Statistical Investigation of Cryogenic Target Defects

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1. Abstract

After hollow cryogenic targets are filled with a frozen layer of DT, images of them are taken and analyzed for quality control. Often, imperfections with an appearance of either cracks (dendrites) or dark spots (darks) appear on the surface of the target. Many aspects of these defects, including origin, composition, and impact on target performance, are not well understood. In order to work towards elimination of these defects, more needs to be known about their nature. Images and information pertaining to a large sample of targets were drawn from a database and different properties were analyzed using various statistical techniques. The numerous tests performed resulted in many small pieces of information about the nature of the defects (e.g. location, size) that rule out some theories and support others. Additional analysis is necessary in order to more fully understand the defects.

2. Introduction

Fusion is the process by which separate nuclei are combined together to form a single heavier nucleus, generally releasing a large amount of energy in the process. In order to achieve fusion, atoms must collide with enough energy to overcome their electrostatic repulsion. In laser fusion, high-intensity lasers are uniformly focused onto a small spherical target (roughly 2 mm in diameter) containing the fuel to be fused.[1] The energy of the lasers causes the surface of the targets to explode, thereby imploding the inner contents at a high velocity. This results in very high temperature and pressure, making fusion reactions possible. At the Laboratory for Laser Energetics, the targets used contain a mixture of deuterium (D) and tritium (T), which fuse together to create helium and a neutron as well as a large amount of energy.

In order for a target to implode properly and initiate fusion, it must contain minimal imperfections. Even minor discrepancies in the target's shell thickness can become magnified greatly during the implosion process, resulting in much lower fusion yield.[2] Because of this required precision, the preparation of a serviceable target involves highly precise operations on the small and delicate target, a complex and laborious process. Targets begin as empty shells prepared in batches by General Atomics. These are then inspected, and only the select few that are pure enough make it to the next stage. At a filling station, the plastic shell is subject to 1,000 atm of pressure and is slowly permeation filled with DT vapor. Then, the temperature is gradually reduced to just below the DT triple point (19.8 K) while the difference in pressure across the shell boundary is maintained below 1 atm.[2] This allows for the formation a thin uniform layer of DT ice contouring the inside of the shell while the center contains some DT gas. When the layer has been formed, the target is held in a cryostat until it is ready to be imploded.

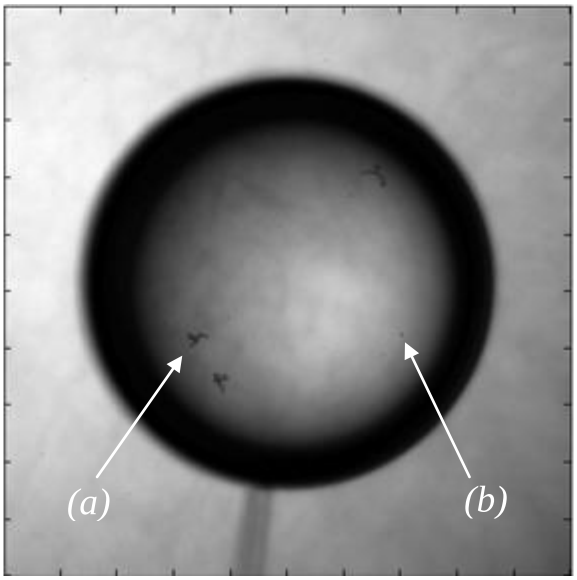


Figure 1: Example image of a typical filled target. Note the two distinct types of defects: (a) dendrite (b) dark

Having DT exist in the solid state is important as it allows for the packing of more fuel into the small shell, resulting in more fusion reactions.

Over the years, procedure optimizations have allowed for more-perfect targets with respect to uniformity of DT ice layers, but the targets still are not without flaws. While held in the cryostat before being imploded, each target is documented with a variety of different information, including images. Ever since images of the first DT targets have been documented, the images have consistently revealed small imperfections (i.e. defects) on the surfaces of the targets.[3] These defects have the appearance of either cracks (dendrites) or dark spots (darks) [Figure 1]. For both types of defects, details including the origin, composition, and impact on target performance are unknown.

