camera. Light-field cameras can be further divided into three categories: the standard or traditional plenoptic camera, the focused plenoptic camera, and coded aperture camera. The standard plenoptic camera is a standardized mathematical model used by researchers to compare different types of light-field cameras; by definition the "standard plenoptic camera" has microlenses placed one focal length away from the image plane of a sensor (Figure 1)[1].

The focused plenoptic camera is a type of camera in which the microlens array can be positioned before or behind the focal plane of the main lens; these modifications sample the light field in a way that trades angular resolution for higher spatial resolution. With this design, images can be post focused with a much higher spatial resolution than with images from the standard plenoptic camera; however, the lower angular resolution can introduce some unwanted aliasing artifacts (Figures 2 & 3)[2].

Figure 1: Traditional Plenoptic Camera.

Figure 2: Focused Plenoptic Camera — Real image in front of the microlens array.

The coded aperture camera is a type of plenoptic camera using a low-cost printed film mask instead of a microlens array, proposed by researchers at MERL in 2007. This design overcomes several limitations of microlens arrays in terms of chromatic aberrations which allows higher-spatial-resolution photos to be captured. However, the printed film mask-based design reduces the amount of light that reaches the image sensor compared to cameras based on microlens arrays[3].

Based on the body of scientific photographs in the world, the use of the conventional camera in science, with both microscopes and telescopes, both refracting and reflective, is known. How effective are light-field imaging cameras when they are used in conjunction with telescopes and microscopes?
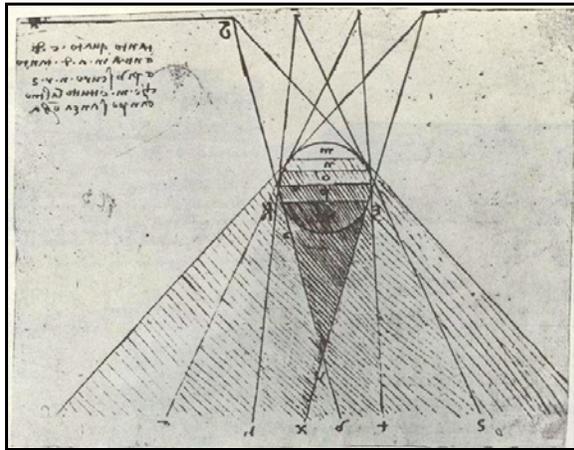
Since the use of light-field imaging cameras has been partially explored in microscopy[4], the question of how effective are the plenoptic cameras in conjunction with reflective telescopes for basic astronomical observations needs to be ascertained. Even though light-field imaging cameras have a depth-of-field function that conventional cameras do not have, another question that needs to be ascertained is at what distance will this depth-of-field cease to function with telescopes. Therefore, the question of the usefulness of light-field cameras is relevant for assessing the practicality of this type of camera.
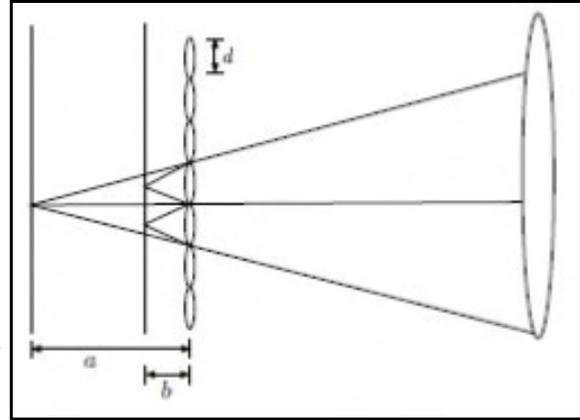
Figure 3: Focused Plenoptic Camera — Virtual image behind the microlens array.

