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Overview of Synthetic Aperture Radar Concepts for the CP-140

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IMPORTANT INFORMATIVE STATEMENTS

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1 Introduction

This document aims to provide a practical overview on airborne synthetic aperture radar (SAR). A high-level approach is taken to explain the typical SAR operating modes, the typical user operating parameters, the limitations of SAR systems, and preferred imaging geometries. A minimal amount of mathematics are used in the explanations. More detailed explanations of SAR operation and signal processing are described in Stimson [1] and Lacomme [2]. The mathematical level of detail in these references is still quite approachable for the SAR operator and those familiar with traditional radar systems.

2 SAR basics

In pulsed waveform radar systems, range resolution is directly related to the frequency bandwidth of the transmitted pulse. Cross-range resolution is limited by the physical size of the receive antenna array. Generally, the larger the physical size of the antenna the smaller the beamwidth. This in turn results in improved cross-range resolution. The issue with these physical antennas is that there is a limit to how big they can be made and be installed them on airborne platforms. Synthetic Aperture Radar (SAR) is a methodology to create a synthetic antenna aperture by moving a physical antenna through space. The main advantages of SAR imaging are:

- a smaller physical antenna can be used to achieve fine cross-range resolution, and
- the cross-range resolution is not range dependent as it is with a physical antenna.

The term “finer resolution” is clarified here. Consider a radar system with a resolution of 3 m. This means the radar is capable of detecting targets which are separated by a distance of 3 m or more; e.g., or the radar is not able to distinguish two targets if they are less than 3 m apart. If another radar system has a resolution of 1 m then it is capable of detecting targets which are separated by a distance of 1 m or more. We say that the radar with 1m resolution has a finer resolution than the radar with 3 m resolution.

2.1 SAR modalities

There are three common SAR imaging modalities: Stripmap mode, Spotlight mode and Inverse-SAR. These are commonly referred to as Strip, Spot and ISAR modes. In Stripmap mode the aircraft flies along a straight line and the antenna steered to illuminate a strip along the ground. The radar imaging data is presented in a continuous waterfall type display. Figure 1 shows the imaging geometry for Stripmap mode.

In Spotlight mode, a target is selected and the antenna is steered at the target throughout the data collection. A sequence of snapshot like images are presented to the operator every few seconds. Stripmap and Spotlight modes are usually selected for land imaging. Since the antenna is steered towards the target point throughout the data acquisition, this mode is capable of generating higher resolution imagery than Stripmap mode. Figure 2 shows the Spotlight mode imaging geometry.

ISAR mode is similar to Spotlight mode except that the relative motion between the radar and the target is reversed. ISAR utilizes the movement of the target rather than the movement of the radar platform to provide cross range resolution. ISAR is

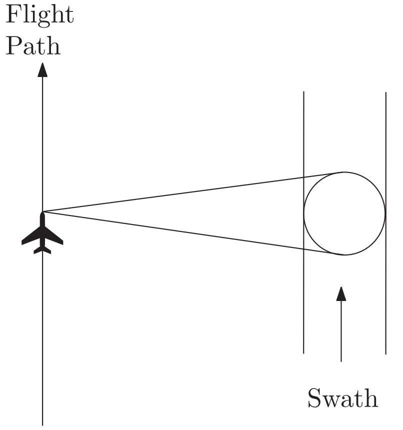

Figure 1: *Stripmap mode geometry.*

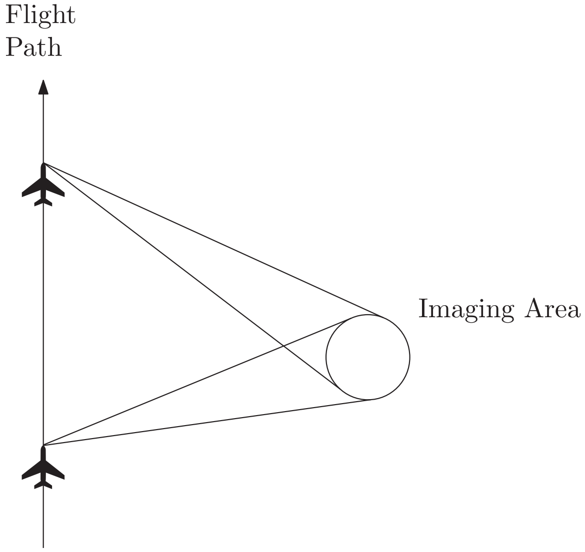

Figure 2: *Spotlight mode geometry.*

commonly used to image ships at sea. In some radar systems ISAR can be used in an air-to-air mode to image other aircraft. Due to the substantially different velocities between aircraft and ship targets, ISAR which images both target classes is not usually available on the same radar system. In the CP-140 community ISAR mode is referred to as Seaspot mode. We will use the term Seaspot for the remainder of this document.

