1.0 IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM OR OPPORTUNITY

Operations under general degraded visual environment (DVE) weather conditions, such as fog, or in rotary wing related brown-out (in presence of dust/sand) and white-out conditions (in snow) are very hard and risky for airborne vehicles' pilots or operators (for unmanned system). A variety of ground-based obstacles like buildings, large rocks, trees, poles, and especially power lines may be masked by the obscurant particles. Also, risk of collision with other aircrafts or drones is significantly higher in DVE conditions. Any high resolution optical and infrared (IR) devices, such as cameras and LIDAR systems, are subject to significant degradation due to their small wavelength compared to the size of obscurant particles. Existing radar systems are either bulky/heavy or have poor resolution/sensitivity. Furthermore, these radars can provide high frame rate only for a very limited field-of-view (FOV), which reduces probability of obstacle detection.

To address the Navy's need, Intellisense Systems, Inc. (ISI) proposes to develop the new **Collision Avoidance Millimeter Wave Radar (CAMWAR) system**, which combines analog and digital beamforming [1] with a multiple-input, multiple-output (MIMO) [2] configuration, as illustrated in Figure 1-1. To support the Navy concept of operations (CONOPS), the ultra-low size, weight, and power (SWaP) millimeter wave (mmWave) radar is a sense-and-avoid (SAA) sensor system that detects and tracks hazards and obstacles, enables collision avoidance, and provides situational awareness under DVE conditions, including brown-out, dense fog, and light rain. The CAMWAR system is specifically designed to fit airborne platforms including tactical unmanned aerial systems (UAS), to meet the SWaP and environmental requirements. It operates in E-band (76-81 GHz) or, possibly, W-band (92-100 GHz) and achieves 360° coverage in a quad-sensor configuration with separate transmit and receive antenna arrays. Figure 1-1 shows key components of the single radar sensor that covers up to 90° in both azimuth and elevation by using three linear antenna arrays: one receive (RX) and two transmit (TX) arrays. Each TX antenna array contains N=24 channels with controllable phase shifters to implement analog beamforming (ABF) using a phased array antenna that supports vertical scan of a fan beam, narrow in vertical and broad in azimuth directions. The CAMWAR receiver implements M-channel digital beamforming (DBF) by concurrently processing down-converted and digitized M=32 receive signals. DBF allows for parallel processing of multiple beams and full utilization of the TX fan beam's energy, resulting in significant reduction of the radar update time or frame (to 10 ms) and latency (to ≤1 ms). The RX antenna array also has a fan beam but it is narrow in azimuth and broad in vertical directions. A cross-section of orthogonal TX and RX fan beams results in a narrow pencil beam. Two TX antennas realize a 2xM MIMO radar configuration. The RX MIMO processing coherently integrates two orthogonal TX waveforms to obtain a 2M virtual linear array length and, consequently, increase the radar angular resolution in azimuth. The CAMWAR's modular architecture allows for easy adjustment of the radar design to specific application requirements by modifying M and N values. Doppler beam-sharpening [3] will be applied to improve the radar azimuth angular resolution for side-looking directions. The use of commercial off-the-shelf (COTS) components reduces development risks and eliminates future obsolescence.

The airworthy CAMWAR is capable of detecting and tracking multiple (tens of) objects at 3-6,000 ft range with high resolution and high (up to centimeter-level) accuracy in both range and velocity. The innovative CAMWAR architecture, based on a combination of analog and digital electronic scanning with a MIMO configuration, achieves a 100 Hz update rate with several thousand beams per frame covering 360°. A wideband, fast, frequency-modulated continuous wave (FMCW) radar waveform with a very high (up to 10^6) time-bandwidth product and adaptive control of TX power provides low probability of detection/low probability of intercept (LPD/LPI). Frequency agility of the radar carrier in a wide band (up to 5 GHz) enables interference-free multi-sensor operation, using channel allocation through registration. The CAMWAR system will fit in a 200 in.^{3} volume envelope, weigh <10 lb, and consume <200 W of power, within the SWaP requirements. It will meet applicable Federal Aviation Administration (FAA) and Radio Technical Commission for Aeronautics (RTCA) specifications, such as RTCA DO-366 [4], and physical and environmental requirements, and it will comply with MIL-STD-810, MIL-STD-704F, and MIL-STD-461G. Leveraging ISI's experience in developing mmWave radars, phased arrays, DBFs, and MIMO transceivers, we will deliver a solid design of the CAMWAR antenna, RF module, and software algorithm for the first prototype, which will enable a rapid advance in technology readiness level (TRL) in Phases II and III of the program. The proposed radar architecture not only addresses the major *NAVAIR* requirements for a military airborne platform collision avoidance system under DVE conditions, but also has significant commercial applications such as drone-based delivery.

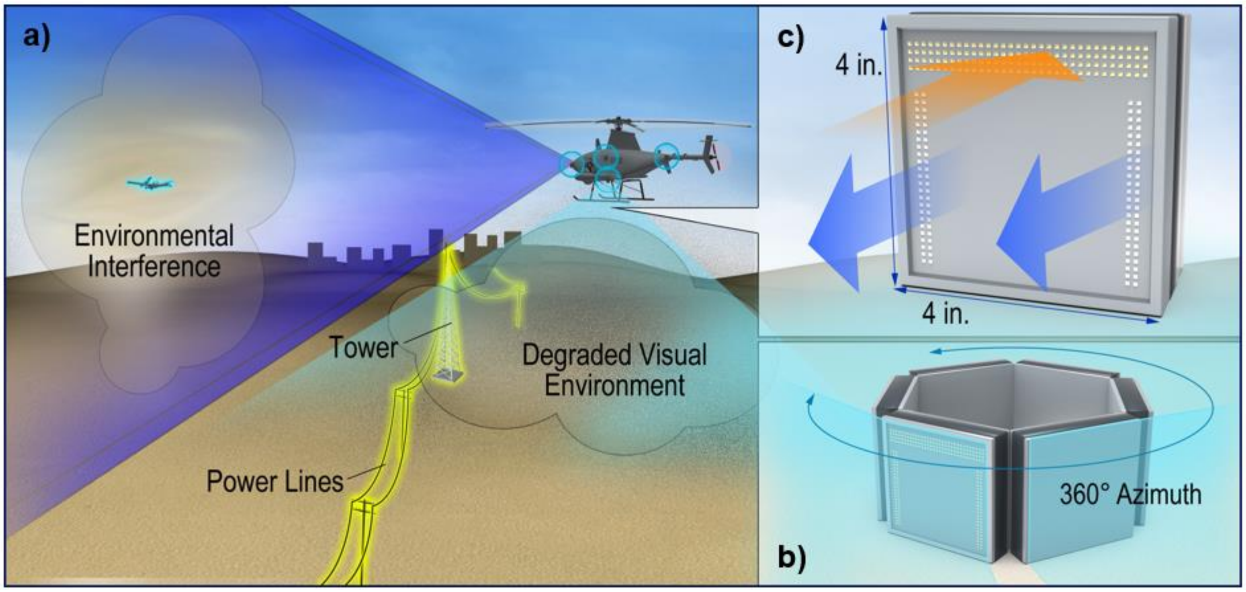

Figure 1-1. ISI's LPD/LPI, mmWave, CAMWAR provides collision avoidance capabilities to airborne platforms under DVE conditions (a). It provides high level accuracy in detecting obstacles at up to 2 km range with a 360° FOV achieved in a multi-sensor (b) configuration (≥4 sensors). (c) The 2xM MIMO analog and digital electronically scanned antenna with orthogonal TX and RX fan beams provides high angular resolution. The compact CAMWAR radar can be installed on tactical UASs, helicopters, or other airborne platforms as an integrated or distributed system and is incorporated with a collision avoidance software suite, Autonomous Aerial Cargo Utility System (AACUS).

The proposed radar architecture has significant advantages over the current radar design approaches to airborne collision avoidance:

- **Ultra-low antenna aperture** and **highly integrated electronic components** enable compact implementation of a 360° CAMWAR radar in a 200 $in.^3$ form factor that weighs <10 lb.
- **Very broad FOV** covers 360° in azimuth and up to 90° in elevation.
- **LPD/LPI operation** due to FMCW waveform and adaptive control of transmit power.
- **Extremely high 100 Hz update rate** due to DBF multi-beam parallel processing with 1 ms latency.
- **High Doppler resolution** due to long dwell and DBF parallel processing.
- **Low development, production, and maintenance cost** as well as low future obsolescence by largely using COTS components.
- **Modular scalable architecture allowing for easy adaptation** of the CAMWAR radar to new applications.

Although electronic scanning antenna technology for radars is well developed in the microwave spectrum up to Ku-band, only mmWave can provide high angular resolution in a low SWaP implementation. Unfortunately, direct scaling of the microwave phased array technology to the mmWave spectrum faces serious technological and even physical limitations that include high total power and power density, high design complexity, and high cost. In addition, a 2D phased array radar without DBF cannot provide 100 Hz update rate due to the successive nature of ABF, and provides no Doppler capability.

Table 1-1 presents a comparison of the CAMWAR system versus state-of-the-art (SOTA) mmWave radar systems. The table compares several existing mmWave radars, which differ in beam-steering methods, sizes, and performance. None of them meets the solicitation requirements. Although high-resolution 2D-angular electronically scanning mmWave radars are not yet available, we can estimate potential performance of such a radar based on the SOTA mmWave technology and components. Thus, we compared a hypothetical phased array (no DBF, no MIMO) quad-sensor radar with 64×24 TX/RX antenna arrays to CAMWAR. Such a radar would match CAMWAR in frequency bandwidth (BW), FOV, angular and range resolutions and exceed it in maximum range, but would consume >6× power and have 10× lower update rate and no Doppler capability. Thus, CAMWAR technology is superior to the alternatives.

