Multi-Aspect Radar Algorithms (MARA) Study

Contract Number N00014-C-09-0440 Progress Report Number Q003

Period: September 1, 2009 through November 30, 2009

Prepared for:
Dr Michael Pollock
Office of Naval Research Code 312
One Liberty Center
875 North Randolph Street
Arlington, VA 22203-1995

Submitted By:
Sci-Teq, Inc.
Worldgate Plaza IV
12801 Worldgate Drive
Suite 500
Herndon, VA 20170

Sci-Teq, Inc. Points of Contact:
Technical: Mr. James K. Hall 703-627-2063; Mr. Donald Coleman 949-677-7619
Contract & Business Matters: Ms. Myrna Hall 703-871-3998

This Document is Unclassified

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Multi-Aspect Radar Algorithms (MARA) Study**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Sci-Teq, Inc.,Worldgate Plaza IV,12801 Worldgate Drive, Suite 500,Herndon,VA,20170**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**43**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Sci-Teq, Inc.

Sci-Teq-MARA-003-11-09
30 November, 2009

Office of Naval Research
ATTN: Dr. Michael Pollock, ONR-312
Michael.Pollock@navy.mil
One Liberty Center
875 North Randolph Street, Suite 1425
Arlington, VA 22203-1995

Subject: Contract Number N00014-09-C-0440, Sci-Teq, Inc, "Technical and Financial Progress, Quarterly Report". Report Number Sci-Teq-Q003 dated 30 November, 2009.

Reference A: Contract Number N00014-09-C-0440, Contract Line Item Number (CLIN) 0001, Contract Data Requirements List (CDRL) Exhibit A, Data Item Number A001.

Enclosure (1): Technical and Financial Progress, Quarterly Report Number Sci-Teq-Q003 dated November 30, 2009

In accordance with the reporting and data distribution requirements identified in Reference A, Sci-Teq, Inc. is pleased to provide Enclosure (1) "Technical and Financial Progress, Quarterly Report" for your review and retention.
Should you have any questions or require additional information of a technical nature, please contact Donald Coleman at 949-677-7619, email: coleman.don@att.net or for questions of a programmatic nature please do not hesitate to contact the undersigned at 703 871-3997, email: jkhall@sci-teq.com.

Sincerely yours,

James K Hall

James K. Hall
Vice President
Sci-Teq, Inc

Distribution: *Administrative Contracting Officer
Attn: Mr. Ronald Rembold
DCMA Virginia
Ronald.Rembold@DCMA.Mil

Director, Naval Research Laboratory
Attn: Code 5596
4555 Overlook Avenue, SW
Washington, D.C. 20375-5320
E-mail: reports@library.nrl.navy.mil

Defense Technical Information Center
8725 John J. Kingman Road
Suite 0944
Ft. Belvoir, VA 22060-6218
E-mail: tr@dtic.mil

* Transmittal Letter Only.

Sci-Teq, INC. • 12801 Worldgate Drive, Suite 500.• Herndon, VA 20170
(703) 871-3997 • Fax: (703) 481-1083

Table of Contents

List of Figures

List of Tables

Multi-Aspect Radar Algorithms (MARA) Study: Contract Number N00014-C-09-0440
Progress Report Number 3 for Period: September 1, 2009 through November 30, 2009

1.0 Executive Summary

Sci-Teq, Inc. submits this report as the third quarterly report on the 18 month study entitled "Multi-Aspect Radar Algorithms (MARA)". The MARA research study is investigating and defining a surveillance system concept for a net-sentric surveillance sensor system. The system will be comprised of multiple, geographically dispersed, multi-band, multi-static Inverse Synthetic Aperture Radar (ISAR) imaging sensors with co-located ESM sensors.

The operational objective of these multi-sensor net-worked systems is to provide area surveillance of maritime traffic with an inherent classification/identification capability through the use of multi-static radar image generation augmented with electromagnetic signature detection and correlation. The networked surveillance system concept would be implemented using a COTS line-of-sight wireless network and GPS time to coherently synchronize and event-time the sensors operating on the network when conducting multi-static data collection and generation. The research study is defining and evaluating algorithms for the generation and processing of the multi-aspect ISAR data from the multi-static radar systems operating within the network. The capture of multi-static, multi-aspect target data is expected to significantly improve the quality and fidelity of the ISAR imagery that is made available to the network for target classification and identification purposes.

The research study is also investigating and defining an architecture and design for a data collection radar system to be implemented with Commercial-off-the-Shelf (COTS) subsystems. The data collection radar system design to be realized from this study, if implemented in hardware, would provide a limited laboratory and range test configuration for the collection of data and operational concept evaluations. These data could then be used to support development and validation of algorithms that provide multi-static ISAR image generation and correlation, use of GPS timing for radar waveform synchronization and event time management with a net-sentric surveillance communications system.

The network will serve to time synchronize and control the operations of the multi-static radars during multi-static data collection testing and operations. Multi-static data collected with the ISAR test configuration will be off-line processed using multi-static imaging algorithms developed under the MARA research study. The MARA algorithm suite could be applied and evaluated with real target radar data. Critical algorithms will focus, polar reformat and correlate multi-static ISAR data for feature extraction and high fidelity image generation as a means to accurately identify maritime targets.

The MARA project studies will also define a system of AESA based radars and Electronic Support (ES) surveillance (ES) sensors that could form an operational sensing network capable of surface surveillance coverage to the horizon, image-while-search, and independent or unified ISAR operations. All systems operating within the network will be phase-locked and time synchronized and will provide all radar imagery and corresponding ESM intercept information to all units on the network including the unit designated as the primary sensing and processing node.

2.0 Introduction

The MARA research study is comprised of system studies, that: investigate and identify operational applications and capabilities for a net-sentric surveillance system; identify representative target sets, their features and characteristics; address algorithm definitions and designs and; address the development and implementation of modeling and system simulations needed to conceptualize and evaluate a dispersed set of multi-band, multi-static ISAR systems operating within a wireless line of sight network. The net-sentric surveillance system addressed in this study is based on a modular open system architecture that will enable low risk technology insertion(s) as needed in the future and will facilitate integration of other sensor technologies and systems such as concurrent ES sensor data collection to enhance situational awareness and wide area surveillance and tracking capabilities.

The MARA research is emphasizing investigations that will provide the basis for development and optimization of: net-sentric surveillance system concepts; algorithms for system control, ISAR data exploitation, information fusion, image formation and maritime target identification. Target models and dynamic system simulations are being developed to aid in identifying and quantifying requirements for system control, synchronization, data gathering and formation of high fidelity images derived from a dispersed set of multi-band, multi-static ISAR systems operating within a cooperative network.

Sci-Teq has developed models to support analysis, focusing and correlation of multi-static radar signals from maritime targets. A radar data collection system design has identified an approach to implement limited capability multi-static ISAR radars that can be used to collect multi-static radar signals in a limited range limited test environment for use in stimulating imaging and correlation algorithms with multi-static received ISAR signals. A summary of this design follows:

MARA Data Collection System

The MARA data collection system design is characterized as multiple radars that operate as mono-static or multi-static sensors to gather ISAR data that can be off-line processed to generate focused images and correlate multi-static images to characterize improvements in image quality over that of conventional mono-static ISAR imagery. The data collection radars are configured with COTS assemblies where practical and implemented with parameter sets consistent with data collected from land site radars against maritime shipping targets in an identified test area. The resulting design description follows:

- **Data Collection Radars - Multiple (2 to 3), Dual band (X and Ku) radars, each with following designs:**
    - Dual mode radar operation
        - Search and Detection - Pulse Doppler with 100 MHz chirp waveforms
        - ISAR Data Collection - Stepped frequency with 100 MHz chirp
    - Common aperture antenna for sequential X-band and Ku-band data collection
    - Common RF power amplifier for X-band And Ku-band
    - Common PLL Signal Source for up-conversion/down conversion to and from X-band/Ku-band
        - Provides 8 or 16 step frequency LO signals over 500 MHz or 1500 MHz RF bandwidth
        - Accommodate LO settling time during pulse-to-pulse step frequency

  - Common broadband mixers for IF conversion to X-band or Ku-band
  - Use of DDS to generate precise 100 MHz linear FM chirp waveforms
  - Quadrature mixer for baseband I and Q analog receiver outputs
  - Digitizing received signal with dual channel ADC for I & Q outputs
    - 12 Bit conversion of I and Q signals over range interval of interest
      - Range interval for detection ~ 1 nautical mile
      - Range interval for ISAR data collection ~ 800 feet
    - Sampling rates ~ 160 MSPS (capable up to 500 MSPS)
    - Integrated FPGA with ADC modules used for chirp signal processing
- **Data Collection System Timing and Frequency Synchronization**
  - Use of GPS receivers at all data collection radar sites
  - GPS one PPS precise timing used as master timing reference
  - GPS disciplined oscillators at GPS receivers provide synchronized and stable reference frequency at ~ 10 KHz
    - Frequency accuracy and phase noise control
    - Timing accuracy and time jitter control
  - Precision frequency multipliers generate references used in the radar for synchronized frequency/phase control.
    - PRI timing and phase reference for direct digital synthesizers
    - Frequency references for up-conversion, down-conversion circuits
    - Timing reference for received signal range sampling window
    - Timing reference for dual channel digitizer ADC
    - Timing reference for FPGA control of DDS, ADC, received data storage, chirp pulse compression, and Doppler detection or data acquisition of ISAR signals.
- **ENCOM 5.8 GHz Wireless Network**
  - Characteristics
    - Operating Frequency Range: 5.25 GH - 5.875 GHz
    - Multiple Security/Encryption Options:
      - A ES-CCM Encryption; 64 bit,
      - 128 bit Wired Equivalent Privacy (WEP) Encryption;
      - Wi-Fi Protected Access (WPA and WPA2);
      - Temporal Key Integrity Protocol (TKIP);
      - Mac RADIUS Server authentication;
      - Extensible Authentication Protocol-Transport Layer Security (EAP-TLS)
    - Multiple Data Rates; 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 48 Mbps, 54 Mbps and 108 Mbps Through Air Rates
    - Multiple Networking Features/Options:
      - Supports Internet Group Management Protocol (IGMP) snooping;
      - Spanning Tree Protocol (STP);
      - Dynamic Host Configuration Protocol (DHCP) Server or Client;
      - Network Time Protocol (NTP);
      - Firewall and Network Address Translation (NAT);
      - Routing; Quality Of Service (QOS);
      - Virtual Private Network (VPN);
      - Virtual Local Area Network (VLAN);
      - Simple Network Management Protocol (SNMP);

            - Bandwidth test tool
        - Hardwired Interface: Industrial Weatherproof 10/100 Base-T Ethernet
        - Wireless Interface: 802.11a or EN-Stream, ENCOM Proprietary protocol
        - Dynamic Frequency Selection: 5 MHz, 10 MHz, 20 MHz and 40 MHz channels available
        - Antenna alignment tool available via software
        - Network Management:
            - Internet Protocol **(**IP**)** discovery tool with remote management;
            - Remote Secure Shell **(**SSH**)**;
            - Simple Network Management Protocol **(**SNMP**)**;
            - File Transfer Protocol **(**FTP**)**
        - Wireless Modulation: Orthogonal Frequency-Division Multiplexing **(**OFDM**)** and/or Direct-Sequence Spread Spectrum **(**DSSS**)** 5.8 GHz
        - Quoted cost per Commercial Off The Shelf System (COTS): $2,500.00
- **Detection Mode Processing**
    - Generate range-time history file of compressed chirp data streams
        - Store received I & Q data from one to two nautical mile interval
        - 1200 range cells (1 mile range interval coverage)
        - Coherent processing interval – 7.68 mSec (64 PRIs)
        - File size – 1200 (range) x 64 (time)
        - Sample size AT 12 bit I/Q – 24 bits
        - Total byte count for 1 mile range interval – 230.4 Kbytes
        - Utilize dual range-time memory files to allow processing of one while filling other.
    - FFT processing extract detections with 13 Hz resolution
        - Non-coherent addition provides enhanced S/N detection outputs
        - X-band Velocity Resolution ~ 0.4 Knots
        - Ku-band Velocity Resolution ~ 0.2 Knots
        - Range Resolution 5 Feet

- **Data Acquisition System**
    - Record digitized I & Q pulse compressed data streams
        - PRI data burst over range interval of ~ 800 feet at target range with ½ to 1 foot resolution
        - Stepped frequencies of 8 or 16 frequencies form full bandwidth ISAR data stream stored
    - Capability to collect data for coherent imaging period of 2 to 5 seconds
- **Modeling and Simulation**
    - Model multi-static radar sites
    - Model effects of timing/frequency errors in GPS synchronized ISAR imaging
        - Frequency drift
        - Timing jitter
        - Phase Noise
    - Simulate ISAR and generate focused images
        - Pristine synchronized GPS reference image generation
        - Noise induced GPS reference image generation
    - Evaluate and define allowable errors in GPS reference

3.0 Technical Approach/Objectives

Sci-Teq's technical approach to the conduct of the MARA Research Study has four fundamental elements:

- Definition of Net-Sentric Surveillance Concept
- System Trade Studies and Requirements Definition
- Define and Optimize System Architecture & Implementation
- Identify and Develop System Algorithm Requirements

3.1 Define/Refine Net-Sentric Surveillance System Concept

Investigations are defining a system configuration and employment concept that includes specifying numbers, types and placement of sensors within the maritime environment identified for the study. Studies are addressing a multi-aspect, multi-static radar test configuration using a GPS disciplined reference oscillator for synchronizing system timing and coherent radar operation during multi-static ISAR data collection. A later phase of the study will address an operational configuration that employs AESA radar designs, image-while-scan functionality, and an extended area surveillance capability utilizing multi-static synchronized radars and electronic surveillance (ES) sensors in a cooperative network.

3.1.1 Define Target Set

Specific target sets will be identified with operating characteristics, physical/geometric features and electronic signature characteristics of maritime targets for input into image algorithm design considerations as well as inputs for simulation modeling. Maritime targets of opportunity will be utilized for the data collection tests.

3.1.2 Define Modeling and Simulation Requirements

Development of models and simulation tools has continued to generate dynamic simulations of the net-sentric surveillance system, representative maritime targets, and environmental characteristics that affect detection, tracking and multi-static imaging. Algorithms have been developed for the fusion of mono-static and multi-static signals and/or images to produce improved quality ISAR imagery over that of individual single mono-static images. Modeling has addressed timing and frequency synchronization issues associated use of GPS as a master reference.

