A High Resolution, Light-Weight, Synthetic Aperture Radar for UAV Application (U)

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ABSTRACT (U)

(U) Sandia National Laboratories in collaboration with General Atomics (GA) has designed and built a high resolution, light-weight, Ku-band Synthetic Aperture Radar (SAR) known as "Lynx". Although Lynx can be operated on a wide variety of manned and unmanned platforms, its design is optimized for use on medium altitude Unmanned Aerial Vehicles (UAVs). In particular, it can be operated on the Predator, I-GNAT, and Prowler II platforms manufactured by GA.

(U) The radar production weight is less than 120 lb and operates within a 3 GHz band from 15.2 GHz to 18.2 GHz with a peak output power of 320 W. Operating range is resolution and mode dependent but can exceed 45 km in adverse weather (4 mm/hr rain). Lynx has operator selectable resolution and is capable of 0.1 m resolution in spotlight mode and 0.3 m resolution in stripmap mode, over substantial depression angles (5 to 60 deg) and squint angles (broadside ±45 deg). Real-time Motion Compensation is implemented to allow high-quality image formation even during vehicle turns and other maneuvers.

1.0 (U) INTRODUCTION

(U) Lynx is a state of the art, high resolution synthetic aperture radar (SAR). Lynx was designed and built by Sandia National Laboratories and incorporates General Atomics' design requirements to address a wide variety of manned and unmanned missions. It may be operated on the Predator, I-GNAT, or Prowler II platforms which are manufactured by General Atomics (GA). It may also be operated on manned platforms. Lynx was developed entirely on GA corporate funds. GA is presently beginning the manufacture of Lynx and intends to sell Lynx units and Lynx services to military and commercial customers.

(U) Lynx is a multimode radar. Its SAR modes include a spotlight mode and two stripmap or search modes. In addition, Lynx has a ground moving target indicator (GMTI) mode. Lynx also features a coherent change detection (CCD) mode which can indicate minute changes in two SAR images taken at different times. CCD may be

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(U) performed with either spotlight or stripmap images. Lynx also features a uniquely flexible user interface. The user interface features a view manager that allows Lynx to pan and zoom like a video camera. Lynx also features a conventional scrolling display for stripmap display.

(U) Lynx operates at Ku band and is capable of 0.1 m resolution in spotlight mode and 0.3 m resolution in stripmap mode. It has a slant range of 30 km in weather and weighs less than 120 lb.

2.0 (U) SYSTEM DESIGN

(U) The Lynx SAR operates in the Ku-Band anywhere within the range 15.2 GHz to 18.2 GHz, with 320 W of transmitter power. It is designed to operate and maintain performance specifications in adverse weather, using a Sandia derived weather model that includes 4 mm/hr rainfall. It forms fine-resolution images in real-time and outputs both NTSC video as well as digital images.

2.1 (U) DESIGN GOALS

(U) The Lynx SAR was designed for operation on a wide variety of manned and unmanned aircraft. In particular, it can be operated from the Predator, I-GNAT, and Prowler II platforms manufactured by GA. During System Integration testing it was operated on board Sandia's DOE DeHavilland DH-6 Twin-Otter aircraft. The Lynx SAR's operating parameters are fully adjustable and self-optimizing for a wide variety of flight geometries and dynamics, with a performance envelope that even includes supersonic velocities.

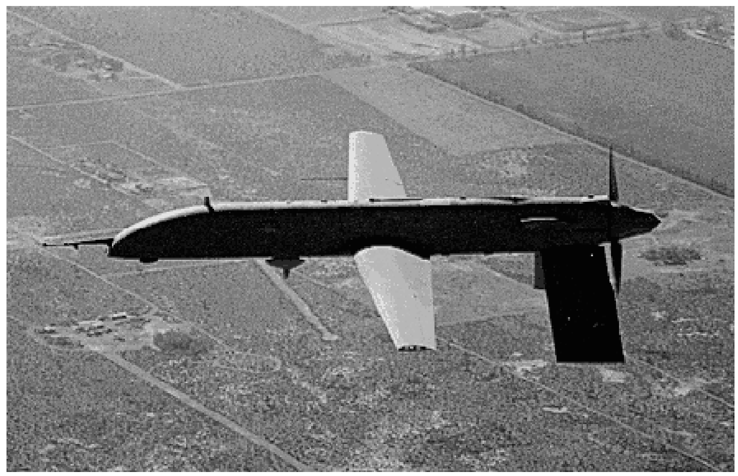

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Figure 1. (U) GA Aeronautical Systems, Inc. I-GNAT UAV

(U) While the Lynx SAR was designed primarily as an intelligence tool, a number of features were incorporated to enhance geolocation of the SAR images for targeting applications, including the use of a Sandia developed propagation model.

(U) A principal focus of the SAR development was ease of use by non-radar specialists. The intent was for SAR to be "just another sensor", fully integrated with, and as easy to operate as any electro-optic sensor.

2.2 (U) OPERATING MODES

(U) The Lynx SAR has four primary operating modes. These are described as follows.

