Synthetic Aperture Radar (SAR) as a tool for mapping remote geology as applied to the Belcher Islands, Nunavut, Canada

by

R. Troy Unrau

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Department of Geological Sciences

University of Manitoba

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Abstract

The application of remote sensing techniques to determine, investigate and obtain information about geology is not new; however, most research has focused on using optical imagery. Synthetic Aperture Radar (SAR) is now being used rather than optical data for a number of reasons: it employs active imaging systems rather than passive ones; it penetrates all weather conditions including rain, snow and cloud-cover; and it can provide additional information on surface textures and rock fabrics when coupled with advanced digital processing techniques. Furthermore, the long wavelength along with interferometric techniques can be used to obtain surface elevations and dynamic information on surface deformation as a function of time. These techniques are known as Interferometric SAR (InSAR) and have recently been the primary focus of SAR research within the geological sciences.

The original objective of this thesis is to carry out preliminary visual inspection of SAR data in the previously well-documented study area, the Belcher Islands.

In this thesis, SAR is used to qualitatively investigate the boundaries between exposed geologic formations within the Belcher Islands, Nunavut, Canada, utilizing the visual texture and backscattering grey level tone of the processed SAR image data. Two single-polarized datasets were obtained from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) instrument. These data were pre-processed to
data level 1.5, as defined by JAXA’s Earth Observation Research and Application Center (EORC).

To supplement this data, a number of optical satellite data images were obtained from the Landsat 7 and SPOT 5 satellites. These images were used to compare the effectiveness and usefulness of the ALOS PALSAR data to the optical data received for the same study area, although the image forming processes of these two types of remote sensing data are quite different.

Image processing techniques, such as histogram colourization, and speckle filtering were used to prepare the data for comparison to the most complete geology map available for the study area, the Belcher Islands. The results show that the ALOS PALSAR data can be correlated to the known geology for certain types of geologic contacts, but other contacts are largely invisible to this qualitative technique.

In a qualitative comparison to the results from the optical remote sensing data, and the past research using optical data, such as air photos and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data, to map the Belcher Islands, the ALOS PALSAR instrument performs reasonably well. This shows that the ALOS PALSAR instrument and, more generally, remotely obtained SAR data can be an effective all-weather tool in mapping geology from space when the rocks are well exposed.
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The data sets provided by geobase.ca and JAXA’s EORC were key to the completion of this thesis. I would also like to thank those software developers who have put their SAR tools under open source licenses making it affordable for a student to undertake this work.

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1. Introduction

Remote sensing is a useful tool in the geologic and planetary sciences to help produce a geologic map without the initial requirement of sending a field geologist to that location to manually produce a map. A number of remote sensing techniques have been developed and have been in use for the investigation of the Earth and other planets since the advent of aerial reconnaissance. Of particular interest to this thesis is the technique of Synthetic Aperture Radar (SAR), which operates on a microwave wavelength and is much longer than visible light in the electromagnetic spectrum (Richards, 2005).

The objective of this thesis is to see if the results from previous studies of optical remote sensing can be replicated using microwave imaging radar or SAR from Earth orbiting satellite remote sensing platforms. The Belcher Islands, Nunavut, were chosen as the remote sensing target area in this thesis because there are considerably more abundant previous studies using other remote sensing techniques, and the relative lack of overburden (Wickert and Budkewitsch, 2004).

To understand how the radar imaging of the Belcher Islands can correlate to the exposed formations, this thesis will review structural, textural and mineralogical information available from past geologic studies of the islands, and their apparent effects on radar scattering processes.
The Belcher Islands consist of a group of several long, narrow islands. The shapes of the islands reflect the underlying geologic structures and show a structural trend in the north-northeast direction as shown in Figure 1 (Jackson, 1960); during analysis and comparison of the results in this thesis, small, rescaled sections of areas shown in this map are used to correlate geologic contacts. The rightmost portion of the map is Tukarak Island. This island prominently features the dome structure that was the focus of the previous work done by Wickert and Budkewitsch (2004).

1.1 Previous studies – a brief review

In order to understand if SAR is an effective tool for distinguishing between different geologic units, the Belcher Islands were targeted since they have a known geology and are well exposed with relatively little overburden (Wickert and Budkewitsch, 2004). Relatively abundant information from previous studies with several remote sensing data sets has led to these remote islands being previously targeted as a test site for verifying various remote sensing techniques.

Parts of this region were initially mapped successfully by manual analysis of air photographs by Jackson (1960). Due to high winds in the region at the time of mapping, certain islands were inaccessible by boat. Using black and white air photos to trace contacts beyond the mapped region allowed parts of this map to be completed. Much of this interpretation has been validated by subsequent mapping efforts (Ricketts and Donaldson, 1981).
In 2004, Wickert and Budkewitsch used data recorded from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor on-board the Terra spacecraft to produce a map of the varying responses of surface rocks to visible and infrared wavelengths. This map was then compared to a field map of the regional geology to determine if some contacts could be distinguished from the orbital altitude of the Terra satellite (Wickert and Budkewitsch, 2004). Their resulting map of the Wickert and Budkewitsch (2004) study is shown in Figure 2, superimposed on Jackson’s (1960) original geologic map.

Figure 3, taken from commercially obtained remote sensing data via Google Earth, shows the structural features of the study area, including several folds and contacts.
Figure 1: Geological map of the Belcher Islands, Nunavut (Map 28-1960 from Jackson, 1960). Parts of this map were compiled using air photos. A high-resolution version of this map is included in Appendix A.2.
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2. Geologic setting

The Belcher Islands are located in the southern part of the Hudson Bay, just north of James Bay. They contain a series of exposed Paleoproterozoic rocks of volcanic and sedimentary origin (Legault et al., 1994), which are thought to have been deposited shortly before the Grenvillian Orogeny (Ricketts and Donaldson, 1981). The stratigraphy was later folded and deformed during the Hudsonian Orogeny to produce its current structural setting (Ricketts et al., 1982).