Theory

The first scientist to think of light and light rays not as beams but as fields was Leonardo da Vinci; he thought light rays as radiant pyramids that interacted by intersecting other light rays without interfering with each other (Figure 4)[5]. In May 1846 Michael Faraday indicated that light was related to the fields of electro-magnetism[6]; though this relationship was discredited the scientific community until James Clerk Maxwell published his article "A Dynamical Theory of the Electromagnetic Field" in 1865[7]. Nobel Laureate, Gabriel Lippmann in 1908 created "integral photography"; integral photography uses an array of microlenses to capture images of an object onto a sensor (Figure 5)[8,9]. During the 1930's, integral photography was upgraded by Herbert E. Ives by using a lenticular lens and a large aperture lens that could capture all the information of the object; the lenticular pattern is similar to the Lippmann microlens array. The term of light-field was coined in 1939 by Alexander Gurshen[10,11]; it was defined as the sum of the light rays present at any particular moment. In 1992, Doctors Edward H. Adelson and John Y. A. Wang proposed the current basic design used in plenoptic cameras today[12].

Figure 4: Diagram of Light Rays by Leonardo de Vinci.

During the investigation and development within the scientific field of optics and light-field photography, it became known that light can be broken into seven different angular coordinates and Cartesian coordinates. Such a view can be termed as a plenoptic view, as it covers all the dimensions of light. Unfortunately, the human eye is unable to perceive light in all the coordinates and can retrieve only five coordinates; three di-
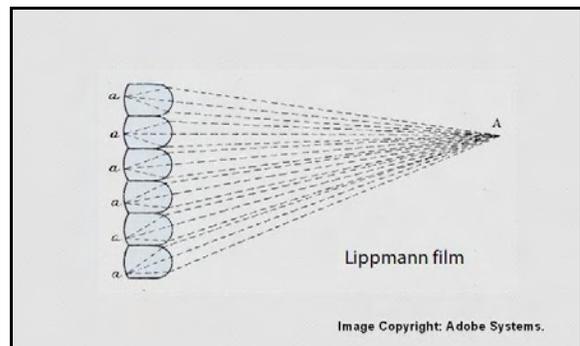
Figure 5: Diagram of Lippman Microlens Array.

mensions for the spatial position and two dimensions for each direction of flow of light. This 5D light-field can be further reduced to a 4D light-field by restricting the two dimensions for flow of light to the flow light of those passing through free-space[13].

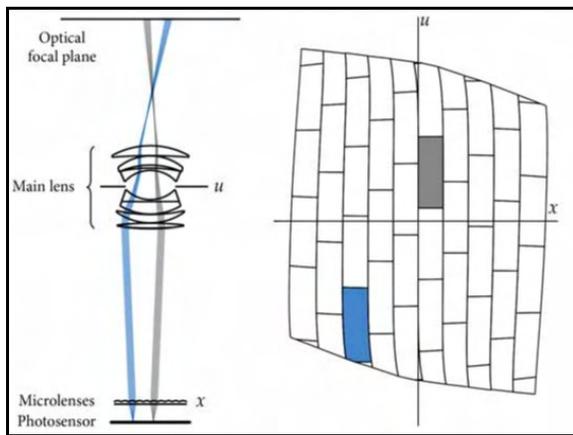How does all of this theory apply to photographs, both conventional and light-field imaging? When a light ray strikes the main lens assembly of a conventional camera, it is bent by the optics of the camera to its imaging plane where the photosensor (or the film for non-digital cameras) is located and the pixel of the photograph is developed from the exposure of all the light rays that strike that pixel (Figure 6)[14]. When a light ray strikes the main optics of light-field imaging
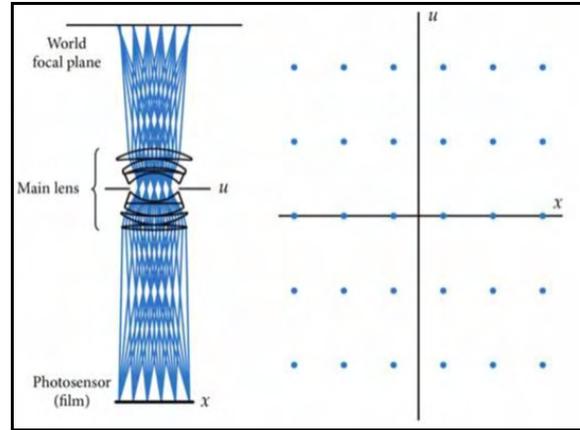
Figure 6: The set of all rays flowing into a conventional camera.

