



École Polytechnique Fédérale de Lausanne

Rotation estimation of detected satellites

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Bachelor Thesis

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Lausanne, June 2021

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Abstract

We present an approach to extract the intensity along the satellite streaks that can be found in images that were obtained by OMEGACAM on the VLT Survey Telescope. In this project, we only analyzed the long tracks that were created by high velocity objects, to try to get an estimation about their rotation. We used Fourier transform to get the periodicity of the intensity along the tracks. Due to the lack of real data about rotation, we first had to create fake streaks with sinusoid intensity and different angles. We manually got the tracks to run the code on them, so ideally this project should be integrated with DetectSat [2] so that all the process can be done automatically. We found very great result with them and run the pipeline on real tracks. By making assumptions about the satellite, like their altitude, we get possible results on real streaks, but since we don't have access to the real values, we can't say if it is close to reality or not.

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Chapter 1

Introduction

This project is about estimating the rotation of spatial objects detected by the OMEGA-CAM on the VLT Survey Telescope. In these times, we have a lot of flying objects, it can be debris, useful satellites or dead satellites, around the Earth and it becomes more and more necessary to have a clear view of all these objects. The project of Yann Bouquet "DetectSat"[2] was focused on detection of the satellite tracks on fits files, but with both, small (low velocity) and long (high velocity) streaks. For this project we had to focus on the long tracks, so that the variation of intensity along the line could be better detected. The rotation estimation can be used to determine which kind of object the streak is and, if it is a satellite, it may be used to better find out which one it is. Ideally, this should be run on the lines detected by DetectSat so all the process could be done with only the fits file as input.

The main challenge is that we don't have access to data about rotation of satellites, so we had to first create our own streaks with sinusoid intensity. This lack of resources is very restrictive, since even if we get a result, we cannot know the precision of this method and we cannot be sure that it is right or completely wrong. This is why we had to begin with creating lines that seem realistic and try with random angles.

The second part of this project was to retrieve the periodicity of the sinusoidal function along the streaks that we have previously generated, and finally try this on real tracks. Since this project does not recognize the lines, we had to find the coordinates of the streaks by hand and give them as input to the pipeline. For this part, there are many

factors that can decrease the precision of the pipeline, e.g., if the line crosses a really bright star, it gives a peak of intensity and can lead to wrong result, or if the brightness of the streak is too small compared to the brightness of the background of the sky on the image.

Chapter 2

Inputs

In this project, we used fits images that were generated by the OMEGACAM on the VLT Survey Telescope, and we used a script to create a mosaic of 32 images, separated by NaN values, that are $4'000 \times 2'000$ pixels. So the image with all the mosaic's dimension is $16'000 \times 16'000$ pixels. A mosaic is approximately 1.5-2 GB of data.

We principally used the fits file "*OMEGA.2020-02-22T02:11:36.295_fullfield.fits*", corresponding to the captured image February 22, 2020, at 02:11:36, and with the pixels scaled using **ZScale** to be able to see the streaks as wanted.

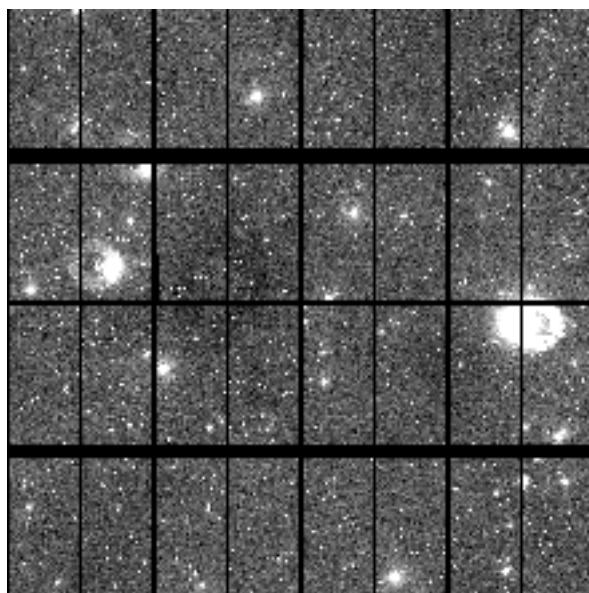


Figure 2.1 – The main FITS image that we used

The pipeline [3] is being run on the entire file, with the coordinates that are relative to the entire file : the origin is at the bottom left of the fits file. The first part of this project, which is about line generation, is completely based on this file Figure 2.1. We chose this file because we can clearly see a really interesting track that goes through the image :



