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UAS Research for Public Safety Applications
Task 5
Detect and Avoid Technology Survey

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TABLE OF ACRONYMS

ACAS	Airborne Collision Avoidance System
ASTM	American Society for Testing and Materials
API	Application Programming Interface
BVLOS	Beyond Visual Line of Sight
CAS	Collision Avoidance System
C-SWaP	Cost, Size, Weight, and Power
DAA	Detect and Avoid
EO	Electro-Optical
EM	Electro-Magnetic
FAA	Federal Aviation Administration
FMS	Flight Mapping Suite
FoV	Field of View
GAO	Government Accountability Office
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
HD	High Definition
IEEE	Institute of Electrical and Electronics Engineers
IMU	Internal Measurement Unit
INS	Inertial Navigation System
IR	InfraRed
ITAR	International Traffic in Arms Regulations
LiDAR	Light Detection and Ranging
LMS	LiDAR Mapping Suite
LWIR	Long Wavelength Infrared
MESA	Metamaterial Electronically Scanning Array
MRL	Manufacturing Readiness Level (MRL)
PANCAS	Passive Acoustic Non-Cooperative Avoidance System
PIC	Pilot-in-Command
PRR	Pulse Repetition Rate
RESEPI	Remote Sensing Payload Instrument
SLAM	Simultaneous Localization and Mapping
sUAS	Small Unmanned Aircraft System
SWaP	Size, Weight, and Power
TCM	Time Channel Mitigation
TRL	Technology Readiness Level
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle

EXECUTIVE SUMMARY

Small Unmanned Aircraft Systems (sUAS) are the focus of major stakeholders in future commercial applications. As the aviation sector approaches integrating these smaller aircraft into the National Airspace System, several safety considerations must be made. In a manned aircraft, the responsibility to See-and-Avoid other aircraft is primarily carried by the pilot. For sUAS without an onboard pilot, the Pilot-in-Command (PIC) must be able to safely maneuver the aircraft away from possible intruders. Therefore, a system must be integrated with the sUAS to Detect-and-Avoid (DAA) other aircraft. Sensors range from acoustic to radar and are limited by the low Cost, Size, Weight, and Power (C-SWaP) available on sUAS. Many DAA technologies have been made commercially available and are currently a focus area of research. This DAA technology survey introduces a majority of the commercially available systems for sUAS integration. Generally, radar systems have a greater range but consequently a lower resolution. The radar systems in this document are the Echodyne EchoFlight and Fortem TrueView radars. Both systems are low C-SWaP and can be integrated with most multirotor sUAS. Light Detection and Ranging (LiDAR) systems are covered, but due to low range capabilities will not be pursued in future objectives of this research effort. A handful of Electro-Optical (EO) systems are presented with Iris Automation's Casia product being the most popular and relevant to DAA for sUAS. Lastly, SARA Inc.'s airborne acoustic sensor is introduced. This system has been evaluated in previous publicly available reports and has shown promise for sUAS applications. Based on this report's findings and initial research, Fortem Tech's TrueView Radar, SARA Inc's acoustic sensor, and Casia's Long-Range system were chosen for future integration with a sUAS to be tested as part of this research effort. Opportunity exists for additional procurement and sensor research of systems not chosen in this report depending on research funding and sensor availability.

1 INTRODUCTION & BACKGROUND

This document serves as a technical review of current Unmanned Aircraft Systems (UAS) sensor technologies that can support Beyond Visual Line of Sight (BVLOS) operations. The outcome of this report will describe two sensor solutions that will be selected for Detect and Avoid (DAA) integration and evaluation.

For each sensor technology presented, a benchmark analysis with appropriate strengths and weaknesses is described. A Technology Readiness Level (TRL) and a Manufacturing Readiness Level (MRL) are assigned to each product. Some of the products reviewed are limited in publicly available information, however each product was evaluated for Size, Weight, and Power (SWaP), Field of View (FoV), Range, Operational Frequency, US-based secure supply chain, and end-user cost. The sensor technologies reviewed in this report were classified by their method of operation, given the following categories: Radar-Based Systems, LiDAR-Based Systems, Electro-Optical and Infra-Red systems (EO/IR), and Acoustic Systems.

1.1 Background

DAA systems are required for BVLOS flight. These system solutions are often comprised of several types of sensor technologies. In general, electromagnetic sensors can be categorized as either active or passive. Passive sensors contain a receiver that detects incoming electromagnetic wavelengths from a target. Active sensors contain both a receiver and a transmitter. The transmitter emits an electromagnetic wave within the operational frequency range and the wave travels to the target before being reflected back to the receiver. Onboard signal processing units extract data from the wave properties of the reflected beam of light and give the end user locational data about the target. The sensor technologies reviewed in this report were classified by their operational electromagnetic frequencies. Figure 1 provides a quick reference to the electromagnetic spectrum's different frequency bands and associated naming conventions (Encyclopædia Britannica, 2019).

Many of the products presented only provided general waveguide frequency bands for their operational wavelength. As such, a quick reference for the frequency band classifiers and wavelengths has been sourced from (Wolff, 2020) and reproduced in Figure 2. There are two common classifier systems: a newer classification used within NATO and a more historical classification used by the Institute of Electrical and Electronics Engineers (IEEE). Figure 2 shows the IEEE classification first, common radar operating ranges second, and NATO's classification third. The frequency values are listed at the top of the graphic, and the subsequent wavelengths are at the bottom.

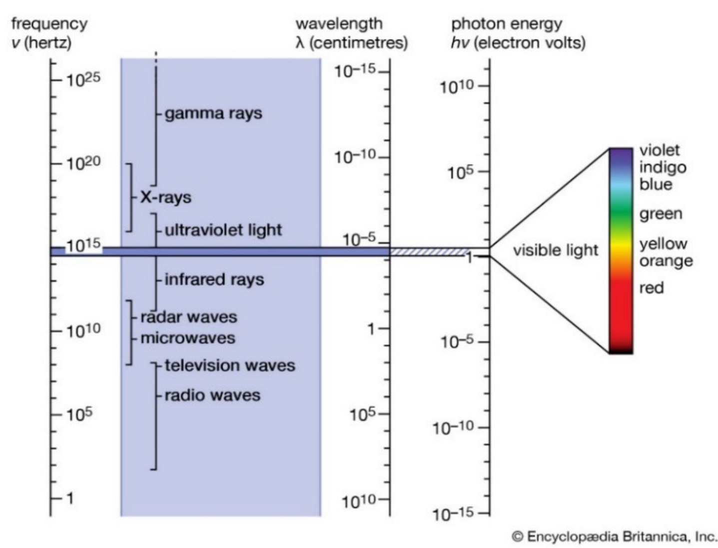

Figure 1. Electromagnetic Spectrum.