2.1 Topography

The Government of Canada produced downloadable Digital Elevation Model (DEM) files for the region including the Belcher Islands, available from http://geobase.ca (accessed February 1st). For this thesis, two of these files were downloaded and stitched together using ParaviewGEO, a free, open source geoscience data visualization program available from http://paraviewgeo.mirarco.org/index.php/Main_Page (accessed February 1st, 2009). In order to produce the combined image, the individual tiles were first loaded, and then the coordinates were translated so that the tiles did not overlap. The resulting image, shown in Figure 4, was then recoloured for clarity, and a scale was added.

The topographic variation is very low throughout most of the islands, with the local maximum (155 m) at the centre of Tukarak Island. In places, the land gently slopes away from sea level while cliffs of up to 60m also exist (Jackson, 1960). These
topographic variations are useful to note when processing radar data, as several types of distortions in observed radar signal response are associated with surface topography and roughness (Richards, 2005).

Figure 4: Topographic profile of the northern portion of the Belcher Islands, with data from http://geobase.ca (accessed February 1st, 2009). Tukarak Island is the local high, at 155m. Sea level is white.

2.2 Stratigraphy

Jackson (1960) was the first to formally map and define the stratigraphy of the Belcher Group of sediments. He initially divided the group into 16 members, many of which were later afforded formation status in Dimroth et al. (1970). Ricketts and Donaldson (1981) produced the stratigraphic section shown in Figure 5 containing 14 named formations. Since the geologic map used in this thesis is from Jackson (1960), I will ascribe both the formation name and his original numbering to the rock units where
possible. In describing the formations, an emphasis is placed on those attributes that are most likely to be detectable using remote sensing, such as thickness, weathering habits, and mineralogy.

Figure 5: The formations of the Belcher Group (after Ricketts and Donaldson, 1981).

### 2.2.1 Kasegalik Formation

The oldest formation exposed in the Belcher Group is the Kasegalik Formation (Jackson, 1960). As described by Ricketts and Donaldson (1981), the formation
consists of five zones. From bottom to top, these are a grey dolostone with 20% red mudstone, a red mudstone, stromatolitic dolostones, cherty stromatolitic dolostone, and argillaceous and tuffaceous dolostone. The bulk composition of this formation can be described as a dolostone.

The Kasegalik Formation is exposed discontinuously within the Churchill Sound and the Kasegalik anticline. In the Churchill Sound area, its exposed thickness is more than 1200 m (Ricketts and Donaldson, 1981; Jackson, 1960).

2.2.2 Eskimo Formation

The Eskimo Formation consists of a series of columnar basalt flows up to 20 m thick, intermixed with some pillowed basalt. Between flows, thin beds of chert, green argillite and poorly sorted lapilli tuff are found. On Tukarak Island, the top of this formation consists of massive agglomerates containing a mixture of angular basalt blocks and argillite blocks (Ricketts and Donaldson, 1981). North of Moore Island, a 1 m thick jasper iron-formation is associated with argillite near the top of the unit (Jackson, 1960).

The Eskimo Formation is well exposed with thicknesses of up to 900 m in the Windy Lake (Jackson, 1960) and Eskimo Harbour (Ricketts and Donaldson, 1981) regions, 600 m in central Tukarak Island, and thinning southward and westward to only a few metres (Ricketts and Donaldson, 1981). The flows tend to be jointed (Legault et al., 1994).
The boundary between the Eskimo and the Fairweather formations is sharp, but slightly irregular (Ricketts and Donaldson, 1981). Ironstone fills depressions in the Eskimo formation and can be up to 2 m thick (Ricketts and Donaldson, 1981).

### 2.2.3 Fairweather Formation

The Fairweather Formation is predominantly sedimentary consisting of argillite, quartzite, dolomite, tuff, arkose and some basalts (Jackson, 1960). The lower part consists of 1 to 30 m thick beds of pisolitic dolostone, followed by a series of bedded green siltstones and sandstones cut by quartz arenite-filled channels up to 80 m wide (Ricketts and Donaldson, 1981). A quartzite bed defines the top of this formation (Jackson, 1960).

This formation is between 300 and 600 m thick in the Kasegalik Lake and Eskimo Harbour areas (Jackson, 1960). One of the best exposures is on Tukarak Island where 338 m of nearly continuous exposure are found, about 10 km southwest of McLeary Point.

### 2.2.4 McLeary Formation

Conformably overlying the Fairweather Formation, the McLeary Formation begins with a distinctive layer of grainstone containing beachrock, known as the Beachrock Marker Bed (Ricketts and Donaldson, 1981). This formation consists of three members: a lower member containing the Beachrock Marker Bed, dololutites and
conglomerates; a middle member consisting of sandstones, dolograinsstones and beachstones; and an upper member of dolomite predominantly of stromatolitic origin (i.e., a reef) (Ricketts and Donaldson, 1981).

This formation is named for McLeary Point, where it obtains its maximum thickness of approximately 430 m (Jackson, 1960). The lower member is best exposed on Tukarak and Mavor Islands (Ricketts and Donaldson, 1981).

2.2.5 Tukarak Formation

The Tukarak Formation consists of an upper and lower member, separated by a bed of shale. The lower member consists of fine grained sandstone, dolomitic sandstone, shaly mudstone, and some dolostone. The upper member is a thinly bedded, brick-red mudstone and dolostone (Ricketts and Donaldson, 1981). At least one bed in the upper member is considered a good marker bed by Ricketts and Donaldson (1981), however the whole formation is considered a marker by Jackson (1960).

The Tukarak Formation is best exposed on Tukarak Island, is 40-93 m thick (Ricketts and Donaldson, 1981), and was mapped through the central and eastern Belcher Islands.
2.2.6 Mavor Formation

This formation consists of thick dolostone and thin shaly lutites (Ricketts and Donaldson, 1981). The Mavor Formation varies from 100 m thick on the west side of Tukarak Island to 160 m thick on Mavor Island (Jackson, 1960).

