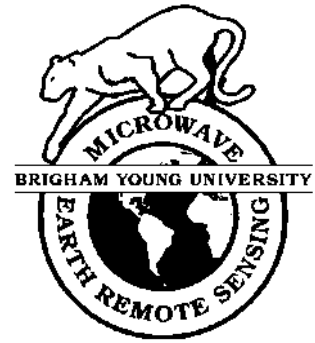


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Improving Temporal Resolution of SIR Images for QuikSCAT in the Polar Regions

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March 25, 2005

Abstract

The current method of separating data into ascending-only and descending-only suffers from diminished temporal resolution when used to create polar QuikSCAT SIR ascending and descending images. The primary causes of this temporal resolution loss are a result of ascending/descending pass overlap, and a loosely imposed day boundary. This paper explains how these cause loss of temporal resolution. In addition, this paper proposes a method for overcoming these shortcomings, by creating images where local time-of-day is used to separate the data. This morning/evening method results in 3–6 hours greater time separation than the current ascending/descending method at extreme latitudes. This method also decreases the area affected by the day boundary, decreasing the temporal variability of the resulting images.

1 Introduction

The SeaWinds instrument aboard QuikSCAT is a spaceborne scatterometer in a near-polar sun-synchronous orbit. Because of its wide swath width and orbit geometry this satellite covers many areas in the polar regions multiple times a day. This high temporal sampling frequency in the polar regions provides a powerful tool for greater study of the ice caps. Current SIR enhanced images make use of QuikSCAT data by organizing the data into images showing the average daily normalized radar cross-section, σ_0 , as well as images showing the daily average σ_0 on ascending and descending passes separately.

Separating the data into images of ascending and descending passes is an easily implemented method of improving temporal resolution over a significant portion of the earth's surface. Particularly at lower latitudes, this temporal separation scheme works well because each satellite makes two passes per day over any given area, one ascending and one descending, each separated by roughly 10 to 12 hours. Each ascending and descending pass occurs

at roughly the same local time every day. At higher latitudes, however, this scheme exhibits several undesirable features.

In this paper we first analyze the current method of creating ascending and descending images. We then propose a new method of temporally separating QuikSCAT images which mitigates the current method’s shortcomings. The next section gives additional background on the images produced from QuikSCAT data. Following this background information, the analysis of the ascending/descending method is given. Then, the new method is proposed.

2 Background on Images produced from QuikSCAT data

QuikSCAT images are currently produced of various regions of the earth’s surface in several ways. The most simple images are produced by merely averaging measurements within each pixel’s area. Gridded images produced by this method result in images with good signal to noise, but suffer from poor spatial resolution. Gridded image spatial resolution is limited by the dimensions of the antenna pattern: roughly 23km. Other images are produced using the Scatterometer Image Reconstruction (SIR) technique that greatly improves spatial resolution, but also introduces some extra noise. SIR images are created using the full antenna footprint to create ‘Egg’ images, and using range-gated footprints to create ‘Slice’ images. Both ‘Egg’ and ‘Slice’ images have variable effective resolution depending on the number and orientation of measurements covering each pixel, but have typical effective resolutions on the order of 9km for ‘Egg’ images, 3–6 km for ‘Slice’ images.

In the production of SIR images, many auxiliary images are also produced. In this paper we are strongly concerned with the image produced by the SIR algorithm that estimates the time that each pixel was measured. This “time” image is referred to as the \mathbf{p} image [1].

3 Ascending and Descending Images and their Drawbacks

In the currently available products, daily data is temporally separated into three images: daily, ascending pass-only, and descending pass-only. Ascending and descending pass-only images are produced to aid the study of diurnal variation and very short-lived natural phenomena. Because the ascending and descending images account for only half of the daily data each, the most general drawback to these images relative to the daily images is the accompanying decrease in spatial coverage. In the Arctic and Antarctic, however, spatial coverage for ascending and descending images is nearly guaranteed, and often repeated many times over for most of the polar regions. Unfortunately, in current ascending and descending images, the temporal resolution is not as good as it could be at the polar extremes due to inadequate temporal separation and grouping of individual measurements. In this section the roots of the temporal-resolution limitations—swath overlap and day boundary effects—and their effect on the available images, is discussed in detail.

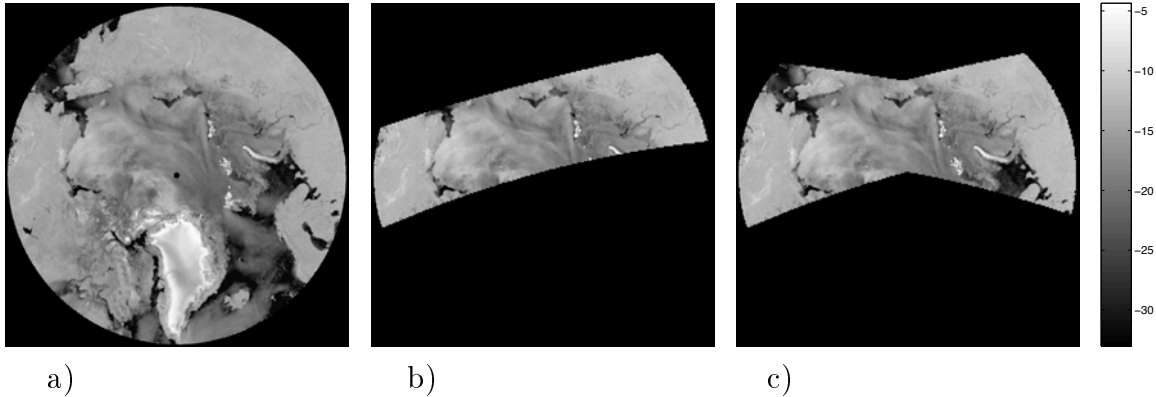


Figure 1: Image shows a) a typical v-pol QuikSCAT SIR image of the Arctic, b) the same image masked to show the structure of a single pass, and c) the same image masked to show the structure of two consecutive passes.

