WAMI Final Report

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TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

1. EXECUTIVE SUMMARY

Wide Area Motion Imagery (WAMI) systems are Intelligence, Surveillance, and Reconnaissance (ISR) weapon systems that are deployed on aircraft with the objective of finding, fixing and tracking ground targets. These systems bring our country situational awareness that cannot be matched. Existing systems, however, are not compatible with the airplanes of the future: Unmanned Aerial Vehicles (UAVs).

UAVs are much smaller and lighter than the manned aircraft WAMI systems are typically deployed on, resulting in a huge reduction in sensor payload weight. As more UAVs are being developed and deployed, the need for a compatible WAMI system has arisen. This is a WAMI system that weighs less than 500lbs.

Our approach consisted of three phases: Conceptual Design, Performance Analysis, and Trade-Off Analysis. In the conceptual design, we decomposed the system and researched historic data and perspective trends for each subsystem. This enabled us to identify and assess potential opportunities for reducing the total weight of the system.

We entered the Performance Analysis phase with a selection of weight-reducing alternatives. By modeling the performance for each combination of the WAMI subsystems, we were able to calculate the total storage required by performance, and associated storage weight. Alternatives that were considered to have a sub-par performance or were above the weight threshold were eliminated from the remainder of our analysis.

In the Trade-Off Analysis phase, we calculated the total value delivered to our stakeholder and selected a sample of best-value alternatives across a variety of system weights. Characteristics of these best-value alternatives were identified and analyzed. Our results enabled us to present to our sponsor, Secretary of the Air Force Acquisition Department, what is sacrificed and gained, with respect to performance and suitability, when the WAMI system weight is reduced.

2. INTRODUCTION

Irregular forces will continue to pose a significant challenge for the foreseeable future and Intelligence, Surveillance, and Reconnaissance (ISR) weapon systems, which drive operations by finding and fixing targets, if designed correctly, offer a 21st century solution. Specifically, Wide Area Motion Imagery (WAMI) sensors bring persistence, precision and unprecedented situational awareness: all key enablers for the Counter Terrorism and Counter Insurgency Operations.

2.1 Background

WAMI sensors, typically mounted on small aircraft, helicopters, balloons, or Unmanned Ariel Vehicles (UAVs), allow for a bird's eye-view of the battle space and offer a unique capability to store and search activity. They initiate the F3EA mission cycle—Find, Fix, Finish, Exploit and Analyze—by identifying low signature targets and providing real-time intelligence to troops on the ground or at home. The military first fielded a WAMI sensor in 2006. Figure 1 below shows the high level Operational Concept Graphic of a WAMI system. WAMI systems provide a "TiVo-like" capability to troops on the ground and all of the data captured during the mission is downloaded to the ground storage site once the plane is on the ground.

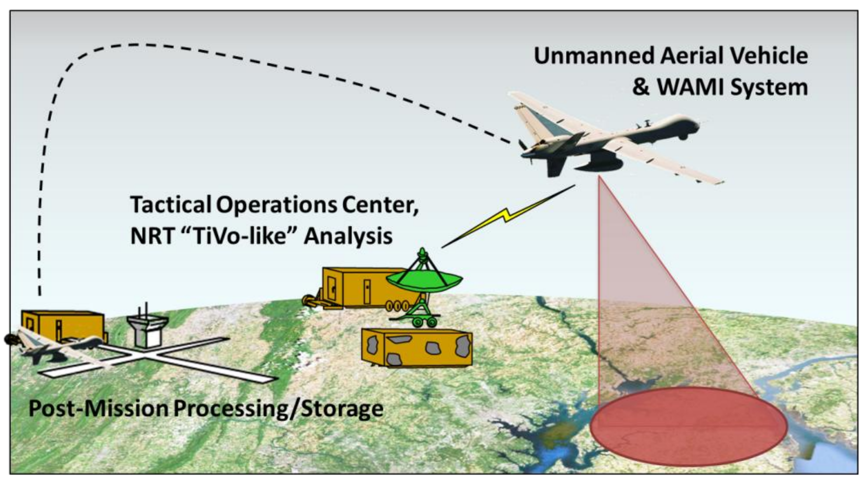


Figure 1: Operational Concept Graphic

With the United States Military involved in two ground wars that heavily focused on battles with irregular forces, the need for unprecedented battle space situational awareness drove the requirement for WAMI sensors in the field. WAMI sensors were deployed as Rapid Response Programs or Quick Reaction Capabilities (QRCs). This essentially meant that no program of record was established and consequently the systems analysis, to include requirements, was never accomplished.

Other solutions outside of WAMI, such as radar and Signals Intelligence (SIGINT), were found to be suboptimal and did not provide the capabilities of the WAMI sensor. Radars, while having the ability to cover large areas, did not give the military the required resolution to identify vehicles and dismounts in urban environments. Signals Intelligence was also not a viable solution because the deployment of such systems would lead to a breach in the activities and methodologies required in order to keep them effective. Simply put, too many of its capabilities are on a restricted need to know basis.

2.1.1 WAMI Attributes

WAMI sensors have the following key attributes:

- Weight
- Geospatial Resolution (Ground Sampling Distance (GSD))
- Temporal Resolution (Frame Rate)
- Processing Power
- Storage
- Area of Coverage (Field of View (FoV))
- Grazing Angle

2.1.1.1 Weight

The weight of the payload is a key attribute as it drives which platform the sensor can be placed on. Platforms in the past, such as the King Air A-90, have weight limits of more than 1000 pounds. This allowed for weight to not be a key design parameter. However, as we move toward future platforms specifically sleek and light UAVs such as the Air Force's Reaper, MQ-1 Predator, Aurora's Orion, or Army's MQ-1C Grey Eagle, weight constraints become a key driver in WAMI sensor design. Weight ultimately affects the platforms endurance the most and therefore is most related to the persistence of the system.

2.1.1.2 Geospatial and Temporal Resolution (GSD and Frame Rate)

Resolution is another key attribute of WAMI sensor design as it is most directly related to precision. "[Geospatial] resolution is defined by the size and number of pixels used to divide a space. A smaller size and higher number of pixels result in a high resolution and more detail, while a bigger size and lower number of pixels result in a low resolution and less detail."[1] For example, a GSD of 0.3 meters indicates that each pixel in an image is 0.3 meters apart, as measured on the ground. For an image that contains the same number of pixels, this would illustrate more detail than if, say, each pixel were 0.6 meters apart. Electro-optical (EO) sensors as used for day-time operations whereas infrared (IR) sensors are used for night-time operations. Temporal resolution refers to the precision of measurement with respect to time. Operational experience and scientific research have indicated the parameters identified in Table 1 yield an acceptable level of performance to identify dismounts and vehicles.

	EO GSD	IR GSD	Frame Rate
Find and Fix Dismounts	~0.2 m	~0.7 m	~5 fps
Find and Fix Vehicles	~0.5 m	~1.0 m	~2 fps

Table 1: Design Parameters for GSD and Frame Rate[2]

2.1.1.3 Processing Power and Storage

WAMI sensor capabilities focus on "smart processing" algorithms to reduce the amount of data to be downloaded on-board. For example, a 400M pixel camera with 0.4m GSD, there would be approximately 8.0 Gbps of data that would need to be downloaded in real time and approximately 700T bits if a 24 hour mission was to be stored on board. "Smart processing" requires the integration of other sensors to automatically cue users and analysts onto an area of interest (also known as SIGACT). These areas of interest are dozens of dynamically selectable ~1M bps chips and are accessible in near-real-time with lossless compression, or without losing the quality of the image. The remaining bulk of the data is downloaded and stored after the aircraft lands. For a WAMI coverage area of 10km by 10km, 1600 250m by 250m chips are

[1] http://geospatial.referata.com/wiki/Resolution

[2] Col Yahn. Robert A. (2011, 08). Wide Area Motion Imagery A game changing enabler for Counter Insurgency Operations. Secretary of the Air Force Acquisition Information Dominance, Washington, DC

included and only a fraction of those chips (approximately 24-36) will be under observation at any given time, roughly 2%.

2.1.1.4 Area of Coverage (Field of View (FoV)) and Grazing Angle

In an urban environment, there is a high probability that vehicles and dismounts will be masked by buildings and trees if the Field of View (FoV) and grazing angle are ignored. The FoV is defined as the area visible to the sensor while the grazing angle is angle between the ground and the FoV. For the same FoV (d), the grazing angle (θ) will change dependent on the height (ht or hs) of the aircraft as shown in Figure 2 below. Also, as the grazing angle increases, the percent of vehicles and dismounts visible to the WAMI sensor increases.

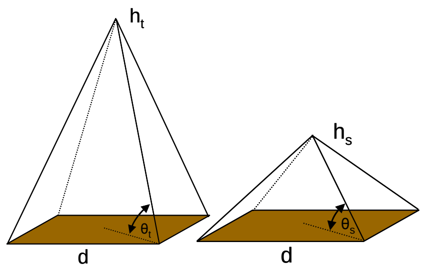


Figure 2: FoV and Grazing Angle

Based on current research of Urban Terrain Zones (UTZs), an analysis was done by the Assistant Secretary of the Air Force, Acquisition to determine the most optimal grazing angle based on the percent of vehicles and dismounts visible to the WAMI sensor. The analysis determined that as the minimum grazing angle acceptable for operations was 45 degrees with approximately 63.1% of vehicles and dismounts visible. The graph in Figure 3 below shows the complete analysis.

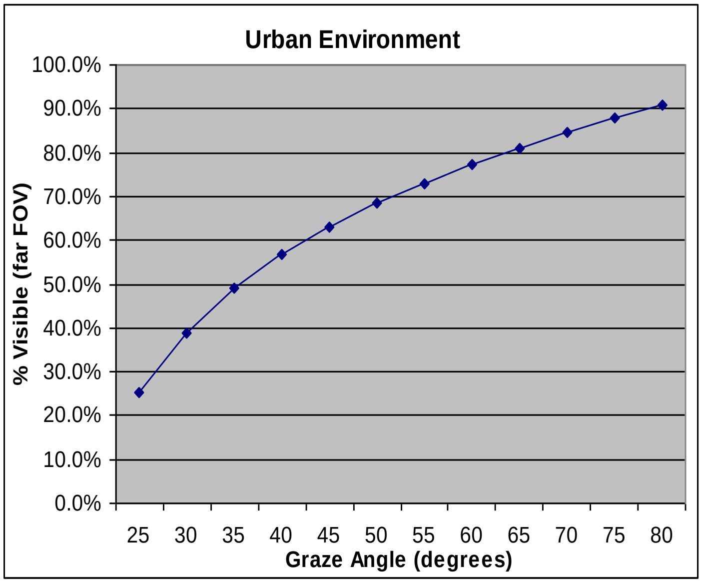


Figure 3: Grazing Angle vs. % Visible For Fielded Systems

There has been multiple WAMI sensor systems developed and fielded today, each with their own unique attributes and challenges.

2.1.1.5 System A

System A was developed at a cost of about $50M in 2007. The first flight test was on a Black Hawk helicopter in 2010 but it was designed for the Boeing A160 Hummingbird, an unmanned helicopter. The 1.8 – gigapixel sensor has four optical telescopes, each with 92 5-megapixel focal-plane arrays, or cell phone camera chips. The airborne processor combines the video output from all 368 arrays together to create a single mosaic image, with an update rate of approximately 15 frames per second.[3] The airborne part weighs approximately 1500lbs, has a GSD of 15 centimeters, and offers a wider FoV than was possible with earlier equipment.

The A160 Hummingbird was deployed to Afghanistan with System A in June 2012. However, the Army issued a stop-work order to Boeing because the aircraft had a high probability of cost,

[3] http://www.aviationweek.com/Blogs.aspx?plckBlogId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog%253a27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%253a881370e5-a10f-46be-bab0-bf60fa08b425&plckScript=blogScript&plckElementId=blogDest

schedule, and technical delays with risks so high it was not in the best interest of the Government to continue the program. An upgraded version of System A is now slotted for the MQ-9 Reaper and will be fielded in May 2013 as the EO solution the upgraded System D, detailed in section 2.1.2.4 below.

2.1.1.6 System B

System B surveillance sensor was primarily developed by the Air Force Research Laboratory (AFRL) in 2006. "It is the first of its kind to provide real-time, persistent, wide area intelligence, surveillance and reconnaissance to a ground commander at a tactical level."[4] The sensor has a 0.5m GSD, a 4km x 4km FoV, and is deployed on the King Air A-90. The Marine Corps purchased one (1) suite which included four (4) sensors deployed in Operation Iraqi Freedom. It is only limited to day operations and weighs only 300 lbs.

While System B is by far one of the smallest solutions fielded to this day, it is a very low quality and low performance system. In an effort to reduce cost, developers of System B chose to remove the gimbal, or stabilization unit, from the design which can cost upwards of $1M. However, "high frequency noise or jitter from the aircraft can seriously degrade the quality of imagery – hence the need for a high-end gimbal to cancel out these vibrations." The design team decided to speed up the frame rate of the system to make up for the loss of the gimbal, however, this reduced the exposure of the images, making them darker.[5]

2.1.1.7 System C

System C, an Army system, arrived in 2006 and was acclaimed as one of the top 10 new systems of that year.[6] It was deployed to Iraq on the Short 360s and to Afghanistan in 2009 on the MC-12W Liberty. The sensor uses Intel CPUs, 500 GB hard drives, and a 96-megapixel camera to provide persistent coverage. Additionally, this system weighs approximately 800lbs, has no IR capability, and only has a GSD of 0.7m. Another disadvantage to System C is that it is more difficult to use and generates video that can only be analyzed by trained analysis.

2.1.1.8 System D

[4] http://www.globalsecurity.org/intell/systems/
[5] http://archive.feedblitz.com/657386/~3895979
[6] http://www.globalsecurity.org/intell/systems/

The Air Force fielded four System D sensors on the MQ-9 Reapers in 2010. It has a 4km diameter FoV for both day and night operations and is an improvement upon System B. System D allows users to choose from the 12 angles that it can broadcast simultaneously while System B allows multiple users to view its imagery but can only broadcast back one at a time.[7] System D weighs approximately 1100lbs, has a 0.75 GSD, and a frame rate of 2 frames per second.

The Air Force will field six upgraded System D sensors in 2013; again on the MQ-9 Reaper. The main improvement is inclusion of System A for its EO capability.

2.2 Project Description

2.2.1 Problem Statement

Of the WAMI sensors fielded today, there is no solution compatible to be fielded on current platforms such as the Air Force's MQ-1 Predator, Army's MQ-1C Grey Eagle or future platforms such as the Air Force's Aurora's Orion. The payload weight limit for each of these platforms is approximately 500lbs and each of the fielded systems described above does not meet that requirement with acceptable performance. The challenge is to find a WAMI solution that is "good enough" within the 500lb threshold. Additionally, the operational altitude of the system is 20,000 ft and it must be able to detect dismounts.

2.2.2 Objectives and Scope

In order to address this problem, the following top-level objectives were identified:

- Assess opportunities to reduce weight of the WAMI sensor
- Understand the impacts that weight reductions have on cost and performance
- Determine if these impacts fall within the threshold for "good enough"

While these objectives address cost, performance, and weight at the system level, a detailed analysis at the subsystem level or lower is necessary to fully evaluate these aggregate measures. Given the nature of this project, information regarding low-level components is habitually classified or proprietary; assumptions that best satisfy areas where information has not been made available are described in the sections that follow.

[7] http://www.airforcetimes.com/news/2009/02/airforce_WAAS_021609/

A conceptual design will be described for a variety of configurations that potentially reduce total system weight to less than 500 lbs. These configurations will be evaluated to determine the delivered level of performance. Stakeholder values will be captured for each performance parameter, and a recommendation will be provided based on a configuration that delivers the most value. At a minimum, the system, operating at 20,000 ft, must be able to detect dismounts on the ground.

2.2.3 Technical Approach

2.2.3.1 Conceptual Design

In order to assess opportunities to reduce the WAMI sensor weight, a conceptual understanding of the system design is necessary. The following approach will identify the system components that, for the specified timeframe, could have the most impact on the total system weight:

- Decompose the system and identify all components
- Research historic data and perspective trends for each component
- Identify the primary weight drivers
- Identify opportunities for savings (weight) and potential costs ($)

2.2.3.2 Performance Analysis

To understand the impact that individual components have on the total system performance, each component must have system performance parameters allocated to it. A model of these performance parameters will then help to assess the impact that configuration variations might have on performance. The following approach will enable such relationships and analyses to be made:

- Research historic data each measure of performance to identify threshold and objective values
- Identify the projected performance (from performance model) of each alternative

2.2.3.3 Trade-Off Analysis

The following approach for trade-off analysis will determine the solutions that deliver the greatest value with respect to performance and cost. These solutions can then be evaluated to determine if performance is “good enough”.

- Elicit stakeholder values for each measure of performance
- Select a set of the most suitable alternatives to reduce weight
- Determine which alternative(s) deliver(s) the greatest value
- Plot the selected alternative(s) on the performance curve

3. WAMI WEIGHT REDUCTION ANALYSIS

3.1 Conceptual Design

This section of our analysis we show our conceptual understanding of the system design. After decomposing the system and identifying components, we conducted a detailed analysis of historical data and perspective trends of each weight driving component. We also identified the static weight components of the system. Using the different alternatives for each weight driving component, we came up will all the possible feasible alternatives of the system.

3.1.1 System Decomposition

The WAMI conceptual system is composed of six main subsystems as described in Figure 4 below. The subsystems are also sub-divided into two smaller groups. These groups are static weight subsystems and weight-reducing subsystems. Static weight subsystems are subsystems found to add a specific amount of weight to the WAMI systems overall. These subsystems are believed to have minimal amounts of future technology insertion. Because of this, the variations in weight of these components are minimal and as such they are considered a constant for this analysis. Weight-reducing subsystems are subsystems that, via new technology insertion or better architecting of the subsystems, yield weight savings that impact the overall weight of the WAMI system.