2.2.7 Costello Formation

The base of the Costello Formation is slate (Jackson, 1960) or shale (Ricketts and Donaldson, 1981), 10 (Ricketts and Donaldson, 1981) to 35 m thick (Jackson, 1960). This grades into interbedded limestone, dolostone, carbonaceous chert and argillite. The carbonate-rich beds tend to weather producing depressions on the surface (Jackson, 1960). The top of the formation is marked by a few beds of dolomitic argillite (Jackson, 1960).

The thickness varies from just over 200 m thick on Tukarak Island to nearly 365 m thick west of Laddie Harbour (Jackson, 1960). This formation is continually exposed in parts of the eastern Belcher Islands.

2.2.8 Laddie Formation

Interbedded red argillite, limestone, dolostone (Jackson, 1960) and shale (Ricketts and Donaldson, 1981) compose the Laddie Formation. It becomes less carbonaceous towards the top, where it is mainly red argillite (Jackson, 1960).
The Laddie Formation is 230 m thick (Ricketts and Donaldson, 1981) southwest of Laddie Harbour, and thickened by folding in the northern parts of Innetalling Island and Kipalu Inlet (Jackson, 1960). The contact with the Costello Formation is gradational (Ricketts and Donaldson, 1981).

2.2.9 Rowatt Formation

The Rowatt consists of two members: a lower member of terrigenous and carbonate clastics, and numerous sandstone-shale cycles producing beds up to 1.5 m thick; and an upper member of buff dolostones (Ricketts and Donaldson, 1981).

The formation is best exposed on Tukarak Island where the dolostones from the upper member form distinctive ridges due to weathering. Total formation thickness is 370 m maximum as exposed south of Laddie Harbour (Jackson, 1960).

2.2.10 Mukpollo Formation

This formation is a quartz arenite with some siltstone and dolomitic sandstone near the base. In places, ironstone pebbles can be found in channel-filling conglomerates (Ricketts and Donaldson, 1981).

The Mukpollo Formation varies in thickness from 40 m near Little Costello Lake, to over 140 m northeast of Moore Island. In most places, it is poorly exposed (Jackson, 1960).
2.2.11 Kipalu Iron Formation

The Kipalu Formation is generally classified as an iron formation (Jackson, 1960). Ricketts and Donaldson (1981) report three major lithologies within this formation: laminated ferruginous argillites, laminated micrites, and granule bearing jasper. The iron takes the form of hematite, but locally present magnetite is also reported (Jackson, 1960).

This formation is poorly exposed except in a few widely disjointed places. Formation thickness ranges from 60 m west of Walton Island to 125 m north of Haig Inlet (Jackson, 1960).

2.2.12 Flaherty Formation

Disconformably overlying the Kipalu Iron-formation (Ricketts and Donaldson, 1981), the Flaherty Formation comprises predominantly basalt with some interflow sediment (Legault et al, 1994). These basalts can be aphanitic to fine-grained, amygdaloidal, massive, pillowed, ropy, or blocky. A few zones of medium to coarse massive, pillowed feldspar porphyry zones exist in the western part of the Belcher Islands. Where pillows exist, the interstitial material is quartz, calcite and, in places, anthraxolite (Jackson, 1960).

Possibly the best studied formation within the Belcher Group, the Flaherty Formation accounts for 60% of the exposed outcrop throughout the region (Ricketts and
Donaldson, 1981). It is 290 m thick south of Laddie Harbour and nearly 2 km thick on the southwest fork of Johnson Island (Jackson, 1960).

### 2.2.13 Omarolluk Formation

Disconformably overlying the Flaherty volcanics, the sedimentary Omarolluk Formation grades from pyritic shale to volcanic sandstone, with rare interbedded tuff. Ricketts and Donaldson (1981) go on to describe these sediments principally as greywackes.

While Ricketts and Donaldson (1981) redefined the upper contact of this formation without clarifying its exposed thickness, Jackson (1960) describes the apparent thickness as being greater than 2 km thick on Gilmour Island. Additionally, the Omarolluk greywackes are well exposed on the small islands in the northern-most part of the Belcher Islands, although the corresponding parts of the map were completed using air photos (Jackson, 1960). Ricketts and Donaldson (1981) suggest that this formation significantly thins out towards the west.

### 2.2.14 Loaf Formation

The final succession of the Belcher Group, the Loaf Formation, is reported by Jackson (1960) to outcrop on only three islands of the Bakers Dozen Islands where hematite-bearing arkose sandstones are found in beds 2 m thick. About 200 m of this unit is exposed. Ricketts and Donaldson (1981) consider the Loaf Formation to be a lateral equivalent of the Omarolluk Formation.
2.2.15 Diabase dikes

A number of diabase dikes cut through the Belcher Islands. In places, these dikes cross-cut all formations except the Omarolluk and Loaf Formations (Jackson, 1960). In the geology map, Jackson (1960) has mapped several outcrops of these dikes that appear to form sills between formations.

2.2.16 Stratigraphic summary and simplification

The Belcher group is defined by a sequence of well-preserved paleo-sedimentary and volcanic rocks. While the Belcher Group is predominantly sedimentary, the Eskimo, Kipalu and Flaherty should be texturally and electrically distinct enough to have a radar contrast against the dominant sediments.

A simplification of the full stratigraphic section is shown in Figure 6, which is further simplified to three units in Figure 7. Some contacts are distinct, such as the contact between the Kipalu Iron Formation and the Flaherty Formation, and where exposed, these contacts should be easily detectable using remote sensed imagery.