2.2.1 (U) SAR GEO-REFERENCED STRIPMAP MODE

(U) In Geo-ref Mode, the operator specifies a precise strip on the ground to be imaged. The SAR then patches together a continuous and seamless string of images to yield the strip until the specified end-point is reached or the radar is commanded to do otherwise. The aircraft is not constrained to fly parallel to the strip, and images can be formed on either side of the aircraft. Specifications for this mode are given in Table 1.

Table 1. (U) Stripmap SAR Mode specifications.

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Resolution	0.3 to 3.0	m	Both slant range and azimuth
Range	7 to 30	km	Slant range (3-60 km at reduced performance)
Ground swath	2600	pixels	Only with 16-node system (to 3500 pixels at coarser resolutions)
View size	934	m	At 0.3 m resolution, 45 deg. depression
Depression angle	5 to 60	deg	Below horizontal
Squint angle	± (45 to 135)	deg	Squint is difference between scene center-line and aircraft velocity vector

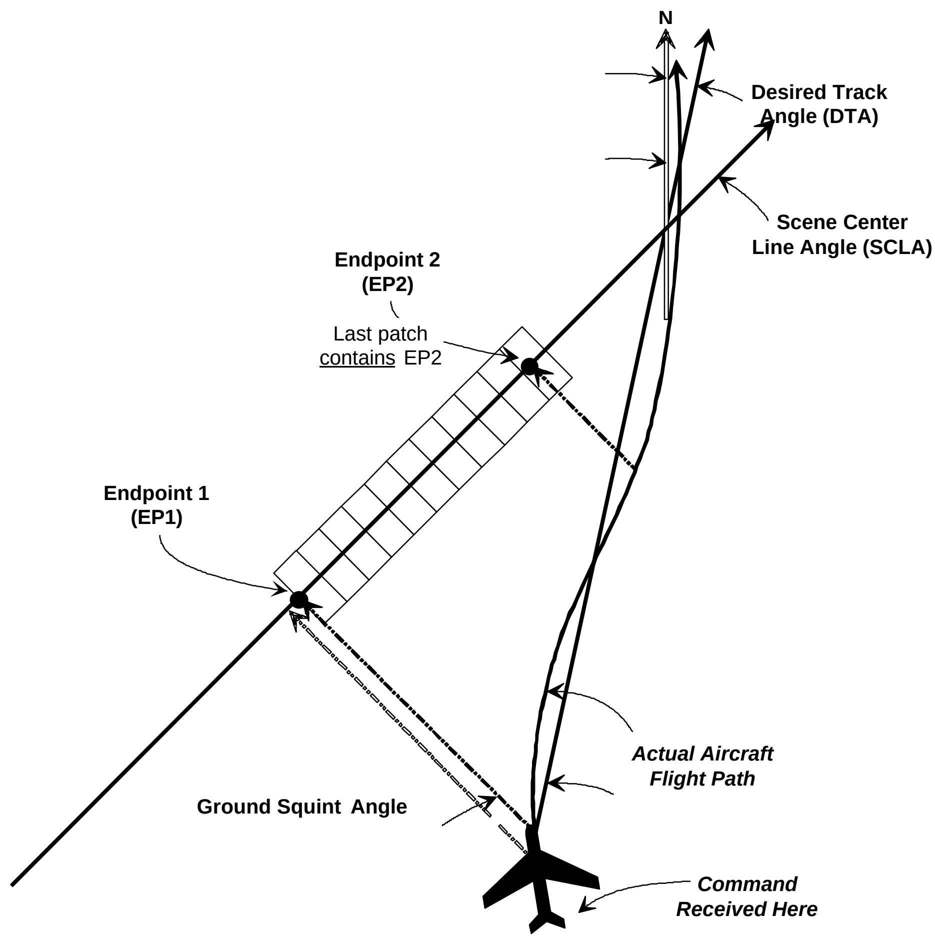

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Figure 2. (U) Geo-Referenced Stripmap Mode

2.2.2 (U) SAR TRANSIT STRIPMAP MODE

(U) In Transit Mode, the operator specifies a range from the aircraft to the target line and the SAR forms a stripmap parallel to the aircraft's flight path. The SAR then patches together a continuous and seamless string of images to yield the strip, and will continue to do so until commanded otherwise, or until the vehicle deviates too far from the original flight path. In the event of such a deviation, a new Transit Stripmap will begin immediately.

(U) In all other respects, the performance of Transit Mode Stripmap is identical to Geo-ref Stripmap Mode.

