

DISSERTATION

APPLICATION OF SYSTEMS ENGINEERING TO
COMPLEX SYSTEMS AND SYSTEM OF SYSTEMS

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ABSTRACT

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This dissertation is an investigation of system of systems (SoS). It begins with an analysis to define, with some rigor, the similarities and differences between complex systems and SoS. With this foundation, the baseline concept is development for several different types of systems and they are used as a practical approach to compare and contrast complex systems versus SoS. The method is to use a progression from simple to more complex systems. Specifically, a pico hydro electric power generation system, a hybrid renewable electric power generation system, a LEO satellites system, and Molniya orbit satellite system are investigated. In each of these examples, systems engineering methods are applied for the development of a baseline solution. While these examples are complex, they do not rise to the level of a SoS. In contrast, a multi-spectral drone detection system for protection of airports is investigated and a baseline concept for it is generated. The baseline is shown to meet the minimum requirements to be considered a SoS. The system combines multiple sensor types to distinguish drones as targets. The characteristics of the drone detection system which make it a SoS are discussed. Since emergence is considered by some to be a characteristic of a SoS, it is investigated. A solution to the problem of determining if system properties are emergent is presented and necessary and sufficient conditions for emergence are developed. Finally, this work concludes with a summary and suggestions for additional work.

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PREFACE

This work investigates the application of systems engineering to systems and system of systems (SoS). A progression from less complex to more complex systems is presented for the primary purpose of contrasting complex systems with SoS and showing the characteristics of SoS. A secondary purpose is to show how systems engineering can be used to develop baseline concepts solutions for complex systems and SoS. The result is a clear definition of SoS, multiple examples of complex systems which do not qualify as SoS, and a detailed analysis of a SoS showing by example the characteristics that make it a SoS. Finally, emergence is examined as a characteristic of SoS.

The discussion is introduced in Chapter 1 which provides definitions for complex systems and SoS. It builds upon prior work, refines it, and presents a definition that allows for a clear distinction between systems that are complex and SoS.

Four complex systems are analyzed. In Chapter 2, the baseline concept for a pico hydroelectric power generation system is developed. It is shown that it does not qualify as a SoS. In Chapter 3, systems engineering of a hybrid renewable electric power generation system is given. It combines multiple electric power generation methods into a larger complex system to achieve performance that each of the individual systems cannot. Systems engineering processes are applied and are shown to be effective in developing a baseline system concept. Chapter 4 describes the systems engineering of a low earth orbital (LEO) satellite system including the low cost consumer gateway terminals. A baseline concept is developed which shows the feasibility of the solution. While the system is complex, it does not qualify as a SoS and the reasons for this are given. Chapter 5 shows the systems engineering of a terabit per second satellite

communication system using Molniya orbit satellites. Molniya orbits are highly elliptical orbits with ground tracks that can be designed for a nearly north-south path in a portion of a hemisphere of the Earth. The baseline solution is a combination of the satellites, consumer gateways, and the operator ground stations. Trade studies and system level analysis are used to generate the baseline configuration and demonstrate its feasibility. These four system examples demonstrate how a system can be complex and yet not rise to the level of a SoS.

In contrast, a drone detection system is considered as a SoS in Chapter 6. The threat posed by drones being used as military weapons or in terrorist plots is real and growing. As a result, systems are required which can detect them so countermeasures can be used to neutralize the threat. The drone detection system utilizes a multi-spectral approach where information from multiple wavelengths is gathered, analyzed, and used to make decisions about the targets. Since multiple wavelengths increase the bandwidth of the information gathered about the target, the system has improved target recognition performance. A separate system is used for each wavelength of information that is gathered. Chapter 7 describes the prototype low cost radar sensor and includes the detailed analysis of the antenna and radar transceiver. The drone detection system is shown to be a SoS.

Chapter 8 describes emergence which is regarded by some as a characteristic of SoS. Emergence for systems engineering suffers from a few challenges including a clear method of distinguishing emergent phenomena from non-emergent. Therefore, necessary and sufficient conditions are developed for a system phenomena to be considered emergent and examples are given. The result is a proposed method for identifying emergence.

This work concludes in Chapter 9 with a summary and recommendation. The summary reviews the characteristics of complex systems and of SoS and how those definitions were

applied to the system baselines developed. The characteristics of SoS can be used as a guide for systems engineers in architecting systems so that maximum interconnectivity between systems can be used to realize increased functionality. Finally, suggestions for additional work are provided.

DEDICATION

Dedicated to Jonie, my wife and best friend forever.

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1. Introduction

History teaches us that human beings seem driven to create complex objects. Consider the ancient Egyptians who created The Great Pyramid at Giza more than 4500 years ago. It still stands as one of humankind's greatest construction projects. The development schedule was 20 years and the estimated cost of construction was the equivalent of \$5B [1]. The engineering, planning, budget, and project management required to complete it must have been comparable in scope to great systems being developed today. Some of the most complex systems developed in modern times may involve multiple billions of dollars and great teams of people working toward the deployment of the system.

An interesting aspect of systems is the level of complexity and interconnection they can achieve. They can have great complexity such as the Space Shuttle or a commercial airliner. They are complex in the sense that they have multiple subsystems and components all functioning together. The individual subsystems may not be useful by themselves, but when combined as intended, the results meet customer needs.

Another level of complexity exists when multiple independent systems are combined to form a system of systems (SoS). In this case, the individual systems function properly by themselves and meet customer needs. However, if they are interconnected together, then they create a more capable solution with functionality that cannot be achieved by the individual systems.

This chapter explores systems in general and develops a definition of a SoS. It builds upon prior work, refines it, and presents a definition that allows for a clear distinction between systems that are complex and SoS.

1.1 Benefits Of This Work

There are several important benefits of this work. First, the baseline concept is developed for several complex systems. For instance, the baseline for a hybrid electric power generation system is developed. Hybrid electric power is important for isolated locations where reliable electric power is not available such as forward military installations and remote villages. The baseline solution for a terabit per second satellite communication system is given using LEO satellites is also presented. In addition, the baseline system is described for a highly elliptical orbit satellite system with attractive features. One result of this work is that systems engineering baseline solutions are development for several meaningful applications.

A second benefit from this work is the baseline concept and advanced engineering prototype of a drone detection system is presented. There is significant concern regarding the possible use of drones as weapons against military, infrastructure, and civilian targets such as airports. What is required is a system that can detect the drones at airports so they can be disabled or destroyed before reaching their targets. This work develops a baseline solution and performs several advanced development efforts which result in a prototype demonstration. The result is a feasible solution worthy of additional development.

Third, this work demonstrates how to apply the practical distinctions between complex systems and SoS. On this approach, only those systems that meet the definition can be classified as SoS. The practical distinction is a tool for systems engineers to use when architecting solutions.

Fourth, emergence is examined for the purpose of generating a method to distinguish emergent phenomena from non-emergent. The necessary and sufficient conditions are developed for emergence and several examples for applying it are given.

Before the analysis begins some preliminary definitions must be provided which is the subject of the next section.

1.2 Definition of System and SoS

There are several terms used in this work that must be defined so that a common frame of reference can be established for the discussions that follow. The definitions here are not necessarily meant to be full and complete definitions—though appropriate care has been invested and references provided so that the definitions presented here can form the basis of a more detailed treatment. Rather the modest goal of these definitions is as stated—A common frame of reference.

Possibly the most important definition to develop here is of a SoS. This is no small task since a standard definition does not exist [2]. Even more challenging is whether SoS is a useful category at all. Or, is it enough to just make the distinction of complex systems? If so, then how is one to distinguish between a complex system and a non-complex system—where's the dividing line or demarcation? If such a demarcation exists to distinguish a non-complex from a complex system, then how is one to determine the point at which a complex system can be considered a SoS? Or, is it wrong to even consider that there is a continuum of system complexity with demarcations between them? Do these categories describe discrete types of systems each with a separate range and domain of activity? These are important questions that deserve answers which is part of the motivation for developing working definitions for them. A definition of systems is supplied followed by a working definition of a SoS with some characteristics of them.

1.3 What Is A System?

This section will define a system. However, before that is done, it is important to discuss why thinking about systems or in terms of systems is important. Traditional engineering is methodologically reductionistic in the sense that the whole is considered to be understood only when it has been decomposed to its lowest level constituent parts; those parts are analyzed, and the whole is reconstructed and described in terms of the function of the parts. For instance, if an automobile is analyzed using reductionism, then it is broken down into its main parts such as the drive train, electrical subsystem, safety subsystem, etc. Then each is further decomposed such as the drive train may be reduced to the motor, transmission, axles, and tires. This process is continued until the required limit of decomposition is achieved. The drive train is then reconstructed and its functioning is described in terms of the analysis of the parts. This is a powerful approach and has resulted in impressive advancements in technology and science.

However, this approach is not the complete story. The systems approach, which is compatible with methodological reductionism, focuses on the whole. It is “synthetic thinking, something to be explained is viewed as part of a larger system and is explained in terms of its role in that larger system ... the systems age is more interested in putting things together than in taking them apart [3].” This distinction between reductionism on the one hand and focus on the whole on the other hand is important for understanding what it means to think in terms of systems.

This approach provides an important perspective for thinking about systems and what they actually are. A working definition of a system is “a set of interrelated components working together toward some common objective ... [and] implies multiplicity of interacting parts that collectively perform a significant function [4].” In other words, a system contains many

constituent parts and each part works together through their relationships to one another to meet desired functions. A further refinement of the definition can be obtained by considering the parts and their relationships. A system is also an “assemblage or combination of functionally related elements or parts forming a unitary whole ... [and] is a set of interrelated components functioning together toward some common objective(s) or purpose(s) [5].” That is, a system is normally structured to contain a hierarchy of subsystems, components, and parts. For systems thinking, the emphasis is on the whole system rather decomposition to its constituent parts.

An important restriction on the definition of a system developed here is that it is constrained to engineered systems such as automobiles, communication systems, and bridges, to name a few. The definition is not meant to apply to the weather, mental activity, family relationship, or similar systems that are not (normally) engineered or part of engineering systems or programs. This restriction is not necessary for a working definition of a system, but it does allow the definition to apply more specifically to the types of systems considered in this work. A working definition of a system is:

An engineered assemblage or combination of interrelated elements which are normally organized in a hierarchy of subsystems, components, and parts all working together as a unitary whole toward some significant common objective(s) or purpose(s).

This working definition provides a common basis for the discussions that follow.

As mentioned earlier, system thinking itself is an important step to understanding the distinctions between complex systems and SoS. Prior investigators have developed several definitions of system thinking, but a synthesis of them is possible which was developed in [6].

Systems thinking has eight components:

- 1) Recognize Interconnections: This is a basic skill in systems thinking and requires the ability to identify the connections between parts of the system.
- 2) Identify and Understand Feedback: This builds upon the ability to identify interconnections by understanding that some of the interconnections form cause-effect feedback loops. System thinking requires the ability to recognize the feedback loops and how they impact system behavior.
- 3) Understand System Structure: This is a level of abstraction above the interconnections and requires understanding of the structure of system elements *and* the interconnections between the elements.
- 4) Differentiating Types of Stocks, Flows, And Variables: This system thinking skill recognizes that systems contain:
 - a. Stocks: These are pools of resources in the system. Resources covers a wide range from physical such as the number of operational optical sensors in a system to team building resources such as trust between long term team members.
 - b. Flows: These are the changes that occur in resources over time. For instance, the number of available optical sensors may change over time due to numerous causes.
 - c. Variables: These are the changeable parts of the system that affect stocks and flows. Examples of variables are the maximum and minimum number of optical sensors that will be operational during the life cycle of a system. Another example is the failure rate and replacement rate of optical sensors as a function of time.
- 5) Identifying and Understanding Non-linear Relationships: This system thinking skill requires the ability to identify which of the flows and variables have non-linear

relationships to other elements of the system and to factors external to the system. This should not be confused with skill 4) which focuses on linear relationships since this skill focuses on the non-linear relationships.

