A software solution to atmospheric turbulence effects in astronomical imaging

By Pedro Agundez Fernandez

Supervised by David Bebbington

Assessed by David Bebbington and Hossein Anisi

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Abstract

When taking pictures of the night sky, one of the problems that are faced is the refraction that light coming from space suffers when it goes through the atmosphere. If a small portion of the sky is observed, the light is mostly refracted with the same angle.

However, due to the turbulence in the atmosphere, this angle is constantly changing. This means that increasing the exposure time tends to blur the images.

To overcome this, a series of short exposure pictures are taken, which results in each of them having a shift in relation to each other.

What this program does is, it calculates the shift of each short exposure image in relation to each other, to then align and combine them to form the result image.

Introduction

What is the problem?

“The telescope is undoubtedly the most important investigative tool in astronomy [1]” and a good telescope needs to have both a high sensitivity and a high resolution. The sensitivity can be defined as “…a measure of the minimum signal that a telescope can distinguish above the random background noise. [2]”, that is, the amount of light it can gather, so, the higher the sensitivity, the fainter the object we can study.

The resolution is defined as “…the smallest angle between objects that can be seen clearly to be separate [3]”.

$$\theta = 1.22\frac{\lambda}{D}$$

The formula above shows how to calculate the minimum angular resolution that a telescope would achieve in ideal conditions, where **θ** is the angle in radians, **λ** is the wavelength of the observed light and **D** is the diameter of the lens aperture.

The angular resolution is inversely proportional to the diameter of the lens, which means that if we wanted to improve the resolution, we would need a wider lens. However, if our telescope is on the earth’s surface, we will reach a point in which increasing the lens size does not improve the resolution, this is due to the distortion caused by the atmosphere.

If we observe a point-like source of light like a star, its spherical wavefront can be treated as a plane [4] (because of the very long distance to the earth), so all the light rays have parallel directions. When the wavefront goes through the atmosphere, the local differences in the temperature (and therefore density) of the air cause the light to get diffracted unevenly, resulting in an aberrated wavefront (see figure 1).

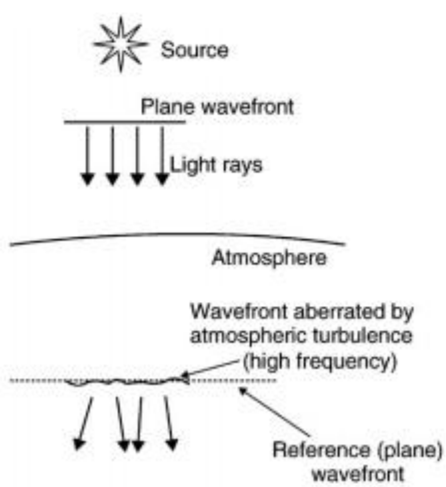

Figure 1

A solution to the atmospheric turbulence aberration is to have the telescope in a place where the incoming light goes through less atmosphere before reaching the sensor. That is the reason why most of the important observatories are on high altitude locations, or outside of the atmosphere, like the Hubble and other space telescopes.

However, it is not cheap to put a telescope in orbit, and even though the effects of atmospheric turbulence are greatly reduced when observatories are placed on top of mountains, they aren't fully mitigated. So, there is a need for systems that correct these aberrations.

Why is this problem important?

But why would we want to improve our telescopes? Astronomy has improved our lives since its beginnings, from helping us to navigate the oceans and mark the seasons, to understanding the influence of the sun on Earth's climate. Astronomy has also changed the way we think of ourselves, the origin of our planet and the place we occupy in the universe. The technological advances of astronomy transfer directly to society. In the industry, the Charge Coupled Devices (CCDs), first used in astronomy, replaced film in cameras. In medicine, the technology of radio astronomy is used in detection of tumors.
A low-energy X-ray scanner developed by NASA is now used in surgeries, sport injuries and third-world clinics [5]. These are just a few of the many cases in which astronomy has benefited us directly or indirectly.

In particular, mitigating the effects of atmospheric turbulence has huge advantages, as Dr. Nicholas Scott from NASA says:

"If you think about the choices of optical telescopes without an atmosphere, it's basically Hubble. Hubble is only a 2-meter telescope and that's pretty small these days. If you can get an 8-meter telescope on the ground and remove the atmosphere, you can obtain the equivalent of space-based observations and obtain the highest resolution images produced today by any single telescope." [6]

What are the solutions?