3.2 System Trade Studies and Requirements Definition

Trade studies continue to examine design, performance and cost options associated with available components that will provide the required waveform generation, required resolution, and the operational timelines for search, track and image. Initial studies have focused on the design approach for a test radar suite for ISAR data collection and the specifics for required fields-of-regard, fields-of view, acquisition approach and target detection criteria.

3.3 Define and Optimize System Architecture & Implementation

System trade studies will be conducted to develop a system architecture for a dispersed system comprised of two or more ISAR sensors with co-located ES sensors, all operating within a cooperative network. Elements of the net-sentric surveillance system will include a GPS receiver at each site on the network that contains an ISAR and ES sensor. The ISAR system architecture would provide an implementation that generates the required clutter suppression and dynamic range during surveillance and tracking of maritime targets at ranges from approximately one nautical mile to the horizon. Approaches to provide detection, track and imaging at ranges of less than one mile will be investigated.

3.4 Identify and Develop System Algorithm Requirements

The MARA algorithm study is based on ultimate utilization of radar data from a single beam of multiple Active Electronically Scanned Antenna (AESA) radar systems, i.e., multi-static image fusion of maritime targets provides the potential for significant improvement in the radar image fidelity. The utilization of AESA technology provides the capability for near simultaneous multiple data capture from different aspects of a maritime target, while allowing the radar to continue area surveillance and tracking. The system architecture, design and algorithms that support these operations are being addressed in the MARA study and will identify the radar systems that operate as mono-static radars during surveillance and tracking modes and as bi-static or multi-static radars in a cooperative ISAR imaging sub-mode of an image-while-scan mode.

Through analysis and studies, the multi-static concept will be refined to provide the basis for specifying the networking control and synchronization requirements for system timing, radio frequency (RF) waveform phasing and spatial correlation of multi-static images. GPS time will be utilized as the master timing source for synchronization of the dispersed radars and will has been modeled as the reference for algorithms that synchronize event timing and for phase locking the multi-static radar waveform(s) references and the digital sampling of the received radar signals. Continuing investigations will define algorithms and processes for linking of maritime target geo-locations to provide for beam pointing, frequency scheduling and time-multiplexing the receiver capture of the multi-static radar signals when they are operating in the cooperative ISAR imaging mode. Near term applications are adapting algorithms for a test radar system for ISAR data collection. Multiple aspect illumination, image generation and

4.0 Study Emphasis & Progress During Reporting Period

During the reporting period, Sci-Teq focused on: definition of a radar collection radar system; definition of a representative data collection maritime environment; and refinement of an employment concept for a net-sentric surveillance system. Significant effort was placed on the development of the system architecture, design concepts mad COTS components for the data collection ISAR radar suite and on continued evaluation and refinement of a total system concept for a net-sentric multi-static radar/ES surveillance system supported by COTS GPS timing references.

4.1 MARA Data Collection System

The data collection system for MARA is characterized as a COTS design for data acquisition of mono-static and multi-static ISAR radar data from maritime contacts from shore installation test sites. The data collection design is geared to use of X-band and Ku-band radar frequencies, manual control of the beam positioning, and automated frequency/phase control of the transmitted waveform, the frequency conversion reference oscillators and the multi-system timing.

4 .1.1 Key Radar System Parameters

The key system parameters for the data collection system are listed in Table 4.1. This parameter list is a preliminary set and some parameters may need to be modified as the system is implemented with available COTS components.

Table 4.1: Key Radar System Parameters

Parameters	X-Band Operation	Ku-Band Operation
Operational Freq Bandwidth	8.4 to 9.5 GHz	16.25 to 17.75 GHz
Operational Modes	Pulse Doppler Detection ISAR Data Collection	Pulse Doppler Detection ISAR Data Collection
Transmit Peak Power min	20 Watts	75 Watts
Transmit Pulsewidth	12 µSec	12 µSec
Pulse Repetition Interval	120 µSec	120 µSec
Transmit Pulse Bandwidth	100 MHz	100MHz
Transmit Waveform	Fixed Frequency LFM Stepped Frequency LFM	Fixed Frequency LFM Stepped Frequency LFM
Number of Frequency Steps	0 8	0 16
Antenna Azimuth Beamwidth	6 Degrees	6 Degrees
Antenna Elevation Beamwidth	4 Degrees	4 Degrees
Antenna Gain	~ 28 dB	~ 28 dB
Beam Steering	Manual	Manual
Receiver Low Noise Amplifier	4 dB	6 dB
A/D Conversion Rate (I&Q)	~200 MSPS	~200 MSPS
System Losses	TBD	TBD

4.1.2 Radar Antenna

An antenna candidate is a common mount, dual aperture antenna with one aperture for Ku-band and the other aperture for X-band. An alternative approach is the use of a broad band antenna that covers both the X-band and Ku-band frequencies of interest. For the separate antenna approach, both antennas can have approximately the same azimuth and elevation beam-widths and the same gains as those listed in Table 4.1. The antennas will be bore sight aligned, and will be steered manually on a common pedestal. An optical sight, aligned with the bore sights of the antennas, will be used to assist in the manual positioning the antennas for target detection and data collection. Figure 4.1 depicts a Rohde & Schwarz (R&S) antenna example that would be sized to provide the required beam-widths for X-band and Ku-band.

Figure 4.1: S&R Reflector Antenna

The common antenna approach would have some compromises in beam-width and gain but would be adequate for the data collection test configuration while mitigating alignment issues. Figure 4.2 depicts two Q-par Angus antennas; each covers the frequencies from 7.5 GHz to 18 GHz. One configuration shows a secondary horn to provide a high gain -low gain capability, a function not needed in the data collection system design.

WBF 7.5-18 WBF 6.5-18

Parameters	WBF7.5-18# feed with QSR340-157	WBF6.5-18# feed with QSR340-157
Frequency	7.5 - 18 GHz	6.5 – 18 GHz
Nominal Gain	26 - 33.2 dBi	24 – 31 dBi
3dB Beam-width	8° - 3°	7.7° - 3.1°
Typical VSWR	< 2 : 1	< 2.5 : 1
Power Handling	500 Watts	~ 500 Watts
Weight	2.14 kg	~ 2.14 kg

Figure 4.2: Q-par Angus X/Ku-Band Reflector Antennas

4.1.3 Radar Transmit Power Amplifier

A rack mounted power amplifier is proposed as the transmitter output stage of the data collection radar. The amplifier will cover the RF band from 7.5 GHz to 18 GHz, thus providing the outputs for both the X-band transmission and the Ku-band transmission. The MT4100 broadband CW TWT amplifier depicted in Figure 4.3 is a candidate power amplifier. This amplifier is rated at 250 watts output with approximately 60 dB gain and 20 dB of attenuation range.

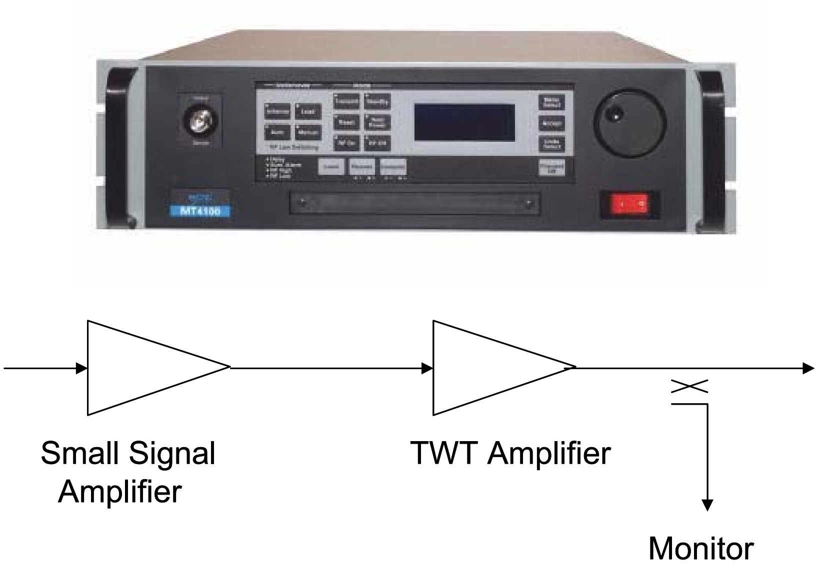


Figure 4.3: MT4100 RF Power amplifier

4.1.4 Radar Waveform Generator:

The proposed waveform for the data collection radar is a linear FM pulse with a 100 MHz bandwidth and a 12 microsecond pulse length. This waveform supports the detection mode and the ISAR data collection mode. The 100 MHz LFM would be imposed on a carrier that would be up-converted in the frequency conversion circuitry to X-band and to Ku-band transmit frequencies. A candidate for the waveform generator is the Euvis Inc DSM202 direct digital synthesizer (DDS) depicted in Figure 4.4. The DSM202 would use a clocking reference of 2 GHz. The DSM202 can be controlled using a user-friendly GUI on a PC. The RF input source is the clock source DDSCK with a minimum input power of 0 dBm. The outputs of the module consist of a pair of differential analog outputs: DDSOP and DDSON.

The DSM202 has the following characteristics:

- 11-bit amplitude and 13-bit phase resolution ROM
- Input clock frequency up to 2.0 GHz
- Output Frequency Up to 1.0 GHz (input clock @ 2.0 GHz)
- Output Power -4 dBm to 0 dBm
- Residual Phase Noise -145 dBc/Hz @ 1KHz
- Frequency update rate of 32 clocks per update
- Two running modes: Free run (Continuous) and Burst Run (Triggered)
- Two chirping waveforms: Ramp and Triangle

Figure 4.4: DSM202 Direct Digital Synthesizer

For the data collection radar, a triggered chirp mode would be used. An example of a chirp waveform generated by the DSM202 is shown in Figure 4.5. The depicted chirp waveform starts at 7.8125 MHz and stops at 125 MHz. The input clock for this waveform is 2.0 GHz. The data collection system waveform generator would generate a 100 MHz LFM chirp signal on a low frequency carrier. A detailed design will define the frequency scheduling for the LFM carrier as well as the up-conversion circuitry. The proposed design uses representative carrier frequency is 500 MHz, i.e., chirp from 500MHz to 600 MHz.

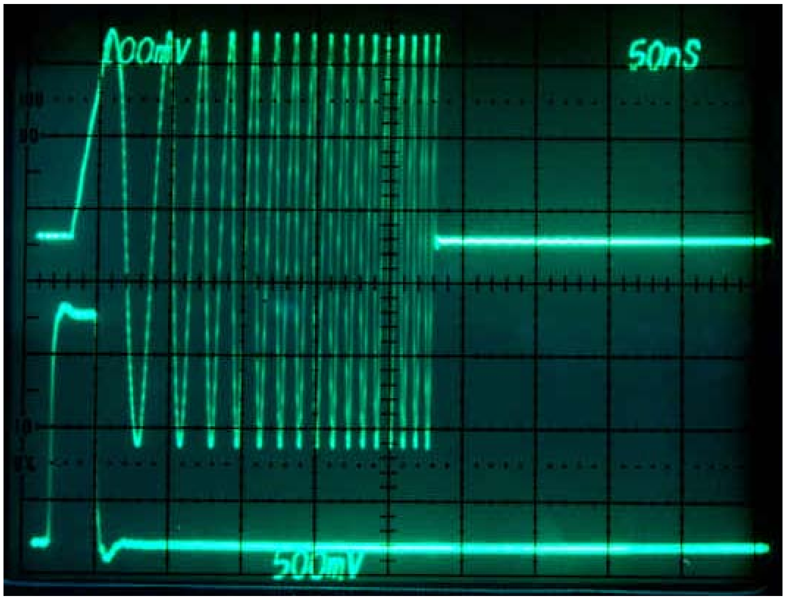


Figure 4.5: Chirp Waveforms Generated by DMS202 DDS

4.1.5 Radar Frequency Conversion Circuitry:

The frequency conversion circuitry up-converts the 500 to 600 MHz DDS generated 100 MHz LFM waveforms to transmit frequencies at X-band and Ku-band, and down-converts the X-band and Ku-band received signals to the base-band. The frequency conversion includes the generation of pulse-to-pulse stepped frequency signals during ISAR data collection and fixed frequency chirp outputs during detection and target acquisition. Single Conversion and double conversion were considered in the design studies. An issue with single conversion is the generation of the basic chirp waveform on a carrier frequency that can be up-converted to both X-band and Ku-Band with sufficient suppression of unwanted sidebands and spurious responses in a single mixer.

The X-band ISAR mode needs a minimum bandwidth of 500 MHz with an eight-step frequency waveform, frequency steps of approximately 62.5 MHz and a pulse repetition interval (PRI) of 120 microseconds. The design approach described supports a 1 GHz bandwidth at X-band. The Ku-band ISAR mode has a minimum bandwidth of 1000 MHz with a sixteen frequency step waveform of 62.5 MHz and a PRI of 120 microseconds. The design approach supports a 1.5 GHz bandwidth at Ku-band. Using a LFM frequency sources that generates a 500 to 600 MHz LFM waveform presents significant design issues with a single conversion mixer outputs at X-band and Ku-band frequencies, i.e. with the local oscillator frequency and the mixer output signals in relatively close frequency proximity, suppression of unwanted sidebands with a band-pass filter is difficult.

The dual conversion circuitry process, depicted in Figure 4.6, mitigates the suppression issue by allowing the filtering to be accomplished at frequencies where larger percentage differential bandwidths are involved. As shown in Figure 6, the first conversion transforms the chirp waveform generator output (500 to 600 MHz LFM) to an IF bandwidth centered at 3550 MHz with a band-pass filter of approximately 100 MHz. The conversion reference is a phase locked loop (PLL) VCO generating a fixed frequency at 3 GHz. The mixer output is a 100 MHz LFM 3500 MHz to 3600 MHz IF signal is band-pass filtered to reject the local oscillator signal and the mixer lower sideband, 2500 MHz to 2400 MHz. After filtering and amplification, the 1st IF is coupled to the second mixer for up-conversion to X-band or Ku-band.

The 2nd mixers use broadband mixers that provides up and down conversion of chirp waveforms for transmit and receive. The reference oscillators provide X-band and Ku-band conversion reference frequencies with pulse-to-pulse frequency steps in the ISAR data collection mode. Two broadband local oscillators are used to provide the reference frequencies for the up and down-conversion mixer when pulse-to-pulse stepped frequency formats are used during the ISAR data collection mode. The use of two PLL oscillators provides the needed settling time when frequencies are stepped on a pulse-to-pulse time basis.