2.2 SAR system limitations

When the radar transmits a pulse there is a minimum distance, R_{min}, before the radar can start receiving data. This distance is necessary to avoid overloading the radar receiver with the power of the returns from near-range objects. For SAR there are also maximum ranges for the various modes. To provide cross-range resolution in SAR the radar must sample the data at a sufficiently high rate. The frequency of how often the pulses are transmitted is called the Pulse-Repetition Frequency (PRF). The time between the transmission of consecutive pulses is the Pulse Repetition Interval (PRI) and is equal to $1/PRF$. The radar needs to receive the return from the first pulse before it transmits the next pulse[1]; therefore, the maximum range is given by:

$$R_{max} = \frac{c}{2 \cdot PRF} = \frac{c \cdot PRI}{2}, \tag{1}$$

where c is the speed of light in m/s, the PRF is in Hz and the PRI is in seconds. Note that at low PRFs, R_{max} may be quite large and the maximum range may instead be limited by either the receive power or the radar horizon. The radar will not be able to collect data over the entire range from R_{min} to R_{max}, since SAR image formation is a computationally intensive process and the system cannot process all the data over this entire range. Instead, the radar will only collect data over a smaller range referred to as the range swath, see Figure 3. The operator will need to select the desired swath width along with the desired resolution at the beginning of a SAR processing run.

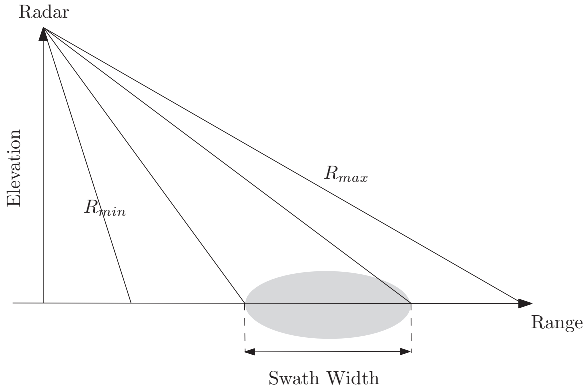

Figure 3: *Range swath.*

This brings us to the trade-off between swath-width and resolution. Achieving finer cross-range resolution requires more computational horsepower than low resolution; therefore, to limit the computational burden at finer resolutions, the swath width generally decreases. Conversely, coarser resolution modes generally have larger swath widths available and provide more coverage area.

The selection of a desired cross-range resolution also constrains the PRF. For a specific cross-range resolution, the PRF must be sufficiently high to adequately sample the data. A finer the cross-range resolution increases the minimum PRF required. This subsequently determines the maximum imaging ranges available for SAR operation.

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[1] There are techniques to address this, but a discussion of that material is beyond the scope of this document.

A detailed discussion of sampling requirements for cross-range resolution is beyond the scope of this report. Additional details on PRF limitations can be found in [1, 2].

2.3 SAR mode selection

A guide for the selection of the SAR modes based on the imaging objective is provided in Table 1. The Primary Parameter is the main parameter that the operator is interested in for the corresponding task. Depending on the user interface this parameter may not be directly available to the operator. As an example, the operator may not be able to directly select the resolution; instead the operator may have to select the range swath and observe what resolutions are available. It should be noted that the preferred imaging geometries may not be attainable due to operational constraints.

Table 1: *SAR imaging objectives.*

Objective	**SAR Mode**	**Primary Parameter**	**Comments**
Area Coverage	Stripmap	Swath Width	Fly straight and level
Locate Area of Interest	Stripmap	Swath Width / Resolution	Fly straight and level
Intelligence	Landspot	Resolution	Flight path may be either straight and level or circular as situation allows
Area Observation	Landspot	Swath Width / Resolution	Fly straight and level
Persistent Surveillance	Landspot	Swath Width / Resolution	Fly racetrack or circular path. Increased time on target may reveal changes over time
Ship Imaging	Seaspot	Integration Time	Fly so that the radar LOS is along the long axis of the ship. Selection of integration time is dependent on ship motion and sea-state.