- 6) Understanding Dynamic Behavior: The interconnections, feedback loops, stocks, flows, variables, and systems elements create dynamic behavior in the system. Dynamic behavior includes unexpected system behavior.
- 7) Reducing Complexity By Modeling Systems Conceptually: This skill is more than just the ability to create models of the system, determine connections, and perform simulations. Instead, this skill also include the ability to simplify systems by abstraction, transformation, and homogenization so that the system becomes accessible cognitively by the stake holders.
- 8) Understanding Systems At Different Scales: This is the ability to simultaneously comprehend the details of a system and the big picture—the ability to recognize the various scales of complexity in systems and SoS.

These skills in thinking about systems are also important in SoS are needed in our complex world of interconnections.

1.4 What Is A System of Systems (SoS)?

The first use of SoS for modern systems appears to have been by Kenneth E. Boulding in 1956 [7]. He used it to describe a spectrum of theories that may help direct research toward gaps in theoretical models in the same way that the periodic table helped direct researchers toward filling in the gaps of known elements. The intent of K.E. Boulding appears to be that if a SoS approach is taken, then a higher level perspective is possible which provides the vantage point to notice gaps in the solution that need to be filled. This early effort has been expanded over the

decades and, as we will see, much sophistication has been added to the definition and scope of SoS. Despite this progress, there is still no universally accepted definition of SoS. We will consider four ways to define a SoS which will lead to the working definition used here.

The first approach is to define a SoS as simply consisting of multiple systems [8]. However, a challenge of this approach is that one man's subsystem is another man's system. This means that to the subsystem developer, who views the subsystem as a system, the next level up is a SoS. Therefore, if this approach is taken, then it may possible to define nearly *any* system as a SoS since the definition will depend upon the level of the observer in the hierarchy of the system(s). Therefore, this approach cannot be correct since it does not provide a good filter for recognizing SoS.

A second approach to defining a SoS may be to describe its characteristics. In this way, a SoS can be said to exist if it possesses most, or preferably all, of the characteristics which is the approach take in [9]:

1. The SoS is comprised of individual and valid systems. In other words, each of the systems in the SoS meet the definition of a system provided in the previous section.
2. When the elements of the SoS operate together, they produce results that the individual systems cannot because of collaboration between them.
3. Many, or most of the systems in the SoS operate independently. In other words, each system will continue to achieve its required purposes even if it is removed from the SoS.
4. Many, or most of the systems are developed and engineered independently for their own purposes independent of the SoS. This means that the development effort is not controlled by SoS developers or managers, though the development of a particular system

may have been commissioned by the SoS. In fact, the SoS may partly or wholly consist of previously existing systems which were developed without the SoS in mind.

5. Many, or most of the systems are independently managed to achieve its required purposes.
6. The systems are often, but not always, geographically distributed. This means that there may be physical separation between the systems and the exchanges between the systems are information and not mass or energy.
7. The systems often, but not always, change and evolve over time. This is partly due to the fact that each system is independently managed and may be modified over time. It can also be due to the fact new functionality will emerge from the SoS that was not expected.

On this approach, the seven characteristic are used to filter out SoS. However, each of the seven characteristics are vulnerable to counter examples. That is, for each of them, it is possible to quote examples that fit the given characteristic but are not a SoS. For instance, a constellation of GPS satellites is geographically dispersed which meets item six in the above list. However, GPS satellites are part of one system so item six alone is not sufficient. Therefore, on this approach the SoS must possess most, if not all, the characteristics in the list.

A third approach developed in [10] attempts to overcome the vulnerability to counter example and emphasizes independent management which is item five in the above list:

A system of systems is a product of a system engineering process that contains one or more systems for which significant aspects of the integration and life cycle development of the component system(s) are beyond the managerial control or influence of the larger system.

An interesting part of this definition is the phrase “of a systems engineering process.” This means that the SoS itself is engineered and not a happy accident that emerges unexpectedly. This definition does not exclude the fact that some functionality in the SoS may emerge unexpectedly, but this definition does mean that the SoS itself is intentional. This also does not mean that the individual systems existed prior to or after the engineering of the SoS. Indeed, on this definition, the component systems may be a combination of prior existing systems and newly developed. This definition along with the list of characteristics of SoS provides an improved method to distinguish, or filtering out, SoS from other systems, but more refinement of the distinguishing features of a SoS is possible.

Table 1. Description of different types of Systems of Systems based upon their level of independent management (After [10]).

Type of System of Systems	Description
Directed	Individual systems are subordinated to the SoS. Objectives, funding, and management authority rest with the SoS.
Acknowledged	Individual systems retain their own management, funding, and management authority in parallel with the SoS.
Collaborative	Individual systems voluntarily work together to address shared or common interests. Objectives, funding, and management at the individual system level only (no separate funding for the SoS).
Virtual	Individual systems unknowingly work together. Objectives, funding, and management at the individual system level only (no separate funding for the SoS).

A further refinement of the independent management aspect of a SoS is given in Table 1 which describes a taxonomy of four types of SoS based upon the level or intensity of the management function [11]. The first type is *Directed* in which the individual systems are subordinated to the SoS. In this type, the objectives, funding, and management authority rest with the SoS. The second type is *Acknowledged* in which the individual systems retain their own management, funding, and management authority in parallel with the SoS. The third type is *Collaborative* in which the systems voluntarily work together and the objectives, funding, and

management rests at the individual system level only. The SoS has no separate funding or objectives, rather the individual systems operate together to address shared or common interests. The forth type is *Virtual* in which the systems operate together, but the individual systems do not know they are cooperating. An example is the Internet which only specifies the communication requirements but very little else. These four types provide additional insight into how independent management can be a defining characteristic of SoS.

Table 2. Comparison of systems engineering and system of systems engineering (after [11]).

Feature	Systems Engineering Perspective	System of Systems Engineering Perspective
Scope	Project/Product Autonomous/Well-Bounded	Enterprise/Capability Interdependent
Objective	Enable Fulfillment of Requirements Structured Project Process	Enable Evolving Capability Guide Integrated Portfolio
Time Frame	System Lifecycle Discrete Beginning and End	Multiple, Interacting System Life Cycles Amorphous beginning and precursors
Organization	Unified and Authoritative	Collaborative network
Development	Design Follows Requirements	Design is Likely Legacy-Constrained
Verification	System in Network Context One Time, Final Event	Ensemble As A Whole Continuous and Iterative

A fourth, and final approach considered here for distinguishing a SoS, the authors in [12] compared traditional systems engineering and systems of systems engineering (SoSE) as shown in Table 2. It describes the engineering perspective toward features of the system and this is a way to know one is dealing with a SoS and rather than a complex system. While this approach is vulnerable to the charge that it depends upon the perspective of the observer as with our first definition (i.e., one person's subsystem is another's system), it does provide a way to consider the uniqueness of SoS since it focuses on the bigger picture. In some ways, it harkens back to the definition provided by Boulding in 1956 which was described at the start of this section. The perspective of the SoS engineering must be larger than the systems themselves so that any

missing systems or connections can be noticed and included. The table provides an additional way to understand the differences between systems and SoS.

The approach taken in this work is to take the best of these four approaches. The first two definitions are accepted so a SoS is a combination of systems which possess the seven characteristics given above. Each of the systems may have their own management and financial control as with definition three. And finally, the engineering perspective of a SoS is different than for a system which is the point of definition four. Though no universally accepted definition of a SoS exists yet, this approach of combining the seven characteristics with emphasis on a refined definition of independent management and the engineering perspective may be step toward it.

1.5 System Architecture and Concept Development

Determining system architecture is an important step in the development of a system baseline concept. This is because it sets many important aspects of the system and guides future development. This work utilizes SoS architecting in the chapter on the multispectral drone detection system. Therefore, it is important that a definition of SoS architecting is provided. As a starting point, consider the definitions:

- 1) In IEEE Std 610,12 architecture as is defined as “the organizational structure of a system or component.” [13].
- 2) In the ISO/IEC/IEEE 24765 International Standard, it is defined as “fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution ... the organizational structure of a system and its implementation guidelines.” [14]



Using SAI Method

Fig. 1. Major steps in the systems engineering process consist of Concept Development, Engineering Development, and Post Development. Our focus in this work is on concept development and for the SoS described in Chapter 5 the SAI method is used (After [15]).

- 3) In [15], the authors define “architecting as the process of structuring the components of a system, their interrelationships, and their evolution over time.”

Though all three of these definitions are useful, the last definition includes the aspect of the system evolving over time. This is an important factor for SoS and as our society becomes more interconnected through data networks, this aspect of the architecture being adaptable to change is critical.

An output from a successful system architecture is a baseline concept. The concept development step in a system’s life cycle is shown in Fig. 1 as the first major systems engineering step for a new system [16]. In this work, all the non-SoS systems are developed to the point of a viable concept. Also shown in the figure is the SoS Architecting with Ilities (SAI) approach [17]. A simplified version of this method will be used for the Multi-Spectral Drone Detection (MSDD) system described in Chapter 6.

The SAI method was developed at MIT and “is an end-to-end process that guides systems architects throughout all phases of conceptual design.” [18] The method is illustrated in Fig. 2 which shows the eight step process in SAI and the interrelationships. The eight steps will be briefly described now and their application will be given in Chapter 6.

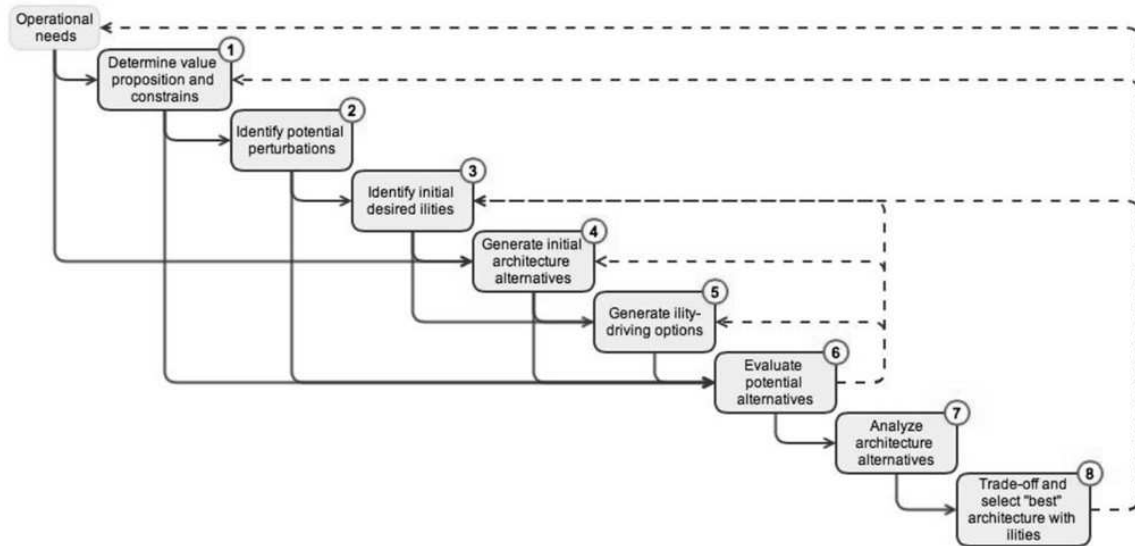


Fig. 2. The eight steps of the SoS Architecting with Ilities (SAI) method of concept development (From [17]).

