Morphological Variation in Dune Parameters on Titan

Reveals Formation Environment of Dunes.

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ABSTRACT

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The equatorial region of Saturn's moon Titan has five large sand seas with dunes similar to large linear dunes on Earth. Cassini Synthetic Aperture Radar (SAR) swaths have high enough resolution to measure dune parameters such as width and spacing, which helps inform us about formation conditions of the sand dunes. Previous measurements in locations scattered across Titan have revealed an average width of 1.3 km and spacing of 2.7 km, with variations by location. We are particularly interested in how these variations are affected by sand availability. This information could help us determine more accurately how much sand is in different regions of Titan, and how sand is transported between regions. We have taken over 1200 new measurements of dune width and spacing in the T8 swath, a region on the leading hemisphere of Titan in the Belet Sand Sea, between -5 and -9 degrees latitude. We have also taken over 900 measurements in the T44 swath, located on the anti-Saturn hemisphere in the Shangri-La Sand Sea, between 0 and 20 degrees latitude. We correlated each group of fifty measurements with the average distance from the edge of the dune field to obtain an estimate of how position within a dune field affects dune parameters. We found that in general, the width and spacing of dunes decrease with increasing distance of the dunes from the edge of the dune field, consistent with similar measurements in Australian sand seas on Earth. This correlation is likely due to the decrease of sand availability at the edges of dune fields. We suggest that in this particular case, the Australian sand seas may provide a better analogy for Titan than the Namib Sand Sea in Africa.

Keywords: Titan, Cassini, linear dunes, Belet, Shangri-La

Contents

Chapter 1

Introduction

1.1 Titan Overview

Saturn's moon, Titan, is unique in the solar system, as the only moon that has a substantial atmosphere. As a result, Titan ranks with Mars and Venus as an interesting object to study. However, until recently, very little was known about Titan due to haze in the atmosphere. The pressure of the atmosphere on Titan is very similar to Earth's atmospheric pressure (150 kPa on Titan and 100 kPa on Earth), but due to its much lower temperature, Titan's atmosphere is about four times denser than Earth's. Titan's atmosphere, like Earth's, is composed primarily of nitrogen, but unlike Earth's atmosphere, it also has a reasonable amount of methane and traces of other hydrocarbons. These hydrocarbons are produced when solar radiation breaks up methane in the atmosphere and the parts recombine to form more complex organic molecules. These organic molecules naturally precipitate out of the atmosphere and collect on the surface. They are then eroded into sand-grain sized particles, which can collect into the large dune fields seen near the equator of Titan (Lorenz 2006; Soderblom et al. 2007).

Like most major objects in the solar system, Titan rotates from west to east, and is tidally locked with Saturn, making this rotation very slow. As a result, Titan's atmosphere has only one circulation cell, unlike Earth's atmosphere. In addition, wind speeds are generally slower than those on Earth. Titan's circulation patterns also vary seasonally. When it is summer in the northern hemisphere, winds are very strong in the northern hemisphere and much weaker in the southern hemisphere. At the equator, surface winds are directed to the northwest in most locations. However, when it is summer in the southern hemisphere, the winds are directed southwest at the equator, and the faster wind speeds are in the southern hemisphere (Tokano 2010). These patterns are due to the eastward rotation of Titan and differential heating. When one hemisphere is pointed toward the sun, the atmosphere is warmed more there. As a result, warm air rises and blows in the upper atmosphere toward the other hemisphere, while cold air blows toward the atmosphere being heated along the ground. Thus, the wind direction close to the surface is toward the hemisphere where it is summer. In addition, the wind speeds are faster in the hemisphere where it is summer, since there is more energy imparted to that location. Thus, the average annual wind direction is generally westward.

During the equinoxes, the winds on Titan change direction, as the pressure gradient between the northern and southern hemisphere switches directions. This also causes the wind to shift briefly to being eastward instead of westward. The winds at the equator are much faster this time of year, due to the converging winds and the greater amount of energy in the equatorial region of Titan. Thus, during every equinox there is a short period of time when there are fast, eastward winds (Tokano 2010). This is significant because the dunes on Titan are streamlined around obstacles in a way that strongly suggests they are formed by eastward winds instead of westward winds. While the westward winds are present for most of the year, they are not as strong, and it is possible they are not strong enough to initiate saltation and sand transport on Titan. It may be that the sands are transported only during the equinox periods when there are fast, eastward winds (Lorenz 2013).

1.2 Sand Dunes Overview

Linear dunes are the only type of dunes that have been found in significant abundance on Titan. Linear dunes are usually found where there is a large sand supply and can form under several wind conditions. In all conditions however, the dunes end up long and straight, and generally parallel to the wind direction. Some form when there are two wind directions with a small angle between them. The dunes will form along the average of the two wind directions. There can also be two wind directions separated by approximately 180 degrees. In this case, the dunes form approximately parallel to both wind directions. Finally, linear dunes can form when there is a single wind direction that varies in angle. The dunes will be parallel to the average wind direction. Linear dunes will usually form in large regions where there is plenty of room for sand to accumulate. It is possible for Barchan, transverse or star dunes to form on Titan, but these dunes tend to be smaller in scale than linear dunes, and the resolution is typically not high enough to spot these kinds of dunes, though some are seen on the margins of dune fields (Ewing et al. 2014; Radebaugh et al. 2009).