2.4 Factors affecting resolution and image quality

The range resolution in SAR is provided along the Line of Sight (LOS) of the radar, thus when imaging targets on the ground there is a loss of effective ground resolution due to the projection of the LOS onto the ground - see Figure 4. Given a range resolution ρ_s the effective ground resolution is given by

$$\rho_g = \frac{\rho_s}{\cos\theta}, \tag{2}$$

where θ represents the elevation angle from the target to the radar. The ground resolution will degrade as the radar altitude increases or as the target range decreases. Many radar antennas have a maximum tilt angle; this will limit the maximum altitude (see Figure 4) for a target at a given range. For the CP-140, the tilt angle is limited to 25° for straight and level flight; the corresponding degradation of the ground range resolution is $\approx 1.10\rho_s$.

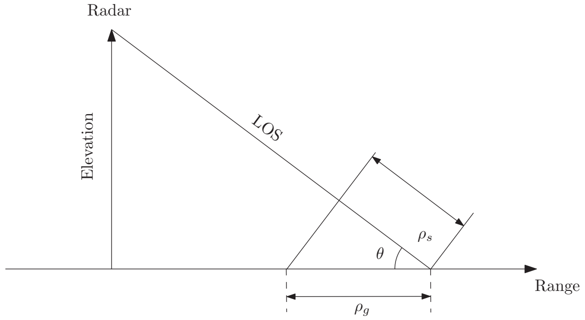


Figure 4: *Effective ground resolution.*

The cross-range resolution is primarily limited by the azimuth beamwidth of the radar antenna and the illumination time, i.e., how long the radar illuminates a particular target. In Stripmap mode an individual target moves through the radar beam as the radar platform moves and thus there is a maximum time during which the target is illuminated by the radar. This maximum illumination time will determine the finest cross-range resolution possible. In Stripmap mode, the best cross-range resolution is obtained when the radar LOS is pointed perpendicular to the swath being imaged. If the radar antenna is pointed forward or aft then this is referred to as Squint mode. Operating in a squinted geometry degrades the cross-range resolution from the optimum value. The squint mode geometry for the CP-140 is shown in Figure 5. Operationally, the angle ϕ is limited to be in the range $30° \leq \phi \leq 120°$, which results in only a minor degradation of the cross-range resolution. This imaging geometry differs from what is traditionally referred to as Squint mode in the radar texts [1, 2], but the geometry shown in Figure 5 offers greater operational flexibility with little loss in performance.

In Spotlight mode the antenna is steered throughout the data collection and the target can be illuminated for longer periods of time. This means that very high resolutions can be achieved in Spotlight mode. Figure 6 illustrates the Spotlight mode geometry. Practically speaking there are several reasons that may limit the resulting resolution.

- Normally for SAR imaging, the cross-range resolution is selected to be close to the range resolution in order to maintain a square aspect ratio.
- Some radar antennas have limited steering capability. This in turn may limit the achievable resolution in straight and level flight. As an example, on some

radars the steering may be limited by the location of aircraft bulk heads or by other physical limitations.

- For long acquisition times, there may be random motion, e.g., moving vehicles, pedestrians, wind effects on trees or tall grass, which produce unwanted artifacts in the resulting imagery.
- As the resolution increases, the speckle effect increases and this may limit the usefulness of the increased resolution. The speckle effect will be particularly noticeable in grassy areas and fields.

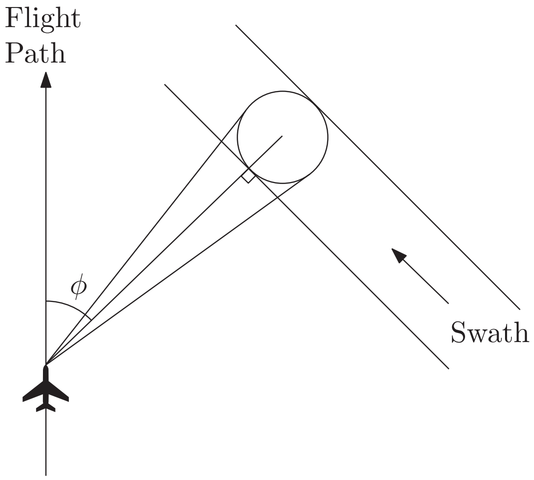


Figure 5: *CP-140 squint mode geometry. The swath is 90° to the LOS of the radar.*