3.1 Swath Overlap Effects

The temporal resolution shortcomings of the current ascending and descending product is, in part, a result of ascending and descending pass overlap. In order to understand the effect of ascending and descending pass overlap on the available images, the satellite’s orbital and instrument geometry must be understood.

The SeaWinds instruments aboard QuikSCAT is a spaceborne scatterometer in a near-polar sun-synchronous orbit. Sun-synchronous satellites are unique because they pass over a given point on the earth’s surface at nearly the same local time for any particular ascending or descending pass. In other words, sun-synchronous satellites maintain a constant angle to the sun, so measurements are always made at a similar local time of day. Having a 6:00 AM ascending node, QuikSCAT crosses the equator northbound at roughly 6:00 AM local time, and again southbound at 6:00 PM local time.

At the polar extremes this concept of constant local time inadequately describes the sampling. Since the satellite has a 6:00 AM ascending node and a 6:00 PM descending node, in its orbit from ascending node to descending node, the satellite transitions 12 local time zones. In the polar regions, lines of longitude, and thus the local time zone boundaries are close together, so that QuikSCAT transitions most of these 12 time zones very quickly at high latitudes. This local time transition is common to all sun-synchronous satellite orbits, and does not directly affect the temporal resolution of the images produced. However, QuikSCAT images produced by separating ascending and descending passes suffer from a loss of temporal resolution due to the conically scanning pencil beam system employed by the SeaWinds instruments.

Figure 1a shows an Arctic QuikSCAT SIR image created from one day of data, and Figure 1b is the same image masked to exclude all but one pass of the satellite. Note that the North pole is in the center of the image. Because the transition point from ascending to descending occurs at the northern-most point in the satellites travel, roughly half of the pass shown in Figure 1b is ascending and half descending. Figure 1c shows the same SIR image masked to exclude all but two consecutive passes. The second pass is much like the

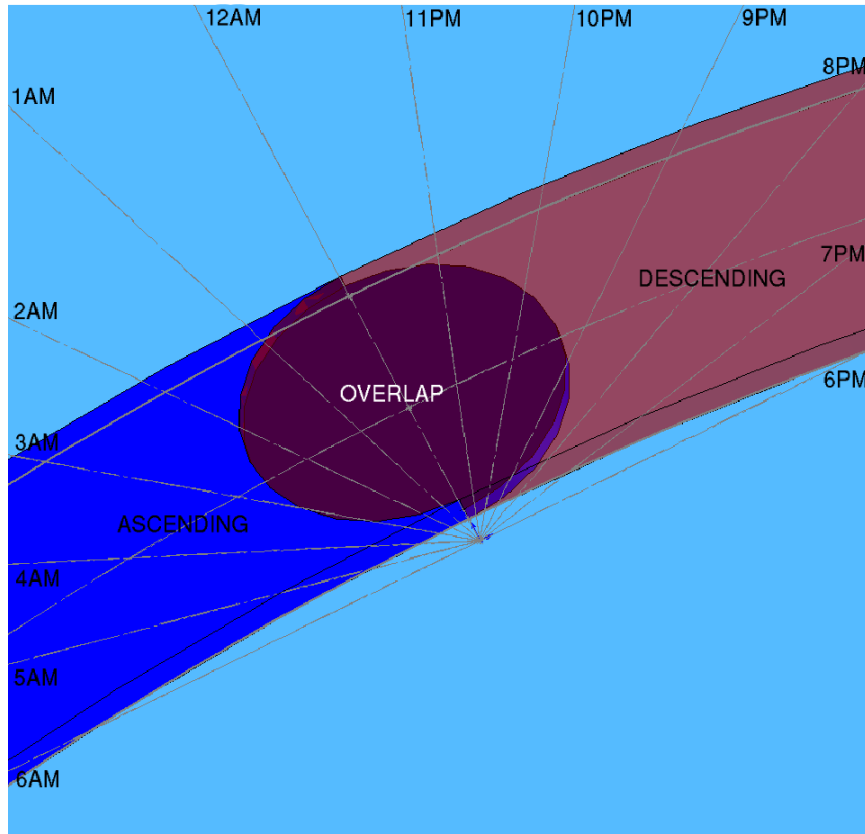


Figure 2: Diagram illustrating the transition from ascending pass to descending pass in the Arctic. The lines radiating out from the center depict the local time zone boundaries. Note that there is significant overlap of the ascending and descending data.

first, but rotated about the pole by some angle due to the rotation of the Earth under the satellite orbit.