As mentioned before, the best way around atmospheric effects is to observe from outside the atmosphere, but given that the estimated cumulative costs of the Hubble telescope in 2010 were $10 billion [7], it is better to consider other solutions. In this case, the solutions that are going to be described are adaptative optics and speckle imaging, the latter being the approach taken in this project. It is important to mention that both techniques can, and are, used together.

Adaptative optics

Adaptative optics imply changing mirrors placement and or shape to correct the aberrated wavefront, the mechanism that is normally used is shown in the diagram below [8, Fig. 2].

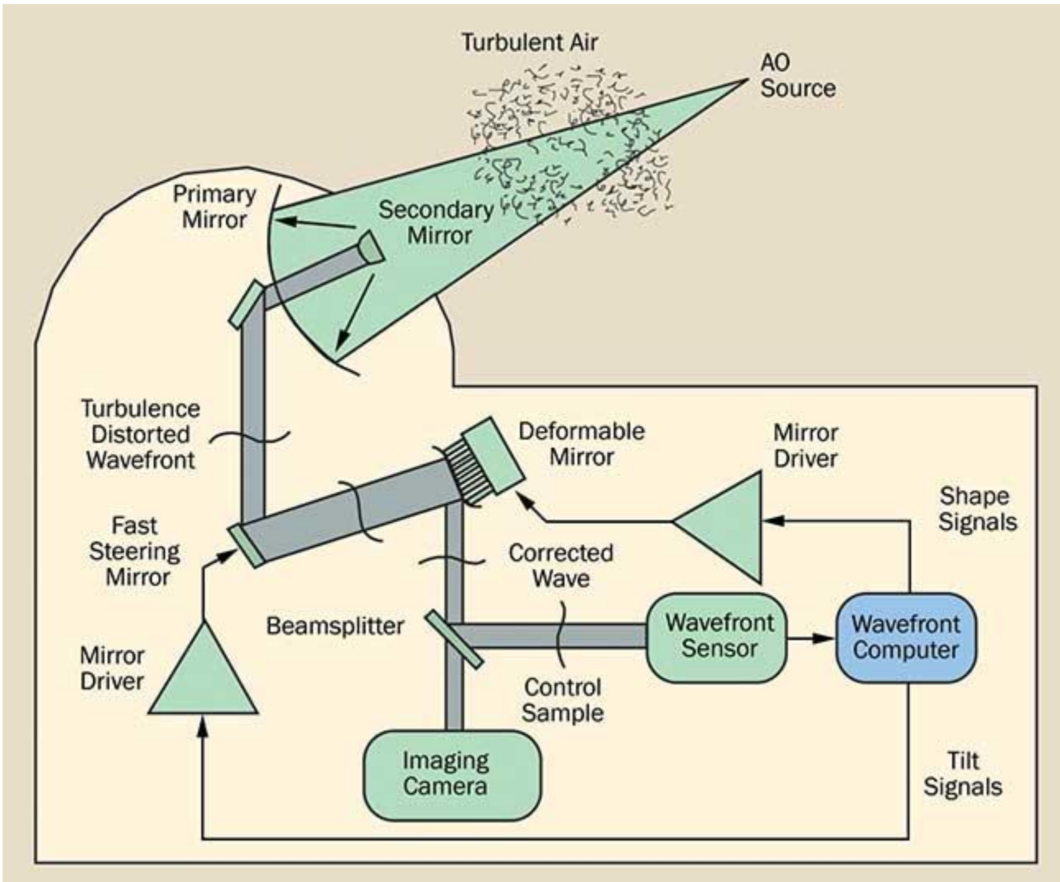

Figure 2

When the aberrated wavefront comes in, a control sample goes to the wavefront sensor, which optically analyzes the sample and sends the data to a computer, the computer calculates the general tilt and the local aberrations of the wavefront, and adjusts the fast steering mirror and the deformable one to correct the incoming beam, resulting in a corrected, high resolution image.

Adaptative optics systems are being used in many important telescopes, such as the Very Large Telescope (VLT) or the Keck I and Keck II telescopes [8].

Speckle imaging

Speckle imaging differs from adaptative optics in that it doesn't require as much hardware, which makes it cheaper and more accessible. For example, the Alopeke telescope, which is the instrument that was used to capture some of the images I have used for this project (see Figure 3), cost less than $300,000 to build [9].

This technique consists in taking multiple short exposure pictures (usually around 60ms), that freeze the variation of atmospheric turbulence, and stacking them to form a complete image with a high signal to noise ratio.