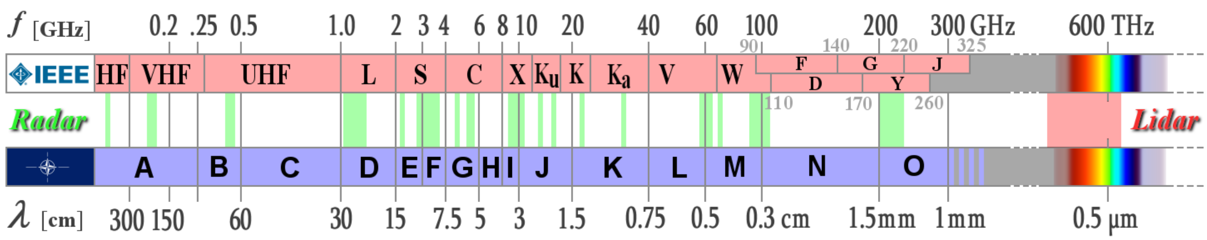

Figure 2. Radar Frequency Bands.

Technology Readiness Level (TRL) describes the technical maturity of a technology, based on demonstrated capabilities of increasing fidelity and complexity (U.S. Government Accountability Office, 2020). The sensor systems reviewed were given a TRL based on the solution's software maturity and the ease to integrate the system onto an aerial platform. MRL describes the production capability and manufacturing availability of a technology (U.S. Government Accountability Office, 2010). With each level criteria defined by the U.S. Government Accountability Office (GAO), TRL is scaled from 1 to 9, and MRL is scaled from 1 to 10. See Appendix A for GAO's definition of each TRL and MRL criteria (U.S. Government Accountability Office, 2020) & (U.S. Government Accountability Office, 2010). For brevity, the general relationship between TRL and MRL has been reproduced in Figure 3 from (U.S. Government Accountability Office, 2010).

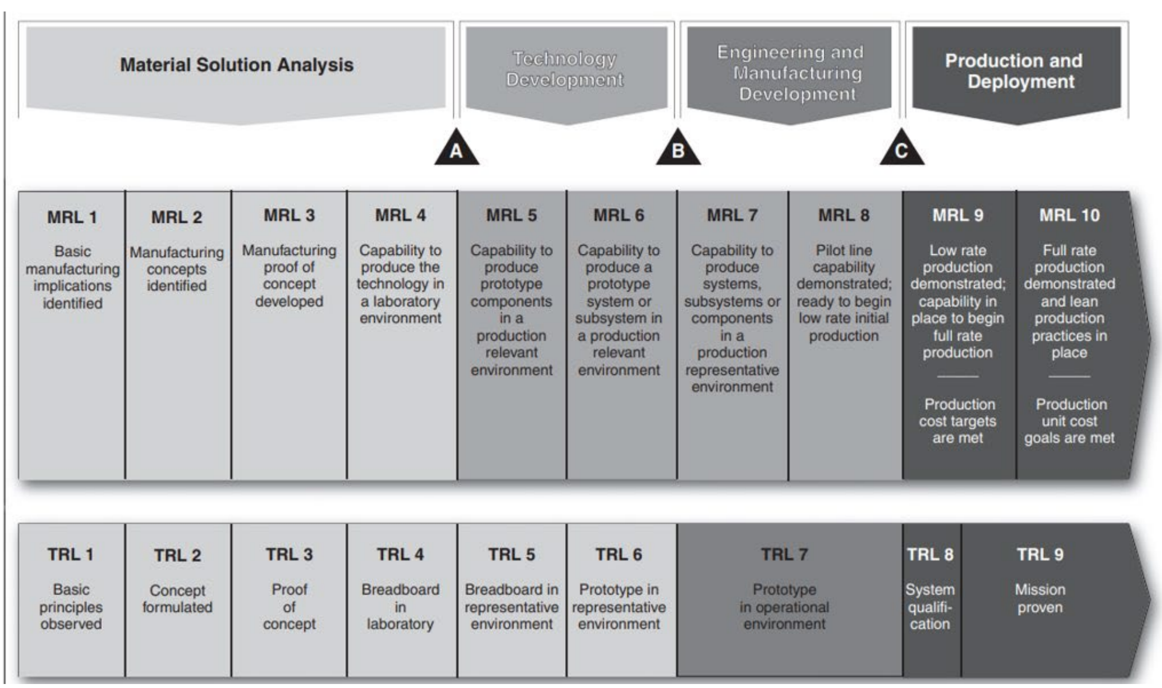

Figure 3. Relationship between Manufacturing and Technology Readiness Levels.

2 RADAR-BASED SYSTEMS

2.1 Overview

In a standard radar, the unit transmits electromagnetic waves out towards a target. These waves hit the target and a portion of the transmitted wave is received by the radar unit. The radar's processing units handle the post-processing components. A radar antenna transmits an electromagnetic pulse in the direction the radar unit is facing. The size and characteristics of this transmitted pulse are both dependent on the antenna's radiation pattern, seen in Figure 4 (Encyclopædia Britannica, 2019). This parameter is important because it describes how an antenna radiates energy and electromagnetic pulses out into space. An antenna's radiation pattern typically has tradeoffs between its main lobe and its side lobes. The main lobe typically contains angle values that describe where the radiated signal strength is at a maximum; whereas the side lobes contain angles where the radiated signal strength is not at a maximum. In radar operation, side lobes normally represent radiation in undesired directions.

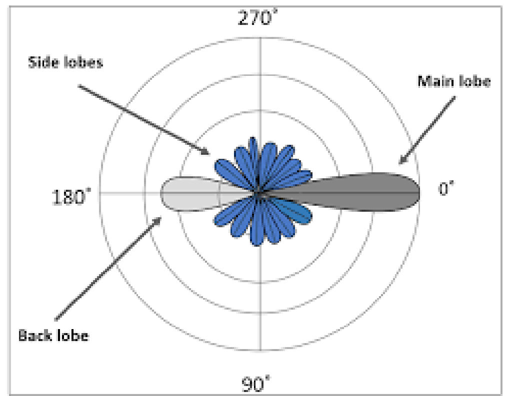

Figure 4. Sample Antenna Radiation Pattern.

The FOV describes how much of the active capture area is explored by the radar when actively transmitting pulses. The angles that describe the main lobe's size also cover the practical FOV of the antenna. A smaller FOV corresponds to an antenna whose sidelobe performance is not as significant, but the main lobe is thinly defined and does not effectively capture a large scene. Conversely, a larger FOV corresponds to an antenna whose main lobe can cover a larger region but is susceptible to sidelobe performance introducing unwanted returns from the radar.