Because QuikSCAT uses a conically scanning pencil beam, every rotation of its parabolic reflector sweeps out a circle on the earth's surface centered around the nadir point of the satellite. This circle of measurements can be divided into two groups, forward-looking and aft-looking. When the satellite reaches its most northern point the pass transitions from ascending to descending. Before this occurs the satellite measures forward from that transition point, and after the transition the satellite continues to measure aft of that transition point. This causes a disk-shaped region where the forward-looking measurements are still ascending, but the aft-looking measurements descending. Figure 2 is a diagram showing more precisely how the measurements of a single pass are divided into ascending and descending passes. This region of pass overlap is a primary cause for temporal resolution loss in ascending/descending images, because the data collected each pass will have data in ascending images that is separated by only a few minutes from similar data in the descending images.

Figure 2 also illustrates the local time transition that occurs in the Arctic region. Note that the northern most point in the satellites travel the local time of day is 12:00 AM at nadir, halfway between 6:00 AM and 6:00 PM. Because the disk-shaped region of overlap for

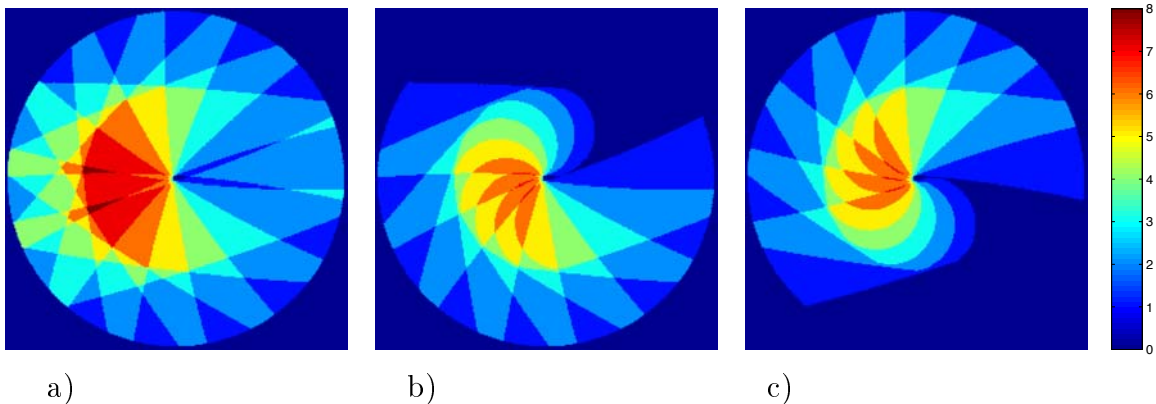


Figure 3: Images show how nine consecutive passes of QuikSCAT overlap in the Arctic for a) full passes (daily images), b) ascending passes, and c) descending passes. Pixel color shows the number of swaths that passed over each pixel. Note the emerging pattern on left of the center. Note that at high latitudes the number of passes exclusive to the ascending vs. descending image is only one or two.

each pass is closely located to the poles, it covers many lines of longitude and thus many local time zones. Because the overlap covers 6–7 time zones, and these latitudes are measured by as many as 8 passes each, with each pass suffering from similar overlap, the resulting images share temporally similar data and suffer from diminished temporal resolution.

Figure 3a shows the number of passes over each pixel that nine consecutive passes make in a typical SIR image. Because the satellite orbits the earth every 100 minutes, the daily averaged σ_0 SIR images include data from roughly 14.25 consecutive passes, repeating the same coverage pattern every 4 days. Figure 3a also shows another interesting feature: after only nine passes the first and the last passes are already starting to overlap, seen on the right side of the image. The overlap shown is a result of the satellite passing roughly the same location twice a day, and is what makes twice-daily full coverage images of the Arctic and Antarctic possible.

Figures 3b, and 3c are images showing the number of passes over each pixel that nine consecutive passes make separated into ascending and descending pass images respectively. The rounded edges on each of the ascending and descending passes are a direct result of the disk-shaped overlap region illustrated in Figure 2.

The effect of these regions of overlap is also illustrated by looking at the swath counts at each pixel in Figures 3a, 3b and 3c. The multiple pass sampling at each pixel is complex, but its structure is apparent in these figures. Note that over a large portion of the high latitude region (75+ degrees N), there are seven swath passes total over any given pixel. Because of the disk-shaped regions of overlap, in the high latitude region, pixels in the ascending image are sampled by five or six passes, and the descending image pixels are also sampled by five to six passes. Since there are only seven passes total, and the ascending and descending images have regions sampled by five or six passes in each, there is very little information in these regions of the ascending image that is not also in the descending image. Because there is a low amount of information from this region exclusive to the ascending or descending images,

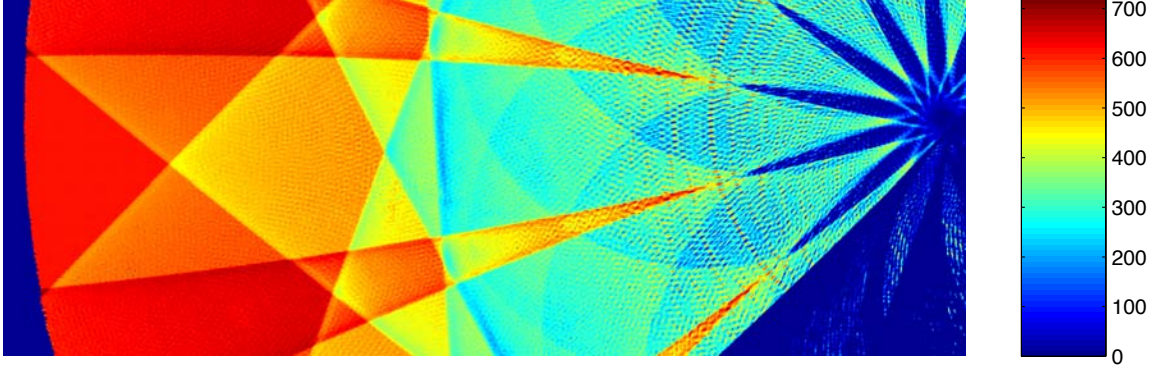


Figure 4: Image showing the time separation in hours between the same-day descending and ascending pass images. Note that the north pole is located in the upper right.

data correlation, both physically and temporally, between the resultant images is very high.

