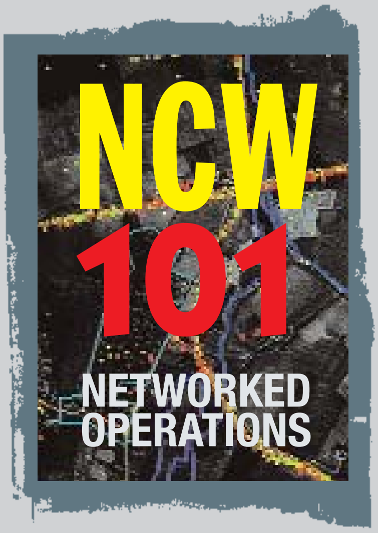

Synthetic Aperture Radar

NCW 101 part 7

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Of all of the technologies used for Intelligence, Surveillance and Reconnaissance (ISR) activities to support networked systems, Synthetic Aperture Radar (SAR) has proven to be the most useful for wide area coverage. Capable of penetrating adverse weather, including sandstorms, SAR provides a 'God's Eye' view of the battlespace typically from ranges well beyond the coverage of defensive weapons.

Radar reconnaissance has a long and colourful history dating back to the 1940s. Indeed, one of the earliest additions to bomber attack radars were 'scope cameras', designed to take a snapshot of the image being displayed.

Later, this technique was heavily used during the early years of the Cold War, when the US repeatedly probed and often penetrated Soviet airspace along key ingress routes to be used for nuclear strikes in times of war. The intention was to collect a library of radar images to provide a navigation aid for Strategic Air Command radar navigators should 'the balloon go up'.

All bombers and most fighter bombers built between the 1960s and mid 1980s were equipped with 'real beam mapping' radar modes for terrain mapping.

The Limitations of Real Beam Mapping

Real beam mapping is the simplest radar ground-mapping mode used. In a typical real beam mapping mode, the radar repetitively sweeps an arc firing pulse trains frequently enough to produce a viewable map of the terrain. Given the duration of the sweep could be of the order of a second, a persistent phosphor material was typically used on the Cathode Ray Tube (CRT) display, so that the image would remain discernable until the next sweep of the antenna.

All radar-imaging modes depend on the reflectivity of the terrain features and objects being imaged. Objects or terrain features which do not reflect well at a given wavelength will be poorly discernable or in extremis, appear as black holes.

OV-1D equipped with the massive APS-94 SLAR, an example of a high resolution real beam mapping radar. Note the sheer size of the sidelooking antenna.

Radar shadowing is a fact of life in complex terrain, as the image can only display that which is along a line of sight to the radar antenna. The prominent dark shadows behind hills, mountains or large buildings seen on radar images are the primary example of this effect. The extent of a radar shadow is dependent upon the elevation of the shadowing object, and the altitude of the aircraft carrying the radar. The taller the shadowing object and the lower the aircraft, the deeper the radar shadow will be. This is a basic side effect of geometry and a limitation inherent in all radars.

Most radars designed for surface mapping operate in the centimetric upper X-band or Ku-band. This is for good reasons. The first is that the radar signature of small objects, large objects with complex shapes and features, and the magnitude of terrain clutter is typically much higher in these bands than it is in the lower decimetric bands favoured for aerial surveillance purposes. Typically, the shorter the wavelength the better, as long as the frequency does not get too close to the water absorption peak of 22.235 GHz. Many dedicated bomber radars operate at 16 - 18 GHz, unlike multimode fighter radars operating at 8 - 10 GHz.

The second reason for choosing shorter wavelengths is resolution in real beam mapping modes. The bigger the antenna relative the wavelength of the radar, the narrower the beam that can be produced and thus the sharper the achievable picture.

The difficulty with all real beam mapping modes is that the resolution of the radar declines with distance, as the width of the terrain mapped by the beam increases. If a radar has an antenna mainlobe width of two degrees of arc, at one nautical mile the smallest feature it can resolve is about 65 metres in size, at ten nautical miles it is about 650 metres in size.

This limitation is inherent in the technology being used, and provided an impetus during the 1960s for the development of the first SAR technology radars.