2.3 Structural and Surficial geology

The best description of surficial deposits on the Belcher Islands comes from Jackson (1960). Widespread glacial erratics composed of mostly locally-outcropping rock types cover significant portions of the islands. Additionally, glacial striae are common on the surface of the outcrop. These striae, coupled with plucking and chatter-marks, indicate that the last ice movements were from the northeast direction.
While the glacial striations are not directly visible from most remote sensing platforms, many of the surface features that resemble plucking are visible in the ALOS PALSAR data, as shown in Figure 8. These patterns tend to cross-cut the original bedrock and are not folded, suggesting that they can be properly ascribed to the glaciation that Jackson (1960) reported on the ground.
Figure 7: Map showing location of the two major volcanic formations within the Belcher Group, and their relatively abundant surface exposure versus the sedimentary rocks (modified from Legault et al., 1994).
Attention to the glacial features is important, as they readily appear in all remotely sensed imagery. These features will play a role in any data analysis and transformations applied to the data, and must not be confused for original bedding.

In addition to the glacial features, Jackson (1960) reports that there are significant deposits of mud, silt, sand and gravel, which occur in well-sorted beach deposits.
These exist from sea-level to an elevation of 60 m. These surficial deposits will obstruct remote observation of the underlying bedrock.

Last among the small-scale surficial structures are a number of frost-weathering features, including domes of jointed bedrock 20 m across; mounds of angular bedrock fragments; and large blocks that have been wedged up along joints in the rock (Jackson, 1960). These weathering features cause additional radar signal back-scattering, contribute to speckle in the radar images and tend to increase the amplitude of the observed radar response (Richards, 2005).

On the scale of the group of islands, the Belcher Islands are a nearly continuous fold pattern consisting of large, double-plunging anticlines and broad synclines (Jackson, 1960). These macroscopic patterns are easy to visually trace using any of the remotely sensed imagery. Faulting is minimal (Jackson, 1960).

Of more possible significance to the application of radar imaging is a number of reported sets of joints. These joints include bedding parallel joints, joints that strike along bedding but dip 90 degrees from the bedding, and sub-vertical joints that strike nearly perpendicular to bedding (Jackson, 1960). The impact of these joints may be to produce the geometry of a trihedral corner reflector, creating a high-amplitude radar response in those places the features are larger than the radar wavelength. The schematic of this geometry is illustrated in Figure 9. The incident SAR signal to these
types of scattering surfaces will be directly reflected back to the source (i.e. SAR antenna) to produce a high-amplitude signal.

Figure 9: The green area represents a trihedral corner (triple) reflecter as developed from a cube. Triple reflector geometry can be formed from sets of three near-perpendicular joints in rocks. They will produce very high amplitude radar responses, when the sides of this type of rough surface has a length much larger than the SAR signal wavelength.
3. Radar theory

The term RADAR originated as an acronym for Radio Detection and Ranging, but is now considered a commonplace noun (Richards, 2005). The technology was originally developed for military purposes as a means to detect ships and aircraft over the horizon. Since then, radar has become increasingly useful as a medium for producing images in circumstances where passive techniques fail, either due to lack of illumination, or due to issues with wavelength (Richards, 2005). For example, radar is commonly used to see through clouds, fog, smoke and precipitation, as these are typically transparent to radar frequencies (Ristau, 1999).

Radar devices operate in the radio to microwave wavelengths of the electromagnetic (EM) spectrum, with a typical operating range from 2 MHz to 220 GHz. These frequencies are further subdivided into radar bands as shown in Table 1. The physical wavelength of a given radar system becomes important when defining limits of resolution (Richards, 2005) and to the design of the radar device.

3.1 Basic radar

Radar signals are emitted using a parabolic or phased-array antenna. These signals can either be emitted as a continuous waveform or as a pulse. The signals then travel outwards from the antenna at the speed of light to be reflected, absorbed, or scattered from the target object(s). Some of the energy from the scattered or reflected radar signal will be returned to the receiver antenna, which can be a distinct antenna or can
be the transmitting antenna reused as a receiver. Most modern radar systems use a monostatic radar antenna (i.e., sends and receives using the same antenna) that generates signal pulses, rather than continuous waves (Richards, 2005).

Table 1: Nomenclature for Radar frequency bands, and their associated wavelengths (Richards, 2005).

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Frequency Range</th>
<th>Radar Signal Wavelength</th>
<th>Wavelength of Common Radar Operating Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>3—30 MHz</td>
<td>100—10 m</td>
<td></td>
</tr>
<tr>
<td>VHF</td>
<td>30—300 MHz</td>
<td>10—1 m</td>
<td></td>
</tr>
<tr>
<td>UHF</td>
<td>300 MHz—1 GHz</td>
<td>1 m—30 cm</td>
<td>88 cm</td>
</tr>
<tr>
<td>L</td>
<td>1—2 GHz</td>
<td>30—15 cm</td>
<td>23 cm</td>
</tr>
<tr>
<td>S</td>
<td>2—4 GHz</td>
<td>15—7.5 cm</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>4—8 GHz</td>
<td>7.5—3.75 cm</td>
<td>5.6 cm</td>
</tr>
<tr>
<td>X</td>
<td>8—12 GHz</td>
<td>3.75—2.5 cm</td>
<td>3.1 cm</td>
</tr>
<tr>
<td>K_u</td>
<td>12—18 GHz</td>
<td>2.5—1.67 cm</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>18—27 GHz</td>
<td>1.67—1.11 cm</td>
<td></td>
</tr>
<tr>
<td>K_a</td>
<td>27—40 GHz</td>
<td>1.11 cm—7.5 mm</td>
<td></td>
</tr>
<tr>
<td>mm</td>
<td>40—300 GHz</td>
<td>7.5—1 mm</td>
<td></td>
</tr>
</tbody>
</table>

Since the radar signal travels at or near the speed of light $c$, the distance from the antenna to the object being observed is given by Equation 1 where $R$ is the slant range (diagonal distance) to the reflector, and $t$ is the time elapsed since the signal was transmitted.

$$ R = \frac{ct}{2} $$

If more than one object fits the criteria of Equation 1, then they will both contribute to the observed signal. This particular problem leads to coherent noise in the radar image.

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known as image speckle (Richards, 2005). To adjust for the effects of speckle, radar signals are typically post-processed digitally with a speckle filter.