In the creation of \mathbf{p} images described in Section 2, each sample's time of day is weighted by its σ_0 measurement before being averaged together. This non-linear method of averaging is used to counteract an inherent time bias due to the SIR process [1]. This weighted time average become the value of that pixel in the \mathbf{p} image. Since each of the passes have an ascending/descending pass overlap region, the separation between the ascending and descending \mathbf{p} images is much less than the ten to twelve hours desired. Figure 4 shows the time separation between the ascending and descending images over a small region corresponding to the region left of the north pole in Figures 1a, 3a, 3b, and 3c. As expected, the areas of high latitude where the ascending and descending images share temporally similar data have very little time separation. The small separation time between the ascending and descending images confirms the temporal resolution loss, as well as showing quantitatively the temporal limitations of these images.

In general overlapping satellite passes tends to suppress transients, and in most cases also decreases temporal resolution. On the other hand, averaging multiple consecutive passes can lessen the effect of noise and other anomalies on the output images. Because of the factors involved, there is a compromise made when one choses temporal resolution over accuracy. Maximizing temporal resolution while maintaining accuracy is an strong motivator for improving the current method of image separation. By eliminating the overlap between ascending and descending passes we significantly improve temporal resolution with minimal change in accuracy. Section 4 describes this method.

3.2 Day Boundary Effects

Perhaps the greatest limitation of using separate ascending and descending images to provide temporal resolution in the polar regions is the effect of day boundaries. The day boundary-affected region is the region of the image where data separated by nearly 24 hours is averaged together. Current polar QuikSCAT SIR images are created from one twenty-four hour time period. All valid data taken during that twenty-four hour period is used to create the

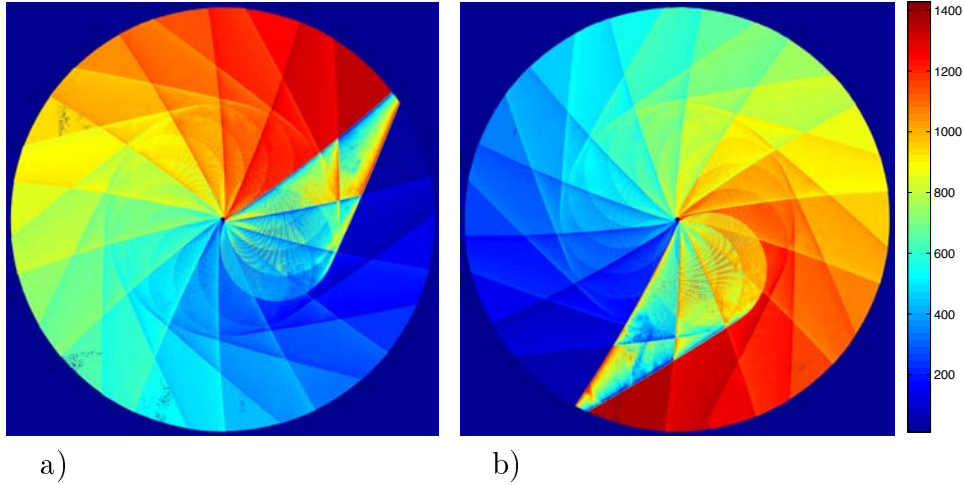


Figure 5: Ascending (a), and descending (b) \mathbf{p} images from JD 258 2003. Note the area to the right of center in (a), and below center in (b), where the first several passes and the last several passes overlap.

images. We note there are significant portions of the Arctic and Antarctic where the first several passes and the last several passes of each day cover the same area for ascending and descending images, due to the wide swath. Figures 5a and 5b are ascending and descending \mathbf{p} images from QuikSCAT that show the areas where the first and last passes overlap. This day boundary-affected region is especially damaging to temporal resolution, because data separated by nearly twenty-four hours is averaged together.

The effects of the day boundary swath overlap are even more apparent in Figure 6. This image shows the time between the ascending and descending images. This difference image shows both positive and negative time separation, because the ascending image precedes the descending image in some regions, while in others descending image precedes the ascending image. The day boundary is the region of the image that separates the ascending-first region with the descending-first region. In general, the apparent (average) time separation is low across the entire day boundary affected region. In the day boundary affected region, the variance of time separation is also much larger than in the zones unaffected by day boundaries, shown in Figure 7. The high variance makes useful data extraction of time of day at any given location depend on the day in question. Conversely, the time of day for any given image is highly dependent on the exact pixel location.

The \mathbf{p} image values in the day-boundary affected region also suffer from another problem, the time value shown is not near the time that any of the measurements were actually taken. Therefore the \mathbf{p} pixel values may be misleading when studying diurnal variations. For any application of the images requiring time of day measurements or better than daily temporal resolution, using ascending and descending images in the polar regions is difficult at best.