Table 1-1. Comparison of CAMWAR and SOTA Radars
Legend: good, moderate, poor performance

Parameter	SBIR Requirement	HALS-3 Sierra Nevada	EchoFlight Echodyne	ARS 408 Continental	4×64×24 Phased Array	ISI's CAMWAR	How Is Solution Implemented?
Azimuth FOV, [°]	360	30	120	18	360	360	4 or 6 patch array antenna panels
Elevation FOV, [°]	not specified	30	80	14	Up to 90	Up to 90	ABF array
Azimuth resolution, [°]	not specified	1.0	~5	2.2	1.6	1.6	DBF with MIMO
Elevation resolution, [°]	not specified	0.8	~15	n/a	4	4	ABF array
Range Resolution, [m]	not specified	0.5	No data	1.8	0.15-1.5	0.15-1.5	Up to 1 GHz modulation bandwidth
Minimum Range, [m]	1.5	6.5	No data	0.2	0.5	0.5	High range resolution
Maximum Range, [m]	1,850	1,500	2,000	250	4,000	2,000	High EIRP=50 dBm Low noise figure (4 dB) Long (1 ms) dwell time
Doppler resolution, [m/s]	not specified	n/a	No data	0.1	n/a	≤2	Long (1 ms) dwell time
Scan update rate, [Hz]	100	2	~1	14	10	100	DBF parallel processing
Probability of Intercept	low	moderate	moderate	moderate	moderate	low	High (up to 10^6) time-bandwidth product
Operational Bandwidth, [GHz]	mmWave, wide	93-95	24.45-24.65	76-77	76-81	76-81	Wide operational bandwidth of the selected components
Beam-scanning type	electronic	mechanical	electronic	electronic	electronic	electronic	Combination DBF and ABF with MIMO configuration
Power Consumption, [W]	not specified	≥300	≤40	6.6	≥1,200	≤200	Highly integrated design
Volume, [in.^{3}]	350	≥2,000	56	8	~300	≤200	Highly integrated design
Weight, [lb]	15	≥50	≤2	≤1	~10	≤6	Highly integrated design

CAMWAR advantages are made possible by the following unique ISI innovations:

- **A novel mmWave radar architecture**, which combines ABF in TX and DBF in RX with a MIMO configuration.
- **A novel 2D-scanning patch antenna configuration** that contains two mutually orthogonal linear arrays with fan beams used on transmit and receive. Orthogonal TX and RX fans produce a narrow pencil beam in two-way radar operation. Additionally, two parallel TX arrays shifted at a distance equal to the length of the RX array allow MIMO operation, improving angular resolution.
- **A new flexible and agile modulation waveform control**, which allows quick optimization of radar parameters to a specific operational case.

By combining these innovative features, CAMWAR directly provides the advantages described above to the end-user and offers an ultra-low SWaP versatile sense-and-avoid system superior to current approaches. The CAMWAR system can be used by all military branches that benefit from 360° or hemispherical radar coverage under DVE conditions in any operational environment.

In Phase I, ISI will develop an initial concept that meets the program needs. ISI will model the wideband radar propagation channel including effects of DVE (brown-out and fog) and light rain. ISI will develop and validate CAMWAR architecture, the patch antenna panel, and RF frontend module through modeling, simulation, and experiments. ISI will also develop DBF and radar DSP algorithms and adapt its tracking algorithm, developed for counter-UAS radar and SAA LIDAR/EO systems, to CAMWAR. ISI will develop a concept prototype. Using modeling, simulations and prototype testing, ISI will validate the approach, demonstrate technical feasibility, characterize performance of the CAMWAR concept, and prepare a clear plan for Phase II prototype development including cost estimates, and a risk mitigation plan to address all of the technical challenges that are identified in Phase I. In the Phase I Option period, ISI will refine the initial concept design and prepare a detailed development plan, backed by solid analysis and cost estimates for the Phase II prototype, including main program risks (both technical and vendor-related) and mitigation steps. These efforts will prepare ISI for a successful execution of Phase II. In Phase II, ISI will further refine the approach validated in Phase I and develop a working prototype of the CAMWAR sensor to demonstrate the functionality, characterize the performance, and validate the models and approach from Phase I. ISI will also incorporate the CAMWAR with a collision avoidance software suite and develop a Phase III transition plan to integrate the capability on candidate platforms. During Phase III, ISI will productize the device, transition it to the Navy, and identify additional military programs and applications. ISI will also explore adapting the design to commercial applications such as commercial unmanned aerial vehicles (UAVs). This plan is based on ISI's previous experience and success in rapidly maturing technology readiness level (TRL) and transitioning SBIR programs into production for our DoD customers.

ISI is experienced in developing mmWave, RF, and radar systems, wideband antennas and beamforming networks, high-bandwidth systems, a variety of modulation waveforms for high range/velocity resolution, and LPD/LPI systems. This extensive experience and ISI's experienced staff, has uniquely positioned ISI to successfully develop and commercialize the CAMWAR technology by leveraging the following capabilities:

- Availability of a rich combination of all the skills at ISI required for the research and development of E-band and W-band radar systems, including design of mmWave transceivers, 1D and 2D phased-array antennas, DBF, MIMO radar, wide coverage antennas with narrow-beam beamforming, and a radar signal processing algorithm. The Principal Investigator, Victor Khodos, has broad experience in developing radar systems, including mmWave radars for fixed (REVS) and rotary wing (HALS) aircraft landing systems under DVE conditions for his previous employer, Sierra Nevada Corporation, and electronically steerable mmWave antennas. He will be supported by a skilled team of ISI scientists and engineers experienced in design of embedded systems, DSP, tracking algorithms, and real-time control software. We will engage an expert consultant in E-band antenna design, Dr. Aram Avakian (Section 10). The existing expertise, infrastructure, and synergistic programs will enable ISI to successfully execute the development and to meet the Navy's requirements.
- ISI's promising commercialization strategy and experience: ISI's commercialization strategy for CAMWAR is based on ISI's past record of production and commercialization. ISI's team has developed multiple systems that integrate radar with LIDARs and optical/infrared cameras, and successfully implemented its commercialization strategy targeting both military and commercial markets.
- ISI's capability for transition and production of new technology: ISI has developed, tested, demonstrated, and delivered numerous mature technologies to the DoD, including under programs of record. ISI has implemented design and quality practices and processes and operates in accordance with (IAW) ISO9001:2015/AS9100D and ISO9001:2015/AS9110C standards. As a development organization, ISI incorporates CMMI DEV:ML3 best practices into its system engineering processes throughout the life cycle of its products and expects to achieve ML3 benchmark by 2019. ISI uses certified laboratories for qualification testing of avionics equipment, including MIL-STD-810, MIL-STD-704F, and MIL-STD-461G. ISI also has established channels to obtain NSA-approved Type 1 encryption modules to meet specific DoD requirements. *ISI's facilities have Secret clearance.*

Transition to Commercial and Military Platforms. ISI has a track record of delivering innovative and timely solutions for the military's immediate needs, and has the maturity and stability to support the entire technology and product development lifecycle. Currently, ISI has two ongoing programs of record, the Micro Weather Sensor™ (MWS™) and the Video Display Terminal (VDT) for the MC-130J, which were developed through full Phase I-II-IIE-III processes. The MWS is now in full-rate production at ISI with two IDIQ contracts under an Air Force Life Cycle Management Center (AFLCMC) Phase III contract and under USSOCOM. The VDT contract was recently awarded by the Air Force, and the production line was constructed to optimize production flow and capacity, enabling expansion for additional product lines. ISI management staff have more than 30 years of experience transitioning SBIR-derived technologies into products that meet or exceed the needs of our customers. Our team has extensive experience in developing innovative solutions, building mature prototypes, and transitioning them to commercial products. The experience in technology transition and the manufacturing infrastructure established at ISI will be valuable in transitioning CAMWAR technology from initial design through development, qualification testing, and on to full rate production.

ISI will transition the CAMWAR technology to the Navy through the appropriate program such as PMA266 Specialized and Proven Aircraft Program. After a successful integration with the airborne platforms, we will work with the DoD to determine other applications that can benefit from CAMWAR. Possible applications include commercial UAVs, general aviation, remote inspection, and search and rescue. ISI will explore partnership with industry leaders, such as Raytheon, who has been interested in applying mmWave MIMO radar technologies to aerospace and ground-based applications (see letters in Appendix A). Such support will ease the transition and integration of CAMWAR into several platforms, furthering the adoption of the CAMWAR system.

2.0 PHASE I TECHNICAL OBJECTIVES

The overall goal of this project is to address the Navy need by developing and, for the first time, demonstrating the feasibility of CAMWAR. The following specific objectives have been established to reach this goal.

Objective 1. Development of a conceptual design of the CAMWAR system that addresses the Navy's needs.
Objective 2. Design and development of simulation models of the CAMWAR operation.
Objective 3. Develop a conceptual prototype. Simulation, analysis, and testing to demonstrate feasibility of the CAMWAR technology.
Objective 4. Definition of the commercial market for CAMWAR.

To meet these objectives, the following questions will be answered in the course of the project

1. Considering atmospheric attenuation and DVE obscurant effects, required spatial and velocity resolutions, SWaP constraints, and component availability, which carrier frequency band mmWave bracket allocated by the Federal Communications Commission (FCC) for radar applications is the best?
2. What is the optimal modulation waveform for improved radar performance and LPI/LPD?
3. How will the CAMWAR technology fit into the Navy synthetic vision systems?

3.0 PHASE I STATEMENT OF WORK

The scope of this project is to develop a conceptual prototype, perform simulations and experimental demonstrations to demonstrate the feasibility of the CAMWAR concept, and to present a clear plan for Phase II CAMWAR prototype development.

3.1 Task Outline

The objectives of the proposed project will be accomplished by performing the following tasks.

Task 1. *Develop a Concept System Architecture (Objectives 1)*
ISI will develop the concept system architecture for CAMWAR. Frequency band, antenna configuration, and modulation waveforms will be selected to satisfy the Navy requirements. ISI will validate the architecture through modeling and simulation.

Task 2. *Design and Develop a Radar Transceiver (Objectives 1 and 3)*
ISI will design a broadband mmWave multi-channel radar transceiver. ISI will analyze and select COTS components, and optimize the design for low cost and SWaP. ISI will validate the transceiver design through modeling, simulations, and experiments.

Task 3. *Develop a Model of the Radar Operation (Objectives 2)*
ISI will model and simulate the radar system's performance under various weather and DVE conditions and for different types of objects/obstacles to establish design requirements for the system components.

Task 4. *Design and Develop an Electronically Scanned Antenna (Objectives 1 and 3)*
ISI will develop a scalable 2-D linear array MIMO antenna configuration, which achieves the highest angular resolution in the limited aperture. The antenna will be modeled and simulated in ANSYS HFSS with the assistance of our consultant, Dr. Avakian.

Task 5. *Demonstrate Feasibility of CAMWAR (Objective 3)*
ISI will develop a conceptual prototype of the CAMWAR sensor. ISI will test and demonstrate the feasibility of the CAMWAR concept by simulating the system's behavior and performance under various conditions, analyzing design tradeoffs, and evaluating performance of the prototype.

