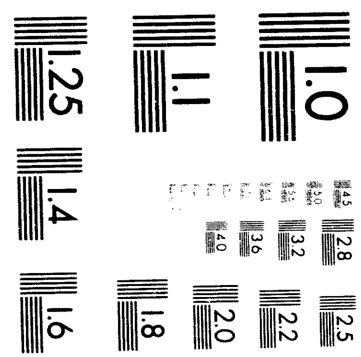
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A COMPARATIVE EVALUATION OF SAR AND SLAR

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Abstract

Synthetic aperture radar (SAR) was evaluated as a potential technological improvement over the Coast Guard's existing side-looking airborne radar (SLAR) for oil-spill surveillance applications. The U. S. Coast Guard Research and Development Center (R&D Center), Environmental Branch, sponsored a joint experiment including the U. S. Coast Guard, Sandia National Laboratories, and the Naval Oceanographic and Atmospheric Administration (NOAA), Hazardous Materials Division. Radar imaging missions were flown on six days over the coastal waters off Santa Barbara, CA, where there are constant natural seeps of oil. Both the Coast Guard SLAR and the Sandia National Laboratories SAR were employed to acquire simultaneous images of oil slicks and other natural sea surface features that impact oil-spill interpretation. Surface truth and other environmental data were also recorded during the experiment. The experiment data were processed at Sandia National Laboratories and delivered to the R&D Center on a computer workstation for analysis by experiment participants. Issues such as optimal spatial resolution, single-look vs. multi-look SAR imaging, and the utility of SAR for oil-spill analysis were addressed. Finally, conceptual design requirements for a possible future Coast Guard SAR were outlined and evaluated.

1.0 Introduction

The objective of the SAR/SLAR comparison was to evaluate, relative to oil-spill remote sensing requirements, the benefits and cost-effectiveness of supplementing or replacing the Coast Guard AIREYE system's real-aperture, AN/APS-131 SLAR with a lightweight, state-of-the-art, fine-resolution SAR capable of producing imagery in near real-time.

The first step was to determine whether a fine-resolution SAR offered an oil-spill detection performance comparable or superior to that of the existing Coast Guard SLAR. A coordinated oil-spill experiment involving the Coast Guard AIREYE SLAR and the

Sandia National Laboratories SAR was conducted over the Santa Barbara Channel in November of 1992 to address this issue. Images from the experiment were compared, and selected SAR images were processed to different spatial resolutions and exposed to different image processing algorithms to help analysts determine the image qualities required for oil-spill reconnaissance. Analysis of experimental data led to basic performance and preliminary design specifications for a future Coast Guard SAR system. The cost-effectiveness of such a system was evaluated by considering the availability and applicability of commercial systems or components; size, power, and weight constraints; operational requirements, and the expected quality and utility of the image products.

2.0 The Experiment

Simultaneous imaging flights were flown by the Coast Guard SLAR and the Sandia SAR on six days, Nov. 10 - 12, 1992, and Nov. 14 - 16, 1993. The SLAR is an X-band system mounted in a Dassault-Breguet Falcon 20 jet. It provides broad-swath imaging to a maximum range of 80 nmi. It's range resolution is 30 m, while the azimuth resolution varies with range, being about 50 m at 2 nmi range and about 500 m at 20 nmi range. The data for the Santa Barbara test were digitally recorded on digital audio tape (DAT) for computer analysis following the experiment. The SAR is a Ku-band system mounted in a DeHavilland DHC-6 Twin Otter propeller-driven aircraft. SAR images were formed with 2-m pixel spacing in both range and azimuth. Because the swath width of the SAR was not as great as the SLAR, a serpentine path was flown by the SAR to acquire strips that could be digitally mosaicked to provide wide-swath coverage.

Simultaneous SAR/SLAR missions were scheduled to acquire data within any one of four possible test areas along the Santa Barbara coast. Only one test area was used per day. Figure 1 shows a chart of the coast and the test areas. All of the images acquired during the experiment came from test areas 2 and 4.