As can be seen in the figure, the eight steps start with an operational needs description which is a statement of the operational goals of the SoS. It is simple, and can be a single sentence or several sentences. The attributes needed for the system are derived from this statement. The eight steps can be summarized as [19]:

- 1) *Determine Value Proposition and Constraints*: This step requires the identification, understanding, and documentation of overall SoS architecture value propositions.
- 2) *Identify Potential Perturbations*: This is the identification and categorization of possible perturbations that can interfere with the SoS value delivery.
- 3) *Identify Initial Desired Ilities*: In this step, the ilities are identified that promote the long-term behavior of the SoS. Combining possible perturbations with desired ilities can begin to distinguish ilities.
- 4) *Generate Initial Architecture Alternatives*: The purpose of this step is to generate value-driven (values from Step 1) alternatives for the SoS architecture. The

alternative definitions will include design variables and operational variables along with concepts of operation.

- 5) *Generate Ility-Driving Options*: This step is concerned with the generation of and selection of options that can be added to architecture alternatives to achieve desired ilities.
- 6) *Evaluate Potential Alternatives*: This is the modeling of various alternatives (generated in Step 4) in terms of relevant metrics. Example metrics are value (attributes and cost), and ility metrics. This may include quantitative modeling and simulation, but can also occur at higher levels of abstraction.
- 7) *Analyze Architecture Alternatives*: This is the deep analysis of data generated in Step 6 for the purpose of developing understandings of the possible trade-offs that exist with the alternative SoS architectures.
- 8) *Trade-off And Select “Best” Architecture With Ilities*: This step uses the deep analysis results from Step 7 to make decisions about the preferred architecture. The output from this final step is the baseline solution that will be carried forward into detailed design. This stage may include advanced development efforts required to reduce the risk of certain technology aspects and to support the selection of the “best” architecture.

A simplified version of this approach for SoS is the conceptual development phase of SoS Engineering (SOSE).

An important benefit of the SAI method is that it was developed for SoS that must sustain value delivery over time when the operational environment is expected to change. This is

important since it is expected that the operational environment of a drone detection SoS will remain uncertain and fast-changing.

1.6 Chapter Conclusions

Mankind is driven, it seems, to create ever complex systems which may be part of the reason for the existence of SoS. The definitions of systems and SoS were given. It was acknowledged that a standard definition of SoS does not exist, but several possible definitions were reviewed and modified. The result is a working definition of SoS that is used in this work. The type of collaboration between the systems was described and the definition of system architecture was given. Finally, the SAI method was described and an application of it will be given in Chapter 6. These definitions and assumptions will be used throughout this work.

2. Pico Hydro Electric Power In The Nepal Himalayas

The first system we will consider is a pico hydro electric power generation system intended for deployment in remote rural areas.¹ The example application is the Nepal Himalayas. Some may consider this a SoS since it contains power generation equipment such as turbines and generators, water gather and transportation using canals and tubes, electric power storage using batteries, power distribution, and consumer usage metering equipment. Such a complex system surely must be considered a SoS—correct? This chapter will describe the baseline concept of a pico-hydroelectric power system and though it is complex, it does not qualify as a SoS.

2.1 Introduction

Pico-hydro (pH) electric power generation has many benefits as a green energy source which includes year round 24 hours a day generation, high reliability (if properly designed), low operating cost, and low environmental impact.

Rural areas in Nepal are a good candidate for pH systems for several reasons. First, less than half the population has access to the state owned electric utility, and supply deficits mean that load shedding occurs up to 16 hours per day [20]. Second, more than 80% of the population lives in rural areas. Third, expansion of the state owned grid into rural areas is technically and financially not viable due to the dispersed population and rugged terrain. This means that it may be many decades (or longer) before grid connection reaches additional rural areas of Nepal. Fourth, water resources exist and the slope of the terrain in many areas means that building head pressure is easily attained. Fifth, 75.3% of the energy used in households is wood which increases CO₂ emissions, deforestation, and reduced health due to the smoke since much of the

¹ © [2016] IEEE. Reprinted, with permission, from: R. Sturdivant, J. Yeh, M. Stambaugh, A. Zahnd, E.K.P. Chong, “Pico-Hydro Electric Power In The Nepal Himalayas,” *IEEE Green Technologies Conference*, Denver, CO, March 30-31, 2017 (to appear).

wood is burned indoors. Electric power can alleviate a portion of the wood burning. These reasons mean that rural Nepal is a good candidate installation site for pH.

The village for installation of the system has been identified and it is Moharigaun, a village of approximately 230 people located at 3150m elevation in the district of Jumla, in the remote North West of the country. The nearest village served by an airport is Jumla at 2350m elevation, and is accessible part of the way by a crude road navigable only by foot, motorcycles, and farm tractors, and only during the dry season. Most people simply walk the 26 km to the village. Jumla is located 350 km from Kathmandu as the crow flies, but 830 km by road through very mountainous terrain.

RIDS-Nepal has worked with the Moharigaun village since 1998, and is the lead organization for the construction and operation of the pH system, under direction of personnel from RIDS-USA and RIDS-Switzerland who are leading the development effort. In fact, RIDS-Nepal has a long track record of successfully deploying solutions to Nepal which are contextualized to the geographical, cultural, and religious environment.

A scientific approach has been taken to the prior systems to monitor and document the effects of each deployment, and this approach will also be used in the pH system. A few examples of prior work by RIDS-Nepal in Moharigaun are a smokeless metal stove which reduces harmful Respirable Suspended Particulate Matter (RSPM), carbon monoxide (CO), and other dangerous gasses in village homes, greenhouse systems which allow for off-season food to be grown, small photovoltaic (PV) solar power solutions for minimal indoor lighting, sanitary pit latrine, and clean water solutions. The next solution under development is the pH system.

Part of the benefit of the long term relationship of RIDS-Switzerland/Nepal and the Moharigaun village is the local context and needs of the users is well understood. This long term

relationship means that there is a pre-existing trust factor and understanding of what is required to build a strong local ownership factor. This benefit is crucial for high impact systems engineering of the solution.

Prior work on pH electric power by other investigators has demonstrated its potential for off-grid electrification. In [21], for instance, an assessment was made of a pH system in a small village in Laos. It focused on improvements to operation of an existing system to increase output and efficiency. However, the long term sustainment of the system was not addressed. Another example is in [22] which shows measured performance of a pH system in Thailand, but focuses mainly on a hybrid system with photovoltaic (PV) and does not address the sustainability of the system or its key subsystems. Another study in [23] investigated pH along with biogas generation as an energy solution for the country of Cameroon in Africa. While the analysis did show that pH with biogas provided a more economic solution, the analysis did not include a standalone pH system. A different approach is taken in [24] where an existing irrigation pump system is used to create water flow that turns a turbine. Beside the concern over the actual net power generation from such a system, this approach is not applicable for systems that use surface water which is the case for the Moharigaun village in Nepal. The source of water is from local rivers and streams. These examples of prior work demonstrate the potential for pH systems.

While these prior investigations by other workers provide valuable results, they all focus either on one or a few of the factors required for a sustainable solution. What is required is a solution from a systems engineering perspective to ensure value sustainment over time to the system stakeholders. Failure to consider the socio-economic factors has been identified as a major cause of failure in long term sustainment of rural green electric power systems [25]. Therefore, the purpose of this work is to describe the systems engineering of a baseline concept

for pH electric power solution in the Himalayas of Nepal that is highly contextualized to the needs of the users. The expectation is that this highly contextualization approach will significantly improve the long term sustainment of the system.

Table 3. Top four user needs of the pico-hydro system.

Need	Description
Simple To Maintain System	Village residents have no exposure to simple modern technology. For instance, most have never held a screw driver.
20-40 Watts Per Household	Allows for 4 LED bulbs per household.
Workable Economic Approach	The cost to the residents must be affordable.
Reliable Power	Reliability will increase economic activity.

2.2 Stakeholder Assessment

An important part of engineering a system is to understand the stakeholders. For the pH system, three stakeholders are identified and their particular needs and interests are described.

The first stakeholder is the users of the system. As stated earlier, a benefit of the long project relationship with the Moharigaun village is a deep understanding of their geographical, cultural, and religious context. This means that an assessment of their needs as stakeholders in the system is less challenging than it would otherwise be.

The needs analysis of the users revealed that there are four primary needs and they are summarized in Table 3. A more detailed description of each is:

- Simple to Maintain System: Many of these villagers have never ridden in an automobile, and have never held a screwdriver in their hand. Access to vulnerable points in the system must be restricted to trained operators, and maintenance procedures must be basic.
- 20-40W Per Household: Although Nepal has a goal to provide 100W per household, sustainment of a system capable of delivering this much power over its lifetime is not practical considering the village's subsistence farming economy, and its anticipated

population growth rate. Of prime importance is that the system be able to drive 4 LED bulbs per household at 2-5W each to reduce indoor air pollution by eliminating the practice of burning wood for light, while enabling education and reading into the evening hours.

- Workable Economic Approach: The villagers are poor subsistence farmers and the solution must be at a cost that meets their needs.
- Reliable Power: Power must be available to drive economic development in order to provide the funds needed to maintain the system

The second stakeholder is the system development and deployment team. The first measure of success of the project is the deployment of the system that can expand to meet customer needs over the expected lifetime of the system. This means that the system functions in a holistic sense technically, financially, and socially. A second measure of success from this stakeholder group is the ability of the system to serve as a test bed to optimize the technical operation, social factors, and long term sustainment. The goal is for the system to be seen as a Nepal solution so that local ownership and sustainment can be accomplished. If this is achieved, then the system can serve as an example for other villages in Nepal that desire reliable electric power.

Table 4. Seven reasons for failure of past systems.

Feature or Equipment	Traditional Approach	RIDS-Nepal Approach
Water Canal	Exposed Canal: Susceptible to destruction from small surface landslides common in the region	Buried Pipe: Delivery of the water to the turbines with protection from surface landslides. Increases reliability.
Turbine	Single Turbine: Offers no system redundancy and its difficult to add turbines due to phasing issues.	Multiple Turbines: Allows redundancy to increase reliability and sustainability, lower replacement cost if one fails, system continues to provide power, and the ability to expand capacity as the village's electrical

		demands and economic vitality increase.
Generator Drive	Belt Drive: Belts usually break within 3 years and are expensive to replace.	Direct-Drive: Each turbine is connected to its own generator. Eliminates risk of belt failure which increases reliability.
Transmission Lines	Overhead Transmission Lines: Used dead trees which rot since they are not treated to resist moisture rot. Support failure results in line fault.	Buried Transmission Lines: No support which removes the risk of rot and transmission lines are protected.
Surge Capability	No Surge Capability: Peak demand over generator capacity requires load shedding.	Battery Surge Capability: A small bank of batteries allows the system to deliver peak power in excess of generator capacity.
Economic System	No Financial Plan: No economic plan to support maintenance and operations. No plan for collection of fees.	Use Smart Pay-As-You Go Meters: The system will only deliver power if the user has pre-paid for the energy.
Excess Energy	Dumped To Exit Water: Excess power is dumped into the exit water stream as heat.	Excess Energy Utilized In The Village: System heats green house, community bathing water, and biogas digester.