Task 6. *Explore Commercial Potential, Technology Transition, and Product Viability (Objective 4)*
ISI will explore the potential to transfer CAMWAR to different military systems and civilian applications. Market research will identify most promising applications. Sources of Phase II and Phase III guidance and matching funds

will be identified early in the project, and these early business partners will be involved throughout development and commercialization.

Task 7. *Manage Program and Submit Reports*
ISI will undertake program management and reporting, as well as communication with the Technical Point of Contact (TPOC). ISI will prepare and submit reports and attend a kick-off meeting in accordance with contractual requirements. The final report will contain a summary of the work performed as well as recommendations for work to be performed in Phase II.

Phase I Option for Transition to Phase II. The Phase I Option will include the preparatory work to bridge the Phase I feasibility efforts to the Phase II prototype development. Specifically, the following tasks will be performed during the Option period.

Task 8. *Refine the System Design (Objective 2)*
ISI will identify and implement the improvements and modifications of the CAMWAR system design and will test and analyze them in simulation. The complete system design will include mechanical drawings of the enclosures and assemblies.

Task 9. *Develop Phase II Plan and Design Description (Objective 3)*
ISI will prepare a development plan for the Phase II prototype, including risk management based on technical challenges identified in Phase I, and a system design with cost estimates, to facilitate the development progress in Phase II.

3.2 Performance Schedule
The tasks will be performed in accordance with the schedule shown in Figure 3-1. All work will be performed at ISI's facilities in Torrance, California, except for work by the consultant, Dr. Aram Avakian, which will be done in Irvine, CA.

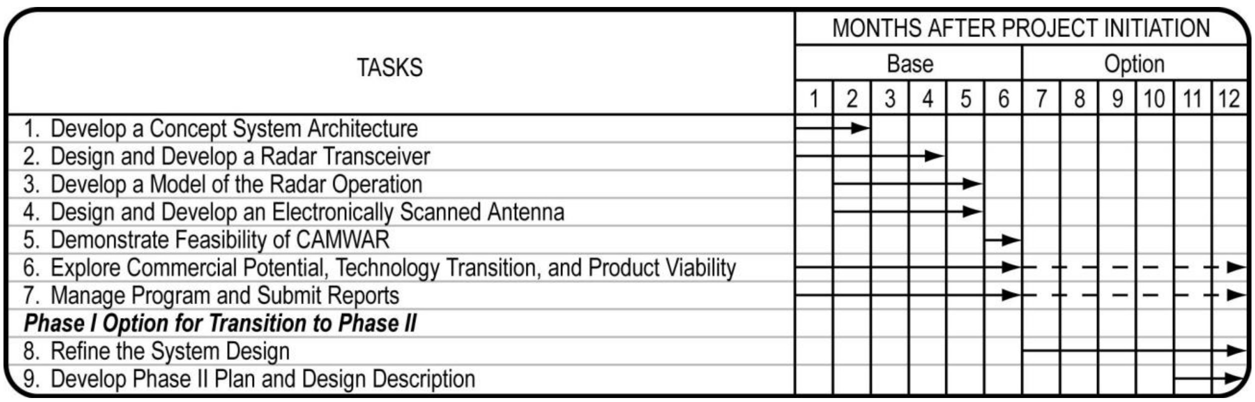

Figure 3-1. Performance schedule.

Deliverables: Reports, presentations, prototype development plans and an Initial Phase II proposal in accordance with contractual requirements.

3.3 Technical Discussion
3.3.1 Develop a Conceptual System Architecture (Task 1)
ISI intends on implementing mmWave electronically scanned radar in the CAMWAR approach. This radar will be capable of high update rate, broad coverage, high resolution 3-D (azimuth, elevation, and range) imaging under DVE conditions, and will meet SWaP constraints. In Phase I, we will develop a concept radar architecture that meets/exceeds the Navy requirements.

The initial CAMWAR system architecture diagram in Figure 3-2 shows a quad-sensor configuration. The modular scalable architecture allows up to eight additional sensors to be added. Each sensor operates independently under control of the Base Unit, which collects and fuses radar data from the sensors and tracks the targets. The Base Unit is an embedded processing module that provides a composite picture to the collision avoidance software suite AACUS. ISI will adapt its tracker algorithm for CAMWAR.

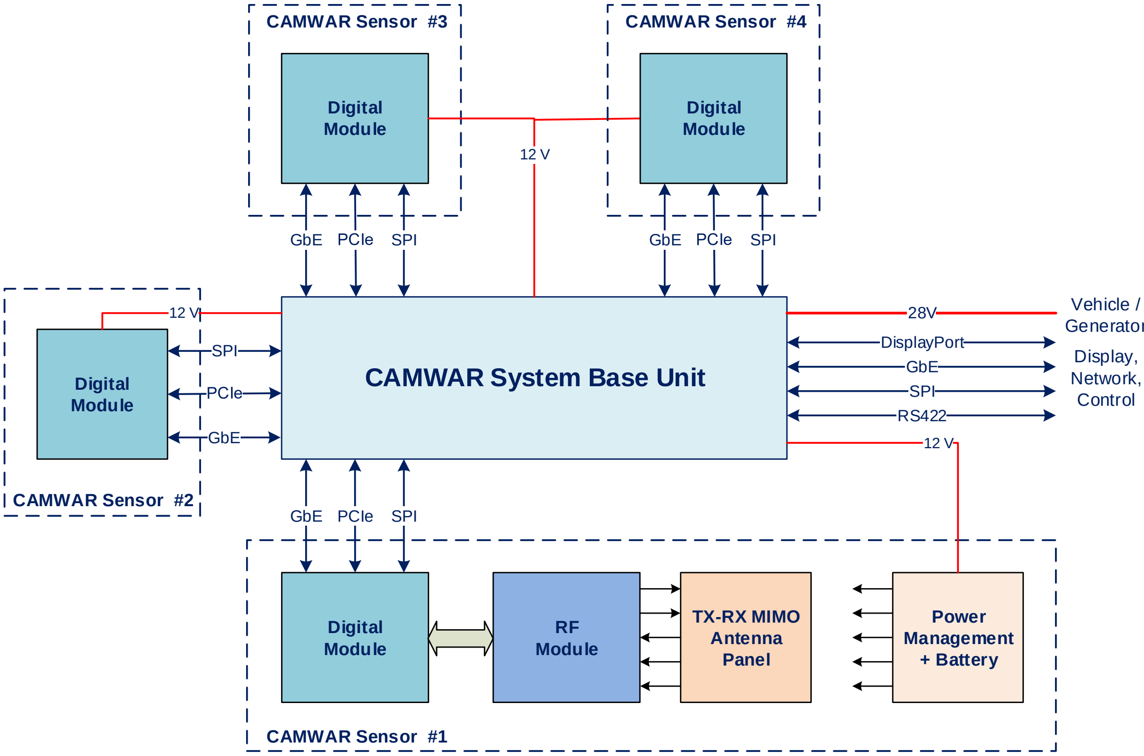

Figure 3-2. CAMWAR concept system diagram.

The sensor unit consists of the TX-RX antenna panel (Section 3.3.4), RF module (Section 3.3.2), and digital module that is based on a Xilinx Zynq® UltraScale+™ MPSoC (multi-processor system-on-chip) that executes the MIMO radar DSP algorithm utilizing hardware processing engines implemented in the programmable logic.

The CAMWAR system uses 28 VDC power provided by the airborne platform that is converted to 12 V used by the sensors.

Although, small and low-cost electronically scanned mmWave radar sensors became available in recent years for emerging autonomous vehicle applications, these sensors have poor angular resolution and short operational range. The major limitations for increasing of 2D phased array aperture size are power dissipation and thermal conditioning. Thus, a 64×24 phased array (see Table 1-1), that achieves the CAMWAR angular resolution with a 1536-element array would consume >300 W (with realistic 0.2 W per channel) concentrated in a very small aperture size. The highest reported number of TX-RX channels for a 2D radar phased array is 64 (8×8) [5].

To overcome the mmWave radar limitations, ISI has designed a new electronically scanned architecture that combines ABF and DBF with a MIMO configuration and allows to a very high update rate to be reached with 360° coverage by implementing parallel operation and processing of multiple radar beams. Figure 3-3(a) shows where antenna arrays and RF components (RFIC – RF integrated circuits) are placed on the single radar sensor panel with up to 90° coverage, and Figure 3-3(b) illustrates the antenna fan-beams cross-section view. Crossing of the multiple parallel vertically oriented receive digital beamforming beams with electronically scanned horizontally oriented transmit beam results in a linear array of narrow pencil beams. A 2-D array of pencil beams is obtained for each frame after completing an electronic vertical scan of TX fan beam.

Figure 3-3(a) presents a conceptual design of the CAMWAR radar RF Frontend with 5 GHz operational bandwidth. For CAMWAR application we are considering two mmWave frequency bands allocated by the FCC: E-band (76-81 GHz) and W-band (92-100 GHz). Other mmWave radar-allocated bands include Ka-band (33.4-36 GHz), which has only 2.6 GHz total bandwidth and requires more than 2× antenna aperture, and V-band (59-64 GHz) with very high atmospheric attenuation (~30 dB/km two-way) that makes the 1 NM range requirement very challenging. Our preliminary selection of the E-band over W-band is based on the current RF components' availability and price driven by the automotive market. In Phase I we will reevaluate the W-band option with 8 GHz bandwidth if RFIC components become available.

