This book covers all aspects of foliage penetration (FOPEN) radar for both airborne military systems and earth resource mapping. It is the first book to be published on the subject.

Readers will learn the characteristics of clutter, foliage scattering, and propagation that affect the detection and characterization of vehicles, buildings, and terrain features that are present under trees.

**Military radar systems engineers** will find methods for using ultrawideband waveform design and analysis for generating signals that will not interfere with emergency or flight safety frequencies, as well as adaptive processing techniques to reconstruct signals in a dense frequency interference environment.

**Earth resource and remote monitoring planners** will use this foundational reference for years to come as they apply this technology for crop monitoring, land mine remediation, creating digital maps under trees, and many other uses of FOPEN radar that will benefit mankind.

**KEY TECHNIQUES AND TECHNOLOGIES**

- Ultrawideband waveform design and analysis.
- Characteristics of clutter, foliage scattering, and propagation.
- Polarization for reduction of false alarms and characterizing vehicles under trees.
- Generation of digital elevation maps for "bare earth" under trees.
- Image formation processing, emphasizing real time high performance processing, change detection, and automatic target detection and classification.
- Simultaneous SAR and GMTI operation.
- Bistatic SAR utilizing a FOPEN GMTI radar’s waveform.

**ABOUT THE AUTHOR**

Dr. Mark E. Davis has over 40 years experience in radar technology and systems development. He has held senior management positions in the Defense Advanced Research Projects Agency (DARPA), the Air Force Research Laboratory, and General Electric Aerospace. At DARPA, he was the government program manager on both the foliage penetration radar advanced development program and the GeoSAR foliage penetration mapping radar. He is a Fellow of both the IEEE and Military Sensing Symposia. Dr. Davis has published well over 100 papers in journals and proceedings.

Raleigh, North Carolina

www.scitechpub.com
Foliage Penetration Radar
Foliage Penetration Radar
Detection and Characterization of Objects Under Trees

Mark E. Davis
Dedicated to my late father,

Capt. Jack E. Davis, USN
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The story of foliage penetration RADAR has had many authors over its almost half century of development. This attempt at reconstructing the early developments owes a great debt to Mr James Rodems, formerly of Syracuse University Research Corporation who lead the research, development and early deployment of one of the two systems in the 1960s. The majority of the material in Chapter 1 came from his archives and personal descriptions of the motivation and trials that led to both ground based and airborne testbed.

There were many pioneers in the second phase of FOPEN development during the late 1980s to mid 1990s. But without the continuous support and technical leadership of Dr Serpil Ayasli of MIT Lincoln Laboratory, the breadth of innovation in phenomenology, waveforms, and image understanding would not have matured into today’s solid foundation of science. Two testbeds were developed as independent efforts, each under a strong leader: Stanford Research Institute’s FOLPEN under Roger Vickers, and Swedish Defence Research Establishment’s CARABAS under Hans Hellsten. Several other testbeds were constructed during this period to provide complementary geoscience or military research objectives. Each of the airborne testbeds that collected and refined the ultra wide band synthetic aperture RADAR signals is covered in Chapter 2. They were conceived to implement an important set of innovations, leading to understanding of the importance of frequency choice, polarization, radio frequency interference removal, and target and clutter characterization for efficient detection of objects under dense forests. Much of this development and test was funded by the Defense Advanced Research Projects Agency under the program management of a sequence of leaders that included Dom Giglio (1988–1995), Mark Davis (1995–1998) and Lee Moyer (1999–2005).

Modern foliage penetration RADAR continues to advance with the continuous improvement in high speed digital signal processing. The single most impediment to its general use is the proliferation of personal and wideband communications into the radio frequency spectrum. Frequency spectrum allocation and protection of specific frequencies for safety of life and emergency
communications requires careful attention to the choice of waveform. It will continue to be important to develop cognitive processing to avoid interference to or from other users of this spectrum.

The author would like to acknowledge all of the pioneers who preceded and succeeded his involvement in foliage penetration radar development. The past 15 years has been a very enjoyable journey into the scientific and geopolitical evolution of ultra wideband radar. He would also like to thank his parents, Jack and Mary Lou Davis for encouraging his scientific development. And most importantly he would like to thank his wife Diane Rogers Davis, and two sons Colin and Shelby for the patience and encouragement in a long journey into RADAR development, test and operation.

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March 2011
Both the military and scientific imaging communities learned from the early foliage penetration (FOPEN) developmental RADAR systems operated in the late-1960 to mid-1970 time frame. Two important system realities affected the growth of the technology: (1) foliage attenuation limited the systems to short-to-medium-range operation; and (2) manned aircraft could not be adequately protected at these ranges. Remotely piloted vehicles (RPV; also known as unmanned air systems, or UAS, in today’s vocabulary) were just starting to be developed. They would address the ability to collect data in hospitable environments. More importantly, the development of wideband data links would enable significant processing and image interpretation on the ground.

By the late 1980s, the image collection community had determined that SAR could provide acceptable and useful detection and characterization of forested regions. These SAR systems required small antennas and modest power; which was acceptable for experiments and might be possible on RPV installations. In 1988, the NASA Jet Propulsion Laboratory started the AIR-SAR program and flew a multiple-frequency SAR platform until 2004 [1]. At approximately the same time, several research groups started experimental FOPEN SAR systems, notably Stanford Research Institute (SRI) [2] and Sweden’s Defence Research Agency (FOA) [3].

Airborne ground-moving target indication (GMTI) FOPEN RADAR systems were significantly more difficult to implement, especially on airborne moving platforms. The size of the antenna for both detection and localization of moving targets prohibited installation on a fixed-wing aircraft. As presented in Section 1.1, the X-band SOTAS development verified the benefit of stationary rotary wing operation for GMTI RADAR. But the size of the antenna at UHF and the lack of unmanned helicopters would not give rise to airborne FOPEN GMTI RADAR for more than 2 decades, when the
FOPEN reconnaissance, surveillance, tracking, and engagement RADAR (FORESTER) system would be developed for the remotely piloted A-160 Hummingbird [4].

With the advances in critical RADAR technologies of wideband waveform generation and digital image formation, the community could start the task of understanding the capabilities and limitations of FOPEN SAR. SAR systems were just starting to gain acceptance in the surveillance community, which had relied on high-resolution optical pictures for decades. Figure 2–1 presents the motivation for the need for tactical FOPEN SAR and an advanced look at what it will provide the operational user—whether it is the military or commercial customer of the image products [5]. All four panes in the figure are of the same scene; a forested region with several vehicles parked under the foliage and in the tree lines, but collected with different imaging technologies. On the left is a moderate to high-resolution optical picture, but the vehicles cannot be observed until the sensor is nadir looking.