After images are taken of each target from multiple points of view, they are processed in a MATLAB routine designed to categorize and characterize the defects. Although the current camera setup cannot capture every viewpoint, the portions that can be imaged are patched together and displayed as an area-preserving Mollweide projection [Figure 2]. The MATLAB code then identifies the defects and gathers various information for each one, including classification, area, and position.

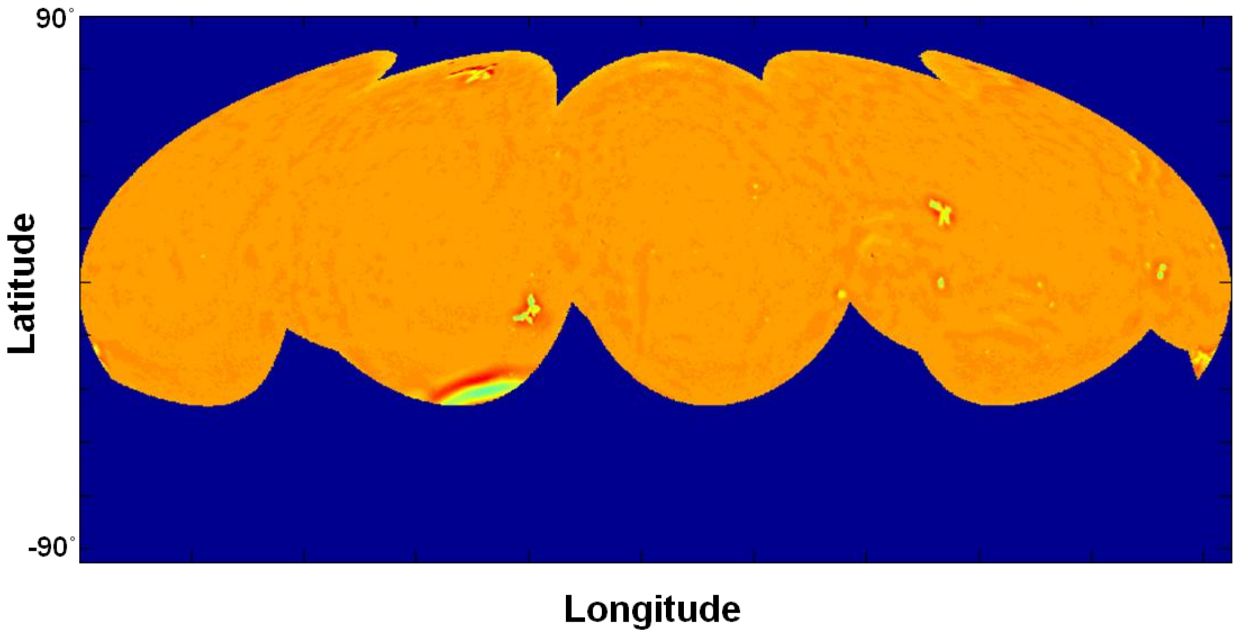


Figure 2: Mollweide projection image of a target. Due to the current camera setup, data is missing from the polar regions of the target, especially around the bottom.

3. Data Analysis

In an effort to understand these defects, a series of statistical tests was performed on data gathered from approximately 175 targets containing thousands of defects. Finding any correlations between defect count and variables such as position on target could provide some insight into the origin of the defects. The results found could support existing theories on why the defects form or reject them and prompt the formation of new theories.

3.1. Presence of Defects vs. Latitude

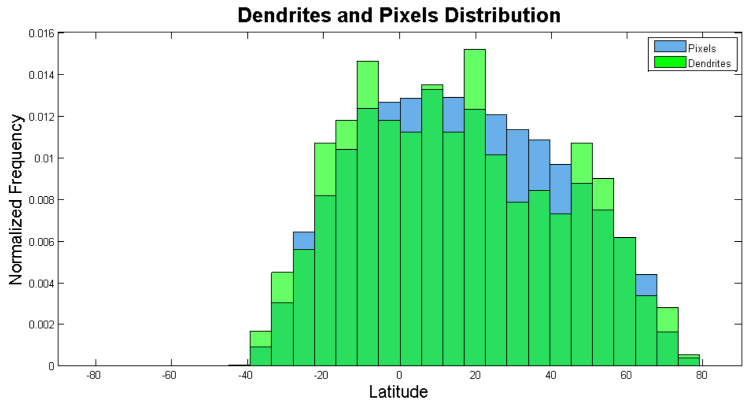
One existing idea about the defects was that the defects have something to do with particulate falling from machinery above the target while being filled. If this were true, then defects would likely be clustered in the northern hemisphere of the target.

