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Antarctica X-Band MiniSAR Crevasse Detection Radar: Final Report

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ABSTRACT

This document is the final report for the Antarctica Synthetic Aperture Radar (SAR) Project. The project involved the modification of a Sandia National Laboratories MiniSAR system to operate at X-band in order to assess the feasibility of an airborne radar to detect crevasses in Antarctica. This radar successfully detected known crevasses at various geometries. The best results were obtained for synthetic aperture radar resolutions of at most one foot and finer.

In addition to the main goal of detecting crevasses, the radar was used to assess conops for a future operational radar. The radar scanned large areas to identify potential safe landing zones. In addition, the radar was used to investigate looking at objects on the surface and below the surface of the ice.

This document includes discussion of the hardware development, system capabilities, and results from data collections in Antarctica.

ACKNOWLEDGEMENTS

This work was funded by the Air National Guard, who will be the primary beneficiary of this work Support from the National Science Foundation's United States Antarctic Program was provided for execution of the test. Raytheon Polar Services Corporation provided support in helping to define and execute the Technical Event (T-event). Kenn Borek Air, Limited assisted in building a mounting structure and the certification, as well as flight test support of the radar installation aboard one of their Twin Otters operated for NSF.   The advisory and ground support by Mark Sletten from the Naval Research Laboratory was also greatly appreciated.

CONTENTS

Executive Summary

For nearly the last 10 years, the National Science Foundation and the New York Air National Guard has been approaching Sandia National Laboratories' Synthetic Aperture Radar departments to demonstrate an X-Band SAR system in Antarctica for the purpose of detecting crevasses in remote landing zones. Recent technology developments incorporated in Sandia National Laboratories' MiniSAR system made a demonstration in Antarctica feasible.

In January of 2006, the price for development of an X-Band variant of MiniSAR finally met their budget and the project within Sandia officially began in March of 2006. The system (and a spare) were built and flown locally for initial checkout in 8 months. Within 9 months of the project start, the X-band version of the MiniSAR was in Antarctica collecting data during the optimal Austral summer time . Results of the tests in Antarctica were quite successful in our ability to detect bridged crevasses. With our initial analysis of the data, we and the NYANG feel confident that the next step should be to integrate the system on 4 to 6 of the 10 LC-130 aircraft they fly in Antarctica.

1. Introduction

In March, 2006, a project was initiated by the New York Air National Guard (NYANG) for Sandia National Laboratories to develop an X-band variant of the MiniSAR radar to demonstrate the capability of this radar for crevasse detection in potential landing areas in Antarctica. This portion of the project culminated with a data collection in Antarctica of known crevasse sites. This document presents an overview of this project.

The desire for crevasse detection in potential landing sites has been known for some time. The U. S. Antarctic program is supported extensively by the LC-130 aircraft fleet. "These heavy-lift, long-range aircraft, with their deep-field landing capability (i.e., landing in areas without prepared skiways) have been instrumental in allowing research to be carried out virtually anywhere on the continent [1]." However, as shown in Figure 1, these aircraft are vulnerable to undetected crevasses which are covered over with a snowbridge. These crevasses are very difficult to detect visually, even in the best of circumstances. Recovery of an aircraft in these deep-field environments is expensive, time-consuming, and potentially dangerous. Therefore, the desire to detect the crevasses a priori and avoid such events is obvious.

Figure 1: Photo of LC-130 in a Crevasse

2. Hardware Development Effort

There was a large effort to develop the system flown in Antarctica other than just making an exact copy of Sandia National Laboratories' MiniSAR system which had been in development for the previous 3 years and was mostly in a prototype state. Time constraints were the major driving factor for building the system, as our goal was to be flying the system in Antarctica in 9 or 10 months in order to take advantage of the Austral summer season for optimal weather in Antarctica. It was also decided to build a complete spare system during this time for backup hardware while in Antarctica, where spares and the ability to overnight hardware is non-existent.

2.1 Conversion from Ku-Band to X-Band

The major effort in building the system was converting the system from Ku-Band to X-Band. The approach used was to build a Ku-Band RF module and then build an external assembly to convert the transmit and receive signals to X-Band. It was felt that building a native RF module to handle this conversion was too risky for the amount of time we had. Other parts in the RF front-end also needed to be changed, these included the Microwave Power module (MPM), all of the components in the front-end were changed, and the antenna and radome had to be redesigned as well. A diplexer had to be added to the front-end in order to prevent the 1^{st} harmonic of X-Band from being transmitted out of the antenna.

2.2 Redesign of the Gimbal Assembly

As mentioned earlier, the prototype nature of the MiniSAR system necessitated a complete redesign of the gimbal assembly. The clearance for some of the cables that are routed throughout the assembly were increased so the cables would not bind and hinder the gimbal's motion. Modifications to increase the ability to balance the gimbal were enhanced so that balance weights could be fastened with bolts instead of double-sided sticky tape. This was added to increase the stability and reliability.

2.3 Addition of Real-Time Strip Map Image Formation

Due to the concept of operations being developed for the NYANG, an additional image processing element needed to be added to the current MiniSAR image formation hardware. This was desirable since the optimal method to gather the large area of landing zone data required strip map image formation processing and MiniSAR was only capable of doing spotlight processing in real-time, ie, it could only form a patch at about every third image needed for real-time strip-map processing. This work should be available for further development of the MiniSAR system.

2.4 Image Mosaic Capability

The current NYANG concept of operation is to map a 5 nmi by 5 nmi area with the radar and look for crevasses prior to landing. In order to evaluate this concept, a post-processing step was added to mosaic the real-time strip map data into an area this large and associate map coordinates with this mosaicked product. The original SAR imagery is in an Sandia National Laboratories internal standard, referred to as “GFF”. This imagery was converted to an NITF-like format, and then mosaicked using ERDAS Imagine® software. The Imagine software performs the mosaic and permits the final result to be read with a free tool called ViewFinder. The user can zoom in or out on the entire mosaic with this software. Another of the advantages of this free tool is that it maintains the position information of the original data and allows the user to obtain a latitude/longitude coordinate for every pixel in the mosaic.

3 System Capabilities

The following system capabilities and modes were utilized in Antarctica data collections.

High Resolution SAR Spotlight Circle Mode:

Band: X-Band (9.9 GHz Center frequency)

Polarization: VV

Resolution: ~8 inch

Sigma_n: -30 dB or better

Range: 3.3 km (Note, this is near the minimum range of the radar in SAR mode)

Depression Angle: 15, 30, 45 degrees

Image SCLA Increment Angle: 15 degrees

Patch Size: Range: ~336 m Azimuth: ~300 m

High-Resolution SAR Spotmap Mode:

Band: X-Band (~9.9 GHz Center frequency)

Polarization: VV

Resolution: 1 ft or coarser

Sigma_n: -30 dB or better

Range: 3.3 km (Note, this is near the minimum range of the radar in SAR mode)

Depression Angle: 15, 30, 45 degrees

Patch Size: Range: ~505 m Azimuth: ~300 m

4 Data Collection

The main purpose of the data collection in Antarctica was to "demonstrate the capability of the Sandia National Laboratories (SNL) Miniature Synthetic Aperture Radar MiniSAR) to detect crevasses in potential landing areas for the New York Air National Guard (NYANG)" [2]. In addition to this goal, data was collected for the purpose of radar checkout, radio frequency interference (RFI) testing, and for the detection of objects on and under the Antarctic ice.

The data collected roughly followed the test plan [2]. The flights were as follows:

> Dec 5, 2006: Initial flight to check out the radar and perform RFI testing at McMurdo Station and Pegasus air field. Figure 2 shows a photograph of the general area imaged for the first flight. Figure 3 shows an approximate layout of the objects found within the Pegasus wreck site, also imaged during this flight. Figure 4 shows a photo of part of the Pegasus wreck site imaged.