A candidate broadband double balanced mixer is the Mini-Circuits SIM-24MH. This mixer has a RF bandwidth of 7.3 to 20, GHz, conversion loss of 5.7 dB, isolation of 36 dB, and an IF Bandwidth of DC to 7.500 GHz. Several oscillator assemblies are listed in Table 2 as candidates for the 1st and 2nd local oscillators shown in Figure 4.6. Settling time is only an issue for the 2md local oscillator. Figure 4.7 depict the Spinnaker broadband local oscillator highlighted in Table 4.2.

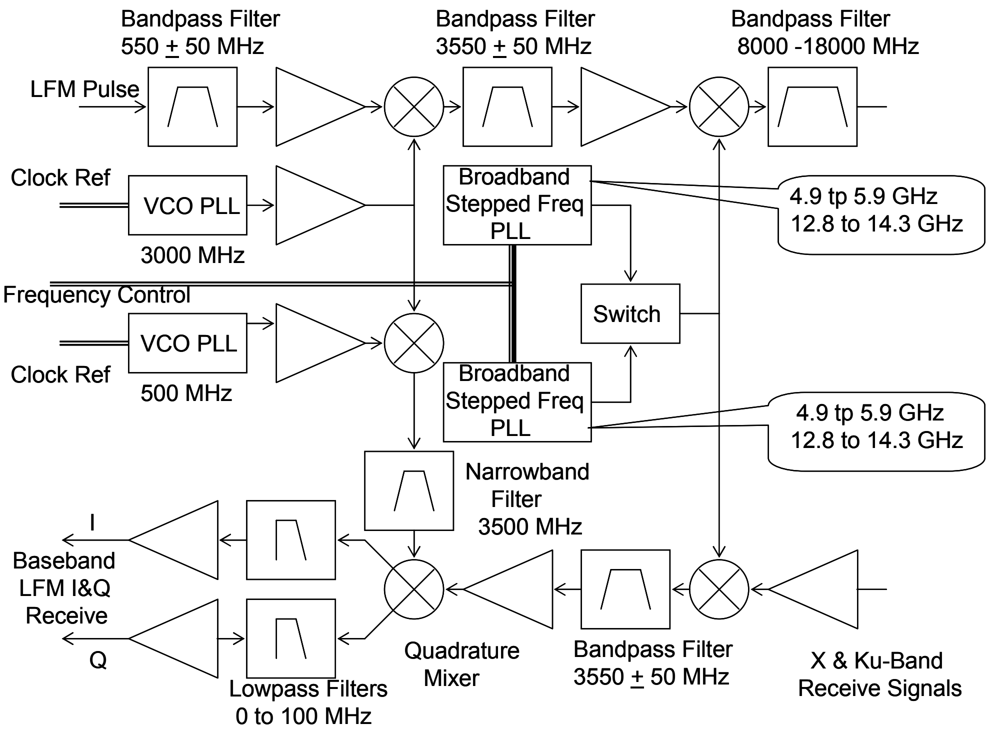


Figure 4.6: Up and Down Conversion Design Approach

Table 4.2: Local Oscillator Phase Lock Loop Assemblies

Manufacturer	Model #	Frequency Coverage	Tuning Resolution	Settling Time µsec	Output Power dBm	Packaging Size
VIDA Products	VPLNS VPBBS Hammerhead	8 to 12 GHz 6 to 14 GHz 5.5 to 18	1 KHz 100KHz 100 KHz	150000 <50000 1000	14 10 13	6.8"x6.3"x1.5" 4"x2.75"x1.38" 5.8"x2.7"x1.2"
GED	LMPL-D Dual Channel	0.1 to 8 GHz	1 MHz		10	3"x3"x1''
Elcom	RS-1000	1 to 23 GHz	1 S-band 2.5 C band 5 Ku band	<50	14	3"x3"x1"
Spinnaker	SMS-B SMS-DA SMS-DU	2 to 20 GHz 0.25 to 4.0 GHz 1 to 26 GHz	2.5 to 10 MHz 0.1 Hz 1 Hz	<50 <0.3 <50	7 10 10	3"x2.9"x0.7" 6.5"x9.5"x2.3" 4"x4.5"x1"
Syntonic	D1000 D3000 D5000	0.5 to 6 GHz 5 to 16 GHz 5 to 26 GHz		<50000 <50000	13 13 13	2¼x2¼x0.65" 2¼x2¼x0.75" 2¼x2¼x0.63"
National Semiconductor	LMX2541 (6 narrow band units)	1.99 to 4 GHz	Model Specifc 250 to 520 MHz			6x6x0.8 mm
Micro Lambda	MLSE0220 MLSE0122	2 to 20 GHz 1-22 GHz	1 Hz 1 Hz	<31000 <31000	20 17	7"x2"x3" 7"x2"x3"

Figure 4.7: Spinnaker Microwave Direct Up-Convert Frequency Synthesizer

The final receiver down-conversion uses a quadrature mixer to produce I & Q signals at base-band. An example of an I/Q mixer that operates in the frequency regions of the MARA data collection radar design is the Spectrum Microwave MIQ3xMS-3 mixer that supports a 3.0 to 6.0 GHz signal input, an 3.0 to 6.0 GHz LO input and a down-converted output at base-band, DC to 300 MHz. Other I/Q mixers are available such as the Marki Microwave IQ-0307 with an RF/LO band of 3.0 to 7.0 GHz and an a base-band I/Q output of DC to 500 MHz and the Polyphase Microwave QD 3040B with an RF/LO band of 3.0 to 4.0 GHz and a base-band I/Q output bandwidth of DC to 275 MHz. These I/Q mixers are characterized with a quadrature phase deviation in the range of 2 to 5 degrees, a conversion loss of 5 to 7 dB, and an amplitude deviation of less than 0.3 dB.

Undesired noise and signals exhibiting a frequency offset from the LO identical to the desired RF signal can corrupt the desired conversion in the form of image distortion. The image reject mixer minimizes the impact of image noise on the system noise figure compared to that of a single sideband mixer. The image reject mixer also suppresses the spurious products generated by undesired signals falling in the system's image frequency range by approximately 25 dB. I/ Q mixers solve the system problem by resolving the phase of the incoming signal in 90° increments. Subsequent processing of the I/Q output allows the determination of whether the RF signal is on the high or low side of the LO frequency. The amount of image suppression obtained with an I/Q mixer is determined by the amplitude & phase balance of the design. The Spectrum Microwave MIQ3xMS-3 mixer is configured to maintain optimal symmetry in order to obtain the high image suppression needed in the ISAR data collection system.

4.1.6 Radar Receive Signal Digitizers

The down-converted received 100 MHz LFM chirp I/Q signals are digitized by a high performance analog to digital converter (ADC). The need for a high sampling rates and a large dynamic range to extract low level ISAR scatterers are primary objectives for selecting the ADC.

The potential to use a dual channel ADC provides the simultaneous conversion of the I and Q signals such that the I and Q signals in the output data streams are time synchronous.

A candidate digitizer is the National Semiconductor ADC16DV160. This 16-bit ADC has a high dynamic range and is a dual channel component. The ADC16DV160 is a monolithic dual channel CMOS analog-to-digital converter capable of converting analog input signals into 16-bit digital words at rates up to 160 Mega Samples per Second (MSPS). This converter uses a differential, pipelined architecture with digital error correction and an on-chip sample-and-hold circuit to minimize power consumption and external component count while providing the large dynamic range performance. Automatic power-up calibration enables reliable dynamic performance and reduces part-to-part variation.

The ADC16DV160 can be re-calibrated at any time through the 3-wire Serial Peripheral Interface. An integrated low noise and stable voltage reference and differential reference buffer amplifier eases board level design. The on-chip duty cycle stabilizer with low additive jitter allows a wide range of input clock duty cycles without compromising dynamic performance. A sample-and-hold stage yields a full-power bandwidth of 1.4 GHz. The interface between the ADC16DV160 and a receiver block can be verified and optimized via fixed pattern generation and output clock position features. The digital data is provided via dual data rate LVDS outputs. The package is a 68-pin, 10 mm x 10 mm LLP package that operates on dual power supplies of +1.8V and +3.0V with a power-down feature to reduce power consumption to very low levels while allowing fast recovery to full operation. The key characteristics are listed in Table 4.3. The disadvantage is the ADC16DV160 is not available as a COTS circuit board element and requires the design and fabrication of a circuit board for the chip.

Table 4.3: Dual Channel 16 Bit ADC with Sampling Rate of 160 MSPS

Parameters	Values
Resolution	16 bits
Channels	2 Channels
SNR	78.5 dB
SFDR	95 dB
Max Sample Rate	160 MSPS
Power Dissipation	1.3 Watt
Min Supply Voltage	2.7 Volt
Max Supply Voltage	3.6 Volt
Nominal Vin	2.4 Vpp
Temperature Min	-40 deg C
Temperature Max	85 deg C
PowerWise	Yes

An alternative ADCs component identified as a potential element of the MARA data collection system is the Innovative Integration X5-G12. If a reduced dynamic range device can be used, the Innovative Integration X5-G12 shown in Figure 4.8 will provide I/O module featuring dual channels of 1 GSPS, 12-bit digitizing with a Virtex5 FPGA computing core, DRAM and SRAM memory, and eight lane PCI Express host interface. A Xilinx Virtex5 SX95T or LX155T with

512 MB DDR2 DRAM and 4MB QDR-II memory provides a very high performance DSP core that would support the demanding applications of the MARA ISAR data collection system.

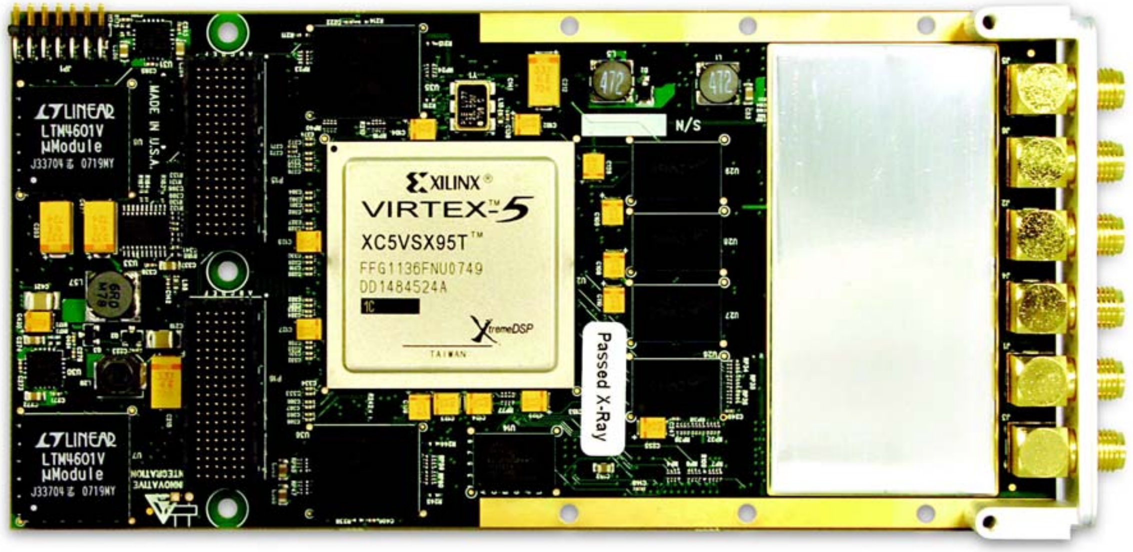


Figure 4.8: Innovative Integration X5-G12 ADC

The close integration of the analog IO, memory and host interface with the FPGA enables real-time signal processing at rates exceeding 300 Giga multiple-accumulate instructions per second (GMAC/s). This capability is potentially sufficient for real-time pulse compression signal processing on the ADC circuit board. The X5 XMC module couples Innovative's architecture with a high performance, 8-lane PCI Express interface that provides over 1 GB/s sustained transfer rates to the host. Private links to host cards with >1.6 GB/s capacity using P16 are provided for system integration.

The X5 family can be customized using VHDL and MATLAB using the FrameWork Logic toolset. The MATLAB BSP supports real-time hardware-in-the-loop development using the graphical, block diagram Simulink environment with Xilinx System Generator. IP logic cores are also available for SDR applications that provide from 16 to 4096 DDC channels. These IP cores transform the X5 modules into versatile receivers using proven logic cores. Software tools for host development include C++ libraries and drivers for Windows and Linux.

Other candidate ADC elements were reviewed. Examples of those reviewed are listed in Table 4.4. These devices are microcircuits that need to be integrated on a PCB designed with appropriate interfaces with the ADC characteristics. Several digitizer circuit boards were reviewed. Other than the X5-G12, none that were reviewed met the desired requirements for sampling rate, bit count, or dual channel capability as listed for the X5-G12 circuit board.

Table 4.4: Candidate ADC Components

Component	Bit Count	Conversion Rate MSPS	Number Channels	SNR dB	Input Bandwidth GHz
Intersil					
KAD5612P-25	12	250	2	66	1.3
Delphi					
ADX3500	8	1500	2		1.7
NXP					
ADC1412D	14	125	2	73	0.65
Analog Devices					
AD9630	14	150	2	72	
AD9627-150	12	150	2	64	
AD9461	16	130	1	78	
AD12401	12	400	1	64	
National Semiconductor					
ADC16DV160	16	160	2	78	1.4
ADC14V144	14	155	1	72	1.1
ADC16V130	16	130	1	78	1.4
Texas Instruments					
ADS54RF63	12	550	1	63	2.3
ADS5474	14	500	1	79	2.3
Innovative Integration					
X5-G12 PCB with FPGA	12	1000	2	64	

4.2 System Synchronization

4.2.1 System Clocking

Synchronous clocking is essential for continuous coordination of the multi-static radar data collection system. Network latency and variability in latency are critical factors to be minimized during the data collection. For effective coherent multi-static radar operation, the transmit source and receivers must operate on the same frequency with phase coherency. For the transmitter, the clocks that provide timing for the transmit path are locked to a highly accurate reference clock. The primary and, if needed, a secondary reference clock are supplied from a GPS that provides the centralized timing source to all of the multi-static radars. The GPS pulse per second signal (1 PPS) is precision time synchronized to maintain loop locking. A PLL is used to lock to this backplane reference, attenuate jitter on the clock signal to remove unwanted noise, and provide a low jitter output clock. The receivers use the same references as the transmitters with additional PLLs to scale the clock frequency to rates up-conversion and for down-conversion to base-band. Local timing would be synchronized to the centralized timing source.