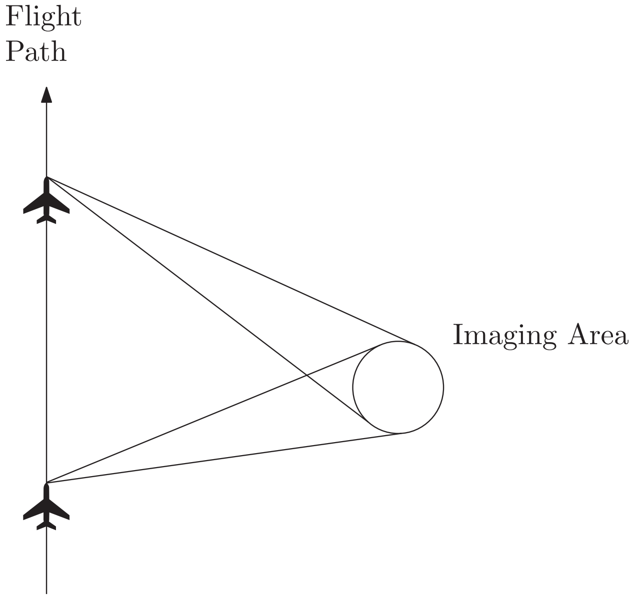


Figure 6: *Spotlight mode geometry.*

An alternative to using the increased illumination time to obtain higher resolutions is to perform incoherent averaging. Incoherent averaging divides the illumination aperture into overlapped sections. SAR images are formed for each section at a specified resolution. The resulting magnitude images can then be averaged together. The incoherent averaging doesn't result in improved resolution but it does reduce the speckle effect. Speckle is discussed in more detail in Section 2.5.

2.5 Speckle

Speckle in SAR images is a consequence of coherent imaging with finite resolution on a large number of randomly distributed scatterers. Speckle is noise-like, but it is not additive noise in the sense of thermal noise. Speckle will still be apparent in the SAR image even if we increase the radar transmitted power. Speckle is often referred to as "salt and pepper" noise because it is similar in appearance to a mixture of black and white particles. Figure 7a illustrates the speckle which results due to imaging a farmer's field. Figure 7b illustrates the reduction of speckle by the incoherent averaging of 10 image frames.

(a) ***(b)***

Figure 7: *7a) Speckle present in a single frame. 7b) Speckle reduction due to incoherent averaging of 10 frames. The areas highlighted in the red circles show the speckle effect and its reduction by incoherent averaging.*

2.6 Flight profile selection

Flight profile selection requires balancing several factors such as: operational requirements, operational limitations, imaging geometry, resolution degradation, and general image quality. This section is more applicable to Stripmap and Spotlight modes. Seaspot mode is discussed briefly but is addressed in more detail in Section 2.7.

Figure 8 shows how the presence of a tall obstruction, such as a building, a tower or trees, can create a shadow zone in the resulting SAR imagery. Because the radar energy cannot penetrate the obstruction, this causes a dark area within the image referred to as a shadow zone. Flying at low altitudes provides the best range resolution, but it also increases the length of the shadow zone. Shadows within the image can provide clues to the height of objects in the image and can provide useful intelligence information. The shadow zone may also hide targets of interest if they fall into the shadow of a building or forested area. Two ways to mitigate targets being hidden in shadows are to change the imaging geometry and to increase the radar platform altitude. Moving the aircraft so that the radar illuminates the target area from a different angle, changes the imaging geometry and moves the shadow zone. The shadow zone will still be present in the SAR image but a different area will now fall in the shadow zone. Increasing the aircraft altitude reduces the length of the shadows, but it also decreases the effective ground range resolution as discussed previously in Section 2.4.