Figure 2.2 – The interesting streak

This track on Figure 2.2, the one that goes through four blocks, was clearly visible and the variation of intensity can also be notified, so it was a great way to test the pipeline with a streak that is not too difficult. Thanks to Marcellin, he could identify this and it turned out that this streak is actually a debris of the European carrier rocket Ariane 2 ! We know that it is at a geostationary altitude, so $\sim 36'000$ [km] and has a speed of $\sim 3'065$ [$\frac{m}{s}$]. We will use this information later to analyze the coherence of the result obtained by the pipeline.

Chapter 3

Line Generation

When we started this project, we had no data about rotation of satellites and their corresponding tracks on a file, so we had to first generate streaks on the image myself, to be able to test the pipeline. First, to generate a line we had to choose an existing star in the file and cut it out to have a PSF to convolve my line with. The PSF : "Point Spread Function" is like the quantity of blurring of a point object. Here, we had to use it so that my generated line seems more realistic in the image.



Figure 3.1 – The line without using the PSF



Figure 3.2 – The line using the PSF

We will now explain the method we have used to achieve this result. First, we have to choose a star by hand and cut it out to use it as a PSF. The dimension of the star cut out is 30px, so we initialized an array of height's dimension of 30px and an arbitrary width,

with zeros everywhere, except at the center of the array, the center line of one pixel of height at the center is set with sinusoid values. Once, we have these two pieces, we can convolve the two arrays together to make the final line with an appropriate PSF.

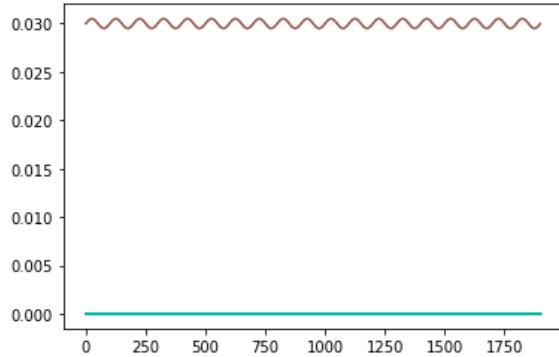


Figure 3.3 – Intensity of each row of the line's array

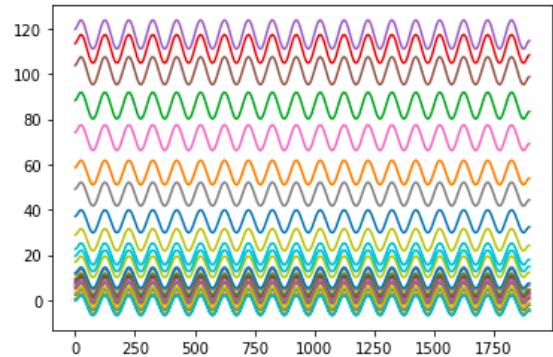


Figure 3.4 – Intensity of each row of the line's array after the convolution

We finally rotated the final convolved line by a random angle and add it to the image by summing up the values with the image's array.

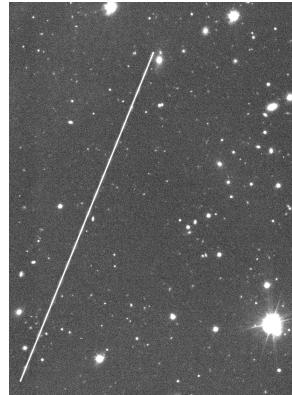


Figure 3.5 – The generated line on the image

The final result of the line in the image is pretty satisfying and coherent, as we can see in Figure 3.5.

The inconvenience of this method is that we had to choose a star by hand and it will work great for this specific file, if we want to make this code works with another image we have to choose a star from the new file to have a coherent PSF to integrate the line better on it.

Chapter 4

Find the Intensity Along the Track

Once the generation part was done, we started the main part of the project that was finding back the periodicity of the previously generated sinusoid intensity streak and finally apply the final pipeline on real tracks.