The Vietnam War era X-band APS-94 Side Looking Airborne Radar (SLAR) carried by the OV-1 Mohawk is a good example in showing the lengths designers went to, pun intended, in maximising real beam aperture size, which proved highly effective in combat (see photo). The system recorded imagery on two 5 inch and one 9 inch film rolls. An interesting note is that an onboard system was used to develop the film in near real time and transmit imagery to a ground station via the UPD-2 datalink.

Synthetic Aperture Radars

The technology of the SAR emerged during the 1950s, with first examples built during the late 1950s. The first SAR used operationally was the Goodyear APS-73 carried by a specially modified GD B-58, serial 55-0668, carrying a reconnaissance pod with the radar, designated Quick Check. The system is claimed to have had a resolution of 50 feet at 80 nautical miles, and was used during the Cuban Missile Crisis. This system did not enter production.

The central idea in SAR techniques is to improve the angular resolution of a surface mapping radar by exploiting the motion of the aircraft, to emulate an antenna which is much larger than the physical antenna used - hence the term 'synthetic aperture'. In effect, the motion of the aircraft is used to create the effect of an antenna aperture hundreds or thousands of feet in length, which results in exceptional focusing ability.

The earliest SARs used optical processing, which used a combination of specially shaped lenses to produce the intended effect, painting the image on a strip of wet film in a cartridge. Many such systems, such as early SARs used for mapping the moon during the Apollo program, recorded the radar image, not unlike a hologram, onto film, and a ground station would then use coherent light from a laser and a projector equipped with special lenses to project the reconstructed high resolution image onto a viewing screen, or onto film. The bulk and weight, and inability to process in near real time, led to the introduction of digital SAR technology by the early 1980s. The then new APG-70 radar on the F-15E and APQ-164 radar on the B-1B were the first in any combat aircraft to use digital SAR processing, now de rigeur in most modern fighter and bomber radars.

The first SAR used operationally was carried over Cuba by a B-58 Hustler, the radar being carried in a special ventral pod.

To appreciate how a digital SAR operates it is necessary to explore the physics (refer Stimson, Introduction to Airborne Radar, page 404).

Consider an aircraft with a side-looking SAR antenna, travelling at 1000 ft per second or 600 KTAS. The radar fires 1000 pulses of microwave energy per second (1 kHz Pulse Repetition Frequency). These pulses travel away from the aircraft at the speed of light, and impinge on the mapped terrain, with reflected energy backscattering and travelling back to the antenna also at the speed of light.

What is the effect of the aircraft's forward motion? Between every transmitted radar pulse, the aircraft's antenna has moved a distance of one foot along the flightpath. Let us assume we aim to synthesise a 50 foot long aperture array. We must therefore collect 50 pulses. Assume we are mapping an area eight nautical miles abeam of the radar. The first pulse is received by the antenna when it has moved some distance, but the second pulse is received once it has moved an additional foot along the flightpath, and so on.

In a trivial, unfocused SAR design, the received pulses are digitised and stored in memory, divided into 'range bins', each 'bin' corresponding to a particular range relative to the flightpath. The received returns are progressively added to the range bins, as the 50 pulses are sent. The result is a strip of image perpendicular to the flightpath. This strip is then stored away in a memory buffer, and the process repeated to create another strip. In this fashion, a map is built up, 'line by line', with the effect of a 50 ft antenna aperture, but using a physical antenna, which might only be three foot wide.

This strip mapping technique is the simplest conceptual model for a digital SAR. It is also seldom used in practice since it is relatively ineffective.

Most SARs today use the more sophisticated focused SAR technique, which allows imaging at a given resolution independent of the range between the SAR and the imaged terrain. In a focused SAR, rather than using a single array of range bins to store radar returns, a large number of arrays is used, forming a matrix of range bins. As the aircraft moves, once an array of range bins is filled, another is started. Once the matrix is filled a computer will reconstruct the focussed SAR image, by not only summing up returns (as above) but also correcting for their relative timing (ie phase). This is also termed azimuth compression.

The focused SAR technique can provide for very fine image resolution, but can incur an enormous computational load. A technique termed Doppler processing can be used to reduce the computational effort and thus compute the picture many times quicker. For a typical example, this technique speeds up the computation more than a hundred fold.

Most SAR capable radars today provide a 'spotlight' mode in which the radar images some square or rectangle in space, and a strip mapping mode in which a swath is imaged.