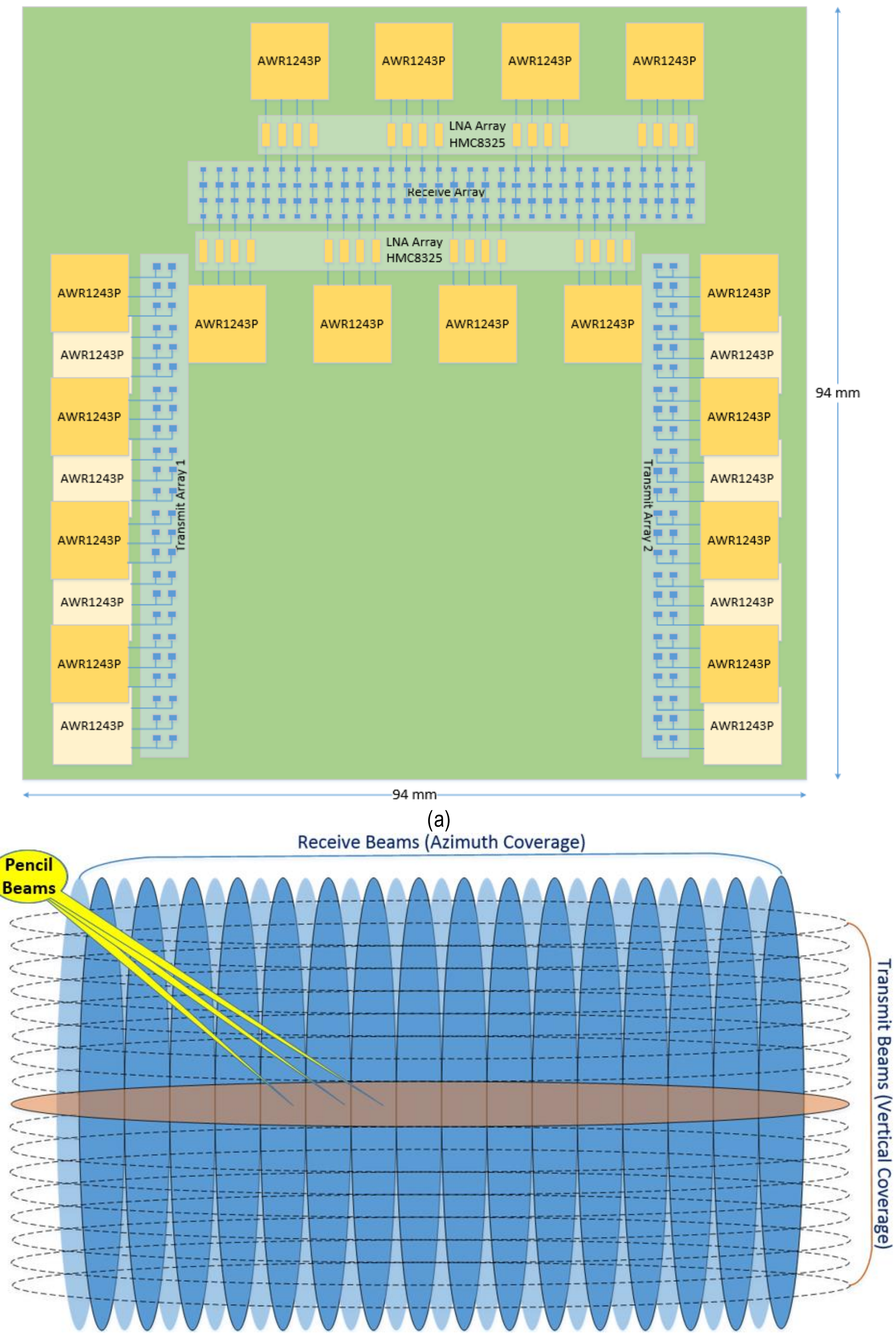

Figure 3-3. (a) CAMWAR sensor antenna panel with up to 90° coverage: a floor plan with one RX and two TX arrays and corresponding RFIC components. (b) Antenna fan-beams - a cross-section view with pencil beams perpendicular to the drawing plane. Only one TX beam is present at a time with dotted-line beams showing the radar scanning operation.

To mitigate the high density placement of the TX/RX channels in mmWave array, minimize the radar SWaP, and achieve a high update rate, the CAMWAR antenna design will follow the following principles:

1. Separate TX and RX antenna arrays implemented as linear patch array antennas.
2. The TX linear arrays are placed orthogonally to the RX linear array.
3. Two parallel TX antenna arrays are placed with a gap equal to the length of the RX array to achieve an optimal MIMO radar configuration.
4. Hybrid ABF/DBF with ABF in TX and DBF in RX paths.

These design principles are illustrated in Figure 3-3. For an explanation of the RF components' functionalities, see Section 3.3.2.

A fast, linear, FMCW modulation waveform is selected as the basic mode for CAMWAR radar. FMCW has significant advantages over the pulsed modulation for mmWave radar due to high (almost 100%) duty cycle, which allows it to use low power and low-cost CMOS and SiGe chip technologies. Another advantage of the FMCW is the lower processing load compared to the pulse compression technique, because the operation of correlation (or demodulation) is implemented in hardware for FMCW. Also, a high duty cycle and lower peak power FMCW reduce probability of intercept of the radar signal. In contrast to traditional long period FMCW, fast FMCW (or fast repetition chirps) allows full Doppler capability. Although, if a very high range resolution is needed, a long period FMCW can be preferred. We will conduct a detailed waveform analysis during Phase I.

Due to simultaneous transmit and receive operation in the FMCW radar, high transmit/receive isolation is required. Separate TX and RX antennas solve this problem. For a traditional microwave radar design, the use of two separate antennas instead one antenna is considered a drawback because of the higher total aperture size. However, for electronically scanned mmWave radar, advantages of the separate TX-RX antennas significantly outweigh the cost of doubling the aperture area. As the CAMWAR design will demonstrate, TX-RX antenna separation provides not only FMCW performance improvement, but also additional capabilities for radar beamforming.

As shown in Figure 3-3, the size of the of the CAMWAR sensor antenna aperture is only 94×94 mm^2. To cover a 360° FOV we plan to use a quad-sensor or hexa-sensor configuration with sensors spread strategically across the airborne platform's fuselage or integrated in a single unit, as illustrated on Figure 1-1. Vertical coverage of the system may vary from 30–90°. Since the narrower vertical coverage increases the operation's range (see Section 3.3.3), we will consider several panel configurations with different FOVs. One possibility to reach hemispherical coverage without sacrificing long-range performance for low grazing angles is by adding a horizontally placed "look down" sensor panel.

3.3.2 Design and Development a Radar Transceiver (Task 2)

In Phase I we will design a broadband mmWave multi-channel radar transceiver, which will combine ABF and DBF with MIMO configuration. ISI will analyze and select COTS components, and optimize the design for cost and SWaP. We plan to use a fully integrated radar transceiver, RFIC AWR1243P from Texas Instruments, that operates in 76-81 GHz band and includes three TX channels with flexible modulation control (based on a phase-locked loop (PLL) synthesizer), and four RX channels with full down-conversion chain and multi-channel analog-to-digital converter (ADC) for complex (I/Q) baseband signals. This RFIC also incorporates the built-in calibration and test, digital control interface, and multi-chip cascading capability. Its package size is only 10.4 × 10.4 mm^2. The functional block diagram of AWR1243P is shown in Figure 3-4.

The AWR1243P RFIC is a fully integrated radar that is programmed by the CAMWAR processor and outputs four digital RX channels that can be easily configured for DBF. AWR1243P supports multi-chip cascading, including operation of the three simultaneous transmit channels (12 dBm each) with individual 6-bit phase control (5.6° resolution), which allows AWR1243P to be used in a TX phased array. By controlling external local oscillator (LO), we will provide frequency agility that enables multi-sensor operation without interference.

The AWR1243P weakness is noisy RX inputs (with noise figure equaled to 15 dB). To improve radar sensitivity we will use an external low noise amplifier (LNA) before feeding RX antenna signals to AWR1243P inputs as shown on Figure 3-3. The HMC8325, a 76-81 GHz LNA from Analog Devices with 3.6 dB noise figure (NF) and miniature size 2.8 × 1.0 mm^2, is good fit for the RX array so it will be considered during Phase I.

Another possible issue with AWR1243P is its relatively high phase noise (-93 dBc/Hz for 1 MHz offset). It can result in radar desensitization if a highly reflective object (e.g., a building) is present in the area. To avoid it, we plan to use an external PLL synthesizer with significantly better phase noise performance. The required phase noise performance will be analyzed, and the best available option for a low phase noise LO for signal generation and its multi-chip distribution will be selected.

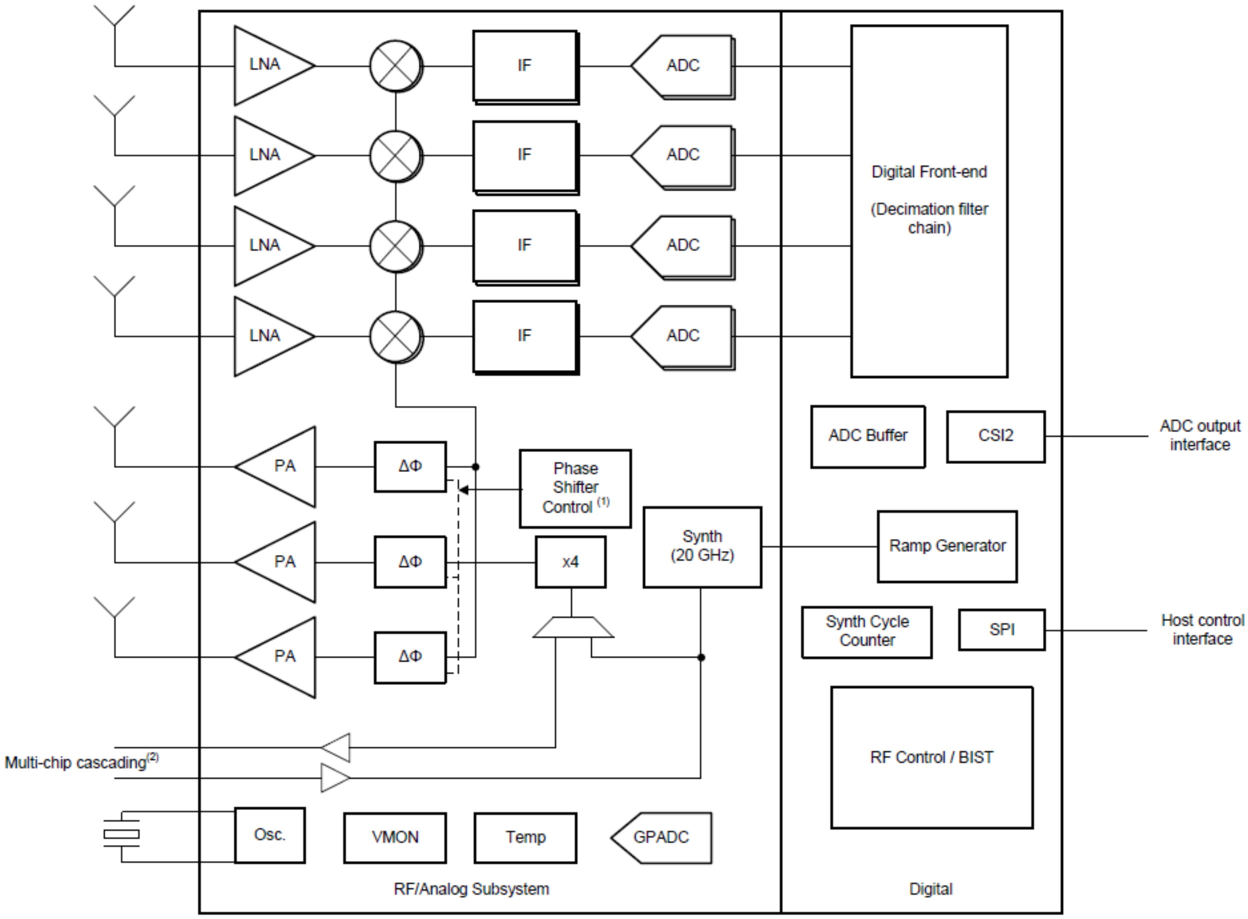

Figure 3-4. Functional block diagram of the AWR1243.