The method that we used was very simple : We just sum up all the values on the y coordinate for all x coordinate, so it returns an array with a height of one and with a width as long as the streak. Here, the width was found manually, since we had to enter the start and the end coordinates of the track as input for the pipeline, it was trivial to recover the width of the line, even when the line was not horizontal, by using trigonometry.

$$\text{width_of_the_line} = \frac{\text{end_line_x} - \text{start_line_x}}{\cos(\text{angle_line_in_radian})}$$

Once we have this array with the intensity of each x point, we can consider it as a signal and use the fast Fourier transform (FFT) algorithm [4] on the array to calculate the discrete Fourier transform (DFT) that can be used to find the frequency of the signal. We also used the inverse FFT to try to remove a bit the noise that we get from the image; indeed the line is not isolated from the background of other stars or other streaks that can add more or less noise to the signal.

We also choose to use a threshold for the number of periods that can be in a track to remove a lot of noise too. We have set it arbitrarily to 100 repetitions, because the width of a streak is limited to the width of one image of the mosaic, which is 2'000px.

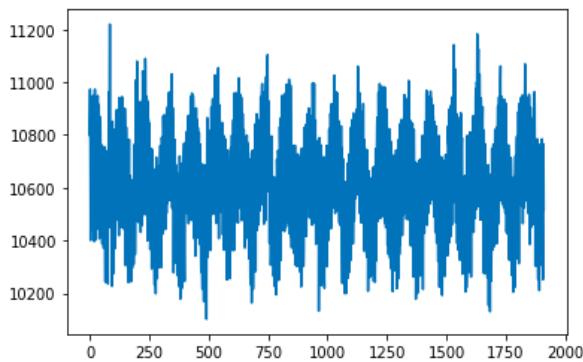


Figure 4.1 – The original signal

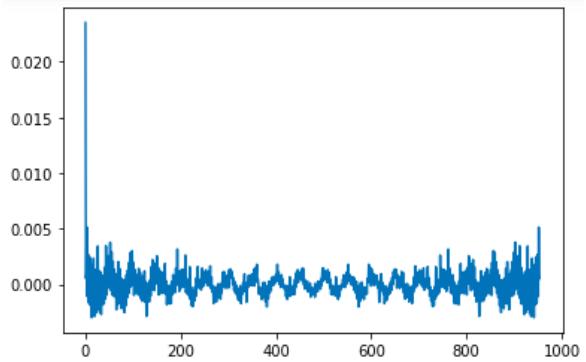


Figure 4.2 – The signal after the inverse FFT

It would mean that we would see a repetition every 20px, so the frequency of the signal would be $0.05 \text{ [px}^{-1}\text{]}$ and, assuming a geostationary object, this would imply 4.18 rotation per second and it is very unlikely that an object has such a high rotation rate.

Finally, we used the "**curve_fit**" function from the `scipy` library that use the least square optimization [5] to find the frequency of the original sinusoid function. But to use this function, we have to make a good first guess of the parameters, so that they will converge fast into the right value by minimizing the difference between the guessed parameters and the intensity data. Here, we optimized the different parameters of the sinusoid function that we have defined :

- The amplitude
- Frequency
- Phase
- Offset

A good first guess for the frequency, which is the only parameter of the sinusoid function that really interests us, is to divide the number of cycles that we found with the Fourier analysis part, by the width of the streak.

Using this pipeline, we usually find good estimation of the wave but it can vary a lot when there are a lot of noises.

We cannot use the result directly found with the pipeline explained just above,

because it expresses the frequency by pixel, to be able to compare it with a reference value as we would like, we have to convert it to spatial scale e.g., for the frequency $[s^{-1}]$. To do this we had to make some assumptions :

1. The flying object is geostationary
 - So the altitude would be $\sim 36'000'000 [m]$
 - With a speed of $3'065 [\frac{m}{s}]$
2. The fits file has a scale of $0.21 [\frac{arcsec}{pixel}]$

With these elements, we can find the rotation rate easily :

$$one_cycle_in_pixel = \frac{1}{frequency_found} [pixel]$$

$$arcsec_by_cycle = 0.21 \times one_cycle_in_pixel [arcsec]$$

$$distance_one_cycle = 36'000'000 \times (\frac{\pi}{180} \times \frac{arcsec_by_cycle}{3'600}) [m]$$

$$rotation_rate = \frac{3'065}{distance_one_cycle} [s^{-1}]$$

This rotation rate, which is the amount of rotation of the object in one second, can be used to compare what we have found with the existing information about the objects that we will detect.

Chapter 5

Final Result

Running the pipeline on a line that we created previously, takes less than 10 seconds, by blocks of the mosaic, using a 1,8 GHz Intel Core i5 dual core on a MacBook Air 2017.