The next image to the right is a typical 1 meter resolution X-band image of the scene taken on the same day. Sporadic detections were obtained, but only when the glint of targets could be captured in the image. Neither of these two image products would satisfy the user, especially when high area coverage rate is needed. The next two images to the right, which are UHF and VHF SAR images, show a more optimistic ability to detect the fixed targets. The UHF

![FIGURE 2–1](image)

Comparison of optical and several RADAR image sources

*Source: MIT Lincoln Laboratory [5]*
panel shows images of many of the man-made targets but high false alarms with the foliage clutter in the scene. The detection at VHF is higher where the foliage attenuation is significantly lower and the target cross sections are larger than the clutter. However, there is limited resolution (i.e., pixels on target) to characterize the objects in the image.

This realization of reliable imaging capabilities for FOPEN SAR was important. It started a 5-year campaign to recharacterize the foliage clutter so that better SAR system engineering could be made possible. It was also realized at that time that a better understanding of the foliage scattering phenomenology would derive civilian uses for the systems. There was a definite dual-use message in the development objectives in the early 1990s.

Every new FOPEN RADAR system developed needed to answer the question of “why VHF or UHF?” This question is easy to answer. Optical photographs and microwave RADARs cannot reliably detect man-made objects that have been hidden in the dense forest cover. Two emerging technologies were being developed that could reduce the unreliable detection of targets under foliage. The first technology was ultra wideband (UWB) waveforms that would enable high-resolution SAR images at both VHF and UHF frequencies. The second technology was use of polarization of the RADAR signal in the FOPEN SAR processing.

High-resolution imagery serves two purposes: (1) provide a better separation of the object scattering from the background clutter; and (2) provide more detail of scattering of objects for characterization. In applications for foliage or terrain characterization, this factor is not as strong a motivation. However, to find a small vehicle or a buried land mine, image resolution is a major consideration.

Polarization diversity has been evolving as a significant capability for both target detection and characterization of terrain and man-made objects. If characterization is an important system objective, then polarization must be factored into the system waveform and processing approach from the start.

The system engineering task was for not only the FOPEN SAR design but also the concept of operations (CONOPS), as illustrated in Figure 2–2. The relevant questions were how much of the system:

- Could be installed on either a small manned or unmanned vehicle?
- Could be processed in real time and onboard the UAS?
- Needed motion measurement and compensation for collection geometries?

The global positioning system (GPS) was not generally available at that time; so inertial measurement and guidance systems were stressed for the long data runs while obtaining a strip map. Tactical data links did not have the bandwidth
Foliage Penetration SAR Collection Systems

FIGURE 2–2
Future requirements for FOPEN RADARs on data link control

to send down all of the data for image processing on the ground, and the ground stations needed to be close to the flight path for real-time operation.

These initiatives and several other military and space science programs were addressing significant CONOPs issues. However, the first task was to gain a significant assessment of the foliage characteristics—scattering and losses. This would enable sizing the RADAR systems and computers that could be built. But remember we had the GPS coming into reality and Moore’s Law in our favor. The first addressed the motion measurement and navigation problem that plagued real-time SAR systems. The latter gave the potential for higher processing through put on small vehicles. So there was soon to be a rebirth of foliage penetration RADAR—albeit focused on SAR systems and not GMTI RADAR.

The first FOPEN SAR system (SADFRAD), summarized in Chapter 1, exploited the coherence of man-made objects when illuminated with dual frequencies. However, the HF did not provide adequate resolution on the objects to characterize the type. It was important to push FOPEN SAR into higher frequencies to improve the range and cross-range resolution.
Both applications provided strong existence proof of the utility of VHF and UHF propagation through forests and the detection mechanism. However, the development of efficient signal processors and the ability to counter the effects of moving clutter and radio frequency interference (RFI) needed significant development. These capabilities were more than a decade in the future.

This chapter will give details on early FOPEN SAR data collection systems built for both civilian and military experimental evaluation. We will first revisit the merits of VHF and UHF for foliage penetration operation. Both are effective for part of the detection and characterization of foliage and of man-made objects under foliage. Understanding the relative merits was important in choice of frequency, bandwidth, and polarization for the several prototype systems.

**SAR Resolution**

Synthetic aperture RADAR (SAR) obtains fine resolution for ground images through two effects. The range resolution $\delta_R$, similar to conventional RADARs, is obtained primarily by the bandwidth of the waveform $B$. Cross-range resolution is obtained by a physical antenna angular pattern and the ability to coarsely resolve objects within the real beam. However, for fine cross-range resolution, it is necessary to form a synthetic aperture length by flying a length $L$ and coherently integrating the returns to obtain the resolution $\delta_{CR}$. This is especially true for imaging from VHF and UHF RADARs, where real beam apertures with any reasonable angular pattern would be impractical on airborne platforms. This section will treat the basic factors for obtaining resolution in range and cross-range with a SAR system. The extension to an UWB SAR will be developed in more detail in Chapter 3 for UWB phenomenology and in Chapter 4 for UWB SAR image formation.

The range resolution $\delta_R$ of a pulse in the slant plane is directly related to the bandwidth of the RADAR and any weighting to reduce the range sidelobe levels by [6]

$$\delta_R = \frac{k_R c}{2B \cos \gamma_g}$$

(2.1)

where:
- $c$ Speed of light;
- $B$ Bandwidth of the waveform;
- $k_R$ Range broadening factor due to aperture weighting;
- $\gamma_g$ Grazing angle with respect to the local terrain.

Normally, a SAR system will illuminate the ground at small grazing angles, and the range resolution is determined primarily by the waveform bandwidth.
However, for foliage penetration RADAR higher grazing angles is important for providing less foliage loss and better signal-to-clutter ratio. So at higher grazing angles the target signal return has the potential to be enhanced relative to the background clutter but with a reduction in ground plane range resolution. Figure 2–3 illustrates the ground plane resolution for VHF and UHF waveforms as a function of bandwidth and grazing angle.

Figure 2–3 illustrates the importance of bandwidth when compared with the carrier frequency as well as the importance to range resolution. For resolutions under a meter, the required bandwidth is above 150 MHz, independent of any range sidelobe weighting. Since the FOPEN SAR must operate at center frequencies comparable to the signal bandwidth, it was necessary to consider the impact of fractional bandwidth on the system design to achieve fine-range resolution.