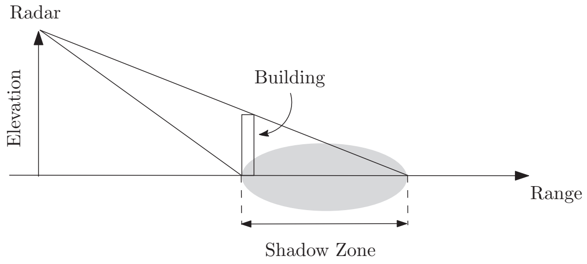


Figure 8: *SAR shadow zone.*

The other main factor in the flight profile selection is the aircraft velocity. In order to provide a given cross-range resolution, SAR systems must sample and process a certain amount of data. Flying at higher velocity reduces the amount of time it takes to collect sufficient data to form a SAR image. Forming high quality SAR images requires precise knowledge of radar position with respect to the imaging area. This positional information is usually provided by blending information from the Global Positioning System (GPS), the Inertial Navigation System (INS) and Inertial Measurement Units (IMUs). The data obtained from blending this information is used to perform motion compensation correction. Flying at higher velocities reduces the demand on the motion compensation system, but it also means that the radar must send the pulses more frequently and the SAR processor must be able to process the data at this higher rate. If the processor is not able to keep up, then data will be lost and the resulting imagery will be degraded. Thus, the radar manufacturer will have a suggested maximum velocity for SAR imaging. Flying at lower velocities means it takes longer to collect the necessary data to form the SAR image and over this time period the aircraft may experience large positional shifts which place increased performance demands on the motion compensation system.

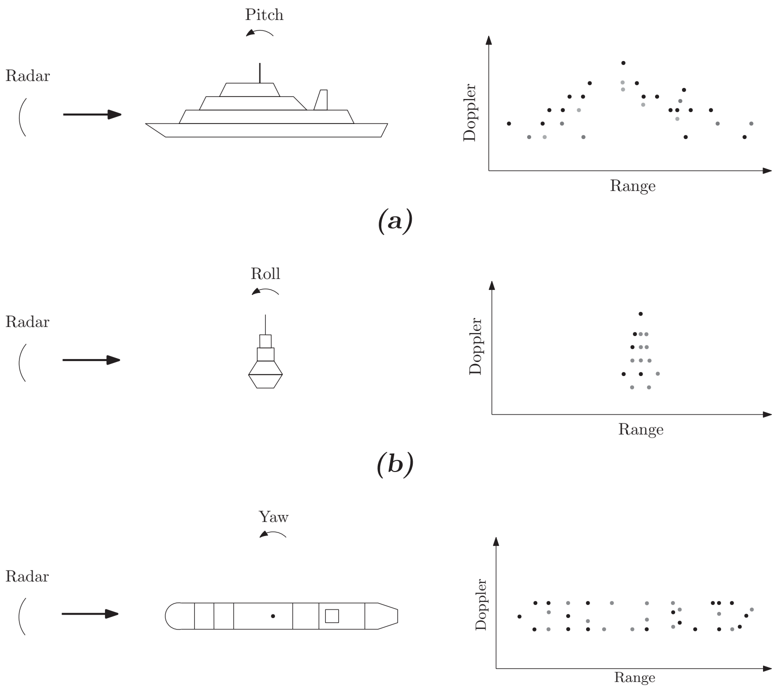
In general, as turbulence increases during the SAR data collection, it places higher demands on the motion compensation system. This may lead to the SAR image appearing unfocused. Therefore, it is desirable to select a combination of flight velocity and/or altitude values which minimize the amount of turbulence when operationally feasible.

In Seaspot mode the targets are generally targets of opportunity and it may not be feasible to select the desired velocity, altitude and imaging geometry. In Seaspot mode the target is non-cooperative and the relative motion of the target with respect to the aircraft has to be tracked. To improve the tracking performance of the Seaspot processor it is again desirable to minimize the amount of turbulence experienced during the data collection.

2.7 Seaspot

In Seaspot mode the range resolution is determined by the pulse bandwidth as described earlier. The cross-range resolution is determined by the relative motion between the radar platform and the target. Generally, in Seaspot mode, the integration times are much smaller than in the Stripmap or Spotlight modes. Most of the cross-range resolution then comes from the motion of the target. In particular, it is the radial motion of the different target components along the Line of Sight (LOS) of the radar which provides the cross-range resolution. The radial motion of the target components is produced by the rotational motion of the target, i.e., roll, pitch and yaw. Because the target elements are at different distances from the axis of rotation, each of the target components will produce a different Doppler shift, allowing the radar to produce a Seaspot image.