5.1 Result on Generated streak

When running it on the generated lines that we talked about above, the pipeline gives pretty satisfying results. Here we can see the result of a basic case with a horizontal line but that runs into a star or bright object.

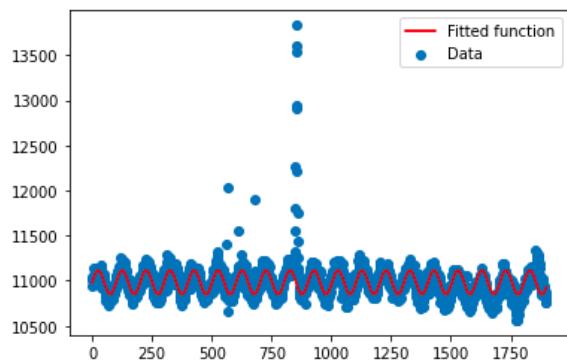


Figure 5.1 – Total intensity by x coordinate on the line

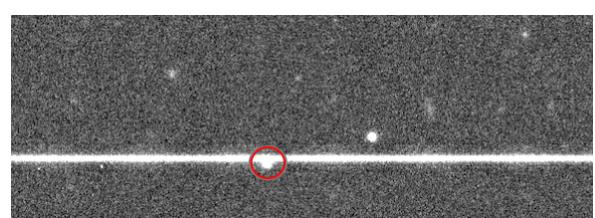


Figure 5.2 – The star that is crossed by the line

As we can see in Figure 5.1, the fitted function seems really close to the data even if

there is a peak of intensity at some point, because of the star crossed. It is a good sign that our pipeline can resist, even if it is a small amount of noise here.

The frequency found by the pipeline is 0.009997 which is really close to the real frequency of the generated line, which is 0.01. In other words, we can say that the value found as an error of 0.03%, it is a really satisfying result, but the generated line is truly bright in comparison with other streaks that can be pretty discrete and even sometimes they can be invisible to the naked eyes. Obviously, using the pipeline on these kinds of tracks will give an imprecise result with a much bigger error percent.

Now let's see the result with a more realistic rotated line that does not run into any specially bright object that could introduce some more noises. The streak is also very bright, so we can say that this is actually ideal conditions.

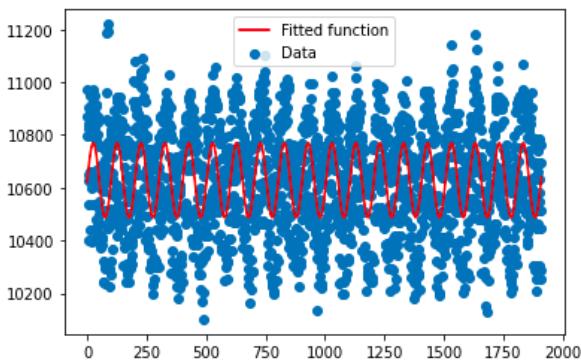


Figure 5.3 – Total intensity by x coordinate on the line

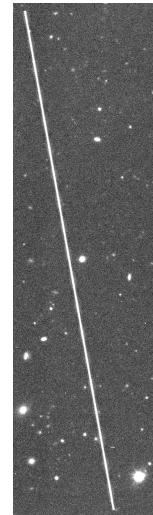


Figure 5.4 – The star that is crossed by the line

We can see that the frequency of the fitted function seems to approximate the data reasonably well. The pipeline finds 0.009962 for the frequency, it is still close to the expected value so we can say that this result is really satisfying. The error of the computed outcome is of 0.38%. This result shows that, when the streak is bright enough, the pipeline performs amazingly well on the generated lines that we have created ourselves. We have tested the pipeline with generated lines for every angle at this position and reported the result on the following graph :