In order to test whether the presence of defects was related to its latitude on the targets, the total surface area at each latitude value was compared to the number of defects found at those corresponding latitude values. If the relative frequency of defects at the latitude values matched that of the relative area, it could be concluded that there is no relationship between the presence of defects and the latitude. Because the images do not reflect the entirety of the target's actual surface area, the appropriate surface area at each latitude range could not be determined using mathematical equations applicable to spheres. Instead, because the image is an area-preserving projection, pixels were used as a unit of area, and the areas at each latitude value were found by counting up the pixels on the image.

After the number of pixels and defects were determined at each latitude value, a two-sample Kolmogorov-Smirnov test (KS test) was used to determine whether the difference between the two samples' cumulative distribution functions (CDFs) was statistically significant. In a KS test, the null hypothesis is that the two CDFs are drawn from the same fundamental distribution (meaning the likelihood of finding a defect would be uniform with respect to latitude), while the alternate hypothesis is the opposite. Inputting two CDFs into the KS test yields a value known as the KS statistic, which then can be used in a preexisting KS equation to determine the *p*-value based on the two sample sizes. If this *p*-value is less than the chosen significance level, α, then the null hypothesis is rejected. Otherwise, it is not rejected.

When the KS test was used to look for correlations between latitude and presence of dendrites using a typical significance level of $\alpha = 0.05$, the obtained *p*-value was 0.32, greater than the significance level. Therefore, the conclusion was that the likelihood of finding a dendrite is uniform with respect to latitude [Figure 3]. As a result, it can be reasonably concluded that dendrites are not related to falling particulate.

(a)



(b)

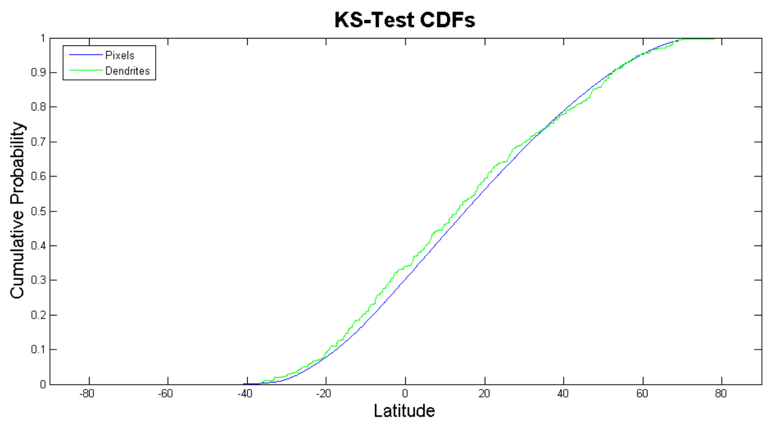


Figure 3: Statistical comparison between the position of dendrites and area vs. latitude. (a) The normalized histograms of number of pixels vs. latitude and number of dendrites vs. latitude superimposed on one another. Note the similar form. (b) A plot of the cumulative distribution functions of pixels and dendrites vs. latitude. The data corresponding to this graph reveals an insignificant difference between the two functions.

The same process was performed on the data for darks. However, the resulting *p*-value was 1.65×10^{-9}, much smaller than the significance level of 0.05. The conclusion, then, was that the likelihood of finding a dark is not uniform with respect to latitude [Figure 4]. Instead, the likelihood of finding a dark appears to be larger between latitude values 0 and 40 [Figure 4(a)].