There are few radars today, other than specialised ISR and mapping radars, which are designed from the outset as SARs. Rather, a SAR capability is added to an existing high performance X-band multimode radar.

Because the motion of an aircraft in space is not uniform, a high resolution SAR must correct for this. Typically this is achieved by adding an inertial reference sensor to the back of the radar antenna, so that the position of the radar in space is known very precisely over time, and thus any motion relative to an ideal straight line in space can be corrected when reconstructing the image.

Another requirement is for an extremely stable (coherent) master oscillator to generate the waveform produced by the radar, typically the more stable the oscillator, the finer the resolution achieved in the image.

Observant readers will have noticed an absence of discussion on range resolution. Extremely sharp range resolution is usually achieved by pulse compression, using chirping techniques. A prerequisite for this is that the radar receiver chain has good bandwidth performance, usually in excess of 100 MHz. Modern phased arrays usually achieve this.

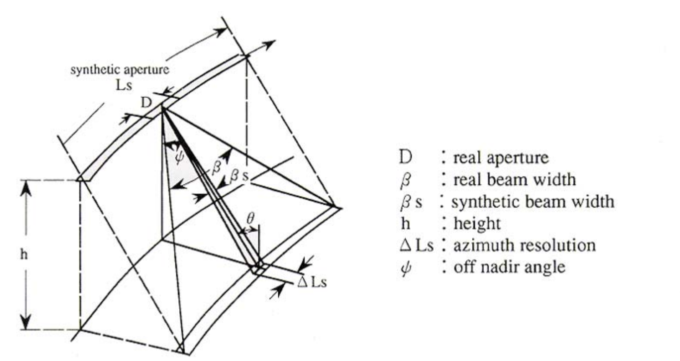


Figure 4.3.1 Relation between real aperture and synthetic aperture radar

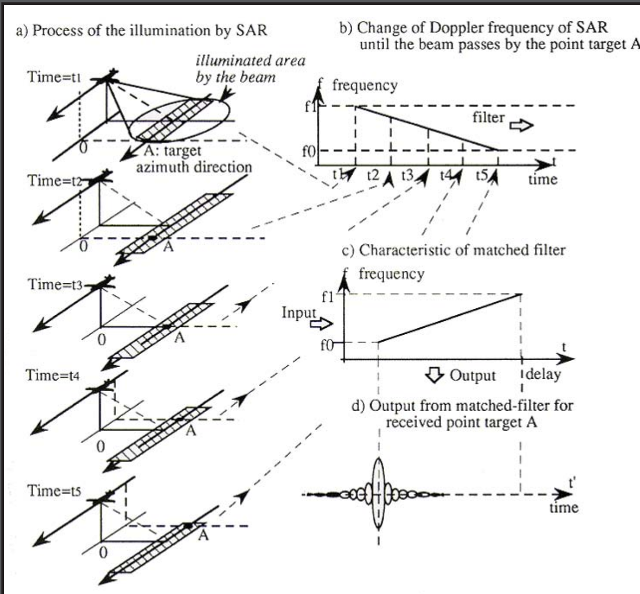


Figure 4.3.2 Basic theory of SAR using Doppler beam-sharpening(modified Fig.9.2 in 1)

(Japan Association of Remote Sensing

It is also important to note that for a SAR to work, the imaged area must have a velocity component normal to the radar, ie if the nose is pointing at the target SAR imaging cannot be performed. The author had an opportunity to experiment with this behaviour when flying the F/A-18F in 2001, and it was remarkable to watch the image quality rapidly degrade as the nose was pointed at the target to be imaged.

The emergence of high resolution SAR modes in recent fighter radars is a byproduct of cheap computing power, as the other design adaptations involving the master oscillator and inertial reference are relatively inexpensive add-ons to the design. In principle, a SAR-capable derivative of a modern fighter radar is not an unusually expensive adaptation. Any new-build legacy fighter today is apt to be supplied with this capability off the shelf, including the latest Russian N-001V and N-011M derivatives. A good case study was the introduction of SAR capability into the F-22A's APG-77 radar some years ago, achieved within the established budget for developing the earlier configuration without SAR, or in simple words, 'at no extra cost'. This was possible since the aircraft had an excellent inertial reference, exceptional bandwidth, surplus computing power, and a high stability oscillator required for other radar modes.

