Inverse Synthetic Aperture Imaging

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ABSTRACT The accurate measurement of radar target scattering properties is becoming increasingly important in the development of stealth technology. This paper describes a low cost imaging Radar Cross Section (RCS) instrumentation radar capable of measuring both the amplitude and phase response of low RCS targets. The RCS instrumentation radar uses wide band waveforms to achieve fine range resolution providing RCS data as a function of range, frequency and aspect. With additional data processing the radar can produce fully focused Inverse Synthetic Aperture Radar (ISAR) images and perform near field transformations of the data to correct the phase curvature across the target region. The radar achieves a range resolution of 4 inches at S-band and a sensitivity of -70 dBsm at a 30ft. Range.

RADAR HARDWARE DESIGN The radar is configured as a very simple modular bistatic, CW/FMCW RF system attached to a software based signal processor. The radar transmitter can be either a synthesizer or sweeper for the band of interest. The transmitter power is normally between5 mw ad 100 mw. The transmitter power is fed through an isolator to an antenna, typically a standard gain horn. The receiver is connected to a second antenna. The radar uses separate transmit and receive antennas to provide isolation since both the transmitter and receiver are active simultaneously.

Several receiver configurations can be used in the radar. The most commonly used receiver is nothing more than a balanced mixer with the RF port fed by the receive antenna and the LO port fed by the transmitter. The IF port of the mixer drives an audio frequency preamplifier with 50 dB gain, followed by an anti-aliasing filter and an Analog to Digital Converter (ADC) mounted in the computer. The mixer forms the mathematical product of the transmitter and received signals. This receiver configuration operated at up to 30,000 samples per second when used with a DAC controller sweep oscillator transmitter.

The radar can be treated as an interferometer with the mixer forming an output related return signal at the mixer output can be derived as a function of θ, the phase difference between the signal and LO mixer inputs.

$\theta = 2\pi r/\text{lambda}$ Where: r = path length lambda = wave length

The mixer output is the product of the transmitted signal (LO port) and the path delayed replica (received signal) with appropriate loss terms included:

$Eo = \sin(2\pi(c/lambda)(t)$ (LO signal)
$K \sin(2\pi(c/lambda)(t)+ \theta)$ (Received signal)

c = propagation velocity t = time K= range and other losses

Using the cosine product rule:

$Eo = .5K \cos(\theta+(4\pi(c/lambda(t)$ (Sum frequency)
$-5K \cos(\theta)$ (Diff Frequency)

The upper sideband which is in the microwave spectrum is not passed by the audio frequency preamplifier, resulting in the mixer output to the computer being the lower sideband:

$Eo = -5K \cos(2\pi r/lambda)$

Notice that the receiver output signal phase is only a function of the path length and wavelength, and is not a function of time. If the RF frequency i linearly stepped at an arbitrary rate, a sampled cosine wave will be produced at the mixer output. The mixer output can be compressed into an equivalent pulse in the range domain by performing a spectral analysis with a Fast Fourier Transform (FFT). This operation is know as pulse or range compression.

The mixer output corresponds tot he inphase (I) or real signal component of the radar return. The quadrature (Q) signal component can be obtained by a variety of techniques. The classical method uses a second mixer channel fed by a 90 degree hybrid, however other quadrature extraction techniques can provide significant advantages.

The quadrature (Q) component can be derived from a single mixer by using a broad band 90 degree phase shifter at the mixer output if any positive or negative frequencies are present. This is true if the target is nearly stationary, unaliased and at a positive range or can be pulse gated to those requirements. The broadband phase shifter can be readily implemented in software by a Hilbert transform. This configuration provides very high phase accuracy with a minimum of hardware.

The quadrature signal can also be obtained by performing a single sideband upconverion using a computer controller phase shifter ahead of an I channel receiver and then performing a quadrature detection in the computer.

This configuration supports CW operations and with over-determined phase shifts can be self calibrating.

The radar achieves a -70 dBsm sensitivity at a 30 ft. Range using a 10 milliwatt transmitter with the single mixer, Hilbert transform receiver. This sensitivity is achieved by using a high pulse compression ratio with the receiver operating in a spread spectrum, matched filter mode. With a transmitter sweep width of 2 GHz, the equivalent of a .5 nanosecond pulse is synthesized resulting in a range resolution of 3 inches. The RF chirp is integrated for 0.2 seconds in the receiver signal processor resulting in a pulse compression ratio of 108. This operation is equivalent to coherently averaging 108 10mw pulses. The result is high sensitivity with simple low power transmitter.