Shown below (figure 3) is how the binary star system HIP 36132 looks at an instant, captured by the Alopeke telescope with an exposure time of 0.06s, the atmospheric turbulence makes the captured images look grainy (formed by speckles), and the stars appear slightly shifted from one image to another.

If the system was captured with a longer exposure time, the changes in the atmosphere would result in a blurry image, similar to the one shown in Figure 4. On the other hand, if the short-exposure images are stacked, the resulting image (Figure 5) looks sharper, with a higher signal to noise ratio.

Speckle imaging has helped identify many binary star systems and is currently being used to look for exoplanets.

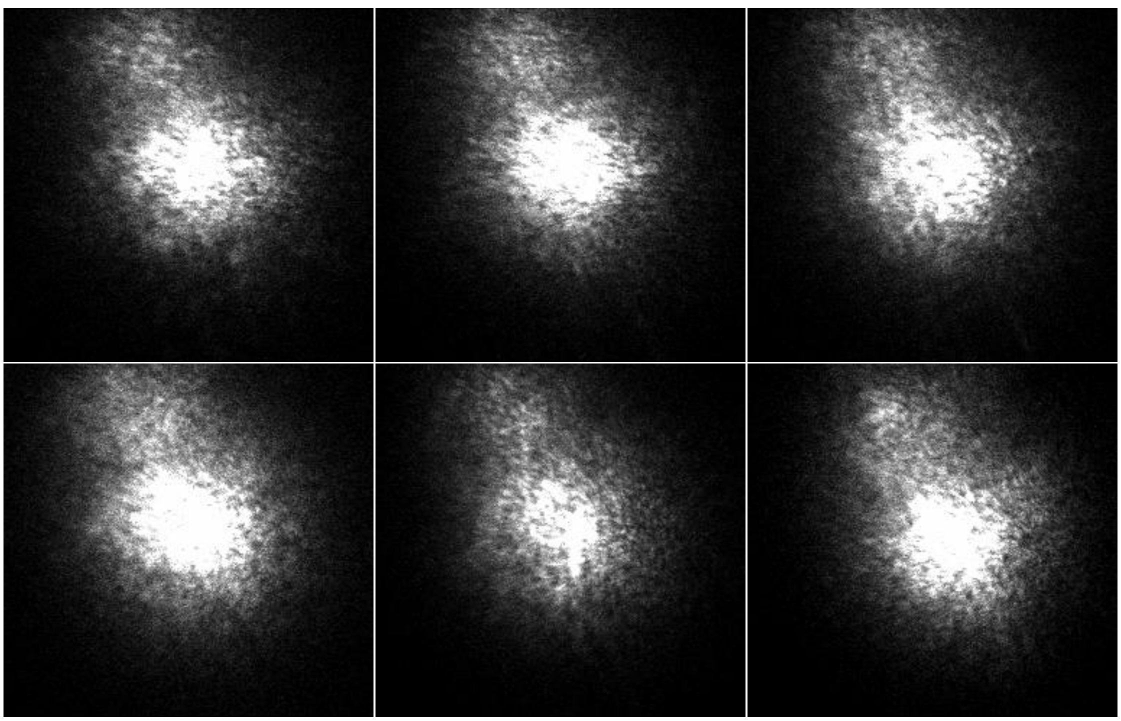

Figure 3

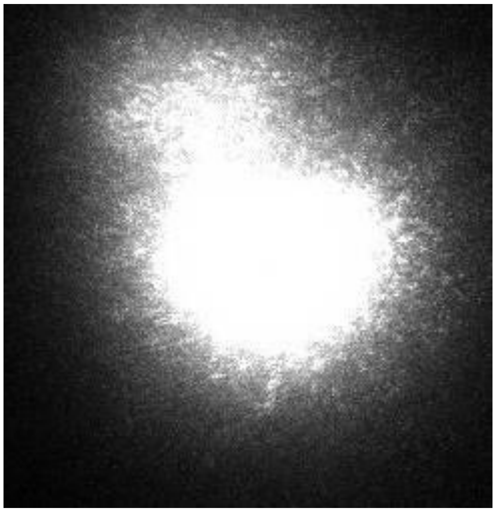

Figure 4

Figure 5

3. Objectives

The aim of this project is to create a program that can process multiple images to reduce the effects of atmospheric turbulence, in situations where the images are shifted and not rotated or deformed. The use in mind for this program is amateur astrophotography and not research grade imaging, with that said, the goal is to achieve a visually noticeable improvement from the input images to the resulting one.