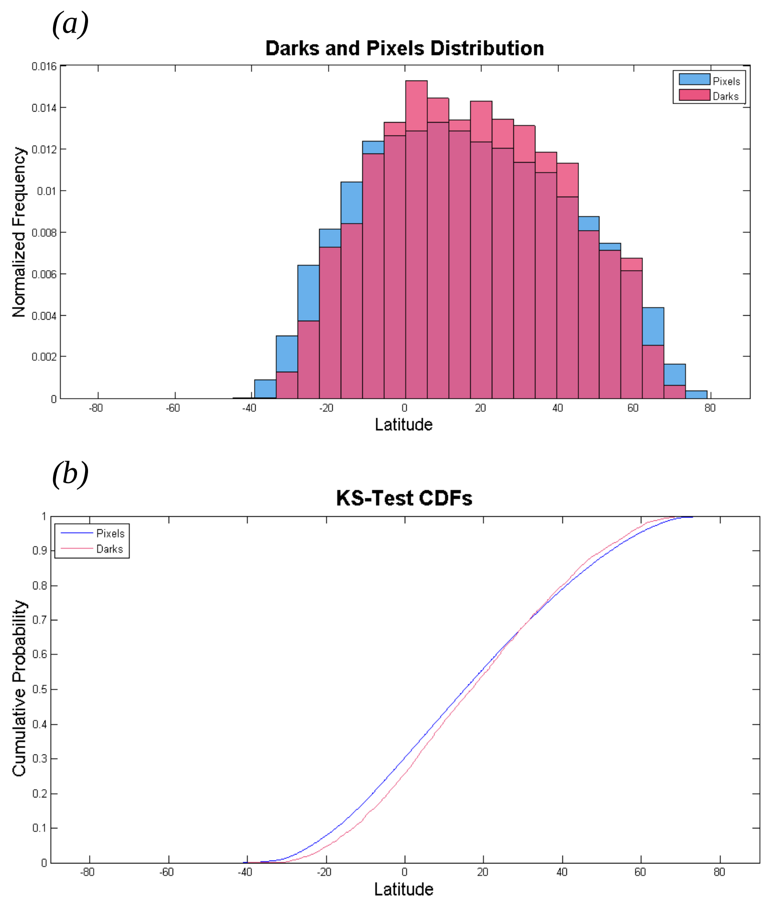


Figure 4: Statistical comparison between the position of dendrites and area vs. latitude. (a) Same as Figure 3(a), but with darks. The relative frequency of darks appears to be higher between latitudes 0 and 40. (b) Same as Figure 3(b), but with darks. The data corresponding to this graph reveals a statistically significant difference between the two functions.

3.2. Presence of Defects vs. Longitude

When targets are prepared for filling, they are positioned in batches of six, surrounding a pole [Figure 5]. Each of the six slots was labeled, and the slot number for the every target was recorded. Another theory regarding the formation of defects was that particulate floating within the filling chamber caused the defects to appear. If this were true, then defects should appear only at longitudes facing away from the pole, exposed to the open air.

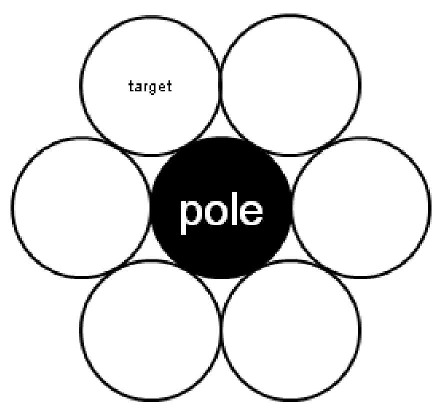


Figure 5: Top view of the target fill rack.