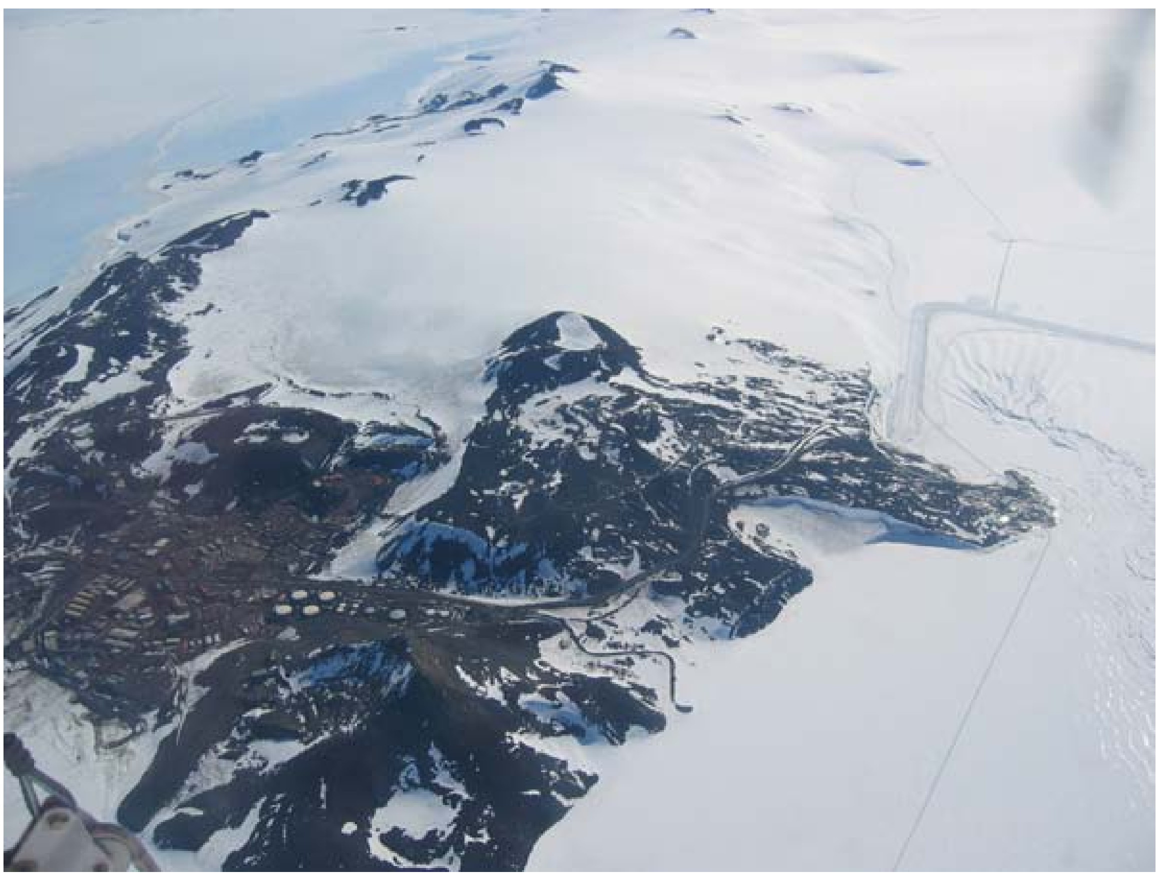

Figure 2: Photo of Area Imaged Dec 5, 2006

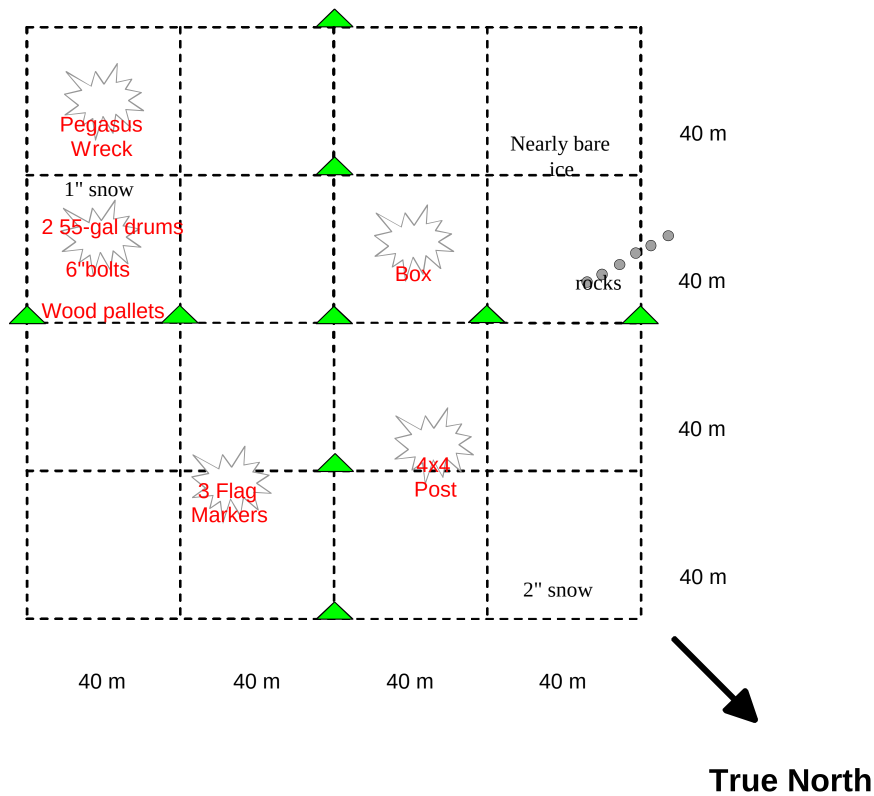

Figure 3: Approximate Layout of Pegasus Wreck Site Imaged Dec 5, 2006

Figure 4: Photo of Pegasus Wreck Area Imaged Dec. 5, 2006

Dec 6, 2006 (morning): Data collected at 1-foot resolution over a 5 nmi by 5 nmi area at the South Pole Traverse (centered at Latitude S 78º 02’ 43.87”, Longitude E 168º 29’ 04.56”). This area was in the Shear Zone and contained the South Pole Traverse route. The area near the traverse route had been mapped with ground penetrating radar and marked for crevasses between late 2002 and early 2003 [3]. Figure 5 shows the approximate area imaged by the MiniSAR radar on the morning of Dec. 6th. No photos are available for this area, but it was reported that from the aircraft the area looked like a flat white ice plain with no particular distinguishing features.

Dec 6, 2006 (afternoon): Data collected at 1-foot resolution over a 5 nmi by 5 nmi area within the Shear Zone we refer to as Tres Hermanas, or 3 Sisters (Latitude S 78º 22’ 08.82”, Longitude E 167º 53’ 59.22”). As will be discussed in this section, this area contained three known crevasses covered with snow bridges. These crevasses were very difficult to see from the air. They were typical of the kind of crevasse that would represent a hazard for an LC-130 landing. Figure 6 shows the approximate area imaged by the MiniSAR radar on the afternoon of Dec. 6th.

Dec 7, 2006: Data collected to examine the effect of resolution and geometry on the detection of the three crevasses referred to above as Tres Hermanas. Data was collected at 15º, 30º, and 45º grazing angles. For each of theses grazing angles, at the 1-foot resolution case, 60 synthetic apertures were collected every 6º around the target area, resulting in a full 360º view of the crevasses. For the 1 m and 8” resolution cases, 36 synthetic apertures were collected every 10º increment for a full circle around the crevasses.

Dec 8, 2006: Data collected to investigate penetration of the ice at a simulated (manmade) crevasse used for mountaineer training (Latitude S 77º 49’ 58.33”, Longitude E 166º 51’ 47.83”). Figure 7 shows a photo of the simulated crevasse area. In addition, we collected spotmap data of the McMurdo and Scott Base area, including the pressure ridge. Figure 8 shows the layout of radar reflectors buried in the wall of the simulated crevasse. Figure 9 and Figure 10 shows the photos of burying the reflectors in the simulated crevasse.

Dec 11, 2006: Data collected in the Taylor Dome area. The region contained several crevasses in sloped terrain. The mountaineers provided coordinates and placed radar reflectors along one of these crevasses. One foot resolution radar data was collected over an approximately 1 nmi by 1 nmi region (centered at Latitude S 77º 52’ 25.44”, Longitude E 158º 50’ 49.80”). Circle data was collected near the crevasse with the reflectors (centered at Latitude S 77º 52’ 39.72”, Longitude E 158º 49’ 04.62”). As a secondary requirement, data were collected at the old drill site, and near the runway to look at object on, and possibly under, the ice. Figure 11 shows the approximate location of these data sets collected by the MiniSAR system on Dec. 11th. Figure 12 and Figure 13 show the crevasse site and runway, respectively, at Taylor Dome.