The resolution performance achievable in current SARs is exceptional, and best case is of the order of inches per pixel. This can be expected to incrementally improve over coming years, with the caveat that the wavelength of the radar itself will become the limiting factor in further improvement.

Interferometric SAR Capabilities

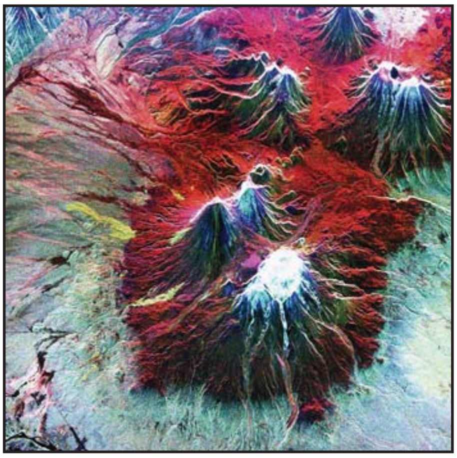
A technology that has emerged over the last decade, primarily in mapping applications, is the Interferometric SAR (I-SAR).

An interferometric SAR uses a pair of vertically displaced antennas, which permit the radar to discern the height of imaged objects. With appropriate post-processing of the raw radar data an interferometric SAR can produce three-dimensional maps of terrain, with resolution performance bounded by the performance parameters of the radar's oscillator, inertial reference and bandwidth.

Perhaps the most dramatic display of the capabilities of interferometric SAR was the Shuttle Radar Topography mission flown in February 2000, during which three dimensional topographic imagery for 80 per cent of the planet's surface was generated, using a pair of C-band (~5 GHz) antennas.

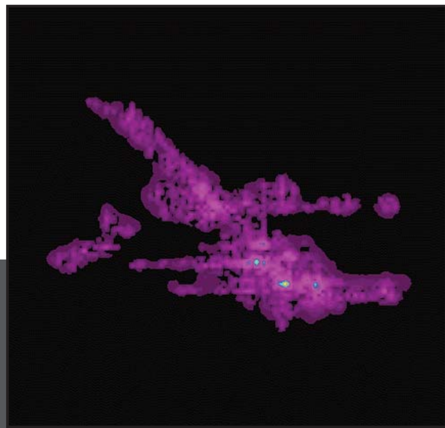
Dornier have built a number of interferometric SAR systems that have been used extensively for environmental and commercial mapping tasks.

This technology has yet to emerge in military applications. Adaptation of an existing multimode radar requires doubling the number of receiver channels and modifying the antenna feed networks to permit the upper and lower halves of a single antenna array to act as a separate pair of antennas. This is a relatively expensive modification, so it is likely that a military interferometric SAR will have to wait for a specific



Kamchatka imaged from low orbit by the Space Shuttle SIR-C radar, in false colour (NASA).

ISR application where the capability is essential. Such a SAR, if built with centimetre class resolution, could image arbitrary surface targets and effectively produce an exact three dimensional image of the target, permitting very accurate identification.



ISAR image of an aircraft, enhanced by Pixon Technology software.

Inverse SAR Capabilities

Inverse SAR (ISAR) is a technique that first emerged in maritime search radars as a means of identifying surface vessels by shape at long stand-off ranges.

Inverse SAR exploits the relative motion of the target with respect to the imaging radar. This motion is manifested in various parts of the target exhibiting different relative velocities, and thus different relative Doppler shifts in the frequency of the radar return. Whereas a conventional real beam radar would see a single return backscattered from the target, an Inverse SAR uses processing to separate these in space by measuring time and Doppler shift differences in the returned radar pulse.

Inverse SAR has also found applications in measurement, where it has been used to measure the radar signature of stealth aircraft in flight. A chase aircraft with an inverse SAR-capable radar formates in trail behind the target vehicle at close range, using a nose mounted radar to measure the signature. A tail-mounted radar is used to measure the forward sector signature of the target.

US sources also report that the F-22A's APG-77 radar has an inverse SAR capability, making it capable of imaging threat aircraft at long ranges well enough to perform identification to facilitate an attack.

The RQ-4A Global Hawk has been used extensively since the OIF invasion of Iraq, depicted is an example SAR images produced by the integrated suite.