4. Technical Documentation

All the technical documentation can be found in the following Gitlab repository:

https://cseegit.essex.ac.uk/ce301_2020/ce301_agundez_fernandez_pedro

5. Project Planning

My planning of the project has consisted in various weeks of intense work, spread over the length of the academic year. In those weeks I have organized myself to leave most of the available time for the project. The rest of the time I have done the opposite, leaving a smaller portion of my time for the project.

The diagram below (figure 6) shows the number of issues created since the beginning of the project. Each “step” corresponds to a period of more intensive work.

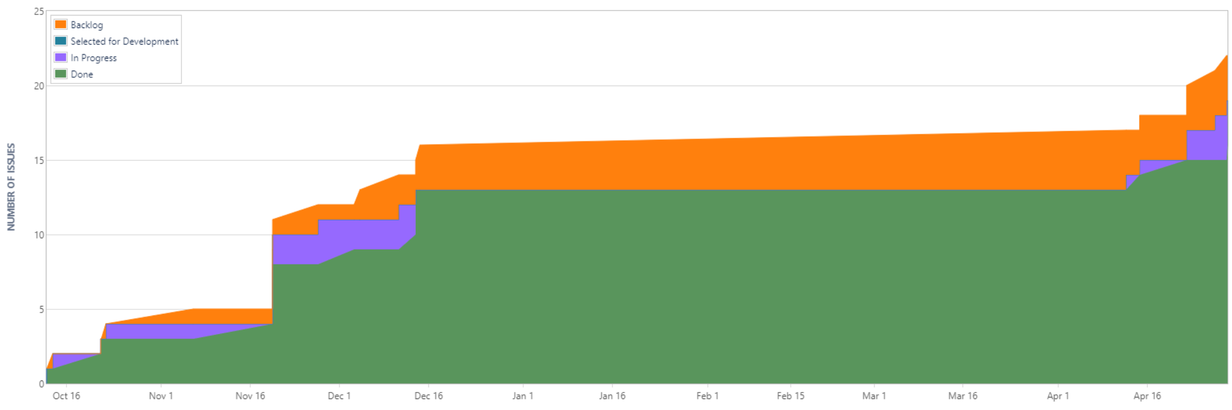

Figure 6

I have found the use of Jira more useful for recording the progress than for planning.

6. Conclusions

To conclude, I will present the results of the tests. The description of each test can be found inside the readme file in the Tests directory of the repository.

Starting with the Jupiter test, it shows that the program successfully mitigates the artificially simulated noise when supplied multiple images. Shown on the left (figure 7) is one of the images supplied to the program, on the right, the result image generated. Please refer to the technical documentation to see the full images.