Figure 5: Approximate Location of 5 nmi by 5 nmi Area Imaged during South Pole Traverse Collect on Dec. 6, 2006

Figure 6: Approximate Location of 5 nmi by 5 nmi Area Imaged during Tres Hermanas Collect on Dec. 6, 2006

Figure 7: Photo of Simulated Crevasse Area Imaged Dec. 8, 2006

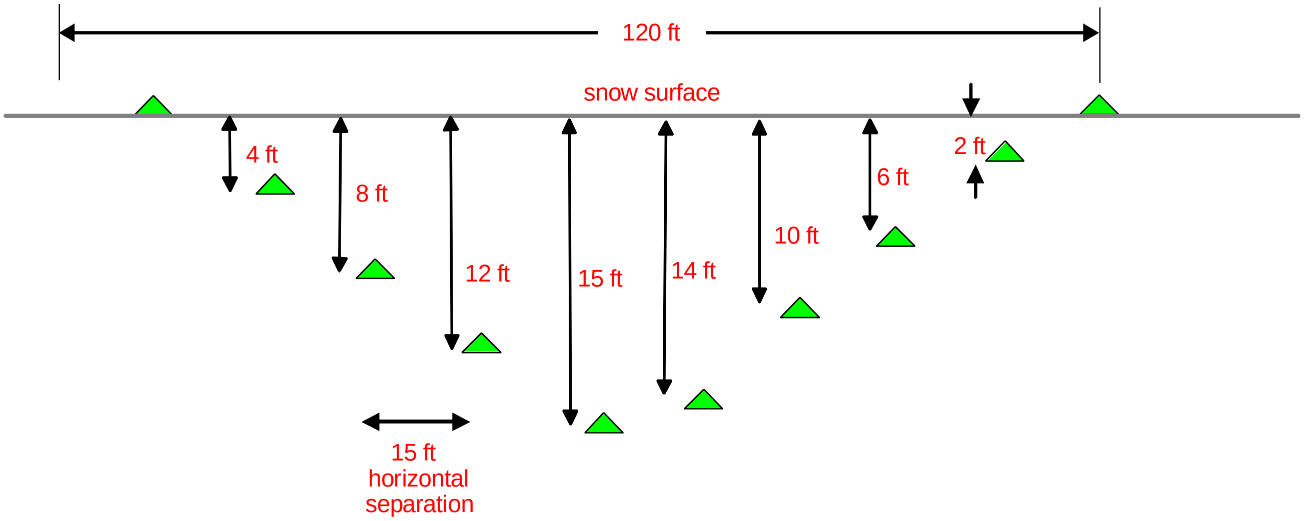

Figure 8: Layout of Radar Reflectors within the Wall of the Simulated Crevasse

Figure 9: Photo of Rough Layout of Radar Reflectors at Simulated Crevasse (these reflectors were buried in the wall at the appropriate depths shown in Figure 8)

Figure 10: Photo of Radar Reflectors before Burying at Simulated Crevasse

Figure 11: Approximate Location of Taylor Dome Collects on Dec. 11, 2006

Figure 12: Photo of Crevasse Site Area at Taylor Dome on Dec. 11, 2006

Figure 13: Photo of Runway Site Area at Taylor Dome on Dec. 11, 2006

In the data collections for large mosaics of the crevasse sites, the radar lines were oriented at nearly 135° (i.e. southeast-northwest). This was because the crevasses of interest, coincidentally or not, tended to run in this direction. It was thought prior to this collect that having the crevasses aligned in the cross-range direction made for better detection in the SAR imagery.

Radar reflectors were placed along the edge of the crevasse in the Tres Hermanas and Taylor Dome crevasse scenes. These reflectors serve as markers in the radar data, to ensure we were actually detecting the crevasse with the radar. Since the reflector locations were surveyed with differential GPS (DGPS), they also permitted the evaluation of the radar image position accuracy. Figure 14 shows back to back radar reflectors mounted on a piece of plywood for insulation. The radar reflectors were intended to have a radar cross-section of approximately 21 dBsm, which allows radar backscatter calibration of the images.

Radar reflectors were also used in the lower priority collects, such as the Pegasus and simulated crevasse, as we have seen already.

Figure 14: Photo of Radar Reflector Along with GPS Survey Equipment

5 Mosaic and Data Analysis

Samples of the radar data from the collection are presented in this section. More imagery can be found in the next section.

Data analysis consisted of visually inspecting the data to see if a crevasse could be detected in the area where we expected to see it. A sample one foot resolution SAR image of the Tres Hermanas crevasses are shown in Figure 15.

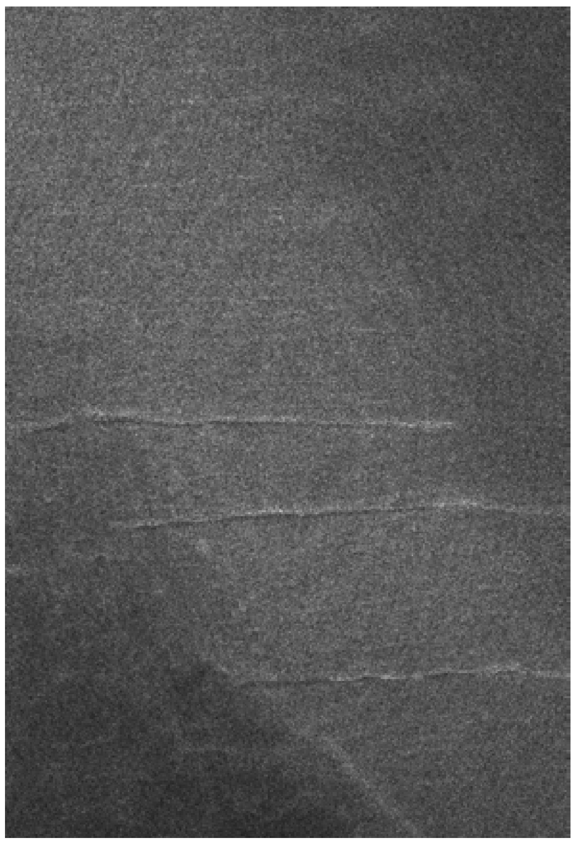

Figure 15: X-band MiniSAR 1-foot Resolution Image of Tres Hermanas Crevasse Site (taken Dec. 6, 2006)

In addition to looking at known crevasse sites, the radar images were put together in a mosaic product to understand the conops of searching a 5 nmi by 5 nmi area for a safe landing zone. The mosaic operation was discussed in a previous section. Figure 16 shows an example of one of these mosaics of the SAR data centered at the Tres Hermanas crevasse area. The mosaic in this figure is shown as an Imagine map, which makes it apparent that the coordinate information is maintained.

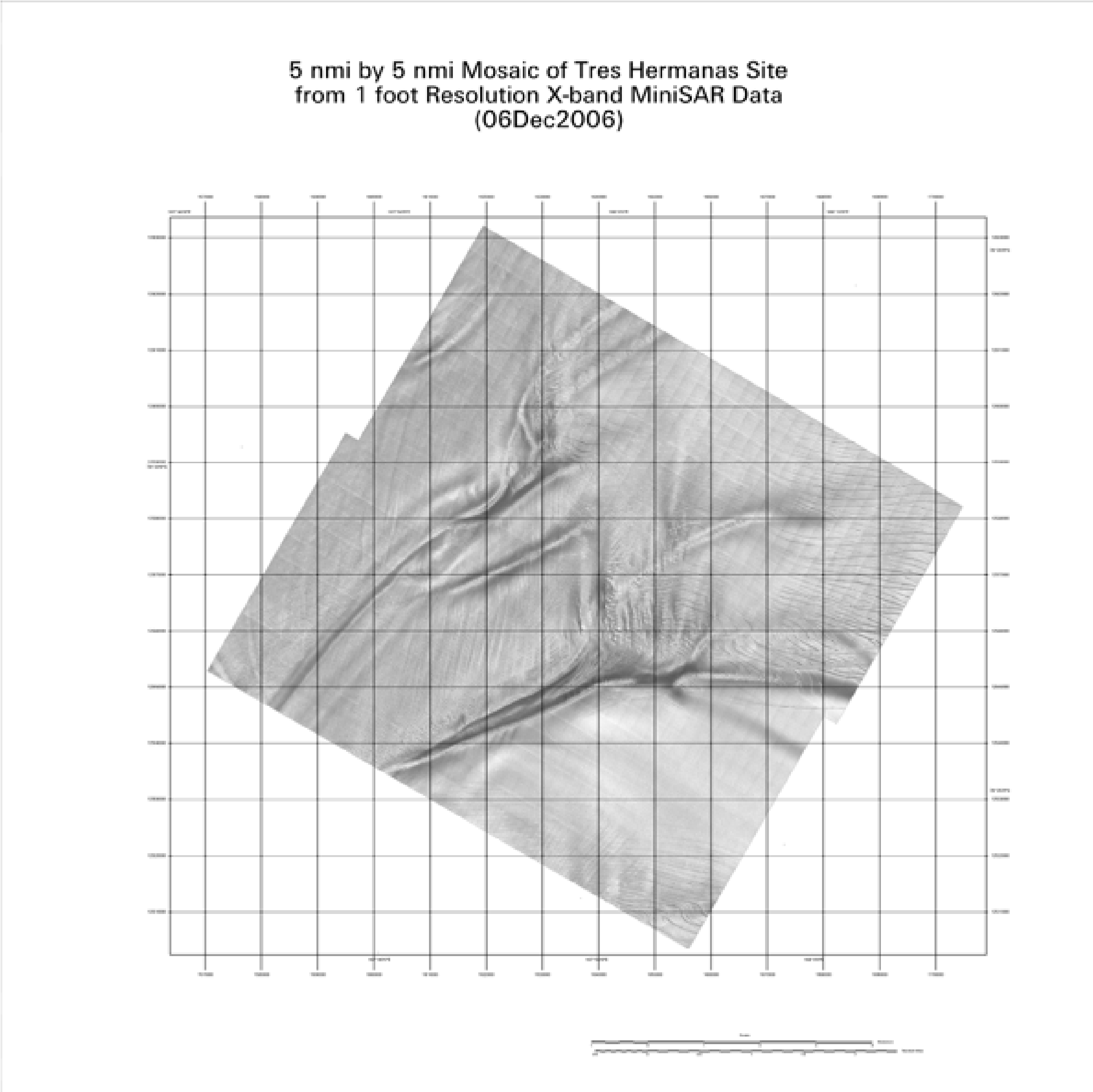

Figure 16: 5 nmi by 5 nmi Mosaic of 1 foot resolution X-band MiniSAR Data Centered around the Tres Hermanas Crevasse Site (taken Dec. 6, 2006)