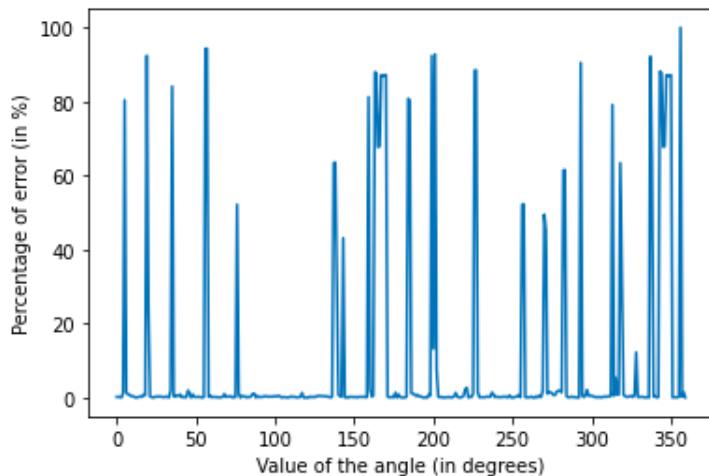


Figure 5.5 – The percentage of error by angle of the line

Thus we have computed the mean percentage of error of the pipeline in this situation, that gives 10.14%, which is globally acceptable. We can explain this result with the fact that depending on the angle of the line, it could cross more or less bright things, like stars and galaxies; thus the signal will be noisier and the result less accurate. We have observed that when the angle was 356 [degrees] the pipeline will not even find the optimal parameters, because it crosses a very bright star that adds a big peak of intensity, which leads to a more difficult optimization of the parameters.

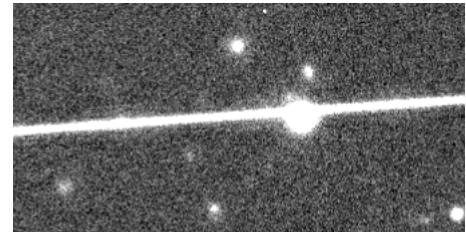
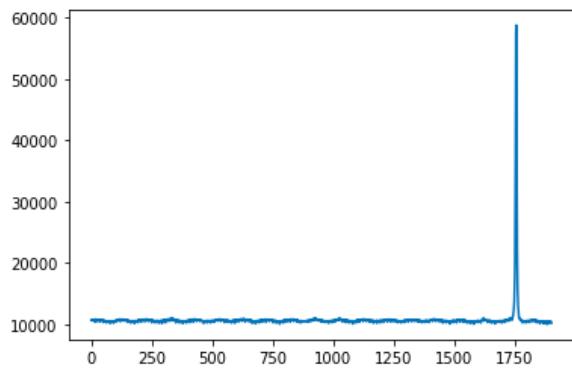


Figure 5.7 – The star crossed by the line

Figure 5.6 – Total intensity by x coordinate on the line with 356 degrees of rotation

We also add Gaussian noises to the original signal and put it on the image with a rotation of 100 [degrees], because at this angle the line does not encounter many stars or bright objects that could also introduce more noise. We have used these noised signals

as input for the pipeline and computed the results for each standard deviation from 0 to 500 with a step of 5.

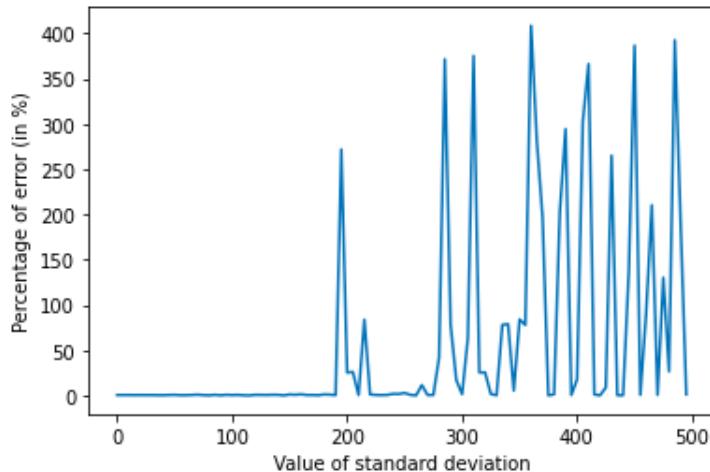


Figure 5.8 – The percentage of error by the standard deviation of the noise

The Figure 5.8 shows that the pipeline is not really affected until a standard deviation of ~ 190 , but is still pretty reasonable until ~ 270 . In fact, when the standard deviation is more than ~ 270 , the results given by the system are randomly correct. We found a mean percentage of error of 56.88% considering the entire graphic, but if we look only the first 60 results, it corresponds to a maximum standard deviation of 300, we now have a much better mean percentage of error of 15.93%.

5.2 Result on Real streak

In this part, we used the track that can be seen in Figure 2.2 to test the final pipeline. Because when we were working on this project, it was the only streak that we have successfully identified. This track is a debris from Ariane 2, we knew it thanks to PredicSat that also compute information about it like the altitude of the object, for this track the altitude is $\sim 35'300 [km]$. That is good news, because it corresponds well with our assumption about the geostationary altitude that we have made in Chapter 4.