Range resolution describes the ability of a radar to distinguish between two or more targets of the same bearing, but of different ranges. The resolution depends on the width of the transmitted pulse, the size of the target, and the system's receiver efficiency; with the pulse width playing the largest role in determining the range resolution. Higher values indicate lower range resolution capabilities (Wolff, 2020). In DAA, resolution is key for determining where in the active scanning area a potential intruder is located. Higher resolution values introduce more uncertainty into the object's location due to an inability to effectively resolve positional data on a small scale.

Radar-based systems in DAA have several key advantages. First, radar waves can penetrate environmental mediums like clouds, fog, and snow. These waves are not contingent on molecules to travel through space, meaning they can transmit through environmental conditions, albeit suffering a loss in the returned signal strength. Additionally, radar systems can describe an object's exact kinematics and give knowledge of the object's position, velocity, and distance from the radar. Finally, radar systems are versatile because they can track multiple objects simultaneously and can store large amounts of data due to its high operating frequency.

However, radar systems also have several key disadvantages. Since radar waves travel freely in air, more time is required for the transmitted waves to reach an object and back. The FOV of a radar also tends to be larger, making the main lobe's range not target-specific. This introduces larger sidelobes in the antenna's radiation pattern, making the radar systems more susceptible to clutter from noise in a scene. Radar systems are also susceptible to external interference from other signals, such as the environment or platform considerations like vibrations on a plane. While radar waves can penetrate through the environment, they tend to lose signal quality by traveling through lossy media and thus losing information to the environment. (Richards, Scheer, & Holm, 2015)

Table 1 depicts the TRL and MRL rating of the radar systems evaluated in this survey. Both the Echodyne and Fortem Tech systems require similar levels integration and were assigned TRL 9.

Table 1. Radar Solutions TRL & MRL.

Supplier	TRL	MRL	Price (Per Unit)
Echodyne: EchoFlight DAA Radar	9	10	$ 20,000
Fortem Tech: TrueView R20/DAN-C	9	10	$ 25,500

Table 2 summarizes the SWaP characteristics of the radar systems evaluated. Of the two systems, Echodyne's EchoFlight DAA Radar is lighter weight and slightly cheaper. No comparison can be made about the range and resolution accuracies of the two systems as TrueView's range is not publicly available.

Table 2. Radar Solutions Summary.

Specification	EchoFlight	TrueView R20/DAN-C
Size (cm)	20.3 x 16.3 x 4	206 x 81 x 55.6
Weight	.817 kg	1.32 kg
Peak Power	40 W	< 38 W
Field of View	120° Az 80° El	120° Az 40° El
Resolution	3.25 m	0.5m (Configurable)
Range	5987 m	---

2.2 Echodyne: EchoFlight DAA Radar

The EchoFlight DAA Radar is based on metamaterial technology, behaving very similarly to a phased array radar. It uses a patented Metamaterial Electronically Scanning Array (MESA) technology that allows Echodyne to avoid using moving parts required in traditional dish systems as well as the phase shifters required for phased array radar antennas. The EchoFlight, shown in Figure 5, was developed for sUAS applications as defined under FAR Part 107 (Echodyne, 2020). It is a lightweight radar that has a relatively low power requirement (peak 40W) that allows it to be used in small Unmanned Aircraft Systems (sUAS). The EchoFlight transmits data and commands through a standard ethernet

Figure 5. Echodyne: Echoflight UAV.

connection. This allows for multiple units to be installed and accessed relatively easily through a standard switch. The EchoFlight also features Time Channel Mitigation (TCM). TCM allows multiple EchoFlight radars to operate on the same frequency in close proximity without degradation of performance. The EchoFlight DAA radar specifications are listed below in Table 3.

Table 3. Echodyne's EchoFlight DAA Radar.

Specifications	EchoFlight
Size (cm)	20.3 x 16.3 x 4
Weight	1.8 lbs.
Power	40 W
Azimuth FoV	120°
Elevation FoV	80°
Horizontal Accuracy	± 2°
Vertical Accuracy	± 6°
Range (min, max)	20 to 5987 m
Range Resolution	3.25 m
Center Frequency	24.45-24.65 GHz

Because of the antenna's aperture characteristics and the TCM feature, multiple EchoFlight radars can be used in tandem with each other to extend the FOV. The increasing beamwidth at the edges of a single radar's FOV likely corresponds to an antenna radiation pattern that satisfies the FOV requirements. The beamwidth increasing at the edges of the FOV is likely a design effect, which may introduce inaccuracies at the edges of the FOV.

2.3 Fortem Tech: TrueView Radar

Fortem Technologies offers the TrueView R20 Radar, Figure 6, as their air-to-air solution. The R20 model is subject to International Traffic in Arms Regulations (ITAR), but the TrueView DAN-C model boasts the same SWaP specifications without the ITAR restrictions. A comparison between the two models is not publicly available.

Table 4 presents both models' specifications. The azimuth and elevation pointing accuracies are within ±2°, and the range resolution is configurable. Fortem states that their TrueView air-to-air radar solutions can detect a small UA within 0.6 mi (1 km) and a manned aircraft within 1.9 mi (3 km).

Figure 6. Fortem TrueView Radar System (Fortem Technologies, 2020).

Table 4. Fortem Tech TrueView R20 & DAN-C.

Specifications	R20 & DAN-C
Size (cm)	206 x 81 x 55.6
Weight	1.32 kg
Power	< 38 W
Azimuth	120°
Elevation FOV	40°
Horizontal Accuracy	± 2°
Elevation Accuracy	± 2°

The TrueView R20 and DAN-C models contain an integrated Inertial Navigation System (INS) and is configurable with Airborne Collision Avoidance System (ACAS). Fortem Technologies also offers an adaptable AI network known as SkyDome that utilizes TrueView and other sensor data to autonomously monitor and detect airborne threats in a given area. (Fortem Technologies, 2020)

3 LIDAR-BASED SYSTEMS

3.1 Overview

Light Detection and Ranging (LiDAR) is an active remote sensing method that uses rapid laser light pulses to measure distances between the system and the target. LiDAR system wavelengths range from approximately 10 μm to 250 nm, and the exact wavelengths used is target dependent. Due to the small wavelengths, LiDAR systems can be used on a variety of materials. Aerial LiDAR systems typically consist of a laser, a scanner, a Global Positioning System (GPS) receiver, and an Internal Measurement Unit (IMU). Like other active sensors, LiDAR emits an Electro-Magnetic (EM) wave which is then reflected by a target. The reflection time intervals and phase angles are received by the LiDAR system and used to calculate distances between the system and its target. For aerial LiDAR systems, this data is correlated with the onboard GPS and IMU to produce a 3D point cloud of the surrounding area. Aerial LiDAR sensors are typically divided into topographic and bathymetric categories. Topographic systems use near-infrared wavelengths to map ground surfaces while bathymetric systems use blue-green wavelengths to penetrate shallow water and enable the mapping of coastlines. The scope of this survey only considers topographic systems as water penetration is not a necessity in aerial DAA systems.