camera, like a conventional camera, the light ray is bent by the lens assembly toward the imaging plane; however, here at the imaging plane is where the microlens assembly of the plenoptic camera is located. The light ray when it reaches these microlenses, along the rest of the light rays, is refocused to the photosensor of the camera (Figure 7)[15]. (If a more detailed explanation of light-field is desired, please read pp. 13–21 of Ren Ng's PhD dissertation and if a more detailed explanation about how optical data recorded, please read pp. 23–47 in the same dissertation.)[16]

Figure 7: Sampling of a plenoptic light field provided by a plenoptic camera.

One of the practical functions of plenoptic cameras is digital refocusing. The simplest application of this function recording of the light-field; this allows the focus of the output photograph to be changed with only one exposure taken. This digital refocusing from the plenoptic exposure has high fidelity due to the light-field being recorded. Another application of this digital function is that it is possible to have a digitally extended depth of field; this application allows every object of the exposure to be in focus at the same time (*i.e.*, like 20/20 vision). (Ren Ng's dissertation is again a good source for a more detailed explanation about digital refocusing, pp. 48–78; for more details about depth of field, please read pp. 52–53 & 57–59.)[17]

Procedures
In order to test the effectiveness of a plenoptic camera, it was proposed that photographs were to be taken by the use of the 20-inch reflecting telescope at Utah State University. The only readily available plenoptic camera for use in this experiment was the Lytro Light-field Camera owned by Professor Vincent Wickwar. And for all of these photographs, the camera was placed on a stand to ensure stability of the camera during the slower shutter speeds necessitated by low-light conditions (Figure 8).

The photographs to be taken for this experiment were to be a series of photographs of different astronomical objects of three different types: stellar, planetary, and earth satellites. These three different categories of astronomical objects were devised to determine the effectiveness of a light-field imaging camera in astronomy.

The stellar object was the Orion Nebula. This stellar object was chosen to see if the plenoptic camera would produce a photograph similar to that of a standard camera. The light-field functions of this camera were not expected to work due to this nebula being at infinity.

There were three planetary objects that were chosen to be photographed: Mars, Jupiter, and Saturn. These were chosen first, to see if the light-field imaging camer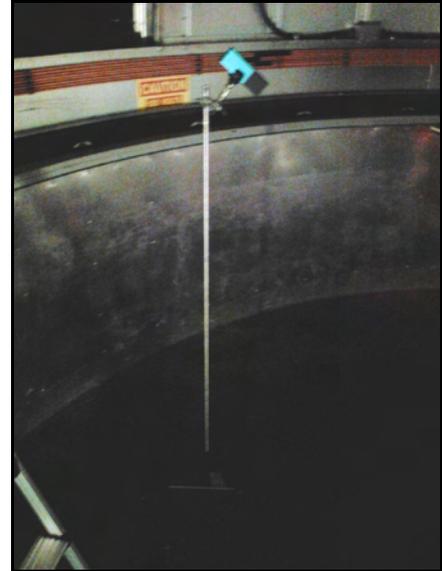a could produce a picture similar to a standard camera, second to determine if the plenoptic functions of the light-field imaging camera could function, and third, if the plenoptic functions did function to see if there were any discernible differences of these functions.

Figure 8: Plenoptic camera on stand.

Of the earth satellites, two were chosen, to test the whether or not they were close enough to allow the plenoptic functions of the camera to work. The first satellite chosen is the largest and most permanent of the natural satellites of Earth — the Moon. The other chosen satellite was the largest of the artificial satellites — the International Space Station.

Figure 9: Failed attempt to photograph Jupiter.

Results

Due to the following reasons, most of the proposed photographs were not taken. Weather was the chief reason for the lack of opportunities for plenoptic photographs. The other reason for the lack of photographs was lack of access to the telescope due to illnesses and a case of bereavement.