In Seaspot mode the radar will always have range resolution because of the pulse bandwidth. However, the cross-range resolution is highly dependent on the imaging geometry and the motion of the target. Figure 9 illustrates the three main imaging geometries. Each subfigure shows the main ship motion responsible for producing the cross-range resolution and a typical Seaspot image plot under this geometry. Figure 9a shows that when the radar is aligned with the long axis of the vessel, pitch motion produces a profile view of the vessel; i.e., as if you were looking at the side of the ship. Figure 9b shows that when the radar is aimed at the side of the vessel, the roll motion produces a front view of the vessel; i.e., as if you were looking at the front of the ship. Figure 9c shows that when the radar is aligned with the long axis of the vessel, the yaw motion produces a plan view of the vessel; i.e., as if you were looking down on the ship from above.



(a)

(b)

(c)

Figure 9: *Seaspot Imaging geometries. 9a) Profile view. 9b) Front view. 9c) Plan view.*

In reality, a ship will have an unknown combination of all three types of motion and the resulting Seaspot image will be a combination of the three types of corresponding images. We see from Figure 9b that when the radar is aimed at the side of the ship the resulting imagery does not produce a great deal of useful information. To obtain the best Seaspot imagery, the operator should strive to have the Line of Sight (LOS) of the radar aligned to the long axis of the ship or as close as circumstances allow. Since the radar always has range resolution, aligning the radar in this manner will maximize the chances of acquiring Seaspot imagery which is similar to that shown in Figure 9a and Figure 9c.

The integration time selected by the operator should correspond to the time during which the target is experiencing a constant rate of rotation, i.e., not accelerating. Unfortunately, this is not normally known by the operator beforehand and there is no practical way of predicting the motion of a ship at sea. Therefore, the operator must use trial and error and be guided by their own operational experience to select an appropriate integration time. To achieve finer cross-range resolution, longer integration times need to be used. However, when a longer integration time is selected it becomes more likely that the target will undergo some rotational acceleration which produces smearing in the resulting Seaspot image. Figure 10 shows a Seaspot image with a 1 second integration period. The figure has resolution in the range direction, but the cross-range resolution is relatively coarse. Figure 11 shows the same ship, but processed with a 2 second integration period. The corresponding increase in cross-range resolution is readily apparent.