3.3.3 Develop a Model of the Radar Operation (Task 3)

ISI will model and simulate the radar system's performance under various weather and DVE conditions and for different types of targets to establish design requirements for the system components.

In accordance with our preliminary estimates, the CAMWAR sensor, based on the design concept and selected components described in Sections 3.3.1 and 3.3.2 and shown on Figure 3-3, is capable of detecting potential targets at up to 2 km range. The radar detection capability depends on the antenna configuration (more specifically, on radar vertical coverage), target radar cross section (RCS) and weather conditions. Graphs in Figure 3-5 show Mathcad simulations of the radar targets' detectability. The simulation demonstrates the range's dependence on the signal-to-noise ratio (SNR) of the CAMWAR sensor's antenna with 30° and 60° vertical coverage for targets with RCS=10 m^2 and RCS=0.1 m^2 in the fog (cloud) and in light rain, respectively. We compared sensor performance in the fog with different water contents of 0.05 g/m^3 (300 m visibility) and 0.5 g/m^3 (50 m visibility), and in light rain with 3 mm/hr rate. The atmospheric attenuation at the sea level (0.8 dB/km two-way) was included for all weather conditions. The atmospheric and weather attenuation coefficients were calculated in accordance with Ref. [6] recommendations.

The simulation model of MIMO radar has 2x24 transmit channels with 12 dBm RF power per channel (as specified for AWR1243P) and 32 receive channels with 4 dB noise figure (for HMC8325). The radar frame time is set to 10 ms to fit 100 Hz update rate. Since the vertical coverage is linked to the RX antenna gain and to radar beam dwell time (period for each beam position during scan), a narrow vertical coverage provides better SNR performance. The RCS=10 m^2 represents relatively large targets like cars or helicopters. Although a strongly reflected object (like a building) can provide RCS on the order of thousands of square meters, we assume that most real targets would have a RCS close to or below 10 m^2. The RCS=0.1 m^2 represents a low limit that characterizes a wire detection capability. As was shown in Refs. [7] and [8], the RCS of standard wire power lines has periodic (about 3° period) structure in the ±15° incident angle region with peaks higher or about -10 dBm^2. Thus, we assume that -10 dBm^2 RCS detectability is necessary for wire detection and identification. Since the horizontally polarized wire RCS is typically higher than the vertical one, we will likely consider horizontal polarization for CAMWAR. Possibilities to use different co- and cross-polarizations (VV, HH, VH, and HV) for object identification or circular polarization to reduce rain clutter will be also analyzed in Phase I.

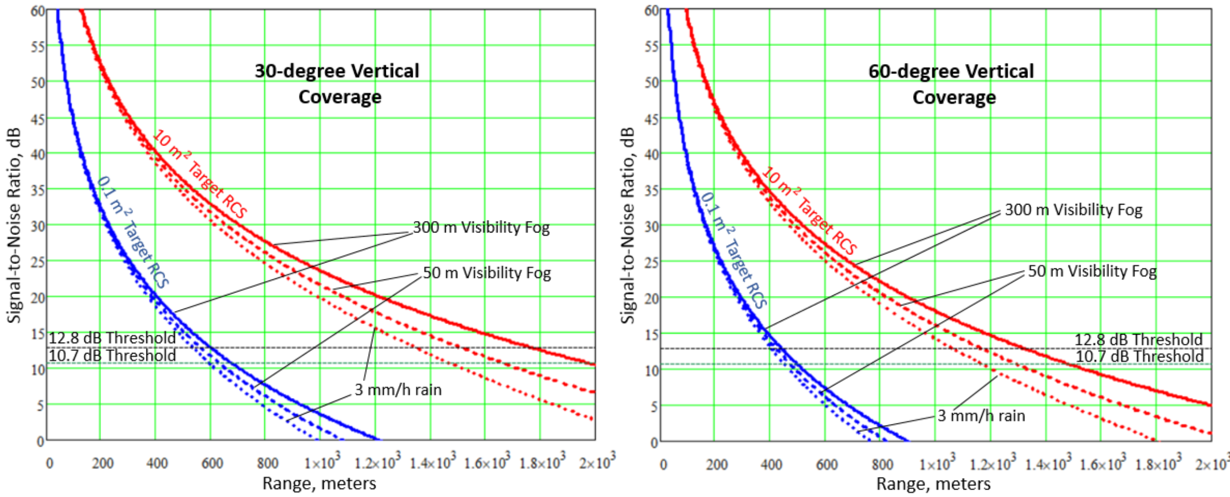

Figure 3-5. Simulation results for CAMWAR radar targets detectability with 30° (left) and 60° (right) vertical coverage and for different fog/rain conditions.

Two threshold values (dashed lines in Figure 3-5 graphs) were calculated for fluctuated target Swerling Case1 model (scan-to-scan decorrelation). The higher threshold, 12.8 dB, corresponds to a single dwell 50% probability of detection (P_d) and 10^{-6} probability of false alarm (P_{fa}). The lower threshold, 10.7 dB, corresponds to a binary m-of-n integration for m=2 and n=10, which yields a cumulative P_d = 90% for P_{fa} =10^{-10}. These simulation results demonstrate that the CAMWAR sensor with 360° azimuth coverage and 30° vertical coverage is capable of detecting objects with RCS≥10 m^2 in ≤2 km range. The same simulation for an antenna with 60° vertical coverage showed the maximum range of 1.5 km. Items with low RCS of 0.1 m^2, for example wire lines, may be detected at up to 700 m with 30° vertical coverage and at up to 500 m with 60° vertical coverage. Fog does not significantly affect the radar's max range. Rain has a stronger attenuation factor, but for light rain (≤3 mm/h) the radar's max range degradation looks acceptable.

To ensure a secure vertical landing of a rotary-wing aircraft, a look-down sensor with a wide angle (up to 120°×120°) coverage can be added to the multi-sensor CAMWAR system. The option will be analyzed in detail during Phase I.

In Phase I, we will analyze effects of a brown-out conditions on the CAMWAR detection range. As reported in Ref. [9], mmWave radars have a negligible attenuation in the dust. However, radar's return signal from the dust itself may be high enough to mask real low-reflected objects like power line wires. We will simulate the radar return of volume clutter from the dust in brown-out conditions and select the radar operation modes that can reduce the clutter effect. Consequently, we will confirm our assumption that the Doppler processing and high range resolution mode can suppress the dust volume clutter to the level sufficient for wire line detection.

We will also investigate different techniques to improve the radar resolution. Thus, we will analyze the use of the Doppler beam-sharpening, which can significantly improve the azimuth angular resolution on the moving airborne platform for side-looking directions.

3.3.4 Develop an Electronically Scanned Antenna (Task 4)

ISI will develop a scalable 2-D linear array antenna configuration, which will allow the highest angular resolution in a limited aperture. We will evaluate the performance of the proposed antenna configuration (Figure 3-3) in modeling and simulation and optimize the M and N values (number of RX and TX channels). We will optimize the vertical beam of the receiver array antenna elements and horizontal beam of the transmit array antenna elements. We will also determine the maximum vertical FOV of the antenna that supports 2 km operational range under DVE conditions and in light rain. We will design patch antennas for different selected beam widths, simulate the antenna scan operation and evaluate the fan beam and pencil beam patterns.

As CAMWAR will operate in multi-sensor configuration to provide 360° coverage, we will analyze configurations with 4-to-7 sensors. We will also consider using sensors with different antenna element sizes for different positions in a multi-sensor system. Since, to avoid collision with an airborne platform, the maximum range for low grazing angles has higher priority than for grazing close to the 90°, and taking into account range-coverage trade-offs (see Section 3.3.3 for illustration), we will consider providing a relatively narrow 30°-40° vertical field of coverage for side-looking sensors and very wide coverage (up to 120°) for a down-looking sensor that has a shorter range.

We will model and simulate the antenna in HFSS [10] and optimize the patch design to achieve maximum gain and wideband operation. The simulated beam patterns and S-parameters will be obtained for different frequencies to verify the broadband capability. In this task we will collaborate with our consultant, Dr. Aram Avakian, who is an expert in mmWave antenna design and in HFSS modeling and simulation and has worked with ISI on several projects.

3.3.5 Demonstrate Feasibility of CAMWAR (Task 5)

ISI will demonstrate the feasibility of CAMWAR by simulating the system's behavior and performance under various conditions, analyzing design tradeoffs, and experimenting with COTS components. A proof-of-concept radar prototype will be built and tested. We plan to procure three evaluation boards with AWR1243P chips and assemble them on the mounting plane to configure a small breadboard prototype version of the CAMWAR radar panel with 2×3 TX channels and 4 RX channels to provide MIMO capability. We will simulate the breadboard prototype parameters, such as angular resolution, range resolution and accuracy, maximum range, and Doppler resolution/accuracy. After that, we will test the concept prototype with different target configurations to compare practical implementation with simulation results. We will demonstrate the feasibility of the CAMWAR concept through simulation and prototype testing, for which we will utilize the ISI tracking algorithm adapted to ISDC.

The feasibility analysis results will be used in the Phase I Option period to refine the system design to facilitate development of the Phase II prototype and to prepare a Phase II Plan and system description with cost estimates. We will also prepare a detailed analysis of the production and maintenance costs in the Phase I Option period, explore partnerships for custom components, and define subcontractor relationships for Phase II.

4.0 RELATED WORK

4.1 Related Work by Others

No known radar system fully address the Navy requirements for collision/obstacle/brown-out with sense and avoidance (COBOSA) applications. The commercially available radars (see Table 1-1), such as the K-band EchoFlight, which has 2 km range and is designed for UAS platforms, are compact, low SWaP, do not support multi-sensor configurations, have poor angular accuracy, and have low scan update rate (~1 Hz). Low SWaP automotive radars like ARS 408 operate in E-band and have only 250 m range, a narrow FOV, and a low scan update rate. W-band radars like HALS-3 applies bulky and slow mechanical scan antenna and limited (30°×30°) FOV. To support electronic steering of the antenna array operating in a wide frequency band and to provide LPD/LPI capabilities to mmWave radars with high angular resolution, a new technology, such as ISI's CAMWAR, must be developed.