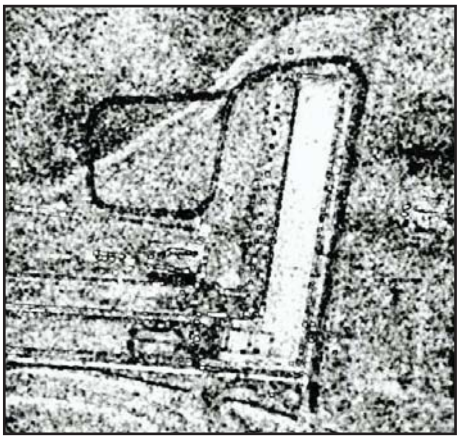
Coherent Change Detection Capabilities

Coherent Change Detection (CCD - not to be confused with imaging chips) is a technique which was first used for analysis of satellite imagery, and later introduced in the Predator's AN/APY-8 Lynx surveillance and mapping radar.

CCD relies on the idea of taking a high resolution SAR image from a specific point in space, and returning to that very same point at a later time, to produce yet another high resolution SAR image. These images are then compared pixel-by-pixel using software on a computer to produce a third image of detected differences between the images. The differences are then typically overlaid over one of the images using false colour, to highlight any observable changes.

The results produced by this technique are often remarkable, and features as indistinct as human footprints or tyre tracks can be discerned. When the US Air Force tried to use this method in Iraq to sweep highways for Improvised Explosive Devices (IED), they not only spotted IEDs but also every piece of trash or other garbage blown by the wind across the road, making the technique unusable in practice.

CCD is exceptionally useful for long-term surveillance, as repeated imaging runs over a long period of time allow a picture to be developed of what is being moved around or constructed in the area of interest.



Sandia Labs imagery using coherent change detection to detect vehicle tracks, colour image for comparison of viewed area.

The APY-3 on the E-8C JSTARS and ASARS-2 on the U-2 have proven themselves repeatedly in combat since 1991.

NCW 101
NETWORKED OPERATIONS

Deployed Systems

Since its humble beginnings in the Goodyear APS-73 of 1960, SAR has become almost ubiquitous in modern warfighting, and has played a critical role in conflicts since 1991.

The broadest division which exists between such radars is that of multimode and attack radars with SAR capability, designed primarily to support strike operations, and dedicated ISR radars intended to gather intelligence.

While resolution performance in some of the more recent multimode radars carried by fighters or bombers approaches that seen in dedicated ISR systems, they usually have limitations in processing capacity, data storage capacity, and they typically operate at 8-10 GHz which is less than ideal for detecting ground targets. A specialised ISR radar will be designed to gather more data, often from greater ranges, and may often operate in the upper X or Ku-Bands to improve target detection performance.

Examples of specialised ISR radars include the massive APY-3 on the E-8C JSTARS, housed in a 26-foot canoe-shaped radome under the fuselage, the ASARS-2 (Advanced Synthetic Aperture Radar System) carried by the U-2, the active array MP-RTIP (Multi-Platform Radar Technology Insertion Program) planned for use on the E-8, E-10 MC2A and RQ-4B Global Hawk UAV, the UK ASTOR system and the APY-8 Lynx on the Predator UAV. While the existing Global Hawk SAR and Predator Lynx have limited power and standoff range, the opposite is true of the APY-3 and its MP-RTIP replacement, both of which will have large effective footprints.

The view propounded by some parties in Australia that a fighter radar with SAR capability can provide 'JSTARS-like' capability is alas nonsense, since the sheer scale of the radars cannot be compared.

Multimode radars on fighters and bombers will be optimised primarily for localised spot mapping to support strike operations, with the exception of the F-22A's APG-77, which is intended to be used in a primary ISR role. Good examples of this class of radar include variants of the Raytheon APG-73/79 (F/A-18), NG APG-68(F-16), NG APG-80(F-16), NG APQ-164 (B-1B), Raytheon APG-70 (F-15), Raytheon APG-63 (F-15), NIIP N-001V (Su-27/30) and NIIP N-011M (Su-30/35), and a number of Phazotron radars.

What the future will bring will be more processing capability, higher resolution, and in time advanced features like interferometric capability. What is clear is that SAR technology will continue to play a key role in networked systems.