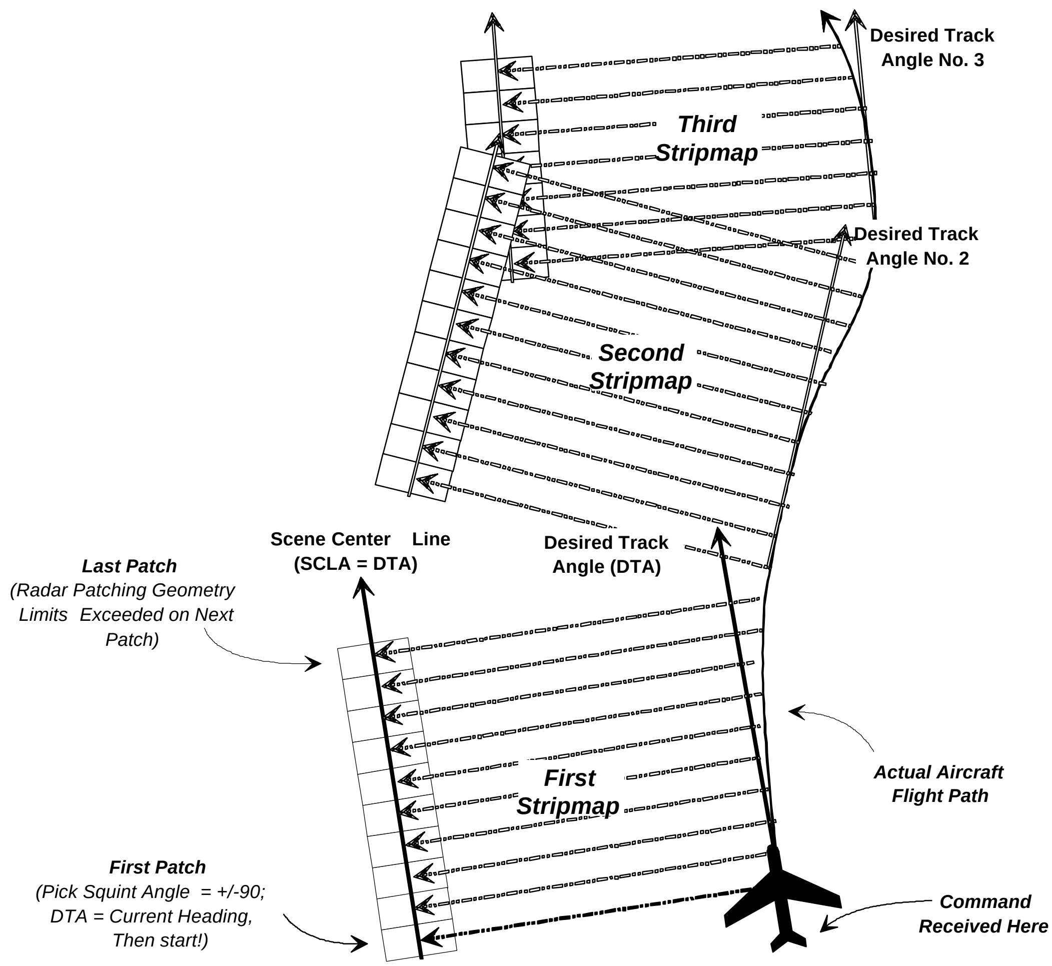

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Figure 3. (U) Transit Stripmap Mode

2.2.3 (U) SAR SPOTLIGHT MODE

(U) In Spotlight Mode, the operator specifies the coordinates of a point on the ground (either numerically, or by pointing and clicking within another image) and the SAR dwells on that point until commanded otherwise, or until the imaging geometry is exceeded. As with Stripmap modes, imaging may be on either side of the aircraft. This mode allows finer resolutions than the Stripmap modes. Performance is summarized in Table 2.

(U) In addition, an auto-zooming feature is also supported, where subsequent images are formed at ever finer resolutions until the SAR's limits are reached, or commanded to do otherwise.

Table 2. (U) Spotlight SAR Mode specifications.

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Resolution	0.1 to 3.0	m	Select one of five
Range	4 to 25	km	Slant range (3-60 km at reduced performance)
Patch Size	2 x (640 x 480)	pixels	
View size	640 x 480	pixels	Over NTSC video link
Depression angle	5 to 60	deg	Below horizontal
Squint angle	± (50 to 130)	deg	
	± (45 to 135)	deg	0.15 m resolution and coarser

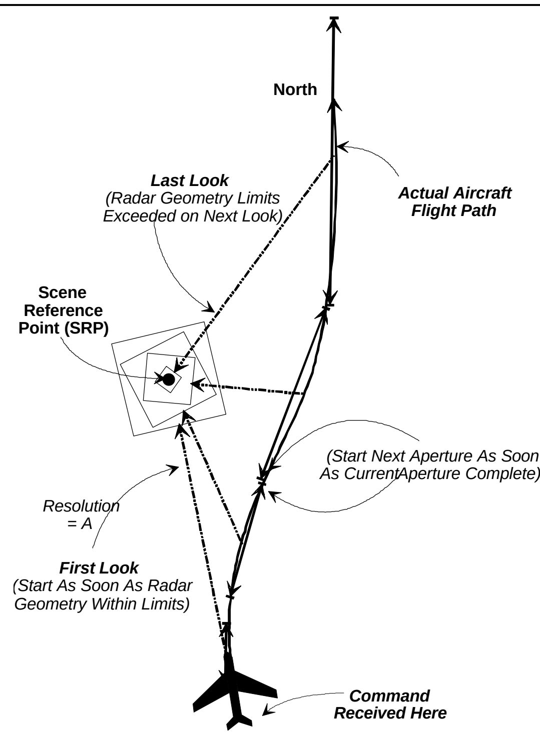

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Figure 4. (U) Spotlight SAR

2.2.4 (U) GROUND MOVING TARGET INDICATION – GMTI

(U) The relatively slow velocities of UAVs allow fairly simple exo-clutter GMTI schemes to offer reasonably good performance. The Lynx GMTI mode allows scanning over 270 degrees with performance summarized in Table 3.