Despite these issues, photographs of the Orion Nebula and Jupiter were taken. The photographs of the Orion Nebula and the first set of photographs of Jupiter were taken without the ocular assembly of the telescope. When these photographs were evaluated, the light-imaging photographs either locked onto the secondary mirror or could not be focused onto the target for each set of photographs (Figure 9).

Figure 10: Plenoptic photograph of Jupiter and two of its Galilean moons — ISO = 250 & Shutter = 1/8 s.

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This problem of locking onto the secondary mirror appears to be chiefly the result of the low-sensitivity of the photosensor. The low-light sensitivity of light-field imaging camera is due to the fact that the camera uses a 40 megapixel photosensor to produce a 4 megapixel plenoptic photograph. This 10:1 pixel ratio which is used for reading the light-ray information also makes the camera more sensitive to light.

When the ocular assembly was reinstalled, multiple photographs of Jupiter were taken. With the focus centered on the planet Jupiter, these photographs were taken at different shutter speeds and different ISO settings. Out the nine separate exposures of Jupiter, the sixth photograph, with the shutter speed set at 1/8 seconds by the camera's auto shutter setting and the ISO setting of 250 yielded the best plenoptic photograph (Figure 10).

Figure 11: Jupiter underexposed — ISO = 80 & Shutter = 1/8 s.

When the first five photographs were taken, they were overexposed; this overexposure was chiefly due to the shutter speed being too long (1–8 s, Figure 12). Once the shutter speed was set to 1/8 s, the ISO setting was adjusted lower in an attempt to obtain a better exposure of Jupiter. However, these three attempts resulted in underexposing of the plenoptic photographs (Figure 11).

When the best exposure is compared to the conventional camera's photograph of the same planet, multiple differences between the types of cameras appear. The first is the clarity of the photographs,

Figure 12: Overexposed Jupiter — ISO = 250 & Shutter = 1 s.

which is mainly due to the output resolution of the two cameras. (The conventional camera has a higher output resolution, which allows one to clearly see the bands of Jupiter's atmosphere that appear in the conventional photograph.) The other reason for this clarity issue is that the conventional camera was able to focus better under the circumstances than the autofocus of the light-field imaging camera. Further, the conventional camera also had a better field of view than the light-field imaging camera; this is evident by the fact that all of the Galilean moons are present in the convention photograph versus the two in the plenoptic camera.

Though not readily evident, a good quality conventional digital camera functions better than this model of plenoptic cameras.

Figure 13: Jupiter and the Galilean Moons from a conventional digital camera.

This model is hard to use effectively, especially when the user has big fingers. The small, interactive LCD screen makes it harder to use for those with large fingers than those with average-sized or small fingers. Meanwhile, good digital conventional camera have larger LCD screens and buttons to making selections easier to make.

Conclusion

Based on the limited success in taking plenoptic photographs in this experiment, light-field imaging cameras do not appear to be better than or as good as a good quality, conventional, digital camera. Since this assessment is based on a small sample of photographs, a more qualified decision about the effectiveness of this type of camera needs a larger sample of photographs. Further, to increase this sample pool, the model of light-field imaging camera needs to be changed from the novelty model, Lytro Light-field Camera, to plenoptic camera Lytro Illum or one similar to it. (The Lytro Illum is more like a DSM Camera which makes caparisons between the two types of camera more equitable.)

Furthermore, until the limit of the depth of field function of light-field imaging camera is ascertained, the telescope should be changed to either low-powered refracting telescope or a low-powered reflecting telescope and the telescopic objects should be changed. These telescopic objects should be distant or intermediate objects of scenery where the depth of field function of plenoptic cameras can be employed. When the depth of field function of plenoptic cameras is employed, the value of light-field imaging camera versus the conventional camera can be ascertained.

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13. Id. Reference #11 (p. 12).

14. Id. Reference #11 (Figure 2.2, p. 15).

15. Id. Reference #11 (Figure 3.1, p. 25).

16. Id. Reference #11.

17. Id. Reference #11.