LiDAR is not affected by light variations and thus can be used day or night. LiDAR is also capable of penetrating dense forest canopies, and some LiDAR techniques enable the mapping of atmospheric gasses. Further advantages include fast and accurate data collection, dense surface sampling, and lack of geometrical distortion in angular landscapes. LiDAR ranges are dependent on wavelength, reflectivity, and laser pulse repetition frequency. For most LiDAR systems, vertical accuracies are around a few centimeters, yet many LiDAR systems can achieve sub-centimeter accuracy with post-processing algorithms. Due to LiDAR's short wavelengths and various atmospheric and environmental reflectivity properties, LiDAR cannot penetrate most cloud cover. (Moran, n.d.) Depending on atmospheric conditions and the exact wavelength utilized, LiDAR systems operational ranges are often only a few hundred meters. And while LiDAR systems maintain a high degree of accuracy, their short range requires them to be used in tandem with another sensor to fulfill the operational range requirements for BVLOS flight.

Table 5 shows the assigned TRLs and MRLs of each LiDAR solution reviewed. Of the LiDAR products reviewed, only Lightware's LiDAR SF40/C solution provided easy integration for use of a DAA algorithm. However, since Lightware company headquarters is in South Africa; their system does not operate under a secure, US-based supply chain. And, like most low-SWaP LiDAR systems, Lightware's SF40/C system does not have the range required for BVLOS flight.

Table 5. LiDAR Solutions TRL and MRL.

Supplier	TRL	MRL
Inertial Labs: RESPI	8	8
Lightware	9	10
Polyexplore	8	10
RIEGL Airborne Laser Scanners	8	10
Teledyne Optech	8	9

3.2 Inertial Labs: RESEPI

The Remote Sensing Payload Instrument (RESEPI), pictured in Figure 7, is a Dual Antenna Global Navigation Satellite System (GNSS) aided INS, datalogger, LiDAR, camera, and communications system. Inertial Labs states on their website that RESPI is completely modular, and customers have the option of supplying their own GNSS receiver and LiDAR sensor. Inertial Labs also provides support for commercially available LiDARs such as Velodyne, Quanergy, Ouster, RIEGL, and LIVOS. Table 6 shows the model specifications of RESEPI, excluding a LiDAR Scanner. (Inertial Labs, 2020).

Figure 7. Inertial Labs RESEPI (Inertial Labs, 2020).

Table 6. Inertial Labs, RESEPI Model without LiDAR Scanner.

Specification	RESEPI
Size (diameter x height)	10.33 x 11.1 cm
Weight	0.37 kg
Power	4 W
FoV	360° (Model Dependent)
PPK Position Accuracy[1]	0.5 cm
RTK Position Accuracy[2]	1 cm + 1 ppm
Pitch & Roll Accuracy	< 0.01°
Heading Accuracy	< 0.05°
Range	~ 450 m

An Inertial Labs technical representative was contacted for more information on RESEPI. The LiDAR solution currently writes data onto a local thumb drive, but Inertial Labs plans to be able to stream data over 1GB ethernet within 1 year. Tracking and object recognition software is not included within the RESEPI package, which leaves the end user to integrate their own software to evolve the RESEPI hardware into a fully developed DAA system. While Inertial Labs is willing

[1] Post Processing Position Accuracy (PPK)
[2] Real Time Position Accuracy (RTK)

to partner and provide technical support to achieve the end user's goals, the readiness level of this technical system does not provide a feasible DAA solution in the context of this survey. Figure 8 pictures the available LiDAR models for RESEPI, and Table 7 details each LiDAR's specifications.

Table 7. Inertial Labs, RESEPI with LiDAR.

Specification	Velodyne VLP-32	Livox Mid-40	Ouster OS1-32	Quanergy M8
Size (diameter x height)	10.33 x 11.87 cm	10.33 x 12.2 cm	10.33 x 11.95 cm	10.33 x 13.3 cm
Weight	1.57 kg	1.47 kg	1.17 kg	1.64 kg
Power	15 W	14 W	18 W	22 W
Point Cloud Precision (Single Pass)	4 – 6 cm	3 – 5 cm	4 – 7 cm	4 – 6 cm

Figure 8. Velodyne, Livox, Ouster, and Quanenergy LiDAR (Inertial Labs, 2020).

3.3 Lightware LiDAR: SF40/C10

Pictured in Figure 9, the SF40/C is a low SWaP laser rangefinder designed to provide Simultaneous Localization and Mapping (SLAM) intelligence for sUASs. With a radial range of 100 meters, this module is capable of scanning in a 360° disc at a rotation speed of 5.5 revolutions per second. This results in a maximum of 20,010 readings per second. See Table 8 for further model specifications. As this model is a disk, there is no vertical or elevation component. The sensor can output data at 20,010, 10,005, 6,670, or 2,001 points per second over a serial connection. The SF40/C comes with software where individualized alarm distances, angular widths, and aiming directions can be specified in up to seven configurable alarm zones. The manual states that the alarms are updated continuously without the need for any external commands, and the status of the alarms can be read from the serial port or through the streaming data. This model is capable of interfacing with both Pixhawk and user-designed Application Programming Interface (API). The laser component of this module is Class 1M, meaning that the beam is

Figure 9. SF40/C10 (Lightware, 2020).

safe to look at with the unprotected eye (Lightware, 2020). Lightware's company headquarters is in South Africa, and the company has several distributors world-wide, including three in the United States. Lightware does not explicitly state if the SF40/C model is under any ITAR restrictions.

Table 8. Lightware LiDAR: SF40/C10.

Specification	SF40/C10
Range	100 meters
Resolution	±3 cm
Peak Power	26 W (6 W motor, 20 W laser)
Average Laser Power	11 mW
Weight	256 g
Size (diameter x height)	79 x 70 mm

3.4 PolyExplore: Polyscanner

PolyExplore partnered with Velodyne LiDAR to produce the Polyscanner aerial mapping solution. At 2.3 kg, the Polyscanner consists of a Velodyne LiDAR sensor, High Definition (HD) camera, and GNSS/INS sensor. This compact system fits within 360 x 150 x 145 mm and has internal storage for up to 2 hours of data. The available LiDAR module characteristics can be seen in Table 9. Both LiDAR modules can rotate at rates between 5 and 20 Hz, thus achieving a 360° view around the aerial platform. The accompanying camera model produces a pixel resolution of 12.94 mm at 60 m. The camera resolution produces 4096 x 2160 imagery. While the onboard GNSS has a real time heading accuracy of 0.1°, it is unclear what the real time resolution accuracy of the LiDAR modules are. The Polyscanner communicates over a standard Ethernet connection (PolyExplor Inc., 2020). Figure 10 shows the PolyExplore Polyscanner.