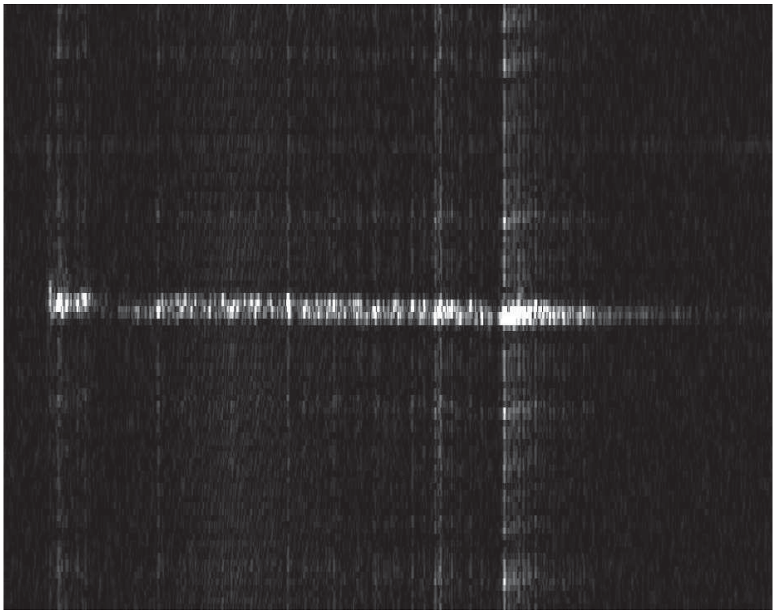


Figure 10: *Seaspot image with 1 second integration.*

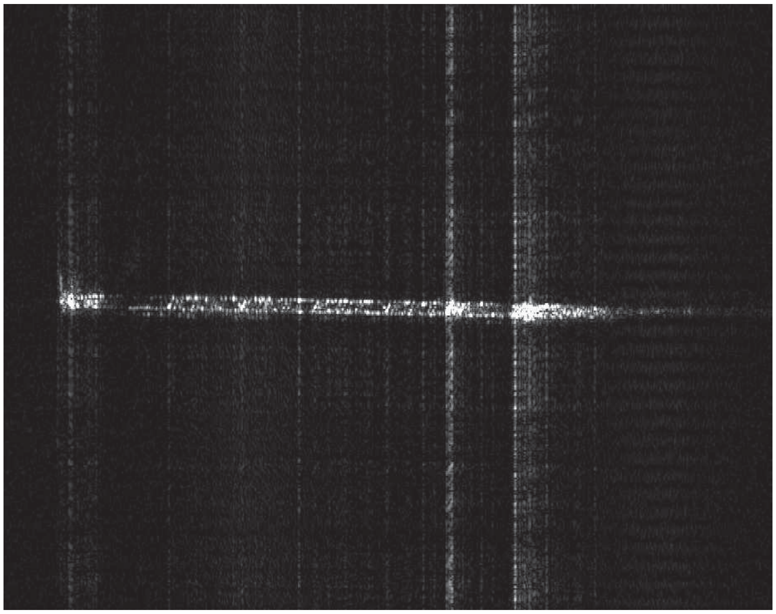


Figure 11: *Seaspot image with 2 second integration.*

Another option in Seaspot processing is to overlap the integration times. Using a large overlap increases the likelihood of capturing the ship motion at a point where there is no radial acceleration, but comes at the cost of requiring more processing power.

There are also Seaspot processing modes onboard the aircraft which use adaptive algorithms to optimize the time window of the data to produce the Seaspot image. These modes may result in higher quality images and can lead to improved target classification and intelligence information. To engage the aperture optimization processing on the CP-140, the operator must select the “High-Order” option from the Seaspot mode parameters and then select the “Aperture Optimization” parameter. The aperture optimization can be used in both the Seaspot and Seaspot Dynamic modes.

3 Possibilities for post-processing

The CP-140 has two systems for replaying and processing data: the Ground Replay and Processing Facility (GRPF) and the Deployable Ground Replay and Processing Facility (DGRPF). These systems allow more advanced processing of the SAR data such as: overlaying map data, overlaying digital elevation maps (DEMs), support for Coherent Change Detection (CCD)[2], and exporting imagery in standard formats, e.g., National Imagery Transmission Format (NITF).

If the raw radar data is recorded during the data acquisition, then it is possible to reprocess the data to extract or enhance areas or targets of interest. In Spotlight mode it is possible to increase the cross-range resolution by selecting longer integration times. The resulting image pixels will have a different aspect ratio because the range resolution cannot be increased to match the cross-range resolution. Another possibility in Spotlight mode is to change the frame overlap. Increasing the overlap causes the frames to appear more quickly and it may be possible to detect transient events.

Seaspot data can also be reprocessed. Similar to Spotlight mode the length of the integration time can be changed to attempt to provide the best resolution. The overlap between the image frames can also be increased so that there is an increased chance of finding the optimum time interval for imaging the target. There are also automated algorithms which attempt to find the optimum time interval for imaging. These algorithms attempt to optimize criteria such as maximizing image contrast or minimizing image entropy. The offline algorithms for reprocessing Seaspot data may also have more sophisticated tracking algorithms because there is more available computational horsepower, and there is no real-time processing constraint as is the case for the airborne processor.

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[2] The CCD capability is currently under development.

4 National Image Interpretability Rating Scale (NIIRS)

The National Image Interpretability Rating Scale (NIIRS) is a rating scale based on the usefulness of the imagery for conducting certain types of tasks. NIIRS is meant to be sensor agnostic. It applies to images coming from a variety of sensors; e.g., optical, electro-optical / infrared (EO/IR), and Radar. The NIIRS rating assigns the image a number ranging from 0 to 9, and can be specified to 1/10th of a level. Level 9 indicates the highest information content and level 0 indicates there is no information content. While the NIIRS criteria takes into account the resolution of the image (ground sampled distance), it is important to note that other factors may degrade the NIIRS rating. As an example, if a SAR system is capable of generating 0.15 m resolution, it would seem to indicate a NIIRS rating of 8. However, the image may be degraded by other factors; e.g., imaging geometry, phase errors, or uncompensated platform motion or interference which may result in a much lower rating. It should be noted that the rating is also somewhat subjective. Experienced radar image analysts often give an image a higher rating than analysts with less experience. Table 2 summarizes the NIIRS system based on the ground sample distance (GSD) and the Task type. Further information on NIIRS can be found in [3].