Examples of the SLAR and SAR data acquired from the experiment are shown in Figures 2 and 3. Figure 2 is a wide-swath SLAR image from the Nov. 12, 1992, mission. The SLAR antenna was south-looking (downward in the image). Azimuth spatial resolution (the azimuth dimension is the horizontal dimension in the image) degrades with increasing range (downward in the image). This characteristic is seen in Figure 2. The four ships in far-range (bottom portion of the image) are well resolved in range, but are spread considerably in cross-range. Figure 3 is a downsampled SAR mosaic from the Nov. 12, 1992, mission. The antenna was south-looking, also. The full mosaic had a size of roughly 9200 pixels by 5600 pixels, which is too large to print on a dye-sublimation printer, so the mosaic was downsampled for display. Figure 4 shows a region-of-interest (denoted by the box in the mosaic) at full resolution. In a SAR image, pixel resolution is nearly uniform across the image. SAR images need not suffer the range-dependent resolution degradation that SLAR images demonstrate.

Surface truth and auxiliary data were also gathered during the experiment. Helicopter surveys by NOAA Hazardous Materials Division (HAZMAT) scientists and Coast Guard Strike Force teams documented sea surface conditions, located significant oil fea-

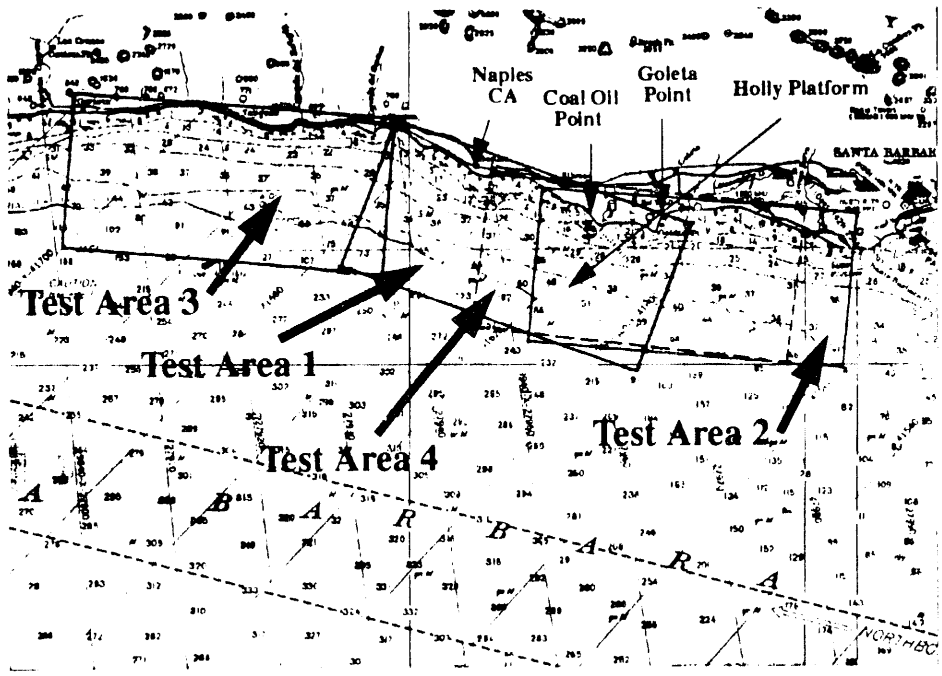

Figure 1. Chart of the Santa Barbara Channel and the potential test areas for the November 1992, experiment.

tures, and commented on the characteristics of the oil at the time of imaging. Meteorological data were available from the Holly oil-drilling platform in the channel. Finally, aerial photographs were collected by the AIREYE KS-87 reconnaissance camera and several hand-held cameras on-board the Twin Otter, AIREYE, and surface-truth helicopters.

3.0 Data Analysis

Both SLAR and SAR image data were captured digitally to enable post-experiment computer processing. The SLAR images were digitized and recorded directly onto digital audio tape in the AIREYE. The tapes were then screened at Sandia National Laboratories after the experiment and edited to extract the data of interest. The extracted images were then transferred to magneto-optic (MO) disk for archive and detailed analysis. The SAR images and their corresponding complex phase histories were digitally recorded during the experiment. The images were intensity-scaled and reformatted for digital mosaicking after the experiment at Sandia National Laboratories. The digital mosaics were also transferred to MO disk. The SAR and SLAR disks were finally delivered to the U. S. Coast Guard R&D Center along with a 486-based data visualization workstation and dye-sublimation color image printer.