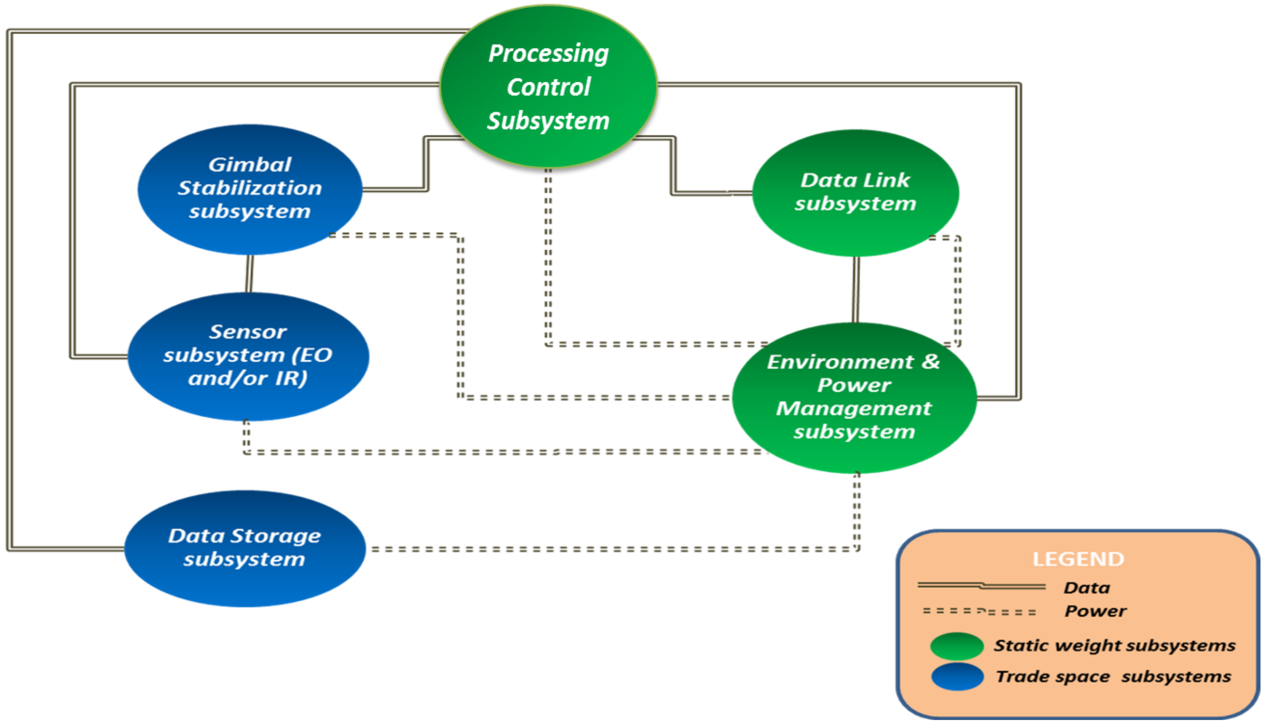


Figure 4: Conceptual System Decomposition

The sensor subsystem includes the electro-optical and/or infrared sensor arrays. These arrays can be housed within or be externally attached to the gimbal stabilization subsystem and is primarily used to capture the target data rich environment for later storage and transmission to user designated external systems.

The gimbal stabilization subsystem includes the structural gimbal that either houses or is externally attached to the sensor subsystem. The gimbal isolates most vibration and shock loads imparted by the carrier craft allowing the sensor subsystem to operate within an optimal vibration free environment.

The processing control subsystem includes the Central Processing Unit (CPU) and associated components (Motherboard, RAM, heat sinks, additional processing units, etc.). It is the heart of the WAMI conceptual system. It receives commands via the data link subsystem or tip/queuing system (external to project) and controls all the other subsystems including when to command the sensor subsystem to start its data collection as well as commanding the data storage subsystems to receive data that it has processed from the sensor subsystem. It monitors all subsystems for any failures and monitors itself with self-check subroutines. It also handles compression of data for downlink through the data link subsystem.

The data storage subsystem includes the drive cages and all hard drives that reside within them. It collects all the processed data collected from the sensor systems and stores it in Solid State Drives (SSDs) for later retrieval.

The data Link subsystem includes the all antennas and encryption gear required to handle the GPS, Uplink and Downlink of data associated with the WAMI system. Specifically it relays all commands, health status and mission queues and alerts through its encryption gear keeping communication secure.

The environment & power subsystem includes the transformer, power management unit, heaters, coolers, and all the fiber optics/cabling found within the WAMI system. It specifically handles all power, and regulates the internal operational environment by heating or cooling for optimal mission performance of all other subsystems with the WAMI system.

3.1.1.1 Conceptual Operational Scenario

Given that the WAMI system will be deployed and used operationally, a high level understanding of how the system interacted within that operational sense was required. Two scenarios were created to see how the six subsystems worked to perform basic mission operations. Figure 5 graphically shows the State of Health (SoH) Scenario. It is a sequence diagram of a routine (SoH) conducted during operation.

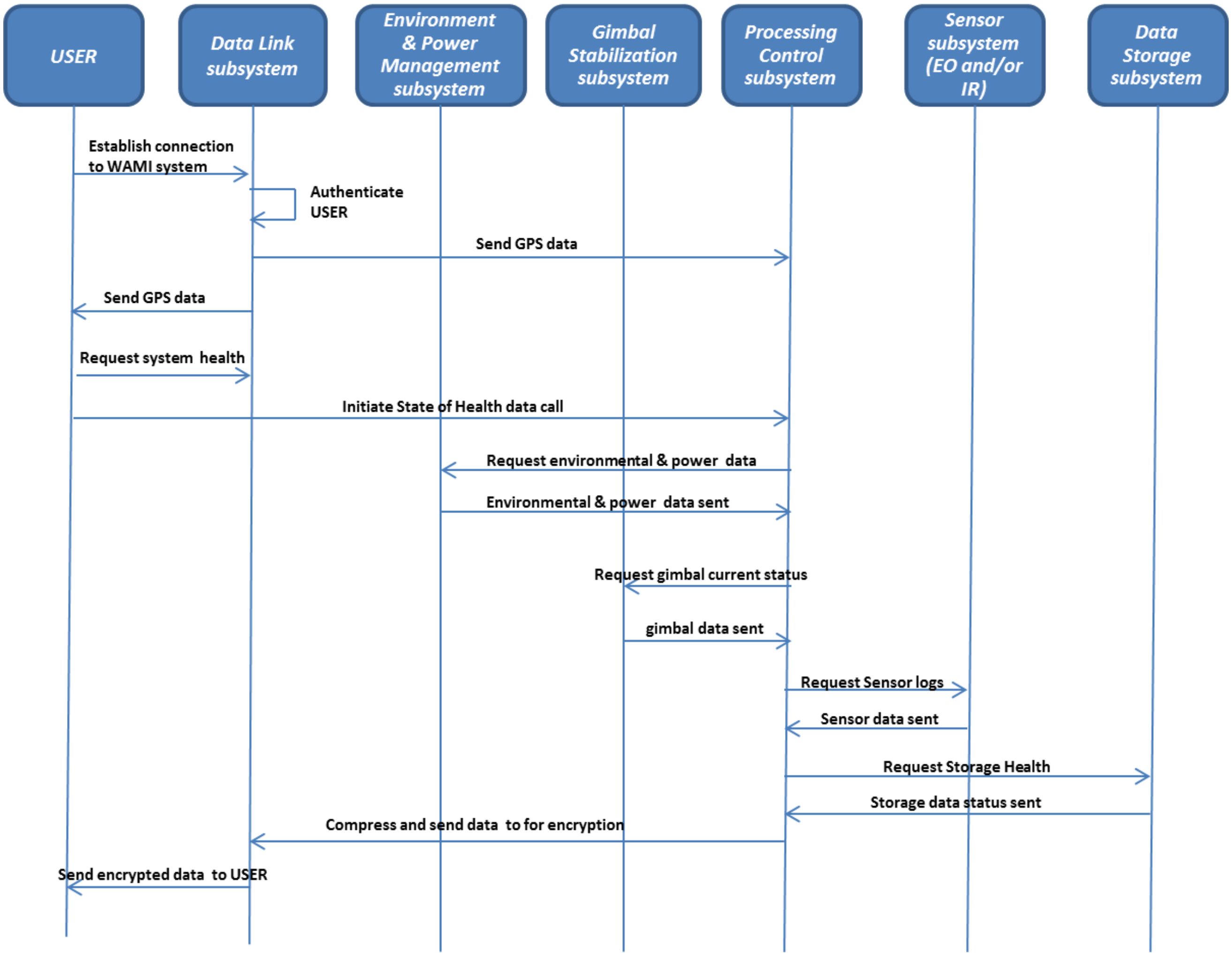


Figure 5: State of Health Scenario

Figure 6 graphically shows the User Initiated WAMI Collection Scenario. It is a sequence diagram of a User Initiated WAMI Collection conducted during operation.

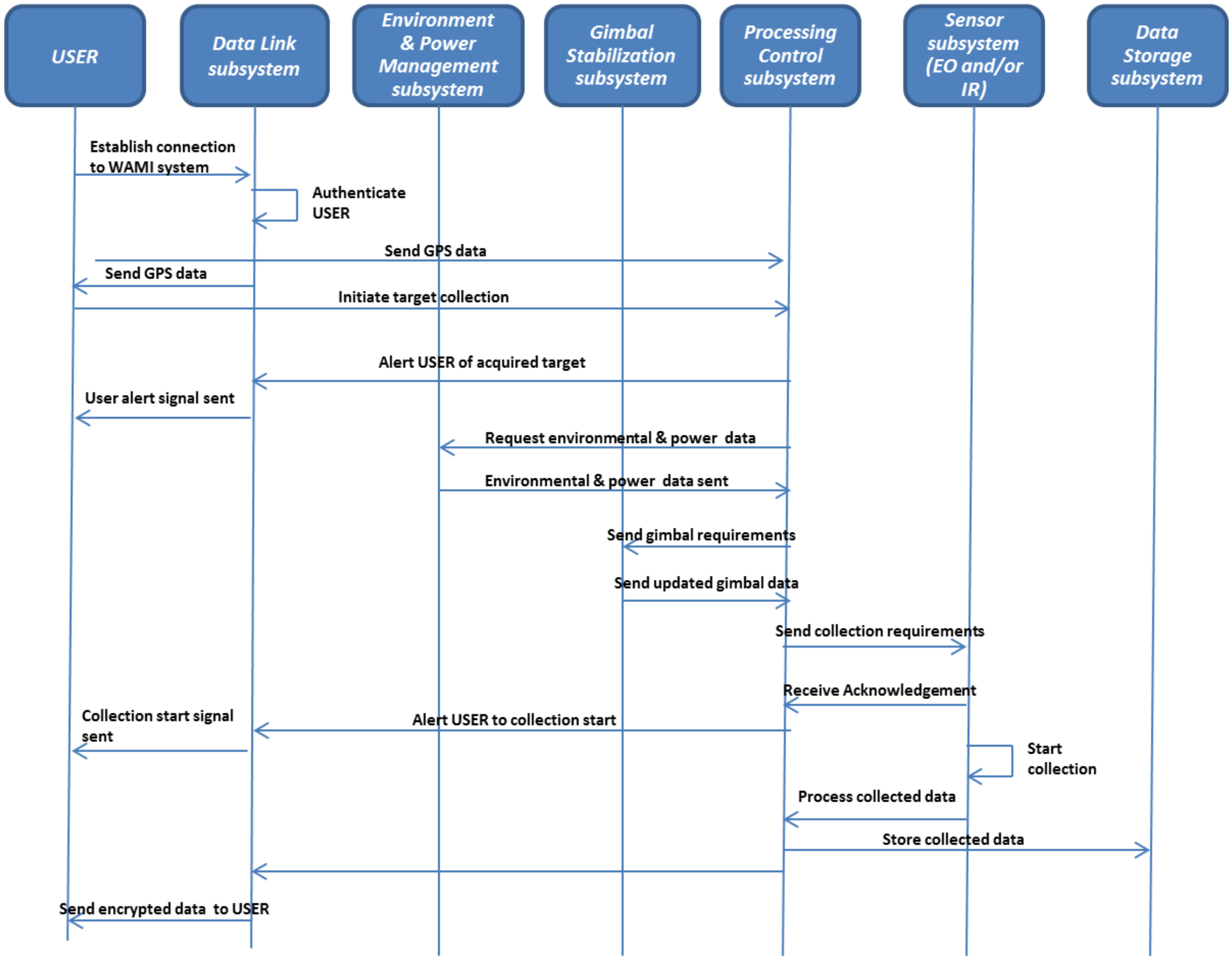


Figure 6: User Initiated WAMI Collection

3.1.2 Static Weight Driving Components

The data link subsystem weight considerations cannot be discounted as a factor in the overall WAMI design. Initial considerations of putting this subsystem into the weight-reducing arena were discussed. The pros of that consideration was that the more components added to the trade space with new technology insertions would allow for the reduction of additional weight off the overall system configuration. The con against the addition of this subsystem as a weight-reducing subsystem came from doing the initial research into the type of military communication gear that would be mandatory for this implementation. Components such as the Common Data Link (CDL) which can operate at a raw bandwidth of 274 megabits per second down-link rate and the encryption unit are standard components that have gone through the stringent military accreditation process for certified use in the field. These pieces of equipment currently would not be in the cycle for replacement in the near future. The reality of this meant that at least for the timeframe for future implementation of the project, the same certified equipment would have to be utilized. This consideration above all others brought the team to the conclusion that the data link subsystem needed to be a static weight subsystem. The data link subsystem components add a combined 40 lbs. of additional weight to the system. This particular weight was chosen based on researching current operational systems and utilizing the average weight of similar subcomponents that functionally mirror the operational objectives of this subsystem.

The environment and power management subsystem followed a similar but not exact level of reasoning for its exclusion within the weight-reducing subsystems. Unlike the other subsystems the level of maturity in the technology used for this subsystem is very high. The military as well as defense contractors have built environmental control units to include heaters and coolers (chillers) and power management units to include transformers for air platforms with a high level of success and very low failure rates. Miniaturization of those components has plateaued at least with current technology. Also because these components are considered auxiliary in nature, the overall attention and focus for new technology insertion and funding are minimal. The last facet to be considered in making this subsystem static in weight is that the gauge wiring. Industry standard shielding and fiber optic cables are static in nature and weight reduction possibilities for them are almost nil. The environment and power management subsystem components add a combined 50 lbs. of additional weight to the system. This particular weight was chosen based on researching current operational systems and utilizing the average weight of similar subcomponents that functionally mirror the operational objectives of this subsystem.

The processing control subsystem weight was regulated to a static weight subsystem because of both redundancy concerns and processing power required for this system. More specifically, even with the miniaturization of processors that in turn raises the number of transistors and processing power every 18 months (Moore’s Law) the massive amount of processing power required for processing 1.8 gigapixels worth of data is daunting. System A, which could be considered the premier current operational system, requires 425 Gbits/sec of image data for processing. This means large amounts of RAM, and large numbers of multi-core processors for massive amounts of parallel processing and a network of heat dissipating components to keep the subsystem from overheating. The other equally important reason that this subsystem is a static weight system is because the requirement for uninterrupted coverage during operation. This drives the system to have a fully functional backup processing control failover subsystem for the unlikely event of mechanical malfunction. Together the complexity and redundancy requirements drove the WAMI team to move this subsystem into the static weight subsystems category. The processing control subsystem components add a combined 110 lbs. of additional weight to the system. This particular weight was chosen based on researching current operational systems and utilizing the average weight of similar subcomponents that functionally mirror the operational objectives of this subsystem.

3.1.3 Trade-Space Weight Drivers

3.1.3.1 Gimbal

A gimbal at its most basic is a pivoted support that allows the rotation of an object about a single axis. A set of three gimbals, one mounted on the other with orthogonal pivot axes, may be used to allow an object mounted on the innermost gimbal to remain independent of the rotation of its support. For example: on a ship, the gyroscopes, shipboard compasses, stoves, and even drink holders, typically use gimbals to keep them upright with respect to the horizon despite the ship's pitching and rolling. Figure 7 below shows the basic gimbal assembly.

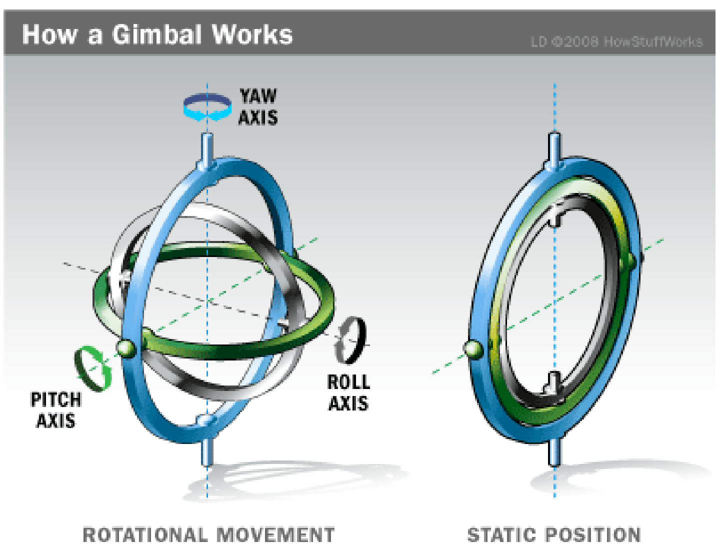


Figure 7: Basic Gimbal Assembly

3.1.3.1.1 Historic Data and Perspective Trends

Historically, the original gimbal design and use goes back to the Greek inventor Philo of Byzantium (280–220 BC).[8] [9] Philo described an eight-sided ink pot with an opening on each side, which can be turned so that while any face is on top, a pen can be dipped and inked - yet the ink never runs out through the holes of the other sides. This was done by the suspension of the inkwell at the center, which was mounted on a series of concentric metal rings which remained stationary no matter which way the pot is turned.[10]

The ancient author Athenaeus Mechanicus, who flourished during the reign of Augustus (30 BC–AD 14), described the military use of a gimbal-like mechanism, calling it "little ape" (pithêkion): When preparing to attack coastal towns from the sea-side, military engineers used to yoke merchant-ships together to take the siege machines up to the walls. But to prevent the shipborne machinery from rolling around the deck in heavy seas, Athenaeus advises that "you must fix the pithêkion on the platform attached to the merchant-ships in the middle, so that the machine stays upright in any angle."[11]

In China, the Han Dynasty (202 BC – AD 220) inventor Ding Huan created a gimbal incense burner around AD 180.[12] There is a hint in the writing of the earlier Sima Xiangru (179–117 BC) that the gimbal existed in China since the 2nd century BC.[13] There is mention during the Liang Dynasty (502–557) that gimbals were used for hinges of doors and windows, while an artisan once presented a portable warming stove to Empress Wu Zetian (r. 690–705) which employed

[8] Ernest Frank Carter: “Dictionary of Inventions and Discoveries”, 1967, p.74
[9] Hans-Christoph Seherr-Thoss, Friedrich Schmelz, Erich Aucktor: “Universal Joints and Driveshafts: Analysis, Design, Applications”, 2006, ISBN 978-3-540-30169-1, p.1
[10] Sarton, George. (1959) A History of Science: Hellenistic Science and Culture in the Last Three Centuries B.C. New York: The Norton Library, Norton & Company Inc. SBN 393005267. Page 349–350
[11] Athenaeus Mechanicus, "On Machines" ("Peri Mēchanēmatōn"), 32.1-33.3
[12] Sarton, George. (1959). A History of Science: Hellenistic Science and Culture in the Last Three Centuries B.C. New York: The Norton Library, Norton & Company Inc. SBN 393005267. Page 349–350.
[13] Needham, Joseph. (1986). *Science and Civilization in China: Volume 4, Physics and Physical Technology; Part 2, Mechanical Engineering*. Taipei: Caves Books Ltd. Page 233–234

gimbals.[14] Extant specimens of Chinese gimbals used for incense burners date to the early Tang Dynasty (618–907), and were part of the silver-smithing tradition in China.[15]

References to gimbals and devices that used them also surfaced in the 9th century recipe book called the Little Key of Painting Mappae clavicula.[16] The French inventor Villard de Honnecourt depicts a set of gimbals in his famous sketchbook. In the early modern period, dry compasses were suspended in gimbals.

But this is ancient history and only serves to point out that the use of gimbals have been around for millennia. Today, gimbals are used in many applications to include ground systems, marine systems airborne systems and even space systems where stabilization and/or steering are required.

Current WAMI Sensor technology requires gimbals mounted in or on airborne platforms. Figure 8 below is an example of a gimbal and payload assemblies mated.

Figure 8: Gimbal

The types of gimbals primarily used for airborne platform stabilization and steering are two - six axis gimbals. They can also be placed in an internally pressurized environment or an external environment. These specific types of gimbals will be considered at length within this paper for consideration in weight reduction.