Figure 10. PolyExplore Polyscanner (PolyExplore Inc., 2020).

Table 9. PolyExplore: Polyscanner LiDAR Modules.

Specification	Velodyne VLP-16	Velodyne VLP-32C
Range	100 meters	200 meters
Resolution	±3 cm	±3 cm
Vertical Field of View	+15° to -15°	+15° to -25°
Angular Resolution (Vertical)	2°	Min 0.33° (non-linear distribution)
Field of View (Azimuth)	360°	360°
Angular Resolution (Azimuth)	0.1° to 0.4°	0.1° to 0.4°

3.5 RIEGL Airborne Laser Scanners: miniVUX Series

The RIEGL family of airborne scanners are a series of LiDAR scanners that offer a range of pulse repetition rates from 100 kHz to 1800 kHz. The products listed in Table 10 utilize a rotating mirror to produce a 360° FOV. All three models contain an SD card for data storage and are capable of streaming data through LAN-TCP/IP interfaces. These models can achieve up to 100 scans per second and produce 200,000 measurements per second, resulting in a high-density point cloud. RIEGL designed these products specifically for forestry and precision agriculture applications, and the wavelength is optimized for use in snowy and icy terrain. Figure 11 shows an image of the RIEGL miniVUX-1.

Figure 11. RIEGL miniVUX-1 (RIEGL Laser Measurement Systems, 2021).

Table 10. RIEGL VUX Unmanned Aerial Vehicle (UAV) Family General Specifications.

Specifications	miniVUX-1UAV	miniVUX-2UAV	miniVUX-3UAV
Max Weight	1.6 kg	1.6 kg	1.6 kg
Min Weight	1.55 kg	1.55 kg	1.55 kg
Operating Voltage, Power	11-34V, 18W	11-34V, 18W	11-34V, 18W
Size	243 x 111 x 82 (mm)	243 x 111 x 85 (mm)	243 x 111 x 85 (mm)
Accuracy	15 mm	15 mm	15 mm
Field of View	Up to 360°	Up to 360°	Up to 360°
Pulse Repetition Rate	Up to 100 kHz	Up to 200 kHz	Up to 300 kHz

As discussed previously, LiDAR ranges depend on atmospheric conditions, the laser pulse repetition rate, and the target's reflectivity. Table 11, Table 12, and Table 13 show the maximum range for each sensor system at various Pulse Repetition Rates (PRR) and target reflectivity. These ranges are based on average atmospheric conditions and full laser power. As the PRR is increased, the power required by the system to maintain its maximum range is also increased. If more than one target is hit, the total laser transmitter power is split, reducing the achievable range. For each system listed, up to 5 targets per pulse can be detected. (RIEGL Laser Measurement Systems, 2021).

Table 11. miniVUS-1UAV Range and Operating Altitude.

Laser Pulse Repetition Rate (PRR)	**100 kHz**
Maximum Measuring Range: Reflectivity ≥ 20% Reflectivity ≥ 60% Reflectivity ≥ 80%	 170 m 290 m 330 m
Typical Operating Flight Altitude: Reflectivity ≥ 20% Reflectivity ≥ 60%	100 m 160 m

Table 12. miniVUS-2UAV Range and Operating Altitude.

Laser Pulse Repetition Rate (PRR)	**100 kHz**	**200 kHz**
Maximum Measuring Range: Reflectivity ≥ 20% Reflectivity ≥ 60% Reflectivity ≥ 80%	 170 m 290 m 330 m	 150 m 250 m 280 m
Typical Operating Flight Altitude: Reflectivity ≥ 20% Reflectivity ≥ 60%	100 m 160 m	85 m 140 m

Table 13. miniVUS-3UAV Range and Operating Altitude.

Laser Pulse Repetition Rate (PRR)	**100 kHz**	**200 kHz (reduced power)**	**200 kHz**	**300 kHz**
Maximum Measuring Range: Reflectivity ≥ 20% Reflectivity ≥ 60% Reflectivity ≥ 80%	 170 m 290 m 330 m	 150 m 250 m 280 m	 170 m 290 m 330 m	 170 m 290 m 330 m
Typical Operating Flight Altitude: Reflectivity ≥ 20% Reflectivity ≥ 60%	100 m 160 m	85 m 140 m	100 m 160 m	100 m 160 m

Though the miniVUS-3 has greater flexibility in PRR frequencies, its maximum ranges are effectively the same as the miniVUS-1 and miniVUS-2. As the transmitter frequencies provide different visibilities on different materials, selection of one of these models depends on the end user's desired applications. The systems' high precision grant maneuverability in congested spaces, such as navigation through a city or a dense forest. However, each of these models are only effective at close range and must be paired with another system to achieve the range necessary for BVLOS flight.

3.6 Teledyne Optech: CL-360

Pictured in Figure 12, Teledyne Optech's CL-360 is a survey grade OEM sensor designed for use in a variety of mobile and static platforms. The CL-360 has two models, the CL-360XR and the CL-360HD. The CL-360XR is optimized for long range applications where vegetation penetration is desired and the CL-360HD is optimized for applications where point density and precision are desired. With scan speeds ranging from 50 to 250 lines per second, both models can collect samples up to 2 MHz. The CL-360 can store 240 GB of data and utilizes 1 GigE ethernet for real time data streaming. See Table 14 for SWaP specifications and Table 15 for ranges by PRR. (Teledyne Optech, 2021)

Figure 12. Teledyne Optech CL-360 (Teledyne Optech, 2021).

Table 14. CL-360 Series General Specifications.

Specification	CL-360
Weight	3.5 kg
Dimensions	310 mm x 160 mm x 116 mm
FoV	360 °
Range Resolution	2 mm
Angular Step Width	0.036 – 1.8 °
Angular Resolution	0.001 °
Input Voltage	11 – 36 V
Typical Operating Power:	
100 Hz	35 W
200 Hz	38 W
250 Hz	40 W

Table 15. CL-360 Series Range and Operating Altitudes.