6 Discussion of Results

This section presents some results of the data analysis. The main result is that the crevasses are readily visible in the X-band SAR data. Finer resolution imagery improves the detection of crevasses in X-band SAR data. The most difficult geometry to detect the crevasse is with the crevasse aligned in the cross-track direction of the radar. Finer resolutions also improve the detectability of the crevasse even in this case.

Major Mark Armstrong and Major Walter Hallman, with the support of the mountaineer personnel at McMurdo Station, Antarctica, identified three crevasses in the Shear Zone that they felt were representative of crevasses that are difficult to detect visually from the air. These crevasses were about 12 feet wide and covered over with about a 6 foot deep snow bridge.

A photo showing those crevasses is given in Figure 17 below. These crevasses were nicknamed Tres Hermanas, or the three sisters. The crevasses in this photo are actually visible, but they required the proper viewing geometry (e.g., proper orientation with respect to the crevasses and the sun angle, distance from the crevasses, etc.) to be visible. Even then, one can see from the photo, that they are difficult to detect.

Figure 17: Close-up Photo of Tres Hermanas Crevasse Site (crevasses are faint horizontal lines at left-center in the photo)

As mentioned in the previous section, data was collected of these 3 crevasses for various geometries and resolutions. Circles were flown around these crevasses at 15º, 30º, and 45º grazing angles for SAR slant-plane resolutions of 1 m, 1-foot, and 8-inch.

Figure 18, Figure 19, and Figure 20 show the difference in detecting the crevasses for resolutions of 1 m, 1 foot, and 8 inches, respectively, at a grazing angle of 30º. As will be presented shortly, the orientation of the crevasse with respect to the radar shown in these figures is the most difficult for detecting the crevasse. It is apparent that finer resolution significantly helps this problem. The detection of the crevasses at 1 m is difficult for this case.

The radar image of the crevasse appears to change somewhat with the orientation of the crevasse with respect to the radar direction. The only significant change in the appearance of the the crevasse in the SAR image with orientation occurs looking directly along the crevasse. This will have an effect on detection of the crevasse in the SAR images; however, resolution appears to be more significant than geometry in detection.

Figure 19 shows the 1 foot resolution X-band MiniSAR image looking along the crevasse direction at a grazing angle of 30º. Figure 22 shows an image 90º out from this, looking perpendicular to the crevasse. This image is essentially the opposite side look from that of Figure 15 above. Figure 21 shows the crevasse imaged at about a 45º with respect to the crevasse. The crevasse is visible in all of these images. The signature of the crevasse in the SAR image appears narrower in Figure 19, looking along the crevasse, than in the other images. The signature appears broader when the crevasse is oriented somewhere between 30º to 60º with respect to the along track direction. The broader the signature (i.e., the more pixels wide), the easier it is to pick out the crevasse. The signature of the crevasse broadens quickly when the crevasse orientation angle moves slightly away from along the range direction towards the along azimuth direction. This seems to indicate that if the proper resolution is used, the crevasse ought to be readily detected at any orientation angle.

Figure 23, Figure 24, and Figure 25 show the effect of grazing angle on the crevasse SAR images for 1 foot resolution with the crevasse oriented perpendicular to the range direction (i.e., along track). The main effect is that the clutter level of the background snow and ice increases with increasing grazing angle. The second effect is that the contrast of the crevasse in the image appears to be reduced with increasing grazing angle. The low return area becomes washed out at higher grazing angles. It appears that grazing angles in the range of 15° to 30° is a good range for imaging the crevasses. We do not have enough data to say if higher or lower grazing angles are worse, but by extrapolation, it appears the mid range of grazing angles is good for crevasse detection.

At this point, we have seen the crevasse viewed by the X-band SAR system from various perspectives. There are some general things of note. First, the signature of the crevasse tends to be a narrow low return line, apparently from the snow bridge, with bright scattering from what appears to be the far range side of the crevasse. Detecting low return areas requires good signal-to-noise ratio, and good multiplicative noise control in the radar. Higher grazing angles, and viewing geometries with the crevasse oriented in the range only direction tend to obscure the low return regions. Finer resolution helps bring back out the contrast.

The results from the mosacking process (e.g., Figure 16) show that a 5 nmi by 5 nmi area can be put together and used for landing site evaluation. The resulting image can maintain position information and resolution if care is taken during the mosaic process. The wide-field perspective helps in making a preliminary determination of landing sites. Maintaining the full resolution allows one to zoom in on the area and make sure there are no small crevasses within this region.

In addition to crevasse hazard assessment for landing zones, the large mosaics might serve a science purpose as well. There was some discussion about this possibility with NSF personnel while we were on site. In addition, it was obvious that experienced mountaineers in Antarctica were able to tell a lot about the ice flow from the mosaic of the SAR imagery.

It was desired that the position accuracy be better than 20 m [4]. In general, it should be noted that the position error for SAR data will be a function of the knowledge of the elevation of the target area, and the accuracy of the GPS solution for that area at the time of the data collection. Better crevasse location requires better underlying maps.

In the final mosaic of the Tres Hermanas site (see Figure 16 above), the position of one of the corner reflectors was off by about 0.5 m, northwest, when compared with the differential GPS (DGPS) survey of the reflector location. Again, general results of the position will depend upon the accuracy of the GPS solution and upon terrain height knowledge. This result is exceptionally good, but cannot be expected every time.

A couple of things need to be mentioned about the data and processing at this point. First, in each of the individual images shown above, there is a trend of an elliptical pattern observed in the radar imagery. This is a known artifact in the image sampling that occurs during image formation. It is known how to avoid this in the future. Due to the compressed schedule of this project, it was decided not to modify to the code to remove this artifact in order to limit the risk of last second code changes to the radar system.

The second thing is that in the mosaics we can see faint lines parallel to the flight direction. These lines are actually due to the mosaic process. Radar data, as with laser data, tends to have a random intensity (sometimes described as a “salt-and-pepper” type look to it). This is referred to as speckle. The random intensity can be smoothed out by averaging independent samples of the same area. In the mosaic process, we overlap data between different radar lines, which are independent samples of the same area. During the mosaic of overlapped regions, the data is “feathered”, which is an averaging process. This averaging smooths the speckle and is detected by the observer as lines in the data. This is a natural occurrence and does not indicate any problem with the underlying data or the final image product.