Two data analysis workshops were sponsored by the Coast Guard R&D Center. The first workshop compared SLAR, SAR, and photographic data in order to identify subsets of the data that showed similar surface-oil patterns or which showed features that are important to sea surface and oil-spill identification. The second workshop studied the

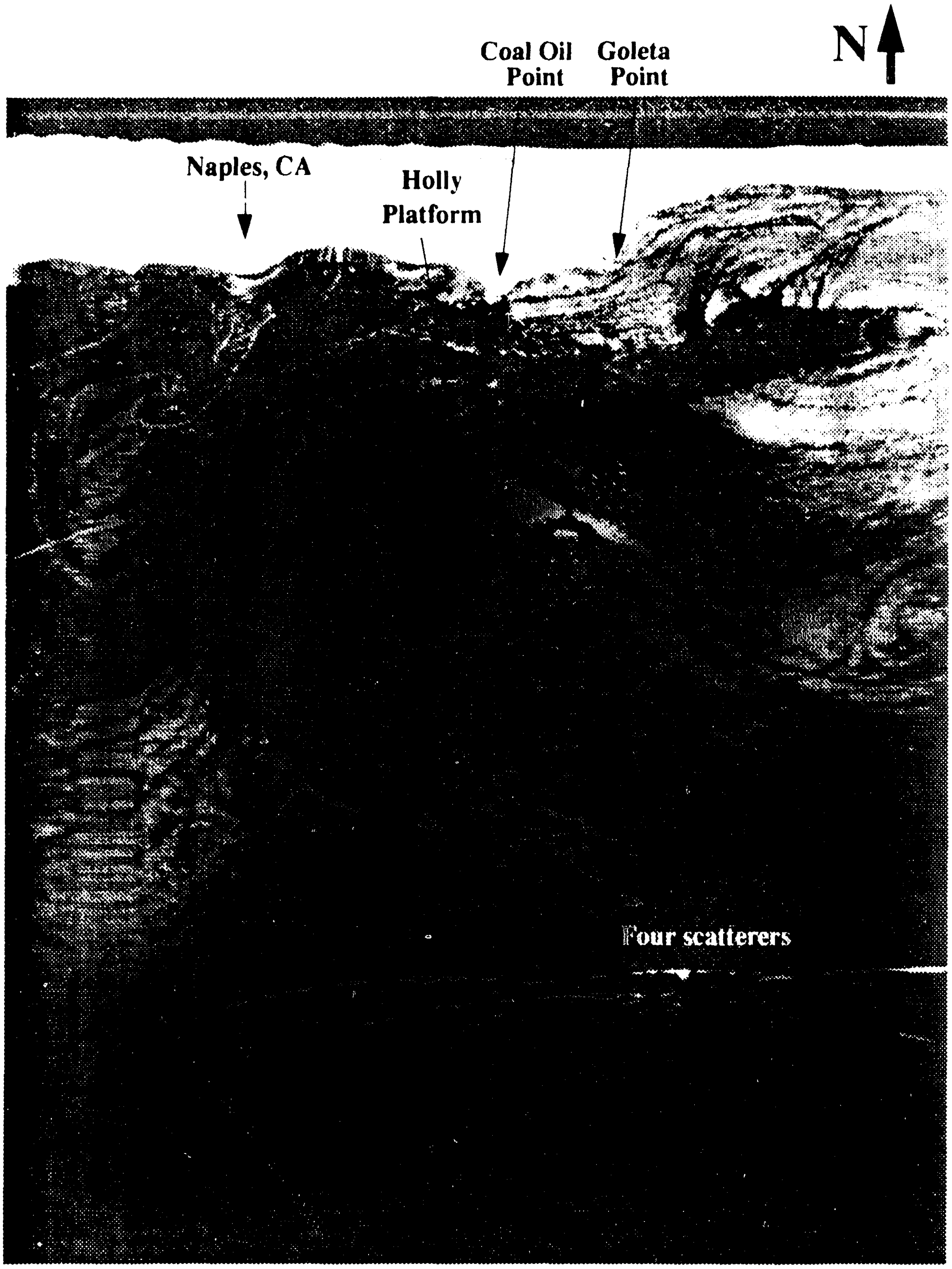

Figure 2. South-looking SLAR full-swath image from Nov. 12, 1992. The azimuth dimension is horizontal and the range dimension is vertical. Note the degradation in azimuth resolution for the four scatterers (ships) that are far in range (bottom of image).