Parameters	CL-360XR			CL-360HD	
Laser Pulse Repetition Rate	50 kHz	200 kHz	500 kHz	200 kHz	500 kHz
Maximum Range:					
10% Reflectivity	610 m	310 m	195 m	205m	130 m
20% Reflectivity	750 m	435 m	250 m	290 m	185 m
50% Reflectivity	750 m	740 m	250 m	490 m	250 m
Operating Altitude:					
10% Reflectivity	390 m	195 m	125 m	130 m	85 m
20% Reflectivity	480 m	275 m	160 m	185 m	120 m
50% Reflectivity	480 m	470 m	160 m	315 m	160 m
Range Accuracy, 1sigma	5 mm	5 mm	5 mm	5 mm	5 mm
Range Precision, 1sigma	4 mm	4 mm	4 mm	4 mm	4 mm

As seen in Table 14 and Table 15, the power required increases as the laser PRR increases, and the maximum range decreases as the laser PRR increases. The CL-360XR model provides the greatest range out of the LiDAR systems reviewed. At the lowest Laser PRR, the CL-360XR can pick up poorly reflective objects at 610 m (2000 ft) and has increased visibility for highly reflective objects. Regarding BVLOS flight, the CL-360XR could potentially be used as a stand-alone solution. However, the variability of LiDAR-based systems ranges requires other sensor systems working in tandem with the LiDAR to guarantee safety.

Teledyne is based in Toronto, ON, Canada, and their operations are primarily located in the United States, Canada, United Kingdom, and Northern and Western Europe. Their CL-360 product is designed for OEM hardware manufacturers, so mounting hardware is not provided. Teledyne provides a variety of software options in order to integrate their hardware solutions. The LiDAR Mapping Suite (LMS) and Flight Mapping Suite (FMS) seem to be directly applicable to UAS DAA efforts. The LMS is designed for high-volume data processing and LiDAR mapping post-processing. The FMS is a flight planning and navigation software designed for optimizing surveying missions. However, it may be possible to integrate these capabilities into an onboard autopilot software.

4 ELECTRO-OPTICAL & INFRARED SYSTEMS

4.1 Overview

Electro-Optical and Infrared systems operate on similar principles where a transmitter emits a beam of light that bounces off a target and onto a receiver. As the InfraRed (IR) spectrum is close to the visible spectrum, many Electro-Optical systems combine the visual and IR sensors into one system. Within the EM spectrum, the infrared spectrum is further divided into three regions, near infrared, mid, and far. The near infrared region are the typical IR sensors, operating from about 700 nm to 1400 nm. Mid infrared operates from 1400 nm to 3000 nm and is typically used for heat sensing applications. The far infrared spectrum operates from 3000 nm to 1 mm and is used for thermal imaging. IR sensors can be further described as either passive or active. Active IR sensors utilize a transmitter to send out a beam of light that is then reflected by a target and onto a receiver. In most IR systems, the transmitter is either a LED for non-imaging application or a laser diode for imaging applications. Passive IR sensors do not use any transmitters and instead detect the energy radiated by a target. In both active and passive systems, amplifiers and signal processing units are required to extrapolate the desired information from the receiver. For the scope of this survey, only active IR sensors were considered. (Shetty, 2015)

Active Electro-Optical sensors are typically arranged in one of three configurations: through-beam, retro-reflective, and diffuse reflection. All three configurations consist of both a transmitter and a receiver. For a through-beam sensor, the transmitter and receiver are placed opposite to each other over some distance. The transmitter projects light to the receiver, and any interruption of the light beam is interpreted as a switch signal by the receiver. This system can operate over large distances, but the object detected must be large enough to interrupt the light beam completely. Retro-reflective sensors place the transmitter and receiver in the same housing. The transmitter emits a light beam that then bounces from a reflector to the receiver. The receiver detects any interruption of the light beam. Diffuse reflection sensors are the most common for remote sensing applications. In this system, both the transmitter and receiver are in one housing, and the transmitted light is reflected by a target onto the receiver. (Agarwal, 2016)

In general, IR sensors have fast response times, are highly stable, and rarely experience noise. These sensors require little power and can operate day or night. Though IR can sense soft-body objects, it cannot pass through solid objects such as walls and doors. IR sensors are also affected by environmental conditions such as rain, fog, pollution, dust, and smoke. Its short wavelengths reduce capabilities to shorter distances than other sensor types. (Soffar, 2019)

Though Electro-Optical systems are limited to daytime use, they are not a new technology, and many implementation and integration resources are openly available. Electro-Optical systems are typically low cost with low power requirements, and like IR sensors, Electro-Optical systems are affected by atmospheric conditions. Electro-Optical systems are also temperature and humidity sensitive; an aerial platform's Electro-Optical system must be weather proofed to ensure image quality. Electro-Optical systems typically have fast response times, so real-time data is available for a DAA algorithm. However, an Electro-Optical system's resolution is limited in part by the sensor's size and by the number of pixels, and thus the accuracy varies by the sensor model's specifications. Post-processing software and algorithms can improve a model's accuracy, but for DAA systems, the sensor model must have sufficient accuracy in real-time. Table 16 below compares TRL and MRL EO/IR solutions.

Table 16. EO/IR Solutions TRL and MRL.

Supplier	TRL	MRL
Iris Automation: Casia	9	9

Ascent Vision: CM62	7	7
Ascent Vision: CM142	9	10
TASE Imagining Systems	9	10

4.2 Iris Automation: Casia

Based in California, Iris Automation developed the first commercially available 360° computer vision DAA system for UAS. Iris Automation continues to refine Casia and their Collision Avoidance Systems (CAS) by partnering with multiple Federal Aviation Administration (FAA) UAS Integration Pilot Programs, NASA's Unmanned Traffic Management Program, and Transport Canada's BVLOS Technology Demonstration Program. Casia is a fully integrated onboard hardware and software solution that is compatible with most commercially available autopilots as a plug-and-play system. Iris Automation designed Casia 360° and its software to meet FAA BVLOS requirements and the emerging standards for risk ratios established by the American Society for Testing and Materials (ASTM). Casia 360° consists of an onboard computer and 5 cameras, whose specifications are reproduced in Table 17. The Casia Long-Range system, pictured in Figure 13, is the same system as the Casia 360°, pictured in Figure 14, just with only one camera. (Iris Automation Inc., 2021)

Figure 13. Casia Long-Range (Iris Automation Inc., 2021).

Figure 14. Casia 360° (Iris Automation Inc., 2021).

Table 17. Iris Automation: Casia.