The Cassini spacecraft uses RADAR imaging to take higher resolution images of the surface, using a wavelength of three centimeters. Sand grain particles are much smaller than three centimeters, so the dunes appear smooth to radar and are thus radar-dark. The substrate underneath the sand dunes is rough to radar, causing the interdunes to be bright. Sometimes they are covered in a thin layer of sand, which causes them to be slightly darker, but in most cases the radar can easily penetrate this layer, so the interdune is still usually visible, even if it does not contrast with the dune as much. Sometimes, when the spacecraft flies parallel to the dunes, the side of the dunes perpendicular to the incoming radio waves causes the radio waves to reflect straight back into the sensor. This causes a glint on the side of the dune. These glints must not be confused with interdunes, since both are radar bright. Glints can be useful for determining dune height, since the incidence angle of the radio waves is known. There are three locations that have been identified as

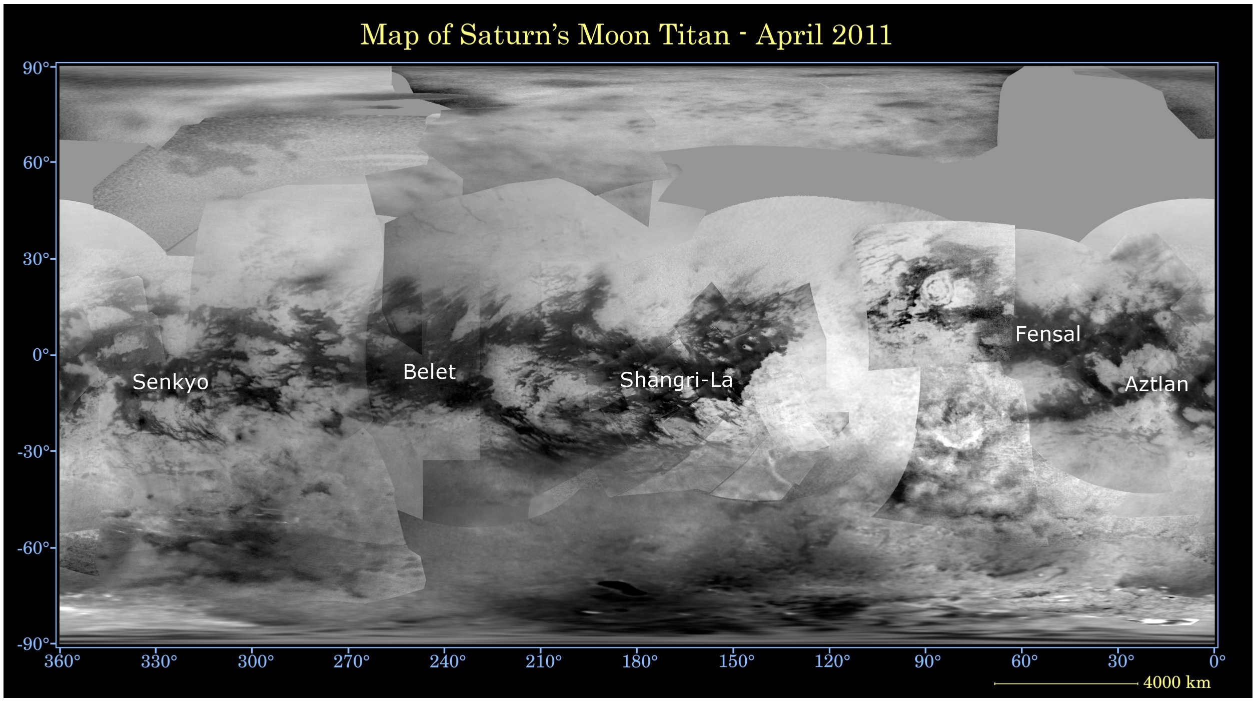

Figure 1.1 The five sand seas on Titan. Image courtesy of NASA/JPL-Caltech (Jet Propulsion Laboratory [JPL]).

having glints on the surface. Two are located in the T08 swath, and the third is in the T44 swath (Neish et al. 2010). Dune height can be used with dune width to estimate the volume of sand, and therefore the sediment supply.

There are five major sand seas distributed across the equatorial region of Titan, between about -30 degrees and 30 degrees latitude. These are the Fensal, Aztlan, Senkyo, Belet, and Shangri-La Sand Seas. The only large region on the equator of Titan that is not covered by sand seas is Xanadu, a large and topographically high area on Titan's equator. The Fensal and the Aztlan, located just east of Xanadu between 0 and 90 degrees west longitude, have more widely spaced dunes and bright interdunes. They are thought to be the least sandy of the five sand seas. The Belet is located between 220 and 300 degrees west longitude, and has narrow, closely spaced dunes and dark interdunes. The Belet is thought to be the most sandy of the sand seas. The Shangri-La is located just west of Xanadu between 150 and 200 degrees west longitude. These dunes are also relatively closely spaced, though not as much so as in the Belet. The interdunes are moderately dark. This sand sea has the most RADAR coverage of any of them. Not much is known about the Senkyo Sand Sea, which is located between 300 and 360 degrees west latitude, and has poor RADAR coverage (Radebaugh 2013).