[14] Needham, Joseph. (1986). *Science and Civilization in China: Volume 4, Physics and Physical Technology; Part 2, Mechanical Engineering*. Taipei: Caves Books Ltd. Page 229 & 231.
[15] Needham, Joseph. (1986). *Science and Civilization in China: Volume 4, Physics and Physical Technology; Part 2, Mechanical Engineering*. Taipei: Caves Books Ltd. Page 234–235.
[16] Needham, Joseph. (1986). *Science and Civilization in China: Volume 4, Physics and Physical Technology; Part 2, Mechanical Engineering*. Taipei: Caves Books Ltd. Page 229 & 231

3.1.3.1.2 Weight Saving Opportunities

Gimbal weight considerations come into play in both the implementation of the gimbal (internal or external) and how the gimbal is designed to interact with the payload. This is because weight and the center of gravity relative to the axis of rotation are key components in payload inertia. Also in steering gimbals, the distribution of weight will create a moment about the axis that can increase or decrease the torque required to accelerate and decelerate the payload. This affects the weight of the gimbal if an increase or decrease in weight and performance characteristics in the gimbal is warranted to meet mission slew rate requirements.

Gimbals operating in internal pressurized aircraft or externally but pressurized within pods are kept in a relatively benign environment. The environment being internal to the crafts or physically anchored onto the airborne craft within a pod, has to only compensate for vibrations and shock loads. Also required would be software used for tracking the intended target but that software is out of scope of this project.

Gimbals made to operate in the external unpressurized environment will have additional factors that it must take into account in order to operate optimally and meet its mission objectives. These factors are temperature, air pressure, and wind loads. These factors affect the design of the gimbal effecting weight because they affect the thermal, heat transfer, structural and electrical design aspects of the gimbal.

Gimbals found on various types of aircraft including UAVs must meet all aviation standards which also will affect weight.

3.1.3.2 Sensors EO and IR

The two types of sensors that are used on WAMI systems are EO and IR. EO sensors are operational only during the day, responding to wavelengths of the visible spectrum from about 0.4 to 0.76 μm.[17] These are wavelengths that are visible to the human eye. IR sensors are typically used for solely night operations. They extend from approximately 0.76 to 1000 μm and are divided into multiple divisions. The areas where WAMI technology focuses is Short Wave Infrared (SWIR) 1.4 – 3 μm, Medium Wave Infrared (MWIR) 3 – 8 μm, and Long Wave

[17] http://www.fas.org/man/dod-101/navy/docs/fun/part10.htm

Infrared (LWIR) 8 – 15 μm[18]. The IR system, in general, weighs more than the EO system because it requires cooling systems and vacuums to keep at an operational temperature. This is because the "energy received by the detector must be at a level higher than the thermal noise generated by the detector circuitry."[19] Some WAMI systems in the field have only EO capability while others have both EO and IR.

3.1.3.2.1 Historic Data and Perspective Trends

Of the current WAMI systems that we researched, the EO and IR sensors weigh, on average, between 100 and 200 lbs each resulting in a total weight of 200-400 lbs for just sensors assuming both day and night capability. Some systems do not have the night vision capability and therefore do not have the weight of the IR sensor.

Much like iPods, iPhones, and computers continue to get smaller, better, faster each year, cameras have similarly followed that same trend. As technology improves, the quality and size of the camera has also become better and smaller. This is not necessarily due to smaller transistors or chips, but because the size of pixels is shrinking and the number of pixels capable of fitting within a given focal length is increasing. As the pixel size shrinks, more pixels able to fit on the same focal length lens, increasing resolution and picture quality. This also decreases the size of the camera as a smaller focal plane is required to obtain the same resolution. Figure 9 below shows the historical data and potential trend of pixel sizes over the years. This data includes pixel sizes of over 130 cameras by Sony, Canon, Kodak, Samsung, Panasonic, Philips, Sharp, Nikon and others for the visible wavelength. The commercial industry reached 1.4μm in 2011, 1.1μm in 2012 and is expecting to reach 0.9μm in 2013. [20] [21]

[18] Byrnes, James (2009). *Unexploded Ordnance Detection and Mitigation*. Springer. pp. 21–22
[19] http://www.fas.org/man/dod-101/navy/docs/fun/part10.htm
[20] http://www.gizmag.com/omnivision-slim-bsi-cmos-camera-sensor/19472/
[21] http://image-sensors-world.blogspot.com/2011/07/tsmc-reveals-its-11um-and-09um-pixel.html

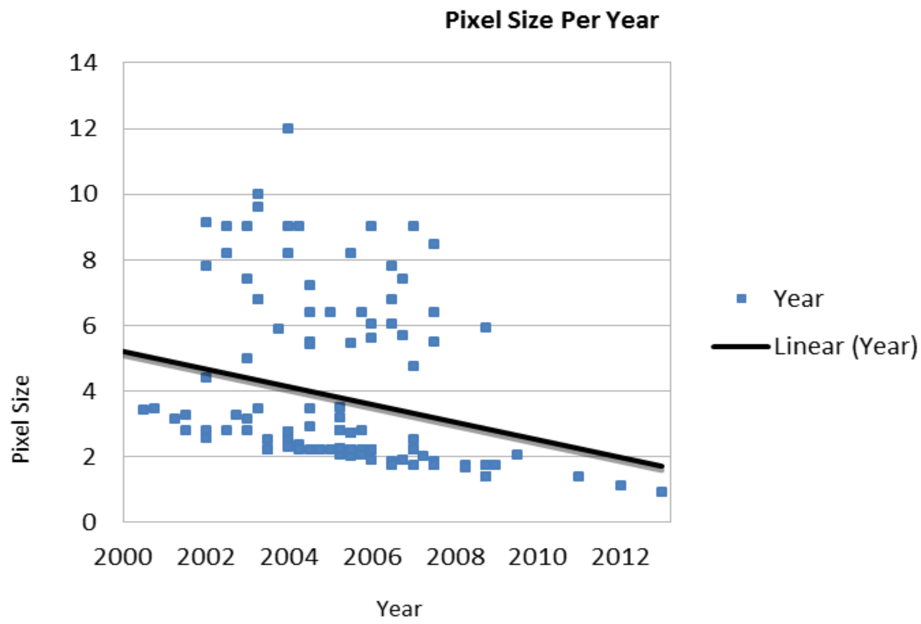


Figure 9: Pixel Size Trend[22]

WAMI sensors fielded today were developed between 2006 and 2010 so the pixel width for the sensors is much larger than the pixel width achievable today.

3.1.3.2.2 Weight Saving Opportunities

As technology improves, sensors will continue to shrink while still maintaining an operational GSD. Unfortunately, this is tied to advancing technology. It is expected in 2013 a pixel width of 0.9 μm will be obtainable and the size will only continue to decrease.[23] As discussed above, a smaller pixel width will result in a smaller focal length and focal plane for the same resolution. We can assume per discussions with industry, that if the pixel width decreases by 50 percent, the focal length and focal plane will also decrease by 50 percent and the weight of the sensor has the potential to decrease up to 40 percent depending on the engineering design. Additionally, we also know that the weight reduction with reduced pixel size is more significant with the infrared spectrum than the visible spectrum because the weight associated with the IR vacuum and cooler systems. As the pixel size goes down, the volume of the vacuum that has to be cooled to cryogenic-temperatures and the cooler size roughly scales with the pixel width. However, even

[22]http://www.bing.com/images/search?q=camera+pixel+size+by+year&view=detail&id=8A3E67C4FF039190FA7BD73A7C3CF00901450D8A
[23] http://image-sensors-world.blogspot.com/2011/07/tsmc-reveals-its-11um-and-09um-pixel.html

with shrinking pixel sizes, there are still some aspects of the sensor that will not be able to reduce in size such as the diameter of the optics. The optics of the sensor still remains constant because the same aperture size is still required to collect the same amount of signal to achieve the same signal-to-noise ratio (SNR) and obtain the same angular diffraction to achieve the same spatial resolution. Therefore, as some things are reducing in size due to pixel width shrinkage, there are still some aspects of the sensor that are not changing and we can only assume up to 40% weight reduction of the camera weight with 50% reduction in pixel width. This assumption was confirmed by undisclosed industry Subject Matter Experts.

For our analysis, we are going to conservatively use 30% weight reduction for the EO sensor and 40% weight reduction for the IR sensor for a 50% reduction in pixel width. This is because, as discussed above, a higher weight reduction of the IR sensor can be expected with the reduction in pixel width.

3.1.3.3 Storage

Computer data storage has steadily increased since the first commercial computers in the 1950's. For the past 30 years, the storage capacity per unit cost has nearly doubled approximately every two years.[24] This growth rate was first classified by Gordon E. Moore in 1965, and later became known as Moore's Law. While Moore's Law describes the growth rate in the number of transistors on integrated circuits, similar trends have surfaced for other related computer hardware measures, like processing speed and the number and size of pixels in digital cameras.[25] Like these items, storage capacity per unit cost is expected to see simlar growth rates in the future.[26] Historically, storage for WAMI systems has been procured as commercial off-the-shelf (COTS) items. Since this will likely be the case for future implementations, Moore's Law is applicable for projecting the future cost and availability of storage components.

3.1.3.3.1 Historic Data and Perspective Trends

The figure below depicts the maximum storage capacity per unit cost for all storage devices since 1955. Widespread flooding in Taiwan disrupted this trend however, in October, 2011. As

[24] http://www.mkomo.com/cost-per-gigabyte
[25] http://glassvisage.hubpages.com/hub/Moores-Law
[26] http://www.futuretimeline.net/subject/computers-internet.htm#data-storage

the second largest maker of hard drive disk (HDD) components, 80% of all HDDs sold in the world depend on parts from Taiwan. As a result, flooding caused a shortage in HDDs that in turn forced HDD prices to climb. This disruption is better illustrated in Figure 10. While industry has recovered from the flood, prices for HDDs still remain larger than pre-flood pricing and have not yet recovered to the level as predicted by Moore's Law.

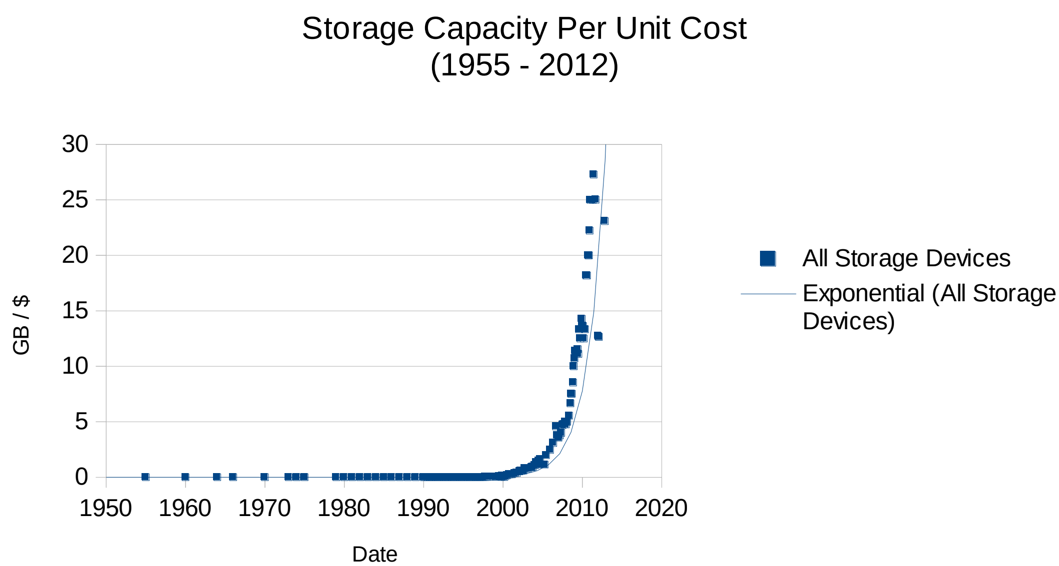


Figure 10: Storage Capacity Per Unit Cost (1955-2012) (All)

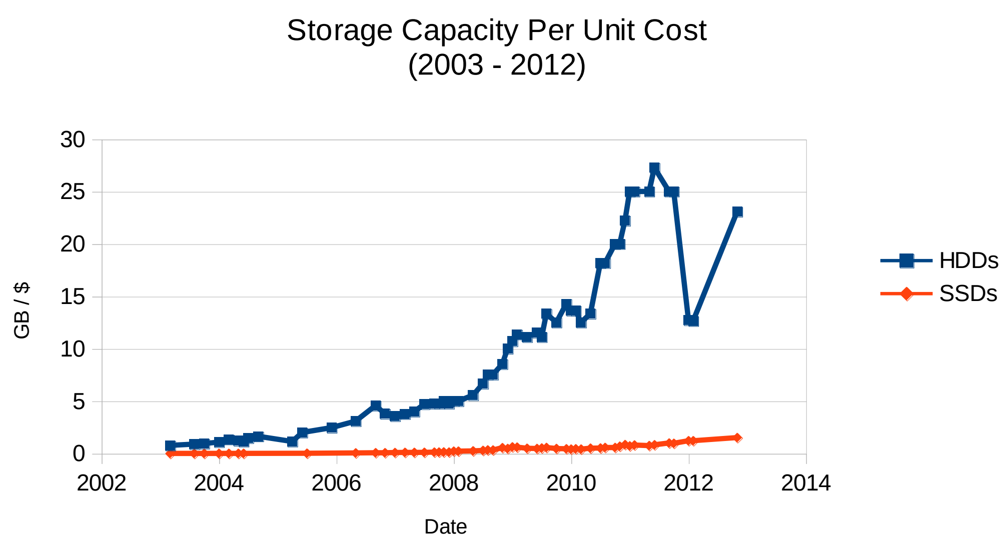


Figure 11: HDD/SSD Storage (2003-2012)[27]

While Moore's Law is useful in predicting the general cost of future storage, it does not help in determing the means by which such storage is delivered. For example, since the 1950's, a plethora of new technologies and storage media have contributed to exponential growth. Assuming similar innovations will continue to increase the capacity per unit cost of computer data storage, Moore's Law will likely hold for the cost of data storage in the future.[28] A closer look into the contributing storage media is needed in order to predict how to implement a future solution that delivers the best value within budget.

The differences in types of storage media are many. Solid state drives (SSDs) are known to deliver superior performance and are substantially smaller and lighter in weight, as indicated in Table 2. These have historically been much higher in cost as well. Due to increases in technology and a nudge from the floods in Taiwan (note above that SSDs were not affected), SSDs are catching up to HDDs much faster than originally anticipated, with respect to storage capacity per unit cost. The figures above are misleading to this trend, however. The maximum storage capacity per unit cost has typically been delivered through "bulk storage" media, for which HDDs will likely remain superior in the foreseeable future. Yet in plotting the historical data for both HDDs and SSDs by class (e.g. 120 GB, 250 GB, 500 GB), we can see that for drives with smaller capacities, SSDs could surpass HDDs in capacity per unit storage within the next few years.

	HDD	SSD
Weight	1.7 lb.	0.17 lb.
Cost	Class dependent	Class dependent
Reliability	Moving parts susceptible to shock/damage	Non-mechanical design (shock-resistant), generate significantly less heat

[27] http://www.jcmit.com/index.htm
[28] http://www.futuretimeline.net/subject/computers-internet.htm

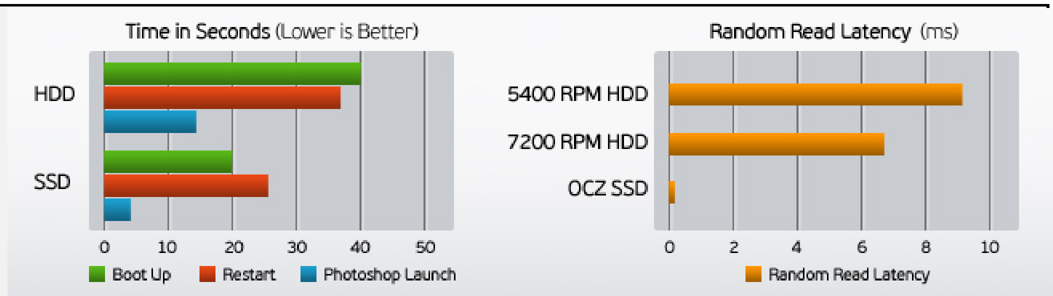
Performance	

Table 2: HDD/SSD Specs[29]

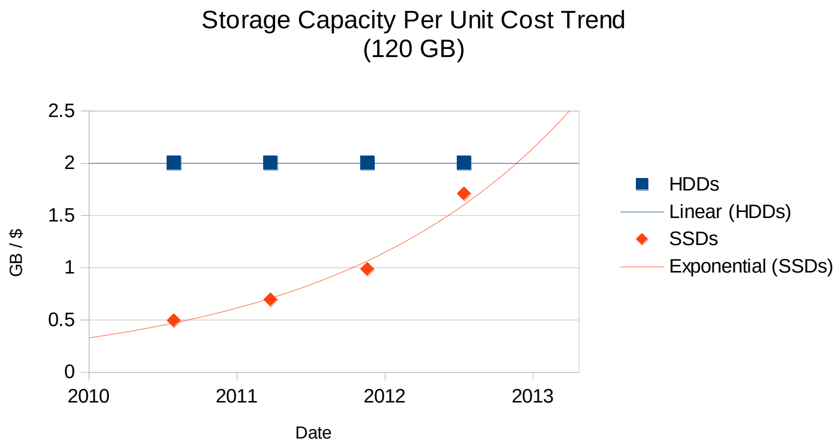


Figure 12: Storage Capacity Per Unit Cost Trend (120 GB)

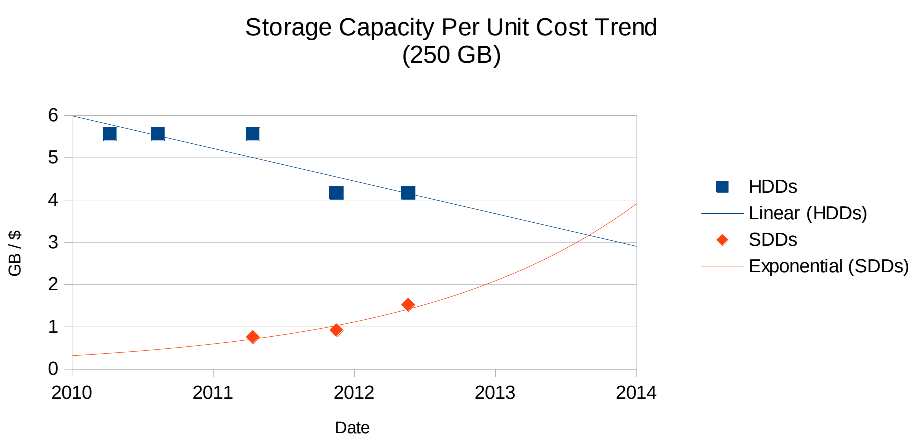


Figure 13: Storage Capacity Per Unit Cost Trend (250 GB)

[29] http://www.ocztechnology.com/ssdzone/ssd-vs-hdd-comparison.html

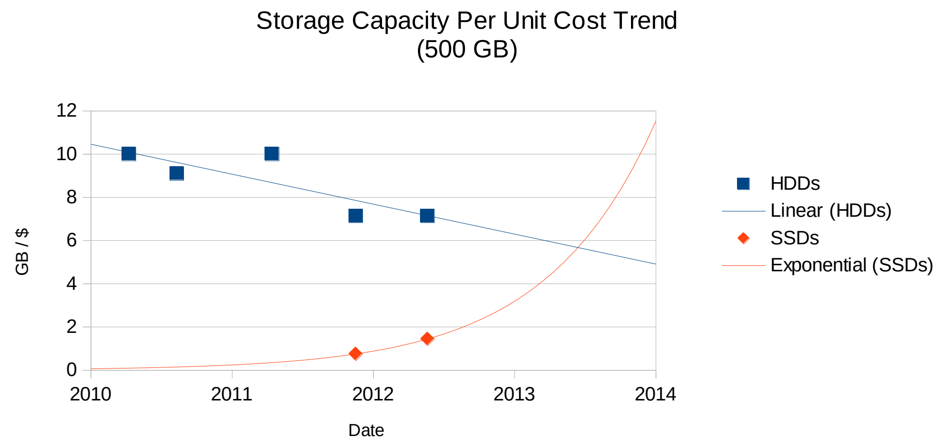


Figure 14: Storage Capacity Per Unit Cost Trend (500 GB)

As the storage capacity per unit cost for higher capacity SSDs approaches a value equal to that of HDDs, it's assumed that HDD manufacturers/retailers will anticipate the upcoming transition and make reductions in supply. This will hinder further exponential growth for that particular class of HDD. For this reason, trend lines for HDDs in the figures above were chosen to be linear. Also, note that cost data for each class of hard drive prior to 2010 is limited. Therefore, the plots above only depict the short term trend, not the trend in the long term. As a result, it's possible that HDDs could have zero, or slightly positive slope for the given time period in the figures above. That being the case, SSDs would not surpass HDDs in capacity per unit cost for a slightly longer period of time. Since SSDs have also progressed according to Moore's Law[30], an exponential trend line has been chosen to fit the SSD data above.