The majority of the radar is implemented as a software based signal processor running in a DEC PDP-11/73 microcomputer. The minimum computer configuration includes a color graphics terminal, a plotter, 2500 Kbytes floppy disks and 128 Kbytes of RAM memory. For extensive ISAR and nearfield processing, a 40 Mbyte Winchester disk and 512 Kbytes or more of RAM are recommended.

SOFTWARE The radar signal processing software is written in a heavily modified version of polyFORTH. The FORTH programming environment provides significant advantages over conventional operating systems, providing full operator and data type extensibility, virtually unmatched interactive program development and unusually compact code. For example, the complete macro assembler source code for the PDP-11/37 computer is less than 2 pages long. The FORTH environment is somewhat like a cross between APL, LISP and the RPN Hewlett-Packard calculators.

The radar program structure is based on state space methods to generate a highly modular program with a clear structure. Central to the state space design is a set of 3 vectors. A minimum and non-redundant set of parameters which define the radar setup and environment form the 1st vector called the state vector. Processed radar returns which are a function of the state and measurement vectors are saved in the derived measurement vector. The state and measurement vectors may be saved to disk for later use. The derived measurement vector can be derived from the state and measurement vectors when required and need not be saved to disk.

The radar signal processor program is written as a set of modules which communicate through the three data vectors.

These modules include:

1. STATE VECTOR EDITOR: The state vector editor provides a human interface to the radar software allowing the user to display and modify the state of the radar. The state editor is implemented as a tree structure menu system.

2. DISPLAY PROCESSOR: The display processor generates graphics and listing displays of data in the state, measurement and derived vectors.

3. DERIVED MEASUREMENT UPDATE: This module updates the derived measurements vector from the state and measurement vectors. The module includes most of the signal processing functions including the Fourier, Hilbert and ISAR transforms.

4. DATA RECORDER: The data recorder saves and restores the state and measurement vectors for later analysis.

5. DATA AQUISITION MODULE: This module acquires the radar return from the actual radar hardware, leaving the results in the measurement vectors. Different data acquisitions modules are used with different hardware configurations.

6. TARGET SIMULATOR: The target simulator generates simulated radar returns for all radar configurations modes based on a target model defined in the state vector.

7. SYSTEM INTEGRITY MONITOR: The System Integrity Monitor (SIM) uses AI expert systems techniques to monitor the health of the hardware and software and provide recommended fault recovery procedures. The SIM also uses the target simulator data base to provide expert guidance in correctly configuring the radar for the required application. As examples, the radar will recommend optimal frequency and aspect sampling densities to meet the Nyquist criteria and check for nearfield violations. During radar setup and operation to SIM continually monitors the radar parameters providing real time recommendations and warnings of potential problems.

The RCS radar program can be used easily reconfigured to operate with a variety of microwave sources such as synthesizers and sweepers and a variety of receivers ranging form simple mixers to SA-1780 receivers. In the following description of program operation, the most common HP-86290B sweeper / simple balanced mixer receiver configuration is assumed.

The radar uses a pair of data buffers in the computer memory to store 2 radar returns. One radar return includes the object under evaluation along with a clutter environment, the other return is of the clutter environment only. The 2 returns may be vector subtracted resulting in a coherent MTI suppression of the clutter signal component. The 2 data buffers can be loaded by the radar hardware, a radar signal simulator or from copies of the 2 data buffers previously saved to disk.

The instantaneous frequency of the microwave sweep oscillator is controlled by a Digital to Analog Converter (DAC) located in the computer. Simultaneously, the radar return is acquired by an Analog to Digital Converter (ADC) and moved into 1 of the 2 data buffers for MTI clutter suppression. The data acquisition process is initiated in phase with the 60 Hz power line to coherently reject power line interference if present. The signal acquisition occurs at up to 30,000 samples per second.

At this point the target + clutter, clutter or MTI enhanced target return may be plotted, listed or statistically analyzed. A warning message is displayed if the ADC has saturated. The 2 data buffers are saved to disk for processing at a later time.

If aspect, ISAR or nearfield processing is required, the radar acquires a set of measurements of the target over a range of aspect angles. The target aspect is controlled by the computer through the use of a software based servo loop. The servo senses the target aspect using a resolver or optical encoder and generates target rotator velocity commands to minimize the servo error.

A simulated radar return may be generated and added to existing data in the measurement vector. The target simulator is used to support target modeling, software development and operator training. The simulator can simulate point, clutter and sphere targets. The sphere backscatter, simulator models the Raleigh, resonance and optical response regions.