The bandwidth of the signal waveform extends from the low-frequency component \( f_L \) to the high frequency \( f_H \). If a uniform distribution of the signal spectral density is assumed, the bandwidth \( B \) is the difference between \( f_H \) and \( f_L \). This spectral density is determined by the transmit waveform generation and any spectral effects that are provided by the antenna system dispersion. The fractional bandwidth \( \Delta B \) of the system is calculated by the ratio of the bandwidth \( B \) to the center frequency

\[
\Delta B = \frac{2(f_H - f_L)}{(f_H + f_L)} \quad (2.2)
\]
The IEEE convention is that a system is considered to be UWB if the fractional bandwidth $\Delta B$ is greater than 25% [7]. For most systems in the VHF and UHF RADAR bands, this fractional bandwidth is significantly above 25%, as shown in Figure 2–4. It is also apparent that almost all cases of bandwidth and center frequency for FOPEN SAR exceed the definition of ultra wideband. A UWB system affects all aspects of the RADAR design (waveform, antenna, signal processing, and phenomenology), as will be shown in Chapter 4. This creates a technical challenge that needed to be addressed in developing FOPEN SAR capabilities. But just as important was the impact of the system characterization as UWB, which restricts where and when the system can be operated. Any operational system must be in compliance with the National Telecommunications and Information Administration (NTIA) in the United States and its counterpart in most of the world. A UWB RADAR needs to operate outside of the conventional RADAR bands, which has caused a significant political challenge. Chapter 5 will address the design complications to meet this requirement for frequency allocation.

The advantage of SAR systems is the improved cross-range resolution over that of a real-beam antenna obtained by flying a long synthetic aperture as shown in Figure 2–5. The cross-range resolution $\delta_{CR}$ for a broadside SAR operation and integration through an angle of $\theta_I$ is given by [6]

$$\delta_{CR} = \frac{k_{CR}\lambda_c}{4 \sin(\theta_I/2)}$$

(2.3)
where:

- $k_{CR}$: Cross-range broadening factor due to aperture weighting;
- $\lambda_c$: Wavelength of the RADAR’s center frequency;
- $\theta_I$: Azimuthal integration angle during SAR image formation.

For VHF and UHF frequencies, the angles needed to get significant resolution are very large. As a result, both the fractional bandwidth and the integration angle are UWB compared with conventional microwave frequency SAR systems. The achievable cross-range resolution as a function of the frequency and integration angles is detailed in Figure 2–6. For VHF it is necessary to have...
an integration angle over 45 degrees to obtain better than 5 meters of cross-range resolution. An integration angle this large posed a major development in system requirements for the integration times, motion measurement, and motion compensation, as well as achieving the comparable range resolution.

The FOPEN SAR data collection systems built in the 1990s had to factor these issues into many aspects of the RADAR design. The remaining parts of this chapter will summarize the differences in design chosen by the airborne RADARs used to demonstrate the capabilities for detecting man-made objects under dense foliage and buried in shallow ground.

2.2 FOPEN SAR Systems

The early FOPEN SAR systems were developed for detecting and characterizing objects under both foliage and through ground penetration. The latter capability was important, as demining operations were required after military actions in war-torn areas. In addition, for finding objects that have been hidden, the systems’ long wavelengths and polarimetric sensing found usefulness in characterizing land use, land cover, and terrain elevation in many geographic areas.

Significant progress was made in the design of antennas and transmitters for FOPEN SAR. The antennas needed to have wide azimuth coverage to enable the requisite illumination angle for achieving the desired cross-range resolution. They also needed to have an efficient match to the transmit waveform over a very large bandwidth to support the range resolution. As will be shown in the following two chapters, polarization has found an important place in FOPEN SAR for characterization of the clutter and objects. Providing UWB polarimetric antennas was an early challenge. The design of the transmit waveform and match to the antenna was also important to limit the spectral transmission as controlled by the need for frequency allocation constraints. These early systems addressed the technical obstacles that were important in the design and use of operational FOPEN SAR systems.

Several early FOPEN SAR systems were developed and flown in the early 1990s. They represent significantly different approaches for image formation processing, the details of which will be presented in Chapter 4. They also provided extensive data on the characterization of both the clutter and the detection of objects under and near the clutter. The five RADARs illustrated in the following sections present a wide variation in frequency, waveform design, image processing, and the use of polarization. Four of the systems have been installed on fixed wing aircraft, which vary widely in size and speed. Two were multiengine planes that allowed onboard signal processing and real-time observation of the data during flight, and two were flown on small
Table 2–1 Comparison of technology from FOPEN SAR experimental systems

<table>
<thead>
<tr>
<th>Waveform</th>
<th>FOLPEN II</th>
<th>Carabas II</th>
<th>P3 UWB</th>
<th>GeoSAR</th>
<th>BoomSAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>Impulse</td>
<td>Freq Jump</td>
<td>Notched LFM</td>
<td>Notched LFM</td>
<td>Impulse</td>
</tr>
<tr>
<td>200–400</td>
<td>20–80</td>
<td>225–740</td>
<td>280–460</td>
<td>50–1100</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>HH</td>
<td>HH</td>
<td>HH, HV, VV</td>
<td>HH, HV or VV</td>
<td>Full Pol</td>
</tr>
<tr>
<td>Transmit RFI</td>
<td>N/A</td>
<td>Freq Notch</td>
<td>Notch</td>
<td>Notch</td>
<td>N/A</td>
</tr>
<tr>
<td>Image Formation</td>
<td>Back Projection</td>
<td>Back Projection</td>
<td>RMA</td>
<td>INSAR</td>
<td>Back Projection</td>
</tr>
</tbody>
</table>

tactical aircraft with onboard data recording and subsequent image formation processing and analysis after the flight.

Much had to be learned to refine the eventual design objective of installation on unmanned air vehicles for operation over remote, and often hostile, environments. The fifth RADAR system to be examined was an instrumentation RADAR installed on a computer controlled “cart” that would provide performance verification of target characterization by allowing high dynamic range collection of both foliage and ground penetration data.

Each of these experimental FOPEN SAR systems embodied a new technology that had the potential for enabling operational system design. Table 2–1 summarizes the critical technologies employed in the design and development of each of the systems. The critical RADAR designs and applications, along with the sections that cover their design, include:

- **Impulse waveform**: (Sections 2.2.4 and 4.2) A very narrow pulse that has wide spectral content
- **Frequency jump burst (FJB)**: (Section 5.1.2) A waveform that covers the required bandwidth by incremental transmission of narrowband pulses, combined with coherent reconstruction
- **Notched linear frequency modulation (LFM)**: (Section 5.1.3) Use of an LFM waveform over a wide bandwidth, with narrow regions of exclusion of critical frequencies
- **Polarization**: (Sections 3.4 and 6.1.1) Transmitting one linear polarization and receiving one or more polarizations. The first letter is the transmit polarization, and the second is the receive polarization (e.g., HV is transmit horizontal and receive vertical)
- **Back projection algorithm (BPA)**: (Section 4.3.1) An image formation process that directly, coherently adds the contribution of each pulse to the
appropriate image resolution cell, after appropriate motion compensation for the imaging platform position and orientation.