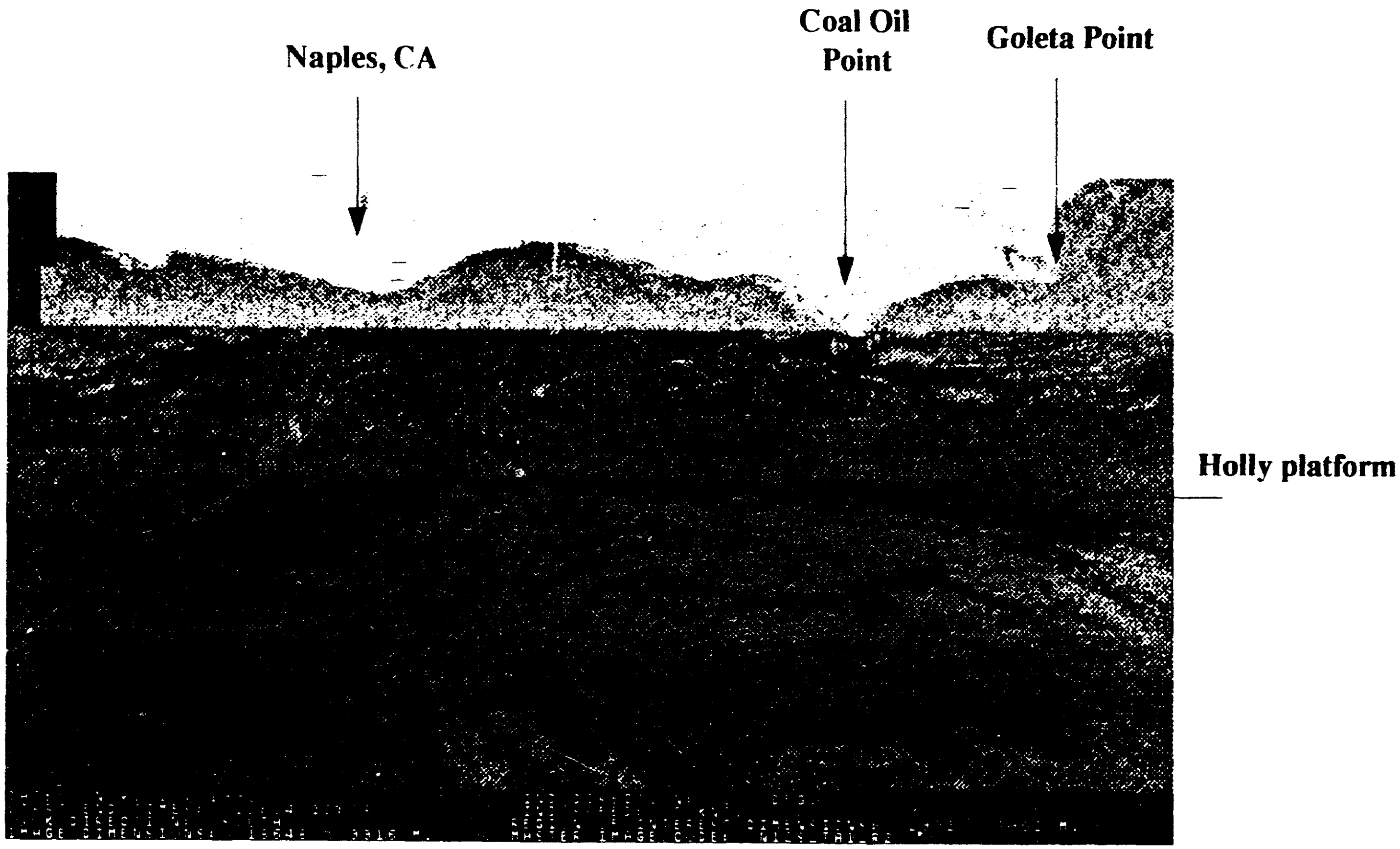

Figure 3. Full-swath SAR mosaic from the November 1992, experiment. This image has been subsampled by a factor of 5 for printing. The white and black bordered box denotes the region-of-interest shown at full resolution in Figure 4.