The point target simulator operates by transforming a simulated target attached to a target rotator model into the radar reference frame. The mixer input at the RF lower band edge is then computed as a complex phasor with the amplitude based on the radar range equation and the phase based on the total path length. The derivative of this phasor with respect to frequency is then computed. The two phasors are used to initialize a Cordic difference equation for which the solution is the desired radar return.

Amplitude and frequency errors in the radar return due to RF source errors can be corrected by a complex multiplication between the radar signal and a complex weighting function. This operation is similar to SAR focusing, except this operation :focuses” the pulse compressor.

The radar signal as functions of RF frequency and range area Fourier transform pair. The I channel receiver output for a point scatter during a linear RF sweep will appear to be a constant frequency sine wave. A Fast Fourier Transform is used to convert the constant frequency to an equivalent sin(x)/x pulse in the range domain. A convolutional window (typically Hanning) is applied in the range domain to reduce the range sidelobes of the compressed pulse. A range loss prewhitening filter is then used to convert quasi-monostatic received power into RCS. The RCS may now be plotted as a function of range.

To determine the target RCS or phase properties as a function of the microwave frequency, additional processing is required. A range gate centered in the region of interest is applied to the Fourier transformed data. The rangegate is a range band pass filter and is implemented as a vector product between the range domain radar signal and a window vector.

The quadrature (Q) channel of the radar signal is derived to simplify the amplitude and phase demodulation process. The quadrature signal when combined with the in phase (I) signal is known as a pre-envelope or analytic signal and can be derived by a broad band 90 degree phase shifter if negative frequency components are not present.1.2 The broad band 90 degree phase shifter is implemented as a Hilbert transform in the range domain by:

$$H(r) = -j \operatorname{sgn}(r)\, G(r)$$

The range gated, Hilbert transformed, range domain analytic signal is inverse Fourier transformed, resulting in a range filtered frequency domain analytic signal.

The real and quadrature Fourier domain signals can be processed simultaneously by combining the Hilbert and inverse Fourier transforms. The real and imaginary signal components are orthogonal allowing the previous equation to be summed with G(f) resulting in:

$$G(r) + j\,H(r) \begin{array}{l} = 2\,G(r),\ r<0 \\ = G(o),\ r=0 \\ = \qquad\ ,\ r=<0 \end{array}$$

This equation states that a complex return can be recovered by taking a single sided inverse Fourier transformed of the range gated data. The resultant complex return is a rotating phasor. The analytic signal allows the instantaneous demodulation of the amplitude, phase and time delay information present in the radar signal. The amplitude and phase can be recovered by converting the analytic signal to polar form. The magnitude of signal is the instantaneous RCS of the target as a function of frequency.

The phase of the analytic signal carries additional information about the target. If a point target with a Raleigh response is measured and the phase shift due to path length is subtracted from the return, the residual phase shift is due to sweeper non-linearity, antenna dispersion and similar effects. The complex reciprocal of this signal with Raleigh correction can be used as a normalizing function to correct radar returns for antenna dispersion, sweeper power and frequency linearity errors.

Motion of a point target will change the received phase. A 3.6 degree phase shift corresponds to a change in target range of 0.005 lambda or at X-band approximately 0.006 inches. Very precise measurements of phase centers and phase flatness can be made by target phase measurements. This capability is useful in range alignment applications and range stability checks.

Complex targets can appear to be at varying range as a function of the instantaneous transmitter frequency the target group delay or instantaneous range as a function of RF frequency can be measured.

Inverse Synthetic Aperture Radar (ISAR) produced images of the target region can be a useful tool in locating scattering regions on the target. ISAR images are produced by rotating the target and processing the resultant doppler histories of the scattering centers.3 If the target rotates in azimuth at a constant rate through a <u>small</u> angle, scatters will be approaching or receding from the radar at a rate depending <u>only</u> on the cross range position. The cross range position is distance normal to the radar line of sight with the origin at the target axis of rotation. The rotation will result in the generation of cross range dependent doppler frequencies which can be sorted by a Fourier transform. This operation is equivalent to the generation of a large synthetic aperture phased array antenna formed by the coherent summation of the receiver outputs for varying target / antenna geometries. For small angles, an ISAR image is the 2 dimensional Fourier transform of the received signal as a function of frequency and target aspect angle.