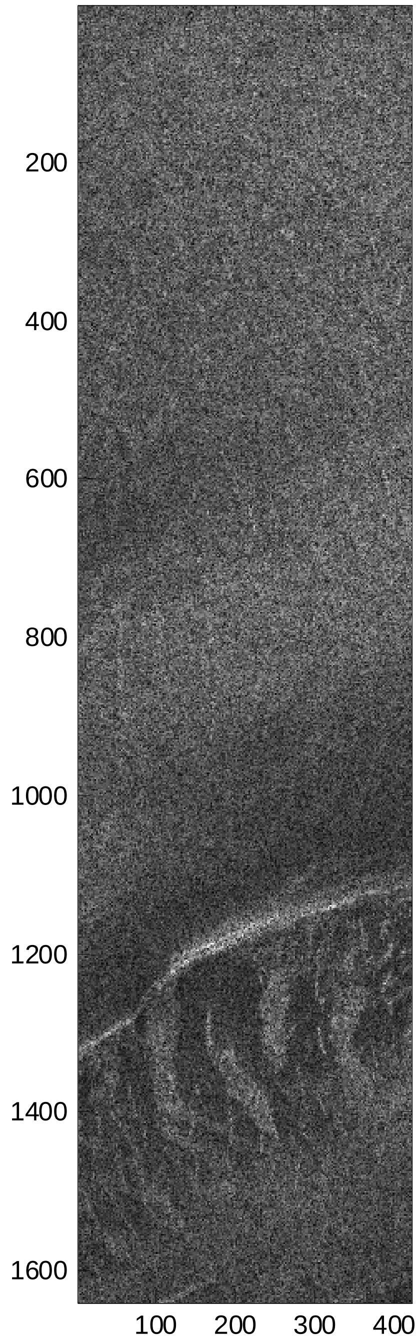

Figure 18: X-band MiniSAR Image of Tres Hermanas Crevasses at 1 m resolution (30° grazing angle, radar looking -45° from true north)

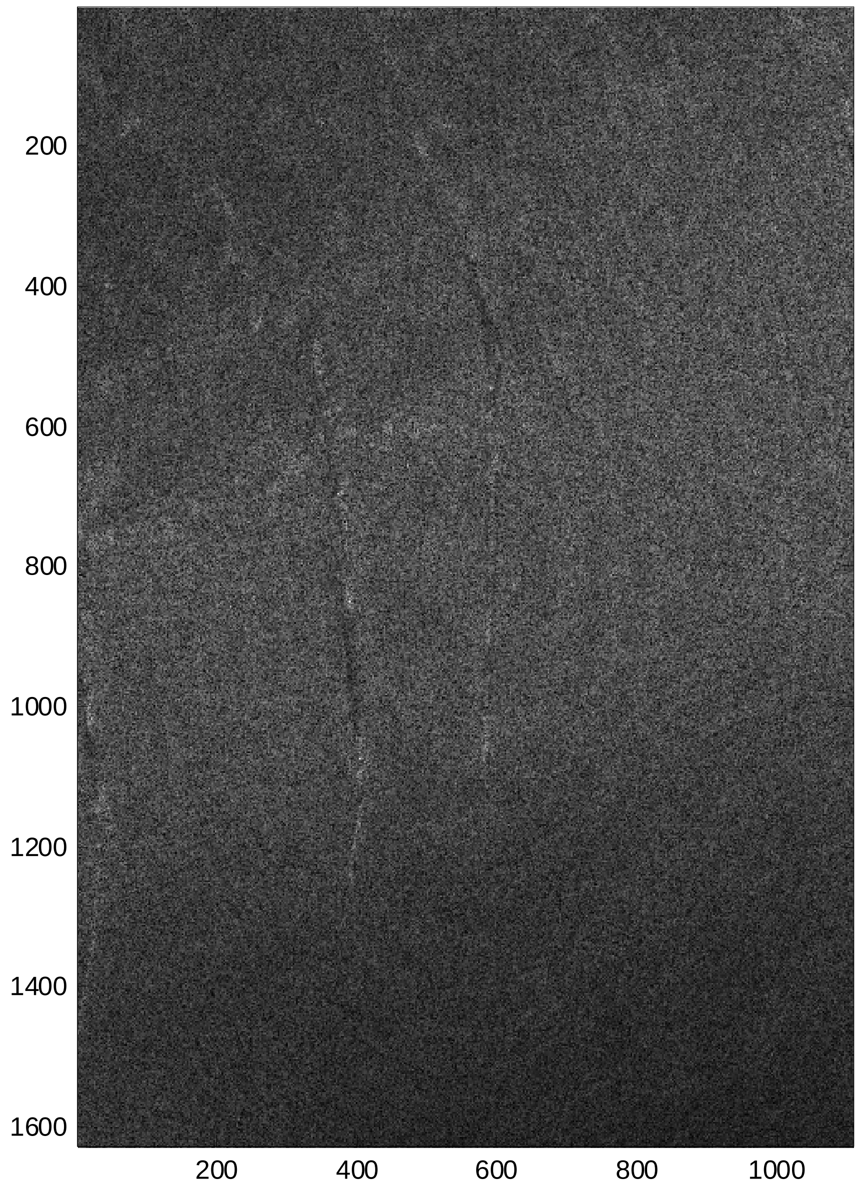

Figure 19: X-band MiniSAR Image of Tres Hermanas Crevasses at 1 foot resolution (30° grazing angle, radar looking -45° from true north)

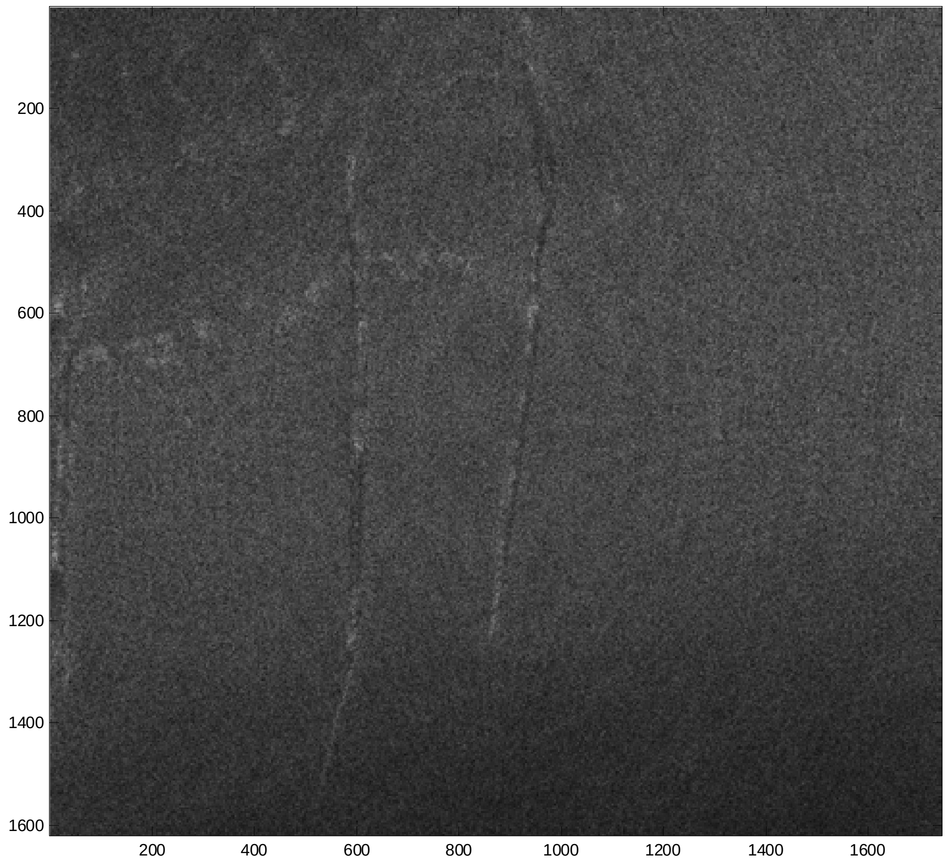

Figure 20: X-band MiniSAR Image of Tres Hermanas Crevasses at 8 inch resolution (30° grazing angle, radar looking -50° from true north)

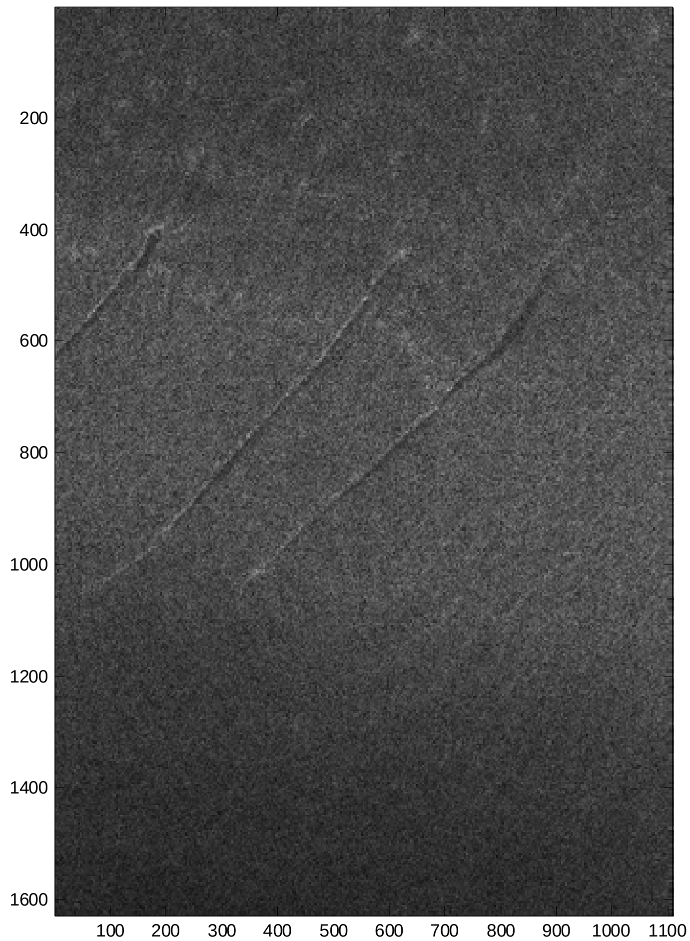

Figure 21: X-band MiniSAR Image of Tres Hermanas Crevasses at 1 foot resolution (30° grazing angle, radar looking -87° from true north)