	Casia Long-Range	Casia 360°
Module Size	77 x 110 x 36 mm	110 x 110 x80 mm
Camera Size	60 x 60 x 105 mm	60 x 60 x 105 mm
Weight	452 g	2400 g
Power	10W Nominal, 15W Peak	60 W
Range	1200 m	1200 m
Horizontal FoV	80°	360°

Vertical FoV	50°	50°

Being a fully integrated system with onboard CAS software, this module is useful for users who require minimal integration on their end. Casia's system contains multiple data interfaces and provides an open software API for configuration. Since this system is Electro-Optical , its use is limited to daytime hours. The initial hardware cost is approximately $3,600 and the software is leased at $10,000 per year.

4.3 Ascent Vision Technologies

Ascent Vision Technologies is owned by CACI International Inc, which is an American multinational service and information technology company located in Virginia. CACI maintains partnerships with many branches of the US government in areas of defense, homeland security, and intelligence. Ascent Vision maintains offices in Australia and Montana, USA.

Ascent Vision Technologies has two UAS gyroscopic imaging systems suitable for sUAS, the CM62, and the CM142. The CM62 is still in development but was included in this review due to its low SWaP and high capabilities. Both modules' specifications are reproduced in Table 18. These two systems utilize Electro-Optical and infrared wavelengths, enabling the user to fly day or night. The CM62's Electro-Optical sensor is able to zoom up to 50x, and its IR sensor can zoom up to 8x. The CM142 provides continuous Electro-Optical zoom and is actively supporting aerial wildfire surveillance in both the US and Australia. Both solutions come with onboard video encoding and processing, thereby reducing payload weight and hardware requirements. Real-time navigation, geo pointing, and object tracking are additional features included with these solution's software. (Ascent Vision Technologies, 2021) Figure 15 shows the Ascent Vision CM142.

Figure 15. Ascent Vision CM142 (Ascent Vision Technologies, 2021).

Table 18. Ascent Vision Technologies.

Specification	CM62	CM142
Size (diameter, height)	63.5 x 101.6 mm	140 x 183 mm
Weight	0.25 kg	1.27 kg
Power (idle)	7 W	15 W
Peak Power	20 W	80 W
Sensors	EO & Long Wavelength Infrared (LWIR) & Laser Pointer	HD EO & LWIR

Ascent Vision's aerial surveillance products come with the OPS-Warden user interface for command and control between the imaging system and user. This software comes with a Force Protection Mode that utilizes automated alerts and security features to ensure maximum, 360° situational awareness. Both the CM62 and CM142 are described as long-range sensors, but no specific range statistic was provided. However, since both surveillance systems utilize LWIR wavelengths, the IR sensor could potentially pick-up heat signatures a few miles away, given optimal atmospheric conditions.

4.4 TASE™ Imaging Systems

TASE™ Imaging Systems is a part of Collins Aerospace, which also owns Piccolo™ Flight Mapping Suite. As such, all TASE Imaging Systems products are compatible with Piccolo's autopilot. The TASE250 and TASE400 payloads were selected for review due to their low SWaP and proven capabilities. The TASE400 LRS series is reviewed in this document given its superior range to the 250 series. The product specifications have been reproduced in Table 19, and optional laser illuminators can be added to either solution. TASE imaging systems share a common command and control interface known as ViewPoint. ViewPoint enables real time object tracking and surveillance while being completely modular and available for external Plugins. (Collins Aerospace, 2021) Figure 16 shows the TASE400 imaging system.

Figure 16. TASE400 (Collins Aerospace, 2021).

Table 19. TASE™ Imaging Systems Payloads.

Specifications	TASE250	TASE400 LRS
Size (diameter, height)	14 x 19 cm	17.8 x 26.7 cm
Weight	< 2 kg	4 kg
Power (average)	28 W	35 W
Power (max)	100 W	100 W
IR Camera	LWIR	MWIR
EO Daylight Camera 1	Stepped Digital Zoom: 4x Resolution: 640 x 480 HFOV: 14.5°-2.5°	Continuous Optical Zoom: 31x HFOV: 55.7°- 1.94°
EO Daylight Camera 2	N/A	Spotter Camera Fixed Zoom: 53x HFOV: 1.06° (SD) / 2.12° (HD)
Range	457 m	2133 m
FoV Rotation	360° continuous pan	360° continuous pan
FoV Tilt	+ 20° / -85°	+ 20° / -85°
Slew Rate	150 °/s	150 °/s
Payload Stabilization	2-Axis active	2-Axis active

5 ACOUSTIC SYSTEMS

5.1 Overview

The acoustic sense and avoid system reviewed uses a microphone array to detect intruding aircraft. A microphone is a passive pressure sensor that measures the oscillation in pressure caused by a sound wave. This information is captured by the movement of a membrane and converts this to an electric signal. The main type of microphone that is used for systems like these are flat response condenser microphones.

Condenser microphones consist of a charged metal back plate and a charged metal diaphragm that are separated by a thin space to form a capacitor. As sound waves reach the diaphragm and cause it to move, the distance between the two plates changes. This in turn changes the capacitance of the system. This change can be measured and used to record the incoming sound (Teach Me Audio, 2020). Figure 17 shows a Condenser Microphone Diagram setup.

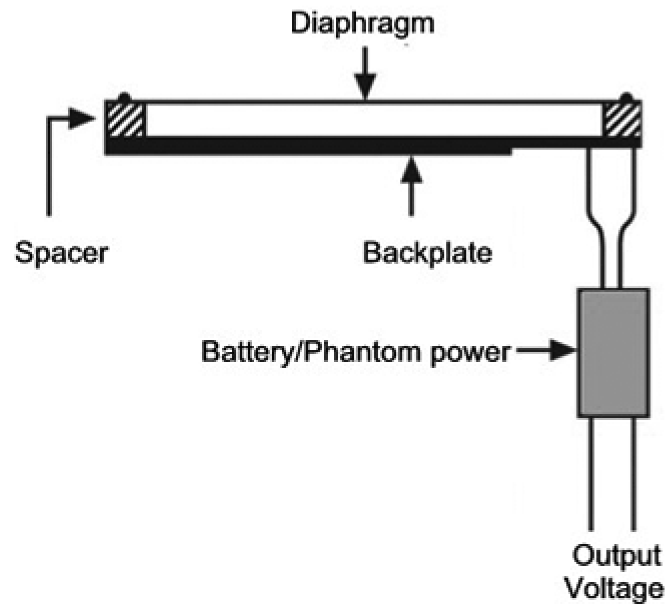

Figure 17. Condenser Microphone Diagram (Teach Me Audio, 2020).

To get the location of an intruder aircraft, an array of microphones is used. Using multiple mics allows for the triangulation of the source of sound to determine the location of the intruder. These signals can also be analyzed for Doppler-induced frequency shifts to determine velocity and heading (Harvey & O'Young, 2018).