Sand is transported along or between dunes by a process called saltation. In this process, sand grains will be suspended by wind for short periods of time, and bounce along the surface. The impact of sand grains with the surface dislodges other sand grains, perpetuating the saltation. There are four forces that determine whether saltation is possible. These are gravitational forces, lift forces, drag forces, and cohesion forces between the particles. In this case, since the air is moving past the particle instead of the particle moving through the air, the drag force actually propels the particle forward. Thus, saltation occurs when the lift forces and the drag forces overcome the gravitational forces and the cohesion forces (Shag and Lu 2000). The threshold wind speed at which this occurs is defined by the equation:

$$u_{th} = A_n \sqrt{(\frac{\rho_p}{\rho_a} - 1) * g * D_p + \frac{\gamma}{\rho_a * D_p}}$$

Where ρ_p is the density of the particle, ρ_a is the density of the air, g is the acceleration due to gravity, D_p is the diameter of the particle, and $A_n \approx 0.111$ and γ describe interparticle forces, where γ varies between 1.6×10^{-4} and 5×10^{-4} for dry dust and sand on Earth (Lorenz 2013). The size of sand grains on Titan is unknown, but it is usually estimated to be about .3 to .5 mm (Lorenz 2013).

It is difficult to determine the threshold saltation velocity for sand particles on Titan because so little is known about the sand. Though the sands are known to be organic in composition, the exact nature of the organics is unknown, since many different types of organics are created in the upper atmosphere of Titan and the process by which the organic particles go from haze in the atmosphere to sand is unknown. The amount of cohesion between the particles, which affects required saltation wind speeds, is also unknown. Liquid methane, known to exist in abundance in certain locations on Titan (Lorenz et al. 2008; Stofan et al. 2007), and perhaps as ground liquids (Barnes et al. 2011; Griffith et al. 2000), would significantly increase particle cohesion just as wet sand on Earth sticks together better than dry sand (Rubin and Hesp 2009). However, the orientation of the dunes and the atmospheric dynamics of Titan provide some indications as to the threshold wind velocity. The dunes are streamlined around topographic obstacles in a west to east direction, indicating that the wind that forms them is generally eastward. As stated above, the average wind direction over most of the year is westward along the equator, but the winds going in this direction are slower than the fast eastward wind that is present during the equinox. Thus, it is likely that the threshold velocity is greater than .8 m/s, which would allow only the faster eastward winds to shape the dunes (Lorenz 2013).

1.3 Titan as an Analogy for Earth

It is often useful to find processes on Earth that are similar to those on other planetary bodies to help make estimates about associated non-observable processes. On Earth, there are linear dunes located in Australia, Namibia, the Kalahari Desert, the Sahara Desert, the Arabian Peninsula, and a few other smaller locations. The geomorphology of the linear dunes in these regions is similar to that of the dunes on Titan. However, it should be noted that dunes are not actively forming in all of these regions. It is more difficult to study processes in areas where the processes are not currently occurring. The Namib Sand Sea and the Sahara Desert are most often used as analogies for Titan, since their dunes are the most morphologically similar to dunes on Titan (Radebaugh et al. 2009). However, it should be noted that each sand sea has slightly different properties, and none of them can be considered a perfect analogy for Titan.

1.4 Previous Work

Some work has already been done to measure parameters such as width and spacing of dunes on Titan. Measurements of dune width and crest-to crest spacing have already been made in the Fensal Sand Sea, the Senkyo Sand Sea, between the Senkyo and the Belet Sand Sea, and on the eastern end of the Shangri-La Sand Sea. Measurements are lacking in the Belet and the Aztlan sand seas, due to the sparsity of radar coverage in these areas. We chose to measure an area in the southern Belet and eastern Shangri-La Sand Seas because the swath is located near the margin of the dune field, and due to the lack of previous measurements in the area. There are some measurements in the T44 swath in the Shangri-La Sand Sea, but for these measurements width and spacing were not taken in the same location.

Arnold (2014) has recently attempted to develop a sand volume estimate across all of Titan. He also developed a contour map of differences in dune width across Titan. However, this map can be very difficult to generate, due to the large gaps between measurements. In many cases, contours were done by hand, assuming width patterns as are exhibited in the Namib Sand Sea. These patterns show that the greatest amount of sand is located in the center of the Namib Sand Sea, and that the dunes there are wider than the dunes on the edges (Lancaster 1989). However, we have observed that the dune widths appear to be greater on the margins of the sand seas, and the dunes there seem to be more widely spaced than those nearer the center. There is a similar pattern in the Australian deserts, where narrower dune widths occur in areas with an underlying substrate that tends to produce more sand, and thus have a greater sand volume (Fitzsimmons 2007). Our goal is to determine which pattern, decreasing or increasing dune width with sand availability, is a better analogue for Titan in the Belet and Shangri-La Sand Seas.

Chapter 2

Data Collection

2.1 SAR and ISS Imaging

Our data were taken from images obtained by the Cassini mission. We used primarily images taken by the Synthetic-Aperture Radar (SAR) and the Imaging Science Subsystem (ISS) instruments. The hazy atmosphere of Titan can be penetrated at near-infrared wavelengths, so the ISS is able to take images of the surface at these wavelengths. These images have a resolution averaging around ten kilometers per pixel. This resolution is far too low to distinguish individual dunes, but the regions that appear dark near the equator in ISS images correlate very well with areas that have been found to contain sand dunes.

SAR imaging is much higher resolution with 350 meters per pixel, but does not cover the whole surface of Titan (Radebaugh 2013). SAR images are taken in swaths each time the Cassini satellite goes by Titan in its orbit. These swaths currently cover about 50% of the surface of Titan (Arnold 2014).