The effects of a day boundary are unavoidable in images made with shorter than daily temporal resolution because the satellite's sun-synchronous near polar orbit and wide swath. In the ascending and descending images, these day boundaries effect a large portion of the Arctic and Antarctic images. Because this effect is inevitable, efforts to lessen the affected

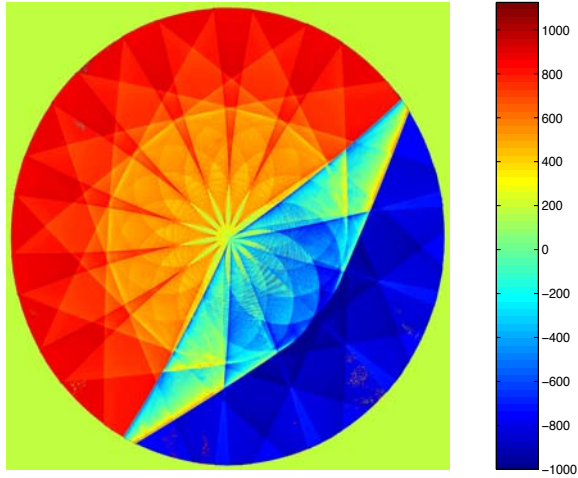


Figure 6: Image showing the difference in time of day of the ascending passes shown in figure 5a and the descending passes shown in figure 5b. Time separation in minutes – descending first is positive.

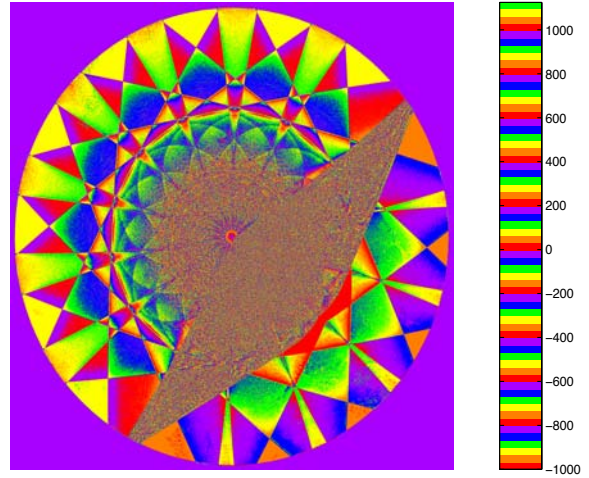


Figure 7: Same image as figure 6 only with different color scheme to emphasize the variance in the day boundary affected region.

area motivates us to improve on the current images. For the new images proposed in the next section this boundary is relegated to a small portion of the image in a predictable manner.

4 Morning and Evening SIR Images

Because there is such variation in local sample time across the wide swath of QuikSCAT and Seawinds in the polar regions, a new method of separating the daily data can be accomplished by using the local times of the samples themselves rather than the direction of the spacecraft's motion. In this method, a specified local time of day is used as a decision boundary. This boundary determines whether to include any given datum into that image. Thus, a particular local time of day is used to separate the data into distinct images. By separating the data according to local time of day, we can guarantee that all temporally similar samples are grouped into the same image.

Because QuikSCAT has a 6:00 AM ascending node and a 6:00 PM descending node a logically intuitive approach is to set the time boundaries at 12:00 AM, and 12:00 PM. As shown previously in Figure 2, these boundaries correspond to a line perpendicular to the spacecraft's travel, almost exactly through the transition point where the spacecraft transitions from ascending to descending and vice versa. Figure 8 shows a similar diagram as Figure 2, indicating the new method of separating the images.

Figure 9 shows three consecutive days of raw QuikSCAT data samples at a given location (84.0468 N 135.3773 W), with the top and bottom plots displaying how the morning/evening method compares with the ascending/descending method. Individual passes are seen as