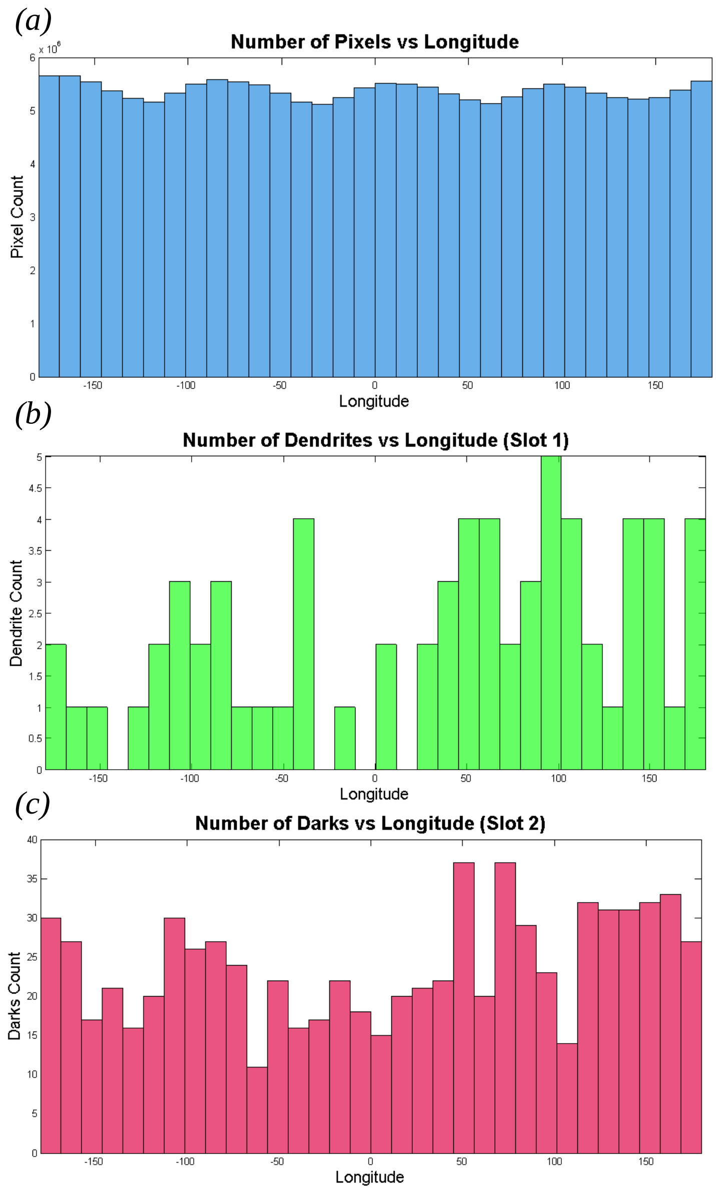


Figure 6: Statistical comparison between position of defects and area vs. longitude. (a) Histogram of number of pixels at each longitude interval. (b) Histogram of the number of dendrites at each longitude interval for targets in slot 1. The histograms of the other 5 slots have a similar appearance. (c) Histogram of the number of darks at each longitude interval for targets in slot 2. The histograms of the other 5 slots have a similar appearance.

The procedure for testing whether the appearance of defects is related to its longitudinal position was similar to that of *Section 3.1*. Before performing the test, however, the targets were separated by their slot number, and the KS test was performed on the targets grouped by slot. In total, twelve tests were done (6 for dendrites, 6 for darks).

For the dendrites, the resulting *p*-values for the 6 slots were mostly above the significance level (0.05), and the histograms did not reveal any noticeable clumping of dendrites. It was concluded that the likelihood of finding a dendrite is uniform with respect to longitude.

For the darks, the resulting *p*-values for the 6 slots were mostly below the significance level, meaning that the distribution of area across longitude does not match the distribution of darks across longitude. However, the histograms do not appear to reveal any noticeable clumping in certain regions, so no other conclusion could be made [Figure 6(c)].

3.3. Defect Count vs. Time Elapsed from Filling to Firing

As mentioned in the introduction, after being filled, targets are held in a cryostat until they are ready to be shot. The amount of time can range from days to weeks, and because of the radioactive nature of tritium, it was proposed that the formation of defects was related to the amount of time a target spent idle.

The number of days elapsed from filling to shooting was determined for all the targets, and the targets were grouped together based on the number of days elapsed. Within each group, the mean number of defects was calculated, and these values of average defects per target were plotted against their respective number of days elapsed [Figure 7]. However, for both types of defects, no relationship was found between the two variables. Linear regression models created for the two plots resulted in coefficients of determination, r^2, of 0.0147 and 0.0562 for dendrites and darks, respectively.