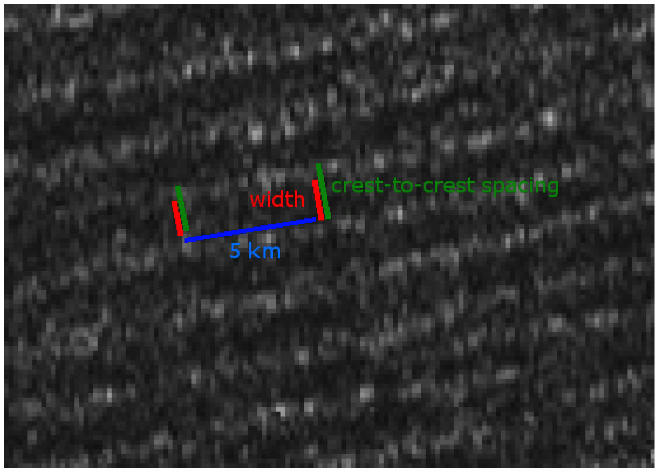

Figure 2.1 Sketch of how measurements are taken

2.2 Procedure

We measured the width and spacing of sand dunes using the method developed by Mills et al. (2013). In this method, measurements for width and spacing are paired together, so that each pair is taken in the same location. The width of the sand dunes is found by measuring the perpendicular distance across the dark streaks that represent the dunes. The crest-to-crest spacing of the dunes is approximated, since actual crest lines are not resolved in the SAR swaths. This is done by measuring the perpendicular distance from one dark-light boundary to the next. Since the measurements are paired, the width of the interdune can be found by subtracting the width of the dune from the crest-to-crest spacing. Each pair of measurements is spaced five kilometers apart along the length of the dune.

Measurements were taken using a program called ISIS (Integrated Software for Imagers and Spectrometers), developed by the United States Geological Survey (USGS). This software is specifically designed to help researchers analyze images obtained by planetary missions. We used the measure function within the software to obtain and record our measurements of width and spacing.

We took 1,232 paired measurements of width and spacing in the T008 swath (Belet), and

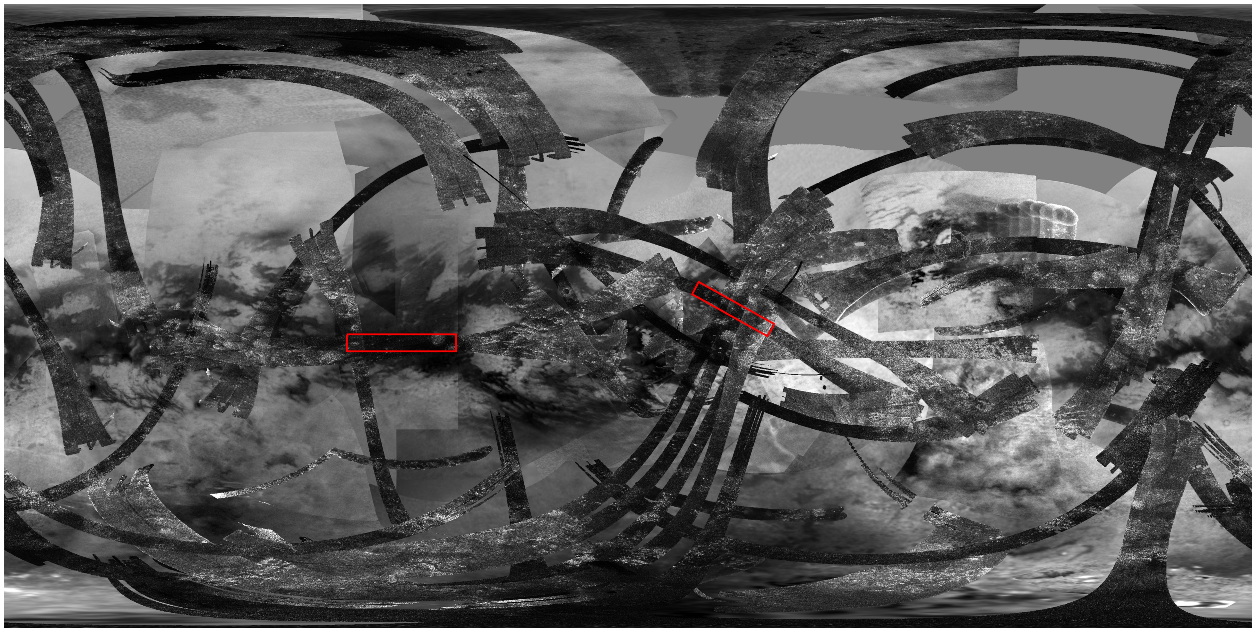

Figure 2.2 A map of the surface of Titan. The base map was taken using the Cassini ISS instrument. Radar swaths are overlaid on the base map. The red box on the left is the T08 swath, and the red box on the right is from the T44 swath.

936 paired measurements in the T044 swath (Shangri-La). Each swath was broken into squares approximately ninety kilometers by ninety kilometers. Fifty or more measurements were taken within each square.

After the measurements of width and spacing were obtained, we found the average width and spacing of each group of fifty measurements. We also found the average latitude and longitude. We then used this information to measure the distance of the average latitude and longitude of each group of measurements from the edge of the dune field. To determine the edge of the dune field, we used the dune field polygons developed by Arnold (2014), which map the edges of each dune field on an ISS mosaic of the surface of Titan. We used the program ArcGIS to take the measurements.