The third stakeholder is the financial sponsors of the system. The sponsors have an interest in the success of the system for philanthropic reasons. Their primary measure of success for the project is the long term sustainment of the system in a way that makes a measureable difference in the lives of the Moharigaun village residents. The secondary measure of success of the system is that it becomes a template or example system that other villages copy. As can be seen, the measures of success for the second and third stakeholder groups are nearly exactly aligned.

2.3 Assessment Of Current pH Systems In Nepal And Solutions For Their Limitations

An important step in systems engineering is to survey the existing solutions to determine if they are meeting current needs. If the existing solutions are not meeting the needs of the users,

then it is critical that the reasons are understood. Then solutions can be identified which become features and requirements for the new system.

While it is true that some prior electric power systems have been installed in Nepal villages, most of these installations suffer failure (often catastrophic failure) within a few months to 2 years of installation and so they are abandoned. As a result, a study was conducted to determine the sources of failure for these systems. The main sources of failure are summarized in Table 4 and a more complete explanation of each is:

1. Water Canal: In the target village, the river water travels approximately 500 meters to create the 30m head needed by the turbines. This means the water must be moved this distance. The traditional method for water transportation is to use exposed canals. The canals are dug using hand tools by the local population which is a big investment of labor. However, these canals are susceptible to small landslides that regularly occur and are a source of failure in prior systems. The proposed system overcomes this limitation by using buried HDPE pipeline.
2. Turbine: Prior solutions use a single turbine which means there is no redundancy for this function in the system. As a result, prior systems have failed. A solution is to use multiple turbines so that if one fails, the system still functions.
3. Generator Drive: The traditional approach is to use belts to transfer the rotational energy from the turbine to the generator. These belts typically fail after 5 months to 3 years. The new system will use direct drive so that each generator is directly connected to its own turbine.
4. Transmission Line Faults: The distribution system from the power house to the village has traditionally been constructed using above ground transmission lines using bare aluminum

wires. However, the supports for these lines are untreated dead trees increasing the already devastating deforestation. After 2-4 years, the trees rot which means the lines either fall to the ground creating a short or the lines are broken creating an open fault. The solution is to use buried armored transmission lines. In this case, no support structure is required and the buried transmission lines will be protected from wear and mischief.

5. Surge Capability: Traditional approaches lacked surge capability so that load shedding was required when peak demand exceeds the capacity of the generator. The new system includes a small bank of batteries to allow the system to have surge capability, e.g. to start motors, well in excess of the turbine capacity.
6. Economic System: The historic systems did not include a viable economic system that provides the funds required for system operations and maintenance. The new system uses pay-as-you-go meters so that residents must pay prior to the delivery of power. Moharigaun already supports the use of pay-as-you-go meters in their future system.
7. Excess Energy: While the handling of excess energy is not a direct reason for failure of prior systems, the efficient use of excess energy can provide benefits to the community which increases overall user satisfaction and therefore village commitment. The new system uses the excess available power to support growth through lights in some of the high-altitude green houses, heating for hot showers and community bathing, and heating biomass for optimum anaerobic digester function for biogas generation.

Table 5. Financial summary showing the construction costs and operating budget for the first five years in 2016 U.S Dollars.

Budget Line Line Item	Total	Village Contribution	Donors Contributions	Budget Deficit
Total Pico-Hydro Power Construction Costs	129,926	17,165	112,761	0
Total pH System Monitoring & Website Costs	43,176	0	43,176	0
Total Operations Costs Over 5 Years	28,150	3,150	0	-25,000
Total Local Staff Cost Over 5 Years	7,009	0	0	-7,009
Total Pico-Hydro Power Transportation & Import Costs	11,617	0	11,617	0
TOTAL Mohorigaun Pico-Hydro Plant (+/-15%) Cost Estimate in US\$ for 2016 out of the total 5 year project	219,878	20,315	167,554	-32,009

2.4 Financial Model

A summary of the financial model is shown in Table 5. There are at least four things to note from the table. First, the table includes the total deployment cost and the operating cost for the first five years except for the cost of travel for RIDS personnel from the USA and Europe. Second, the table shows that the local residents will participate in the construction and operating cost. Third, budget assumes contributions from donors of approximately \$167.5K (U.S. Dollars). Forth, and possibly most important, there is a budget deficit of approximately \$32,000 and all of it is associated with the operating cost and local labor cost for maintenance.

However, the system includes four generators, but only one of them is used and paid for by the village for the first few years. The other three are to show scalability of the system and for operational trade studies to understand the capabilities and issues as the system scales. Therefore, the plan is to have the 75% of the budget short fall to be covered by additional donors. The remainder will be covered by increased economic activity in the village.

Therefore, this plan includes economic development enabled by the availability of electric power as an assumption for long term viability.

Based on the current economy in Moharigaun, the village has already committed to pay 150 Nepali Rupees per month per household, approximately 1.50 USD, toward an O&M fund. This is enough money to pay a modest salary to the trained operators of the system, but not enough to create a significant maintenance fund. Economic development is needed to create the income stream needed by the village to sustain their system in the long term.

Significant work has already been done in Moharigaun to lay the foundation for economic development. In addition to the improvements needed to address the health and education of the village, one example is that 10 people in the village have been trained as

carpenters, and are already producing high quality furniture using hand tools. Considerable efficiency can be gained with the introduction of electricity to drive power tools such as a band saw, table saw, drill press, and planar, but this by itself does not guarantee a successful business. In addition to efficiency and skill, marketing, availability of raw materials, and transportation can be challenges in remote areas.

A custom carpentry shop holds significant promise. Although the authors know of no statistics on the total number of households in the area around Moharigaun, insight into the market size can be gleaned from a survey conducted in 2014 and a more detailed survey in 2015. They included the 6 villages that are in a project partnership with RIDS-Nepal since 2010 and 2013 respectively and are also potential furniture customers. In addition, 13 neighbor villages that have requested to partnership with RIDS-Nepal. Based on the detailed 2015 survey, by the end of 2016, it is estimated that there are a total of 2072 households in the 19 villages (the 13 new ones and the 6 present partner villages), providing an even larger potential market for furniture.

Given the 2.5% annual growth rate, approximately 50 new homes would be built each year in just these 19 villages. In addition to window frames, doors, and furniture, most of these homes will install built-in cabinets and shelves to air-dry dishes to kill waterborne pathogens.

The furniture is currently built using crude hand tools, taking considerable effort with mixed results, so the value-add of a skilled and motorized custom carpentry shop would be significant. Transportation costs would be minimal since their customers are all within walking distance. Marketing can be done using word of mouth, and personal contacts.

Furthermore, Moharigaun has a plentiful supply of wood close by because the forests have not been deforested due to its remoteness. Although external competition should be

minimal due to transportation of goods and the need to send personnel into homes and businesses to take measurements, similar businesses could be created in close by villages even though Moharigaun would have a slight advantage due to its easy access to wood.

In addition to the 50 new homes built each year in these 19 villages, additional villages and many existing households have delayed these improvements due to lack of skills, cost, or time. The net effect is that there should be a good market for a custom carpentry shop, and Moharigaun is poised to succeed in this market.

It is also important to keep in mind the local context and understanding of electricity. Because of the lack of experience to live with electricity, the local users in Moharigaun still do not have a clear understanding of its value. Therefore, there is learning that must occur over time—learning to live with and develop opportunities with their new access to electricity.

2.5 Baseline Concept Description

The baseline concept for the system from the intake to the power house has been developed. As can be seen in Fig. 3(a), the system will create a 30m head at the turbine house. Fig. 3(b) shows the settling pond is near the intake. The water flows from the intake for 500 meters using 2.5 PN HDPE pipe penstock to the turbine house and the last portion will use PN4 pipe.

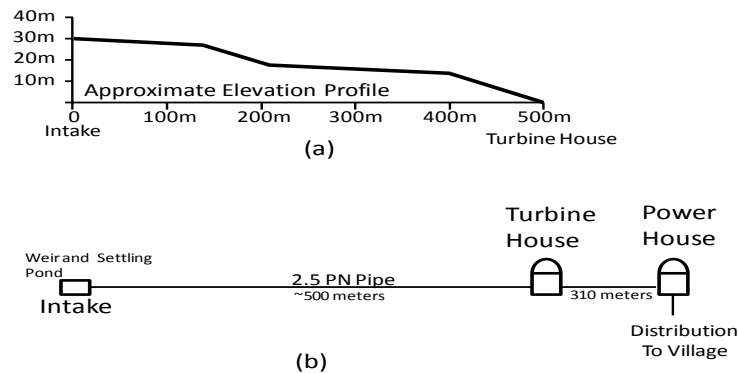


Fig. 3. Illustration of the elevation, distance from intake to turbine house, and settling pond.

The turbine house has four turbines, each of which includes an integrated permanent magnet generator. Each turbine/generator is rated at 1600 W. The system includes battery power storage for surge capability and to provide a stable voltage for the charge controllers.

From the turbine house to the distribution station, the power lines will be buried. The baseline configuration will use PVC insulated power cables with aluminum conductors. The power cables have 4 cores and each core is 16mm² cross-section and complies with IS8130 specification (higher voltages, such as 350V, may be used so smaller cross section wire can be used). The cabling includes an armor layer of galvanized steel strips and a PVC outer sheath.

The power house handles the distribution of electric power to the community as shown in Fig. 4. Note that the plan includes lighting that is distributed throughout the community as walking path lighting.

An important part of the pH solution is the sensors that are distributed through the system. The sensors gather data which is relayed to the power house. The sensor data is aggregated and transmitted via satellite link back to the U.S.A. and Europe where it is analyzed.

From our analysis, there are 26 candidate sense points in the system, but many of the points have multiple items to sense. For instance, some voltage sense points for the

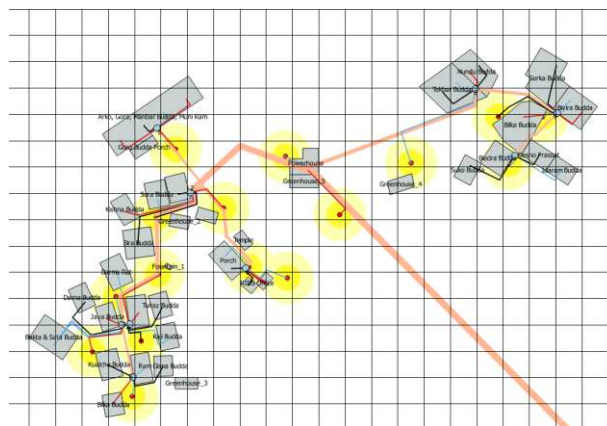


Fig. 4 Village distribution and lighting plan.

generators are sensing at each generator and there are four generators. As a result, there are 83 separate measurements that can be sensed.

2.6 Conclusions and Assessment at a SoS

The team that has developed prior solutions in Nepal is RIDS-Nepal. The team for the pH system also includes Azusa Pacific University (California, USA) and Aurora Power and Design of (Boise, Idaho, USA)

As stated earlier, the installation site has been identified and the development team has made several visits to obtain details on the terrain and ensure the village population is still enthusiastic about the system since they will be providing most of the manual labor required to install the system.