Synchronization to the source ensures clock synchronization across all nodes in the multi-static radar network. The PLLs used may require a low loop bandwidth to filter unwanted jitter from the clock signal. The PLL can be implemented discretely using an integrated clock IC or a Voltage-Controlled Crystal Oscillator (VCXO), phase detector, and loop filter. A discrete solution provides obtains the lowest possible jitter and best possible phase noise. Processors or ASICs can be used to integrate the phase detector and charge pump within the IC so that only a VCXO and external loop filter are required. As a disadvantage, a discrete PLL is sensitive to board-level noise requiring special design considerations in PCB layout. A discrete PLL typically provides a single output frequency. If the design's frequency requirements change, a separate VCXO must be implemented. To address these shortcomings, dual, quad, and any-rate programmable VCXOs are available to address multi-rate applications by replacing multiple discrete VCXOs with a single device. Ideally, the MARA data collection system can operate on a single output frequency for all testing.

An alternate approach is the use of a jitter attenuating clock multiplier, which integrates PLL circuitry on-chip. The clock multiplier maintains lock to the reference clock, filters unwanted jitter, and generates a multiplied frequency output clock for the transmitter/receiver. A high performance clock multiplier provides the jitter performance necessary to meet the synchronization and timing requirements. The key specification is maximum jitter generation. A clock multiplier that specifies maximum jitter best enables an allocation of a jitter budget among the data path and timing components and ensures there is sufficient margin under the collection radar's operating conditions. The loop bandwidth options available on the clock multiplier need to be examined. The clock multiplier supports all required frequency plans for the radar sensor.

As an example, a global-positioning system-disciplined oscillator (GPSDO) by Jackson Labs provides a 10-MHz GPSDO that requires no calibration, delivers greater stability than typical rubidium-clock references, and meets the stability requirements of a Stratum 1 frequency standard. The unit, shown in Figure 4.9, offers less than 10^{-12} frequency drift per day; 4.5W power consumption; a phase-noise floor of –155 dBc/Hz, and low spurs and jitter. The device generates a one-pulse-per-second output, phase-synchronized to UTC (Universal Time-Coordinated) and adjustable to UTC in 1-nsec steps. You can control the unit through an RS-232 port using industry-standard SCPI commands (Standard Commands for Programmable Instruments).

Figure 4.9: Jackson Labs GPS Disciplined Oscillator

A clock solution is preferable to a discrete solution when system-level clock functions are required. An example of this is hitless switching between input clocks, in which the clock monitors the quality of a primary reference clock and switches to a secondary reference upon detection of an alarm condition on the primary clock. Another popular system-level clock requirement is holdover, in which the clock continues to generate a stable output clock in the absence of a valid reference clock. Clocks are available from multiple suppliers that address these system-level requirements. Table 4.5 summarizes when an XO, VCXO, or clock solution should be used.

Table 4.5: Timing Solution Guide

	XO	VCXO	Clock
Primary Functions	Asynchronous Timing Clock & Data Collection Reference Clock	Synchronous Timing Clock multiplication/jitter attenuation as part of a discrete PLL Generates single output clock	Synchronous Timing Clock multiplication and jitter attenuation Generates multiple output clocks System level functions
Frequency	Fixed	Continuously variable over tuning range (typically ± 100 ppm)	Reconfigurable via interface to support large number of frequency plans
Design Complexity	Low	High	Low
Integration	High	Low	High
Jitter Filter	No	Yes (discrete)	Yes (Integrated)
Use When	Need local oscillator	Lowest phase noise/jitter performance required PLL circuitry integrated in ASIC/FPGA	Integrated solution is preferred Jitter attenuation and/or clock multiplication required Frequency flexibility required Need system-level functions

For the ground based multi-static MARA data collection radar, time and frequency synchronization can be obtained using the global positioning system (GPS), which provides a highly stable pulse-per-second signal (1 PPS). Independent GPS disciplined low phase-noise crystal oscillators are used to maintain site-pair coherence. The standard deviation of the PPS signal between two low-cost commercial GPS units seeing the same satellites can be as low as 15 nsec. Using this PPS signal to synchronize a highly stable quartz crystal oscillator, a standard deviation of less than 5 nsec can be expected. Frequency synchronization is realized by generating all needed frequencies by dividing, multiplying or phase-locking to the GPS disciplined oscillators at the transmitter and receiver sites.

Time synchronization between the separated transmitter and receiver of a bi-static radar is required for range measurement. The time accuracy is on the order of a fraction of that of the frequency. A typical requirement for time synchronization is about the tenth of the transmitted compressed pulse width, i.e., for the 500 MHz bandwidth data collection radar, the (typical time transfer accuracy capability is about $\delta t = 0.2$ nsec). It is possible to attain coherence by using the Global Positioning System, which provide a highly stable pulse-per-second signal. In the planned data collection scenarios, the receivers would be using the same satellites for timing.

Using a very long baseline technique developed by the Jet Propulsion Laboratory, sub nanosecond accuracy can be obtained at a lower cost than that of the two-way link over a communications satellite. With the VLBI common-view method, where both GPS modules receive the signal from the GPS-units, same satellites at the same time, the ultimate accuracy is about 1 ns. Employing off-the-shelf low-cost, low-power commercial GPS units, which use only the L1-signal at 1575.42 MHz, a standard deviation of 15 nsec can be achieved between the 1-PPS signals at the different sites. Disciplining stable local oscillators with these 1 PPS signals yields a standard deviation of a few nanoseconds. Higher capability GPS disciplined oscillators can yield sub nanosecond timing accuracy. Jitter reducing clock multipliers used in conjunction with a GPSDO can reduce system timing jitter to less than a pico-second range. The jitter attenuating clock will provide clock multiplication jitter attenuation and clock distribution with sub pico-second jitter performance. Examples of jitter reducing clock multipliers are shown in Table 4.6. These devices accept multiple clock inputs and generate multiple independent, synchronous clock outputs ranging from 2 KHz to 1.4 GHz with sub pico-second jitter characteristics.

Table 4.6: Candidate GPS Disciplined Oscillators

Manufacturer Model #	Output Frequency	Jitter Characteristics
Brandywine Communications PTS-SAASA	10 MHz	< 40 nSec
Jackson Labs – Fury	10 MHz	< 20 nSec
MTI GPSDO	32 KHx, 100 MHz	< 20 nSec
Silicon Labs Jitter Attenuating Clock Multiplier – Input Frequency		
Si 5319 – 2 KHz to 710 MHz	2 KHz to 20 MHz	0.3 picosec
Si 5323 – 8 KHz ti 707 MHz	8 KHz to 1650 MHz	0.3 picosec
Si 5324 – 2 KHz to 710 MHz	2 KHz to 1417 MHz	0.29 picosec
Si 5366 – 8 KHz to 707 KHz	8 KHz to 1050 MHz	0.3 picosec
SI 5368 – 2 KHz to 710 MHz	2 KHz to 1417 MHz	0.3 picosec

4.2.2 Signal Data Flow and Collection

The collection of data from the Multi-static radar data collection system involves a sequence of data collection, data processing, and data acquisition and recording for off-line processing and evaluation of ISAR data to obtain mono-static and multi-static imagery of maritime targets. The design approach for the data collection radar provides two basic radar modes: a detection mode and an ISAR data collection mode. The radar beam position in both modes is manually controlled with visual optical telescopic augmentation.

Detection Mode: The radar detection/acquisition range window covers the target range of uncertainty, confirm the target is within the data acquisition window for ISAR data collection, and provide the capability to adjust the range window to center the target in the window. This mode is available for X-band and Ku-band transmissions. The waveform used for the detection mode is a coherent pulse Doppler linear FM. A one-mile range capture window with the 12 μSec LFM pulse requires data from 24 μSec for pulse compression of data in the desired one-mile range window. A total of 512 pulse intervals (PRIs) are used for the Doppler detection after the received waveforms are pulse compressed. Thus, the coherent processing interval (CPI) is established as 61.44 milliseconds with a resulting coherent detection bandwidth of approximately 16 Hz and a velocity resolution of about ½ Knot at X-band and 0.3 Knots at Ku-band. The pulse Doppler received signal data is depicted in Figure 4.10.

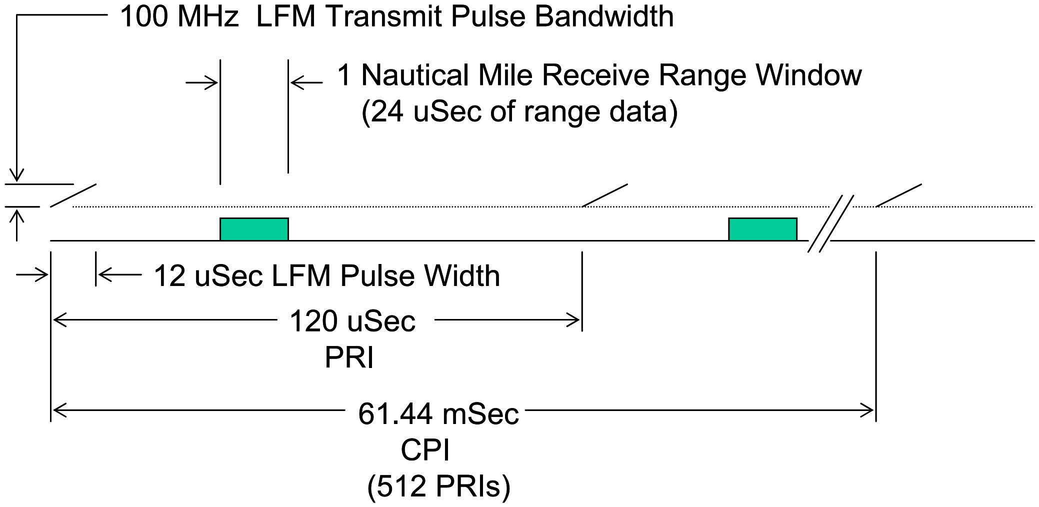


Figure 4.10: Pulse Doppler Received Signal Data

The 12 μSec pulse length data from the one-mile range window of the radar receiver is digitized as I and Q signals and pulse compression processed to form 1-mile of 5-foot range cells, i.e., 1800 range cells, each represented by 12 bit I and 12 bit Q data. The pulse compressed data is fed to a range-time history storage file for subsequent FFT processing to obtain a range-Doppler map over the target velocities of interest. Maritime target velocities no more than ± 25 Knots would size the Doppler map as about are 100 cells for X-band data and about 166 for Ku band data. These velocity limits are well within the PRF/2 unambiguous velocity regions. The detection display would use a PC with 1200 range cells by 166 velocity detection cells. The data flow for the detection mode is depicted in Figure 4.11.

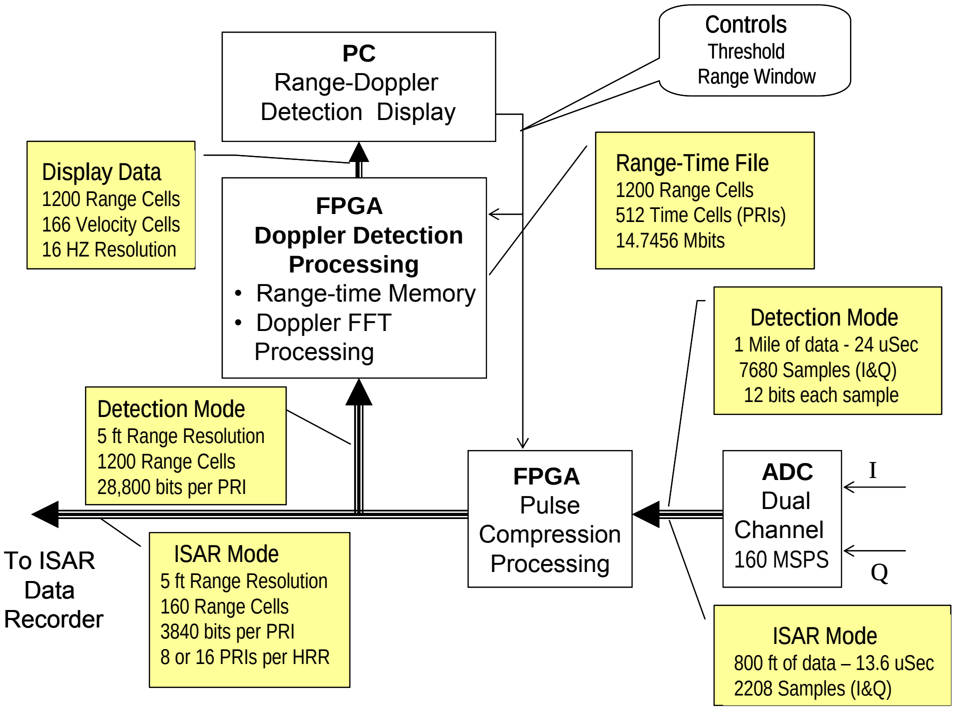


Figure 4.11: Data Collection Radar Data Flow Diagram

ISAR Mode: The radar ISAR data collection mode samples signal returns from a target located with the Doppler detection mode. The transmit waveform is changed from a chirp only modulation to a chirp plus stepped frequency modulation to provide a greater bandwidth and higher range resolution for the ISAR data collection. The basic high resolution bandwidth is 500 MHz provided by an eight frequency stepped waveform of the 100 MHz chirp signal. An alternative bandwidth that could be applied is a 16 frequency step chirped waveform that provides 1 GHz or more of bandwidth and range resolution of a few inches. A range window of 800 feet is used to minimize the collection data while provide sufficient range coverage to capture a maritime targets ISAR image data. Figure 4.12 provides a depiction of the ISAR received data for an eight stepped frequency waveform.

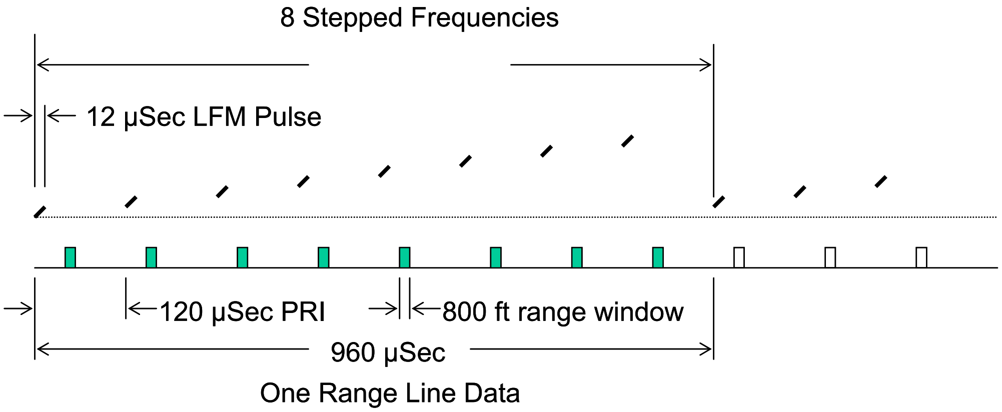


Figure 4.12: Mono-Static ISAR Received Signal Data, Chirp Processed

The chirp waveforms are processed the same as the Doppler mode processing to generate 5 foot resolution 12 bit I and Q data streams from the 800 foot range interval selected based on the target location obtained from the detection mode. As depicted in Figure 11, the compressed pulse data in the ISAR data collection mode represent 160 range cells at 24 bits per cell. This data stream is down loaded to a data acquisition storage media into files consisting of range lines, i.e., receiver data for 8 frequency steps for the 500 MHz bandwidth data collection, 16 frequency steps for 1 GHz or larger bandwidth data collection.