If the target is rotated through large angles, the doppler frequency history of a scatter will become non linear, following a sine wave trajectory. This doppler history can not be processed directly by a Fourier transform because of the smeared doppler frequency history which results in the loss of cross range resolution. The maximum rotation angle which can be processed by an unmodified Fourier transform us determined by the constraint that the aperture phase error across the synthesized aperture should vary by less than an arbitrary amount, usually 45 degrees. This occurs when the synthetic aperture to the target range is less than required by the 2D2/lambda limit where D id the required lateral extent of the target. At this point the synthetic aperture is within the target nearfield region and requires focusing. The focusing is accomplished by applying a phase correction to the synthetic aperture.

The radar signal processor program uses several different algorithms to produced fully focused ISAR transforms. For very large scan angles, up to 360 degrees, the radar performs a direct integration in the region of interest. Cordic difference equations are used in conjunction with a band limited decimation of the range gated radar return to substantially improve computational efficiency.

The radar image can be viewed during the integration process. Note that with large scan angles, 2 dimensional CW imaging becomes possible because the cross range axis rotates with the target aspect angle.

Fully focused 2 dimensional images can be produced for objects of arbitrary width and depth and if a height which does not violate the 2D2/lambda limit. Objects suited to these requirements include missiles and aircraft. If targets have excessive height, a 3 dimensional ISAR image is required. The fully focused 2D ISAR image is a planar representation of the RCS scattering centers in complex form, with phase front distortion removed.

Errors in the ISAR imaging process generally result in defocusing and geometry errors in the image. ISAR transform errors include:

1. UNKNOWN TARGET OR ANTENNA MOTION: Unmodeled motion will cause the target image to defocus and be at an incorrect location. This error is controlled by suitable mechanical design or by the use of auto-focus techniques. This error can be measured by the analytic signal phase measurement method described earlier.

2. VERTICAL NEARFIELD ERRORS: Unless 3D ISAR is performed, the vertical target extent at right angles to the horizontal synthetic aperture must fit within the vertical far field limit. Tall targets will defocus and move to incorrect positions. The 2D ISAR representation of a target region is a planar surface.

3. INTEGRATED SIDELOBE RETURN: ISAR image quality is degraded by range and azimuth compression sidelobes. The sidelobes are due to data truncation and can be reduced by the application of appropriate window functions. The sidelobes can cause significant image degradation. First, the peaks of the stronger sidelobes may cause a string of progressively weaker targets to appear on either side of a strong target. Second, the combined power of all sidelobes tends to fog or washout detail in low RCS areas. The integrated sidelobe level can under poor conditions reach a level 10 dB below the peak target return.

4. FREQUENCY AND AZIMUITH SAMPLING ERRORS: Incorrectly selected frequency or aspect deltas will result in aliased images, creating spurious targets. The SIM program described earlier specifically monitors for aliasing errors effectively eliminating this error source.

5. ANTENNA ABERRATIONS: Aberrations in the geometry result when the antenna phase center position is dependent upon the antenna aspect or RF frequency. This error source is normally controlled by using small, simple antennas over narrow frequency bands at long ranges. First order corrections to frequency dispersive antennas such as log periodics can be handled by phase

correcting the received signal. Full correction of the aberrations can be accomplished by a direct integration of the ISAR transform using the aberrated geometry.

6. TARGET DISPERSION: Dispersive targets have a non-minimum phase response, appearing to shift in position with RF frequency Examples of dispersive targets include RF absorbers in which the absorption depth is a function of frequency and various antenna in which the phase center position is frequency dependent. CW ISAR imaging or in some cases preprocessing prior to a FMCW ISAR transform an eliminate dispersive defocusing of the target image.

MULTIPATH: Multiple reflections can result in ISAR imaging distortions such as the classic ghost image trails from jet aircraft tail pipes.

The ISAR transform converts RF data as a function of aspect and frequency to an image consisting of RF data as a function of range an cross range. The ISAR images can be gated in both the range ad cross range dimensions, to select a region of interest. An inverse ISAR transform can be computed resulting in 2 dimensionally gated RF data as a function a frequency and aspect. The earlier described radar target simulator essentially performs the inverse operation of the ISAR transform and can be considered to be an Inverse ISAR transform.

A technique for transforming radar data acquired at a given location in space to another location in space (i.e., the form the near-field to the far field) is to form a fully focused ISAR image of the target region and then use that image as a target model. The target model can be evaluated directly to be passed to the radar simulator and then be reprocessed by the radar.

The classical method of transforming a set of FMCW radar measurements to an ISAR image is the unfocused or planar wave-front 2 dimensional Fourier transform. N inverse 2 dimensional Fourier transform will convert a focused ISAR image to the equivalent far field returns.