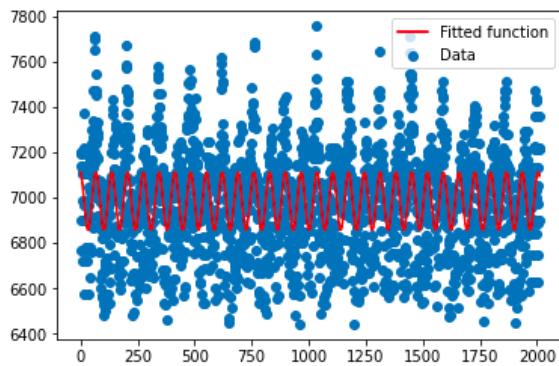


Figure 5.9 – Total intensity by x coordinate on the first part of the track

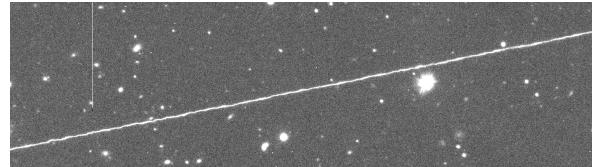


Figure 5.10 – The first part of the track

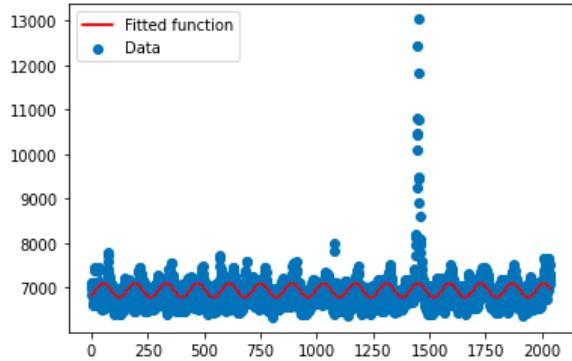


Figure 5.11 – Total intensity by x coordinate on the second part of the track

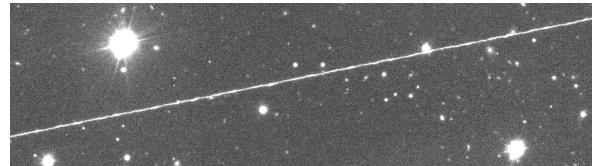


Figure 5.12 – The second part of the track

We get the same result for the rotation rate for the first, third and fourth part of the track (Figure 5.9, Figure 5.13, Figure 5.15) : $\sim 1.20 [s^{-1}]$. Only the third part outputs a rotation rate of $\sim 0.6 [s^{-1}]$. We can observe that on the graphic in Figure 5.11 that the data are a bit noisy, it is hard even with eyes to observe any kind of sinusoidal shaped function. Now we can see the limit of this system, even if the fitted function seems pretty correct, it would also look great using the same frequency found with the other parts of the track. So there are multiple possible results and it can be hard to determine which one is the most accurate. In fact, we cannot, with only one part of the track, tell if it is right or wrong. We have to have some knowledge about what values are possible and not, given that we do not have access to any kind of information about the rotation of the objects that appeared in the images that we had, we cannot really say if the rotation rate found by the pipeline is correct or not.