Chapter 3

Analysis and Results

3.1 Parameters of Dunes in Belet and Shangri-La

We found that the average width of dunes in the T08 swath located in the Belet Sand Sea is 1.3 km, and the average crest-to-crest spacing is 2.4 km. The average width of dunes in the T44 swath, located in the Shangri-La Sand Sea, is 1.4 km and the average crest-to-crest spacing is 2.7 km. These are similar to averages obtained by Savage et al. (2013) for dunes across Titan, which have a width of 1.3 km, and a spacing of 2.6 km.

The distribution of the width, crest-to-crest spacing, and interdune spacing for each swath is shown in Figures 3.1 and 3.2. Each distribution is approximately normal, though slightly skewed towards the left. Both locations show a similar distribution, though the measurements from T44 have a larger tail. These unusually large measurements tend to be from regions where there are a large number of obstacles surrounding the dunes.

Maps of swaths T08 and T44 are shown in Figures 3.3 and 3.4. These maps show the divisions into ninety kilometer squares. The average crest-to-crest spacing is shown on the top in orange, and the average width is shown on the bottom in yellow. The standard deviation for each measurement

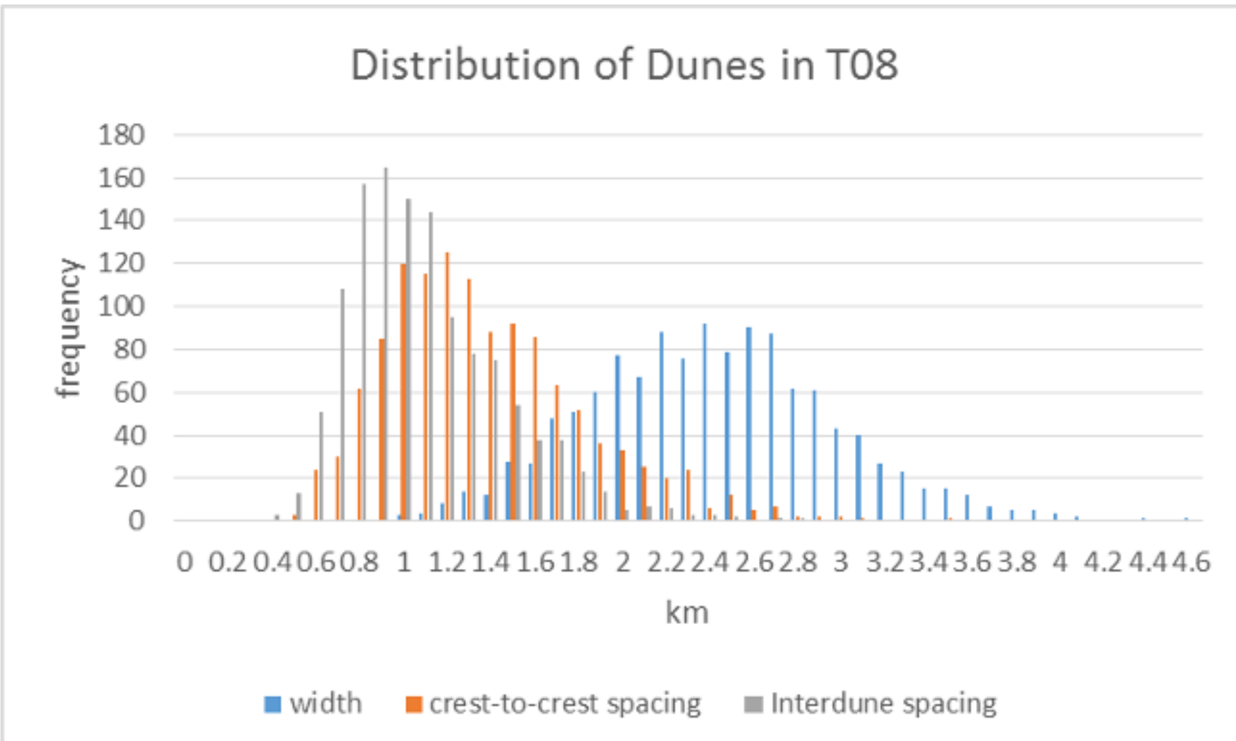

Figure 3.1 Histogram of the distribution of dune sizes in the Belet Sand Sea. Width, crest-to-crest spacing, and interdune spacing of dunes is shown on the same plot. Each is roughly a normal distribution, slightly skewed to the left.