4.2 Related Work by ISI

The science and engineering team ISI selected to execute the proposed development draws upon many directly related works. In particular, ISI has extensive experience in developing a wide range of radar and RF systems, scanning LIDAR systems, passive RF scanners, and other threat detection, identification, and tracking solutions. The CAMWAR development will benefit from the significant and diverse technological and commercialization expertise that ISI provides: digital signal processing, digital and RF electronic design, multi-GHz RF system design, antenna design, MIMO radar and communication systems, tracking and visualization software, embedded system and software design. ISI has extensive experience in the design and development of radar systems for military and government applications that operate in a wide range of frequencies (from **S-band** to **W-band**). ISI's experience in **tracking software** will be used in development of the CAMWAR tracking algorithms. ISI is currently developing several FMCW MIMO radars that provide compact low-cost detection and tracking capabilities and networked operation, including man-portable and vehicle-mounted radars (Figure 4-1(a)).

As shown in Figures 4-1(b) and (c), ISI's portfolio of technologies is strategically based around integrated sensor systems, display and visualization systems, and augmented intelligence capabilities, all contributing to a broad and growing legacy of products and innovations. ISI has developed numerous SBIR technologies to high technology readiness levels (TRLs) and high manufacturing readiness levels (MRLs), such as WEARNET®, SNAPNET®, and the Micro Weather Sensor™ (MWS™). The small, self-contained, and lightweight MWS™ design enables weather sensing, imaging, autonomous operation, and built-in satellite communications in a hand-portable device that is at TRL-9 and MRL-9. ISI has also developed derivatives from this product, including meteorological measurement equipment for ballistic fire control on ground vehicles. In addition, ISI draws upon its existing patent portfolio in performance of its contracts, including the intellectual property established by the ISI team.

(a) (b) (c)

Figure 4-1. Examples of previous efforts relevant to CAMWAR development. (a) Counter-UAS man-portable and vehicle-mounted radars; (b) MWS™ (top) and Submarine-Deployable Weather Sensors (bottom); (c) Visualization avionic displays.

4.3 Company Background

ISI is a leader in cutting-edge integrated systems comprised of unique sensor, programming, and optoelectronic technologies with innovative implementations of modern electronics, computing, and augmented intelligence. ISI's technologies enable new levels of situational awareness and informed decision making through improved data gathering and processing, information visualization, and human machine interfacing (HMI). ISI not only has the agility of a small business to provide timely and innovative solutions to our customers, but also has the stability of an established corporation that can support the entire technology and product development life cycle.

ISI generates over $26 million in annual revenue from a combination of government contracts and commercial sales. ISI maintains over 46,300 ft2 of state-of-the-art facilities including office, laboratory, and manufacturing spaces. ISI has a diverse staff of more than 130 employees with extensive experience in critical technical areas. The technical team is comprised of skilled scientists and engineers, more than 50 of whom hold advanced degrees in engineering and science. Military veterans make up 6% of our staff and they support technology development with an understanding of warfighting, applications, and military concepts of operation (CONOPS), which will benefit the development, transition, and commercialization of the technology. ISI has established all design, development, testing, in-house manufacturing, quality practices, and processes necessary to commercialize technology as evidenced by our commercialization success. With almost $15 million in assets and solid financial backing, ISI is well positioned as a competitive small business both on its own merits and by leveraging partnerships with major prime defense contractors in the rapidly growing defense market.

ISI personnel have more than three decades of experience successfully transitioning SBIR technologies through accelerated technology development and commercialization capabilities. ISI has an established infrastructure to support technology transition, based on well-established processes and quality management systems, including top-notch in-house research, engineering, product development, testing, and production capabilities. ISI has a well-established DoD program of record based on SBIR-derived technology, as well as full-rate production programs with Defense Contract Management Agency (DCMA) oversight and compliance. ISI has produced new breakthrough products in the Micro Weather Sensor™ (MWS™) for USSOCOM and the Video Display Terminal (VDT) for Air Force, both were developed through a full Phase I-II-IIE-III process and are now under programs of record. ISI continues to develop and transition new technology solutions to our customers.

4.4 Similar Projects at ISI, Past and Present

The following are projects that are relevant to a particular area of the proposed development that were accomplished by ISI employees, or are ongoing at ISI.

Portable Anti-UAS (PAN-UAS) Device (Army Contract No. W909MY-19-C-0006)

Contact: Justin Miller *Completion:* 05/31/21 *Email:* justin.m.miller78civ.@mail.mil

The PAN-UAS device design combines state-of-the-art airspace monitoring technology with novel UAS countermeasure approaches and packages them into a man-packable system. Innovative miniaturized and ruggedized radar detection and RF jamming systems will enable the PAN-UAS device to detect and counter both individual and swarms of UASs while being self-contained in a very portable form factor. PAN-UAS offers a tactical, ruggedized solution that is <100 $in.^3$, <3 lb, and costs <$15k, which is appropriate for squad and platoon level operation.

SUAS Killer, Identifier, and Tracker (SKEET) (USSOCOM Contract No. H92222-18-P-0024)

Contact: Jonathan Hathaway *Completion:* 10/09/18 *Phone:* (813) 826-4638

SKEET offers a tactical, ruggedized solution to USSOCOM's need for a system to detect, locate, track, and either disable and/or destroy a small unmanned aerial system (SUAS) from a distance. Innovations in accurate, high-speed tracking will enable fire-control-augmenting system data to be generated with enough fidelity to calculate dynamic, real-time firing solutions which can be fed to a motorized gimbal or to a weapons operator via heads-up display or digital spotting scope, allowing personnel to take appropriate offensive or defensive action.

Compact Wind Radar (CoWiR) (Navy Contract No. N68335-18-C-0131)

Contact: Mark Blair *Completion:* 03/23/20 *Phone:* (723) 323-7310

CoWiR is an all-weather system capable of providing precise information about the distribution of wind velocity vectors surrounding a ship with accuracy better than 1.5 knots and a data update rate of up to 10 Hz. Implementation of a new electronically reconfigurable antenna will allow for measurement of wind velocity and wind direction with a range resolution of 10 ft and a maximum range of 300 ft.

Sense-and-Avoid Postern Insect Eye/Neuromorphic (SAPIEN) Sensor System (Air Force Contract No. FA8650-14-C-2535)

Contact: Capt. Eric Yerly *Completion:* 11/21/16 *Phone:* (937) 938-4522

SAPIEN addresses the Air Force need for a postern SAA system that can enable remotely piloted aircraft to perform real-time reporting of mid-air-collision (MAC) threats. SAPIEN combines multi-aperture imaging, ranging and warning over a wide field in a strap-down configuration. The sensor system employs a compact eye-safe laser ranger using high bandwidth photo-detectors and custom Kalman/probability propagation algorithm to detect, locate, and track MAC threats.

5.0 RELATIONSHIP WITH FUTURE RESEARCH OR RESEARCH AND DEVELOPMENT

Successful Phase I research will demonstrate the feasibility of using CAMWAR to provide a LPD/LPI SAA mmWave radar for airborne platforms with the Phase I concept design being capable of supporting a 2 km range with 360° coverage under DVE conditions. During Phase II, ISI will refine the system design, including hardware and software, and develop a prototype of the CAMWAR system that is capable of operating under adverse conditions with LPD/LPI. This will lead to development of a complete operation-ready CAMWAR system in Phase III that will support the Navy in transitioning the technology for Navy use and will target other military and commercial applications. In Phase II, ISI will further refine the approach validated in Phase I and develop a working prototype of the CAMWAR radar, including hardware and software, to demonstrate the CAMWAR functionality and validate the models and approach from Phase I. ISI will also incorporate the CAMWAR with a Government-provided collision software suit and develop a Phase III transition plan to integrate the capability on candidate platforms.

6.0 COMMERCIALIZATION STRATEGY

6.1 Introduction

Product Vision. CAMWAR radar will be installed on airborne platforms and used for collision avoidance under DVE conditions. The compact mmWave MIMO radar sensor will fit into 4×4×2 in.^{3} form factor, weigh <10 lb, and consume <50 W of power during operation. The CAMWAR system will be capable of detecting with up to centimeter-level resolution ground obstacles like large rocks, power wires, trees, buildings, and other aircraft, covering 360° FOV in azimuth (in quad-sensor or hexa-sensor configuration) and 90° in elevation at up to 2 km range.

Target Military/Government Applications. CAMWAR's primary application is SAA sensor solutions for tactical UAS, helicopters, and other airborne platforms. Other military/government applications for CAMWAR radar include a landing system augmentation solution, a close proximity formation flying solution, and ground manned and unmanned vehicles for autonomous operation and/or in DVE. CAMWAR will be adapted for security and surveillance applications that can benefit from a compact high-resolution detection system.

Target Commercial Applications. CAMWAR can be used in commercial applications with minimal/no modifications. Possible applications include use in commercial UAVs and general aviation, remote inspection, and search and rescue.

Transition to Military Markets. We believe that the key to transitioning will be the engagement of the program office and prime contractors, Lockheed Martin and Raytheon, early in Phases I/II, to design CAMWAR to meet platform requirements. We expect to produce a Phase II prototype that is ready for qualification in Phases IIE/III. ISI's manufacturing department will help in design for manufacturing reviews to facilitate a rapid transition to production.

Transition to Commercial Markets. We plan to collaborate with Raytheon and other partners in transition of CAMWAR technology to commercial markets. ISI has a long history of customizing products developed for DoD for specific commercial markets. Recently, we expanded our Business Development (BD) Department to specifically seek new commercial opportunities for transitioning Phase I/Phase II prototypes to commercial products. The company has invested internal funds to achieve certifications necessary to supply products for commercial applications. We will follow a transition path similar to that of the MWS™ to address the commercial market described below.

Determining Market Need and Market Size. This proposed technology addresses a large potential market need of over $13.5B according to MarketsandMarkets [11]. Based on an analysis of projected markets and ISI's potential market niche from these opportunities in years following completion of this project, the potential market niche from the proposed technology and its related products can reach more than $15M within five years of this development (see Table 6-1).