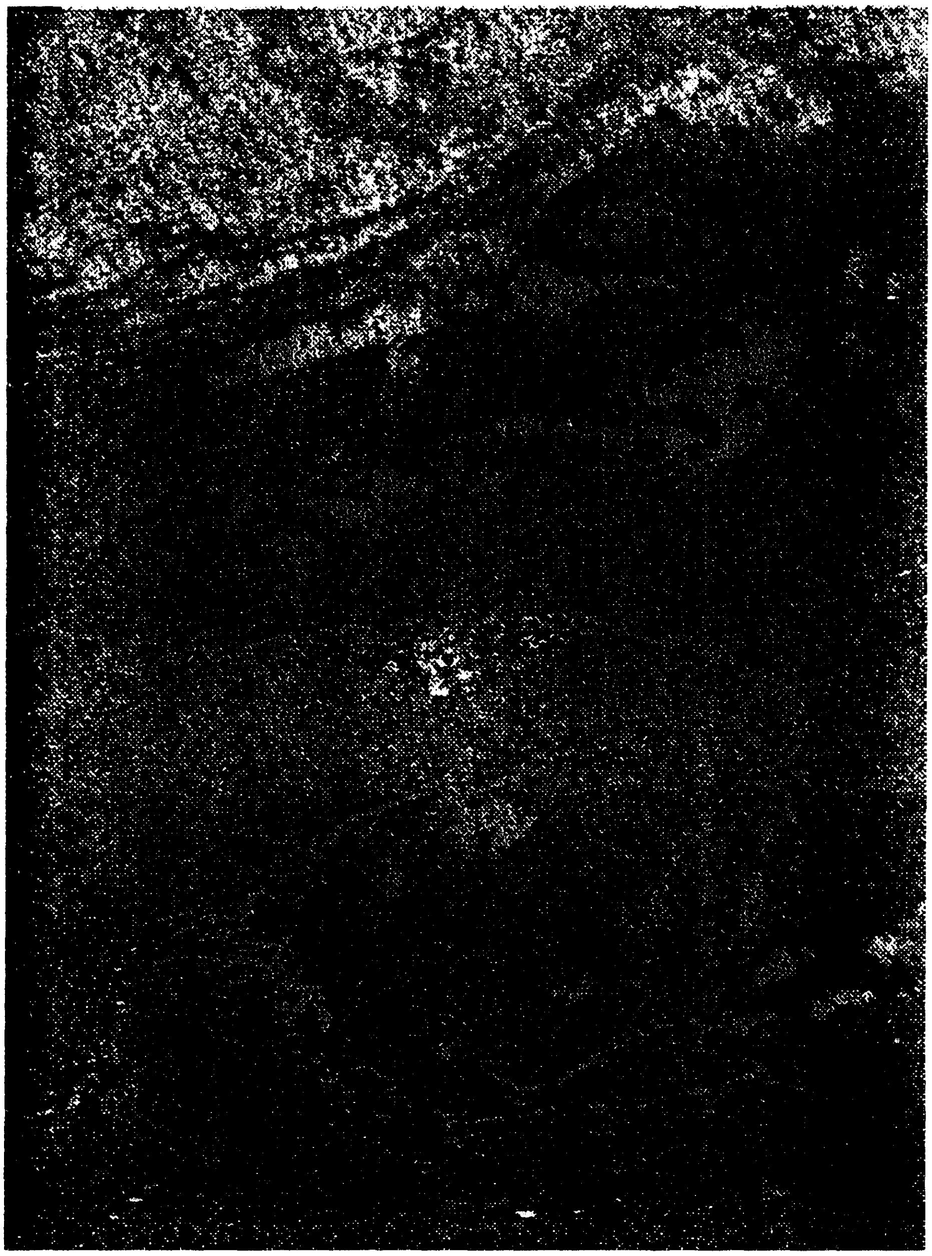

Figure 4. Full resolution region-of-interest extracted from the mosaic shown in Figure 3. Note the wave pattern from open sea (top), the linear features shaped like a wishbone resulting from radar returns from emulsified oil and flotsam (lower half), and the dark areas resulting from mirror-like scattering of radar energy away from the SAR by a thin film of oil (lower 2/3 of image except for wishbone feature).

influence of image resolution, speckle suppression, single-look and multi-look imaging, and wave motion on SAR imaging in comparison to traditional AIREYE SLAR imaging. The workshops were attended by a multi-disciplinary team of analysts representing the Coast Guard R&D Center, NOAA-HAZMAT, Coast Guard Air Station Cape Cod, the Coast Guard Strike Teams, and Sandia National Laboratories.