Table 3. (U) GMTI Mode specifications.

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Min. Detectable Velocity	5.8	kts	At 35 m/s (near range)
Range	4 to 25	km	Slant range
Angular Coverage	–135 to +135	deg	Total possible swept angle
Ground swath	10	km	Less at nearer ranges
Min. detectable target	+10	dBsm	
Max. Clutter	–10	$dBsm/m^2$	Average distributed clutter

2.2.5 (U) Coherent Change Detection – CCD

(U) While not listed as a primary operating mode of the radar, CCD is nevertheless listed here as a fifth output format that Lynx was designed to provide. This is a normal and routine Lynx product.

(U) Coherent Change Detection is a technique whereby two SAR images of the same scene are interfered. Any changes in the complex reflectivity function of the scene are manifested as a decorrelation in the phase of the appropriate pixels between the two images. In this manner, even very subtle changes in the scene from one image to the next can be detected. Necessarily, the images themselves must remain complex for this to work [3].

(U) In the SAR modes, the radar can output complex (un-detected) images that are necessary for Coherent Change Detection to work. These images can be transmitted to the ground station where ground-processing of the current image along with a library image allows near-real-time detection of changes in the scene. This operates with either Stripmap or Spotlight SAR images.

2.3 (U) USER INTERFACE

(U) Consistent with the philosophy for other sensors of the GA UAV family, the user interface for the SAR was designed to allow easy operation by an operator with minimal radar-specific knowledge. The operator selects resolution and operating mode, and then basically ‘points and shoots’ the radar, much like the optical sensors.

(U) Radar images are transmitted to the radar operator by any of two means. The first is an NTSC video link which allows the SAR to be treated as “just another sensor” to a UAV payload operator. The radar actually forms larger images than can be displayed over the NTSC video link, but novel View Manager software allows the

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Figure 5. (U) UAV Ground Station

(U) operator to pan and zoom within its memory. Images may be saved in on-board buffers for later viewing.

(U) The second means of image transmission is a digital data link that can transmit an entire image at full resolution. This data can then be formatted to comply with the National Imagery Transmission Format, NITFS 2.1.

(U) Target coordinates are easily extracted from any SAR image to facilitate pointing the SAR for new images. In GMTI mode, locations of detected movers are transmitted for display on map overlays.

(U) In both UAV and manned aircraft flights, the image stream may be recorded. In addition, during manned flights (mainly due to the larger aircraft), the phase histories themselves can also be recorded.

2.4 (U) SAR IMAGE QUALITY

(U) The Lynx SAR was designed to provide images with quality second to none. Operating parameters are automatically chosen to provide the best possible impulse response, and to minimize the system noise level. Specifications for the Lynx SAR are listed in Table 4, but these are routinely bested.

(U) All SAR performance limits are based on maintaining acceptable SAR image quality. However, many of the stated performance limits may be exceeded at the expense of slight image quality degradation. For example, operating range can often be extended at the expense of noisier images.

Table 4. (U) SAR Image Quality Requirements.

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Noise Equivalent Reflectivity Limit	–25	dBsm/m^2	Used for determining range limits. Normal operation is to make this as low as possible for any range.
Peak Sidelobes Asymptotic Limit	–30	dBc	Envelope = $20 \log_{10}[(2.59/U)^2+1] - 30$ dB for $\lvert U\rvert>1.5$ resolution cells.
Multiplicative Noise Ratio	–13	dBc	Design budget sums to –17.6 dBc. Dominated by motion measurement nonlinearities.
Dynamic Range	75	dB	Greater with finer resolutions

(U) Data are processed with a Taylor window in both dimensions, with –35 dBc sidelobes and *nbar* = 4.

2.5 (U) CALIBRATION

(U) A number of hardware and software features are incorporated to perform and maintain calibration of the Lynx radar, even in-flight. These include the ability to perform in-flight noise measurements, receiver gain measurements, channel equalization, I/Q channel balancing, and timing corrections.

3.0 (U) HARDWARE

(U) While SARs tend to be fairly complex instruments, a primary goal for Lynx was ease of manufacture. This drove all aspects of design. Consequently, the basic Lynx design is very modular, allowing for relatively easy expansion and upgrading of components, subassemblies, and capabilities.

(U) The system has been designed as two relatively generic packages. These are the Radar Electronics Assembly (REA) and the Sensor Front-End or Gimbal Assembly. The combined weight is currently about 125 lb with some variance due to different cable assemblies for different platforms. The first production units are expected to weigh less than 120 lb.

3.1 (U) RADAR ELECTRONICS ASSEMBLY – REA

(U) The REA contains radar control, waveform generation, up-conversion, receiver, video, ADC, and signal processing functions. These functions exist in a custom VME chassis, which facilitates ready expansion of, and addition of new boards, interfaces, and capabilities. Individual boards/assemblies are roughly divided as follows.