One approach to capture received multi-static ISAR data is depicted in Figure 4.13. This approach is to time and frequency synchronize multi-static transmissions such that the multi-static receiver captures the multi-static received signals within the same PRI as that of the mono-static radar receiver, effectively increasing the data capture by a factor of three. This approach utilizes the precision timing synchronization provided by the GPS disciplined timing references. There is an increase in the clutter level on the multi-static signals from the longer range clutter returns of the mono-static range at the ranges that coincide with the timed range windows of the multi-static signals. As long as land clutter does not fall into these range windows, the increased sea-clutter signal level is not a significant issue.

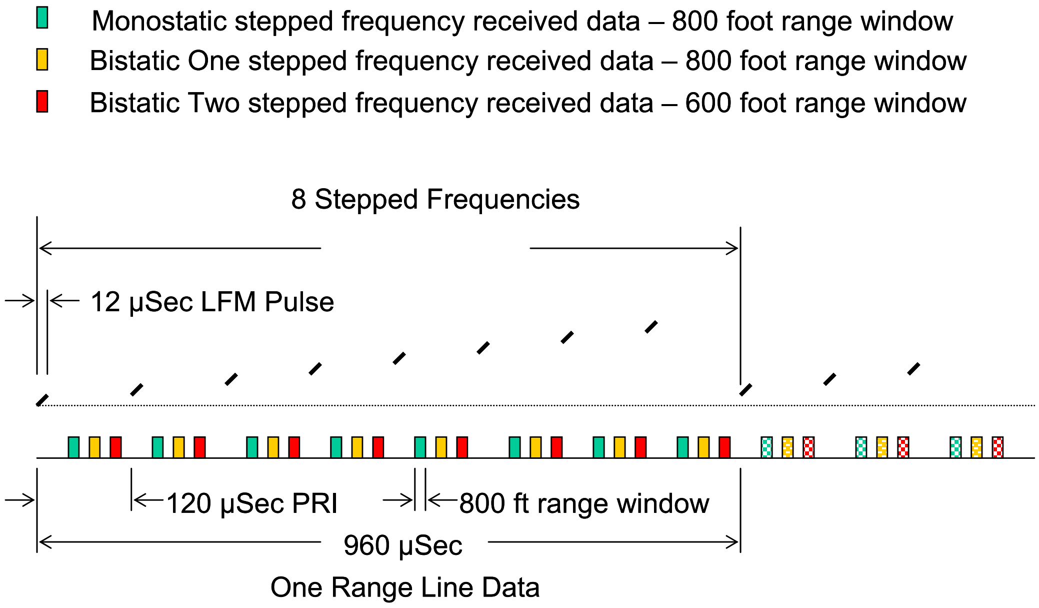


Figure 4.13: Multi-static ISAR Received Signal Data – Chirp Processed

The data collection time for needed for image generation will vary with the operational scenario and target dynamics but is estimated that collection times of 2 to 5 seconds are required. The data acquisition storage media supports collection of data for up to 5 seconds from each of three multi-static radars in the data collection system. The signal flow and the output signal data from the collection radar with one-foot range resolution (8 stepped frequencies) is listed in Table for mono-static ISAR data collection and for multi-static data collection (2 bi-static radars and one mono-static radar). Off-line processing will provide the stepped frequency pulse compression and the ISAR image generation for the collected data shown in Table 4.7 to be up to 4.8 Gbits for a 5 second ISAR dwell period.

Table 4.7: Collection Radar Data Flow and Outputs

Collection Interval	Monostatic Digital Data	Multi-static Digital Data
Processed Chirp 800 Foot Range Window (800 ft/5ft x 24 bits)	3.84 Kbits per PRI	11.52 Kbits per PRI
One Range Line of 800 Foot Range Windows 8 Stepped Frequencies	30.72 Kbits per range line	92.16 Kbits per range line
ISAR Dwell Period • 2 sec Collection • 5 sec Collection	640 Mbits per ISAR dwell 1.6 Gbits per ISAR dwell	1.92 Gbits per ISAR dwell 4.8 Gbits per ISAR dwell

Not included in the bit counts listed in Table 4.7 are data headers used to identify and catalog data groups from radar stepped frequency bursts and from different radar emitters that are interleaved in the output data streams. Data rates are not identified will depend upon the processing latency of the chirp pulse compression processing which needs to complete one PRI of processing prior to starting processing on the next PRI of data, i.e., 120 μSec. For the multi-static data collection, the data flow rate would need to be faster than 11.52 Kbits/120 μSec, i.e., 1 Gbits/sec including added header and time reference data.

4.3 Modeling and Simulation Algorithms

The use of GPS timing signals as the master timing reference for the MARA data collection system makes use a the very stable, but low data rate GGP timing signal received at 1 PPS. Timing and frequency errors that result from the GPS reference were evaluated in terms of their impact on ISAR image quality degeneration. Modeling of these error sources provided a means to assess ISAR image generation performance.

Letting the master clock time at site *k* be a function of the true time *t* over *N* radar pulse bursts:

$$t_k = t_k(t) = t + a_k t + \frac{1}{2} b_k t^2 + n_k(t) \text{ where } 0 < t < N \cdot PRI$$

In this equation, a_k is the error in the clock crystal frequency, b_k is the instability in the clock crystal frequency, and $n_k(t)$ is a random noise component which was modeled as

$$n_k(t) = \int_0^t N_k \, dt$$

The random clock frequency error N_k is chosen once per PRI. A GPS disciplined master clock was modeled by setting $a_k = 0$ and forcing the instability term $\frac{1}{2} b_k t^2$ and cumulative noise term n_k to reset every second in the equations that follow.

The transmitted phase of a carrier frequency *f* cycles per master clock second from site *T* is $\phi_T = 2\pi f t_T$ and the actual propagating frequency is

$$f_T = \frac{1}{2\pi}\frac{\partial \phi_T}{\partial t} = f\,\frac{\partial t_T}{\partial t} = f\,(1 + a_T + b_T t + N_T)$$

After propagating a distance *R*, the carrier phase of a stationary target at the receiver antenna is

$$\phi_{T+P} = \phi_T + \phi_P = 2\pi\, f\, t_T + 2\pi\, f_T\, \frac{R}{c}$$

The down converted baseband phase is

$$\phi_{T+P+R} = \phi_T + \phi_P - \phi_R = 2\pi\, f\, t_T + 2\pi\, f_T\, \frac{R}{c} - 2\pi\, f\, t_R$$

$$= 2\pi\, f\left(t + a_T t + \frac{1}{2} b_T t^2 + n_T\right) + 2\pi\, f\, \frac{R}{c}\left(1 + a_T + b_T t + N_T\right) - 2\pi\, f\left(t + a_R t + \frac{1}{2} b_R t^2 + n_R\right)$$

$$= 2\pi\, f\left[\left(a_T - a_R\right)t + \left(n_T - n_R\right) + \frac{1}{2}\left(b_T - b_R\right)t^2 + \frac{R}{c}\left(1 + a_T + b_T t + N_T\right)\right]$$

The perceived Doppler frequency of a stationary target introduced by the phase error is

$$f_D = \frac{1}{2\pi}\frac{\partial \phi_{T+P+R}}{\partial t_R} \cong \frac{1}{2\pi}\frac{\partial \phi_{T+P+R}}{\partial t} = f\left[a_T - a_R + N_T - N_R + \left(b_T - b_R\right)t + \frac{R}{c} b_T\right]$$

The introduced Doppler is modeled as a perceived range rate, common to all carrier frequencies, as

$$\dot{R} = \frac{c}{f}\, f_D = c\left[a_T - a_R + N_T - N_R + \left(b_T - b_R\right)t + \frac{R}{c} b_T\right]$$

Note that for mono-static radar, the perceived range rate is Rb. For a GPS disciplined mono-static radar the range error grows to Rb and then jumps to zero each second.

The effect of clock noise was investigated using a simplified ship model with 14 point scatterers and with no shadowing. The radar sites were arranged as shown in Figure 4.14. The distance from site 1 to the ship model is 10 Kilometers. The sites are spaced 5 Kilometers from each other.

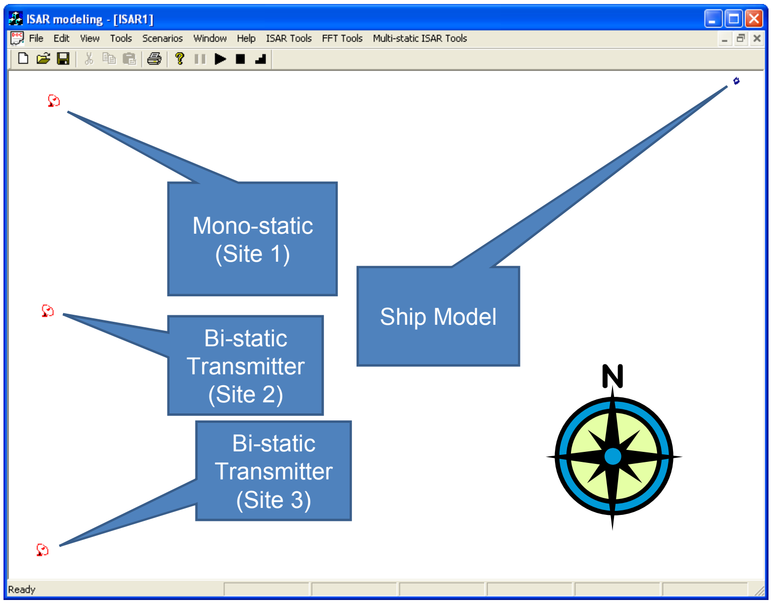
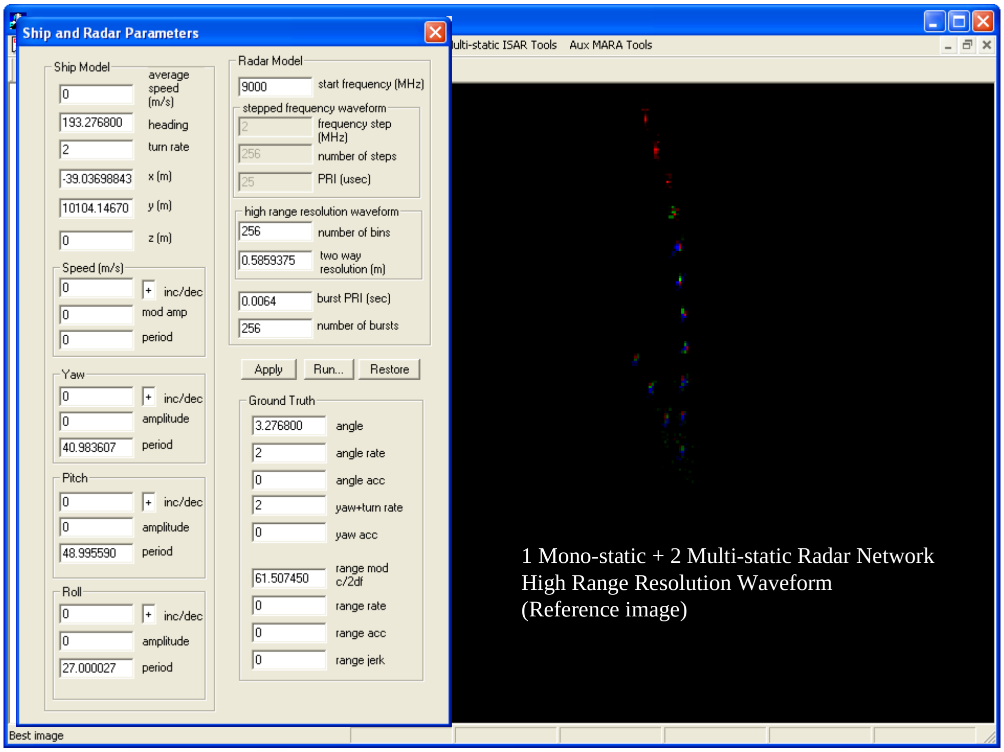


Figure 4.14: Simulation Radar Site Model

As a basis for comparison, the screen capture in Figure 4.15 shows the simplified ship model imaged with no noise applied to the signals. The signals have a frequency of 9GHz with a bandwidth yielding 256 range bins that are separated (in two way range) by 0.59 meters. The broadband signal is transmitted 256 times (bursts) having a PRI of 6.4 milliseconds. The wavelength is $\lambda = \frac{c}{f} = 0.03$ meters. The ambiguous Doppler velocity is then

$$v_D = \frac{\lambda}{PRI} = 4.7 \text{ meters/second.}$$

The red pixels are the site 1 mono-static ISAR image, the green and blue pixels are the site 1 + site 2 and site 1 + site 3 multi-static ISAR images, respectively.



Ship Model

0 average speed (m/s)
193.276800 heading
2 turn rate
-39.03698843 x (m)
10104.14670 y (m)
0 z (m)

Speed (m/s)

0 + inc/dec
0 mod amp
0 period

Yaw

0 + inc/dec
0 amplitude
40.983607 period

Pitch

0 + inc/dec
0 amplitude
48.995590 period

Roll

0 + inc/dec
0 amplitude
27.000027 period

Radar Model

9000 start frequency (MHz)

stepped frequency waveform

2 frequency step (MHz)
256 number of steps
25 PRI (usec)

high range resolution waveform

256 number of bins
0.5859375 two way resolution (m)

0.0064 burst PRI (sec)
256 number of bursts

Ground Truth

3.276800 angle
2 angle rate
0 angle acc
2 yaw+turn rate
0 yaw acc
61.507450 range mod c/2df
0 range rate
0 range acc
0 range jerk

Figure 4.15: ISAR Image Screen Capture

Four of the point scatterers in the basis image are shown in Figure 4.16 with their intensity plotted to show any side lobe energy.