Of particular importance to the workshop participants was the determination of the coarsest spatial resolution required of a SAR to identify oil-spill features of significance to oil-spill response. The 2-m pixel resolution of the Sandia SAR was generally believed to be too fine for operational oil-spill response work. The acuity of the 2-m pixel images was excellent, but the volume of data that would need to be stored and analyzed when acquiring operational data in 25 nmi swaths was considered to be too great. Analysts were willing to trade off spatial resolution in order to attain a more manageable volume of data and reduce the cost of a potential Coast Guard SAR. At the same time, most analysts believed that a higher spatial resolution than is currently achieved with the AIREYE SLAR would be preferred. The workshop participants decided to examine resolution-degraded versions of the Santa Barbara SAR images to identify an ideal spatial resolution for oil-spill surveillance.

The optimal technique for resolution-degrading is to resample the SAR complex phase histories and form new detected images, but this approach was beyond the scope of the project. Reprocessing all of the SAR data collected in the experiment was too time consuming and too expensive. The accepted alternative was to resample the fine-resolution detected images directly in order to simulate the effect of phase history resampling. Techniques for simulating resolution-degraded single-look and multi-look SAR images from the original 2-m pixel resolution single-look imagery were developed and implemented on the Coast Guard computer workstation. These simulations were verified by selecting one region-of-interest in a SAR image, resampling the complex phase history for that region-of-interest (both single-look and multi-look), simulating the resolution degradations by processing only the detected images (both single-look and multi-look), and comparing the results. Clearly, the phase history resampled and simulated downsampled SAR images had different coherent speckle characteristics, but both techniques affected the acuity of large features-of-interest similarly.

Analysts agreed that 10-m pixel resolution was preferred for oil-spill surveillance. In some cases, features-of-interest such as wind rows or fingers of entrained oil were only a few pixels wide at 10-m resolution. These features were readily visible in 10-m single-look SAR images, but analysts believed that coherent speckle degraded image acuity near these features. One means of addressing this concern is to digitally filter the single-look image to smooth speckle. The disadvantage of this technique is that filtering destroys high spatial frequency information in images, and this is not always desirable. An attractive alternative is to acquire multiple independent looks of the scene during aperture synthesis. The noncoherent average of these multiple looks creates a resultant image that retains high spatial frequency integrity while averaging out random speckle. Simulated 10-m multi-look images were analyzed by workshop participants and were determined to be superior to 10-m single-look images.

Another important result of the analysis workshops was the recommendation that two forms of image display be provided to operators of a future SAR. Even at 10-m pixel resolution, the amount of data available for a 25 nmi swath is extensive (over 4600 pixels per column in the range dimension). There are too many pixels to portray on a standard video monitor at full resolution. One alternative is to provide two monitors, one showing the entire swath at reduced resolution so that the entire scene may be studied. From this display, operators could cue smaller regions-of-interest for full resolution display on a second monitor. The finer resolution display would allow the operator to identify detailed features that are important for defining oil slick boundaries. When required, these region-of-interest images could be electronically down-linked to parties responsible for spill response.

4.0 A Conceptual Design

A number of project activities provided inputs to the SAR conceptual design. These activities were: a) identification and documentation of Coast Guard operational requirements, b) conduct of a SAR vendor capabilities survey, c) execution of a literature search pertaining to previous use of SAR for oil-spill monitoring, and d) completion of the SAR/SLAR data analysis workshops. The recommended design (see Table 1 and Figure 5) is a broad-swath, 10-m-resolution SAR operating in the X band. The imaged swath would extend from 8.5-km near-range to 54-km far-range (about 25-nmi swath). Azimuth resolution achieved by this system at far-range would be a factor of 80 better than that of the