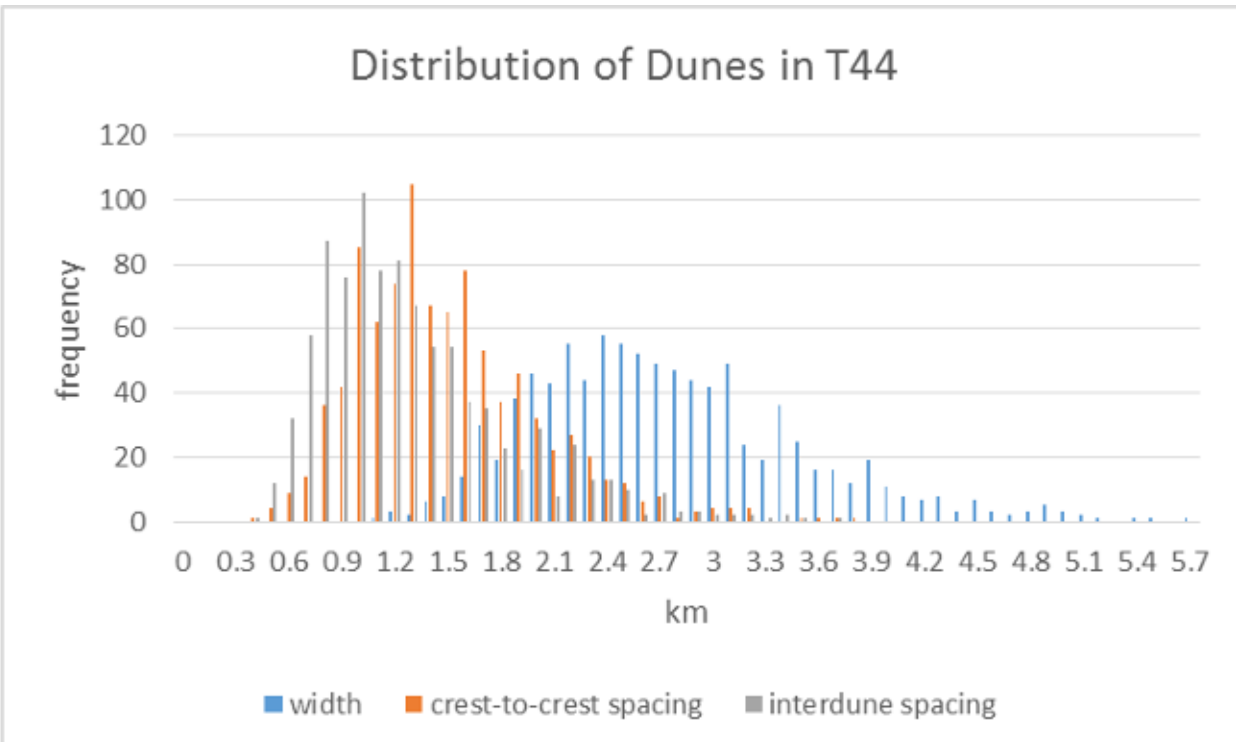

Figure 3.2 Histogram of the distribution of dune sizes in the Shangri-La Sand Sea. Width, crest-to-crest spacing, and interdune spacing of dunes is shown on the same plot. Each is roughly a normal distribution, slightly skewed to the left, although the distribution is not as smooth as the distribution of dunes in the Belet.

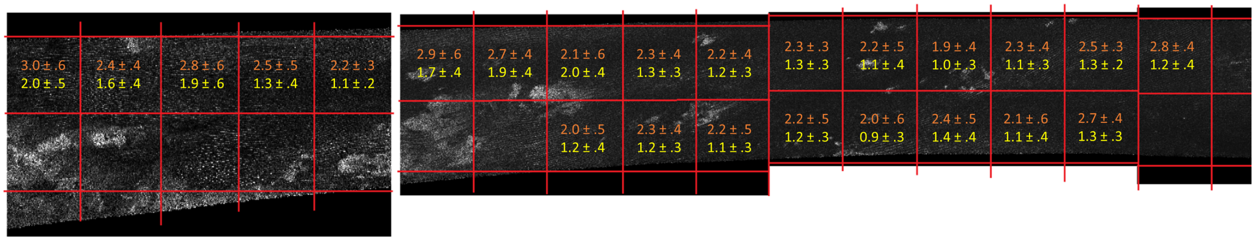

Figure 3.3 Map of T08 swath in the Belet Sand Sea. The orange numbers show the crest-to-crest spacings, and the yellow numbers show the widths of dunes. Standard deviations for each section are also shown.

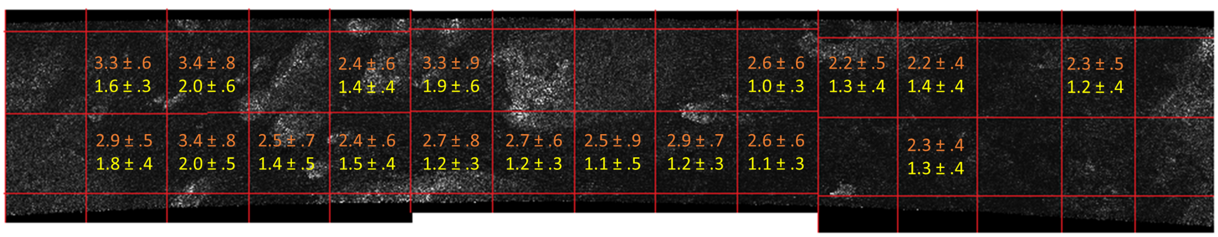

Figure 3.4 Map of T44 swath in the Shangri-La Sand Sea. The orange numbers show the crest-to-crest spacings, and the yellow numbers show the widths of dunes. Standard deviations for each section are also shown.

is also shown. The dark regions on the map represent sandy areas, and the bright regions represent obstacles or other types of terrain. It appears that the larger measurements of width and spacing are located close to the edge of the dune field, and the smaller measurements are more toward the center.

Plots of the average width and crest-to-crest spacing of each group with the distance of each group from the edge are shown in Figures 3.5 and 3.6. There appears to be some correlation between the distance from the edge of the dune and the width and spacing of the dunes, but the correlation is not very strong. This is possibly due to the fact that in Arnold's (2014) map of the edges of the dune fields, many of the small obstacles in the middle of a dune field were considered an "edge" due to their brightness. However, these small obstacles do not have much of an effect on the sand availability. Thus, it would be better to measure the distance from the edge of the dune field eliminating these small obstacles as possible edges. We recommend this as an avenue for future work.