The relationship between growth rates for HDDs and SSDs can also be modeled using S-Curves, which also gives insight into when SSDs could surpass HDDs in capacity per unit cost for each capacity level. Also known as the logistic function or logistic curves, S-Curves model growth behavior of some population where initial growth is exponential, but gradually the growth rate diminishes. When the population being modeled is a technology or innovation, as with storage capacity, new technologies emerge that allow for further improvement and render old technologies obsolete. Therefore, while storage capacity per unit cost continues to grow

[30] http://www.deloitte.com/assets/Dcom-Global/Local%20Assets/Documents/TMT/Predictions%202012%20PDFs/16470A%20Hard%20time%20lb2.pdf

exponentially by Moore's Law, different technologies will and have emerged, each with its own S-Curve, to fuel the overall growth rate of storage capacity per unit cost.

Such is the case with HDDs and SSDs, as shown for each particular class in Figure 15. Historical data suggests that due to the 2011 floods in Taiwan, the S-Curve for HDD storage has been pushed to the right. As indicated earlier, SSDs were not affected, and this lateral shift narrowed the price premium between the two.[5] We also see each class of HDD storage device phasing out as capacity per unit cost for SSDs surpasses them, which has been modeled using the historical data provided above. While it's difficult to predict the intersections for HDD/SSD devices with larger storage capacities (i.e. the Innovator's Dilemma), it's believed that the widespread transition from larger capacity HDDs to SSDs could happen within the next 10 years.[31]

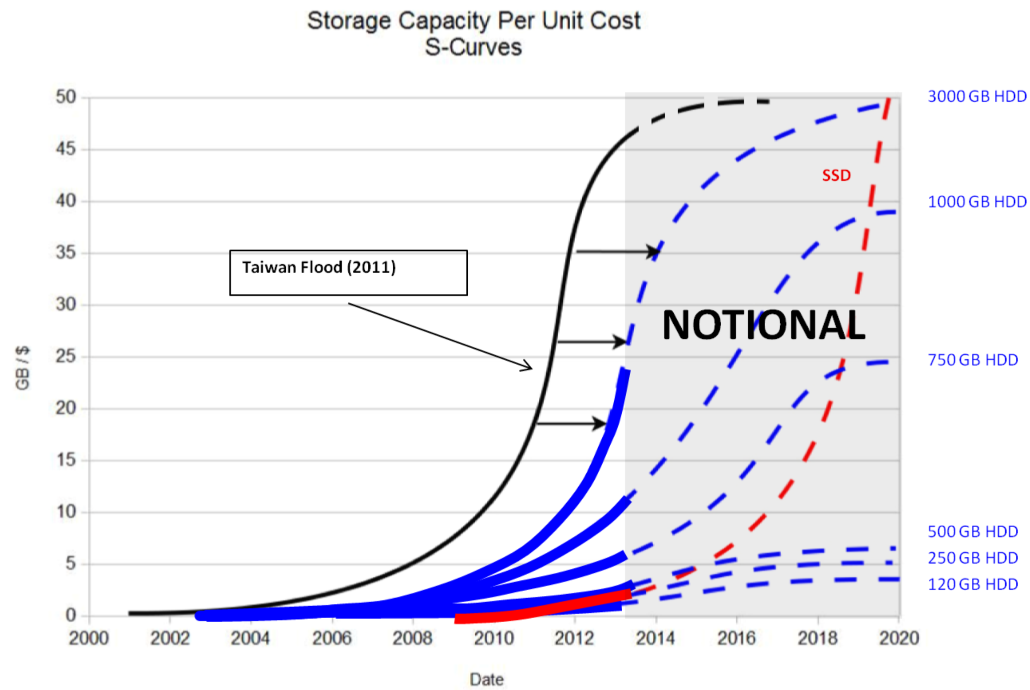


Figure 15: Storage Capacity Per Unit Cost S-Curves

3.1.3.3.2 Weight Saving Opportunities

[31] http://www.tomshardware.com/reviews/ssd-reliability-failure-rate,2923.html

Based on these perspective trends, SSDs are a viable alternative to HDDs in the foreseeable future. It's clear from Table 2 that the weight differential between the two (1.7 lb for HDD and 0.17 lb for SSD) is significant, especially when dealing with large storage capacities needed to fulfill the WAMI missions. Since storage capacity for the WAMI sensor is calculated based on the quantity and quality of the data being captured, it is difficult to predict how much impact storage weight will have on the aggregate system weight without first determining the performance of the other components.

For each alternative, the needed storage will be determined, as will the number and type of HDDs or SSDs to use. The costs associated with each can be estimated. SSDs, however, will deliver measurable reductions in weight, increased reliability, and significant performance benefits that could have a great impact on the overall system.

3.1.3.4 Pod

Some of the existing system use pods to enclose the system outside the aircraft. These pods can weigh upwards of 150lbs in some cases. However, the use of the gimbal as the stabilization unit for the sensor is rugged enough to enclose the sensor without any additional protection. The remaining components such as storage, processor, and data link, can be fitted inside the belly of the aircraft without having the bear the additional weight of the pod. For this reason, the pod as an alternative has been eliminated as part of our analysis.

3.1.4 Requirements

Requirements for the WAMI system are as follows:

- The system shall be less than 500lbs.
- The sensor subsystem alternatives shall be able to detect dismounts at an operational altitude of 20,000 ft.
- The gimbal subsystem alternatives shall support a total sensor weight less than or equal to its own weight.
- The storage subsystem alternatives shall include HDD and SSD media that are readily available in the current market
- The storage subsystem alternatives shall include HDD and SSD media that are projected to be readily available in the 2013/2014 market

- The storage subsystem alternatives should include HDD and SSD media that are projected to have an acceptable impact on the total system cost.

3.1.5 Feasible Alternatives

The choice of gimbal alternatives came down to the sizing associated with the gimbals themselves. From a performance perspective, sensor platforms integrated into the gimbal assembly itself reduces the overall size of both subsystems as well as maximizes the gimbals ability to isolate vibration and shock loads. This configuration also allows for more optimal steering of the sensor(s). The WAMI team factored in that the sensor subsystems will be reduced in size due to optimization and pixel width shrinkage. With this information, it was determined that the maximum size used in this analysis for the gimbal (26 inches) should be based on the average (estimated) sizing that is currently being fielded by operational systems such as System A, System B, and System D. This evaluation was also based on the understanding that the future gimbal subsystems would not be larger but smaller as compared to today's gimbal subsystems. Those gimbal sizes range from 26 inches at the maximum with alternatives at 25 inches, 23 inches and 18 inches. These four alternatives we will use for our analysis. To identify a weight associated with each of these alternatives, we looked at historic data for various sized gimbals. This data was provided to us by an industry Subject Matter Expert. As seen in Figure 16 below, there is a linear relationship and if we continue this line, we can come up with an educated estimate of the expected weight for each of the gimbal alternatives.

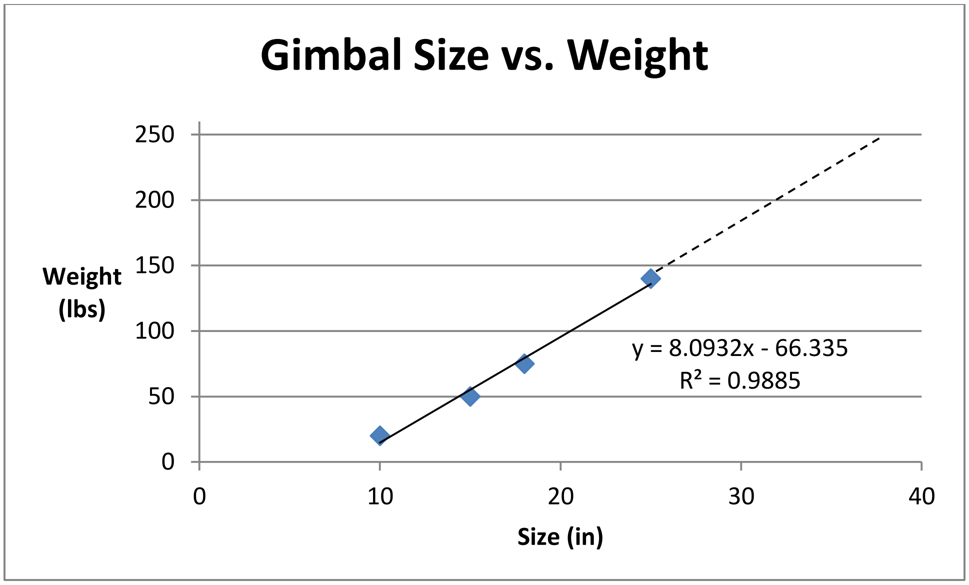


Figure 16: Gimbal Size vs. Weight

Our gimbal alternatives and their associated weights are identified below in Table 3.

Gimbal Size (in)	Gimbal Weight (lbs)
26	144
25	135
23	120
21	103
18	79

Table 3: Gimbal Alternatives and Associated Weights

To come up with the best sensor alternatives to include in our analysis, we used an existing system as our baseline. This system has a pixel with of 2.2µm and weighs 100lbs, both EO and IR. Assuming a pixel width reduction to 1.32µm (40%), 1.1µm (50%) and 0.9µm (60%) we would get the weights identified in Table 4 using the resulting 40% weight reduction in IR and 30% weight reduction in EO as discussed in section 3.1.3.2.2.

Pixel Width Size (µm)	Percent Pixel Reduction (%)	EO Weight Reduction (lbs)	EO Alternative Weight (lbs)	IR Weight Reduction (lbs)	IR Alternative Weight (lbs)
1.32	40	24	76	32	68

1.1	50	30	70	40	60
0.9	60	36	64	48	52

Table 4: EO and IR Pixel Width Reduction Impact on Sensor Weight

Additionally, for our analysis, we want to have the option of no EO or IR sensor included in the system. Therefore, the following alternatives for sensors are listed in Table 5 below.

EO Sensor Alternatives	IR Sensor Alternatives
0	0
1.32	1.32
1.1	1.1
0.9	0.9

Table 5: EO and IR Alternatives

The storage alternatives were chosen based on the perspective trends identified in section 3.1.3.3.1 and the estimated timeline for when the proposed system would be designed/developed. Existing and future technologies (foreseeable) were both considered. As such, the 3000 GB HDD and 500 GB SSD were chosen based on their projected high availability and low impact on cost in the 2013/2014 market. While neither a 6000 GB HDD or 750 SSD are available today, the two were considered as future technologies that would likely be available with an acceptable impact on cost. These alternatives are summarized in Table 6 below.

HDD	SSD
3000 GB	500 GB
6000 GB	750 GB

Table 6: Storage Alternatives (HDD & SSD)

These alternatives for weight-reducing components yield a total of 320 different combinations of viable WAMI alternatives. Note that many of these alternatives will be eliminated for a variety of reasons, which is described in the next section.

3.2 Performance Analysis

The conceptual design phase involved decomposing the system to identify and examine the many options of reducing aggregate system weight. The performance analysis phase allocates various performance requirements to the 320 reconstructed alternatives, which include GSD, FoV, Mission Duration, and Frame Rate, respectively. Performance measures were derived from the expected operating environment and systems that have been fielded or are currently in development. Using this data, the storage requirements for each alternative have been calculated, with the associated storage weight. Coupled with the weights of the other components, a total system weight has been calculated for each alternative, and those alternatives that do not meet the 300 lb threshold were eliminated. Note that, while our weight threshold was 500 lbs, we determined that 200 lbs were static, as discussed in section 3.1.2.

3.2.1 Current System Performance Measures

Performance measures were derived from the specifications of WAMI systems that have been fielded in the past, in particular Systems A, B, C, and D (which are also described in section 2.1.2). A summary of their performance is displayed in Table 7 below. Note that not all data points were available. Additionally, because of the proprietary nature of this information, some of the values in this table have been estimated or derived from data that has been made available. All estimations, including those done for threshold and objective values, were determined from Subject Matter Expert (SME) input, historic data, and/or perspective trends.

	Typical Mission Duration (hr)	EO FoV (km)	IR FoV (km)	EO Avg GSD (pixel,m)	IR Avg GSD (pixel,m)	EO Frame Rate (fps)	IR Frame Rate (fps)	Total Camera Resolution (MP)	Cost/ unit (mil)	EO Sensor Weight (lbs)	IR Sensor Weight (lbs)	Total Weight (lbs)
System A	13	7.2	7.2	0.15	0.7	15		1840		100	100	1500
System B		2.5	4	0.25	0.7	1.2	1	66	15			300
System C			N/A	0.7	N/A	2	N/A	96	15	200	N/A	800
System D	13	4	3.75	0.5	0.75	2	2	80 (32 IR)	15	200	200	1100
System D (upgraded)	13	8	8	0.25	0.65	2	2	1840 (32 IR)		150	200	1500
Threshold	12	4	4			2	1					
Objective	96	10	10	0.2	0.7	8	4					500

Table 7: Fielded WAMI System Specifications

The performance measures in the table above are related per the following equations:

$$(1)\ Focal\ Length\ = \left(\frac{PixelWidth}{Ground\ Sample\ Distance}\right) * Range$$

$$(2)\ Sensor\ Length = 2 * Focal\ Length * \tan\left(\frac{1}{2} Angle\ of\ View\right)$$

$$(3)\ Resolution = \left(\frac{SensorLength}{PixelWidth}\right)^2 \quad \text{or} \quad Resolution = \left(\frac{FoV}{GSD}\right)^2$$

$$(4)\ Storage\ Capacity = \frac{10\ bits}{pixel} * Resolution * Frame\ Rate * Mission\ Duration$$

Range is defined as the operational altitude (a constant of 20,000 ft). Focal length, FoV, Angle of View (AoV), and sensor size are depicted in Figure 17 below.

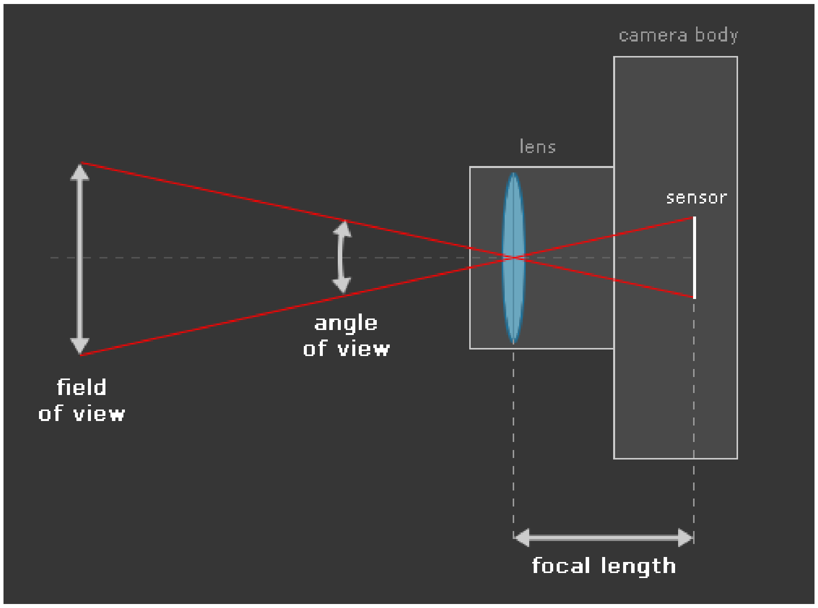


Figure 17: Camera dimensions[32]

3.2.2 Performance Measures for Each Alternative (i.e. "Good Enough")

Using the values form the table above, the following were derived as a practical set of performance measures. These measures represent our boundary for performance that is "good enough". For our trade-off analysis, the measures shown in red below indicate performance that is most desirable.

EO GSD (m/pixel)	IR GSD (m/pixel)	EO FoV (km)	IR FoV (km)	Mission Duration (hr)	EO Frame Rate (frames/sec)	IR Frame Rate (frames/sec)
0.2	0.7	6	6	12	2	1
0.15	0.65	8	8	24	5	2
0.1	**0.6**	**10**	**10**	48	**8**	**4**
				72		
				96		

Table 8: Performance Requirements

Calculating the many combinations of performance requirements resulted in 3,645 different variations. Taking the 320 different combinations of weight-reducing components, and combining these with the 3,645 performance variations resulted in 1,166,400 different

[32] http://martybugs.net/blog/blog.cgi/learning/Field-Of-View-And-More.html

alternatives. However, this value is misleading as many alternatives were eliminated for reasons as follows:

- 933,418 alternatives were eliminated on the basis of sensor-gimbal pairing. Selection of an appropriate gimbal is dependent on the weight of the sensor—the heavier the sensor, the heavier the gimbal needed to stabilize and maneuver it. As a result, sensors were paired with gimbals of equal weight, and all combinations with unequal pairings were removed.
- 207,256 alternatives were later removed on the basis of weight. These eliminations were a direct result of excessive weight due to large storage requirements. A summary of the alternatives removed for weight is provided in Figure 18. Note that the majority of these eliminations are for alternatives that capture EO images in higher resolutions.
- 72,900 alternatives included only a single camera (or no camera at all). After conducting the trade-off analysis, these were discarded based on customer feedback and the notion that night operations alone do not deliver enough value to justify eliminating the EO camera.

Note that in many instances, a single alternative fit two or three of the criteria described above. Consequently, a total of 111,389 viable alternatives were left after elimination.