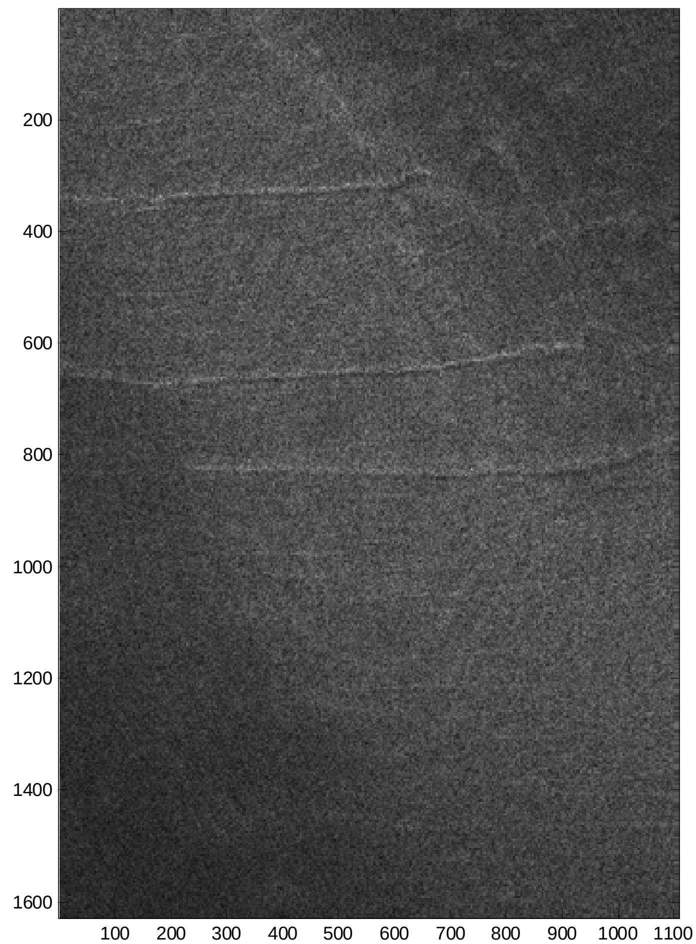

Figure 22: X-band MiniSAR Image of Tres Hermanas Crevasses at 1 foot resolution (30° grazing angle, radar looking -135° from true north)

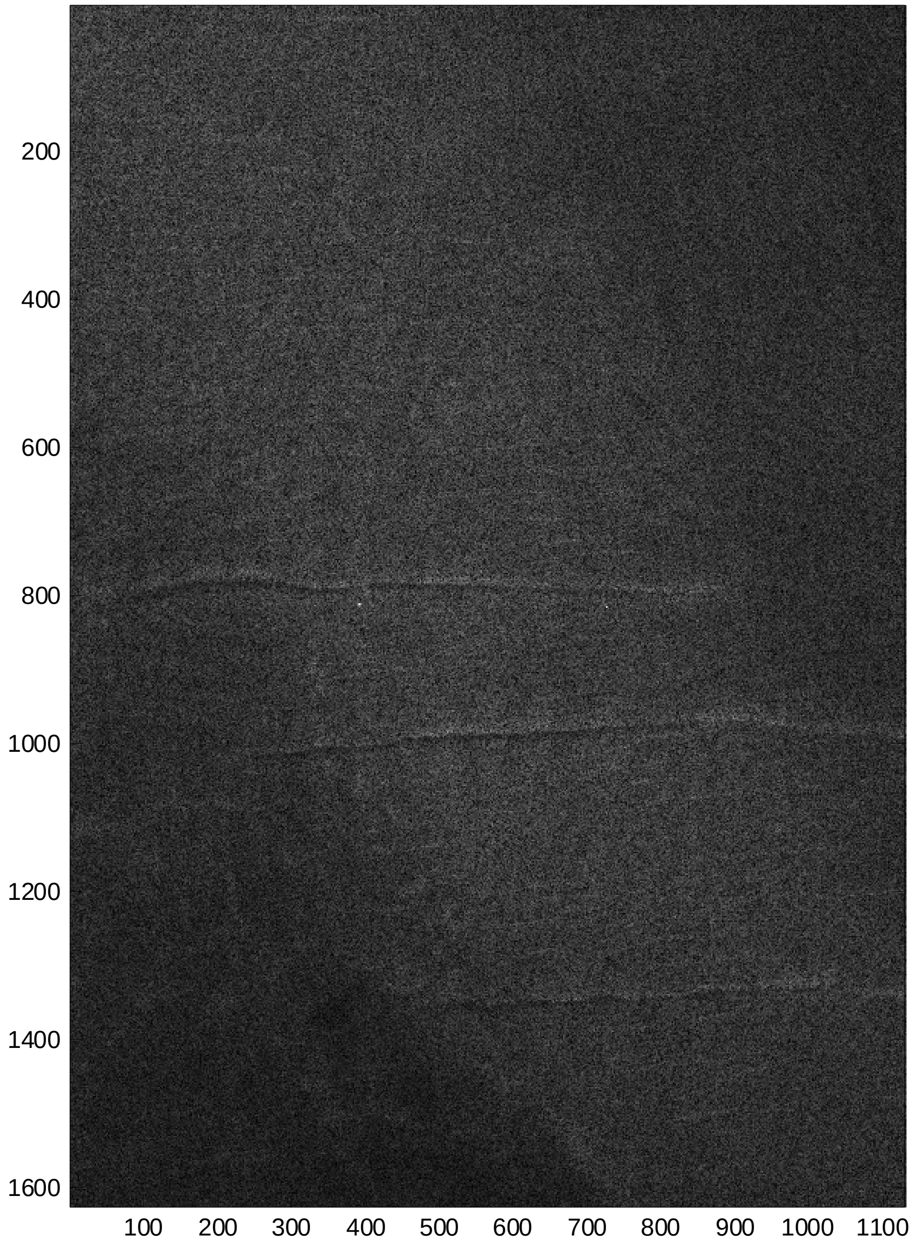

Figure 23: X-band MiniSAR Image of Tres Hermanas Crevasses at 1 foot resolution (15° grazing angle, radar looking +45° from true north)