The approach to this pH system and prior solutions deployed in Nepal follows a change management process to ensure the villagers actually adopt the changes long term. Unfortunately, without economic improvements, these and previous gains will not be sustainable by the villagers alone, requiring continued external support to maintain the improvements and expand them to new families. Electricity is a prerequisite for economic development. This is why this program exists to help Moharigaun build a modular pico-hydroelectric system, complete with the means to remotely monitor its operation. The vision is for this system to be optimized over time so that a reliable and scalable design can be used throughout the region.

On a different note, one of the concerns for deployed power systems is their eco-friendliness. This approach considers more than just the carbon foot print of a power generation system, but also considers it from a wider context and other impacts to the environment as in [26]. One example is that only a small portion of the stream is diverted to power the turbines,

and this is done without dams. While care has been exercised in the design of this system for eco-friendliness, more work is still possible to improve in this area.

SoS Assessment

The pico-hydro electric power system is complex since it has many different components and subsystems. As discussed, properly addressing the limitation of prior systems requires a systems engineering perspective that considers all stakeholder concerns. The PH system is complex.

Regardless of the complexity of this system, it does not rise to the level of a SoS for at least three reasons. First, the system is not comprised of individual and valid systems. Instead, the system is comprised of multiple subsystems. Second, the system is not comprised of separate systems each under independent management. Instead, the complete system is under management control of one team. Third, the system is not comprised of independently developed systems. Instead, it is comprised of subsystems which are developed together for one purpose. For these reasons, the PH system is not a SoS.

3. Systems Engineering of Hybrid Electric Power

The second to be considered in the progression for low complexity systems up to the final SoS example is a hybrid electric power generation system.² This system is a good example of a complex system with several standalone systems that can exist on their own. However, the resulting combination does not qualify as a SoS since each of the elements lack independence management. Instead, the systems are intentionally managed as a complex combination.

Systems engineering uses a set of tools and techniques that can be applied to a variety of system development projects. For instance, they have been applied to radar development and satellite systems for many decades.

Systems engineering has also been applied to renewable systems. For instance, [27] investigates the ways that systems engineering must be modified to be useful in a renewable energy research environment. In [28] the benefits of systems engineering to renewable wind energy is investigated by examining the modeling tools related to wind energy systems. They find that systems engineering is useful for optimizing the full wind plan to achieve the lowest cost and maintain production. The work in [29] takes a similar approach and shows how systems thinking can be used to analyze the sustainability of wind energy. A different approach is taken in [30] which examines the concept development for wind and civilian nuclear power. All of these approaches show how systems engineering can be applied to particular energy systems.

A different line of analysis is taken in [31] which acknowledges the benefits of hybrid power systems and reviews the simulation and design models that have been used. Along the same line of thinking, the optimum sizing of each renewable energy source in a hybrid system is

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analyzed in [32, 33]. They found that various sizing methods can be applied to realize a techno-economically optimum hybrid renewable energy system. While these approaches for the development of hybrid energy systems yield useful results, they do not take advantage of the benefits of a systems engineering approach for the development of a hybrid energy system.

Therefore, this chapter shows how systems engineering methods and tools can be applied with benefit to the development of hybrid renewable energy systems. We focus on a standalone system that is applicable in remote or off grid applications where a baseline power source and one zero emission energy source are combined. More than two electric power sources could be combined, but this would add undesired cost and complexity to the system.

3.1 Concept Development

In this section, we perform a needs analysis and develop the system concept. The concept development uses a trade study to explore the possible alternatives. This allows the baseline design to be selected.

3.1.1 Needs Analysis

Initially, this system was conceived based upon the needs of one niche customer group with high availability of solar irradiation. However, several other customer groups were identified that shared common requirements. The additional customer groups make the economic opportunity more attractive. The three customer groups are:

1. Remote Energy Users: Typically in people-groups in economically disadvantaged nations.
2. Emergency Response Government Agencies: These groups are concerned with restoring electric power to essential infrastructure.

3. Military Agencies: These groups must provide electric power to remote operating units.

Adding these groups as potential customers increases the financial viability of the system.

These customers have common needs which are:

1. Stand-Alone System: The system must be off grid.
2. Portable: The system must be capable of being transported using standard shipping containers.
3. Availability of at least 90%: The combination of power generation systems must provide electric power at least 90% of each day.
4. Renewable Energy: The energy sources must be renewable.
5. At Least 250kW of Power: The system must be capable of generating at least 250KW of electric power.
6. Low/Moderate Relative Cost: Deployment cost must be managed to increase the possible customer base.

In addition, this program has a list of requirements. These requirements are meant to maintain a reliable system. They are:

1. Low Development Risk: The system must use proven technology.
2. High Efficiency: The energy conversion must maximize efficiency.

3.1.2 Concept Analysis and Baseline Selection

The concept development for this system follows one of the systems engineering methods of combining and swapping functions to create new alternatives [34]. Because of the requirement that the system must only use renewable energy sources, and because this is actually a system-of-systems, our approach to generating concepts that meet customer needs is to combine the

available renewable energy systems. For our analysis, we considered eight of the available renewable energy systems:

1. Biomass: Biological materials are converted into fuels using either anaerobic digestion or pyrolysis.
2. Geothermal: Energy converted from the heat below the surface of the Earth.
3. Hydroelectricity: Energy stored in a watershed such as a dam is used to generate electricity.
4. Hydrogen: Using hydrogen as a fuel with electric power and water as byproducts.
5. PV Solar: Electric power using photovoltaic solar cells.
6. CSP Solar: Systems that concentrate the sun’s power onto a material that is heated and used to generate electric power.
7. Wave and Tidal Energy: Using waves from the ocean and the conversion of the mechanical energy into electric power.
8. Wind: The energy in wind is converted to electric power.

While this list presents several possible alternatives, it can be immediately noticed that several will not meet customer needs. Therefore, we will make decisions based upon non-conformance to eliminate them. The initial decimator is the requirement of transportability.

	Biomass	Hydrogen	PV Solar	CSP Solar	Wind
Biomass		✓	✓	✓	✓
Hydrogen			✓	✓	✓
PV Solar				✓	✓
CSP Solar					✓
Wind					

Fig. 5 Matrix of possible combined systems assuming only two systems will be combined.

Based on this requirement, geothermal, hydroelectricity, and wave/tidal energy can be eliminated for the simple reason that these energy sources cannot be transported.

The remaining five options can be examined. The possible 10 combinations are shown in Fig. 5 . As stated earlier, only two systems will be combined. Each one of the options is considered concepts that are possible solutions to meet customer needs. The next step is to evaluate the possible options and select a baseline design.

During this phase of development, the concepts are explored and subject to trade study analysis. As part of the trade study analysis, several selection criteria are generated based upon requirements for the system. The criteria being used here are portability, technology maturity, provides at least 250kW of electric power, low development risk, investment cost, efficiency, and availability.

Each of the criteria is given a weighting, W_k , which is related to its importance to the mission of the system. Each of the energy generation options is assigned a value, V_k , for its ability to achieve each of the criteria. If this is done, then the score for each option is given by

$$Score = \sum_{k=1}^n W_k V_k . \quad (1)$$

Where n = the number of criteria which is seven in our case. The trade study was implemented in a spread sheet.

The trade study is shown in Fig. 6. Note that the technology options of hydroelectricity, wave/tidal energy, and geothermal are not part of the trade study since they are not portable systems. The trade study shows biomass and hydrogen as the two base power options and PV solar, CSP solar, and wind are the zero emission energy system options. The base power solutions supply electric power when the other systems cannot due to lack of solar energy or wind energy.

Criteria	BioMass	Hydrogen	PV Solar	CSP Solar	Wind
Portability	5	5	5	5	5
Technology Maturity	3	1	5	5	5
At Least 250kW	5	3	5	5	5
Low Development Risk	3	1	5	5	5
Cost (LEC)	3	1	5	5	5
High Efficiency	1	3	1	5	3
Availability	5	5	1	3	1

Key
5 = High
3 = Medium
1 = Low

Criteria	Weighting	Base Power System Options						Zero Emission Energy System Options					
		BioMass		Hydrogen		PV Solar		CSP Solar		Wind			
		Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)		
Portability	3	5	15	5	15	5	15	5	15	5	15		
Technology Maturity	1	3	3	1	1	5	5	5	5	5	5		
At Least 250kW	1	5	5	3	3	5	5	5	5	5	5		
Low Development Risk	1	3	3	1	1	5	5	5	5	5	5		
Deployment Cost	1	3	3	1	1	5	5	5	5	5	5		
High Efficiency	1	1	1	3	3	1	1	5	5	3	3		
Availability	2	5	10	5	10	1	2	3	6	1	2		
		10		40		34		38		46		40	

Fig. 6. Trade study analysis for choosing the power generation technologies where the only two candidates the can supply base power are BioMass and Hydrogen since Solar and Wind are intermittent energy sources.

The result of the trade study analysis is that biomass is ranked higher than hydrogen as the base power source. CSP is ranked highest for the zero emission energy system. As a result, biomass and CSP were selected as the baseline design.

The trade study reveals the primary reasons that CSP was chosen over PV. The reasons are that CSP has higher efficiency, lower investment cost, and has an inherent thermal capacity which increases its availability. Thermal capacitance means that instantaneous changes in output electric power do not occur in CSP systems. It is less sensitive to intermittent cloud cover [35]. For PV systems, output electric power drops instantaneously with intermittent cloud cover. Therefore CSP has greater availability.

3.2 Detailed Design

This section is concerned with the initial steps of detailed design of the system. We will first consider the main elements of the CSP system and choose between four options. Then, the elements of the biomass system are considered and a choice is made between two options.

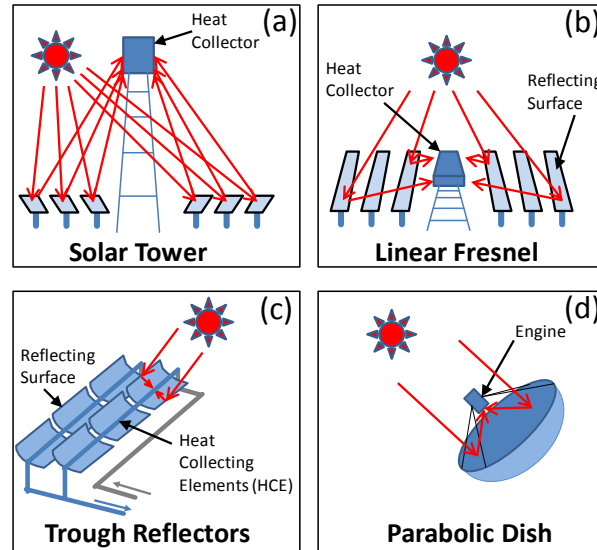


Fig. 7. Illustration of the four types of concentrated solar power generation technologies (a) solar tower, (b) linear Fresnel, (c) trough reflectors, (d) reflector. (after [9]).

3.2.1 Concentrated Solar Power

Those countries that are below 45°N and above 45°S latitude are subject to an annual average irradiation flux of over 1.6MW h/m² [36]. This means that enough solar irradiation energy falls in the Mojave Desert in approximately 3 minutes to supply a full year of power to the United States. Of course, not all the energy can be captured, but this does illustrate the magnitude and rate of the solar energy.

CSP can be realized using four different techniques which are illustrated in Fig. 7 [9]. Note the solar tower approach shown in Fig. 7(a) which uses reflectors situated below a SPT with tower mounted heat collector. The sun's energy is reflected to the tower which collects the energy and transfers it to the HTF. Fig. 7(b) illustrates the LFR method which uses a line array of reflectors reflecting the sun's energy to a heat collector. Fig 7(c) shows a PTC field which uses parabolic shaped reflecting troughs to focus the sun's energy to HCE which carry the HTF. Fig. 7(d) illustrates the parabolic dish approach which uses a dish and heat conversion engine to generate electric power.