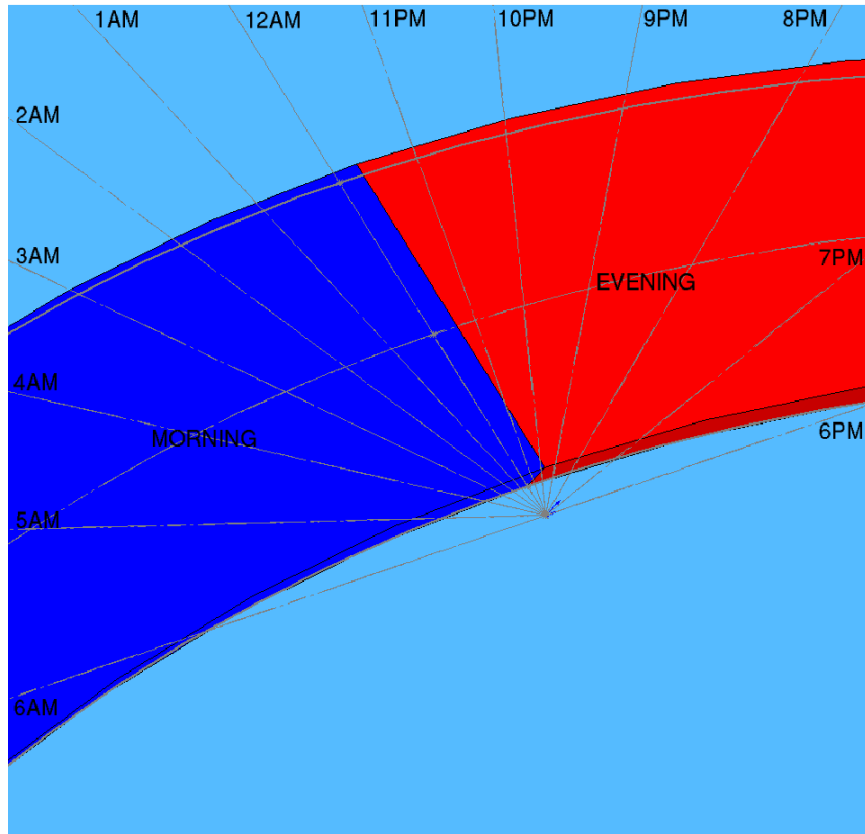


Figure 8: Diagram illustrating the transition from morning pass to evening pass in the Arctic. The lines radiating out from the center depict the local time zone boundaries. Note that there is no overlap of the morning and evening data. Contrast with Figure 2.

nearly vertical columns of data, because the measurements are separated at most by a few minutes. In the ascending/descending scatter plot of the data samples, the effect of ascending and descending pass overlap described previously is shown: both ascending and descending data samples are found in satellite passes spread over a 6 hour period daily. As expected, the morning/evening method, which uses the local time directly to separate the data, shows the transient behavior of the measurements, and increases the effective separation times between the two daily images as well. It can be concluded that using the new method, the two resulting image values for this pixel represent better temporal sampling.

Figure 10 further illustrates the improvement, showing the time separation between the morning and evening images over a small region corresponding to the region left of the north pole in Figures 1, 3a, 3b, and 3c. In contrast to the ascending/descending method whose time separation is shown in Figure 4, Figure 10 shows much better time separation in the high latitude region north of 75 N latitude. Likewise, Figure 10 also shows agreement with Figure 4 in the lower latitudes thus showing that the ascending/descending method works equally well for images in non-polar regions.

The resulting improvement of temporal resolution in morning/evening images over the current method is due to the temporal grouping of data. A change in the shape of the ap-

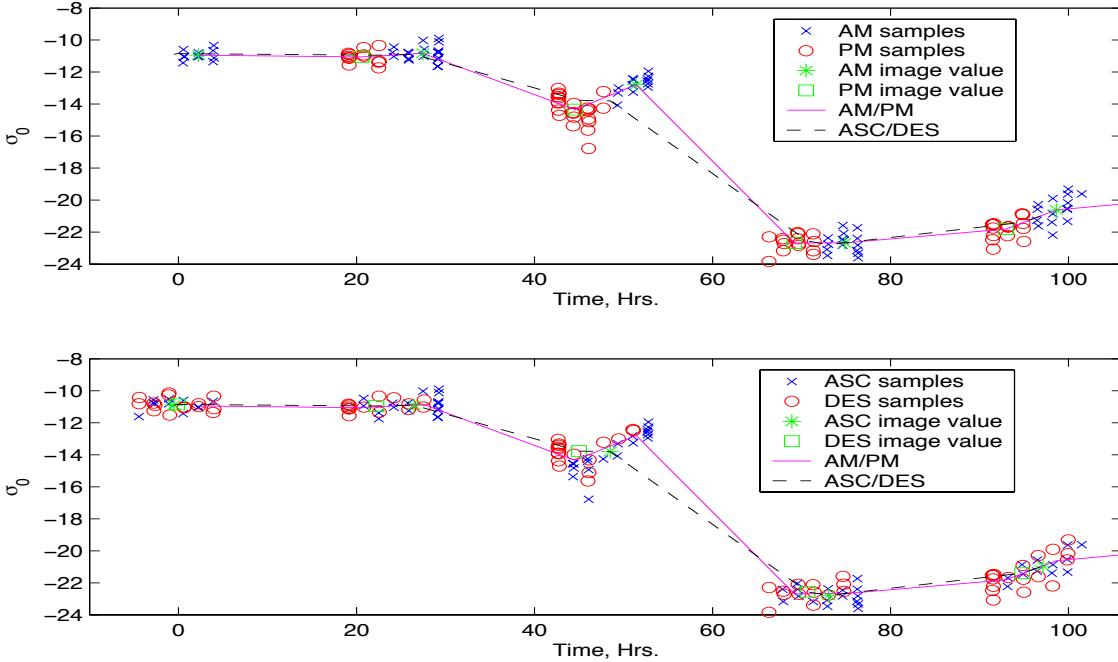


Figure 9: Graph comparing the ascending/descending method (top) of data segregation and the new morning/evening method (bottom) (84.0468 N 135.3773 W from JD 163 to JD 166 2003). Note the morning/evening method follows transients better and has closer to uniform samples.