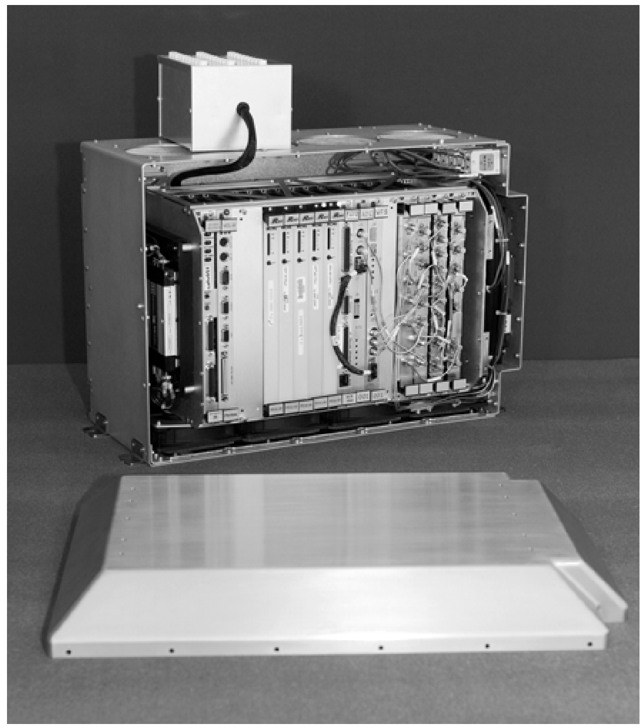

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Figure 6. (U) Lynx Radar Electronics Assembly

(U) The RF/Microwave functions are within a set of five VME boards/assemblies. These include the STALO module, Up-converter module, Ku-Band module, Receiver module, and the RF interconnect module. The only major RF/microwave functions not found in these modules are the transmitter TWTA and the receiver LNA. The modularity of these modules lend themselves to fairly straightforward modification to other radar bands.

(U) Digital Waveform Synthesis (DWS) is accomplished by a custom VME board that generates a chirp with an effective 50-bit internal chirp parameter precision at 1 GHz. This allows incredibly precise chirps even for long pulses. The output is a 9-bit waveform that drives a DAC chosen for its low spur-free dynamic range, nominally better than –50 dBc at 1 GHz. Although the board is custom, all components are off-the-shelf.

(U) The Analog-to-Digital Conversion (ADC) is also accomplished by a custom VME board that operates at 125 MHz and provides 8-bit data. This data can be presummed and otherwise pre-processed before being sent across a RACEway bus to the signal processor. Conversion is for I and Q channels, with custom circuitry to facilitate channel balancing.

(U) The Signal Processor consists of 16 nodes of Mercury Computer Systems RACEway-connected 200 MHz Power PCs. These implement a scalable architecture for image formation. Fewer nodes may be installed for a less capable SAR system. Four additional nodes are used for other radar functions including Motion Measurement, Radar Control, and optional data recording.

3.2 (U) GIMBAL ASSEMBLY

(U) The Gimbal assembly contains antenna, motion measurement hardware, and front-end microwave components including the TWTA.

(U) The gimbal itself is a 3-axis gimbal custom designed and built by Sandia specifically for the Lynx radar. All components are mounted on the inner gimbal. The range of motion includes 5 to 60 degrees of depression angle, and –135 to +135 degrees of azimuth angle (with respect to the nose of the aircraft). Margins are built in to accommodate some degree of roll, pitch, and yaw of the aircraft.

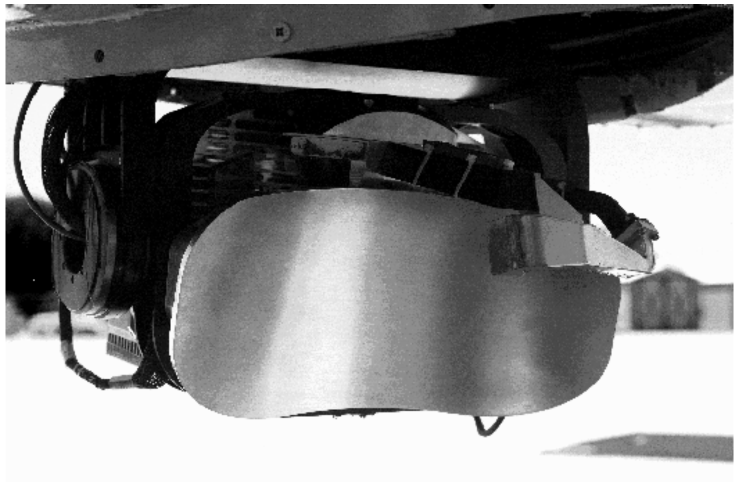

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Figure 7. (U) Lynx Gimbal Assembly

(U) The antenna was custom designed at Sandia specifically for the Lynx radar. It is a vertically polarized horn-fed dish antenna with a 3.2 degree azimuth beamwidth and a 7 degree elevation beamwidth as measured at the –3 dB points. Sidelobe performance was a major concern, and ultimately was held to better than –23 dBc in elevation and azimuth.