A trade study was performed to help choose between the four CSP options. The same scoring approach using (1) was used. The result is that the trough reflector approach was selected as the baseline. The main reason is that the relative cost of the trough system is lowest cost among the four alternatives and yet it offers a low/moderate LEC [10]. LEC is the cost to install a system (after rebates) divided by the electric power it provides over its lifetime which can be written as [37, 38]

$$LEC = \frac{\text{Total Lifecycle Cost}}{\text{Total Lifetime Energy Production}} \quad (2)$$

Where the total lifecycle cost includes the initial investment cost for construction, annual operating cost, depreciation, and effect of interest rate. The total lifetime energy production includes the energy produced and effects of interest rate

An image of a PTC is shown in Fig 8. Note the large aperture troughs. They provide improved performance over more common small aperture troughs since they reflect more of the sun's energy to the HCE. The reflectors and structure in the image have the added benefit of not being made of glass. These non-glass reflectors are lighter (easier and lower cost to transport) and more immune to bullets (important for military and some commercial customers) which can shatter glass reflectors. The non-glass reflector uses a polymer mirror film.



Fig. 8. Image of a parabolic trough collector (PTC) array with large aperture troughs. (Courtesy of Gossamer Innovations, gossamersf.com)

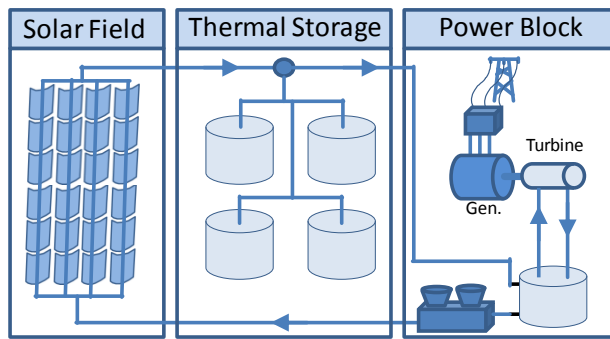


Fig. 9. CSP system showing the solar field, thermal storage, and power block.

A simplified view of the CSP system is shown in Fig. 9. Note how it shows the solar field, thermal storage, and the power block. The heated liquid leaves the solar field and is either passed into storage or is sent onto the power block. In the power block, the heated liquid passes through a heat exchanger and the energy is used to turn a turbine. The turbine turns the generator to create electricity. When the liquid leaves the heat exchanger, it passes through the condenser and then back to the solar field.

Molten salt offers significant advantages compared to oil as the heat transport fluid. For instance, it can reduce the levelized energy cost by 10-15% or more [39, 40].

3.2.2 Biomass

There are two types of biomass generation. One is biological based such as anaerobic digestion or fermentation. In this process, microorganisms are used to ‘digest’ or break down biological material. One of the outputs from this process is (biogas) methane (CH_4).

The other is thermal based and includes pyrolysis. Pyrolysis uses heat to break down organic material at elevated temperatures to create biogas. Fig. 10 illustrates a portable pyrolysis system. We are proposing the use of pyrolysis biomass technology over anaerobic technology since portable versions of these systems are in development. One of the benefits of pyrolysis is the range of materials that can be used in the process.



Fig. 10. Image of a transportable pyrolysis system (Courtesy of Trio Renewable Gas, Inc.).

3.3 Chapter Summary and Assessment as a SoS

We have applied systems engineering methods such as needs analysis, concept development, and trade study analysis in the development of a hybrid power system baseline concept using concentrated solar power and biomass as the energy sources.

As was demonstrated, this is a complex system with independent systems combined together. Therefore, this system can be considered a complex system, but it does not qualify as a SoS since the individual systems are under common managerial control and they are geographically co-located.

4. Systems Engineering of AESAs for LEO ground stations

The third system that will be considered in the progression from low complexity systems up to the final SoS example is a combination of low earth orbit (LEO) satellites and low cost active electronically scanned arrays (AESAs).³ In this example the systems are far removed from each other by thousands of km and they are each complex. For instance, a LEO satellite has dozens of subsystems and requires a diverse team of highly trained engineers for its development and production. The ASEAs are also complex. However, as will be shown, this complex system does not qualify as a SoS since each of the elements lack independence management and they do not provide functions or fulfill purposes by themselves. Rather, the LEO satellite and AESAs need each other and other parts of the overall system to provide a useful function.

Phased arrays use transmit/receive (T/R) modules to achieve the electrical functions required for antenna beam steering. They also contain the high power amplifiers for transmit signals, and low noise amplifiers for the receive signals. Phased arrays using T/R modules have been used or proposed for use in:

- Military radar systems such as the AN/APG-79 radar used in airborne systems [41].
- Communication systems for data transfer with unmanned aerial vehicles (UAVs) [42].
- Deep-space communication systems [43].
- Ground stations for communication between submarines and satellites [44].
- Wi-Fi communication systems to overcome multipath and crowded spectrum issues [45].
- SatCom on the move systems with the Tx and Rx functions performed in separate modules [46].

³ Rick L. Sturdivant, Edwin K.P. Chong, "Systems Engineering of low cost AESAs for high volume consumer LEO satellite ground stations," *Ka and Broadband Communications Conference*, Cleveland, OH, Oct. 2016.

More recently, AESA phased arrays have been proposed as a solution for Low Earth Orbital (LEO) satellite systems. This represents a significant and emerging opportunity due to the number of ground stations that will be required. Other areas of research for phased arrays are 5G networks and internet of things (IoT) systems [47]. However, these new phased arrays will need to use innovative T/R module technologies, integrated circuits, and planar antenna elements with feature sets required to achieve the cost, performance, manufacturability, and reliability necessary.

As a result the complete life cycle of the AESA must be reexamined for these high volume commercial (non-military) and consumer systems. Customer requirements and functions must be examined so that proper technology choices result. To this end, five elements of systems engineering of an AESA are presented that are particularly important in order to support the new opportunities that have emerged.

Customer needs are discussed. A customer survey is performed as an objective means to understand customer needs. The System and Context Description is explored in Section 3. The AESAs used in LEO systems have a context that is different than traditional AESAs. This context must be clearly described and understood prior to development of baseline concept. Next, the system functional description is described. Some of the major functions of the AESA used in these new systems are common with prior systems. However, the differences are significant enough and for a complete treatment a description of the more unique features is presented. Trade Studies are then covered. Results of two trade studies are presented and one of them is shown and described in detail. They are the configuration of the T/R module and the choice of semiconductor material for the front end electronics. The engineering trade studies provide data that is used during the detailed engineering development phase. The Baseline

Solution Description is also shown. Based on the customer needs, required context interactions, and trade studies, a baseline solution is described mainly in terms of functions. For several key functions, specific solutions are discussed and major components are defined. The chapter paper concludes with a summary and discussion about this system being a complex system or system of systems.

4.1 Customer Needs Analysis

The primary end customer for the proposed system is consumers. A customer needs analysis is required to confirm the expectations of the customer so that a feasible solution can be developed. The three top customer needs are reported, an initial analysis of them, and results of an internet survey of potential customers.

The analysis of customer needs focuses at the consumer level. The top three customer needs are: cost of the hardware, size of the antenna, and performance of the system. The initial needs analysis is performed from the perspective of the end user. The initial needs analysis results are summarized as:

1. Cost: Consumers are used to a particular price point for the hardware (satellite dish, low noise block (LNB), and set top box) portion of a satellite TV service. This sets a cost expectation for the consumer for any type of satellite connectivity. Based on this, the satellite TV market hardware cost was chosen as a guide for what consumers are willing to pay for the hardware portion of an AESA LEO ground station.
2. Antenna Size: Consumers expect small antennas for their satellite connectivity. This is because the antennas are mounted on the tops of homes, apartment balconies, and other visible locations. It is anticipated that customers will need a solution that is similar to their prior experience with satellite antennas. Like it or not, satellite TV systems have set

an expectation with consumers on antenna size. This means that the size of the AESA LEO ground terminal will need to be similar to the 0.6 m² of satellite TV systems.

3. Availability of The System: The system must perform in weather conditions such as rain fade and snow. Customers expect a reliable system with very high levels of availability (i.e., maintain data rate).

While this initial analysis was useful and provided insights into customer needs, a more objective analysis was required. Therefore, an internet survey was performed using a third party internet survey company [48]. Five questions were generated to either confirm or modify the initial needs analysis. Following suggestions in [49] the questions were configured to allow customers rank levels of importance for the three needs being reported. The survey was administered to a sample size of 250 persons [50, 51, 52]. The sample size was calculated using

$$n = \frac{z^2 p(1-p) / e^2}{1 + \left(\frac{z^2 p(1-p) / e^2}{e^2 N} \right)} \quad (3)$$

Where:

n = sample size

N = population size

e = margin of error

p = expected proportion (prevalence) which is estimated at 50%.

Z = Z statistic based on level of confidence desired (i.e., for 95% confidence, Z = 1.96).

For a potential customer base of 5 million users (n = 5,000,000), 95% confidence (Z = 1.96), and a margin of error of 6%, calculations using the above equation give the required sample size as 267. Since a sample size increment of 250 falls within a pricing block of the survey company hired for administering the survey, a sample size of 250 was chosen. This increases the margin of error to 6.2% which is acceptable for this investigation. Additional statistically important information was gathered regarding the survey respondents such as income levels, age, and

gender. 43.57% of respondents had a household income of less than \$49.99K, and 19.5% were \$50-74.99K. The age population distribution was distributed in four brackets of 18-29 years old (24.52%), 30-44 years old (23.75%), 45-59 years old (24.52%), over 60 years old (27.02%). As far as gender, 52.1% were female, and 47.89% were male.

The survey questions address the three needs of cost, size, and availability. However, the initial needs analysis focused on the cost of the system hardware while the survey questions also include the monthly service cost. This additional parameter was added to provide additional insight into the cost sensitivities of the customer. The questions are:

1. In order for you to be interested in buying a satellite internet system, what size must the outside antenna be?
 - a. The same size as a typical satellite TV antenna,
 - b. Smaller than a typical satellite TV antenna,
 - c. It can be as large as twice the size of a satellite TV antenna.
2. Assuming the per month service price is attractive, what is the maximum price you willing to pay for the equipment?
 - a. Less than \$75,
 - b. Between \$75 to \$150,
 - c. Between \$150 to \$250.
3. How many times per year can the service be unavailable due to weather (rain/snow) before you will consider cancelling your service?
 - a. Once is too much,
 - b. 1 to 3 times,
 - c. 3 to 5 times,

- d. 5 to 10 times.
4. Which is more important to you?
 - a. Installation price.
 - b. Monthly service price,
 - c. The size of the antenna that is mounted outside on your house or apartment.
 5. Rank the four items below on level of importance
 - a. Installation price,
 - b. Monthly service price,
 - c. The size of the antenna,
 - d. Performance of the system during rain/snow.

The responses to question 1 are shown in Fig. 11. Note that approximately 93% of the respondents said that they expect the antenna to be the same size or smaller than existing satellite TV antennas. This should come as no surprise and agrees well with the customer expectation of solutions with an antenna area of approximately 0.6m or less.

It should also come as no surprise that approximately 70% of respondents to question 2 expected the cost of equipment to be less than \$75.