- **Range migration algorithm (RMA):** (Section 4.3.2) The image formation process that uses a two-dimensional mapping of range and Doppler curvature during the imaging process to provide efficient image formation processing

- **Interferometric SAR (InSAR):** (Sections 2.2.3 and 8.4) The technique of forming two SAR images, displaced by a distance to enhance differences in either the terrain height or surface target motion for image processing

Details of these technologies and their experimental results for clutter and target characterization will be covered in subsequent chapters. Significant publication of the design details and results occurred in that decade. As a result, the lessons have been shared and formed the designs of more recent systems for the next decade. Several SAR data collections provided comparison on the same terrain and objects. These collections will be covered in Chapter 3 along with the characterization of foliage clutter and attenuation. One of those collections included both an X-band and a UWB UHF collection over Camp Roberts in California to evaluate both foliage penetration and digital elevation model (DEM) generation. The image is of a small segment of the wooded area shown in Figure 2–7.

**FIGURE 2–7**
Comparison of X-band and UHF SAR images—forested hide position [5]
The first image, Figure 2–7a, is an X-band SAR made by the ERIM IFSARE system to provide high area coverage rate DEM with fine elevation accuracy [8]. This image was collected on the same day that several military vehicles were been placed under the foliage area known as “Sherwood Forest.” It is apparent that only the tops of the trees are visible in the X-band image.

The second image, shown in Figure 2–7b, was collected with the UWB P-3 FOPEN SAR, also built by ERIM [9]. The three tactical targets under the foliage were revealed only in the UHF image and at horizontal polarization. However, it is clear that false alarm rates would be very high if only the horizontal polarization image were to be used. It should be noted that the strong return in the foreground was from one of the instrumentation trihedrals deployed to calibrate the multiple polarization sensitivity.

This comparison of X-band and UHF SAR provides sufficient evidence to many operational users of the importance of UWB SAR at VHF or UHF for detecting man-made objects under foliage. However, it was as important to quantify the performance with available technology prior to development of an operational system. The next five sections provide the quantitative performance of the experimental FOPEN SAR systems employed from 1990 to 1998 to obtain support for these important system developments.

2.2.1 SRI’s FOLPEN RADARs

One of the first FOPEN SAR systems to be built was the FOLPEN series that was developed by SRI. The FOLPEN II and FOLPEN III systems, shown in Figure 2–8, were both based on a very high peak voltage impulse transmitter. This was an effective source of UWB RADAR signal, whose spectral...
characteristics were determined by the impulse shape and the interface to the antenna assembly. Because the pulses were only a few nanoseconds in length, the average power of this RADAR was very limited.

FOLPEN II was used in early trials for foliage characterization and for demonstrating land mine remediation [2]. The short-range operation was not an issue. As the need for wide area coverage and target discrimination evolved, SRI developed a two-channel polarimetric system (FOLPEN III) that would alternate horizontal and vertical polarization transmissions [10].

The earlier FOLPEN II system was limited to 200 MHz bandwidth, or nominally 1 meter resolution, due to the limited match between the impulse transmitter and the multiple dipole antennas under the wing of the aircraft. The later FOLPEN III system was improved to 0.5 meter resolution, with the closer coupling of the transmitter to the multiple polarization ridge waveguide antenna.

SRI pioneered using the BPA for image formation processing. By combining the aircraft navigation measurement with a differential GPS, they were able to form moderately wide swath images with very good image quality. The later operation of FOLPEN III also included a real-time image formation processor followed by a target detection system [11]. Characteristics of the FOLPEN RADARs are summarized in Table 2-2.

The FOLPEN II RADAR participated in the 1993 Maine collection campaign. The collection scenario included several trucks in a narrow forest road to determine both the clutter characteristics and the ability to detect and characterize man-made objects. The SRI RADAR provided high-quality SAR images as indicated in the figure, found on the SRI Web site. These clutter data were analyzed by MIT Lincoln Laboratory and are included in the clutter scattering and loss characteristics shown in Section 3.3.

### Table 2-2 Characteristics of FOLPEN RADAR © 2002 IEEE [11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
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<tbody>
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<td>Altitude [Km]</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity [m/s]</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>200</td>
<td>400</td>
<td></td>
<td></td>
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<tr>
<td>Bandwidth [MHz]</td>
<td>200</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna Type</td>
<td>Array Dipole (II)</td>
<td>Crossed Dipoles (III)</td>
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<td>HH, VV, HV (III)</td>
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<tr>
<td>Waveform</td>
<td>Impulse</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Peak Voltage [Mvolt]</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Width [μsec]</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>Range [m]</td>
<td>1.0 (II),</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Resolution [m]</td>
<td>0.5 (III)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cross Range [m]</td>
<td>1.0 (II),</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Resolution [m]</td>
<td>0.5 (III)</td>
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<td>Slant Range [Km]</td>
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<td>Swath Width [Km]</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Developed</td>
<td>SRI</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The major target detection advance at that time was the use of several image processing techniques to discriminate man-made objects from background clutter, as illustrated in Figure 2–9 [12]. The panel titled “nominated targets” illustrates the results of applying several spatial filters to the horizontally polarized data. In fact this is the first known published receiver operating characteristics (ROC) curve on FOPEN target detection. As indicated, the raw constant false alarm rate technique yields false alarm density of over 10 per square kilometer at the 80% detection probability. Many users would consider this level of false alarms excessive. SRI applied two techniques to the data: multipixel phase filtering and a subaperture phase filtering to the data. Both techniques reduced the false alarm density significantly below 1 per square kilometer. The subaperture technique achieved better than 1 false alarm in 10 square kilometers by exploiting the cardinal flash of the large vehicles. These results were encouraging for future development in automatic target detection and characterization performance.

Figure 2–10 illustrates the location and types of targets along the road. This ground truth was used to score the detection probability at several thresholds depending on the false alarm density. This ROC technique is a measure of the effectiveness of image processing technique for detecting targets and
2.2 FOPEN SAR Systems

FIGURE 2–10
FOPEN II receiver operating characteristics from maine collection [12]

discriminating from local clutter. The panel titled “nominated targets” illustrates the results of applying several spatial filters to the horizontally polarized FOPEN SAR data. This is the first-known published ROC curve for FOPEN target detection.

2.2.2 Sweden’s CARABAS RADAR

The Swedish National Defence Research Establishment (FOA) developed a unique, low VHF-band FOPEN SAR called coherent all radio band sensing (CARABAS) in the early 1990s. CARABAS used a majority of the short waveband for operation. The motivation for the system development at VHF band is the reduction of speckle, which improves the ability to detect and discriminate man-made targets. When the wavelength is near the Rayleigh limit of the target, the speckle is significantly reduced, and detection is enhanced. Speckle in SAR is reduced by operating over more than an octave bandwidth and with a resolution comparable to the wavelength of the signal [3].