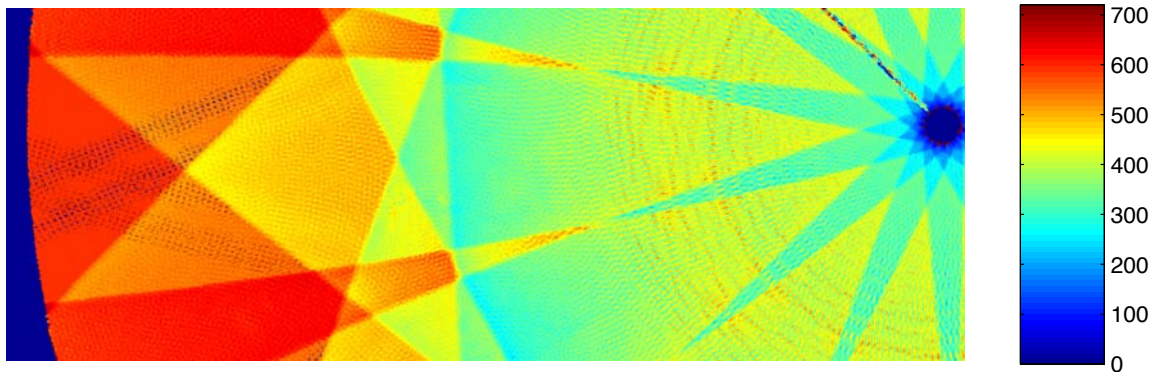


Figure 10: Image showing the time separation in minutes between the same-day morning/evening images for JD 166. Note that the north pole is located in the upper right. Contrast this with Figure 4, which shows the same image for the ascending/descending pass images. Note the increased separation with the morning/evening image method shown especially in the right half of the image.

parent swath as it reaches its northern apex is a direct result. Figure 8 mentioned previously shows how the swath is divided in the new method. Contrast this diagram with Figure 2, which shows how the swath was separated for the ascending/descending method. The sharp

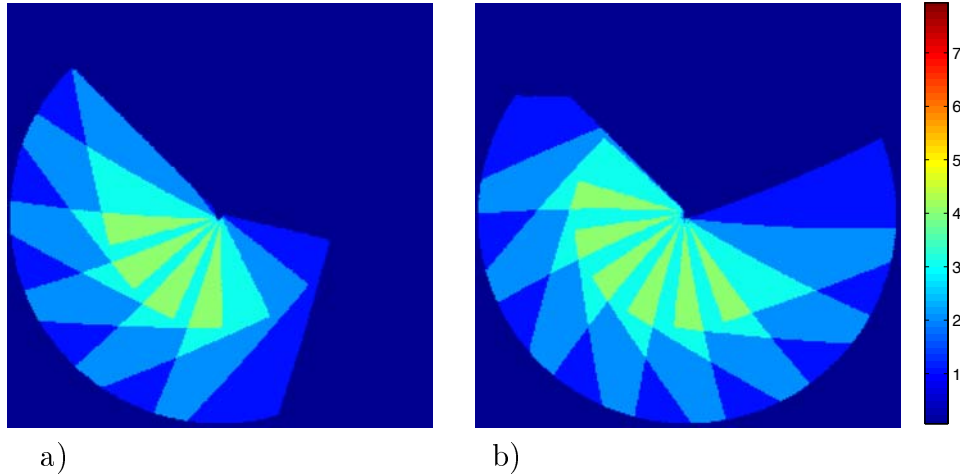


Figure 11: Images show how seven consecutive passes overlap in a) morning image and b) evening image in the Arctic. Pixel color shows the number of swaths that passed over each pixel. Compare with the same image for full passes in Figure 3a, while contrasting with the ascending/descending images in Figures 3b and 3c.

division results in a pattern illustrated by Figures 11a and 11b, that show the geometry of several consecutive passes separated by local time into morning and evening images respectively. In contrast to the swath geometry shown in Figures 3b and 3c, the number of swath counts in the high latitude region is only 3 or 4 for the morning and evening images, and the sum of the two images never exceeds the total swath count shown in Figure 3a. Essentially, the temporal sampling variability of the data in the ascending and descending images has been drastically reduced, resulting in two temporally distinct images.

Using the local time of day as the decision rule for separating the data and creating SIR images has the added benefit of controlling and relegating the day boundary affected region to a small portion of the image. Intuitively, the local time of day filter places this region right over 180 degrees longitude, at or near the international date line. The day boundary affected region is only as wide as the antenna footprint coverage area, an area several pixels in width.

The morning/evening images have a clear line visible along the 180° longitude line, as a result of the day boundary affected region being concentrated at this location. This does have some negative repercussions. For one, the line clearly appears as an anomaly as the data transitions a twenty-four hour temporal discontinuity. This anomaly may negatively affect certain studies of ice movement in this portion of the world, making it more difficult to track the ice's movement across this day boundary without taking this into account.

Contrast the morning/evening boundary-affected region in Figure 12a, a portion of which is shown in the upper right corner of Figure 10, with the ascending/descending day boundary-affected region shown in Figures 12b, 6, and 7. From these figures it becomes apparent the morning/evening method is certainly an improvement, albeit more visibly notable in morning/evening σ_0 images shown in Figures 13a and 13b. The visible transition these images make, is noticeable only because it is condensed, whereas the day boundary for the