Table 6-1. Market, Market Niche, and Quantitative Commercialization Results

Year	2020	2021	2022	2023	2024	2025	2026	2027
Total Market ($B)	13.5	14.0	14.4	14.9	15.4	15.9	16.5	17.0
Year-to-Year Market Growth (%)	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38
ISI's Market Niche ($M)		0.5	2	5	8	11	15	20
Funding Level ($M)	0.375	0.375	0.400	0.500	2.000	2.000	3.000	4.000
Source	Phase II		Phase IIE/III		Phase III		Procurement contracts	

6.2 Technology Transition Infrastructure and Capability

ISI has implemented processes and procedures that have enabled ISI to become a prime developer and manufacturer of numerous military-grade products transitioned from SBIR. Leveraging and building upon ISI's experience transitioning SBIR technology, ISI has established its quality management system, manufacturing facilities, configuration management, logistics, and documentation capabilities for its production of WEARNET®, SNAPNET®, and the Micro Weather Sensor™ (MWS™). These products are being sold to government and commercial customers around the world. ISI expects to use a portion of its current facility and its full capabilities and infrastructure for design, development, and production of CAMWAR.

ISI has an experienced scientific, engineering, and management team to execute the program from development, test, and qualification through production. Established lab facilities have the capacity and availability to accommodate the proposed development based on a standard single-shift work schedule. Additional shifts can be added, if necessary, for additional production capacity should the demand arise. ISI's production facilities include inventory/tools, work-in-progress, and final assembly cabinets; kitting, quality inspection, soldering, subassembly, and final assembly work stations; test stations and custom automated test equipment (ATE), and Environmental Stress Screening (ESS) chambers. ISI has a total of 5,950 ft^2 of manufacturing floor space. As shown in Figure 6-1, ISI has 4,200 ft^2 of production floor space to support sensor system products and has another production facility with over 1,750 ft^2 of additional floor space to build displays and other products. In addition, ISI has full access to test equipment necessary to support development and testing, including environmental chambers for MIL-STD-810G compliance testing, EMI chambers for certified MIL-STD-461F/G testing, and programmable power supplies for MIL-STD-704 testing at nearby test facilities.

Figure 6-1. ISI has a total of 5,950 ft^2 of floor space dedicated to production. (a) Floor plan and photo of ISI's 4,200 ft^2 manufacturing facility for MWS production. (b) Floor plan and photo of ISI's existing 1,750 ft^2 production facility for displays and other products. There is ample room to include future product development and production.

ISI's Quality Management System (QMS) is certified to ISO9001:2015/AS9100D and ISO9001:2015/AS9110C standards, operates in accordance with the guidelines and standards of CMMI-DEV-ML3, and is expected to achieve ML3 benchmark in 2019. To support production, ISI's Quality Assurance (QA) Department addresses all facets of the applicable quality standards, from contract compliance to technical, logistics, and manufacturing compliance. The QMS takes a proactive and preventive approach to quality management of product development and manufacturing by focusing on addressing quality requirements during front-end product realization processes, including contract review, quality planning, design control, process validation, and configuration management. This approach ensures a smooth transition into production, where robust supplier management and product quality verification processes ensure that compliant products are produced in support of customer product and delivery requirements. Figure 6-2 depicts ISI's QMS tied to QA processes and procedures.

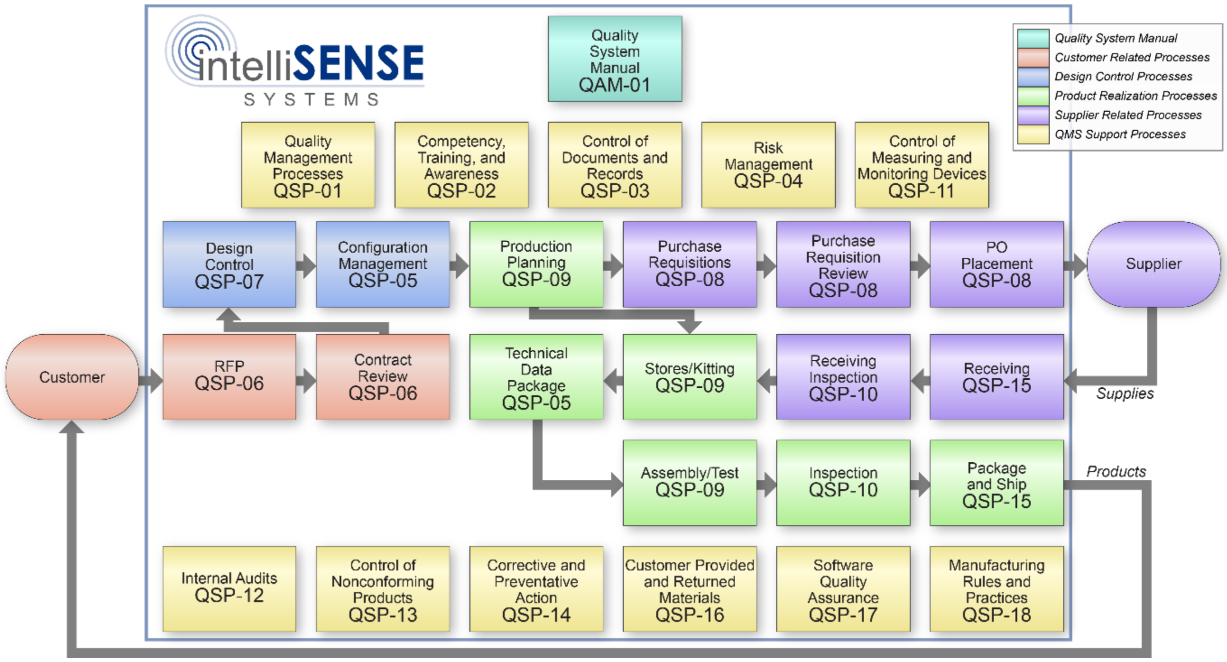

Figure 6-2. ISI's QMS processes are well-defined and documented to meet customer requirements.

6.3 ISI's SBIR Transition Results

ISI was founded on a rich history of successful SBIR transition of products into programs of record by leveraging DoD technology investments and applying technologies to different applications across multiple services. As a recent example, ISI transitioned the Micro Weather Sensor™ (MWS™), which started as a U.S. Special Operations Command (USSOCOM) Phase I SBIR in 2010 and is now a program of record with the Air Force Life Cycle Management Center (AFLCMC) in the Battlefield Airman (BA) Program Office in support of USSOCOM under a $24.5M IDIQ contract. Under a series of SBIR and non-SBIR development contracts with the DoD, 48 prototype MWS™ systems were successfully field tested throughout development in more than 55 countries worldwide to ensure the capture of critical lessons learned, which were then used to further mature the technology. An Industry and Government Integrated Product Team (IPT) was formed very early in the development cycle to ensure transition success and today serves as a model for cooperation on all future ISI development efforts. ISI is currently in full production with the MWS and is also manufacturing new variants of environmental and flood sensing systems derived from MWS, in our Torrance facility for defense and commercial customers. Additionally, ISI is preparing for production of a variant of the MWS that will be retrofitted onto the M1A2 Sep V4 modernization program for the U.S. Army as well as a maritime variant for the U.S. Navy.

For airborne applications, ISI is under contract to complete the engineering re-design and qualification of a 15 in. Video Display Terminal (VDT) replacement for the MC-130J Combat Systems Operator (CSO) crew station. Production deliveries of the VDT are slated to start beginning July 2019 under an SBIR Phase III contract with production performed by ISI in our Torrance facilities. In addition, ISI is currently executing a $1.5M Phase II-E contract with the U.S. Air Force to design, develop, qualify, and deliver 20" × 8" form-factor Large Area Display (LAD) units as part of the B-52H advanced targeting pod Multi-Function Color Display replacement. This program has a requirement for 182 display deliverables during full rate production.

ISI has successfully worked with Integrated Product Teams (IPT) and connected users to a SBIR technology development at program onset, and our success in transitioning technologies like the MWS™ will follow this same paradigm. The critical field testing early on in the development of a technology, coupled with a strong customer relationship, enabled the ISI team to engineer a robust final product and successfully transition the technology to full-rate production for multiple variants of the MWS™ product at the end of 2017. ISI also strategically invests its own internal research and development (IR&D) funding into technologies to speed maturation and manufacture advanced prototypes that are displayed at ten regularly attended annual trade shows and used at DoD experimental or technology demonstration events. Additionally, early on in the development of an SBIR technology, ISI identifies other service program offices with similar requirements in order to grow the market applicability for the technology. Moreover, based on our demonstrated success in the MWS™ SBIR transition, today ISI has multiple government and commercial contracts to develop derivative systems from the same technology for submarines, naval vessels, and ground vehicles. As an example, ISI recently received a $3.6M development contract from General Dynamics Land Systems for a new Meteorological (MET) Sensor as a part of their Engineering Change Proposal (ECP) 1B for the U.S. Army's upgraded M1A2 Sep V4 tank.

The track record, infrastructure, and capabilities described above, combined with ISI’s financial strength, place our company in an excellent position to ensure the best possible success for SBIR technology transition for this project and to rapidly commercialize resulting products.

7.0 KEY PERSONNEL

The proposed development of CAMWAR will be performed by an ISI scientific team of U.S. citizens with a successful record of developing technologies under contracts and grants from federal agencies and commercial organizations. ISI’s commercialization activities are performed by our business development staff, the resume of one of whom is included in this proposal. ISI considers commercialization to be a corporate responsibility, and carries business development staff on corporate overhead; therefore, he will not appear in the cost proposal or charge time to this or any other individual project.

Key Personnel/Principal Investigator. Mr. Victor Khodos will serve as the Principal Investigator.