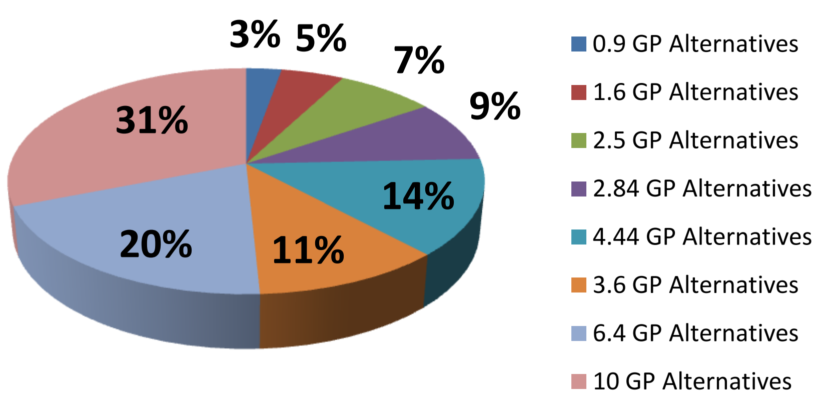


Figure 18: Alternatives Eliminated by Weight (EO Resolution)

The process used to determine the aggregate system weight of each alternative is described below.

3.2.3 Aggregate System Weight

Using the above performance measures and equations defined in section 3.2.1, we were able to calculate the image resolution and storage requirements for each alternative. A summary of these calculations is provided in Appendix A. Since storage capacity is proportional to the quality and quantity of images being collected, the sensor performance of each alternative was needed first.

3.2.3.1 Sensor Performance

For the sensor, we used equations 1, 3, 4, and 5 and the selection of threshold and objective GSDs (0.2 m/pixel, 0.15 m/pixel, and 0.1 m/pixel for the EO sensor and 0.7 m/pixel, 0.65 m/pixel, and 0.6 m/pixel for the IR sensor) and FOV (6 km diameter, 8 km diameter, and 10 km diameter). This enabled us to find the various focal lengths. We were then able to come up with the required camera resolution. Table 9 below shows a sample of the alternative performance data for the sensors. Appendix A includes the spreadsheets used for calculating resolution, with equations included.

Pixel width (microns)	Range (inches)	GSD (m/pixel)	Focal Length (in)	FoV (km)	Sensor Length (inches)	Camera Resolution (GP)
1.32	240,000	0.2	1.584	6	1.55905596	0.90000097
1.1	240,000	0.2	1.32	6	1.2992133	0.90000097
0.9	240,000	0.2	1.08	6	1.0629927	0.90000097

Table 9: Excerpt from Appendix A – Image Resolution.xlsx

To meet the same performance requirements, sensors with different pixel widths must be designed differently. For example, to capture images from 20,000 ft with a FoV of 6 km and a GSD of 0.2 meters/pixel, the above sensor lengths are required for various pixel widths. We can see that, while the resulting camera resolution is the same for all three alternatives, the camera with a pixel width of 0.9 microns has a smaller focal length and requires a smaller sensor. Subsequently, the camera weighs less.

3.2.3.2 Storage Capacity

Similarly, with the image resolution of each alternative, storage requirements can be calculated for each alternative with greater precision. Storage capacity is proportional to the quality and quantity of the images being stored. As a result, storage is a function of image resolution, mission duration, and frame rate. These calculations are quite simple using equation (4) above, with the necessary conversion factors (e.g. bits to bytes, seconds to hours). A key assumption in our calculations was that, for each mission, only 2% of that mission's data is actually being stored. This assumption is based a combination of the "smart processing" capability, as described in Section 2.1.1, and data compression.

Based on each alternative's storage capacity, a storage weight was calculated based on the size and type of storage media being used. This weight was added to the weights of each alternative's other components (gimbal, EO/IR sensors) to determine the total system weight. As summarized above, 207,256 alternatives were eliminated due to excessive weight.

3.3 Trade-Off Analysis

With the performance and total system weight of each viable alternative known, a trade off analysis was performed to determine which solutions, and which characteristics of the solutions, deliver the greatest value to our stakeholder with respect to Performance and Suitability.

3.3.1 Value Hierarchy

The Value Hierarchy for the WAMI system is shown in Figure 19 below. Note that storage capacity has been intentionally left out of the performance category--this was calculated from the performance measures (FoV, GSD, Mission Duration, and Frame Rate). As discussed, storage capacity directly influences the aggregate system weight of each alternative.

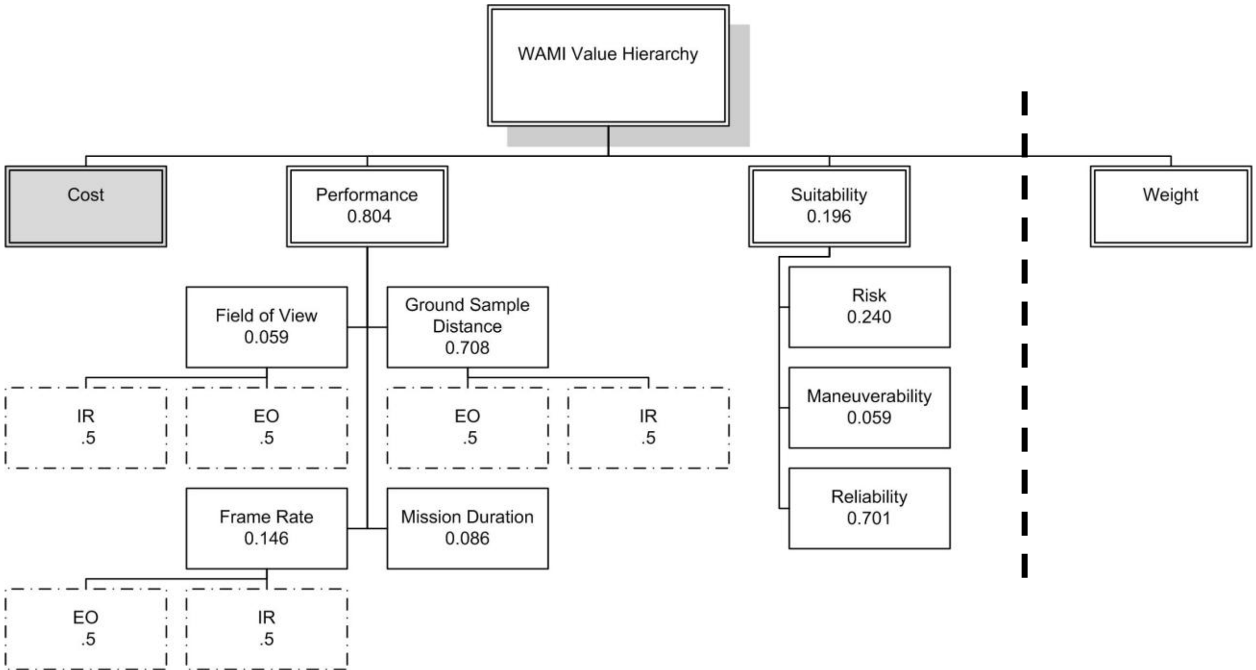


Figure 19: Value Hierarchy

The Stakeholder Weights were calculated using the Expert Choice software. This software was chosen for many reasons, including its pairwise comparison function, ease of use, and various user interface options. While many methods exist for extracting stakeholder weights, pairwise comparison was determined to be satisfactory for the purposes of this project, providing a consistent, mathematical approach to capture judgments and transform them into quantitative measurements. Using an interval scale, pairwise comparison measures the value of a single attribute relative to another attribute. An interval scale is favored as it distinguishes the distance between the stakeholder utility for each attribute. This is particularly important for deriving the values used in the utility functions, provided below. While it's argued that pairwise comparison can be time consuming[33] (for N criteria there are (N-1) + (N-2) +…1 comparisons that need to be made), the WAMI value hierarchy illustrates that we did not have many attributes to compare, thus this was not a concern. Also, weights were extracted from only a single stakeholder, therefore methods such as ranking, which could be more advantageous when simultaneously extracting weights from multiple individuals or a group, were not desired.

[33] http://www.robustdecisions.com/making-robust-decisions/2008/09/why-pairwise-comparisons-are-waste-of.php

Using Expert Choice, a set of pairwise comparisons were performed with our sponsor to calculate the stakeholder weights identified in the above Value Hierarchy and the utility functions below. In answering a series of questions regarding independence, we determined from our sponsor that the attributes above were additively separable and met all of the necessary conditions for the additive utility function.

$$U_{WAMI} = 0.804_{Performance} + 0.196U_{Suitability}$$

$$U_{Performance} = 0.059_{FoV} + 0.708_{GSD} + 0.086_{Mission\ Duration} + 0.146_{Frame\ Rate}$$

$$U_{Suitability} = 0.24_{Risk} + 0.059_{Maneuverability} + 0.701_{Reliability}$$

$$U_{FoV} = 0.5_{IR} + 0.5_{EO}, U_{GSD} = 0.5_{IR} + 0.5_{EO}, U_{Frame\ Rate} = 0.5_{IR} + 0.5_{EO}$$

These additive utility functions were used to score each alternative, with hope of identifying a set of alternatives, and characteristics of those alternatives, that deliver the greatest value. As a result, a sample of best-value alternatives were chosen, but not for the purpose of identifying a single alternative as being the best. On the contrary, this sample of alternatives was assessed based on the weight-reducing components that were used, the total performance/suitability delivered, and the trades associated with reducing system weight. This was the objective of the trade-off analysis and is discussed in the sections that follow.

In the Performance Analysis section above, performance measures were allocated to each alternative. In the absence of a formal analysis for risk, reliability, or even maneuverability, scales were developed to help measure these less tangible attributes under Suitability. These scales were specifically structured to be symmetrical about a middle value/category to enable interval-like approximations, where the distance between each of the available levels is equal. It’s important that the scale be symmetrical to avoid any unnecessary bias towards a negative or positive result. Such bias would carry over into each alternative’s final score and could influence the outcome of the final results. These scales were then used to assess the impact of Suitability for each weight-reducing component, as discussed in the sections below.

3.3.1.1 Cost

Cost was excluded from our trade-off analysis and is grayed-out of the value hierarchy above for this reason. After interviewing our sponsor, it became clear that the inclusion of Cost in our analysis would deliver very little additional value; our customer only desired weight to be the sole constraint for this project. Recognizing that Cost is typically included as a constraint in most trade-off analyses, it has been included in our value hierarchy, but excluded from the analysis itself. Should future work require a Cost analysis, where cost is a constraint, Cost would then join Weight as an additional constraint.

3.3.1.2 Weight

As previously described, the primary objective of this project was to assess whether performance is "good enough" for WAMI systems that weigh less than 500 lbs. It is critical to note that weight is a fixed value here. The dotted line in the value hierarchy represents the division of Weight from the fundamental objectives, for the sole purpose of illustrating that Weight is an independent variable. Weight defines the boundary of our trade space, in which Performance and Suitability may vary. As stated previously, it is the only constraint for considered in our trade-off analysis.

3.3.1.3 Performance

The key performance parameters of Ground Sampling Distance (GSD), Field of View (FoV), and Frame Rate are described in detail in section 2.1.1. The mission duration of the system is defined as the time (hours) that the system is in operational use. As discussed, these measures were determined in the Performance Analysis.

3.3.1.4 Suitability

The Suitability attributes required a measurement scale to assess the potential impact of each weight-driving component. Symmetric scales were developed, and used when applicable.

3.3.1.4.1 Risk

Total risk has been measured for each alternative based on the risks associated with each of its components. The likelihood for each risk is measured primarily on the basis of technological maturity, and whether or not the component has been tested or otherwise proven in an operational environment. The impact of each risk has been assessed based on the relative criticality of that component. While an extensive evaluation of risk is outside the scope of this project, risk has been estimated and considered based on potential impacts to cost, schedule, and performance throughout the system lifecycle.

In general, the risks identified with the system alternatives are largely associated with the sensor subsystem and the gimbal. We used the risk impact scale in Table 10 to determine the risk level for the various system components. The risk impact scale maintains a uniform measurement for all project parameters.

Level	Impact	Likelihood
1	Minimal	Very Low
2	Low	Low
3	Moderate	Moderate
4	Major	High
5	Unacceptable	Very High

Table 10: Risk Impact Scale

The sensor alternatives and their associated risk are shown in Table 11 below. Since new technology yields higher risk, the smaller pixel widths have a higher score associated with them.

EO Sensor Alternative	Impact	Likelihood	Score (Impact * Likelihood)
0	---	---	---
1.32	3	1	3
1.1	3	2	6
0.9	3	3	9
IR Sensor Alternative	**Impact**	**Likelihood**	**Score (Impact * Likelihood)**
0	---	---	---
1.32	3	1	3
1.1	3	2	6
0.9	3	3	9

Table 11: Risk for Sensor Alternatives

The risk associated with the gimbals is relatively low and is shown in Table 12 below. This is because the technological maturity associated with gimbals is relatively high and the potential risks that could cause a cost, performance, and/or scheduling impact is negligible.

Gimbal Alternative	Impact	Likelihood	Score (Impact x Likelihood)
26 inch	3	1	3
25 inch	3	1	3
23 inch	3	1	3
18 inch	3	1	3

Table 12: Risk for Gimbal Alternatives

Similarly, the storage components present little risk. Both HDDs and SSDs are, or are projected to be, readily available and reasonable in price. Performance for both technologies has been tested or operationally proven for this application. A low impact has been allocated based on redundancy within the system, but also on the criticality of storage in the successful completion of a mission.

Storage Alternative	Impact	Likelihood	Score (Impact * Likelihood)
3000 GB HDD	2	1	2
6000 GB HDD	2	1	2
500 GB SSD	2	1	2
750 GB SSD	2	1	2

Table 13: Risk for Storage Alternatives

3.3.1.4.2 Reliability

Reliability refers to the ability of the system to remain operational for the total mission duration. It also refers to the amount of time the system takes to repair (Mean Time to Repair (MTTR)) and the maximum amount of time it remains operational without failure (Mean Time Between Failure (MTBF)). The reliability impact scale is identified in Table 14 below.

Level	Impact
1	Reliable
2	Moderate Reliability
3	Unreliable

Table 14: Reliability Impact Scale

The reliability impact for each of the storage alternatives is identified in Table 15. SSDs have a non-mechanical design; therefore have a reliability of 1 based on the fact that they are largely shock resistant. On the other hand, HDDs are built with moving parts that are subject to damage caused by shock. Therefore, HDDs have a reliability impact of 2.

SSD Alternatives	Impact
500 GB	1
750 GB	1
HDD Alternatives	**Impact**
3000 GB	2
6000 GB	2

Table 15: Reliability for Storage Alternatives

For the purposes of this project, reliability is not applicable for the gimbal or sensor subsystems since it is highly dependent on the actual gimbal and sensor design such as materials, use, and assembly. These attributes cannot be determined based on our approach and scope of the project. Additionally, since we know the gimbal is designed to be rugged and withstand the vibrations and shock of the aircraft, we can assume that the subsystem, and the sensor subsystem which it contains, are very reliable.

3.3.1.4.3 Maneuverability

For the purposes of this project, maneuverability refers to the ability to maneuver the camera to accommodate dynamic or diverse operating environments. This measure is directly associated with the gimbal.

Gimbals are not only used for isolation of vibrations and shock loads from the airplane, helicopter, or UAV. They are also used to for steering the payload outside of the maneuvering ability of the craft it's attached too. This allows for additional degrees of freedom to shift the FoV towards the mission target area. Slew rate comes into play as a bounding factor on how fast or more specifically how precise the gimbal can shift to keep the target within the FOV while keeping the sensor in the correct orientation. In most cases, the gimbal is built with the correct level of internal stabilization electronics for the payload associated with its size. For this reason, with the integration of a payload that is proportional in weight to the gimbal and can be correctly mated to the gimbal yields high precision slew rates. Slew rate levels are identified in Table 16 below and the slew rate score for each alternative is identified in Table 17.

Level	Slew Rate
1	Low Precision
2	Medium Precision
3	High Precision

Table 16: Slew Rate Levels

Gimbal Alternative	Slew Rate
26 inch	3
25 inch	3
23 inch	3
18 inch	3

Table 17: Slew Rate Score

3.3.2 Results

The tables above were referenced within spreadsheets and mapped to each alternative based on its components. Scores were then summed for each alternative to provide a measurement on the final Suitability impact. After normalizing the Suitability and Performance measures, the additive utility functions were applied at each level of the value hierarchy to compute a final score. This score represents the overall value that each alternative delivers, and should be assessed relative to the scores of the other alternatives. The results were then plotted in various ways to identify which alternatives, and characteristics of those alternatives, deliver the greatest value.

3.3.2.1 Normalization

All attributes were normalized using min-max normalization, a method that uses linear transformation to rescale the original data to a scale that covers an interval between 0 and 1 (0 being the worst, 1 being the best). This method was chosen based on our utility function and its broad range of criteria, each of which is measured using different scales and units. The minimum and maximum values for each attribute are known, extreme values or outliers don't exist, and the data is not skewed about a particular point, thus ruling out other normalization techniques like Z-Score or Log normalization. Since min-max normalization is scale invariant, it preserves the relationships in the original data. For example, Figure 20 shows a basic scatter plot for weight against mission duration. Comparing this to a scatter plot of weight against the normalized values for mission duration in Figure 21, we see that each plot is equivalent except for the scale used for the y-axis. Preserving relationships in the original data is important as it eliminates potential bias, which could ultimately affect the outcomes produced by the utility function.

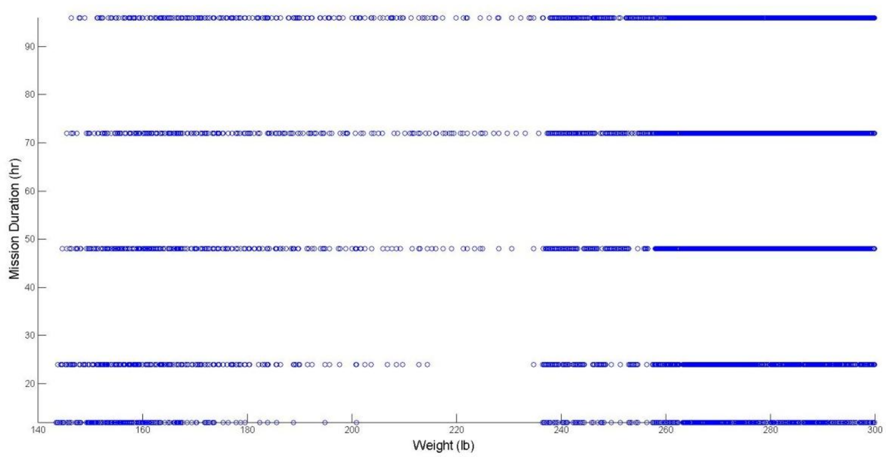


Figure 20: Weight vs. Mission Duration

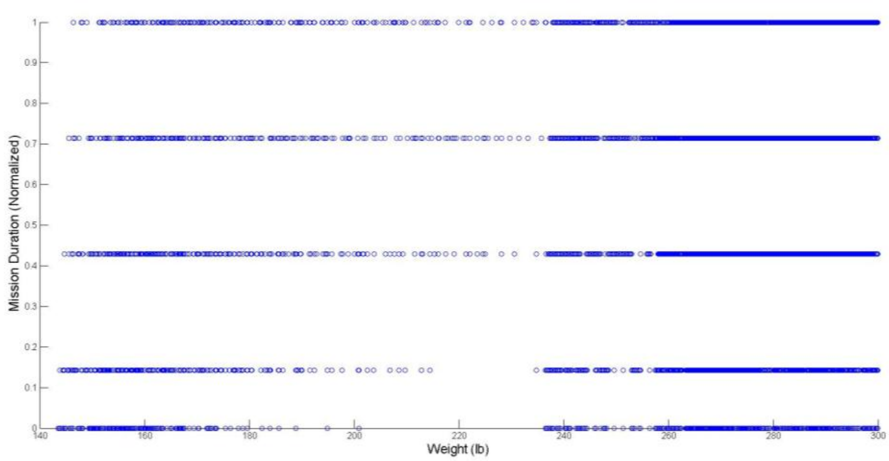


Figure 21: Weight vs. Mission Duration (Normalized)

Note that, when attributes like Risk, Reliability, and Maneuverability were normalized, a new scale was determined based the worst and best possible outcomes. In instances where the impact of a component could not be assessed (e.g. not applicable), those attributes were simply exempt from the normalization process.