The CARABAS system was flown in two configurations on a Saberliner aircraft, characterized by the two antenna configurations as shown in Figure 2–11. CARABAS I used two inflatable sleeve antennas that trailed the aircraft. This contrasted with the more permanent antenna installation of
CARABAS II, where two composite material antennas were attached to the front of the aircraft [13,14].

Because the antennas are mostly in free space, there would be no natural suppression of the individual pattern backlobes. However, since the two wideband dipoles are placed side by side within a fraction of a wavelength distance, they interact with each other. The resulting backlobe suppression has been measured to be about 10–11 dB in CARABAS-II with true time-delay steering on transmit [13]. The suppression is further increased by digitally combing signals from respective antennas, as shown in Section 7.2.1.2. Measurements have shown that backlobe suppression is improved to 21 dB [16]. The principal system characteristics of the CARABAS SAR system are high power, wide swath width, and efficient detection of targets under foliage, with the principal RADAR characteristics summarized in Table 2–3.

In addition to the unique antenna construction and pattern control, CARABAS-II had several design innovations. By operating in a shared radio band, significant interference sources need to be avoided and excised from the image processing. Therefore, the transmit waveform used a frequency jump

Table 2–3 CARABAS RADAR characteristics [3], [13]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude [Km]</td>
<td>6.0</td>
</tr>
<tr>
<td>Velocity [m/s]</td>
<td>100</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>20–90</td>
</tr>
<tr>
<td>Bandwidth [MHz]</td>
<td>2.5</td>
</tr>
<tr>
<td>Antenna [m]</td>
<td>5.5, Segmented</td>
</tr>
<tr>
<td>Length, Type</td>
<td>Dipole</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH</td>
</tr>
<tr>
<td>Waveform</td>
<td>FJB, N bursts</td>
</tr>
<tr>
<td>Peak Power [Kwatt]</td>
<td>1.0</td>
</tr>
<tr>
<td>Pulse Width [μsec]</td>
<td>0.1</td>
</tr>
<tr>
<td>PRF [KHz]</td>
<td>100/2/N</td>
</tr>
<tr>
<td>ADC [MHz]</td>
<td>2.5, 12 bits</td>
</tr>
<tr>
<td>Range [m]</td>
<td>3.0</td>
</tr>
<tr>
<td>Resolution</td>
<td>Cross Range [m] 3.0</td>
</tr>
<tr>
<td>Resolution</td>
<td>Slant Range [Km] 10–25</td>
</tr>
<tr>
<td>Swath Width [Km]</td>
<td>15</td>
</tr>
<tr>
<td>Developed</td>
<td>FOA Sweden</td>
</tr>
</tbody>
</table>
burst of up to 37 frequencies, with the first center frequency at 21.25 MHz and a 1.875 MHz step to cover the nominal band 20–90 MHz. The sequence and spacing of the frequency steps were maintained between CARABAS-I and CARABAS-II. However, in the later system, notching in the individual steps was used to avoid the radio frequency interference. A wide dynamic range analog-to-digital converter (ADC) provided very good imagery, even in the presence of RFI [17].

The maximum bandwidth of CARABAS II operation was 70 MHz, yielding a 3 meter range resolution. Typically the collection angle was 60 degrees, providing a corresponding 3 meter azimuth resolution. The high peak power provides moderately long-range SAR maps, and use of BPA image formation processing enables wide swath operation. These characteristics of the VHF system design provided for the high area coverage rate of 1 km²/sec [17].

The first flight trials with CARABAS-I were conducted in Sweden during 1992. And CARABAS-I participated in the 1993 Maine FOPEN data collection, where several large vehicles were assembled in the open and under a tree-lined road to determine the effects of foliage on the detection of trucks. The objective of the 1993 collection was to measure clutter return and attenuation for characterizing the foliage phenomena. The quantitative analysis of these factors will be presented in Chapter 3. However, it is illustrative to look at the same geometry and target array with two frequency bands—FOLPEN II at low UHF band and CARABAS I at low VHF band. Figure 2–12 provides

![Comparison of VHF and UHF target detection 1993 maine collection](Image1)

**FIGURE 2–12**
Comparison of VHF and UHF target detection 1993 maine collection  
*Source: MIT Lincoln Laboratory [18]*
a side-by-side comparison of images from the two collection platforms. MIT Lincoln Laboratory carried out independent image formation processing and calibration on recorded data from both platforms based on the respective SAR system characteristics and recorded navigation data. As such this should be a real comparison of the phenomenology at two collection frequencies [18].

The attenuation on the targets in foliage is significantly less in VHF than UHF, as is the clutter return. However, the targets in the low UHF band image exhibit strong scattering characteristics that were considered as discrimination for target characterization. These two points will be presented in Chapter 3 in more quantitative detail.

CARABAS II also participated in the 1997 Keystone collection in Pennsylvania and demonstrated the improvements in performance of the intervening 4 years. The major difference between the two was the change in the antenna to rigid booms and refinement in signal processing. Other noteworthy differences were (1) average power significantly increased (10 dB) by introducing linear frequency modulation in each pulse; (2) Doppler aliasing above 55 MHz eliminated by increasing effective PRF (one side illumination only and fewer frequency steps); and (3) narrowband notching introduced on transmit.

The images shown in Figure 2–13 provide further evidence of the benefit of VHF on target detection in foliage clutter. They are of different geographic locations and a different array of targets; however, both have essentially the

![Carabas I
Maine Collection 1993
Carabas II
Keystone Collection 1997](image)

**FIGURE 2–13**
Comparison of CARABAS I and CARABAS II target detection
*Source: MIT Lincoln Laboratory [18]*
same image resolution. The image on the left was from CARABAS I and illustrates enhanced target cross section and lower clutter in low VHF band. The trucks were easily discerned from the cultural clutter providing good detection probability. In the image on the right, the focus of the foliage returns appears to be sharper than in the earlier collection. In addition, it is clear that the ability to cancel the RFI has been improved. The area in the middle of the scene is a clearing in the trees, and the noise equivalent $\sigma_0$ has been improved by approximately 7 dB. Unfortunately, no quantitative analysis of these observations was carried out.

### 2.2.3 NADC’s P-3 Ultra-Wideband SAR

The Naval Air Development Center (NADC) in Warminster, Pennsylvania, developed a series of multiple bandwidth SAR systems under contract with the Environmental Research Institute of Michigan (ERIM). The last in the series was a UWB UHF SAR system that had full polarization capability [19]. Each of these RADAR test beds was installed on a Navy P-3C aircraft, as shown in Figure 2–14. The size of the platform allowed significant instrumentation and recording for data collection missions. It also had the speed and endurance to collect long data runs at several remote foliage test sites.