(U) Motion measurement is a Carrier-Phase-GPS-aided Inertial Navigation System centered around a Litton LN-200 Fiber Optic IMU. This is augmented by an Interstate Electronics Corporation GPS receiver.

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Figure 8. (U) Litton LN-200 IMU

(U) The front-end microwave components include a TWTA capable of outputting 320 W at 35% duty factor averaged over the Lynx frequency band, for pulses as long as 250 microseconds. Also included is an LNA that allows an overall system noise figure of about 4.5 dB.

4.0 (U) IMAGE FORMATION

(U) Image formation in all SAR modes is accomplished by stretch processing [2], that is, de-ramping the received chirp prior to digitizing the signal. After the ADCs, presumming is employed to maximize SNR in the image and minimize the load on the subsequent processors. The algorithm used thereafter is an expanded version of the Sandia developed Overlapped-Subaperture (OSA) processing algorithm[1], followed by Sandia developed Phase-Gradient Autofocus (PGA) [3]. Either complex images or detected images can be exported to View Manager software to allow manipulation by the radar operator.

(U) While OSA processing is currently implemented and is by its nature very suited to the parallel/pipeline processing environment of the signal processors, the general nature of the Mercury Computer nodes readily allows other image formation algorithms, and image processing techniques to be added or employed.

5.0 (U) MOTION MEASUREMENT/COMPENSATION

(U) Motion measurements are received from an Inertial Measurement system mounted on the back of the antenna itself. These are augmented by carrier-phase GPS measurements and combined in a Kalman filter to accurately estimate position and velocity information crucial to proper motion compensation in the SAR. This processing is done on a single Power PC processing node.

(U) The Motion Compensation philosophy for this radar is to perform compensation as early as possible in the signal path. Waveform parameters are adjusted, as well as pulse timing, to collect optimal data on the desired space-frequency grid. This is prior to digital sampling, and minimizes the need for subsequent data interpolation [4]. During image formation, residual spatially variant phase errors are compensated as spatial coordinates become available during OSA processing. Finally, any errors due to unsensed motion are mitigated by an autofocus operation.

6.0 (U) FLIGHT TESTS

(U) Flight tests began in July 1998 with the radar mounted in Sandia's DOE Twin-Otter manned aircraft, and continued through February 1999. The first flights in a GA Aeronautical Systems, Inc. I-GNAT UAV occurred in March 1999 and continue. To date, two Lynx SARs have been built by Sandia. GA is currently constructing a third unit, and will build all subsequent units.

(U) Training time for an operator to operate the radar is about 10 minutes, with reasonable proficiency in about 30 minutes. The ultra-fine resolution of the SAR allows target recognition and identification even by non-specialists.

(U) The SAR currently meets its image quality goals and routinely makes high-quality ultra-fine-resolution images. The first CCD images have been processed at the time of this writing. For GMTI mode, data has been collected and is undergoing analysis to adjust the processing for optimal performance.

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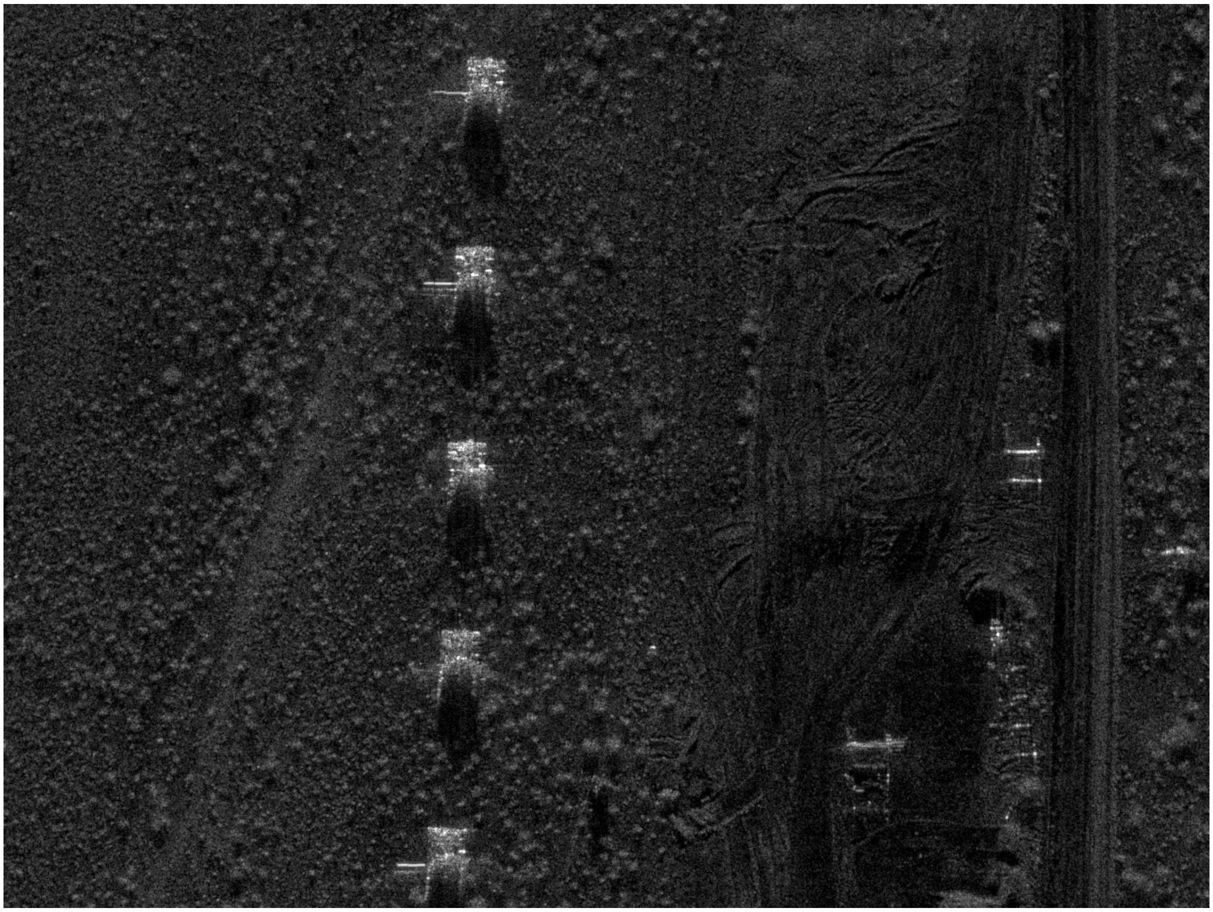
Figure 9. (U) Sandia National Laboratories DOE DeHavilland DH-6 Twin-Otter.