Using a single antenna introduces some limits of resolution to radar imaging. Even with a narrow, focused signal beam, a typical radar antenna will produce very low resolution. An object at a slant range $R$, using a signal wavelength $\lambda$ and antenna length $L_a$ has a resolution $\rho_a$ as defined by Equation 2 (Ristau, 1999).

$$\rho_a = \frac{R\lambda}{L_a}$$

(2)

The limits of resolution can also be related to the wavelength of the incoming radar signal. To estimate the distance between two objects (i.e., antenna and target) where the reflected signals arrive at slightly different times, the incoming peak reflection must be offset by at least one quarter of a wavelength, which is known as Rayleigh’s criterion (Sheriff and Geldart, 1995).

For a radar platform such as an airplane or satellite, the SAR antenna typically points perpendicular to the direction of the platform’s forward motion as shown in Figure 10. This direction is known as the range direction while the direction straight-downward from the orbiting platform is known as nadir. For range resolution, the limit of resolution is governed by the antenna aperture, while the angular off-nadir resolution is governed by the look angle and the Raleigh criterion (Ristau, 1999).
3.2 Synthetic Aperture Radar (SAR)

Since the size of antenna limits the range resolution of a radar image, and the physical dimensions of the antenna for on-board aircraft and space-based platforms are limited, a technique known as aperture synthesis has been developed to improve resolution. This technique makes use of the motion of the platform and advanced processing techniques to simulate an antenna with a much larger aperture, as shown in Figure 11.

Figure 10: Geometry of SAR imaging (modified from Braun, 2008). Slant range is the distance between the SAR platform and the surface target being observed, and nadir is the point on the ground directly below the SAR platform.
These platforms then orient their antennae at right angles to the direction of motion to maximize the resolution in that direction (Lowrie, 2007).

![Synthesis of the synthetic aperture radar.](image)

**Figure 11:** Synthesis of the synthetic aperture radar. The smaller radar antenna moves along the orbit (azimuth direction) and mathematically stitches together the information received at each position to create a single, combined data set that is the equivalent to a much larger antenna (modified from Braun, 2008).

The first applications of SAR were military, and the technique was classified from its inception in 1953 until the first published paper in 1961 (Kovaly, 1976). As early as 1970, SAR was being used as part of NASA’s Magellan mission to map the surface of
Venus, a body permanently shrouded in clouds. This technique was then proposed as a technique suitable for an orbiting platform to observe the Earth and other planetary bodies (Kovaly, 1972).

Since orbital radar platforms were first conceived, a number of SAR systems have been developed. These are summarized in Table 2.

Table 2: Summary of SAR-capable satellites and shuttle missions (Won, 1993; Braun, 2008; and Wikipedia, accessed February 16th, 2009 for more recent information).

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Launch Date</th>
<th>Wavelength</th>
<th>Ground Resolution (m)</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasat</td>
<td>1978</td>
<td>L</td>
<td>25</td>
<td>HH</td>
</tr>
<tr>
<td>SIR-A</td>
<td>1981</td>
<td>L</td>
<td>40</td>
<td>HH</td>
</tr>
<tr>
<td>SIR-B</td>
<td>1984</td>
<td>L</td>
<td>17-58</td>
<td>HH</td>
</tr>
<tr>
<td>ERS-1</td>
<td>1991</td>
<td>C</td>
<td>30</td>
<td>VV</td>
</tr>
<tr>
<td>JERS-1</td>
<td>1992</td>
<td>L</td>
<td>18</td>
<td>HH</td>
</tr>
<tr>
<td>SIR-C</td>
<td>1994</td>
<td>C, L, X</td>
<td>10-30</td>
<td>Quad-pol (C &amp; L),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>VV (X)</td>
</tr>
<tr>
<td>RADARSAT-1</td>
<td>1994</td>
<td>C</td>
<td>8-1000</td>
<td>HH</td>
</tr>
<tr>
<td>ERS-2</td>
<td>1994</td>
<td>C</td>
<td>6</td>
<td>VV</td>
</tr>
<tr>
<td>SRTM</td>
<td>2000</td>
<td>C, X</td>
<td>30</td>
<td>HH, HV, VV, VH</td>
</tr>
<tr>
<td>Envisat</td>
<td>2002</td>
<td>C</td>
<td>12.5-1000</td>
<td>Dual-pol</td>
</tr>
<tr>
<td>ALOS</td>
<td>2006</td>
<td>L</td>
<td>7-100</td>
<td>Quad-pol</td>
</tr>
<tr>
<td>SAR-Lupe 1-5</td>
<td>2006-2008</td>
<td>X</td>
<td>0.5</td>
<td>HH, HV, VV, VH</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>2007</td>
<td>X</td>
<td>1.34-30</td>
<td>Quad-pol</td>
</tr>
<tr>
<td>RADARSAT-2/3</td>
<td>2007-</td>
<td>X</td>
<td>3-100</td>
<td>Quad-pol</td>
</tr>
<tr>
<td>COSMO-</td>
<td>2007-</td>
<td>C</td>
<td>1-100</td>
<td>Dual-pol</td>
</tr>
<tr>
<td>SkyMed 1-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAOCOM 1-2</td>
<td>Pending</td>
<td>L</td>
<td>10-100</td>
<td>HH, VV</td>
</tr>
</tbody>
</table>
4. Data acquisition

In order to test the technique of SAR imaging for the purposes of distinguishing geologic features, a target must first be chosen, as well as a source of SAR imagery. The Belcher Islands were chosen due to the well-exposed outcrops or rock and readily available previously completed geological remote sensing work on these islands.

4.1 Data description

Two datasets for the Belcher Islands were downloaded from the ALOS PALSAR library as part of the ALOS Principle Investigator (PI) account #00139 (PI: Prof. Wooil Moon). These datasets are labelled ALPSRP097382480-H1.5GUD and ALPSRP098911120-H1.5GUA and are included in Appendix A.7. Some of the data acquisition specifications for these data sets are listed in Table 3.