Design of the UWB RADAR and development of the ground image formation processor presented a number of challenges caused by the RADAR’s large percent bandwidth and wide synthetic aperture integration angles [20]. Several of the unique designs were in critical hardware subsystems. The characteristics of the P-3 UWB SAR are summarized in Table 2–4.

With an available waveform bandwidth of 515 MHz, it was possible to conduct experiments with 0.33 meter range resolution. However, a unique solid-state high power transmitter was needed to support this larger percentage
bandwidth and high average power. The wide UHF spectrum also presented a new problem, since there are many critical users with sensitive frequencies. To address these issues, chirp waveform modulation techniques were developed to synthesize programmable notches and to avoid interfering with critical users.

The UWB transmitter was a challenge due to the need for matching the output power and impedance to the antenna. The state of the art in solid-state amplifiers was such that the power versus frequency could vary by as much as 8 dB over the band. This affected the UWB SAR waveform in two ways, as illustrated in Figure 2–15: (1) the average power transmitted would be degraded by the low-power components; and (2) the range side lobes of the waveform would be degraded by the amplitude variation over the spectrum.

### Table 2–4

ERIM navy P-3C UWB FOPEN characteristics © 1996 IEEE [20]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude [Km]</td>
<td>7.5</td>
</tr>
<tr>
<td>Velocity [m/s]</td>
<td>135</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>215–730</td>
</tr>
<tr>
<td>Bandwidth [MHz]</td>
<td>515</td>
</tr>
<tr>
<td>Antenna Area, [m²]</td>
<td>1.0</td>
</tr>
<tr>
<td>Type</td>
<td>Flared Notch</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH, VV, HV</td>
</tr>
<tr>
<td>Waveform</td>
<td>LFM, Notched</td>
</tr>
<tr>
<td>Peak Power [Kwatt]</td>
<td>1.0</td>
</tr>
<tr>
<td>Pulse Width [μ sec]</td>
<td>26.3</td>
</tr>
<tr>
<td>PRF [Hz]</td>
<td>500–1200</td>
</tr>
<tr>
<td>ADC [MHz]</td>
<td>30, 6 bits</td>
</tr>
<tr>
<td>Range Resolution [m]</td>
<td>0.33</td>
</tr>
<tr>
<td>Cross Range [m]</td>
<td>0.66</td>
</tr>
<tr>
<td>Waveform</td>
<td>LFM, Notched</td>
</tr>
<tr>
<td>Developed</td>
<td>ERIM</td>
</tr>
</tbody>
</table>

![UWB Transmitter Amplitude Before Correction](image1)

![Predistorted UWB Transmitter Response](image2)

**FIGURE 2–15**

UWB SAR transmitter amplitude response [21]
As a result, a predistortion approach was adopted in an attempt to equalize the power over the band. Figure 2–15 also shows the output power from the transmitter before and after predistortion of the drive power. Because of the improved power spectral density across the 515 MHz bandwidth of the pulse, it was possible to greatly improve the SAR waveform. The measured waveform response after the predistortion technique was applied, in both range and cross-range, is shown in Figure 2–16. The specified peak sidelobe envelope of –30 dB is also indicated in the figure, illustrating the anticipated excellent response of the system [21].

The FOPEN SAR research required full polarization to investigate novel target detection and discrimination techniques. A fully polarimetric antenna with critical size constraints for installation into the P-3 aircraft was developed. The result was a 1 square meter flared notch antenna constructed with temperature and vibration stabilized material to preserve the phase center between each of the polarizations. The constant area antenna provided a beamwidth of 60 degrees at the low end of the band and 18 degrees at the high end of the band. For the 0.66 meter azimuth resolution, this provided 31.7 degrees of integration angle support at the center frequency of 470 MHz [22].

RFI is present from VHF and UHF TV stations, and this inhospitable environment necessitated the development of techniques to remove RFI in the SAR returns while preserving SAR image quality. Since the notched spectrum on transmit is synonymous to a thinned array in the spectral support, the sidelobes in the image response will be degraded. These notches need to be compensated in the range compression filter to obtain adequate image quality. The techniques developed for the P-3 UWB SAR to remove the RFI will be described in Section 5.2.3.
The FOPEN SAR’s low frequency of operation, together with its fine azimuth resolution (wide azimuth beamwidth), required the creation of long synthetic apertures lengths or, equivalently, large integration angles. In turn, these large integration angles lead to severe range migration or differential range curvature of the scatterers during image formation, as presented in Section 4.1. Moreover, scatterers at different locations in an imaged scene experience different levels of range migration. This variation makes selection of the proper image formation algorithm critical. While it is straightforward to compensate range curvature for a given range bin, it is difficult to compensate range curvature for all range bins simultaneously.

A number of algorithms are available for fine-resolution SAR image formation, as detailed in Section 4.2. Two algorithms that are commonly used to minimize the motion of scatterers across the image are the BPA and the RMA. The former is computationally complex, requiring order of $N^3$ operations, where $N$ is the number of pixels in the array. The RMA is unique in that it provides an exact solution to the problem of differential range curvature and has a computational complexity on the order of $N^2\log_2 N$. RMA was selected to provide the most efficient image formation that could be integrated into the long-term objective of a real-time onboard processor [22].

A final problem in low-frequency UWB SAR is the presence of dominant interfering radio frequency signals. These signals originate from a number of sources, the most serious being VHF and UHF television transmitters and cellular telephones. To improve the received image, a simple filtering scheme was employed to remove most of the interference energy prior to image formation. An important image quality metric is the multiplicative noise ratio (MNR), or the ratio of the image intensity in a low return area (e.g., water) to the return from bright clutter, such as the foliage. Many factors contribute to MNR, as will be detailed in Section 7.3.1. However, RFI is a major contributor to the background interference affecting target detection. Without RFI rejection, the MNR was $-9 \text{ dBm}^2/\text{m}^2$, and after RFI rejection it was reduced to $-20 \text{ dBm}^2/\text{m}^2$.

With approximately 1 km swath, moderate areas could be collected at three polarizations to provide significant data for fully polarimetric SAR characterization. The image shown in Figure 2–17, which was one of the early ERIM performance verification tests, demonstrated the ability of multiple polarizations to provide improvements in target discrimination. The image covers a biological field station in Michigan with an array of trees and other cultural objects. The figure includes some ground truth photographs of the instrumentation and the vehicles used for image characterization. It is interesting to note in the image that the large trihedrals, used for calibrating the polarization channels, have persistent sidelobes in the range dimension (horizontal,
with far range to the right in this image). These sidelobes are due to notching out of strong RFI sources, and, although quite persistent, are still over 30 dB down. This prompted additional research into methods of RFI suppression to fill notches in the received spectrum. The low noise equivalent clutter return is also evident in the open areas [22].