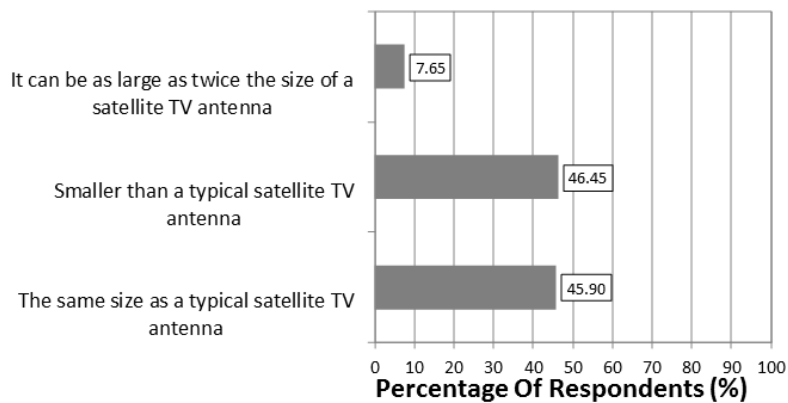


Fig. 11. Summary of responses to Question 1.

A bit unexpected is that approximately 45% of respondents to question 3 were willing to have the service unavailable due to weather conditions 1 to 3 times per year before considering the cancellation of the service.

On question 4, the vast majority of respondents, approximately 94%, rank the monthly service charge as more important than installation price and the size of the antenna. The size of the antenna was ranked as more important by only about 2% of respondents.

Question 5 is nearly the same as question 4. However, there is an important difference and the results of the survey illustrate the difference. Since question 5 asks the respondents to rank the importance of the four options, this question provides insight into the relative rank between the four alternatives. The interesting result here is that installation price and availability of the system were ranked the second most important concerns by over 75% of respondents (35.85% and 39.94% respectfully). As expected from question 4, fully 74% of respondents ranked monthly service charge as most important. Interestingly, 72% of respondents ranked the size of the antenna as the fourth most important concern.

Based on these results, the initial customer needs analysis was essentially confirmed except that monthly service cost was added to the cost parameter. In addition, cost and availability are now ranked as more important customer needs than size of the antenna.

4.2 System and Context Description

A LEO satellite system differs from the more familiar geostationary (GEO) satellite. For the GEO systems, the satellite is stationary relative to the surface and rotation of the earth. This is an important advantage since it allows ground stations to use antennas that are fixed and do not move. For instance, this is the case for satellite TV dishes. The dish is installed and permanently points to the same position in the sky.

For LEO satellites, the situation is very different. LEO satellites move relative to a position on the earth. This means that for an observer on the surface of the earth, the LEO satellite will move from one horizon and across the sky to the other horizon. From the perspective of the consumer ground terminal, the most important difference between the GEO satellite and LEO satellite system is antenna must scan to maintain connection with the satellite. In other words, the antenna beam must point to satellite as it moves across the sky. This can be accomplished mechanically so that the antenna rotates using electric motors or other means. Alternatively, the antenna beam can scan electronically. Electronic scanning can be achieved using an AESA which can keep the antenna beam 'locked' on the satellite as it moves across the sky. The AESA can also switch rapidly to a different satellite as the current satellite moves out of range.

Mechanically scanned systems suffer from limitations of cost, reliability, manufacturability, size, and slew rate. Slew rate is the time it takes the antenna to move across its field of view (FOV). For these reasons, this work considers only AESA solutions and focuses on the systems engineering concept development of the T/R modules used in these systems.

The context diagram is shown in Fig. 12. Note how It shows the LEO communications satellite in a up/down link to the AESA with time and location information being received from the GPS satellite. Another important factor is the environment with weather such as rain. The user is connected to the AESA through the modem/processor and router. Data is passed from the end users up to the AESA to complete the up/down link to the LEO communications satellite.

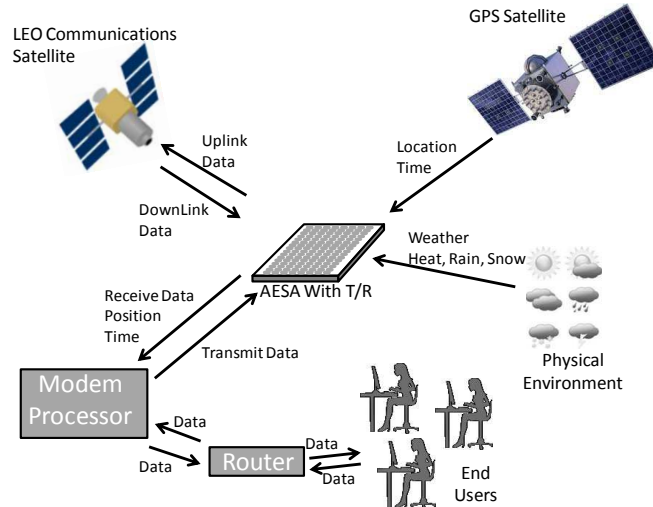


Fig. 12. Context diagram showing how the AESA interacts with the external elements.

4.3 System Requirements

A set of functional requirements is developed. This is not a detailed performance specification, since it comes later in the development. Rather, it is a description of what the system should do—“tasks or activities that the system performs during its operation” [53]. Although most AESAs adhere to a fairly common set of functions, this analysis reveals the functions that are unique to Consumer LEO-GS systems. Also, the functional requirements cover the AESA and the complete ground terminal. The top 8 functional requirements are:

- The system should automatically determine its position, orientation, and time of day so that the pointing algorithm will know where to point the AESA for connection to the LEO satellite.
- The complete system should be less than \$100 to the consumer with a goal of less than \$75.
- The system should be capable of at least 20MBPS data down link connectivity.
- The AESA shall provide the receive G/T performance and transmit EIRP to maintain connectivity in the presence of rain fade with degraded data rate allowed.

- The AESA shall have a sufficient scan range without grating lobes for always having at least one satellite in the field of view (FOV) capable of supporting the required data bandwidth.
- The system must maintain high availability. The required availability can be calculated by letting T_{NA} equal the number of days the system is not available which the consumer survey gave as 3 days and T_A equal the number of days in the year the system is available which is $365 - T_{NA} = 362$. The availability is then given by

$$A_0 = \frac{T_A}{T_A - T_{NA}} = \frac{362}{362 + 3} = 99.18\% \quad (4)$$

- The AESA antenna shall not be larger than 0.6m^2 . This requirement is at odds with the G/T and EIRP requirement.
- The AESA must operate over the environmental temperature range of -40 to $+60$ C and survive 100% humidity.

These functional requirements capture the main functional requirements for the system.

4.4 Trade Studies

The trade studies provide data and decision traceability for the engineering development activity of the product life cycle. The results of two trade studies are given in this section. Because of size constraints only one of the trade study table is included in this report.

The first trade study is on the possible configurations for realizing the T/R modules. This study is important since prior generations of T/R modules will not meet the size or cost constraints of consumer LEO ground stations [54]. The trade study considers eight possible configurations which includes the variations on the T/R module electronic packaging and materials. The result shows that the T/R module must be integrated as part of the antenna itself to

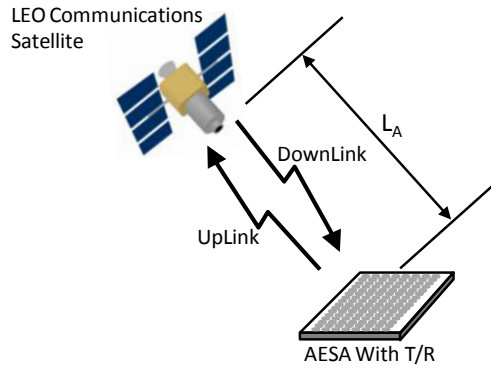


Fig. 13. Uplink and Downlink that exist between the AESA and the satellite.

meet the size, cost, and performance. The impact of T/R module configuration on cost and size is obvious. The performance impacts of T/R module configuration are less obvious. The communications link budget depends upon key electrical performance such as receive noise figure and transmit power. Those parameters are directly impacted by the T/R module configuration.

One of the key parameters for the T/R configuration as it relates to the overall system is the link budget between the ground station and the satellite. Fig. 13 illustrates the link.

The key parameters in the link are the power of the transmit signal (P_T), the gain of the transmit antenna (G_T), the noise temperature of the receiver (T_{SYS}), the gain of the receive antenna (G_R), the frequency of operation, and the slant distance between the satellite and ground antenna (L_A). With this information it is possible to calculate the signal to noise ratio at either the satellite or the receiver using

$$\frac{S}{N} = P_T G_T \left(\frac{\lambda}{4\pi R} \right)^2 L_A \frac{1}{k B T_{SYS}} G_R \quad (5)$$

Where λ = wavelength of operation, k = Boltzmann's constant = $1.38 \times 10^{-23} \text{ m}^2\text{kg/s}^2\text{K}$, B = data bandwidth (Hz). This equation can be used to find the signal to noise ratio at either the satellite

Criteria	Si-CMOS	SiGe	GaAs	GaN	InP
Integration Complexity	5	5	3	1	1
Relative Cost	5	5	3	1	1
Production Capacity	5	5	3	1	1
Output Power (TX)	3	3	5	5	5
Receive IP3	3	3	5	5	5
Receive Noise Figure	1	3	5	5	5
DC Power Consumption	5	5	3	1	1

Key
5 = High
3 = Medium
1 = Low

Criteria	Weighting	Si-CMOS		SiGe		GaAs		GaN		InP	
		Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)
Integration Complexity	2	5	10	5	10	3	6	1	2	1	2
Relative Cost	2	5	10	5	10	3	6	1	2	1	2
Production Capacity	2	5	10	5	10	3	6	1	2	1	2
Output Power (TX)	1	3	3	3	3	5	5	5	5	5	5
Receive IP3	1	3	3	3	3	5	5	5	5	5	5
Receive Noise Figure	1	1	1	3	3	5	5	5	5	5	5
DC Power Consumption	1	5	5	5	5	3	3	1	1	1	1
	10		42		44		36		22		22

Fig. 14. Trade study results for selecting the semiconductor technology.

(for the uplink) or the AESA ground station (on the downlink). It is very common for the parameter E_b/N_0 to be used instead of S/N , but they are related by

$$\frac{E_b}{N_0} = \frac{S}{N R} \quad (6)$$

Where R = digital data rate. This give the ratio of the energy per bit transmitted to the power spectral density of the noise.