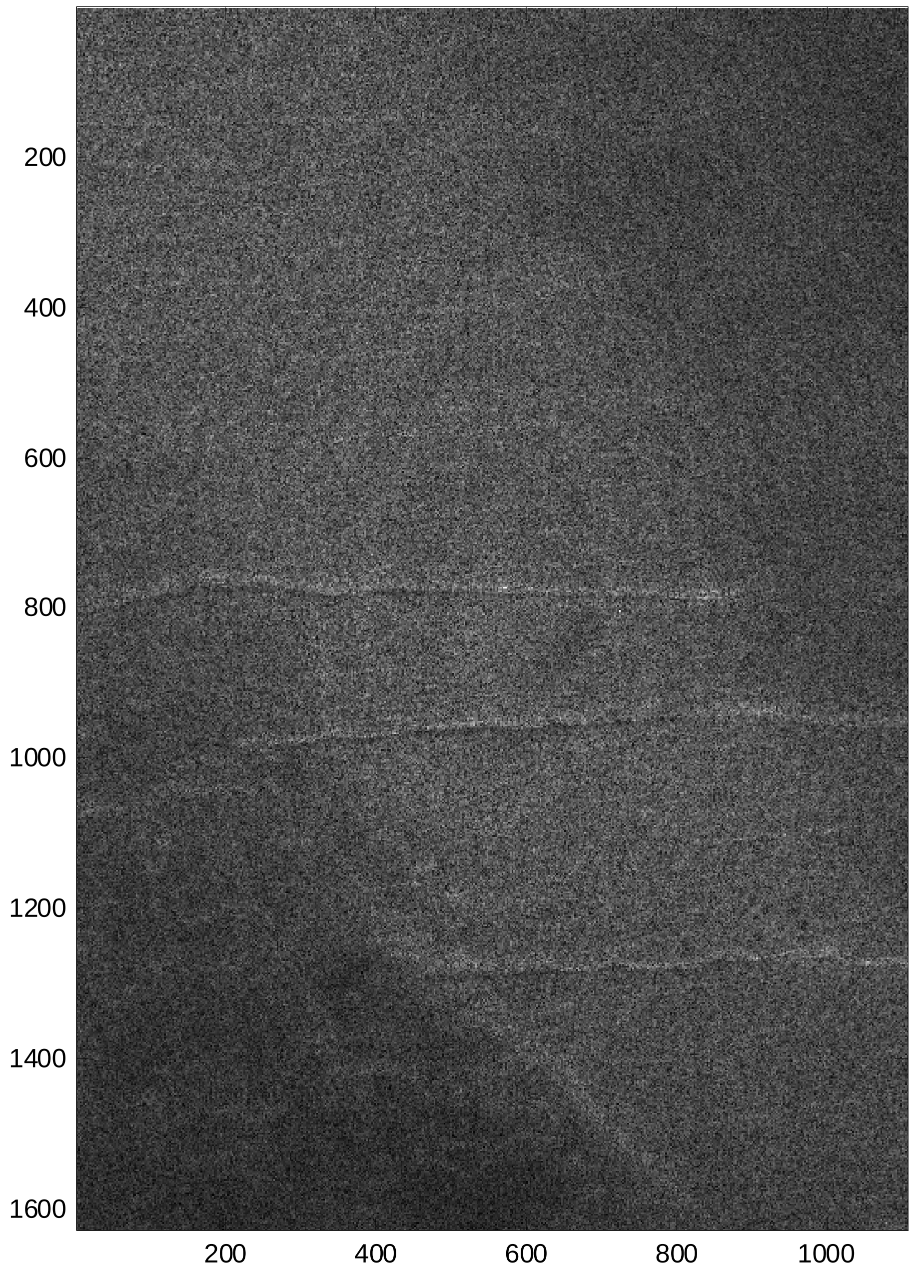

Figure 24: X-band MiniSAR Image of Tres Hermanas Crevasses at 1 foot resolution (30° grazing angle, radar looking +45° from true north)

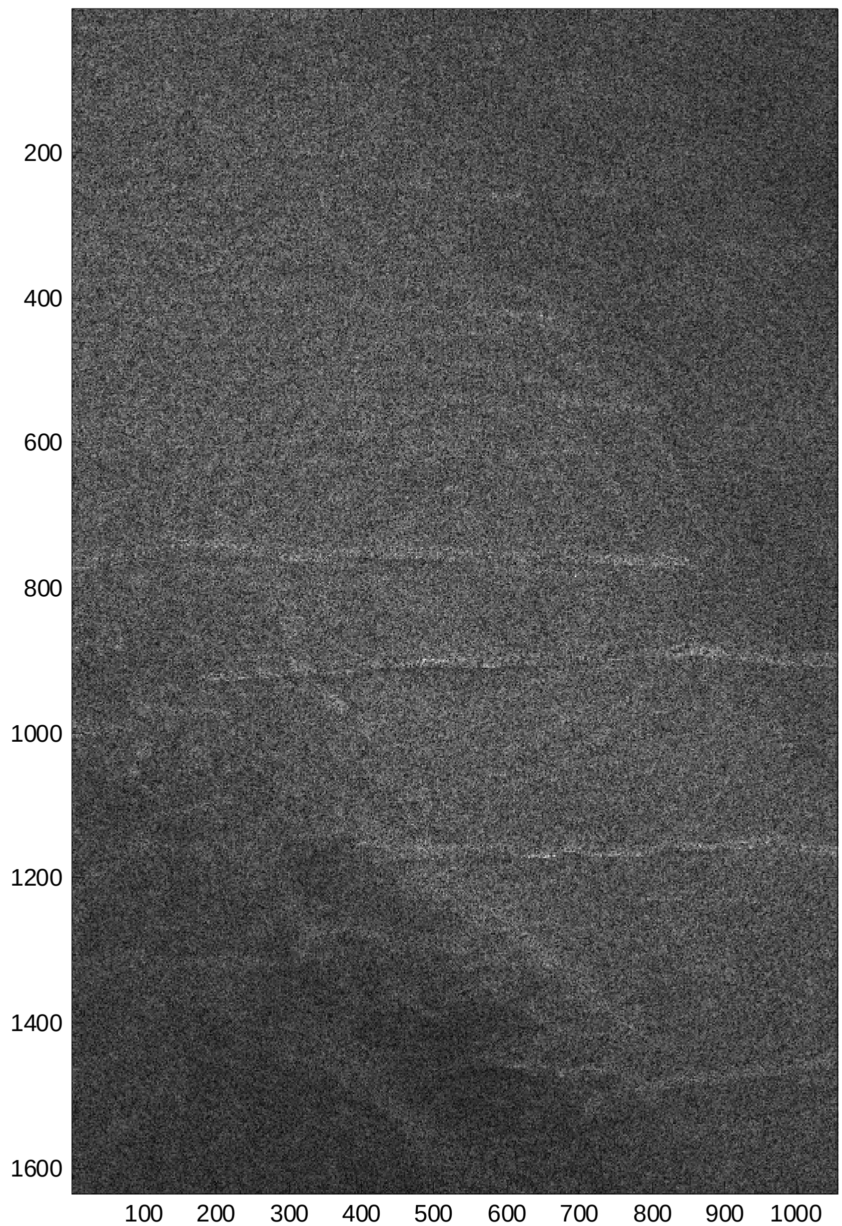

Figure 25: X-band MiniSAR Image of Tres Hermanas Crevasses at 1 foot resolution (45° grazing angle, radar looking +45° from true north)

The conclusions that could be drawn from the simulated crevasse experiment are not clear at this point in time. The data analysis on this collection has been limited since it was a lower priority. In addition, the reflectors were found to have tilted when we went to retrieve them. Also, the snow that was packed around the reflectors was found to have turned to ice.

The X-band SAR images of the simulated crevasse area clearly show the surface reflectors, but there is no clear determination of whether the subsurface reflectors can be detected. Figure 26 shows the resulting SAR image for the case of 8” resolution, 45° grazing angle at broadside. The next figure shows a close up of the area around the simulated crevasse with a couple places highlighted as potential buried reflectors. Both of these bright dots (potential buried reflectors) show up in more than one of the images from other grazing angles and resolutions. The leftmost bright dot shows up fairly regularly in the images, and more often than the center dot. Based upon these images, one could only conclude that we are potentially seeing 4 foot into the snow and ice. However, we do not see the reflector that is only 2 foot deep. It is difficult to draw any solid conclusion about the penetration. Also, with the reported snow/ice conditions at the simulated crevasse, it would be difficult based upon this data set to attempt to draw any conclusion about the scattering mechanism at a crevasse.