If processed over the appropriate aperture angles, the image contains the required information to reconstruct the target response at certain other positions in space which could include the far field. The ISAR image represents a scattering plane which can be illuminated by a radar. The energy at any arbitrary point in space ca determine as a consequence of Huygens principle. The validate and limits of this technique are determined by the planar approximation of the target region.

Errors in the 2D planar Inverse ISAR transform include:

1. IMAGE BLOCKING MODELING ERRORS: The Inverse ISAR transform currently assumes that scatters are on a planar surface an cannot block other scatters.

2. IMAGE MULTIPATH MODELING ERRORS: The Inverse ISAR transform currently does not model the multipath environment. Note the current ISAR transforms also do not correctly process multipath.

If a forward and then an inverse ISAR transform of a target environment is performed with the same geometry and frequency parameters, no change to the radar signals will occur. This is true even for multipath and dispersive environments since transforms neither add or delete any information, they only change the reference frame. As the state vectors (geometry, frequencies, etc.) are changed between the forward and inverse ISAR transforms, the derived radar signal accuracy will degrade gradually.

CONCLUSIONS A powerful yet low cost imaging radar has been described. The radar uses a simple hardware configurations with a computer based signal processor to provide RCS amplitude and phase measurements, ISAR radar images and near field transformations of the data. Technique of processing ISAR images and then performing Inverse ISAR transforms to derive far field results for a large class RCS targets has been defined.

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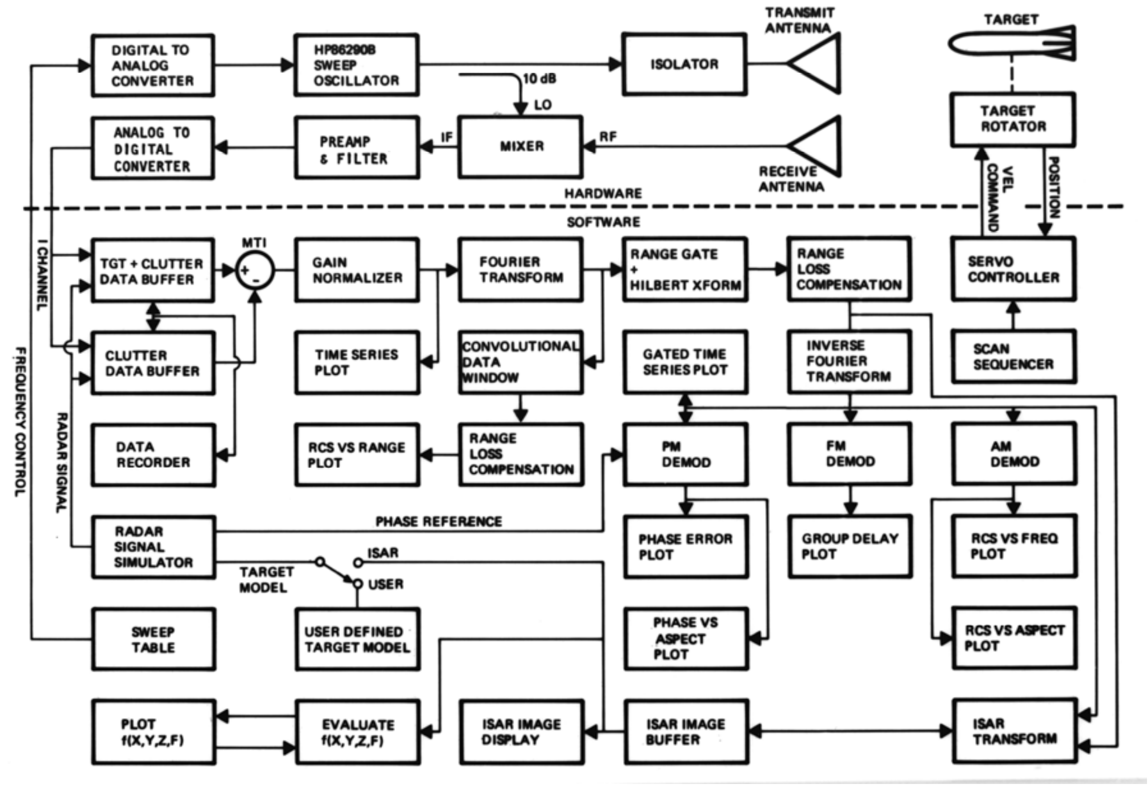

Figure 1. Radar System Block Diagram