The P-3 carried a multiple-channel wideband recording system. All of the data were recorded and calibrated after each flight. Significant advances in waveform generation, image formation processing, and automatic target detection and characterization were made with this instrument from 1995 to 2000.

2.2.4 NASA JPL’s GeoSAR P-Band Interferometric Mapping SAR

GeoSAR is an interferometric mapping SAR development in the late 1990s to enable digital terrain elevation data (DTED) formation and terrain characterization for a “bald earth.” The motivation for the program was a major earthquake in Los Angeles, California, where significant damage was
exacerbated by insufficient knowledge of the terrain characteristics over much of the state. If a single platform could collect terrain elevation and structural characteristics at ground level, it was postulated that the loss of property could be avoided by better procedures for building and land-use planning. The development proceeded under a “dual-use” commercial consortium, where JPL provided the technology, DARPA; and the California Department of Conservation provided the end-user requirements; and EarthData provided the aircraft and commercialization plan for worldwide mapping services. It should be noted that the international geosciences community use the notation of P-band instead of UHF band for the frequency of operation. GeoSAR operates in the middle of the frequencies for FOPEN SAR operation and shares many of the same technical and geopolitical challenges for worldwide operation of an UWB RADAR.

NASA JPL had pioneered interferometric SAR for terrain characterization extensively on its AIRSAR platform [1]. At the same time, the IFSARE system had been collecting accurate DTED measurements over large areas, albeit in open areas or on the tops of trees [8]. JPL provided the interferometric mapping processor for IFSARE, and there was significant application to GeoSAR, along with the need to improve the processing for the UWB imaging and interferometric products. The prospect of having two accurate, cross-track mapping RADARs on the same platform was considered to be a major innovation for terrain height and land characterization. The completed system installed on a Gulfstream II is shown in Figure 2–18.

DARPA funded the effort with NASA Jet Propulsion Laboratory to build the dual-frequency, interferometric SAR (InSAR) system: X-band for open

![FIGURE 2–18](image)

GeoSAR interferometric mapping platform [24]
2.2 FOPEN SAR Systems

Table 2–5  GeoSAR P-band interferometric SAR characteristics © 2001 IEEE [23, 24]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>Km</td>
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</tr>
<tr>
<td>Velocity</td>
<td>m/s</td>
<td>220</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>MHz</td>
<td>350</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>MHz</td>
<td>80, 160</td>
</tr>
<tr>
<td>Antenna Area, Type</td>
<td>m²</td>
<td>0.57, 4-element Array</td>
</tr>
<tr>
<td>Polarization</td>
<td></td>
<td>HH, HV; VV, HV</td>
</tr>
<tr>
<td>Waveform</td>
<td></td>
<td>LFM, Notched</td>
</tr>
<tr>
<td>Peak Power</td>
<td>Kwatt</td>
<td>4.0</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>μsec</td>
<td>40</td>
</tr>
<tr>
<td>PRF</td>
<td>Hz</td>
<td>500, per side</td>
</tr>
<tr>
<td>ADC</td>
<td>MHz</td>
<td>360, 10 bits</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>m</td>
<td>1.0</td>
</tr>
<tr>
<td>Cross Range Resolution</td>
<td>m</td>
<td>1.0</td>
</tr>
<tr>
<td>Slant Range</td>
<td>Km</td>
<td>25</td>
</tr>
<tr>
<td>Swath Width</td>
<td>Km</td>
<td>10–12</td>
</tr>
</tbody>
</table>

terrain DTED, and P-band for DTED below the foliage. The P-band bandwidth of the GeoSAR system, as shown in Table 2–5, would not be as broad as FOPEN SARs used for tactical target detection. However, several innovations in waveform generation, multiple polarization antennas, and signal processing were made. These features provided well-calibrated data for two objectives: DTED under dense forest; and polarimetric characterization of terrain features [23].

The operational objective was to collect four 10 km swaths simultaneously, one at each frequency and one on each side of the aircraft. Efficient image formation, RFI rejection, and DTED formation processing were required for both the civilian and commercial applications for GeoSAR.

The dual-polarization P-band antennas are housed in the wingtip pods as shown in Figure 2–18. Each pod has two antennas, one looking port and one starboard. GeoSAR is a dual-baseline, single-pass system simultaneously collecting both ping-pong and single-antenna transmit interferometric modes. Ping-pong processing is used for improved DTED resolution on relatively flat terrain and in single-antenna transmits processing for rugged terrain. Additionally, the polarization channels on either pod can be used for land use data characterization. Fugro EarthData maintains, modernizes, and enhances the GeoSAR system and continues to provide commercial GeoSAR DTED and land use mapping services worldwide [24].

The use of interferometric SAR had been well developed when GeoSAR was started. The technical challenge was to produce two well-focused images from each antenna, which could be aligned precisely pixel by pixel. Figure 2–19 illustrates the basic geometry used in InSAR processing.
However, this figure has been simplified by omitting the four additional illumination beams to form an interferometric pair, at the two frequencies and on the port and starboard side of the aircraft.

For each InSAR case, two antennas of area $A_1$ and $A_2$ in separate pods illuminate the scene swath. The slant range distance from the phase center of the two antennas to the scene pixel is given by $\rho_1$ and $\rho_2$, as shown in Figure 2–20. When the pixel on the ground has a scattering amplitude of $A_b$ and phase $\varphi_b$, the signal at the two antennae can be measured as $S_1$ and $S_2$ [25]:

\[
S_1 = A_b e^{j\varphi_b} e^{j\frac{4\pi}{\lambda} \rho_1} \\
S_2 = A_b e^{j\varphi_b} e^{j\frac{2\pi}{\lambda} (\rho_1 + \rho_2)}
\]

Equations (2.4) and (2.5)

Based on the accurate knowledge of platform orientation and distance from the image plane, the angle difference between the two signal vectors is used to determine height of the local terrain. Taking $A_1$ as the reference, the interferometric phase to each pixel is given by

\[
\varphi_1 = \frac{2\pi}{\lambda} (\rho_2 - \rho_1)
\]

Equation (2.6)

The digital elevation map is obtained by measuring the phase to each pixel in the two images formed in a single pass. Since the phase is modulo $2\pi$, this phase must be unwrapped to get accurate height information. More importantly, the absolute baseline $D$ between the two phase centers needs to be known within a small fraction of a wavelength. These challenging objectives were obtained by using an accurate laser baseline measurement system with several targets on each antenna pod to obtain the range and orientation of the apertures. To obtain the two-frequency InSAR map for determining the
2.2 FOPEN SAR Systems

GeoSAR developed several innovations in image processing to make this possible. First, the focusing of the images over wide angles and swath widths are important [26]. If autofocus were used to take out variations in the phase errors due to terrain variation or propagation uncertainties, the absolute accuracy would be degraded. Second, the measurements in each band need to be radiometrically calibrated for estimating the signal correlation and scattering center [27]. Finally, the effects of RFI and transmit notching need to be accounted for in the waveform reconstruction [28]. These developments have been accomplished and are being used to provide commercial imaging services with GeoSAR.