Another possible explanation for why the correlation in Figures 3.5 and 3.6 does not appear to be very strong is that the grid shown in Figures 3.3 and 3.4 is very coarse. As stated above, it is possible to see a general decrease in width and spacing as distance from the edge of the dune field increases, but each group of measurements contains variability in width, spacing and distance from the edge of the dune field. Thus, the grouped average measurements do not fully represent the complete distribution of measurements. It might be possible to find a stronger correlation by measuring the distance of each individual width and spacing measurement from the edge of the dune field, instead of grouping the measurements into ninety kilometer squares. Taking the measurements this way would increase the sample size used to determine the correlation in Figures 3.5 and 3.6 by a factor of 50. We recommend investigating this approach as a means of increasing the correlation.

3.2 Discussion

We measured distance from the edge of a dune field with the assumption that sand availability increases with distance toward the center, as has been found in the Namib and Australian sand seas on Earth (Fitzsimmons 2007; Lancaster 1989). Our goal was to find a correlation between sand availability and dune width and spacing. While this correlation was not as strong as we hoped, we still have reason to believe there is a correlation between these two variables. Our measurements were taken in two different sand seas on the surface of Titan. The T08 swath is located in the Belet Sand Sea, while the T44 swath is in the Shangri-La. Arnold (2014) found that the Belet Sand Sea has a much greater volume of sand than the Shangri-La Sand Sea. This may provide additional

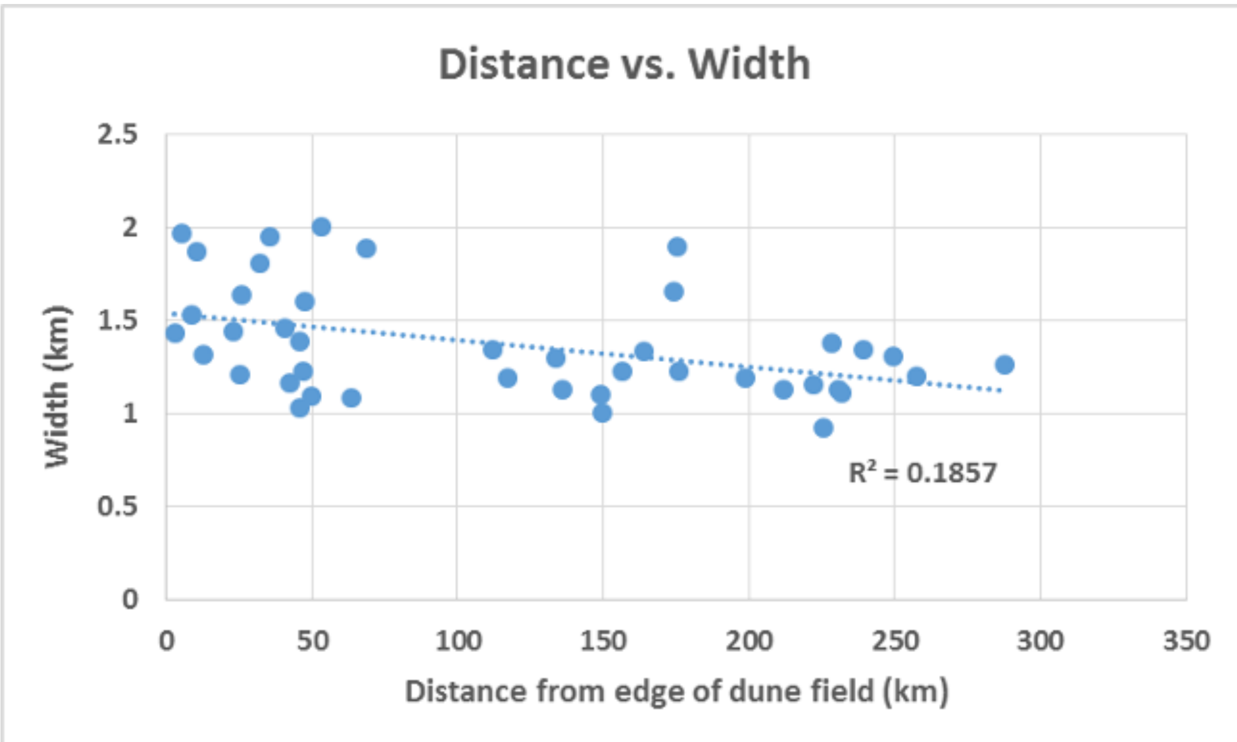

Figure 3.5 Plot of distance of each section from the edge of the dune field vs. the average width of dunes in the section.