Preliminary images were created from the downloaded data using ASF MapReady 2.0.13, a free SAR processing utility produced by the Alaska Satellite Facility, Geophysical Institute, University of Alaska Fairbanks (see Appendix A.1). Since the produced images were too large for most software products to handle, they were then downscaled to 20% of their original resolution in order to view the entire image at once. The images are included in Figure 12 and Figure 13.
Table 3: Some information on the ALOS PALSAR data files obtained for the Belcher Islands.

<table>
<thead>
<tr>
<th>File</th>
<th>ALPSRP097382480-H1.5GUD</th>
<th>ALPSRP098911120-H1.5GUA</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTM Zone</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH</td>
<td>HH</td>
</tr>
<tr>
<td>Pixel Spacing (m)</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>Off nadir angle</td>
<td>34.3</td>
<td>34.3</td>
</tr>
<tr>
<td>Bits per pixel</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Scene centre</td>
<td>56.349°N 79.403°W</td>
<td>56.351°N 79.192°W</td>
</tr>
<tr>
<td>Scene size (pixels)</td>
<td>12600 x 11000</td>
<td>12900 x 11400</td>
</tr>
<tr>
<td>Data size</td>
<td>279.4 MB</td>
<td>295.9 MB</td>
</tr>
</tbody>
</table>

Figure 12: SAR image of data set ALPSRP097382480-H1.5GUD, amplitude image, downsampled to fit page, projected to UTM Zone 17. See Appendix A.6 for full resolution image.
4.2 Data pre-processing

The ALOS PALSAR data received was pre-processed data, meaning it has already been radiometrically and geometrically calibrated. Included in Appendix A.8 are the ALOS Data Users Handbook (EORC, 2008a) and the ALOS/PALSAR Level 1.1/1.5 product Format description <English Version> (EORC, 2008b), which provide detailed descriptions of the data processing procedures for the Level 1.5 data files. These
processing steps are summarized below as follows. Note that altitude corrections are not performed.

4.2.1 Range compression

This process involves converting the raw SAR data into frequency domain data using a Fast Fourier Transform (FFT). This data is then noise reduced, and correlated to the corresponding reference function in the range direction. The data is then reassembled using an Inverse Fast Fourier Transform (IFFT) (EORC, 2008a). The flow chart of this procedure is outlined in Figure 14.

4.2.2 Multi-look azimuth compression

This stage operates on the output of the range compression routine. First a FFT is performed on both the data and a reference function. The output of both is then correlated, each look is processed, and IFFT is applied. The data is then converted into a real number and an operation known as multi-looking is performed. The flow chart of these operations is outlined in Figure 15.

In the course of multi-looking, the equivalent aperture is divided by the number of looks, reducing the resolution, but the speckle noise is improved by $\sqrt{N}$ where $N$ is the number of looks (EORC, 2008a). The Level 1.5 data sets received were processed for two looks.
4.2.3 Radiometric corrections

This step involves an Automatic Gain Control (AGC) correction, a Sensitivity Time Control (STC) correction, a correction for the antenna array pattern, and a correction on the difference in propagation path length (EORC, 2008a). The combined effect of these corrections is to adjust the data gain for error and reduce the dynamic range of the image (Bierens and Otten, 1998).

Figure 14: Range compression operations (from EORC, 2008a).
4.2.4 Geometric corrections

This stage consists of two operations, a map coordinate system conversion and a histogram conversion or amplitude normalization.

To convert the ALOS PALSAR image to a map projection, a coordinate transform operation is performed. It will convert the rectangular data array into an appropriate map projection, such as Universal Transverse Mercator (UTM) coordinates. The result may include skewing, resizing, or rotation of the data pixels. The 2-D coordinate transform equations appear in Equation 3, where \((u, v)\) are the input coordinates and \((x, y)\) are the output coordinates. The values of the coefficients \(a\) through \(h\) are determined by the orbital parameters, and the map projection used (EORC, 2008a).

\[
\begin{align*}
    u &= ax + by + cxy + d \\
    v &= ex + fy + gxy + h
\end{align*}
\]  
\[ (3) \]

The schematic end result is a map projection oriented as shown in Figure 16.

Next, a histogram is used to determine the dynamic range of the image. After the data pixel maximum is determined, the histogram is adjusted using a non-linear function involving a square-root. The modifying function, with \(a\) and \(b\) as constants, is shown in Equation 4.

\[
y = a \sqrt[\frac{x}{b}]
\]  
\[ (4) \]
Figure 15: Multi-look azimuth compression operations (modified from EORC, 2008a).
Figure 16: Geocoded data, projected to UTM, will appear as shown (modified from EORC, 2008b).

The final product is a Level 1.5 image, geocoded to UTM Zone 17, with amplitude being represented as a 16-bit unsigned integer, and a pixel spacing of 6.25 metres (EORC, 2008a).

4.3 **Auxiliary data sets**

While the focus of this project is on the feasibility of using SAR data to visually determine various contrasts in the SAR image, including geologic boundaries, this is not the only available remote sensing data that are able to provide this information. For example, Wickert and Budkewitsch (2004) used optical data obtained from the ASTER probe to correlate various geologic contacts to Jackson’s (1960) map. In order to augment the visual interpretations made using the ALOS PALSAR images within this thesis, a number of optical images were acquired to supplement the SAR imagery.
These obtained supplemental images include the freely available Landsat 7 multispectral and panchromatic imagery covering the whole island (see Appendix A.4), as well as the SPOT 5 multispectral and panchromatic imagery for the portion of the islands where they were available (see Appendix A.9). The multispectral imagery is decomposed into specific wavelengths of light, while the panchromatic image is a higher resolution amplitude image of arbitrary wavelength. This data was made publicly available on the Canadian Government website geobase.ca (accessed June, 2008).