3.3.2.2 Best-value alternatives

The best-value alternatives were chosen based on their final scores, yet care was taken to select a set of alternatives that scored highly across a variety of system weights. As a result, the alternatives identified in Table 18 were taken from data points located at the top of the curve, filled in red. While the EO-only alternatives (first twelve points from left to right) are perfectly viable, it is clear that the EO and IR combinations deliver superior value with the current collection of stakeholder weights. Since the difference between EO and IR sensors are night and day, literally, it is not likely that mission requirements will change enough to affect the stakeholder weights and the outcomes shown below. Therefore, the EO-only alternatives were not considered beyond this point. The elimination of single-sensor configurations was also described previously in Section 3.2.2.

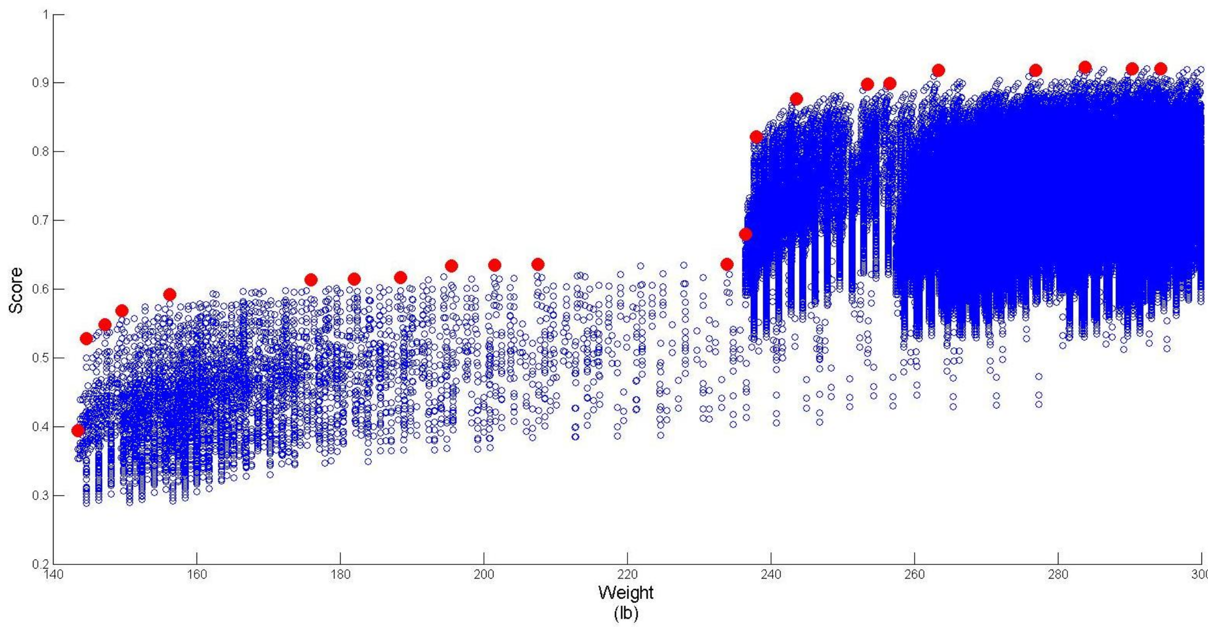


Figure 22: Best-value alternatives (EO-only and EO/IR)

Weight	Pixel Width (in)	GSD (m/pixel)	FoV (km)	Resolution (Pixels/Image)	Frame Rate	Gimbal (size)	Storage (GB)	Mission Duration	Performance Score	Suitability Score	Total Score
236.51	0.9	0.2	6	9E+08	2	23	750 SSD (x3)	24	0.669936	0.950515	0.720121
	0.9	0.6	6	1E+08	4						
238.04	0.9	0.1	6	3.6E+09	2	23	750 SSD (x12)	24	0.858736	0.950515	0.862288
	0.9	0.6	10	2.78E+08	4						
243.65	0.9	0.1	6	3.6E+09	2	23	750 SSD (x45)	96	0.93245	0.950515	0.917794
	0.9	0.6	10	2.78E+08	4						
253.51	0.9	0.1	6	3.6E+09	5	23	750 SSD (X103)	96	0.959825	0.950515	0.938408
	0.9	0.6	10	2.78E+08	4						
256.57	0.9	0.1	6	3.6E+09	8	23	750 SSD (X121)	72	0.962629	0.950515	0.940519
	0.9	0.6	10	2.78E+08	4						
263.37	0.9	0.1	6	3.6E+09	8	23	750 SSD (X161)	96	0.9872	0.950515	0.959021
	0.9	0.6	10	2.78E+08	4						
276.97	0.9	0.1	6	3.6E+09	8	23	500 SSD (X241)	96	0.9872	0.950515	0.959021
	0.9	0.6	10	2.78E+08	4						
283.77	0.9	0.1	8	6.4E+09	8	23	750 SSD (X281)	96	0.9931	0.950515	0.963464
	0.9	0.6	10	2.78E+08	4						
290.37	1.32	0.1	6	3.6E+09	8	25	750 SSD (X161)	96	0.9872	0.965361	0.965459
	0.9	0.6	10	2.78E+08	4						
294.37	0.9	0.1	6	3.6E+09	8	25	750 SSD (X161)	96	0.9872	0.965361	0.965459
	1.32	0.6	10	2.78E+08	4						

Denotes EO
Denotes IR

Table 18: Best-value Alternatives

3.3.2.2.1 Sensors

There are many similarities between the above set of best-value alternatives. Almost all of them deliver the most desirable performance as defined in Section 3.2.2. For example, all but the lightest alternative have the best GSD. Most use the best Mission Duration and Frame Rate, especially for the heavier alternatives of the set. However, none of the best-value alternatives deliver the most desirable EO FoV (10 km); on the contrary, all but one delivers the least desirable (6 km). In fact, not a single alternative out of the 111,389 delivered the most desirable performance across all performance attributes. As shown in the table, many alternatives come really close, only lacking in EO FoV. Those alternatives that do deliver the most desirable performance for all attributes weigh more than permitted by our weight threshold. Thus, EO FoV is a trade for weight.

From equation (3), the greater the FoV, the greater the resolution, assuming GSD is held constant (i.e. the better the quality of the images being collected). Yet 6 km is the least desirable FoV, and is contributing to greater overall value across the respective weight classes. Figure 23 illustrates the image resolutions of the 111,389 alternatives with respect to final score. Most of the best-value alternatives deliver a resolution of 3.6E+09 pixels, which can only be calculated from the most desirable GSD (0.1 m/pixel) and the least desirable FoV (6 km). Yet it is not clear from this plot why other image resolutions do not deliver greater value in each respective weight class.

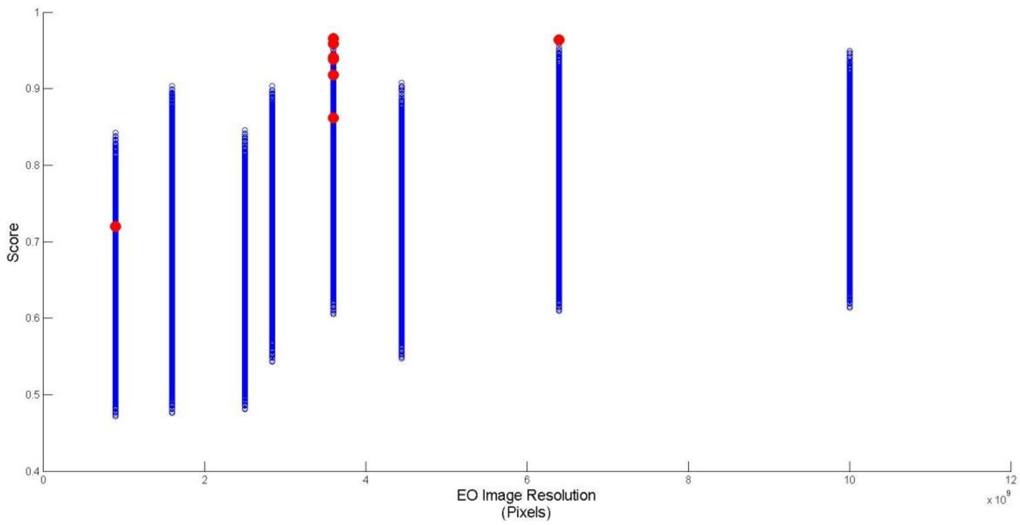


Figure 23: EO Image Resolution vs. Score

Referring to the utility functions, it's evident that FoV has the least stakeholder value in relation to all of the other performance attributes. Therefore, a small FoV has little impact on the final score relative to other performance attributes, especially GSD. Based on the stakeholder preferences for the performance attributes, one must conclude that an EO GSD=0.9 and an EO FoV=0.6 delivers the greatest value, in general, across the variety of possible total system weights. Note, however, that the highest scoring alternative was the only one of the best-value alternatives to deliver an EO FoV greater than 6 km (8 km). Figure 24 shows a scatter plot of the final 111,389 alternatives, classified by EO FoV. We see that those alternatives that delivered a larger FoV consistently delivered lower value. The fact that all of the feasible alternatives exhibit this same behavior confirms that EO FoV is a trade for weight.

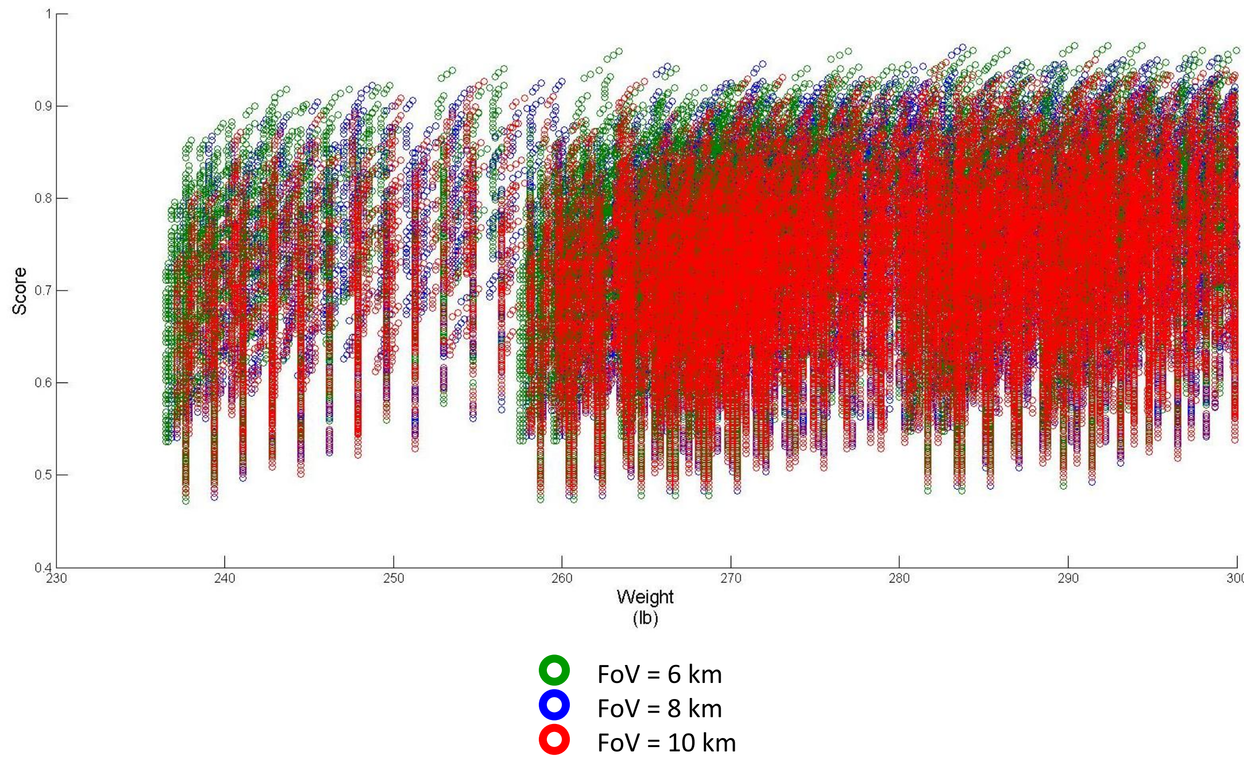


Figure 24: Results by EO FoV

The above plot illustrates that EO FoV is a trade for weight, with respect to stakeholder value. As shown below, exclusive of stakeholder preference, EO FoV is also illustrated as a trade for weight. The scatter plot in Figure 25 shows weight plotted against storage capacity, which is a great indicator of performance. Storage capacity is calculated from the entire set of performance attributes; it's based on the quality and the quantity of the images being collected. While frame rate and mission duration are used to calculate image quantity, FoV and GSD impact image quality (i.e. resolution). The larger the FoV, the larger the resolution, assuming GSD is held constant. Similarly, the larger the resolution, the more data is being stored, and the more the total system weighs. The diagonal in the figure below represents the maximum possible storage capacity for each respective weight class. Like the sample of best-value alternatives, none of the alternatives that lie on this diagonal delivered the most desirable FoV of 10 km. Therefore, in order to store the most amount of data within the weight threshold (i.e. deliver performance most efficiently with respect to weight), the most desirable EO FoV cannot be used.

Also interesting is the fact that most of the alternatives in Figure 25 deliver nearly equal value, as shown in Figure 22. Yet we see huge differences in the amount of data that can be stored across the set of best-value alternatives. The small difference in utility is the result of high stakeholder preference for GSD, as opposed to the other performance attributes. Attributes like mission duration and frame rate, while contributing significantly to the amount of data being stored, are rather insignificant with respect to value delivered to the stakeholder.

Also notice that 3 of the 4 heaviest alternatives in Figure 25 exhibit some minor, but key differences from the alternatives preceding them. From the table above, it can be seen that seventh lightest best-value alternative is the only alternative to utilize a 500 GB SSD. The two heaviest best-value alternatives are the only ones that have an EO or IR pixel width of 1.32, and consequently have a 25 inch gimbal. These alternatives do not deliver the greatest storage capacity, yet scored highest in their respective weight classes. In these cases, older or heavier components are used when alternate components exist that weigh less. Simply put, performance is delivered less efficiently with respect to weight.

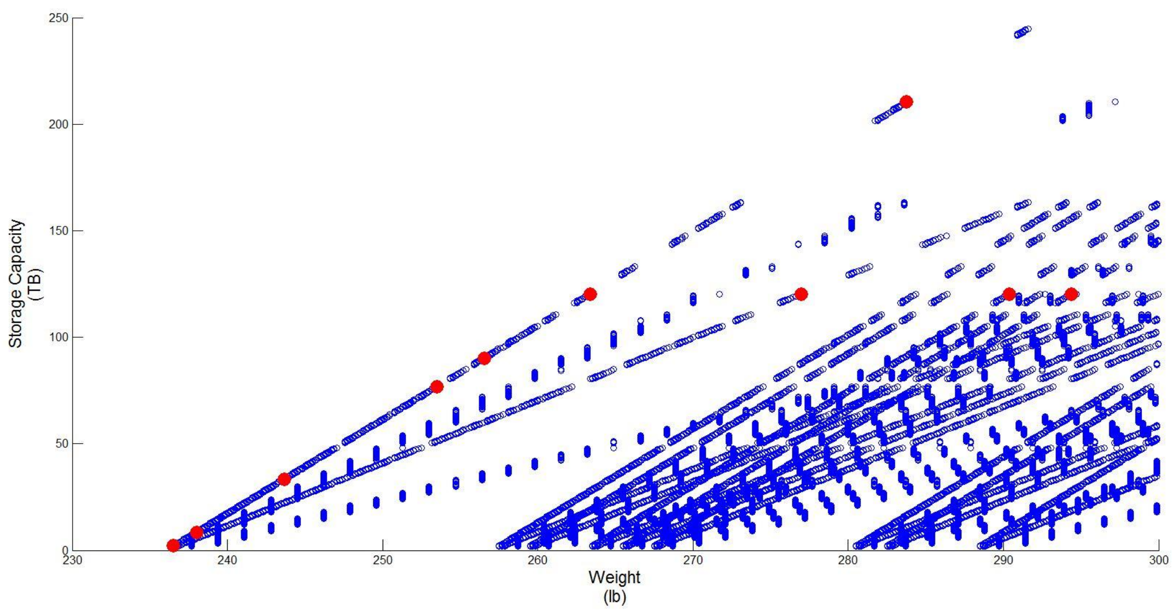


Figure 25: Weight vs. Storage Capacity

Note that a smaller GSD is acceptable for IR images. Except for the first, all of the best-value alternatives deliver the most desirable IR GSD and IR FoV. Since lower-resolution images are acceptable for IR, these have significantly less impact on the weight associated with storage, and therefore less impact on the total system weight. For this reason, only EO FoV is a trade.

3.3.2.2.2 Storage

Each of the best-value alternatives are comprised of either a 500 GB SSD or a 750 GB SSD. Provided the available storage alternatives, this is not surprising. Each SSD delivers equal storage capacity for less weight in all applications except for when 500 GB SSDs are used in lieu of 6000 GB HDDs. Given the widespread occurrence across all weight classes, 750 GB SSDs are recommended as the storage component to deliver the best-value per unit weight. This is shown in Figures 26 and 27 below.