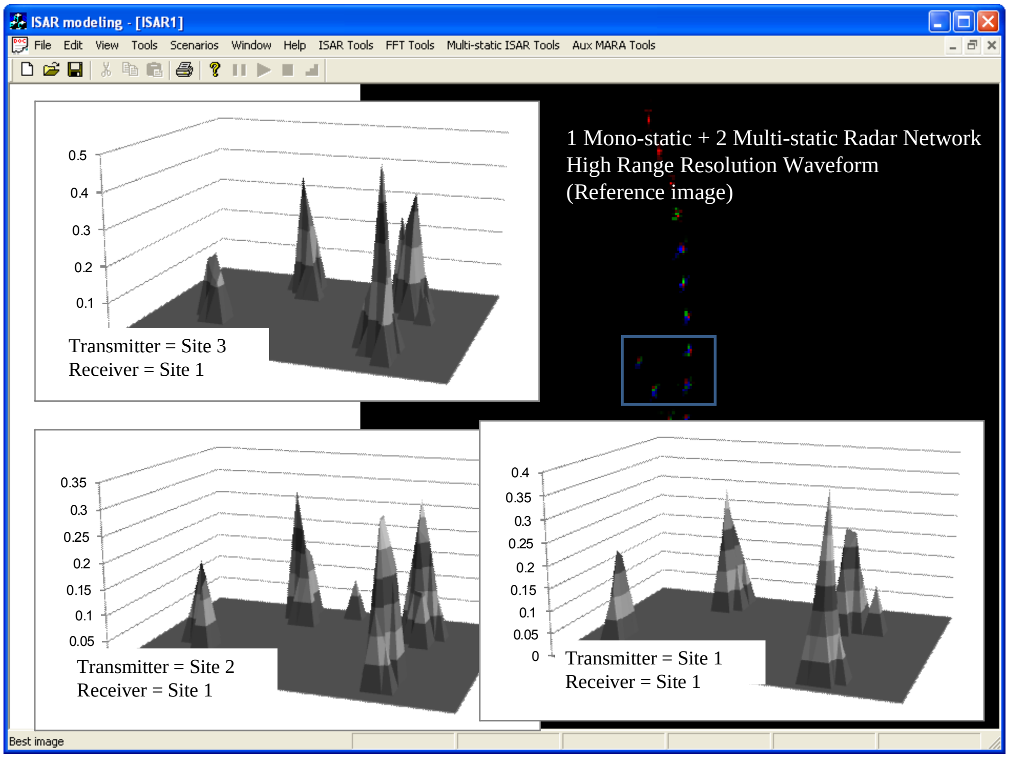
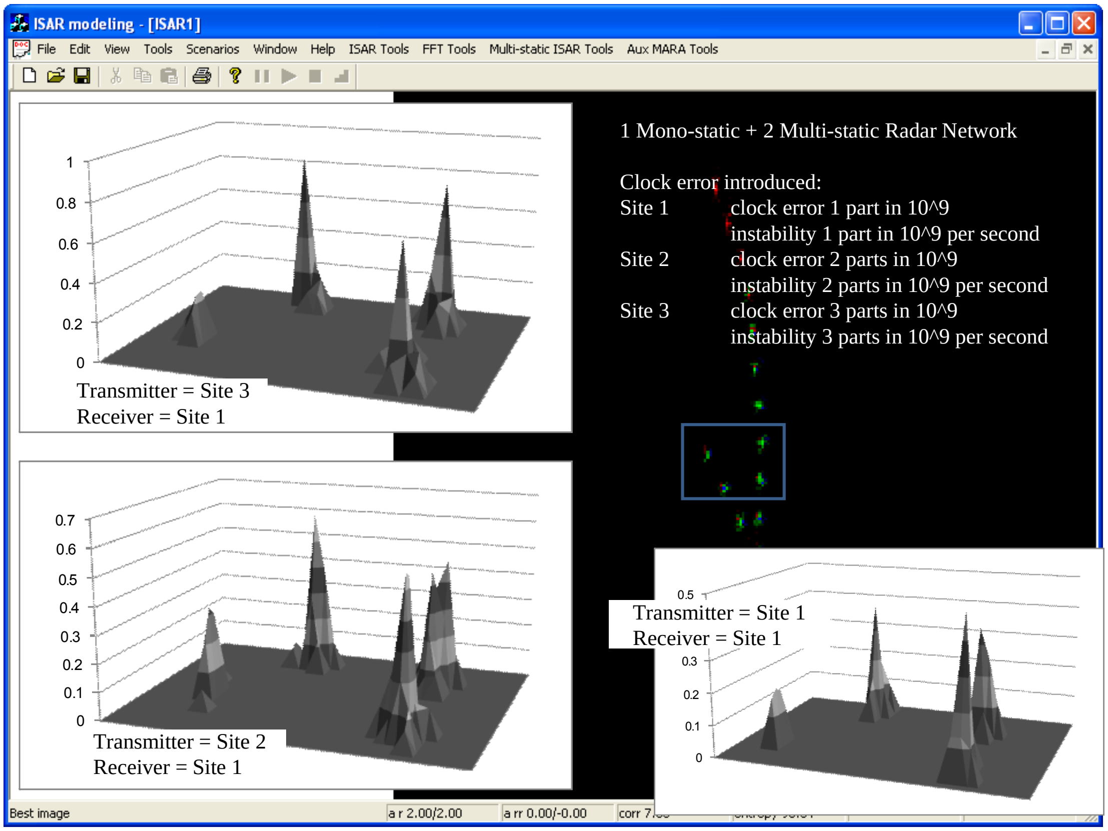


Figure 4.16: ISAR Image Response

As shown in the mathematical model, the clock error and clock instability are identical to a range rate and range acceleration. If these errors are introduced and the image is focused to its least entropy using translational motion compensation associated with polar reformatting, the accumulated phase error of approximately 50 cycles of Doppler is mitigated, Figure 4.17.

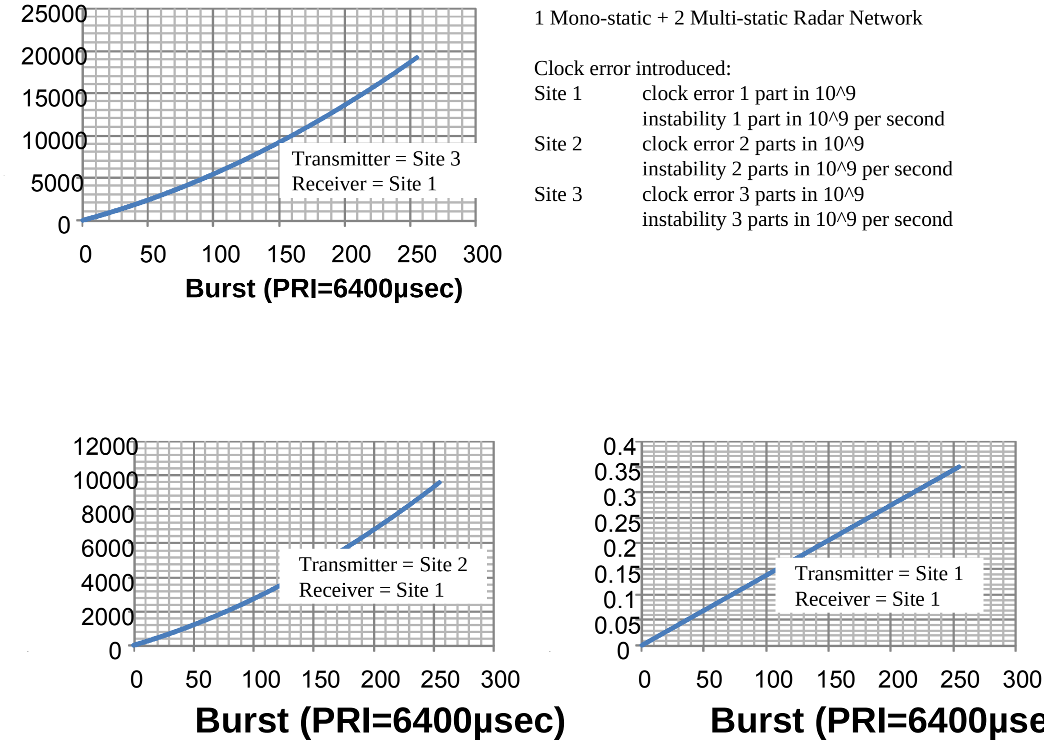


1 Mono-static + 2 Multi-static Radar Network

Clock error introduced:
Site 1 clock error 1 part in 10^9
instability 1 part in 10^9 per second
Site 2 clock error 2 parts in 10^9
instability 2 parts in 10^9 per second
Site 3 clock error 3 parts in 10^9
instability 3 parts in 10^9 per second

Figure 4.17: Phase Error ISAR Image Response

The phase errors for the three images is plotted in Figure 4.18. The modeled algorithm provides the means of adding the clock errors and instabilities from the transmitter and receiver. For the mono-static case, only the instability contributes to the defocusing. For the multi-static cases, the equivalent range migration takes place through several range cells, since each range cell is 20 wavelengths wide and the phase error grows to 55 cycles and 27 cycles for the two multi-static geometries modeled.



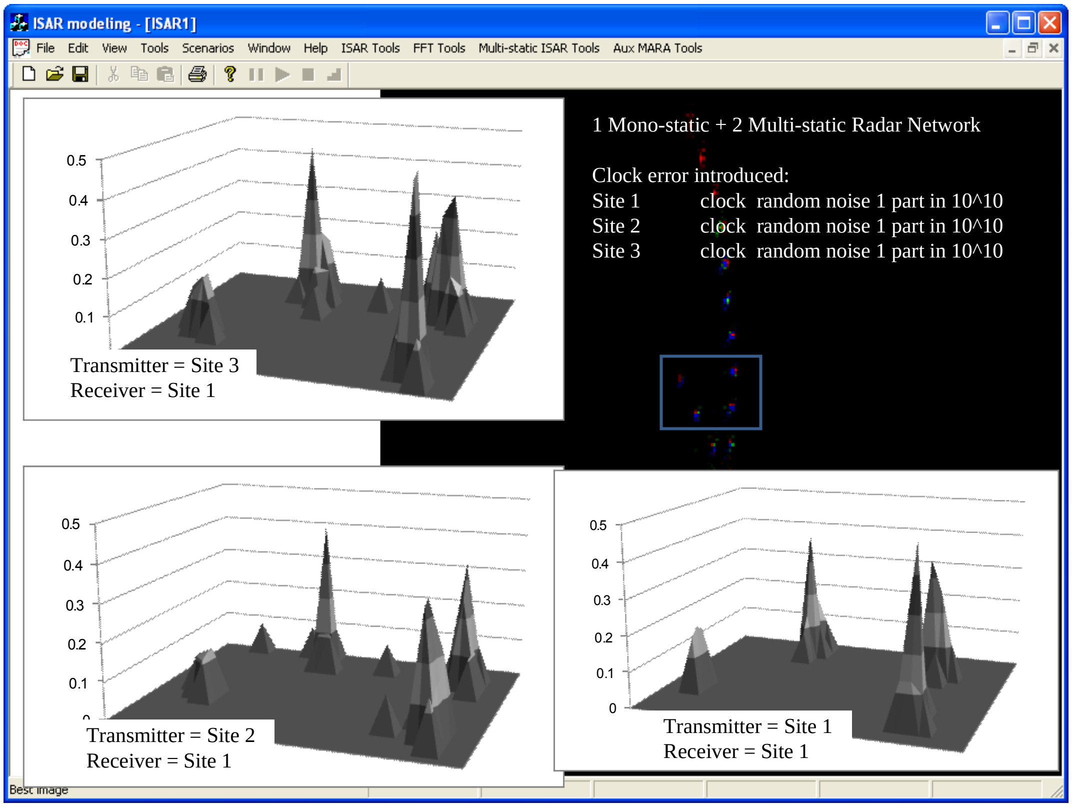
1 Mono-static + 2 Multi-static Radar Network

Clock error introduced:

Site 1	clock error 1 part in 10^9 instability 1 part in 10^9 per second
Site 2	clock error 2 parts in 10^9 instability 2 parts in 10^9 per second
Site 3	clock error 3 parts in 10^9 instability 3 parts in 10^9 per second

Figure 4.18: Multi-Static Modeled Phase Errors

In the mathematical model, the clock noise is identical to a range rate that varies randomly burst to burst. If we introduce noise errors, translational motion compensation cannot focus the image. Therefore the accumulated phase error due to clock noise must be a small fraction of a full cycle. The resulting ISAR image and the same four points are shown in the Figure 4.19 for a clock noise standard deviation of 1 part in 10^{10} for all three radar sites.

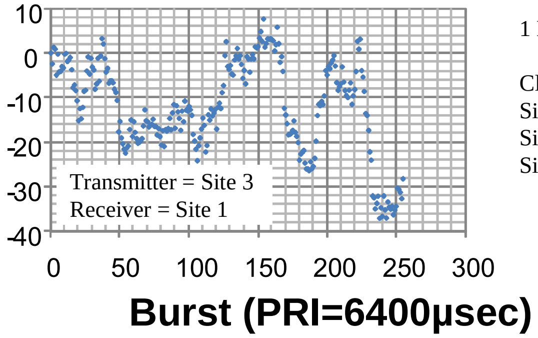


1 Mono-static + 2 Multi-static Radar Network

Clock error introduced:
Site 1 clock random noise 1 part in 10^10
Site 2 clock random noise 1 part in 10^10
Site 3 clock random noise 1 part in 10^10

Figure 4.19: ISAR Image Response (clock noise standard deviation of 1 part in 10^{10})

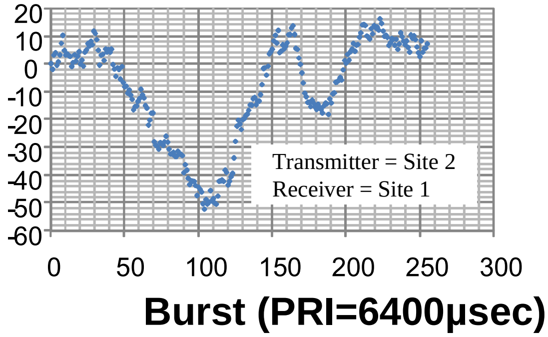
The phase noise for the three images is plotted in Figure 4.20. For the mono-static case there is no phase error when only noise, and no clock error or instability, is applied. For the multi-static cases the phase error stays less than 50 degrees and so the signal remains fairly coherent during the 256 bursts.