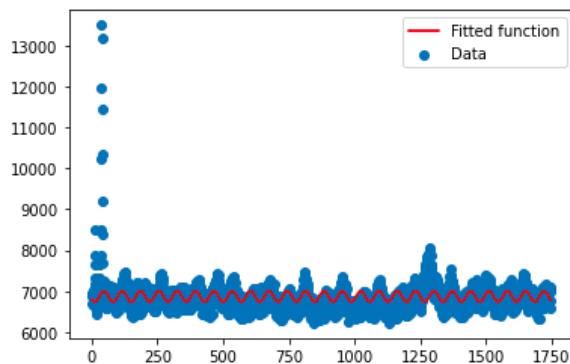


Figure 5.13 – Total intensity by x coordinate on the third part of the track

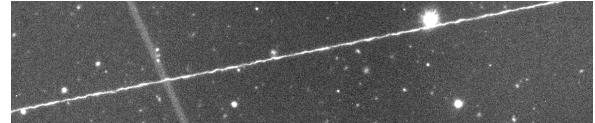


Figure 5.14 – The third part of the track

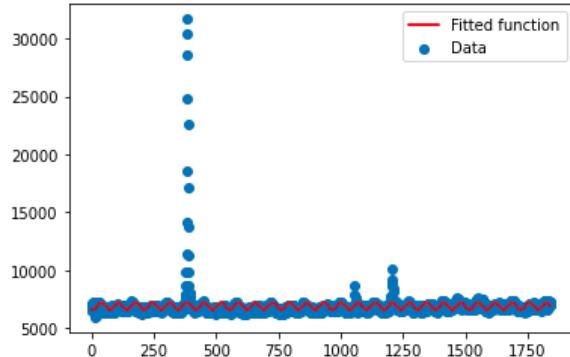


Figure 5.15 – Total intensity by x coordinate on the fourth part of the track



Figure 5.16 – The fourth part of the track

Since this track was made by a spatial debris, the result of ~ 1.20 rotation per second, which is already a very high rotation rate, is plausible for this type of object.

We tested our pipeline on another track that was nicely bright, but we did not know what satellite or object it corresponds to. Therefore, we cannot verify the result of the pipeline precisely. We can only observe by eye on the graph that the fitted function sticks pretty well the data, so this is already a good sign.