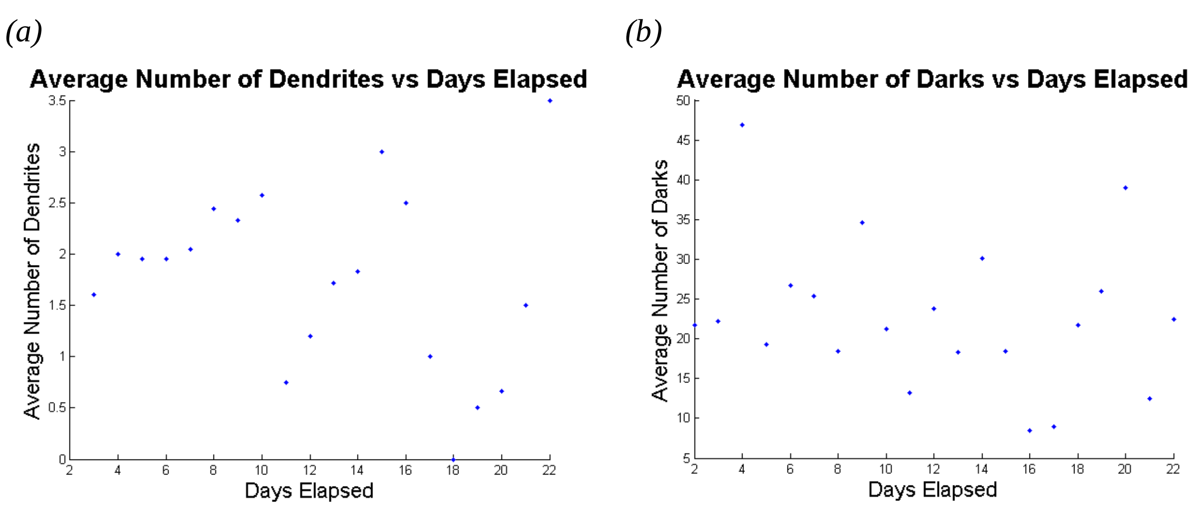


Figure 7: Plot of average number of defects on a target vs. the number of days elapsed between filling and shooting. In both cases, no trend can be seen. (a) dendrites. (b) darks.

4. History of Target Defects at LLE

In addition to attempting to discover more about the nature of the defects by comparing certain variables with others, a few plots were created in order to gauge the prevalence of defects and whether there have been any trends in the past few years of target fabrication at LLE.

4.1. Number of Defects per Target over Time

For both types of defects, a simple scatter plot was created of the defect count on targets vs. the date the target was imaged. In both cases, the plots did not reveal any striking trends [Figure 8]. The number of defects per target has remained consistently unpredictable over the past several years.

(a)

(b)