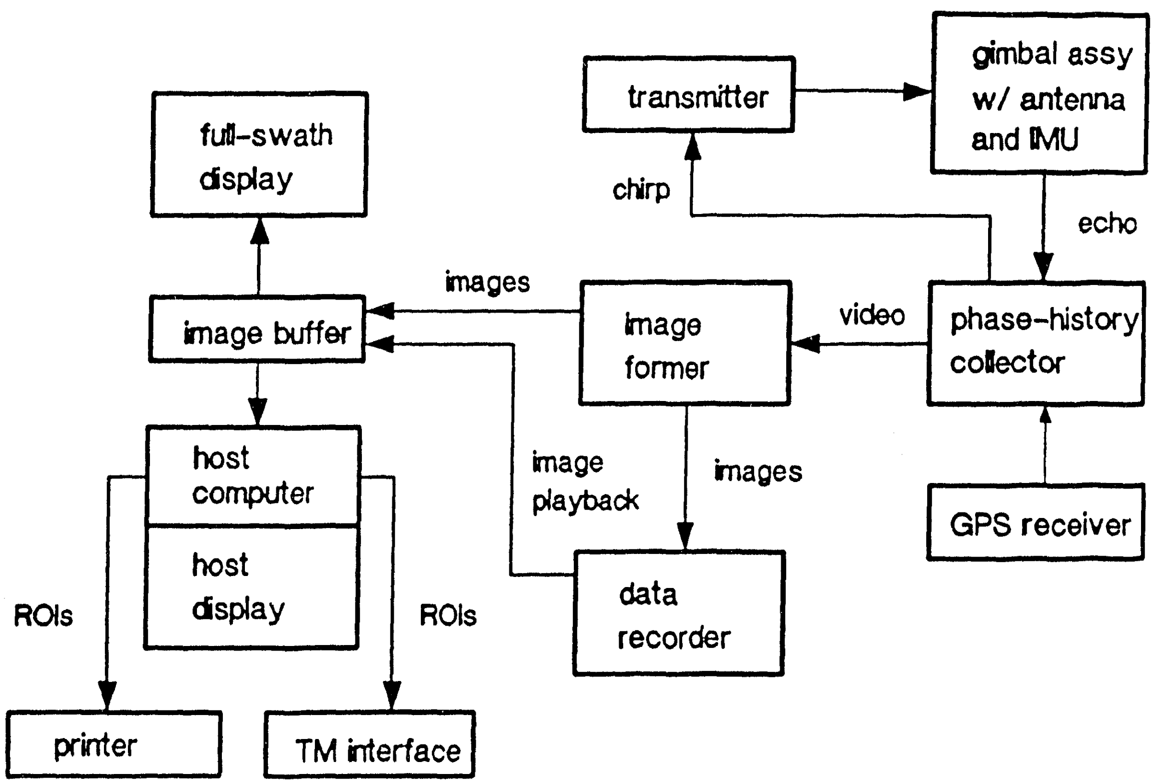

Figure 5. High-level block diagram of the SAR system

Table 1. Coast Guard SAR System Specifications

Parameter or Attribute	Units	Value or Description
Prime Usage of System	----	oil-spill imaging
Secondary System Usage	----	imaging of moving targets
Aircraft Platform	----	Falcon 20
platform velocity	m/s	90-124
Radar Supported Modes	----	side-looking strip map;
	----	real-time multilook imaging;
	----	either RAR or MTI mode for ships
Real-Time Image Attributes		
real magnitude	----	recorded
slant-range resolution ρ_r	m	10/30 (ROI/full-swath display)
azimuth resolution ρ_a (@ 25 nmi)	m	10/30 (ROI/full-swath display)
image slant-range swath	nmi	25
Minimum-detectable σ^o Required	dB	-45 (@ 54 km, SNR = 6 dB)
Geometry		
altitude	km	$\leq$ 6 km
slant range (near range)	km	$\leq$8.5
slant range (far range)	km	$\leq$54 (25 nmi swath)
Multilook Processing (real-time)		
temporal, $\Sigma_i \vert V^i_{j,k} \vert /N$	looks	9 @ 10-m resolution
Operating frequency	GHz	$\simeq$9.3 (X band)
Peak tx power (at antenna)	W	$\simeq$500
Maximum average tx power	W	$\simeq$65
Antenna		
polarization	----	vertical
elevation pattern	----	$csc^2(\phi)$; ϕ = depression
azimuth beamwidth	°	2
length x height	m	0.92 x 0.3
steering	----	gimbal, wide-angle
Real-Time Image Formation Algorithm	----	channelized in range; azimuth FFT with interpolation
estimated floating point op's	GOP/s	0.35
Data Handling	----	4-mm tape; record images and auxiliary data
record-time capacity	hours	5-10 (8-bit images)
Dual Image Displays	----	one for ROIs; one for full swath
Motion Compensation	----	real-time
Mechanical Characteristics		
total power to system	kW	2.3
physical volume of system	m^3	1.4

existing Coast Guard SLAR. Achievable system sensitivity (minimum detectable scattering coefficient) would be about -45 dB at 6-dB signal-to-noise ratio and at 54-km range.