A FOPEN SAR image of the Amazon River is shown in Figure 2–21 [29]. Both the X-band and P-band imagery are combined in false color to illustrate land use. The RGB image is made of a combination of X, P, and P–X returns from the system. For open areas the X-band provides significantly better texture of the return with its shorter wavelength.

However, as expected the X-band images only the tops of the trees, whereas the P-band penetrates the foliage. The plots on the right show three transects through the image. The top traces show the X-band DEM of the tops of the trees. The lower traces provide the derived DEM below the trees (combined X-band and P-band IFSAR processing).

These data show a difference of between 5 meter and 25 meter in the forested area when the X-band and the P-band traces are compared. However, in the open areas, the difference between the two DEMs is small. Thus, there is a definite benefit from the P-band interferometric image in determining the elevation below the treetops.
2.2.5 ARL’s BoomSAR

The BoomSAR was an experimental instrument developed by Army Research Laboratory (ARL) in Adlephi Maryland. The developmental effort to investigate critical technologies for penetrating foliage and the ground to detect and characterize hidden objects was started in 1988. The test bed UWB RADAR system was designed to provide controlled imaging over a 1 GHz bandwidth from HF to L-band and fully polarimetric illumination and data recording with parameters summarized in Table 2–6 BoomSAR instrumentation and

| Altitude [Km] | 0.05 |
| Velocity [Km/hr] | 1.0 |
| Frequency [MHz] | 40–1200 |
| Bandwidth [MHz] | 50–1100 |
| Antenna Area, [m²] | 1.0, TEM Horn |
| Polarization | HH, HV, VH, VV |
| Waveform | Impulse |
| Peak Voltage [Mvolt] | 2.0 |
| Pulse Width [n sec] | 1.0 |
| PRF [Hz] | 750 |
| ADC [MHz] | 60, 8 bits |
| Range Resolution [m] | 0.15 |
| Cross Range [m] | 0.3 |
| Resolution | |
| Range Bins | 4092 |
| Noise Equ.σ₀ [dBm²/m²] | –50 |
| Developed | Army Research Laboratory |
algorithm research focused both on foliage and ground penetration phenomenology, target detection and discrimination and on understanding the interaction of dense foliage on the scattering characteristics of obscured objects [30].

Its 50 meter high boom, shown in Figure 2–22, was controlled over wide geometries to insure accurate measurement of grazing angle effects on foliage loss, clutter characteristics, and complex target scattering. Moreover, the boom and RADAR subsystems were installed on a 50 meter high boom lift platform so the SAR collection would emulate an airborne collection. However, at a 1 km/hour velocity, the images were certainly not collected in what would be considered real time. The BoomSAR system operated at several test ranges such as Yuma, Arizona, and Aberdeen, Maryland, where military targets and unexploded ordinance could be characterized in a scientific and operationally significant environment.

The antenna consisted of a set of four TEM horns, which were impedance matched to the impulse transmitter to provide calibrated spectrum and polarization characteristics. Each of the transmit antennas operates from 40 MHz to 1200 MHz with a beamwidth of 90 degrees. This provides the illumination support in both angle and spectrum to satisfy the system range and
cross-range resolution objectives. Two of the horns transmit and two receive, with orthogonal polarization, to provide the full polarization matrix.

The system was used extensively to collect high-resolution, fully polarimetric data using the RADAR’s UWB waveform and to develop two-dimensional (down-range versus cross-range) images of a controlled swath area. Within the controlled swath area were targets in the clear, targets under foliage, subsurface targets, and natural and man-made clutter. The system provided the image swaths of up to 300 meters down-range by 1 Km cross-range, with spatial resolution in each dimension of less than 0.3 meter. The high-range resolution was obtained by using waveform bandwidth greater than 1 GHz and comparable high-speed sampling and recording techniques. A 2 megawatt impulse transmitter produced the UWB signal, having a spectral response extending from 60 MHz to over 1 GHz.

Through careful matching between the transmitter and the antenna and attention to receiver dynamic range and match to the ADC assemblies, the instrumented noise equivalent sigma-naught $\sigma_{\text{ne}}^0$ was a very low –50 dBm$^2$/m$^2$. To illustrate this impact on image processing, Figure 2–23 shows greater than 60 dB dynamic range image from one of the foliage penetration runs at Aberdeen, collected over the frequency range of 130–1,100 MHz. A number of 42 cm trihedrals are visible in an open region between two areas of trees, and a 50 cm sphere is located at the edge of the woods. The resolution of the RADAR is demonstrated by the pair of lines running between the poles along the lower edge of the image. The first of these lines is the return from the wire.

![BoomSAR image from Aberdeen MD © 1996 IEEE [31]](image)
strung between the poles, whereas the second is the multipath return from the ground reflection of the signal [31].

The Army Research Laboratory had a strong in-house team developing algorithms for image formation and target recognition. The wide dynamic range image recordings were processed in a high-performance computer to test and verify performance predictions. Figure 2–24 shows the screen capture of data from the test range at the Army Research Laboratory facility. Significant metrology was built into the analysis tools to quantify the signal processing and target recognition figures of merit [32].

Several critical FOPEN phenomena are shown in Figure 2–24, from the ARL image analysis tool. First, there is an excellent example of a long wire above the ground, indicated by the parallel lines in the near range of the figure. The closest return is the direct path from the RADAR to the wire. The next two parallel lines are the single and double bounce of the return from the ground, respectively. This clear return is a benefit of collecting SAR image over a wide beamwidth, with very fine-range resolution.

The second critical example is based on the return from two similar corner reflectors, one in the open and one 40 meters in the woods. Figure 2–25 shows
FIGURE 2-25
Impact of foliage loss variation on corner reflector [33]

the cross-range resolution of the RADAR measure from the corner reflector. The narrow resolution is characteristic of the wide-angle SAR collection. However, the return from the corner reflector in the foliage has degraded cross-range resolution due to the variation of loss and blockage of the forest, as a function of collection angle [33].

References

2.3 References