In an attempt to automate the NIIRS rating and aid in the development of imaging systems with specific NIIRS capabilities, researchers have developed the General Image-Quality Equation (GIQE). The GIQE attempts to derive the NIIRS value of an image based on measured quantities such as Signal to Noise Ratio (SNR), Ground Sample Distance (GSD) and others. The GIQE was originally developed for optical based imagery; work is ongoing for the development of a standard version for radar imagery. Further information on the GIQE can be found in [4, 5].

Table 2: *NIIRS Rating Scale.*

Rating	GSD	Task
0	N/A	Image unusable due to hardware failure or interference.
1	>9 m	Detect a large cleared swath in a densely wooded area. Detect lines of transportation (either road or rail), but do not distinguish between them.
2	4.5 - 9 m	Detect the presence of large bombers or transports. Detect a military installation by building pattern and site configuration. Identify athletic stadiums.
3	2.5 - 4.5 m	Detect medium-sized aircraft. Detect vehicle revetments at a ground forces facility. Identify a medium-sized railroad classification yard.
4	1.2 - 4.5 m	Distinguish between large rotary-wing and medium fixed-wing aircraft. Detect individual vehicles in a row at a known motor pool. Detect all rail/road bridges.
5	0.75 - 1.2 m	Count all medium helicopters. Distinguish between river crossing equipment and medium/ heavy armored vehicles by size and shape. Count railcars by detecting the breaks between them.
6	0.4 - 0.75 m	Distinguish between variable and fixed-wing fighter aircraft. Distinguish between small support vehicles and tanks.
7	0.2 - 0.4 m	Identify small fighter aircraft by type. Detect road/street lamps in an urban residential area or military complex.
8	0.1 - 0.2 m	Distinguish the fuselage difference between similar aircraft. Identify the dome/vent pattern on rail tank cars.
9	< 0.1 m	Detect major modifications to large aircraft (e.g., fairings, pods, winglets). Identify trucks as cab-over-engine or engine-in-front.

References

[1] Stimson, G. W. (1998), Introduction to Airborne Radar, Second ed, Scitech Publishing.

[2] Lacomme, P., Hardange, J., Marchais, J., and Normant, E. (2001), Air and Spaceborne Radar Systems: An Introduction, William Andrew Publishing.

[3] Federation of American Scientists: National Image Interpretability Rating Scales (online), `http://www.fas.org/irp/imint/niirs.htm` (Access Date: June 1, 2016).

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[5] Nolan, A. R., Goleya, G. S., and Bakichb, M. (2012), Performance Estimation of SAR imagery using NIIRS techniques, In *Proc. SPIE 8394, Algorithms for Synthetic Aperture Radar Imagery XIX.*

5 List of Symbols / Acronyms

AIMP	Aurora Incremental Modernization Project
CCD	Coherent Change Detection
DEM	Digital Elevation Map
D-GRPF	Deployable Ground Replay and Processing Facility
DRDC	Defence Research and Development Canada
EO/IR	Electro-Optical / Infrared
GIQE	General Image-Quality Equation
GPS	Global Positioning System
GRPF	Ground Replay and Processing Facility
GSD	Ground Sample Distance
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LOS	Line of Sight
NIIRS	National Image Interpretation Rating Scale
NITF	National Imagery Transmission Format
PRF	Pulse Repetition Frequency (Hz)
PRI	Pulse Repetition Interval (Secs.)
SAR	Synthetic Aperture Radar
SNR	Signal to Noise Ratio

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The Build 3 delivery of the Aurora Incremental Modernization Project provides increased radar capabilities to the sensor suite of the Aurora. The operational community contacted Defence Research and Development Canada (DRDC) to provide additional details on Synthetic Aperture Radar (SAR) imaging. This document provides an overview of: SAR technology, operating modes, imaging phenomenology, and prefer-red imaging geometries. The material is presented at a readily accessible level with minimal use of mathematics.

La livraison de la version 3 du Projet de modernisation progressive de l'Aurora offre des capacités radar améliorées à la suite de capteurs de l'Aurora. Le milieu opérationnel a communiqué avec Recherche et développement pour la défense Canada (RDDC) pour fournir des détails supplémentaires au sujet de l'imagerie du radar à synthèse d'ouverture (SAR). Le présent document donne un aperçu des aspects suivants : technologie SAR, modes d'exploitation, phénoménologie de l'imagerie et géométries d'imagerie privilégiées. Le matériel est présenté à un niveau facilement accessible avec un minimum de données mathématiques.

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Synthetic Aperture Radar