1 Mono-static + 2 Multi-static Radar Network

Clock error introduced:

Site 1	clock random noise 1 part in 10^10
Site 2	clock random noise 1 part in 10^10
Site 3	clock random noise 1 part in 10^10

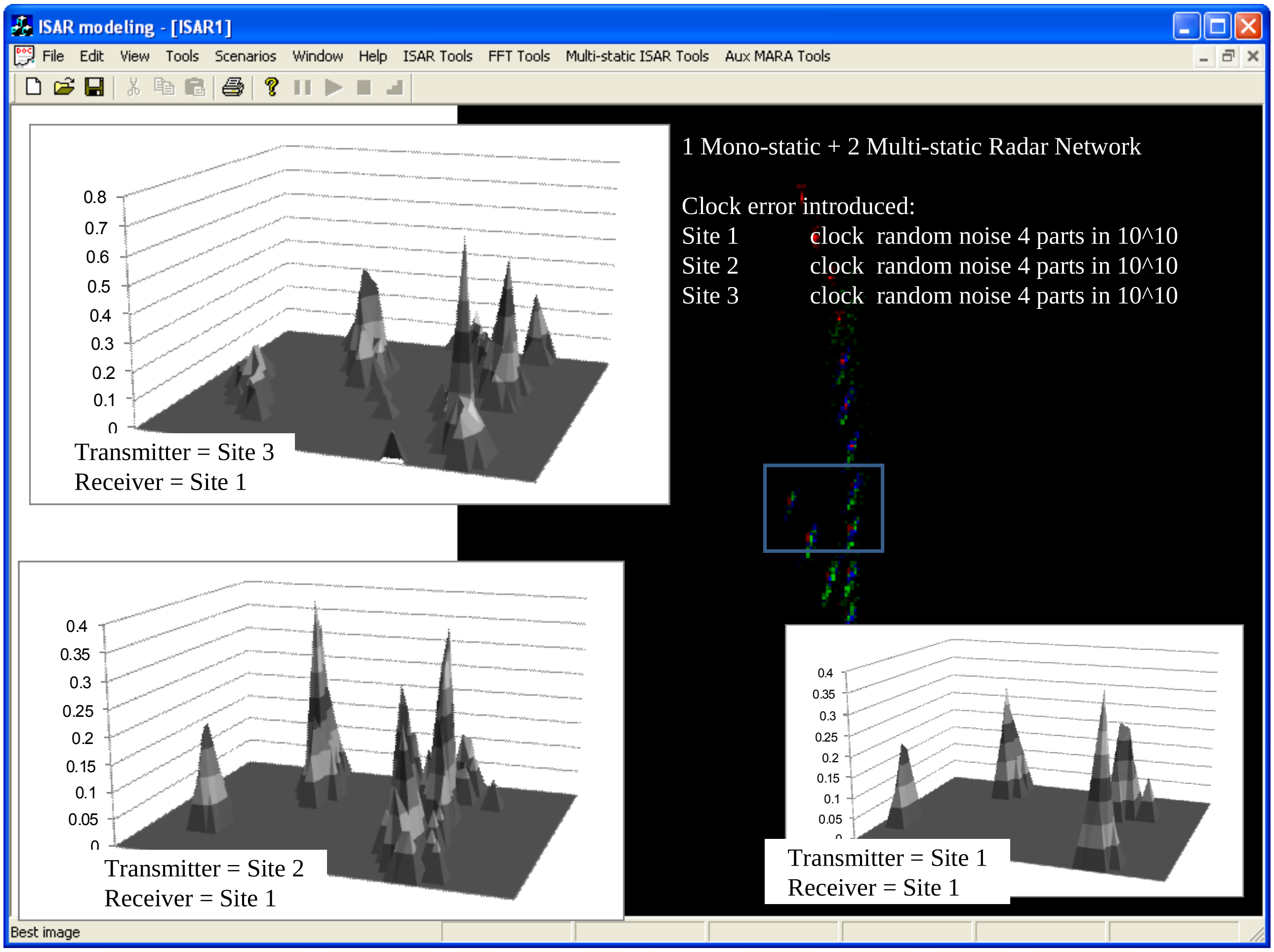


No Phase Error
in Mono-static Case

Transmitter = Site 1
Receiver = Site 1

Figure 4.20: Multi-static ISAR Modeled Random Phase Noise

The ISAR image and the same four points are shown below with a clock noise of 4 parts in 10^{10}. When the random phase noise is a significant fraction of a RF cycle, the signal becomes unfocused. The side lobe energy is visible in the ISAR image and in the intensity plots for the two multi-static signal paths. The mono-static signal path is not affected by clock noise as modeled and shown in Figure 4.21.

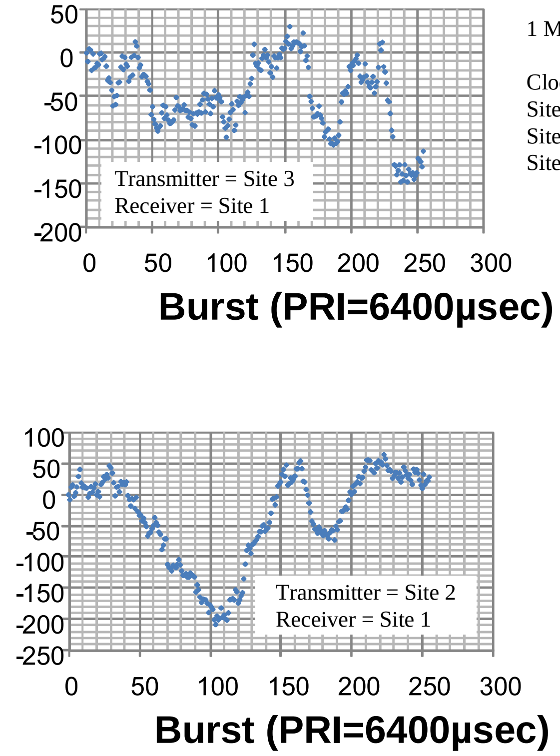


1 Mono-static + 2 Multi-static Radar Network

Clock error introduced:
Site 1 clock random noise 4 parts in 10^10
Site 2 clock random noise 4 parts in 10^10
Site 3 clock random noise 4 parts in 10^10

Figure 4.21: Multi-static ISAR Images (Clock random noise 4 parts in 10^{10})

The phase noise for the three images is plotted in Figure 4.22. For the multi-static cases the phase error is a roughly 180 degrees and causes the onset of incoherence of the signal during the 256 bursts.



1 Mono-static + 2 Multi-static Radar Network

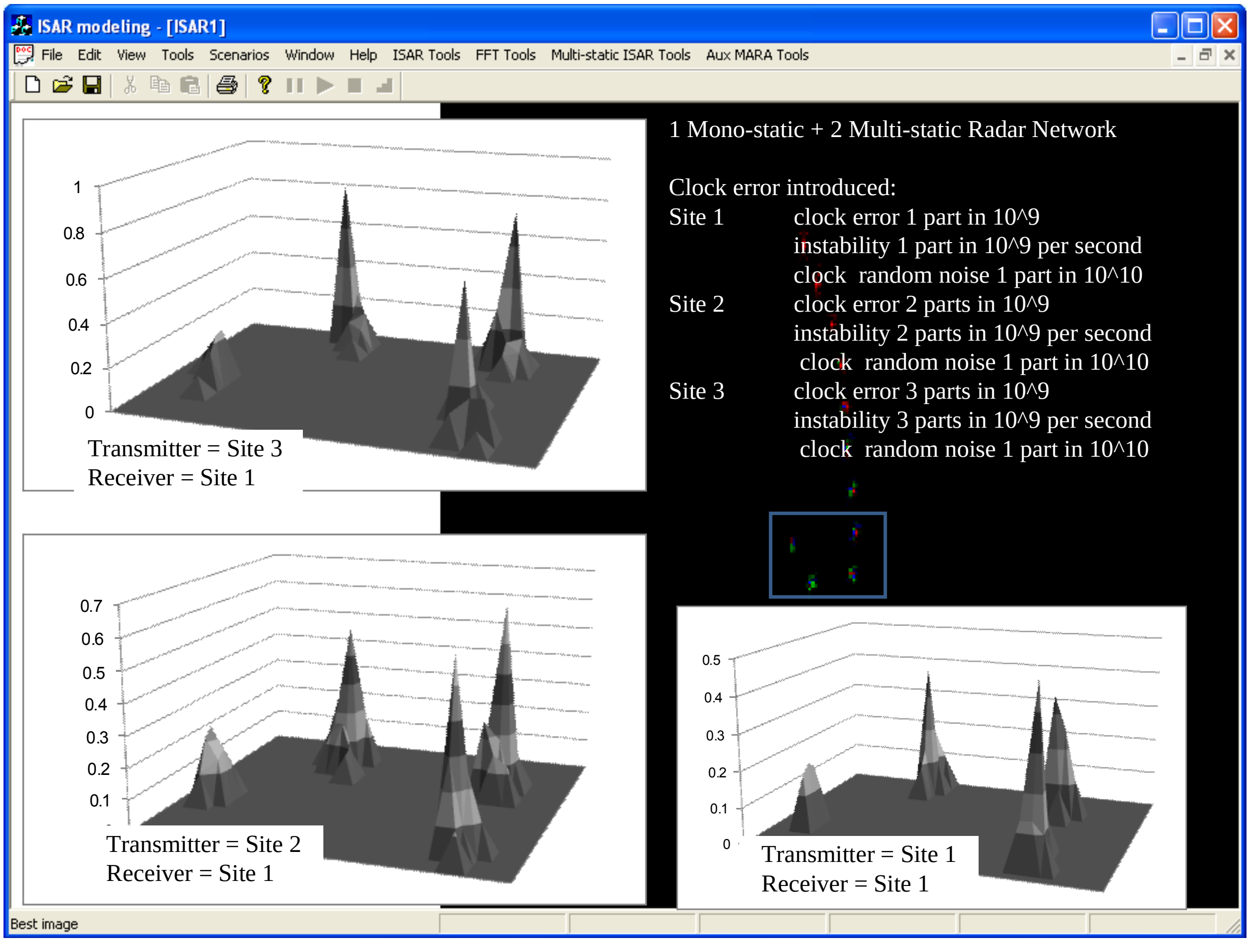
Clock error introduced:
Site 1 clock random noise 4 parts in 10^10
Site 2 clock random noise 4 parts in 10^10
Site 3 clock random noise 4 parts in 10^10

No Phase Error
in Mono-static Case

Transmitter = Site 1
Receiver = Site 1

Figure 4.22: Phase Noise for the Three Images Plotted in Figure 4.21

The results using all three noise sources are shown in the Figure 4.23. The clock noise has a standard deviation of 1 part in 10^{10} for all three radar sites and the clock error and instability is the same as used above. Since the clock errors and instabilities are equivalent to range rate and acceleration, and the noise is small enough to allow focusing as discussed, the phase errors are mitigated by minimum entropy focusing. Few visible side lobes are present in the intensity plots.



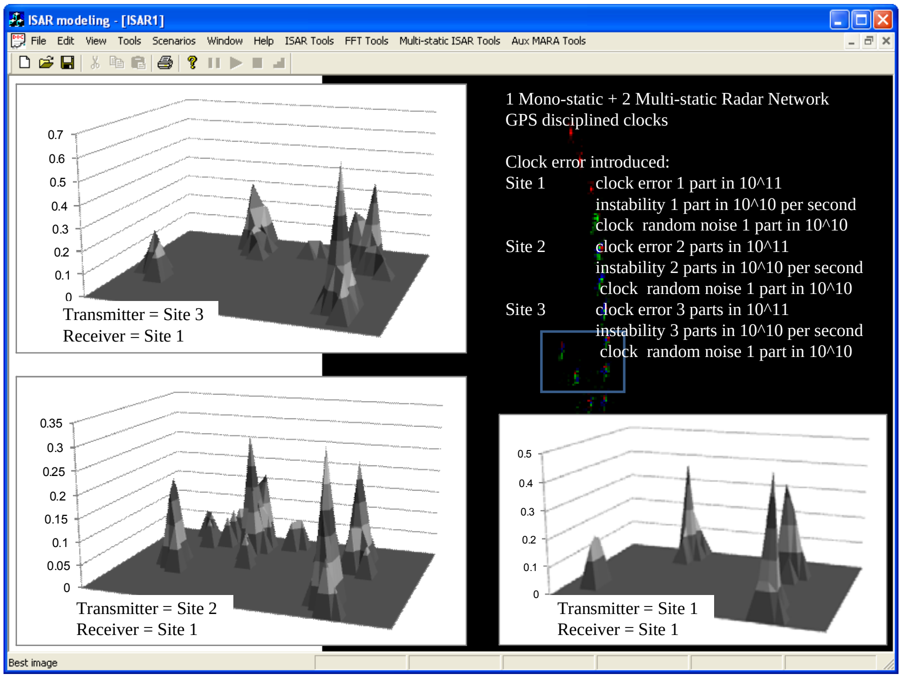
1 Mono-static + 2 Multi-static Radar Network

Clock error introduced:

Site 1 clock error 1 part in 10^9
instability 1 part in 10^9 per second
clock random noise 1 part in 10^10
Site 2 clock error 2 parts in 10^9
instability 2 parts in 10^9 per second
clock random noise 1 part in 10^10
Site 3 clock error 3 parts in 10^9
instability 3 parts in 10^9 per second
clock random noise 1 part in 10^10

Figure 4.23: Multi-static Images with Three Noise Sources

GPS disciplining the clocks at the three radar sites requires that the clock instability be small enough that the jump in target range caused by resetting the clocks every second does not distort the final ISAR image. The range acceleration aspect of translational motion compensation, which cancels the effect of clock instability in a non-disciplined case, cannot retain coherence though the jump in range. (It may be possible to design a range acceleration compensation that can account for resetting the clocks every second, and will be studied). The results are shown in Figure 4.24 and 4.25.