Resolution	0.1 m
Range	6.5 km
Depression Angle	17.3 deg
Squint Angle	82.8 deg
Platform	DeHavilland DH-6 Twin-Otter

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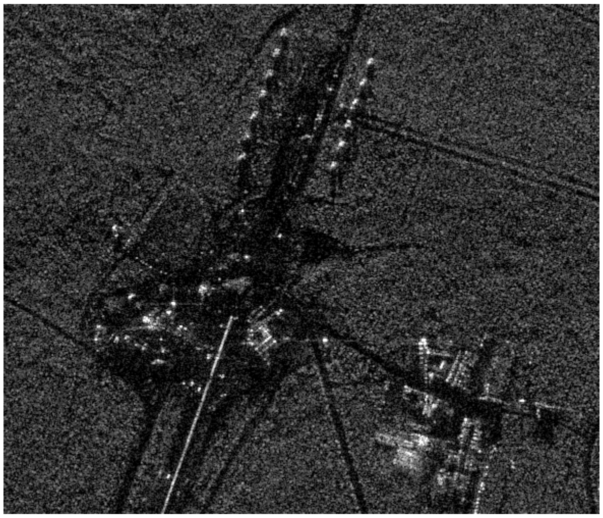
Figure 10. (U) M-47 Tanks on Kirtland AFB, Albuquerque, NM., February 8, 1999.



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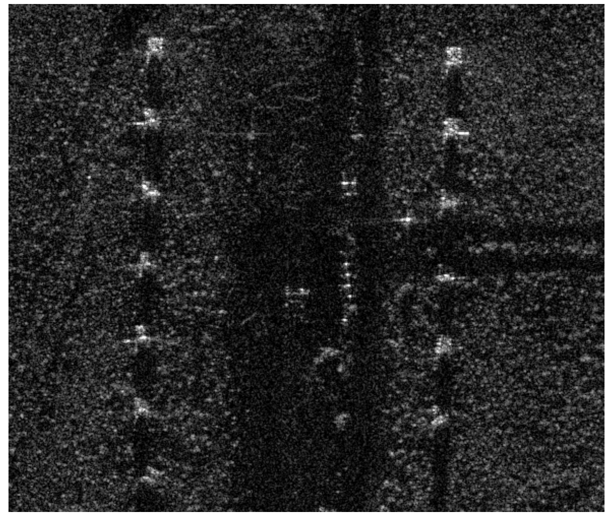
a. (U) Resolution = 1 m



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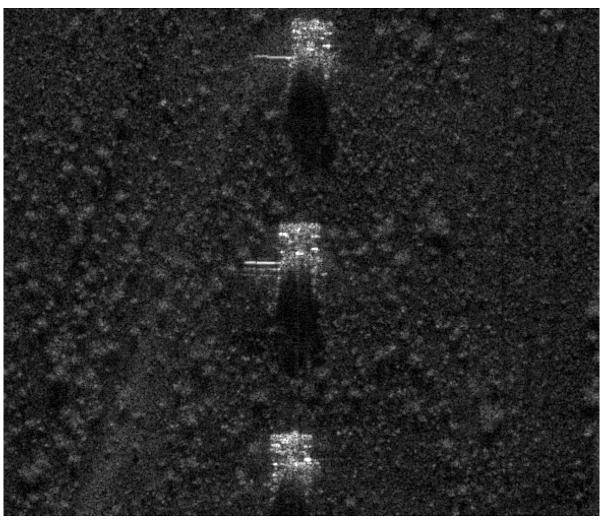
b. (U) Resolution = 0.3 m