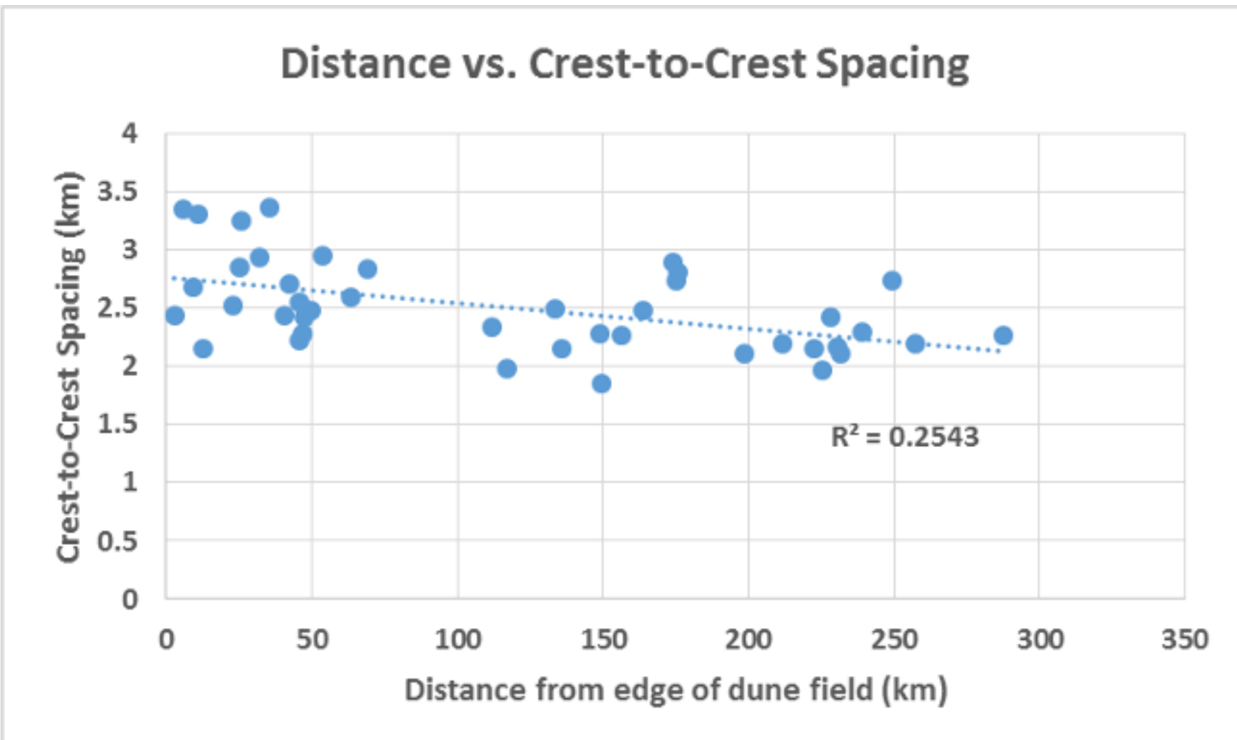

Figure 3.6 Plot of distance of each section from the edge of the dune field vs. the average crest-to-crest spacing of dunes in the section.

evidence that the width and spacing decreases with an increase in sand availability. In Figures 3.5 and 3.6, the measurements that are closer to the edge of the dune field are mostly from the T44 swath, while the group of measurements that are further from the edge of the dune field are from the T08 swath. Since the Belet Sand Sea is much sandier than the Shangri-La Sand Sea, it is still true that the more sandy regions are towards the right side of the plot, and the less sandy regions are towards the right side of the plot. Thus, the width and spacing still decrease with an increase in sand availability. This is opposite from the correlation that has been found for the Namib Sand Sea (Lancaster 1989). It is also slightly unexpected, since wider dunes in areas with less sand would require the height of the dunes to be significantly smaller in the regions with less sand. However, for the Strzelecki and Tirari Deserts in Australia, it was found that dunes in sandier regions were narrower than dunes in sand-poor regions (Fitzsimmons 2007). Neither sand sea is a perfect analogy for Titan's sand seas, so it is likely that in this particular aspect, the Australian dunes provide a better analogy than the African ones.

It is interesting that the Belet Sand Sea seems to be sandier than the Shangri-La Sand Sea. The Shangri-La Sand Sea is just west of Xanadu, so it could easily be reasoned that with eastward blowing winds that transport sediment, sand would build up in the Shangri-La. However, Belet, which is just west of the Shangri-La, seems to contain more sand. This could be explained by the patterns seen in the Australian Sand Seas. In Australia, the dune width and the amount of sediment seemed to be correlated with the substrate that the dunes formed on (Fitzsimmons 2007). It is difficult to tell differences in substrate based on radar images alone, especially when the substrate is covered in sand. While it is difficult to verify, differences in substrate should be considered as a possible cause for differences among sand seas on Titan.

3.3 Conclusions and Future Work

Our purpose in measuring the average width and spacing of dunes in the T08 and T44 swaths was to determine if there is a correlation between these parameters and the distance of those measurements from the edges of the dune fields. While the map of swaths T44 and T08 suggest some correlation between the width and spacing and the distance of the dunes from the edge of a dune field, it is possible that refining the measurements by removing inselberges from the definition of edges could yield a stronger correlation. It may also be possible to detect a stronger correlation by measuring the distance of each individual width and spacing measurement from the edge of the dune field. There still appears to be a correlation between dune width and sand availability, with width decreasing in areas where there is more sand available. This may be affected by the substrate the dunes form on, as is the case in Australia (Fitzsimmons 2007).

There is much room for additional research in this field. The measurements of distance of dunes from the edge of a dune field should be revised so as to better approximate sand availability. Measurements of distance fom the edge of the dune field should also be taken for each width and spacing measurement instead of for each group of fifty measurements. It would also be interesting to correlate the height and width of dunes for different types of dune fields. If there is an accurate way to predict dune height from width and other variables, it would be useful in finding more accurate sand volume estimates on Titan. It would also be interesting to map widths and spacings of an entire dune field on Titan, to determine the variations in dune parameters across the entire field.

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