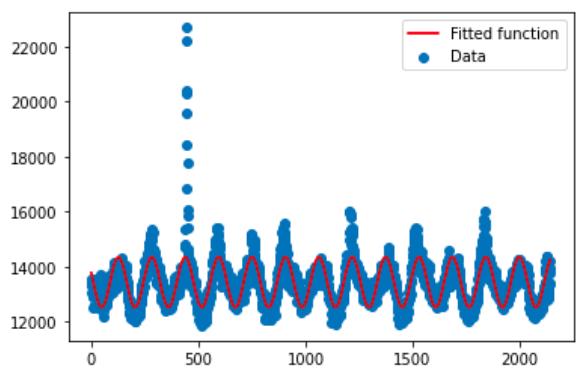


Figure 5.17 – Total intensity by x coordinate on the first part of the track

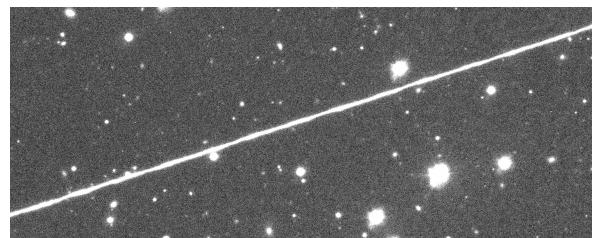


Figure 5.18 – The first part of the track

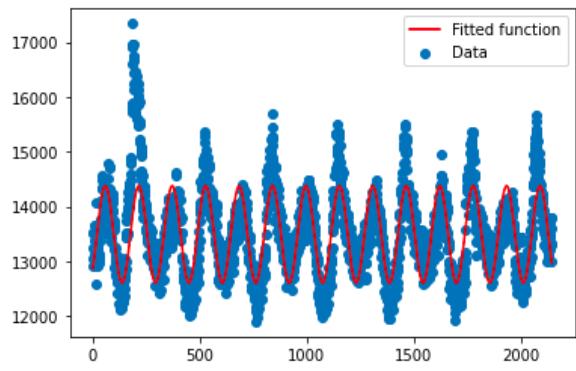


Figure 5.19 – Total intensity by x coordinate on the second part of the track

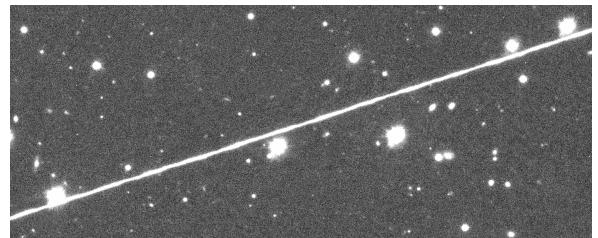


Figure 5.20 – The second part of the track

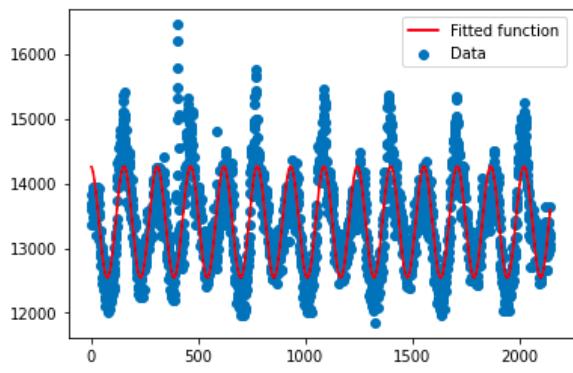


Figure 5.21 – Total intensity by x coordinate on the third part of the track

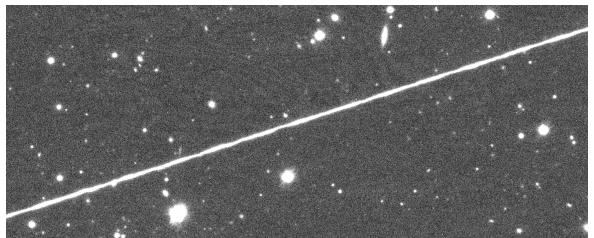


Figure 5.22 – The third part of the track

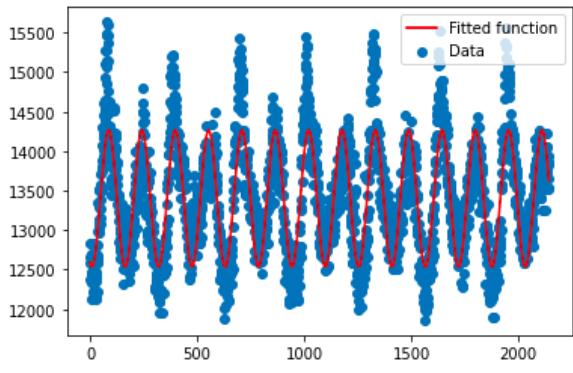


Figure 5.23 – Total intensity by x coordinate on the fourth part of the track

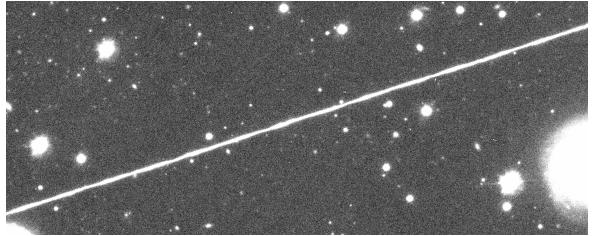


Figure 5.24 – The fourth part of the track

The rotation rates found on this streak are the same for every part : $\sim 0.54 [s^{-1}]$. It would mean that the object performs a rotation every $\sim 1.85 [s]$, still assuming a geostationary orbit, which is feasible. Unfortunately, we have no real information about the object that has produced this track, so we cannot tell if it is correct and how accurate this result is. But if we only look at the graphs, the output of the pipeline seems pretty valid.

Chapter 6

Conclusion

This project aims to estimate the rotation speed of the different spatial objects that are represented as streaks in images. Ideally, this could be used to determine if the object is a satellite, or if the rotation is too fast so this would be a debris. We could use this pipeline to classify the tracks.

In reality, we could not tell if this requires some modifications or if the current state of the pipeline is precise enough, because of the lack of real information on the subject. This was the main concern when doing this project. We were not able to find any rotation speed of any object that we encountered when we were exploring images. The only streak that we have successfully matched with a known object was the main track (Figure 2.2), that was a debris of the European carrier rocket Ariane 2. The result we obtained for this streak seems possible but we cannot say with confidence that this is actually completely accurate, and how precise the outcome is. Also the real tracks may not produce a perfectly sinusoidal intensity, so this could also lead to imprecision when using this system. The pipeline seems to produce coherent result when launched on the other track that we have tested. Unfortunately, we have not discovered the real information about this object, so we could not verify our result. The real streaks can also be really darker than the one that we studied, so the noise will have a more significant weight, thus the result of the pipeline could be pretty uncertain. This pipeline can produce only an estimation and not a very precise result, due to the difficulty of this kind of detection [6].

This was the reason why we started by producing our own streaks, so that we could modify the frequency as we wanted and have the real value to compare it with the obtained one. This part works well and produces pretty realistic tracks, but it has the disadvantage to be dependent on a custom PSF that we have to find for each image. Otherwise, this could maybe be used to train a machine learning algorithm to detect satellites as it can generate streaks where we want to.

The second part of the project, which we discussed in Chapter 4, could ideally be used combined with DetectSat, so that the lines that are detected are automatically given as input to the pipeline. It is indeed useful to directly have information about the track that we have detected, as it can be used later to classify the kind of object that the streak is.

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