Figure 17 shows the obtained Landsat 7 panchromatic image, which has been enhanced using the utilities in Adobe Photoshop CS3 using the built-in auto-contrast adjustment filter. It has also been downsampled. Original resolution of this image is 15 metres/pixel. Figure 18 shows the channel 3 (0.79 to 0.89 μm) image from the SPOT 5 satellite. As with the Landsat 7 image, this image has also had its contrast auto-adjusted. The original resolution of the SPOT 5 multispectral image is 20 metres/pixel.
Figure 17: Landsat 7 panchromatic image, contrast adjusted and resampled. Original resolution: 15 m/pixel. UTM Zone 17. The dome structure on Tukarak Island (on the right) is visible as well as a contrast between the darker Flaherty Formation and the lighter sediments. Data from geobase.ca (data accessed June, 2008; acquired 2000/08/09).
Figure 18: SPOT 5 channel 3 image, contrast adjusted and resampled. Original resolution: 20 m/pixel. UTM Zone 17. This image shows a brightness contrast between the darker Flaherty Volcanics and the sedimentary formations. Data from geobase.ca (data accessed June, 2008; acquired 2006/08/11).
5. Data processing and interpretation procedure

The principal techniques used to determine the usefulness of the SAR data for mapping surface geology are based on traditional image analysis. SAR data presentation tools are combined with image handling software such as Adobe Photoshop to compare and contrast the two SAR images with the optical imagery and Jackson’s (1960) map.

5.1 SAR image processing

The two SAR images were loaded into the Next ESA SAR Toolkit (NEST) Display and Analysis Tool (DAT) version 2A (see Appendix A.5). This software automatically renders greyscale images for amplitude and intensity (amplitude squared) for each loaded dataset.

An export of this rendered image produced a 561 MB tiff file, far too large to be loaded or viewed by most software. In order to visually represent the stages of processing, two images of reduced size are produced using simple screen-grabbing. A fully panned image is presented as well as a true pixel representation. These steps are illustrated using the ascending orbit dataset, and the true pixel representation is a magnified area within Flaherty Island.

5.2 Raw images

Figure 19 shows the full pan of the raw amplitude data, while Figure 20 shows raw amplitude data for a section of Flaherty Island at true resolution. Figure 21 shows the
intensity, rather than amplitude, data for the same magnified scene as Figure 20. The intensity image helps improve feature contrast in the greyscale image.

Figure 19: Panned back SAR image of unprocessed amplitude data, ascending orbit data. Pixel zoom is 1:17.43.
5.3 False colour visualisation.

In order to better visualise the range of amplitudes seen in the image, applying a colour scale based on the data histogram is sometimes useful, as seen in Figure 22. High amplitude spots show in warm colours, while low amplitudes show in cool colours. The zoomed portion of Flaherty Island is shown in Figure 23, while the fully panned image is included in Figure 24. Lineation between red and blue becomes apparent in the false colour images, which is sometimes useful for visually identifying geologic features such as contacts.
5.4 Speckle filtering

Since the processed SAR images contain a fair amount of speckle, an effect that is often undesirable, a speckle filter can be applied to remove some of the speckles. The tradeoff is that speckle filtering can degrade the quality of the data to a certain degree, and may introduce unwanted distortions in contrast or in other image parameters. To test if a speckle filter can improve the clarity of the ALOS PALSAR images, the Frost algorithm and the Lee algorithm were tested using the default options presented in
NEST DAT 2A, operating on the amplitude data. The effect of the filters on the data can be seen when comparing histograms, as in Figure 25. A comparison of the images is given in Figure 26.

Since both the Frost and Lee filters produce similar results, both in the histogram and upon inspection of a zoomed image, the choice of filtered output to use becomes less important in this case. Since we will proceed with filtered data, the Lee filtered data was arbitrarily chosen as the preferred output.
5.5 False colour enhancement

After the output of the Lee filter was loaded into the histogram, the image was modified using the spectrum as defined in Figure 27 to produce the false coloured image as shown in Figure 28. The spectrum used was chosen to make the surrounding water look black. This image, at full resolution, was exported to a tiff file for further
contrast enhancement in Adobe Photoshop and comparison to Jackson’s (1960) map of
the Belcher Islands.

Figure 24: Zoomed out, unprocessed, false coloured SAR image of ascending orbit dataset. 1:17.43
pixel zoom.

5.6 Image overlay and comparison with known geology

After the false coloured, speckle filtered ALOS PALSAR image was created, it was
then loaded in Adobe Photoshop CS3 alongside a high-resolution scan of Jackson’s
(1960) map of the Belcher Islands geology. Using Photoshop, the SAR image was set to be the background while the map was set to be the foreground image. The map opacity was set to 60% to allow the SAR image to be visible underneath. The map was then rotated, resized and repositioned until the drawn edges corresponded reasonably well to the edges within the SAR image. The resulting image is shown in Figure 29, while a more detailed image of Flaherty Island (near Windy Lake) is shown in Figure 30 and a detailed look at Tukarak Island is shown in Figure 31.

Figure 25: Comparison of histograms for unfiltered data, Frost filtered data, and Lee filtered data. The Frost filter used a 3x3 window and a damping factor of 2. Lee filter used a 3x3 window.

Figure 26: Comparison of 6.25 metres/pixel zoomed unfiltered data, Frost filtered data, and Lee filtered data. Frost filter used a 3x3 window and a damping factor of 2. Lee filter used a 3x3 window. Image is a zoomed portion of Flaherty Island.
Figure 27: False colouration histogram for Lee speckle filtered SAR data. The left histogram shows the entire histogram while the right shows a zoomed section.

Unfortunately, due to the nature of Jackson’s hand-drawn map, the borders do not precisely align in all locations. The shorelines also change depending on the season and the tides, so precise alignment is not expected. A more detailed image of Flaherty Island (near Windy Lake) is shown in Figure 30 while a detailed look at Tukarak Island is shown in Figure 31.
Figure 28: False coloured, Lee speckle filtered ascending orbit ALOS PALSAR image. Red corresponds to high amplitude response while blue is low amplitude. See Appendix A.6 for full resolution image.
Figure 29: Jackson’s (1960) Belcher Islands geology map drawn over the ALOS PALSAR data to show correlation between the SAR image amplitude and surface geology. See Appendix A.6 for full resolution image.
Figure 30: Flaherty Island near Windy Lake showing the correlation of surface geology with the ALOS PALSAR amplitude image. See Appendix A.6 for full resolution image.
Figure 31: Tukarak Island, showing the correlation between surface geology and ALOS PALSAR amplitude image. See Appendix A.6 for full resolution image.
6. Results
In the integrated images of ALOS PALSAR amplitude and surface geology produced, a number of formations are identifiable, including both volcanic assemblages. A number of contacts are also traceable due to colour contrasts.