Acoustic sensors excel in low-traffic, low-noise environments. By nature, their systems are omnidirectional and long range. Implementing acoustic sensors does, however, require extensive knowledge of the acoustics of the ownship aircraft and is therefore much less "plug and play" than the other DAA solutions. It also runs the risk of degraded performance in an environment that has a lot of ambient noise such as near highways or next to factories with larger machinery.

5.2 SARA Inc: PANCAS

The SARA Passive Acoustic Non-Cooperative Collision Avoidance System (PANCAS) consists of a microphone array and a small computer. It is an extremely low SWaP sensor that was the first to be recognized by the FAA as satisfying the DAA requirements for a noncooperative aircraft sensor (SARA, 2020). Their system has demonstrated the ability to reliably detect an incoming intruder at a range of 5.4 nautical miles with no missed detections and no false alarms (Ferguson, 2018).

As the SARA PANCAS system is still in development, the TRL and MRL assignments in Table 20 were based on what information is available. SARA describes their products as "typically TRL-7 technologies" that are "ready for integration with your system" (SARA, 2021).

Table 20. Acoustic Solutions TRL and MRL.

Supplier	TRL	MRL
Sara PANCAS	7	8

Figure 18. SARA PANCAS microphone (SARA, 2020).

According to Dr. Ferguson in the *Pathfinder Focus Area 2 Phase III Report*, this sensor excels at long range detection and is very small and lightweight. One risk with this system is that there is no "flight heritage" that would help predict the final positioning of the intruder aircraft (Ferguson, 2018). The sensors have all-weather collision avoidance and can be integrated onto any Class I, II, or III UAS and can even detect impulsive events such as a gunshot and will reposition to safety and report the position of the gunshot heard (Harvey and O'Young, 2018). Figure 18 shows the SARA PANCAS system and Tables 20 and 21 list the TRL/MRL values and model specifications respectively.

Table 21. Acoustic Sensor Specifications.

Specifications	Sara PANCAS
Range	10km (32808 ft)
Field of View	360°
Weight	Light

6 CONCLUSION

In general, radar-based systems have a greater range due to their large wavelengths. This is beneficial for BVLOS applications, but the larger wavelengths provide less accurate resolution. However, post-processing software can improve a radar's resolution. In contrast to radar systems, LiDAR systems' smaller wavelengths provide highly accurate resolution at the cost of a reduced range. LiDAR systems also produce highly dense point clouds that can require greater post-processing power than other systems. Electro-Optical and infrared systems provide more than adequate range for BVLOS applications, but such sensors require on-board object recognition and tracking software to fully integrate these sensors with a DAA algorithm. Electro-Optical and infrared systems that include this type of software cost more than regular Electro-Optical systems.

Some sensors will be excluded from future research for a few reasons. The Ascent Vision CM62 boasts the necessary range, weight, and power draw to be a viable solution. However, researchers cannot test this model because it has not yet been released to market. Although the only solution meeting range requirements, the Teledyne Optech CL-360 has little range margin of error. LiDAR is susceptible to weather conditions and low reflectivity objects, so unfavorable conditions can significantly affect performance.

Researchers selected one radar-based system and one Electro-Optical system for further analysis as a DAA BVLOS solution. Scientists will procure and integrate Fortem Tech's TrueView Radar and Casia's Long-Range aboard a sUAS, with the expectation of integrating the Casia 360 system when released in 2021. In previous research, the Raspet Flight Research Laboratory integrated the EchoFlight DAA Radar system on a larger platform. This makes Fortem Tech's TrueView Radar a natural extension of Raspet's capabilities. Researchers' previous work will serve as a base point for comparing the TrueView's system capabilities as a DAA solution. The Casia Long-Range system requires more integration effort because the single camera has a limited FOV. Initially, the Casia Long-Range system will be evaluated with its limited FOV, with the expectation that the Casia 360 system will perform the same, if not better. The integration of the multiple cameras may support the system as a feasible BVLOS solution. The next steps in the research will be designing flight tests that test these systems. Testing will include favorable and unfavorable conditions, as well as corner cases that can be a stress test to the system. Likely, a combination of multiple heterogenous systems will provide a sUAS with the necessary safety case for pursuing BVLOS operations.

7 APPENDIX A

NASA Hardware Technology Readiness Level (2013)		
TRL	**Definition**	**Description**
1	Basic Principles Observed & Reported	Scientific knowledge generated underpinning hardware technology concepts/applications
2	Technology Concept and/or application formulated	Invention begins, practical application is identified but speculative, no experimental proof or detailed analysis is available to support the conjecture.
3	Analytical & experimental critical function and/or characteristic proof of concept	Analytical studies place the technology in an appropriate context & lab demo, modeling &simulation validate analytical prediction.
4	Component and/or breadboard validation in lab environment	A low fidelity system/component breadboard is built & operated to demonstrate basic functionality and critical test environments & performance predictions are defined relative to the final operating environment
5	Component and/or breadboard validation in relevant environment	A medium fidelity system/component brassboard is built & operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for development phases
6	System/sub-system model or prototype demonstration in an operational environment	A high-fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.
7	System prototype demonstration in an operational environment	A high-fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test & analysis for its intended operational environment and platform
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.

NASA Software Technology Readiness Level (2013)		
TRL	**Definition**	**Description**
1	Basic principles observed & reported	Scientific knowledge generated underpinning basic properties of software architecture & mathematical formulation
2	Technology concept and/or application formulated	Practical application is identified but speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts are defined. Basic principles coded. Experiments performed with synthetic data.
3	Analytical & experimental critical function and/or characteristic proof of concept	Development of limited functionality to validate critical properties and predictions using non-integrated software components.
4	Component and/or breadboard validation in lab environment	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant environments defined & performance in this environment predicted.
5	Component and/or breadboard validation in relevant environment	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.
6	System/sub-system model or prototype demonstration in an operational environment	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.
7	System prototype demonstration in an operational environment	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.
8	Actual system completed and "flight qualified" through test and demonstration.	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.

9	Actual system flight proven through successful mission operations.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.

Manufacturing Readiness Level	
MRL	**Description**
1	Basic manufacturing implications identified
2	Manufacturing concepts identified
3	Manufacturing proof of concept developed
4	Capability to produce the technology in a lab environment
5	Capability to produce prototype components in a production-relevant environment
6	Capability to produce a prototype system or subsystem in a production-relevant environment
7	Capability to produce systems, subsystems, or components in a production-representative environment
8	Pilot line capability demonstrated; ready to begin low-rate initial production
9	Low-rate production demonstrated; capability in place to begin full-rate production
10	Full-rate production demonstrated, and lean production practices in place

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