The phase-history collector generates the X-band chirp waveform that is routed to the traveling-wave tube (TWT) to be amplified. The TWT output is then routed to the antenna for transmission. Echoes collected by the antenna are amplified and sent to the receiver in the phase-history collector. The phase-history collector contains all mixing, digitizing, and prefiltering circuitry. Its output is a stream of complex-valued digital samples destined for the image former. Formed images are recorded to tape and simultaneously sent to an image buffer for display processing. A dual-display approach is recommended; one for viewing down-sampled (30-m-resolution), full-swath images; and one for presentation of operator-selected, full-resolution (10-m-resolution), regions of interest. The host computer would be capable of manipulating and processing regions of interest for display, disk storage, printing, and downlinking (via the TM interface).

The image former would produce sequential, fully-focused, overlapping SAR image patches. These patches would then be combined, noncoherently, to form real-time, multi-look images at the required resolution. Up to 9 looks could be obtained within the contraints of the system defined in the study. Because of the extremely wide swath, image formation processing must partition echo pulses into a number of adjacent range channels, and sub-image patches for each patch would be formed, resampled, and multi-looked separately; then multi-look images from the various channels would be merged to assemble the full-swath image. This processing approach allows both azimuth resolution and the number of looks to be held nearly constant across the wide swath, thus assuring spatial uniformity of the image. In the image former, motion compensation data derived from precise navigation measurements would be applied to echo data in real time to allow accurate imaging of the ocean-target area. The recommended design approach for the image formation processor would employ an i860-based parallel processing architecture.

A number of trade-offs were considered in the design. The X-band operating frequency was chosen because it provides good oil/open-ocean contrast in SAR imagery, it is relatively immune to atmospheric and rain attenuation, and high-power rf sources are readily available in this band. Vertical antenna polarization is optimal for ocean imaging at small grazing angles. The antenna's beamwidth was chosen to make the antenna small enough to be gimbal-mounted, and hence, steerable.

The secondary Coast Guard mission requirement of imaging moving vessels at sea cannot be met with the basic SAR design described above. Either a real-aperture (RAR) mode or a moving-target-indicator (MTI) mode must be included. Addition of the RAR mode allows moving ships to be imaged, but no suppression of ocean clutter is achieved, so radar sensitivity against ship targets is poor. A conceptual design approach was developed for a SAR/MTI mode that provides up to about 40 dB better performance against moving ships than either RAR or SLAR.

The study concluded that the SAR design described above is well within the reach of current technology and that a new-design SAR could be readily developed to meet the stated requirements. The vendor capabilities survey revealed that while a number of existing SARs exhibit characteristics that are close to those specified in the conceptual design, all of the SARs surveyed also exhibit significant differences, compared to the conceptual design. A prime SAR candidate for modification to meet Coast Guard requirements would be one that provides a good match to the conceptual design in the portion of the system that includes the transmitter, the gimbal assembly, and (especially) the phase-history collector. The digital portions of the system (image former, data recorder, host computer, and displays) should be then be developed using new designs tailored to Coast Guard requirements.

5.0 Conclusions and Recommendations

On the basis of superior image acuity and resolution uniformity, SAR should be considered as a possible future replacement for existing Coast Guard SLAR systems. SAR does, however, incur some substantial increases in cost, both for system development and unit replication. The data analysis and conceptual design studies determined several important characteristics that should be included in any future SAR procurement. These include:

1. 10-m pixel resolution and a 25 nmi image swath.
2. X-band radar.
3. Real-time motion compensation.
4. Real-time multi-look image formation.
5. Image and auxiliary data recording.
6. Full-swath and region-of-interest displays.
7. Moving target indicator mode.

Finally, a survey of commercially available SARs has demonstrated that several existing systems have capabilities that are very close to the capabilities outlined in the conceptual design section of this paper. It is possible that these existing systems could be modified to meet Coast Guard requirements with a minimal additional investment.

6.0 Acknowledgments

The authors would like to acknowledge the assistance of several people and organizations that participated in this project. These are the U. S. Coast Guard, NOAA-HAZMAT, and Sandia National Laboratories (including Ross Aviation) flight crews; Jeff Mason's colleagues who helped form images, deliver data, and supply the radar visualization workstation; Jeff Plourde of Analysis and Technology, Inc. for his preparation of data for the analysis workshops, and Dr. Jerry Galt, of NOAA, for his special contributions to analyzing the data. This work was funded by the U. S. Coast Guard through a Military Interdepartmental Purchase Request (MIPR) with the U. S. Department of Energy and Sandia National Laboratories.

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