Mr. Victor Khodos, Senior RF Engineer, will bring to the project his expertise in **RF and radar system design**. Specifically, he will be responsible for developing the RF circuits and antennas. He has more than 25 years of experience in analog, RF, microwave and mmWave system design. In 2003, he joined Waveband Corporation (ISI’s sister company) where he developed multiple **radar** systems and subsystems, interferometers, radiometers, and advanced **antenna** products operating in various spectral bands. He developed an X-band transceiver for the U.S. Navy’s periscope detection radar and was responsible for the architecture and **DSP** algorithm development, and **transceiver designs** for several **mmWave** radars, including the 94 GHz **FMCW** 3D imaging radar for an aircraft landing system in DVE conditions. He was actively involved in the design, fabrication, and testing of multiple innovative electronically reconfigurable antennas that resulted in numerous U.S. patents. At ISI he has worked on C-UAS and other **radar** and **RF** systems. Mr. Khodos received an M.S. in electrical engineering from Gorky State University (Russia) in 1983, and worked at the Institute of Applied Physics of Russian Academy of Sciences as a researcher in microwave spectrometry. He has published 20 papers and authored ten patents. *Mr. Khodos is a U.S. citizen.*

Relevant Publications by the Principal Investigator, Mr. Victor Khodos:

1. A. Brailovsky, J. Bode, P. Cariani, J. Cross, J. Gleason, **V. Khodos**, G Macias, R. Merrill, C. Randall, D. Rudy, “REVS™: A Radar-Based Enhanced Vision System for Degraded Visual Environments,” *Degraded Visual Environments: Enhance, Synthetic, and External Vision Solution, Proc. of SPIE*, vol. 9087, 2014.
2. V.A. Manasson, L. Sadovnik, V. Litvinov, R. Mino, I. Gordion, A. Avakian, M. Felman, D. Jia, M. Aretskin, **V. Khodos**, A. Brailovskiy, “Electronically Reconfigurable Aperture (ERA): A New Approach for Beam-Steering Technology,” doi: 10.1109/ARRAY.2010.5613294.

Senior Personnel. In his work, the Principal Investigator will be supported by a team of ISI staff members that will include Drs. Alireza Behbahani and Min-Yi Shih, Messrs. Alexander Genusov and Alexander Kuyper, and business development representative, Mr. Mark Thompson.

Dr. Alireza Behbahani, Research Scientist, will bring to the table his expertise in wireless communication and signal processing. Specifically, he will be responsible for **modeling and simulation** of the channel and system modules and development of the ALC algorithm. Dr. Behbahani earned his B.Sc. (1992), M.S. (1996), and Ph.D. (2009), all in electrical engineering, from Tehran Polytechnic (Tehran, Iran), K.N. Toosi University of Technology (Tehran, Iran), and the University of California, Irvine, respectively. He is a member of the Center for Pervasive Communications and Computing (CPCC), where he has been a recipient of the UC Irvine CPCC graduate fellowship. Dr. Behbahani has 27 years of experience in research and development of **simulation algorithms, models, and software for signal processing,** wireless communications, wireless sensor networks, Bayesian networks, estimation, and **detection systems**. Dr. Behbahani has been on the technical program committees and a reviewer for several symposia, conferences, and journals in the areas of signal processing and wireless communications. He is an author of 26 technical papers. *Dr. Behbahani is U.S. citizen.*

Dr. Min-Yi Shih, Vice President and General Manager, Electro-Optics Systems Department, will bring to this project his expertise in **program management, technology transition,** and **commercialization.** Specifically, he will be responsible for executing tasks related to commercialization and technology transition to military applications. Dr. Shih received his B.S. in physics from Tam-Kang University, Taiwan. He received his M.S. and Ph.D. in 2001, both in electrical engineering, from Pennsylvania State University. He has extensive engineering and research and development experience in optoelectronic system **development and transition** of **custom RF, micro-wave, mmWave**, and EO/IR **sensors for military applications**. Over the years, he has been leading the technology transition efforts **beyond SBIR Phase II** including multiple Phase II Enhancement (IIE) programs as well as delivering commercial products based on technologies developed in SBIR programs. He is a certified Six-Sigma Green Belt. *Dr. Shih holds a Secret clearance and is a U.S. citizen.*

Mr. Alexander Genusov, Director, Electronic Systems Development, will bring to the project his expertise in developing DSP, radar, and embedded systems. Specifically, he will be responsible for system architecture design and project management. He earned an M.S. in semiconductor physics and a B.S. in electrical engineering, both from St. Petersburg Polytechnic University, and pursued graduate studies in microelectronics at Technion—Israel Institute of Technology. Before joining ISI, Mr. Genusov worked as a principal engineering manager responsible for development of **electronic products** for **DSP**, **radar**, computing, imaging, networking, and communication applications from requirements to production. For over 30 years he led and managed design and development of electronic systems and acquired hands-on experience with a wide range of development tools and methodologies, standards, and protocols. He headed development of DSP systems for DARPA and of several MIL-qualified products. The author of 8 patents, he has published 12 technical papers and numerous technical reports. *Mr. Genusov is a U.S. citizen.*

Mr. Alexander Kuyper, Senior Staff Systems Engineer, will bring to the project his expertise in **algorithm development**, **modeling** and **simulation**. Specifically, he will be responsible for the tracking algorithm. Mr. Kuyper has more than 20 years of research and development experience, including the development of **tracking algorithms** for several **radar**, LIDAR, and electro-optical systems. He has also designed algorithms for Army soldier kinematic pose estimation using inertial sensors, and developed image processing methods for a harbor monitoring vessel classification system. With his previous employer, he delivered to the Missile Defense Agency (MDA) three independent, **optimally fused passive ranging Kalman filter algorithms for airborne tracking of boosting targets**. While with L-3 Communications in Tulsa, OK, he developed **optical tracking and trajectory estimation algorithms** which were flown and run real-time during operational tests aboard the High Altitude Observatory (HALO-II). Earlier in his career, with Raytheon Missile Systems in Tucson, AZ, Mr. Kuyper was a multi-discipline member of the Navy's Tactical Tomahawk Digital Scene Matching Area Correlator (DSMAC) design team. He earned his B.S. in applied mathematics, engineering, and physics (A.M.E.P.) from the University of Wisconsin-Madison. *Mr. Kuyper is a U.S. citizen.*

Mr. Mark Thompson, Director, Business Development, will be responsible for contacting customers and users of the proposed CAMWAR technology. He has over 16 years of experience in the Aerospace and Defense industry, with a wide breadth of experience in many aspects of DoD programs. At ISI he is responsible for the business development of advanced technologies and emerging products. Specifically, Mr. Thompson will be responsible for the growth of various data acquisition and storage and display technologies, ground vehicle situational awareness solutions, and counter-unmanned aerial system (UAS) applications. He oversees critical relationship management and customer interactions with multiple service Program Managers, TPOCs, and Contracting Officer Representatives (CORs). Prior to joining ISI, Mr. Thompson spent sixteen years at a Fortune 500 company and played a pivotal role in growing their avionics portfolio to become one of the leaders in the military aerospace and defense industries. He earned a B.S. in business and operational management from Purdue University in 2019. He has served in the U.S. Navy and holds an active Secret clearance. *He is a U.S. citizen.*

8.0 FOREIGN CITIZENS

No foreign citizens will be involved in the execution of this project.

9.0 FACILITIES/EQUIPMENT

Located in Torrance, California, 10 miles south of Los Angeles International Airport, ISI occupies 46,300 ft^2 of facilities in several locations. ISI's facilities comply with all applicable ITAR provisions and meet all applicable environmental laws and regulations including, but not limited to, the following groupings: airborne emissions, waterborne effluents, external radiation levels, outdoor noise, solid and bulk waste disposal practices, and handling and storage of toxic and hazardous materials. *ISI has a facility security officer (FSO), an assistant facility security officer (AFSO), and facilities cleared to the Secret level. ISI is U.S. owned and operated with no foreign influence as defined by DoD 5220.22-M, National Industrial Security Program Operating Manual, and can safeguard classified material IAW DoD 5220.22-M during the advanced phases of this contract if required.*

ISI has established state-of-the-art laboratories and manufacturing facilities. The capital assets for these facilities were acquired through investment of almost $15 million. While all of the company's facilities will be available for this project, most of the work will be performed in the ***Advanced Sensor, Cyber Security***, and ***Environmental Test*** laboratories.

The ***Advanced Sensor Laboratory*** has state-of-the-art equipment for fabricating nanostructured and developing microstructured (MEMS) sensor elements, microwave and **mmWave electronics**, terahertz (THz) devices and high-speed optoelectronic devices. In addition, it has a full set of high-precision electronic equipment including a variety of RF spectrum analyzers, multi-GHz oscilloscopes, signal and waveform generators, mmWave components and development/evaluation kits, radars, FPGA and SOC development kits, and a suite of 3D printers and machining equipment to facilitate rapid prototyping of new ideas.

The ***Cyber Security Laboratory*** is equipped with a suite of network security and penetration testing tools residing on dedicated computing platforms to enable rigorous testing and vulnerability assessment of cyber physical systems in a safe, isolated environment. ISI also tests its implementation of standard encryption like AES-128 and FEC in communication devices.

The ***Environmental Test Laboratories*** are equipped with high-accuracy weather, gas, and particulate measurement systems and test equipment for MIL-STD-810, MIL-STD-704F, and MIL-STD-461G compliance testing, including thermal/humidity test chambers (-70° to +200°C), a rain inundation chamber (multi-directional), a vibration table (multi-axis), and an electrostatic discharge (ESD) test system.

10.0 SUBCONTRACTORS/CONSULTANTS

Dr. Aram Avakian will serve as a consultant to this project. An expert user of design and simulation software packages such as ANSYS HFSS and Mathcad used for antenna design, he will bring to the ISI team additional expertise in the area of antenna design and simulation. Dr. Avakian received his M.S. in radio-physics from the Yerevan State University and his Ph.D. from the Armenian Academy of Science. He has 30+ years of experience in developing microwave and optical beam forming/steering systems, as well as feed networks, amplitude, polarization and phase control components. He authored over 25 technical papers and received 14 patents. *Dr. Avakian is a U.S. citizen and holds an active Secret clearance.*

- Hourly rate: $100, total # of hours: 100 (Base), 80 (Option), total cost: $10,000 (Base), $8,000 (Option).
- SOW: design, modeling and simulations of 28 GHz and 70 GHz antenna tiles.
- Deliverables: HFSS models and simulation results for 28 GHz and 70 GHz antenna tiles.

11.0 PRIOR, CURRENT, OR PENDING SUPPORT OF SIMILAR PROPOSALS OR AWARDS

ISI has no prior, current, or pending support for the proposed work.

12.0 COST PROPOSAL

A detailed cost proposal (Volume III) has been uploaded via the DoD SBIR Web site.

13.0 COMPANY COMMERCIALIZATION REPORT

ISI's SBIR commercialization record (Volume IV) has been uploaded via the DoD SBIR Web site. ISI is an affiliate of POC, a company that has introduced to the market ***over 100 products*** and has, launched ***seven spin off companies***. More than eighty POC employees joined ISI and leverage their experience in technology transition, manufacturing, and commercialization gained at POC to produce new products at ISI. ISI has been awarded 6 Phase II contracts since its operations began in February of 2018 and another 25 Phase II contracts have been novated from POC to ISI. Four additional Phase II awards are pending the results of negotiations.

14.0 REFERENCES

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