6.1 Visual interpretation of ALOS PALSAR data
The lower contact of the Flaherty Formation is visible throughout the final integrated image. This formation is labelled as number 13 on the map in Figure 1 and generally appears red against the surrounding formations in Figure 29. The lower contact is with the Kipalu Iron Formation, labelled number 12 or with a diabase dike labelled number 14. Both the iron formation and the diabase dike are bluer than the Flaherty Formation signifying a much lower amplitude response. This is likely due to a contrast in either texture or electromagnetic properties. Since the iron formation shows a lower amplitude response, it is reasonable to assume that this difference in amplitude is due to a contrast in rock properties.

On both Tukarak Island (Figure 31) and in central Flaherty Island (Figure 30), the contact between the Eskimo Formation volcanics (labelled number 2) and the Fairweather Formation (number 3) is fairly sharp. Jackson (1960) described pockets of ironstone at this contact, which, as with the Kipalu Iron Formation, should help to produce a significant difference in the electromagnetic properties at this contact.
A number of other contacts are traceable on Tukarak Island including the Fairweather-McLeary (numbers 3 and 4) and the Rowatt-Mukpollo (numbers 9 and 10) contacts.

The contrast between these formations can be high in places, but locally subtler, requiring some assumptions about continuity.

Lastly, in a number of places, such as in the southern parts of Flaherty Island, a number of linear features occur that follow the structural trends but are fully contained within the Flaherty Formation volcanic rocks. These may correspond to contacts between volcanic flows within the Flaherty Formation, due either to textural or compositional variations.

### 6.2 Visual interpretation of optical image data

The optical data from Landsat 7 and SPOT 5 were compared to the map. In general, the optical images were sufficient to observe the structural trends, but were less effective in determining the locations of certain contacts.

In the Landsat 7 panchromatic image (Figure 17), the lower contact of the Flaherty Formation is clearly visible throughout the region, as well as the contact between the Eskimo and Fairweather Formations on Tukarak and Flaherty Islands. In this image, the volcanic rocks appear darker than the sediments, unlike in the ALOS PALSAR image.
The SPOT 5 panchromatic image lacks sufficient contrast in the unmodified image to determine the location of contacts. In the channel 3 (0.79 to 0.89 μm) image (Figure 18), however, the contrast at the base of the Flaherty Formation is comparable to the Landsat 7 image where visible on Innetalling Island. Only the southern tip of Tukarak Island is visible in the SPOT 5 data, but the contrast between the Eskimo and Fairweather Formations is also comparable to the Landsat 7 panchromatic results. For both contacts, the volcanic rocks are darker than the sedimentary rocks.
7. Discussion

The images produced from the HH singly-polarized ALOS PALSAR data were successfully used to determine the locations of several geological contacts within the Belcher Islands. It was particularly successful in visually determining the major contacts between geological formations composed of volcanics (basalts) and the surrounding sedimentary formations. Using only the SAR data, it would likely be possible to reproduce the generalized map of the Belcher Islands as shown in Figure 7.

These results compare favourably to those that have been obtained using the optical remote sensing data available for the Belcher Islands. The results achieved by Wickert and Budkewitsch (2004) could reasonably be complemented using SAR imaging techniques. Using SAR images to produce this type of integrated remote sensing and geological map image has the additional advantage of SAR being an active rather than passive imaging technique, because SAR is capable of imaging through all weather conditions and even at night.

These visual and qualitative results show that SAR is a useful technique to supplement mapping of remote areas with difficult access, when the geology is well exposed. Additional data, such as phase information or fully-polarimetric data, could further improve these results by adding information that can be used to compare and contrast adjacent formations. Additionally, being able to quantitatively determine the location of the contacts would be useful as this process could then be fully automated.
8. Conclusions
The HH single polarisation SAR data obtained from the ALOS PALSAR instrument is capable of aiding in the production of geologic maps in regions of good exposure and sufficient contrast between formation properties. In qualitatively testing the obtained speckle filtered amplitude data by using basic image processing techniques, a number of contacts could be distinguished. The most noticeable contrasts within the Belcher Group were between the volcanic formations and the sedimentary formations (particularly the iron formation) and would be sufficient to reproduce Legault et al.’s (1994) simplified geology map. These results complement those produced by Wickert and Budkewitsch (2004) using only the ASTER optical data.

Additional, fully polarimetric SAR data and more sophisticated quantitative processing promise to improve these results further and improve the usefulness of this active imaging technique for mapping remote, exposed regions of terrestrial planets.
9. References


Appendix A: Index of data on DVD

Included with this thesis is a DVD containing some raw data, processed data, and where appropriate, copies of the software used in processing. A listing is shown below.

1. ASF MapReady – copy of software used to make preliminary images, freely redistributable under the 4-clause BSD license
2. Belcher Map (Jackson, 1960) – a PDF copy of the Belcher Islands Map
3. Copy of Thesis – a MS Word 2000 formatted copy of this document
4. Landsat 7 Data – satellite imagery from geobase.ca
5. NEST DAT 2A – copy of software used to process PALSAR data, freely redistributable under the GPL version 2 license; sources included
6. ALOS PALSAR Processed Data – images and other output from NEST DAT and ASF MapReady
7. ALOS PALSAR Raw Data – copies of the original PALSAR Level 1.5 data
8. References from Internet – JAXA’s ALOS PALSAR manuals in PDF format
9. SPOT 5 Data – satellite imagery from geobase.ca