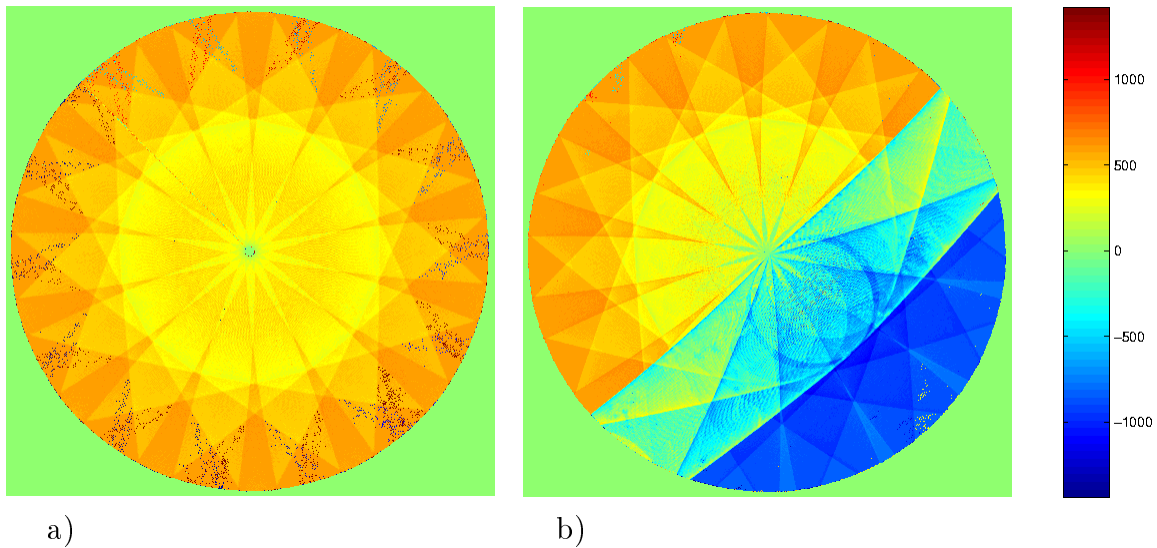


Figure 12: Image showing the difference in time of day of between the morning/evening images (a), and the ascending/descending of JD 166. Time separation in minutes – evening and descending first is positive. Note the differences in the day boundary-affect regions.

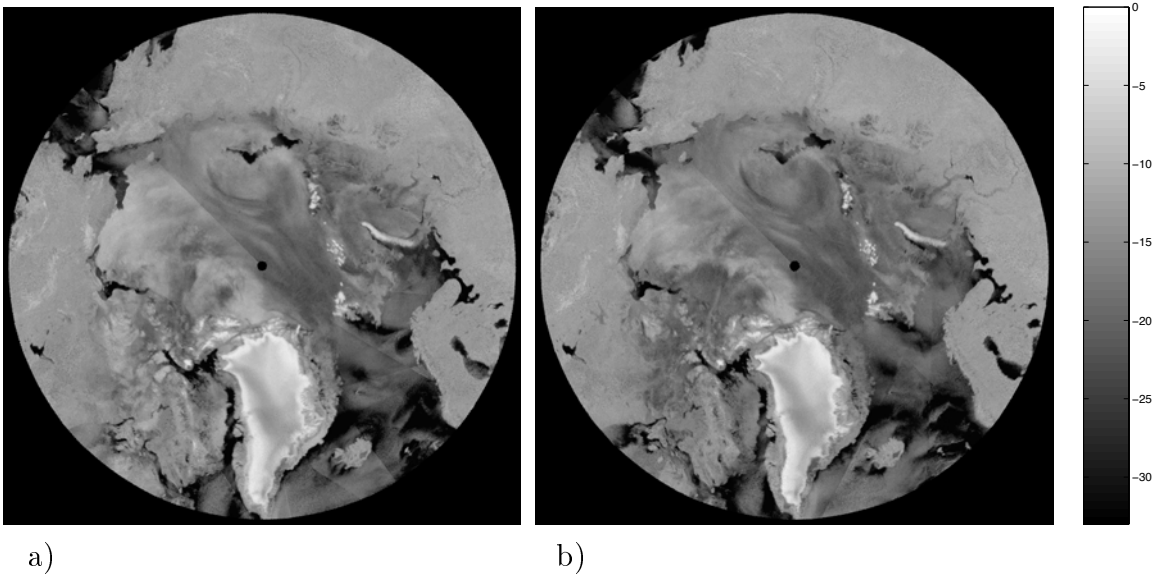


Figure 13: A) a v-pol QuikSCAT SIR Morning image of the Arctic, and b) a v-pol QuikSCAT SIR Evening image of the Arctic for JD 165 2003.

ascending/descending images is much more diffuse, masking it's effects.

5 Conclusions

We have shown that the QuikSCAT ascending/descending method suffers from several issues that result in loss of temporal resolution: ascending-to-descending swath overlap, and day boundary effects. The first of these, swath overlap comes as a result of segregating the data based on the spacecraft's motion and the conically scanning pencil beam. This decreases temporal resolution by increasing the temporal variability of measurements in each image, and by decreasing the mean separation time between the two images. The second of these issues, day boundary effects, are the result of having the first and last passes of the day overlapping each other, causing variable pixel time separation, and pixel times to be far removed from the actual measurements. This issue is unavoidable in full coverage twice-daily polar images; however, it is poorly handled by the current method.

A new method, the morning/evening method, mitigates the effects of these temporal resolution damaging issues. By separating the individual measurements directly based on local time of day into morning and evening images, the effect of overlapping swaths that plagues the current ascending/descending images is completely eliminated. This increases the time separation between the images by 3–6 hours in regions of high latitude, and decreases the temporal variability of the measurements as well. The morning/evening method also handles the unavoidable day boundary effect well, by containing it to a small predictable region of the image. This drastically decreases temporal variability of pixel times in the region previously affected under the current method, increasing temporal resolution.

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