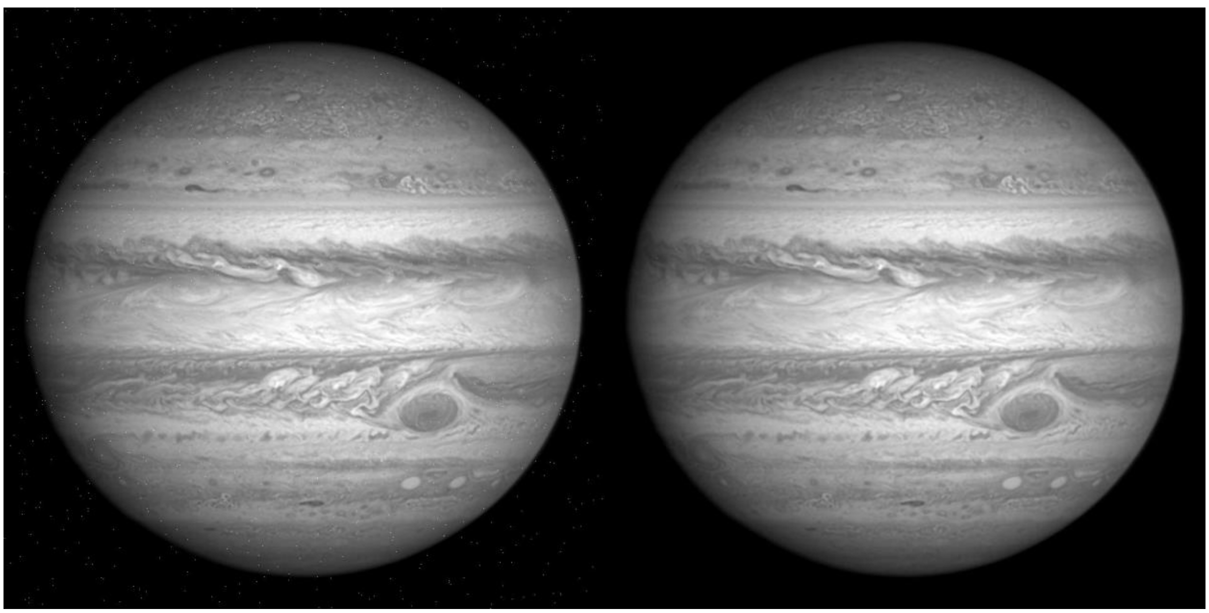

Figure 7

The noise in the images was measured for 25 runs of the test, where noise was randomly generated each time. The result shows that every time, the noise was reduced significantly.

Figure 8 shows the signal-to-noise ratio of both images for the 25 runs.

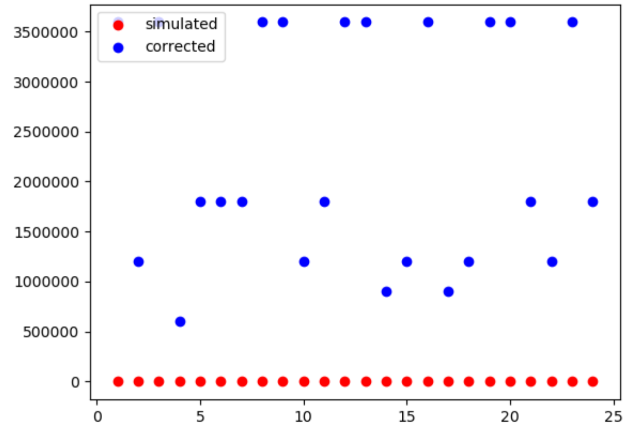

Figure 8

The next test I am going to mention is the night sky test, the results of this test show that the program is capable of correcting the shift of the images, and that it corrects image noise when it is not simulated. On the left (figure 9), one of the input images and on the right the result image.

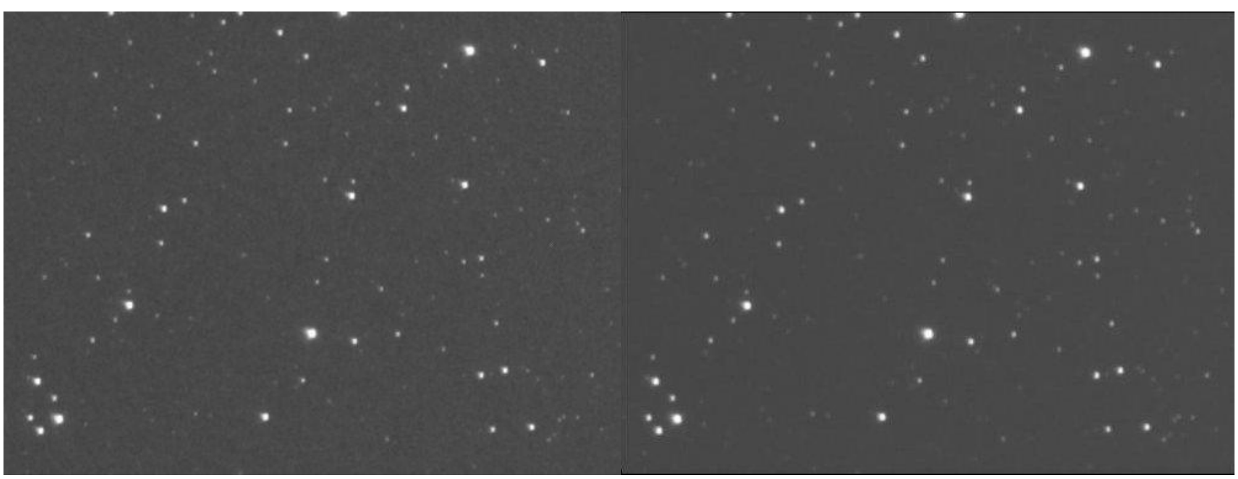

Figure 9

Finally, the test of the soy sauce bottle shows how the program can be used for normal cameras too, to reduce the noise of images and improve their resolution.

On the left (figure 10) is one of the input images, with noticeable noise, on the right, the result image, much sharper and with considerably less noise.

Again, please refer to the technical documentation to see the full-size images.

Figure 10

After testing the program, I can conclude that it performs well when the image of the object observed shifts with time, if a series of short-exposure pictures of the object are processed.

The program has also been proven useful for mitigating the noise of images in various conditions.

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