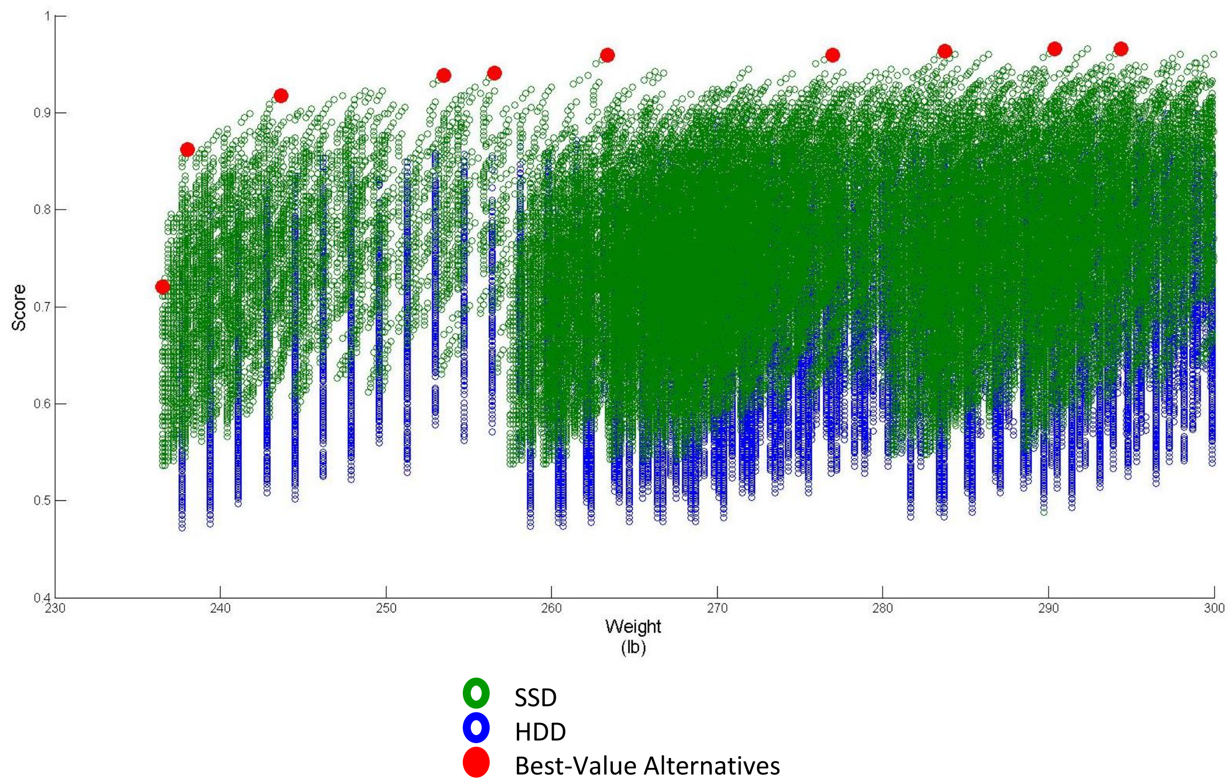


Figure 26: Results by Storage Type

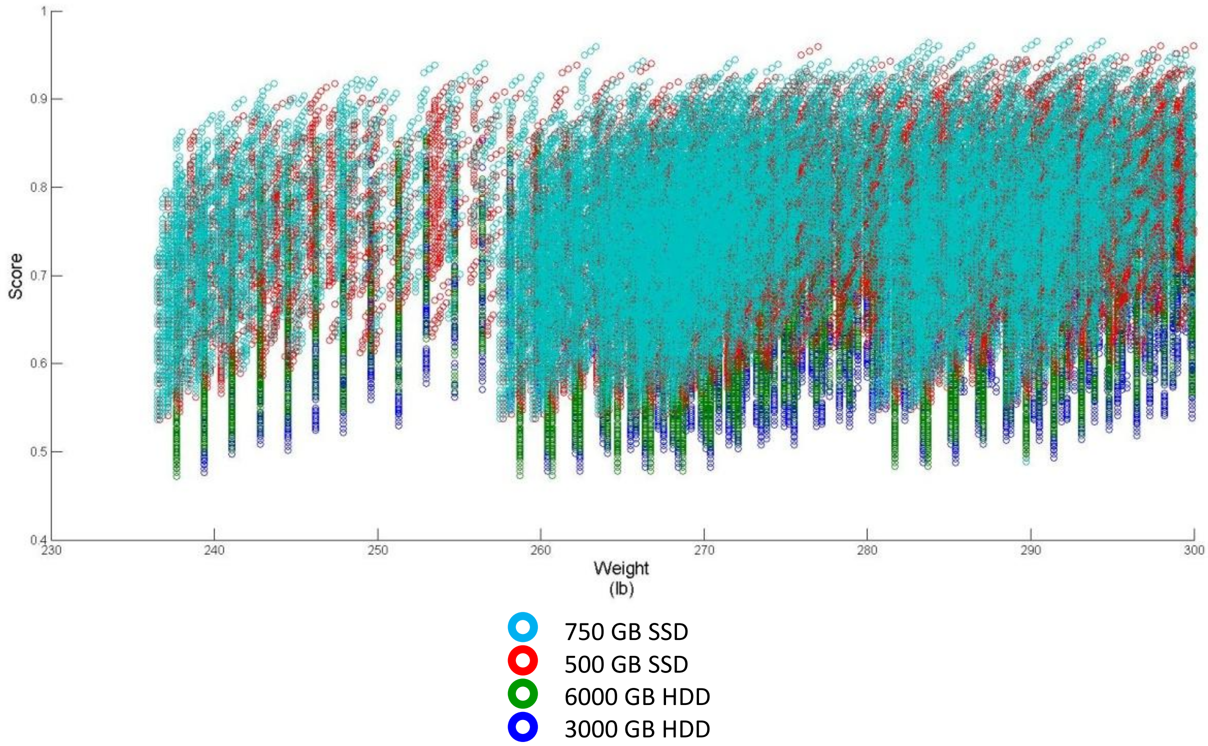


Figure 27: Results by Storage Type and Capacity

3.3.2.2.3 Gimbal

All of the 18-inch gimbal alternatives were eliminated with each single-sensor alternative (EO or IR), since these were the only alternatives light enough for the 18-inch gimbal to support. Similarly, many of the 26-inch gimbal alternatives were eliminated on the basis of excessive weight. In particular, these were the alternatives that either delivered greater performance and required more storage (and more weight), or delivered performance less efficiently. As a result, the 23- and 25-inch gimbals were the only components used by each of the best-value alternatives. Note that the second and third best scoring alternatives each use a 25-inch gimbal; the rest use a 23-inch gimbal.

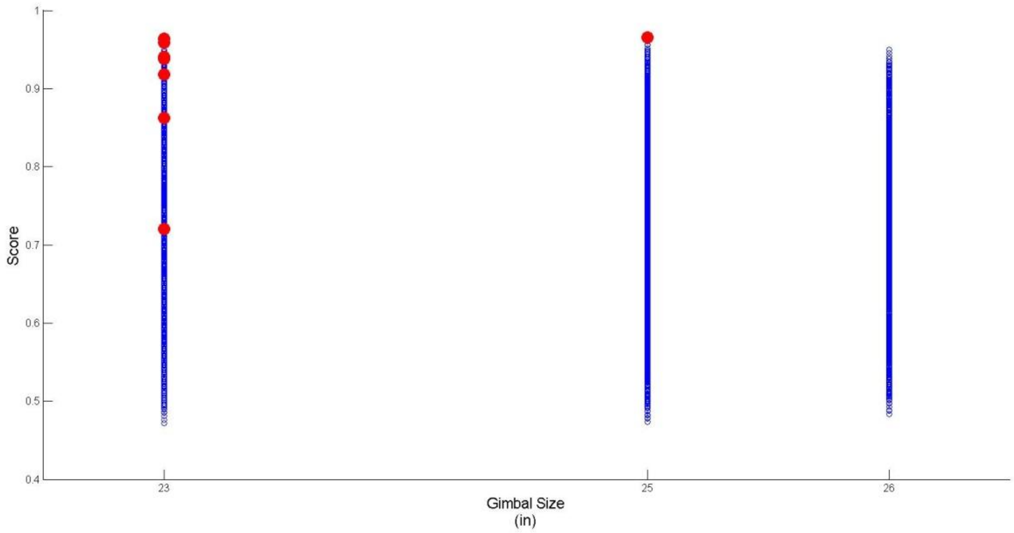


Figure 28: Gimbal Size vs. Score

Also note that gimbal size does not affect performance, since it's assigned to each alternative based on the total sensor weight. Gimbals are chosen strictly on the basis of weight. The scatter plot below illustrates this—a 23 inch gimbal cannot be used for alternatives that weigh less than 236 lbs (there actually aren't any), the 25 inch gimbal cannot be used for alternatives that weigh less than 258 lbs, and a 26 inch gimbal cannot be used for systems that weigh less than 280lbs.

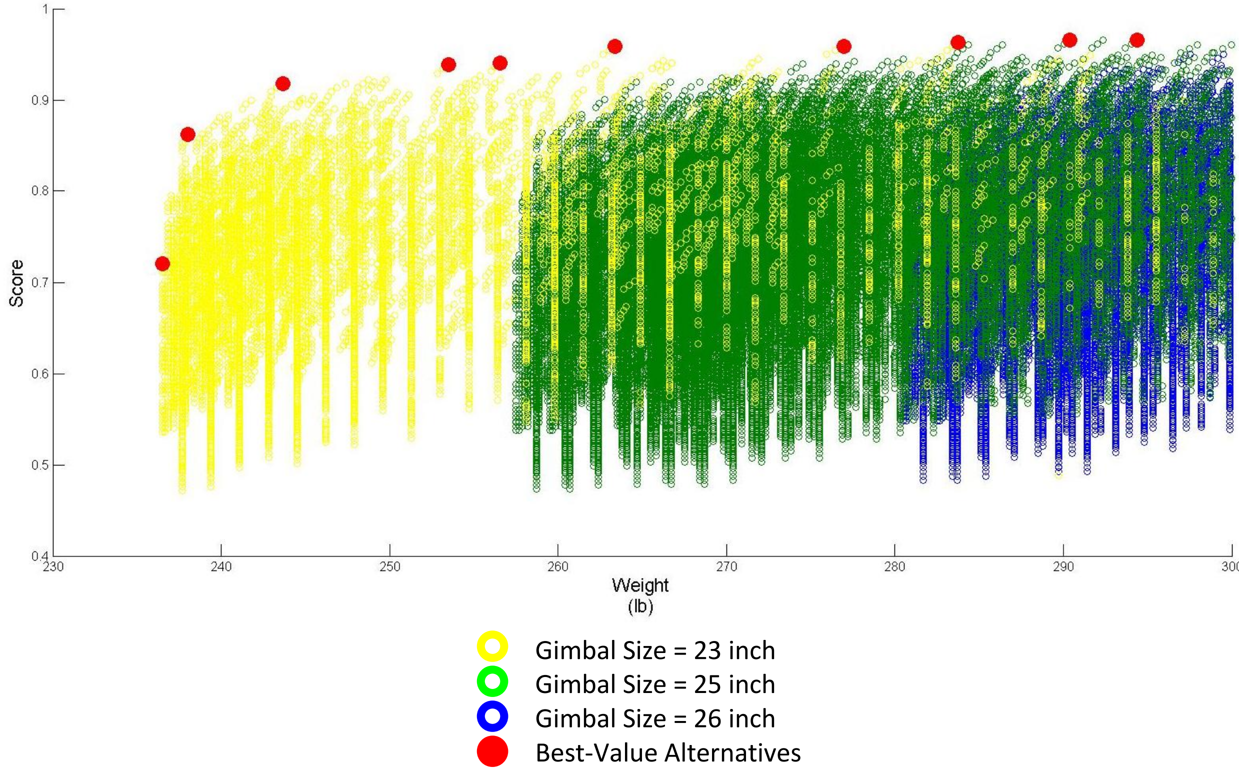


Figure 29: Results by Gimbal Size

3.3.2.3 Sensitivity Analysis

The objective of the sensitivity analysis was to increase our understanding of the relationships between our inputs and outputs (i.e. stakeholder values and final scores). With such a high number of alternatives to consider, most of which scored very closely, it was predicted that some variability in the data would exist after varying stakeholder weights. Using the top level of the value hierarchy, stakeholder weights were varied for the Suitability and Performance objectives in two different ways. The first figure below illustrates the stakeholder weights, as collected, where Performance has significantly more value. The next plot illustrates a hypothetical scoring for stakeholder weights where the stakeholder is indifferent between Suitability and Performance. Next, Suitability is illustrated as holding greater stakeholder value than Performance.

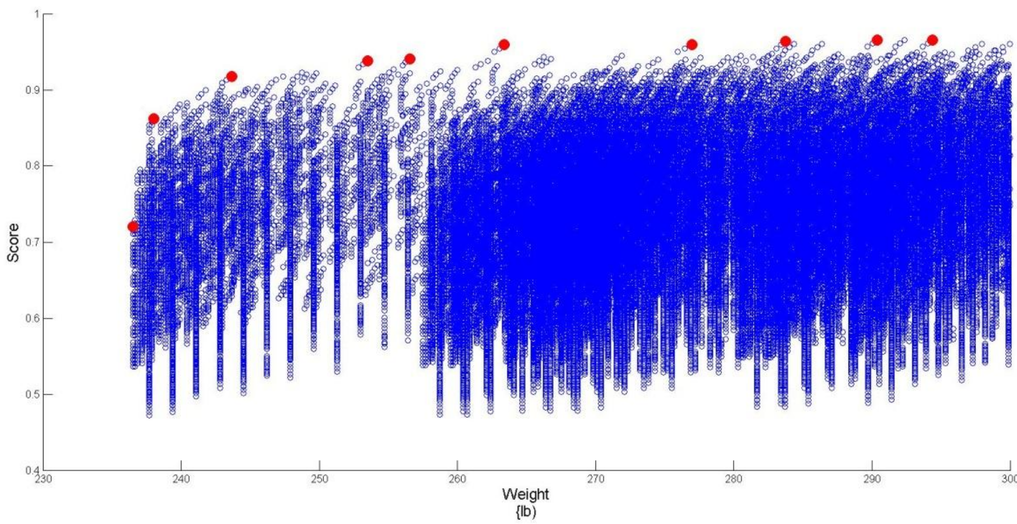


Figure 30: As Collected: Performance = 0.804, Suitability = 0.196

In the scatter plot below, notice that the six alternatives that weigh the least maintain their status as the best-value alternatives in their respective weight class. The heavier components are surpassed in total value, but not by much.

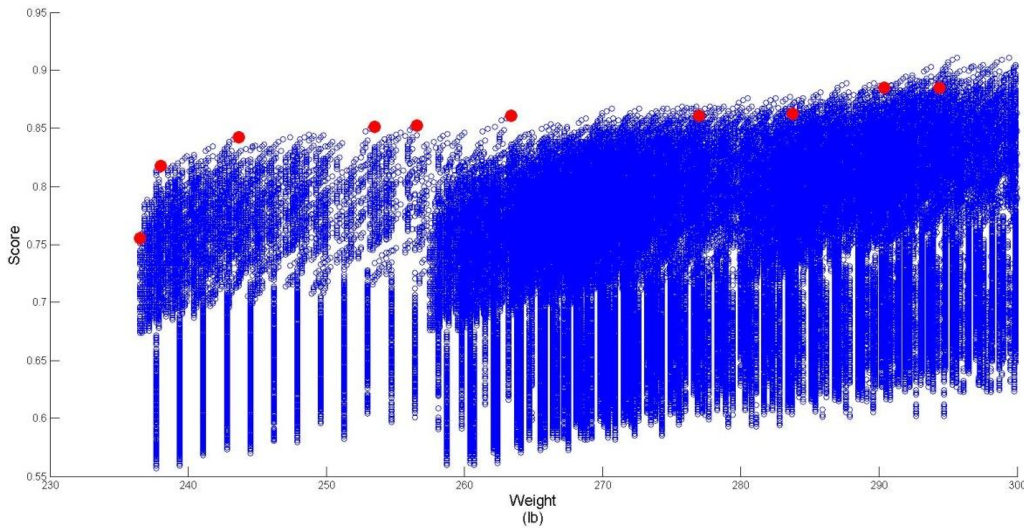


Figure 31: Performance = 0.50, Suitability = 0.50

When Suitability is preferred over Performance, we see a gap emerge between the final scores of the alternatives. This shows the value delivered by SSDs (on the top), and HDDs (on the bottom). Clearly, SSDs deliver superior value with respect to Suitability. Even so, the 4 best-value alternatives that weigh the most are barely surpassed by other (potential) alternatives. The lighter best-value alternatives remain at the top within their weight class.

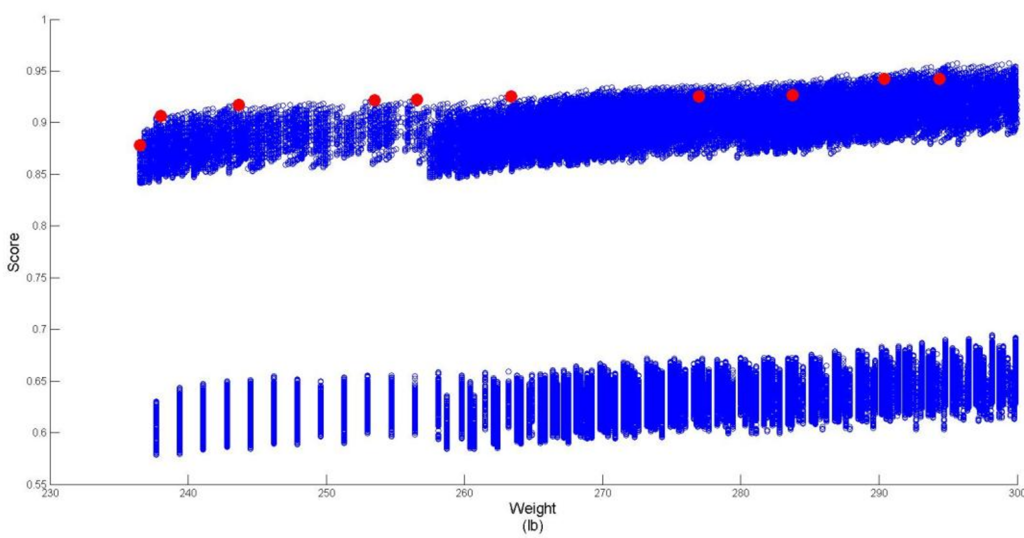


Figure 32: Performance = 0.25, Suitability = 0.75

In each instance, the first 6 alternatives maintained their status as delivering the greatest value in their respective weight class. Thus, these were not affected by variations in stakeholder weights. Conversely, all four of the heaviest alternatives were surpassed by others that delivered greater value. Much can be said by this.

As alternatives move from less system weight to more system weight in the plots above, more alternatives become available that utilize a different set of components. This is illustrated below in Figure 33, for EO pixel widths. Notice the variety of alternatives that weigh closer to the 300 lb threshold and deliver nearly equal value. From the sensitivity analysis, alternatives that lie in the region to the right (i.e. that weigh more) were determined to be the most sensitive to variations in stakeholder weights.

However, should the level of uncertainty in the stakeholder weights rise, alternatives that lie in this region still may deliver greater value than those alternatives that are not sensitive and lie in the regions to the left. In our case, sensitivity to stakeholder weights is not necessarily a bad thing. Those alternatives that are less sensitive, while still maintaining status as the best-value alternative in their respective weight class, consistently deliver decreasing value as stakeholder weights change. In the case where stakeholders are uncertain about their preferences in Suitability and/or Performance, these alternatives are less fit and guarantee less value. Those best-value alternatives that are sensitive lie in a region where more alternatives exist to deliver greater value, irrespective of the stakeholder weights.