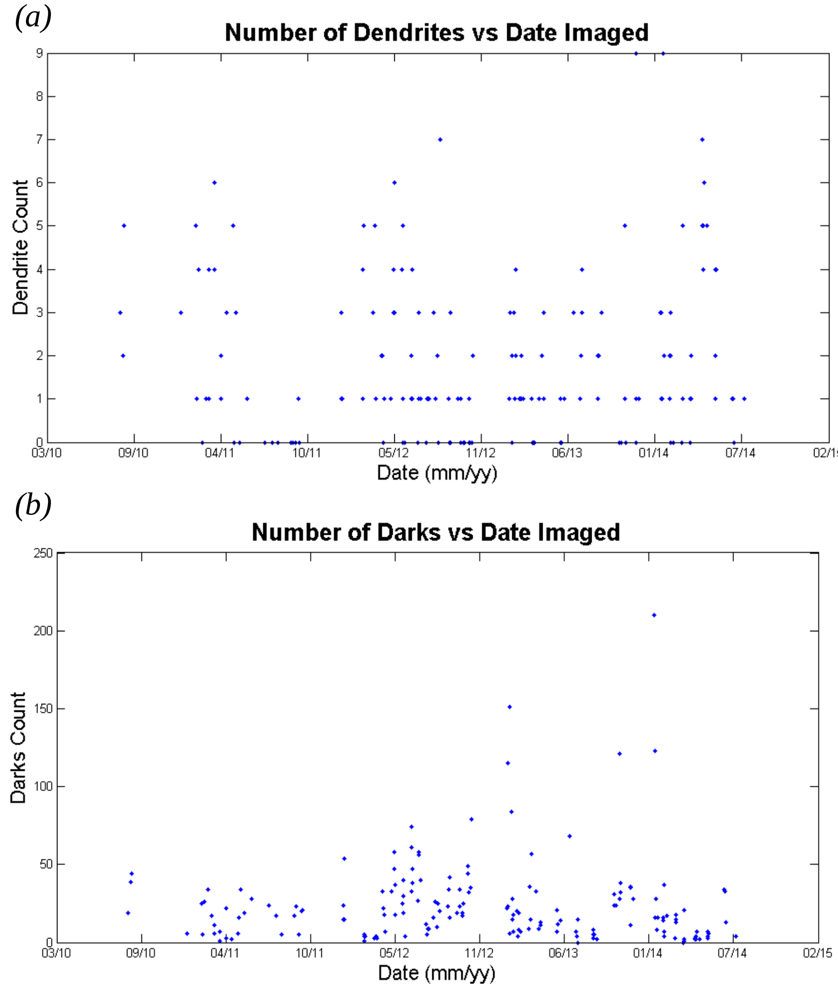


Figure 8: Plot of number of defects per target vs. date imaged for (a) dendrites and (b) darks. There does not appear to be any predictable trend.

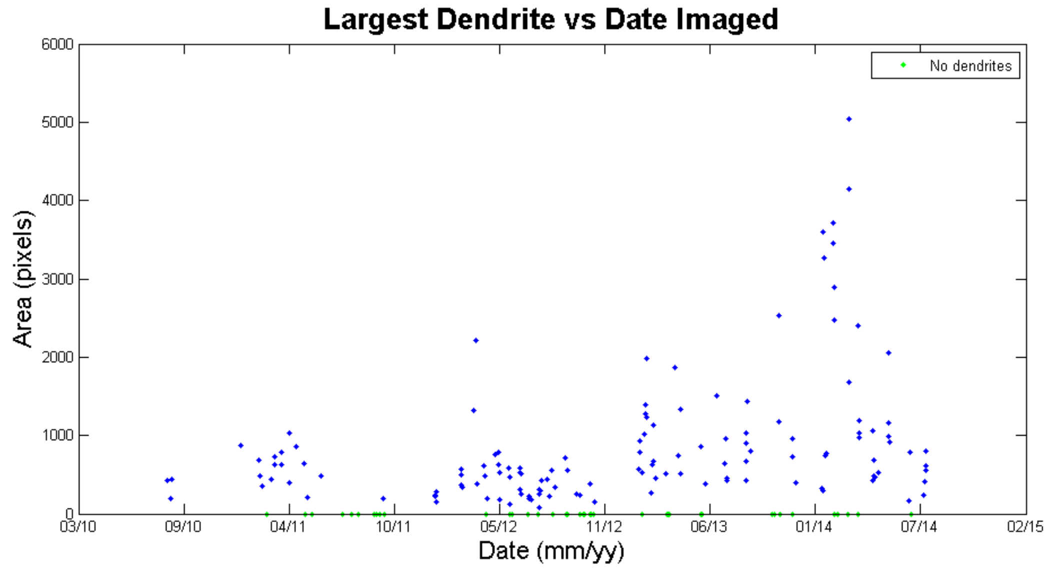


Figure 9: Plot of largest dendrite on a single target vs. date imaged. In the past several years, it appears that the largest dendrite has become larger.

4.2. Largest Dendrite on a Single Target over Time

While darks are small and generally look the same, dendrites have varying shapes and can be very large at times. Based on the assumption that larger dendrites would impact target performance more, there is particular interest in the size of the largest dendrite on targets. To determine whether there was any trend within the past years, the area of the largest dendrite on each target was determined and plotted based on the date it was imaged [Figure 9]. It was found that the largest dendrite has been increasing in size over the past several years.

5. Conclusion

Existing data on past targets and defects was analyzed for any possible correlations between the count of defects and variables such as position. It was concluded that the probability of finding a dendrite on a target is uniform with respect to latitude and longitude. However, for darks, it was concluded that the probability of finding one is not uniform with respect to latitude or longitude, though no obvious patterns were found in the data. For both dendrites and darks, no relationship was found between their frequency and the amount of time a target spent idle between filling and shooting. Additionally, no obvious trends were observed when comparing the number of these defects per target over the past few years. However, it was found that the largest dendrite on a single target seems to have grown in size over the past years. In the future, a continued search for relationships between variables about the defects could provide further insight into the defects' nature.

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References

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[2] "Cryogenic DT and D_2 Targets for Inertial Confinement Fusion," LLE Review **108**, 167 (2006)

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