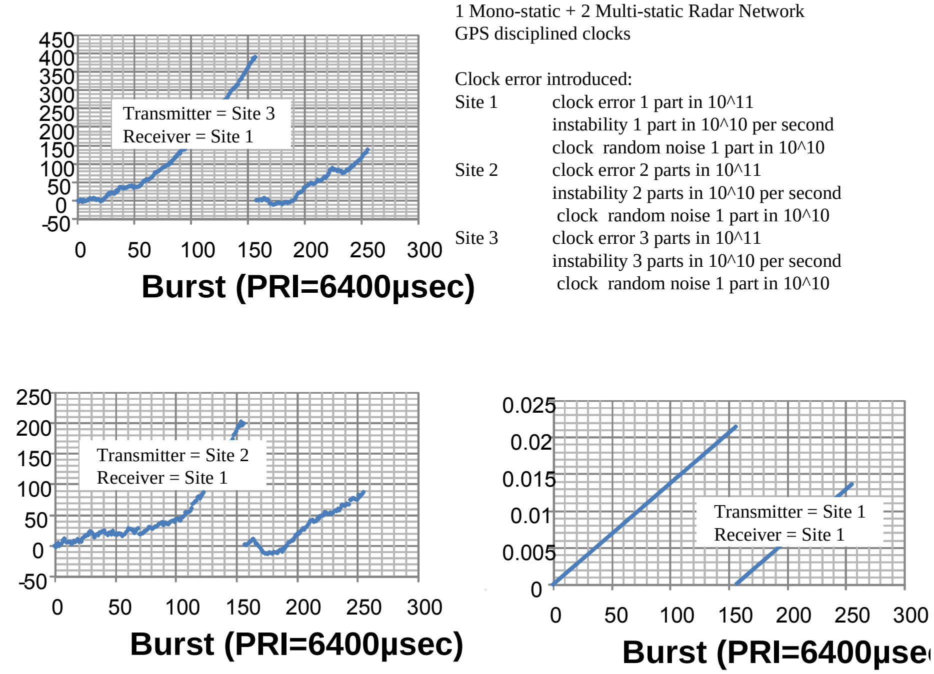
1 Mono-static + 2 Multi-static Radar Network
GPS disciplined clocks

Clock error introduced:

Site 1	clock error 1 part in 10^11
	instability 1 part in 10^10 per second
	clock random noise 1 part in 10^10
Site 2	clock error 2 parts in 10^11
	instability 2 parts in 10^10 per second
	clock random noise 1 part in 10^10
Site 3	clock error 3 parts in 10^11
	instability 3 parts in 10^10 per second
	clock random noise 1 part in 10^10

Figure 4.24: ISAR Images with Uncompensated Phase Error Jumps

The jump in phase error that occurs every second when the clocks are GPS-disciplined is clearly visible in the phase noise for the three images plotted below.



1 Mono-static + 2 Multi-static Radar Network
GPS disciplined clocks

Clock error introduced:

Site 1	clock error 1 part in 10^11
	instability 1 part in 10^10 per second
	clock random noise 1 part in 10^10
Site 2	clock error 2 parts in 10^11
	instability 2 parts in 10^10 per second
	clock random noise 1 part in 10^10
Site 3	clock error 3 parts in 10^11
	instability 3 parts in 10^10 per second
	clock random noise 1 part in 10^10

Figure 4.25 Radar Burst with Phase Error Jumps

4.4 Multi-static ISAR Data Collection Test Scenario

The San Diego, California harbor approach area has been evaluated as a candidate for a multi-static radar data collection site. Figure 4.26 depicts a typical from the sea approach to San Diego harbor where three test radars could capture mono-static and multi-static ISAR data for use in off-line image processing. The scene shows that when sea traffic approaches within four to five miles of San Diego harbor, the approach requires a turn to take an easterly course until the ship passes Buoy "SD" as shown on the Figure 26 chart. Once past the Buoy SD, shipping is under San Diego Harbor control and are advised to initiate a turn to port (Northeast) and remain in that turn until they are on a course that brings the ship to a course that is in a straight line to the harbor entrance. As also shown in Figure 26, three data collection radar systems (Radar 1- Pt Loma shown in Red, Radar 2 North Island shown in White, and Radar 3 shown in Blue) can be deployed to detect approaching ships and each can maintain beam coverage of a ship targeted for data collection through the entire turn to line up with the harbor channel. The deployment shown will insure that approaching ships are in the field of view of all three radar as they approach, as they turn and as they exit the in bound turn approach. These maneuvers present a changing target aspect over time and provide opportunities for multiple data bursts with ISAR multi-static data collection during each burst. The range of these ship movements are well within the power-aperture parameters that have been identified for the data collection radars.

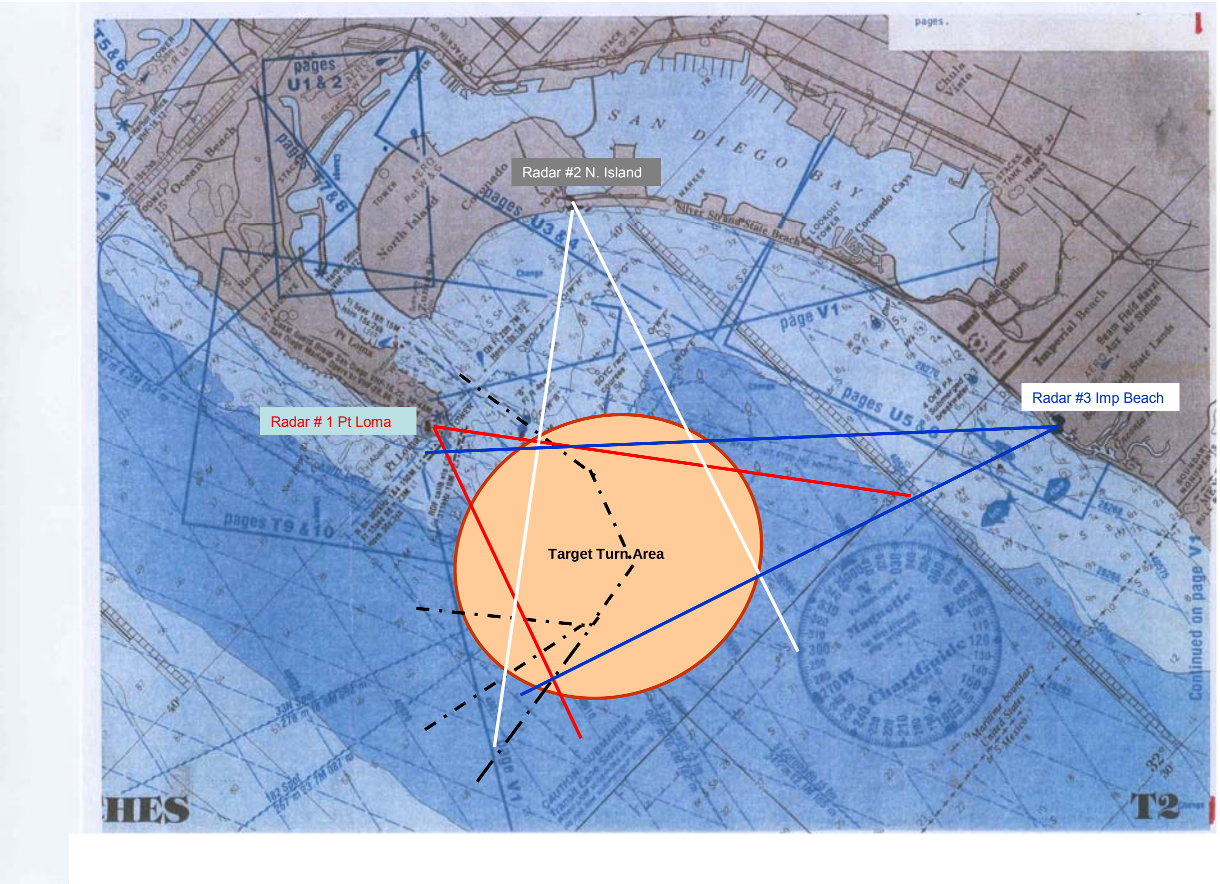


Figure 4.26: Multi-static ISAR Data Collection Test Scenario

5.0 Unanticipated Technical Issues

None

6.0 Plans for Next Reporting Period

The planned MARA development schedule is shown in Figure 6.1. As the research effort progresses, the schedule has been adjusted to reflect variations that occur in the planned development schedule. Four subtasks describe the content of the research. Additional detail for each subtask is provided in the following discussion:

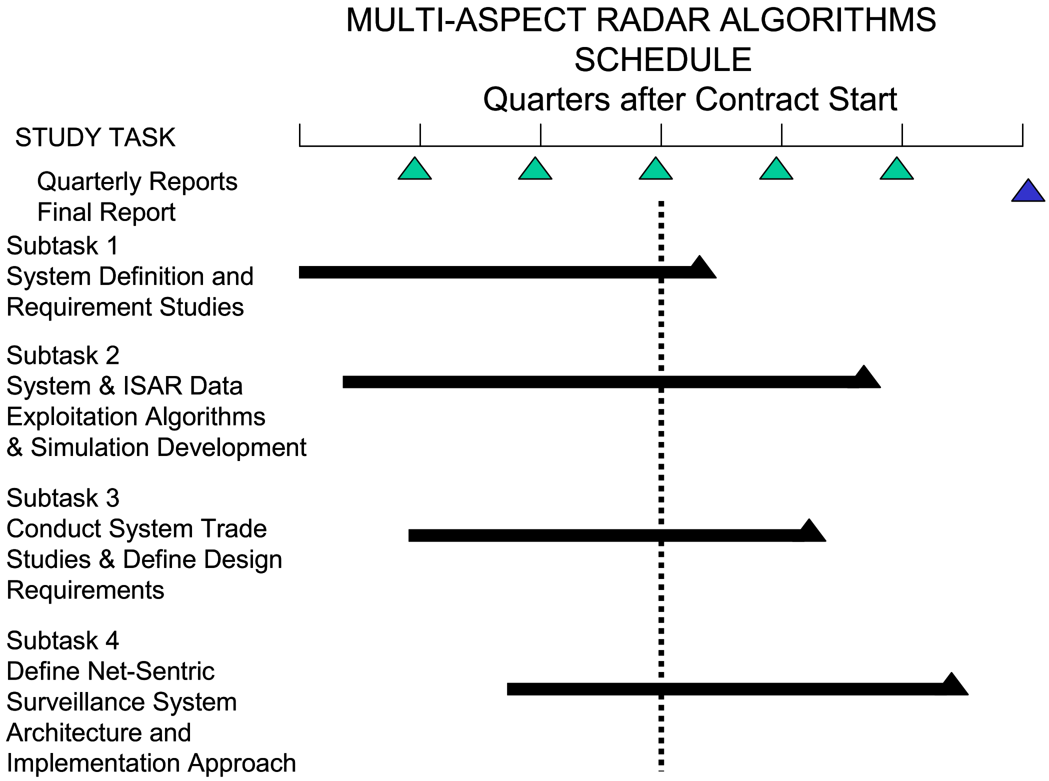


Figure 6.1: Multi-Aspect Radar Algorithms Development Schedule

Subtask 1: Research under this task focused on the definition of the system elements of a multi-static ISAR net-sentric system that acquires, processes, and generates high definition radar imagery of maritime vessels. The requirements studies conducted within this subtask are focused on two system configurations, both supported by GPS timing synchronization and net-sentric control:

(1) The initial approach defined a data collection radar design that uses available wide bandwidth radar technologies to configure single beam X-band or Ku-band radar designs dedicated to collection of ISAR data from multiple test radars operating in mono-static or multi-static modes. Research under this was completed. Due to the single beam capabilities of the test radar design, the data collection configuration emulates the ISAR performance of a single beam of an AESA system and is range limited to operate in the defined test scenario. The ISAR data collection capability is augmented with a pulse Doppler detection capability to locate targets and

place data capture range windows a targets position. Commercial Off The Shelf (COTS) radar modules have been defined and incorporated into the design definition of the collection radar for key radar subsystems with multi-band (X-band and Ku-Band) common use elements defined to the extent they are available. The system operating characteristics were optimized for the target set operating in the test scenario defined in this research study. The design definition is the basis for extending the radar design definition to an AESA implementation.

.

(2) Effort continues in the next reporting period on the second design definition that extends the design of definition of the ISAR data collection system to a full scale multi-function, wide-area surveillance, track, and image-while-search AESA radar that utilizes the multi-static ISAR imaging algorithms developed during the current study to produce a net-sentric target classification and recognition capability. The AESA design definition continues and includes an assessment of the combined use of multi-static radar imagery and ESM signature correlation for improvements in target identification. The use of AESA radar technology for this design approach is based on the potential need for pulse-to-pulse beam steering to provide interlaced imaging and surveillance waveform generation and signal processing. The study supports an expanded definition of the net-sentric requirements for the multi-aspect, multi-static ISAR imaging, surveillance and ESM system.

Subtask 2: Research continues under this subtask that is focused on the exploitation of ISAR image data that can be obtained from multi-static radar operations. Algorithms that focus, polar transform, and form ISAR images have been developed. Modeling and simulation using these algorithms has graphically demonstrated composite ISAR multi-static imaging. The research is addressing the development of algorithms that correlate multi-static imagery and determine image fidelity improvement that may result from combining the multi-static images.

Timing synchronization and phase coherency of the multiple radars used for the multi-static data collection tests has been supported by use of GPS disciplined timing reference signals. Algorithms that characterize the data collection timing sequences, the radar pulse timing, and the control logic for the coherent reference phase locked loops of the multiple radars have been developed and are being used in simulations of multi-static testing and focusing issues associated with timing jitter, frequency drifts and phase noise in the GPS referenced synchronization of the multi-static data generation. An alternative test sequence being considered is the potential for precise time and frequency control of multi-static radars to obtain simultaneous illumination of maritime targets from different sites, thus presenting the opportunity to explore the effects of waveform augmentation and cancellation on image data received at the multi-static radar receivers.

Subtask 3: Research continues under this task that involves system trade studies that will lead to:

- Costing and packaging requirements for the data collection test radar components that have been defined.
- Trade studies for components of an AESA version of wide area maritime surveillance, tracking and image-while-search ISAR.
- ESM design requirements for maritime vessel ESM data collection by radar receivers co-located with surveillance and imaging radar.
- Refinement of the Net-Sentric design requirements for a network that supports control, data acquisition, and data correlation from the multi-static radars and their co-located ESM systems.

Subtask 4: Research under this task is developing a definition of the Net-Sentric Surveillance System that encompasses multi-site AESA ISAR sensors, ESM sensors, a network for control and image transmittal, and the utilization of GPS assets for overall synchronization and coherency control of the sensors within the network. The definition will characterize the Net-Sentric system architecture, parameter definitions for key elements of the network, and a definition of the required characteristics for major subsystems and components that comprise the Net-Sentric Surveillance System.

7.0 Funding Summary and Status

The program funding summary outlined below provides the amounts invoiced to the contract during the period September 01, 2009 through November 30, 2009, and the cumulative amount invoiced since contract award. As advised to the sponsor it is currently planned to complete this study in May 2009 vice original plan of July 2009. No funding issues to report.

Total Contract Program Funding:	$643,653.00
Expended September 01, 2009 – November 30, 2009:	$103,471.29
Cumulative Invoiced to Date:	$260,000.13
Funds Remaining on Contract:	$280,181.58