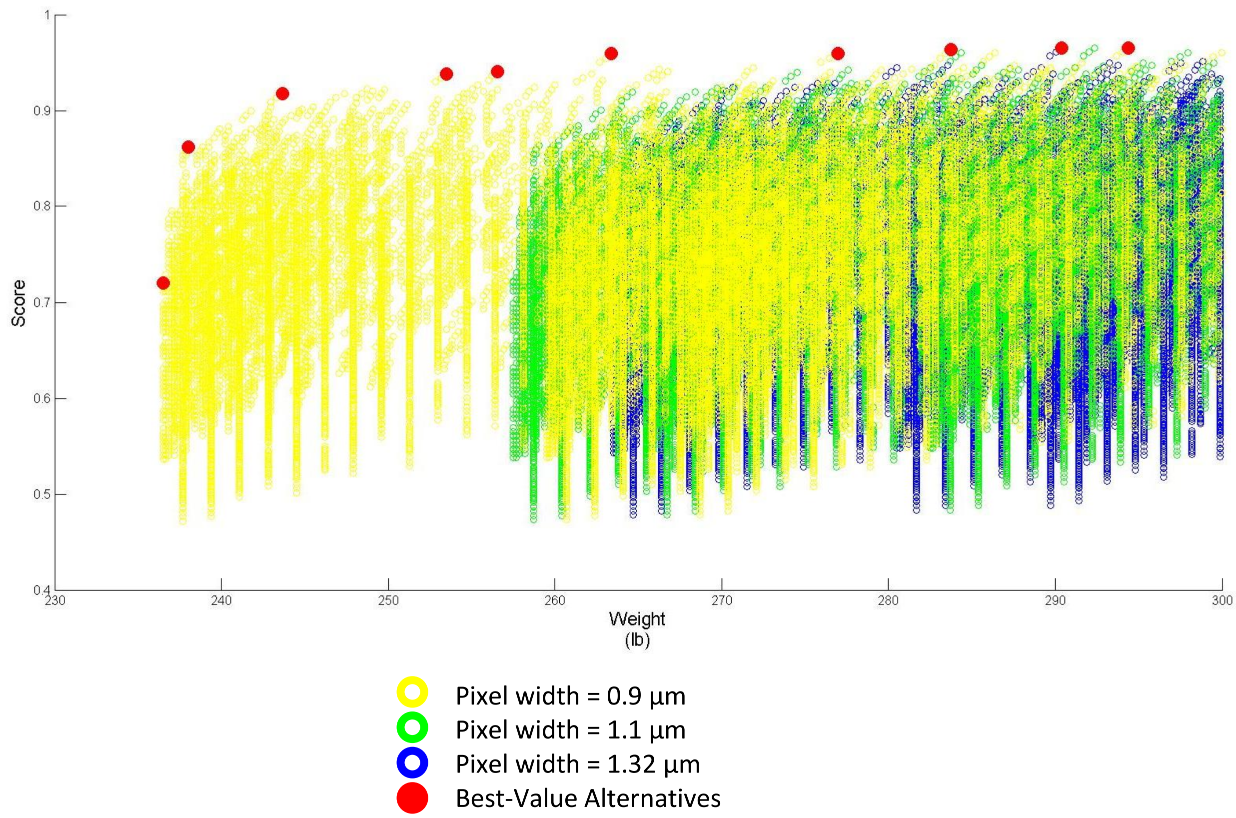


Figure 33: Results by pixel width

4. RECOMMENDATIONS AND FUTURE WORK

As the next generation WAMI system is designed and developed, this analysis will enable our stakeholders to develop requirements with greater specificity. The needs of the warfighter have been captured in our definition of performance, which has been deemed "good enough". Similarly, through research and interactions with industry SMEs, the horizon of existing and new technologies have been explored that could potentially deliver performance to meet the warfighter needs, while reducing total system weight. This analysis helps bridge the gap between achievable technology and the warfighter's needs, assessing the performance that's obtainable today and reachable tomorrow under the constraint of weight.

By today's standards, it is feasible to reduce WAMI system weight to less than 500 lbs while maintaining performance that is "good enough". In fact, using technologies that are projected to be available in the near future, system weight can be reduced to well below 500 lbs with little difference in total utility. However, those alternatives that weigh less also store less data, and are forced to use technologies that are not yet available. If lower weights are desired for the WAMI system, then requirements should be written accordingly. For example, the scatter plot showing weight vs. storage capacity illustrates the maximum achievable storage capacities for each respective weight class. This could inform performance requirements for GSD, mission duration, frame rate, and FoV. Similarly, it's clear that SSDs should be used to help deliver performance in a weight-efficient manner.

Of all the weight-reducing components assessed in this study, none can be recommended that would deliver greater value in all instances of changing stakeholder utility, except for SSDs. With respect to performance, greater value is delivered by each alternative using SSDs when compared to the HDD substitutes, as shown in Figure 26. With respect to suitability, alternatives that use SSDs are superior in value than those that use HDDs, as shown in the large gap between the alternatives in Figure 32. Also, SSDs should have a minimal impact on cost, based on the cost assessment described in Section 3.1.3.3. Accordingly, there should be a requirement that stipulates the use of SSDs. Typically, government requirements shouldn't prescribe an implementation, but there is an argument that HDDs should no longer be considered as a viable storage alternative. As a result, if this study were to be repeated, those alternatives that use HDDs should be removed entirely.

In the same way, performance measures for "good enough" could also be redefined to improve the results of this analysis and generate better requirements. For example, it's clear that the least desirable performance can be achieved quite easily, and the most desirable performance just nearly. Performance measures could be derived that stretch the most desirable even further. For example, improved performance can be assigned for GSD (say, 0.07 m/pixel), which is the attribute that our stakeholder values more than any other. This would eliminate even more alternatives on the basis of weight (greater GSD = higher resolution images = more data stored = more weight), and new trades may emerge for performance attributes that must be sacrificed to stay under 500 lbs. In any case, in considering these new trades, requirements could be developed that solicit the maximum performance achievable within the weight constraint.

But weight is not the only constraint. Weight is not independent of size. Typically, weight is addressed in a Size, Weight, and Power (SWaP) analysis. This study serves as a foundation for a SWaP analysis. For example, size and power requirements can be added and further eliminations can be made for alternatives that are inappropriate. Similarly, cost cannot be ignored as a constraint. New technologies may be too expensive. Eliminations could be made based on impacts to cost. In all, this would narrow down the set of viable alternatives to a more finite set, ideally one that is small enough to repeat the trade-off analysis and sensitivity analysis, but this time with different objectives. With confidence, a small selection could be chosen, from which a single alternative could be identified that delivers the greatest value across the board. Requirements could be written to that alternative.

In all, requirements that are more specific to the needs of the warfighter and the capabilities that can be delivered by industry should contribute to a better, next generation WAMI system. Coupled with a Request for Proposals (RFP), more specific requirements should help industry gauge the expectations of the government, and enable them to more accurately estimate cost and schedule. This could also influence the type of contract awarded. With better proposals submitted, our stakeholders would be able to more confidently choose the better vendor, hopefully with less risk to overruns in cost and schedule. In the end, greater performance is also achieved from a system that weighs less than 500 lbs.

REFERENCES

1. http://geospatial.referata.com/wiki/Resolution
2. Col Yahn. Robert A. (2011, 08). Wide Area Motion Imagery A game changing enabler for Counter Insurgency Operations. Secretary of the Air Force Acquisition Information Dominance, Washington, DC
3. http://www.aviationweek.com/Blogs.aspx?plckBlogId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog%253a27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%253a881370e5-a10f-46be-bab0-bf60fa08b425&plckScript=blogScript&plckElementId=blogDest
4. http://www.globalsecurity.org/intell/systems/
5. http://archive.feedblitz.com/657386/~3895979
6. http://www.airforcetimes.com/news/2009/02/airforce_WAAS_021609/
7. Ernest Frank Carter: “Dictionary of Inventions and Discoveries”, 1967, p.74
8. Hans-Christoph Seherr-Thoss, Friedrich Schmelz, Erich Aucktor: “Universal Joints and Driveshafts: Analysis, Design, Applications”, 2006, ISBN 978-3-540-30169-1, p.1
9. Sarton, George. (1959) A History of Science: Hellenistic Science and Culture in the Last Three Centuries B.C. New York: The Norton Library, Norton & Company Inc. SBN 393005267. Page 349–350
10. Athenaeus Mechanicus, "On Machines" ("Peri Mēchanēmatōn"), 32.1-33.3
11. Needham, Joseph. (1986). *Science and Civilization in China: Volume 4, Physics and Physical Technology; Part 2, Mechanical Engineering*. Taipei: Caves Books Ltd. Page 233–234
12. Needham, Joseph. (1986). *Science and Civilization in China: Volume 4, Physics and Physical Technology; Part 2, Mechanical Engineering*. Taipei: Caves Books Ltd. Page 229 & 231.
13. Needham, Joseph. (1986). *Science and Civilization in China: Volume 4, Physics and Physical Technology; Part 2, Mechanical Engineering*. Taipei: Caves Books Ltd. Page 234–235.
14. http://www.fas.org/man/dod-101/navy/docs/fun/part10.htm
15. Byrnes, James (2009). *Unexploded Ordnance Detection and Mitigation*. Springer. pp. 21–22
16. http://www.gizmag.com/omnivision-slim-bsi-cmos-camera-sensor/19472/
17. http://image-sensors-world.blogspot.com/2011/07/tsmc-reveals-its-11um-and-09um-pixel.html
18. http://www.bing.com/images/search?q=camera+pixel+size+by+year&view=detail&id=8A3E67C4FF039190FA7BD73A7C3CF00901450D8A
19. http://www.mkomo.com/cost-per-gigabyte
20. http://glassvisage.hubpages.com/hub/Moores-Law
21. http://www.futuretimeline.net/subject/computers-internet.htm#data-storage
22. http://www.jcmit.com/index.htm
23. http://www.futuretimeline.net/subject/computers-internet.htm
24. http://www.ocztechnology.com/ssdzone/ssd-vs-hdd-comparison.html
25. http://www.deloitte.com/assets/Dcom-Global/Local%20Assets/Documents/TMT/Predictions%202012%20PDFs/16470A%20Hard%20time%20lb2.pdf
26. http://www.tomshardware.com/reviews/ssd-reliability-failure-rate,2923.html

27. http://martybugs.net/blog/blog.cgi/learning/Field-Of-View-And-More.html
28. http://www.robustdecisions.com/making-robust-decisions/2008/09/why-pairwise-comparisons-are-waste-of.php

APPENDIX A - SENSOR ALTERNATIVES AND PERFORMANCE

The following table was used to calculate the image resolution for each sensor combination.

EO											
Pixel width (microns)	Pixel width (inches)	Range (inches)	Acceptable GSD (m/pixel)	GSD (inches/Pixel)	Focal Length (inches)	FoV (km diameter)	FoV (inches)	Angle	Sensor Length (inches)	Image Resolution (Pixels)	Image Resolution (GP)
	=A3/25400			=D3*39.3700787	=(B3*C3)/E3		=G3*39370.1	=ATAN((H3/2)/C3)	=2*F3*TAN(I3)	=(J3/B3)^2	=K3/1000000000
1.32	5.1969E-05	240,000	0.2	7.87401574	1.584	6	236220.6	0.45732879	1.55905596	900000974	0.90000097
1.32	5.1969E-05	240,000	0.2	7.87401574	1.584	8	314960.8	0.58069927	2.07874128	1600001731	1.60000173
1.32	5.1969E-05	240,000	0.2	7.87401574	1.584	10	393701	0.68694345	2.5984266	2500002705	2.50000271
1.32	5.1969E-05	240,000	0.15	5.905511805	2.112	6	236220.6	0.45732879	2.07874128	1600001731	1.60000173
1.32	5.1969E-05	240,000	0.15	5.905511805	2.112	8	314960.8	0.58069927	2.77165504	2844447522	2.84444752
1.32	5.1969E-05	240,000	0.15	5.905511805	2.112	10	393701	0.68694345	3.4645688	4444449254	4.44444925
1.32	5.1969E-05	240,000	0.1	3.93700787	3.168	6	236220.6	0.45732879	3.11811192	3600003895	3.6000039
1.32	5.1969E-05	240,000	0.1	3.93700787	3.168	8	314960.8	0.58069927	4.15748256	6400006925	6.40000693
1.32	5.1969E-05	240,000	0.1	3.93700787	3.168	10	393701	0.68694345	5.19685321	1E+10	10.0000108
1.1	4.3307E-05	240,000	0.2	7.87401574	1.32	6	236220.6	0.45732879	1.2992133	900000974	0.90000097
1.1	4.3307E-05	240,000	0.2	7.87401574	1.32	8	314960.8	0.58069927	1.7322844	1600001731	1.60000173
1.1	4.3307E-05	240,000	0.2	7.87401574	1.32	10	393701	0.68694345	2.1653555	2500002705	2.50000271
1.1	4.3307E-05	240,000	0.15	5.905511805	1.76	6	236220.6	0.45732879	1.7322844	1600001731	1.60000173
1.1	4.3307E-05	240,000	0.15	5.905511805	1.76	8	314960.8	0.58069927	2.30971254	2844447522	2.84444752
1.1	4.3307E-05	240,000	0.15	5.905511805	1.76	10	393701	0.68694345	2.88714067	4444449254	4.44444925
1.1	4.3307E-05	240,000	0.1	3.93700787	2.64	6	236220.6	0.45732879	2.5984266	3600003895	3.6000039
1.1	4.3307E-05	240,000	0.1	3.93700787	2.64	8	314960.8	0.58069927	3.4645688	6400006925	6.40000693
1.1	4.3307E-05	240,000	0.1	3.93700787	2.64	10	393701	0.68694345	4.330711	1E+10	10.0000108
0.9	3.5433E-05	240,000	0.2	7.87401574	1.08	6	236220.6	0.45732879	1.0629927	900000974	0.90000097
0.9	3.5433E-05	240,000	0.2	7.87401574	1.08	8	314960.8	0.58069927	1.4173236	1600001731	1.60000173
0.9	3.5433E-05	240,000	0.2	7.87401574	1.08	10	393701	0.68694345	1.7716545	2500002705	2.50000271
0.9	3.5433E-05	240,000	0.15	5.905511805	1.44	6	236220.6	0.45732879	1.4173236	1600001731	1.60000173

EO											
Pixel width (microns)	Pixel width (inches)	Range (inches)	Acceptable GSD (m/pixel)	GSD (inches/Pixel)	Focal Length (inches)	FoV (km diameter)	FoV (inches)	Angle	Sensor Length (inches)	Image Resolution (Pixels)	Image Resolution (GP)
	=A3/25400			=D3*39.3700787	=(B3*C3)/E3		=G3*39370.1	=ATAN((H3/2)/C3)	=2*F3*TAN(I3)	=(J3/B3)^2	=K3/1000000000
0.9	3.5433E-05	240,000	0.15	5.905511805	1.44	8	314960.8	0.58069927	1.8897648	2844447522	2.84444752
0.9	3.5433E-05	240,000	0.15	5.905511805	1.44	10	393701	0.68694345	2.362206	4444449254	4.44444925
0.9	3.5433E-05	240,000	0.1	3.93700787	2.16	6	236220.6	0.45732879	2.1259854	3600003895	3.6000039
0.9	3.5433E-05	240,000	0.1	3.93700787	2.16	8	314960.8	0.58069927	2.8346472	6400006925	6.40000693
0.9	3.5433E-05	240,000	0.1	3.93700787	2.16	10	393701	0.68694345	3.543309	1E+10	10.0000108

IR											
Pixel width (microns)	Pixel width (inches)	Range (inches)	Acceptable GSD (m/pixel)	GSD (inches/Pixel)	Focal Length (inches)	FoV (km diameter)	FoV (inches)	Angle	Sensor Length (inches)	Image Resolution (Pixels)	Image Resolution (GP)
	=A3/25400			=D3*39.3700787	=(B3*C3)/E3		=G3*39370.1	=ATAN((H3/2)/C3)	=2*F3*TAN(I3)	=(J3/B3)^2	=K3/1000000000
1.32	5.1969E-05	240000	0.7	27.55905509	0.45257143	6	236220.6	0.45732879	0.44544456	73469467.3	0.07346947
1.32	5.1969E-05	240000	0.7	27.55905509	0.45257143	8	314960.8	0.58069927	0.59392608	130612386	0.13061239
1.32	5.1969E-05	240000	0.7	27.55905509	0.45257143	10	393701	0.68694345	0.7424076	204081853	0.20408185
1.32	5.1969E-05	240000	0.65	25.59055116	0.48738462	6	236220.6	0.45732879	0.47970953	85207192.8	0.08520719
1.32	5.1969E-05	240000	0.65	25.59055116	0.48738462	8	314960.8	0.58069927	0.6396127	151479454	0.15147945
1.32	5.1969E-05	240000	0.65	25.59055116	0.48738462	10	393701	0.68694345	0.79951588	236686647	0.23668665
1.32	5.1969E-05	240000	0.6	23.62204722	0.528	6	236220.6	0.45732879	0.51968532	100000108	0.10000011
1.32	5.1969E-05	240000	0.6	23.62204722	0.528	8	314960.8	0.58069927	0.69291376	177777970	0.17777797
1.32	5.1969E-05	240000	0.6	23.62204722	0.528	10	393701	0.68694345	0.8661422	277778078	0.27777808
1.1	4.3307E-05	240000	0.7	27.55905509	0.37714286	6	236220.6	0.45732879	0.3712038	73469467.3	0.07346947
1.1	4.3307E-05	240000	0.7	27.55905509	0.37714286	8	314960.8	0.58069927	0.4949384	130612386	0.13061239
1.1	4.3307E-05	240000	0.7	27.55905509	0.37714286	10	393701	0.68694345	0.618673	204081853	0.20408185
1.1	4.3307E-05	240000	0.65	25.59055116	0.40615385	6	236220.6	0.45732879	0.39975794	85207192.8	0.08520719
1.1	4.3307E-05	240000	0.65	25.59055116	0.40615385	8	314960.8	0.58069927	0.53301059	151479454	0.15147945
1.1	4.3307E-05	240000	0.65	25.59055116	0.40615385	10	393701	0.68694345	0.66626323	236686647	0.23668665

IR											
Pixel width (microns)	Pixel width (inches)	Range (inches)	Acceptable GSD (m/pixel)	GSD (inches/Pixel)	Focal Length (inches)	FoV (km diameter)	FoV (inches)	Angle	Sensor Length (inches)	Image Resolution (Pixels)	Image Resolution (GP)
	=A3/25400			=D3*39.3700787	=(B3*C3)/E3		=G3*39370.1	=ATAN((H3/2)/C3)	=2*F3*TAN(I3)	=(J3/B3)^2	=K3/1000000000
1.1	4.3307E-05	240000	0.6	23.62204722	0.44	6	236220.6	0.45732879	0.4330711	100000108	0.10000011
1.1	4.3307E-05	240000	0.6	23.62204722	0.44	8	314960.8	0.58069927	0.57742813	177777970	0.17777797
1.1	4.3307E-05	240000	0.6	23.62204722	0.44	10	393701	0.68694345	0.72178517	277778078	0.27777808
0.9	3.5433E-05	240000	0.7	27.55905509	0.30857143	6	236220.6	0.45732879	0.3037122	73469467.3	0.07346947
0.9	3.5433E-05	240000	0.7	27.55905509	0.30857143	8	314960.8	0.58069927	0.4049496	130612386	0.13061239
0.9	3.5433E-05	240000	0.7	27.55905509	0.30857143	10	393701	0.68694345	0.506187	204081853	0.20408185
0.9	3.5433E-05	240000	0.65	25.59055116	0.33230769	6	236220.6	0.45732879	0.32707468	85207192.8	0.08520719
0.9	3.5433E-05	240000	0.65	25.59055116	0.33230769	8	314960.8	0.58069927	0.43609957	151479454	0.15147945
0.9	3.5433E-05	240000	0.65	25.59055116	0.33230769	10	393701	0.68694345	0.54512446	236686647	0.23668665
0.9	3.5433E-05	240000	0.6	23.62204722	0.36	6	236220.6	0.45732879	0.3543309	100000108	0.10000011
0.9	3.5433E-05	240000	0.6	23.62204722	0.36	8	314960.8	0.58069927	0.4724412	177777970	0.17777797
0.9	3.5433E-05	240000	0.6	23.62204722	0.36	10	393701	0.68694345	0.5905515	277778078	0.27777808