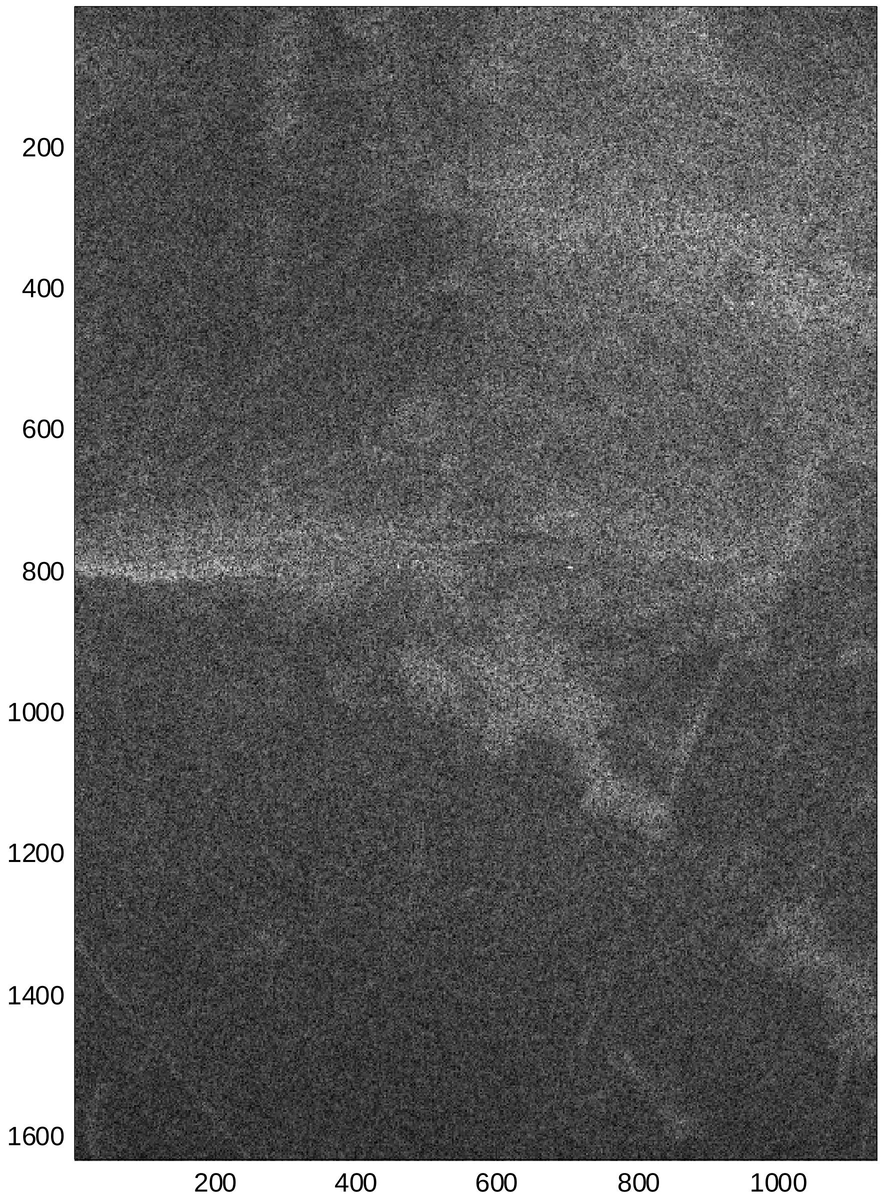

Figure 26: X-band MiniSAR Image of Simulated Crevasse and Buried Reflectors (8” resolution, 45° grazing angle at broadside)

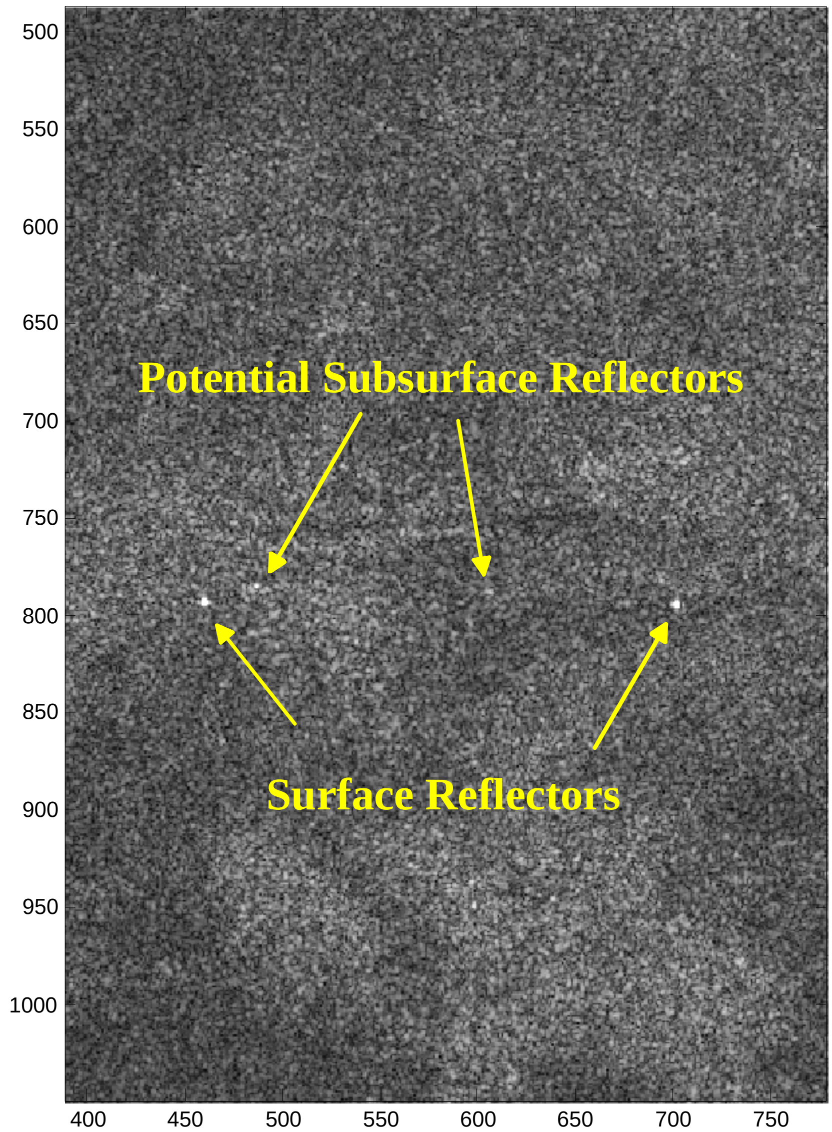

Figure 27: Close up of Area Around Simulated Crevasse from Figure 26 Indicating Surface Reflectors and Potential Subsurface Reflectors

Another lower priority task was to look for objects at the Pegasus site (refer to Figure 3 and Figure 4). The detection of these objects were a function of viewing geometry. Certain orientations of the radar with respect to the objects were better for object detection. Also, at lower grazing angles, the objects were easier to detect because the surface clutter, i.e., the snow and ice, had a smaller backscatter coefficient at these geometries. Figure 28 shows an example X-band image from the Pegasus wreck site at 8 inch resolution and 15° grazing angle.

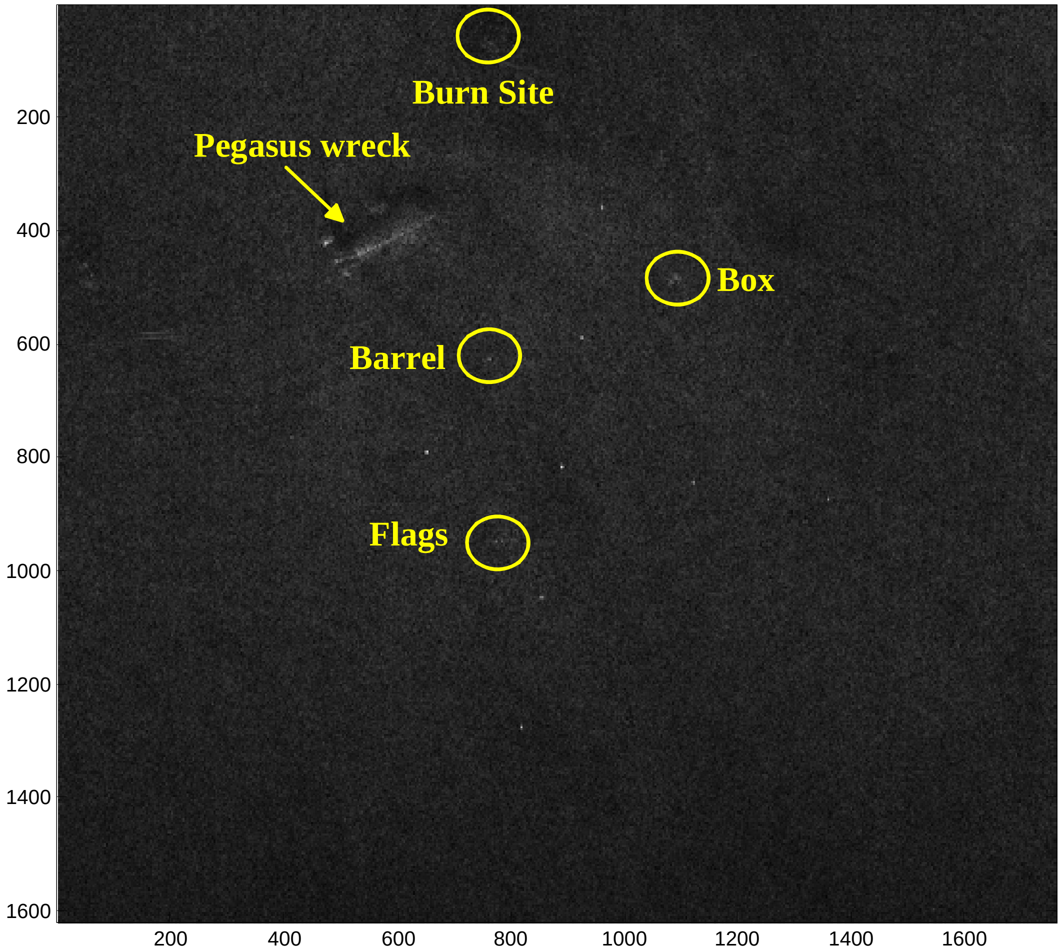

Figure 28: X-band SAR Image of Pegasus Wreck Area; 8” resolution, 15° grazing angle (taken 2006Dec05)

7 Conclusions

The SNL MiniSAR was successfully converted to an X-band crevasse detection radar system. This system was used to collect data of crevasses in Antarctica during December, 2006. The X-band MiniSAR system was shown to be an effective way to detect crevasses. SAR resolutions of one foot or finer are important for detection.

8 References

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