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c. (U) Resolution = 0.1 m

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d. (U) optical photograph

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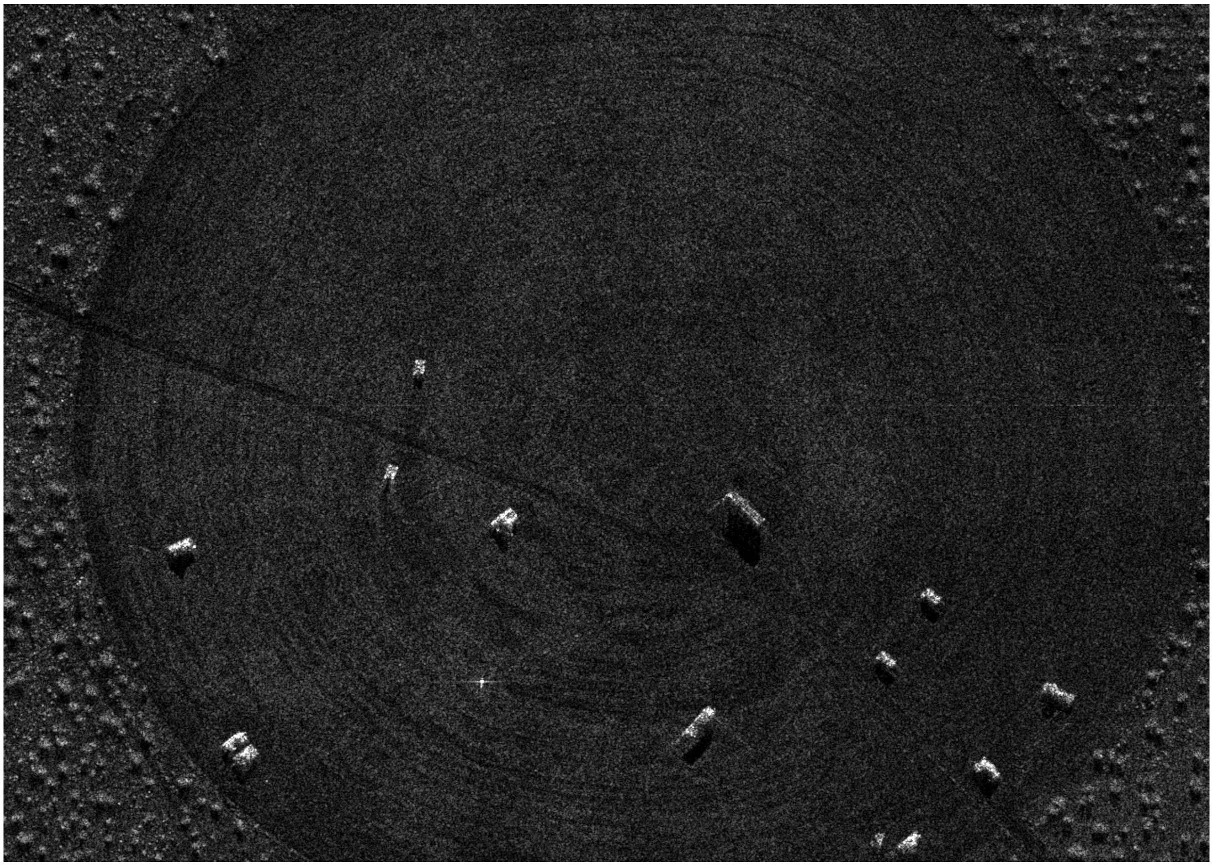
Figure 11. (U) Resolution comparison of M-47 Tanks on Kirtland AFB, Albuquerque, NM.



Resolution	0.3 m
Range	24.7 km
Depression Angle	20.5 deg
Squint Angle	133.3 deg
Platform	General Atomics, Aeronautical Systems, Inc. I-GNAT UAV

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Figure 12. (U) Edwards AFB, Precision Bombing Site 11, May 6, 1999.

7.0 (U) SUMMARY

(U) The combined expertise of General Atomics and Sandia National Labs has designed, built, and flown a new high-performance SAR known as Lynx. Lynx operates in the Ku band and features spotlight and stripmap SAR modes, a GMTI mode, and CCD. In spotlight mode it is capable of 0.1 m resolution, while in stripmap mode it is capable of 0.3 m resolution, over a wide range of flight geometries and dynamics. At the finest resolution in weather, Lynx has a slant range of 25 km, but at coarser resolution can be operated up to 45 km. It is designed to be operated on a variety of manned and unmanned platforms. All the image processing is done on board the in-flight vehicle and the imagery (real or complex) is downlinked from an unmanned platform. Phase histories and/or imagery may be recorded in a manned platform. No post-processing of the imagery is required (except CCD). The Lynx production weight is less than 120 lb. Lynx also features a novel user-friendly mode of operation that allows the SAR to be used like a video camera.

8.0 (U) ACKNOWLEDGMENTS

(U) Many other individuals, both at Sandia and at GA, provided crucial efforts towards making the Lynx SAR a reality. This was truly a team effort that transcended corporate boundaries. The authors wish to acknowledge them and thank them. It is a real pleasure to work with good people.

(U) Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

9.0 (U) REFERENCES

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