The second trade study is on the integrated circuit technology options and the trade matrix is shown in Fig. 14. The analysis includes integration complexity, relative cost, production capacity, output power (transmit), receiver third order intercept (IP3), receiver noise figure, and DC power consumption. The trade study considers silicon CMOS (Si-CMOS), silicon germanium (SiGe), gallium arsenide (GaAs), gallium nitride (GaN), and indium phosphide (InP) semiconductors. The result shows that the semiconductor material of choice is SiGe since it offers key performance parameter performance needed such as noise figure and output power at a cost that meets system needs. One may argue that the ranking of 3 for the noise figure of SiGe and 5 for GaAs is not correct since SiGe noise figure is approaching GaAs. While this is true, GaAs still achieves lower noise figure which is a major determining factor in system G/T. More important, if the ranking of SiGe is increased to be equal to GaAs, the result of SiGe as the

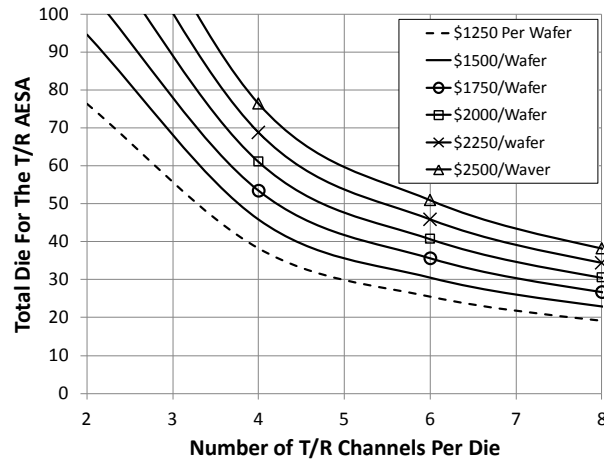


Fig. 15. Total cost of die for the AESA as a function of the number of T/R channels per die.

solution will still be achieved but with even greater margin since SiGe rank would increase from 44 to 46 and all others would remain the same. So such an objection will not affect the result. Another observation is that Si-CMOS is a close second to SiGe. While this is true, it has lower noise figure than SiGe which, as already stated, is an important system performance parameter. Therefore, SiGe is selected as the material of choice.

As part of the trade study analysis, the total cost of the SiGe die used to populate the phased array was analyzed. The analysis used a fixed die size of 4mm x 4mm, an array size of 18" x 18", with 20 x 20 elements. One of the results of the analysis is shown in Fig. 15. It shows the total cost of die used in the array as a function of number of T/R channels per die and the cost of fabrication of the SiGe wafer. In other words, each SiGe IC can have multiple T/R channels. Note the total cost of SiGe die drops below \$30 for the case of 5 channels per die at a cost of \$1250 per wafer. This analysis assumes a 12 inch wafer and a die yield of 85%. Note that for every million consumer ground stations produced, approximately 10,000 wafers will be required.

If the current customer base of satellite TV suppliers is an indication of the available market for these systems, then these types of systems will require trillion wafers. The current number of

worldwide satellite TV subscribers is approximately 950 million [55]. If this is multiplied by the 10,000 wafers per 1 million consumer ground stations, then the result is a need for 9.5 trillion SiGe wafers to support this market.

The size of the array in these trade studies is approximately 0.2 square meters which is well below the goal of 0.6 square meters.

4.5 Baseline Solution Description

A baseline is chosen and described. The baseline design for the AESA is described in terms of the T/R module configuration, integrated circuits, and the antenna system.

T/R Module and Integrated Circuits: The T/R module is realized using SiGe integrated circuit technology. This choice is based on the required noise figure, output power, and cost. Alternatives such as GaAs and GaN are too costly to be viable alternatives. Si-CMOS does support the cost objectives, but it does not simultaneously support the noise figure requirements and receive linearity requirement (at least at this point in time).

The antenna system is planar and proposed to be fabricated using low cost laminate circuit board material.

4.6 Suggestions for Future Work

This work presents the concept development stages of an AESA based ground station for LEO satellite communication. Much more systems engineering is required before the detailed work can begin. In fact, a complete analysis on the feasibility of the baseline solution should be one of the next steps in this investigation.

Several of the important systems engineering activities are presented and results for the AESAs intended for Consumer LEO-GS systems. The Customer Needs analysis revealed a few surprising results from the customer survey. Namely, the number one concern among customers

is the monthly service cost and the size of the antenna ranked behind monthly cost, hardware cost, and availability. However, the survey also revealed that the existing satellite TV systems are setting many of the expectations on cost, size, and availability. The Functional Specifications outlined the major functions that the T/R modules must perform and how the functions are tied to the customer needs. The Trade Study analysis focused on the two items that drive measures of effectiveness (MOEs) and in particular cost. The baseline solution is then discussed as a feasible solution that meets the customer needs.

The analysis showed that for every 1 million Consumer LEO-GS produced, there will need to be approximately 10,000 SiGe wafers produced. The analysis revealed what may be the most significant result of this analysis which is that the addressable market for SiGe wafers for this type of system is 9.5 trillion wafers. If this line of thinking is correct, then this raises important questions about the world wide fabrication capacity in SiGe to meet this demand.

Moreover, some specific systems engineering work that should be conducted includes the up/down link, the LEO satellite, the AESA, and the rest of the ground station such as the processor and array controller. A formal risk assessment and mitigation plan is also required.

4.7 Assessment As A SoS

Although this system may at first seem to be a good candidate for a SoS since the elements of the system fulfill several of the characteristics of SoS, closer examination shows that it is not. For instance, systems are far removed from each other by thousands of km so this meets one of the characteristics. In addition, the system elements are each complex. For instance, a LEO satellite has dozens of subsystems and requires a diverse team of highly trained engineers for their development and production. The ASEAs are also complex. However, this complex system does not qualify as a SoS since each of the elements lacks independence management and they

do not provide functions or fulfill purposes by themselves. Instead, the LEO satellite and AESAs need each other and other parts of the overall system to provide a useful function.

5. Engineering of a Terabit Elliptic Orbit Satellite System

The fourth system to be considered is a terabit per second satellite network using highly elliptical orbits and phased array ground stations.⁴ This is another example of a complex combination of subsystems which are themselves extremely complex, but when combined do not meet the requirements of being considered a SoS. The reasons are that each of the elements lack independence management and operational independence. One entity manages the subsystems and the subsystems need each other in order to provide a useful function.

The desire high data rates for users and machines continue to increase. Providing access to these users and machines is a growing concern and opportunity. One possible solution is to use satellites to provide connectivity access which is why high-throughput satellites (HTS) are being considered. Most of the solutions considered so far are based on low earth orbit (LEO) or geostationary (GEO) satellite systems. This work performs systems engineering of a baseline concepts for an alternative system based upon elliptic orbit satellites such as Molniya or low apogee elliptic virtual geo orbit satellites.

Molniya orbits are one type of elliptical orbit and have been used in Russian television broadcasting for many decades. In fact, the word Molniya is Russian for ‘lightning’ which refers to the speed at which the satellites travels at perigee. The approach of using Molniya satellites and single axis scanning antennas has been investigated by others. For instance, it was proposed by the late W.T. (Bill) Brandon who found that if the Molniya orbit satellites use an eccentricity near 0.722, then they will follow nearly the same ground track in a north-south path at medium to high latitudes as described in [56, 57]. This approach was also proposed in [58, 59]. A similar

⁴ © [2016] IEEE. Reprinted, with permission, from R. L. Sturdivant, Edwin K.P. Chong, “Systems Engineering of a Terabit Molniya Satellite and Phased Array Ground Station for IoT Connectivity and Consumer Internet Access,” *IEEE Access*, vol. PP, no. 99, pp. 1-17.

approach, but with much lower apogee elliptical orbits, was proposed in [60]. A good summary of various elliptic orbit satellites is provided in [61, 62].

However, these prior investigations suffer from four important limitations. First, prior work does mention single axis ground stations [56, 60], but they do not present a viable concept for a low cost consumer ground station which is an important step in the systems engineering of a complete solution. This is a limitation because a complete system solution is required which includes the satellite *and* ground station. This limitation was certainly due to the fact the necessary technology was not available nor on the horizon at the time these prior systems were proposed. Second, the prior investigations did not analyze the variation in the Molniya orbit as viewed from the single axis ground station which is critical since it directly affects the requirements of the ground station antenna. Instead the prior workers focused on analysis of the ground track path of the satellites which is important, but does not address the pointing requirement for the ground station. Third, the prior investigations do not discuss implications from the link budget on the requirements for the consumer ground station. That is, the prior efforts in this area did not perform the analysis demonstrating how system level link budget requirements impact the requirements for the consumer ground terminal. This is an important limitation in the prior work since demonstrating a baseline link budget and translating it to the subsystem requirements is critical for a viable baseline concept. Fourth, they do not address the systems engineering of HTS using elliptic orbit satellites in any meaningful fashion. This work addresses these limitations.

This work is distinct from other prior work and is significant in the following ways. First, a systems engineering baseline is described using elliptic orbit satellites and low cost single axis ground stations in sufficient detail to show feasibility. To the knowledge of the authors, a system

level baseline solution with Molniya satellites and a viable consumer ground station as a complete system has not been presented as a HTS solution.

Second, the needs analysis includes the opportunity motivators, customer market analysis, and financial viability of the solution in the context of the system design which is a new contribution. It is significant since the baseline solution must demonstrate not only technical feasibility but also financial viability and a valid customer need [63, 78].

Third, this analysis shows that the variation in the north-south satellite elevation angle (as seen from the consumer ground station) will be accommodated by the consumer ground station. Prior work, as mentioned above, focuses on the ground track rather than the apparent elevation angle variation of the satellite as seen from the consumer ground station. This is significant since it directly impacts the consumer ground station antenna requirements.

Finally, this work shows the connection between the link budget and the consumer ground station and that technology (such as semiconductor solutions) is available that can achieve the main performance metrics such as receive noise figure and transmit output power.

It is important to keep in mind that this work is concerned with systems engineering of a baseline concept. As a result, it is not intended to provide optimization of any particular feature—instead to demonstrate feasibility. Optimization and detailed design will occur in a later design phase of the system. As a result, detailed engineering efforts such as optimization of components and detailed engineering design are out of the scope of this work.

This work is divided into eight sections which demonstrate the soundness of the technical approach supporting the premise that a feasible baseline concept is presented. In Section 5.1, the opportunity motivators are presented. These are the motivations prompting the investigation and are a necessary first step in the engineering of a new system. In Sections 5.2-5.5, the customer

needs analysis, financial analysis, and reasons the system is attractive are presented. This is an important step since it ensures that the solution will be relevant to particular requirements. Section 5.6 presents details on elliptic orbit design and important orbit characteristics. The main outputs from this section are evidence that a Molniya orbit satellite can provide the necessary coverage and that the variation in elevation is consistent through the orbit to allow single axis consumer ground station antennas and further demonstrates the soundness of systems engineering. Section 5.7 describes the consumer ground station. This is where the top level concept for the ground station is presented. The cost of the consumer ground station is considered in Section 5.8. The cost of the main integrated circuits and antenna circuit boards is analyzed. The link budget is analyzed in Section 5.9 which includes the satellite and ground station up/down links. Finally, the summary is presented in Section 5.10 along with some suggestions for further study. Section 5.11 discusses this system as a SoS. Together, these sections demonstrate the feasibility of the system and technical soundness of the approach.

5.1 Opportunity Motivators

There are many opportunity motivators for developing HTS solutions. The first one considered here is the need to bridge the disparity gap that exists for access to high speed internet access which is acute for rural areas and marginalized people groups. In the United States of America (USA), for instance, a recent report by the Federal Communications Commission (FCC) found that approximately 39 percent of individuals living in rural areas and 41 percent living in Tribal lands lack access to high speed internet [64]. Their speed benchmark for access is 25Mb/S download and 3 Mb/S upload. The report also concluded that advanced telecommunications capability is not being deployed in a reasonable and timely fashion. These findings are not unique to the USA. For instance, the country of India has a similar disparity between urban and

rural for access to wireless [65]. In addition, a recent study as part of the Oxford Internet Institute found a similar result in Britain. The study found that, “there is a digital divide that separates urban and rural areas in Britain ... leaving rural areas with a fraction of the service that is enjoyed in urban areas” [66]. The report found that poor internet connectivity impacts not only individuals but also small businesses. Satellite internet service is able to reach rural areas which means the lack of rural connectivity provides an opportunity motivator for HTS solutions.

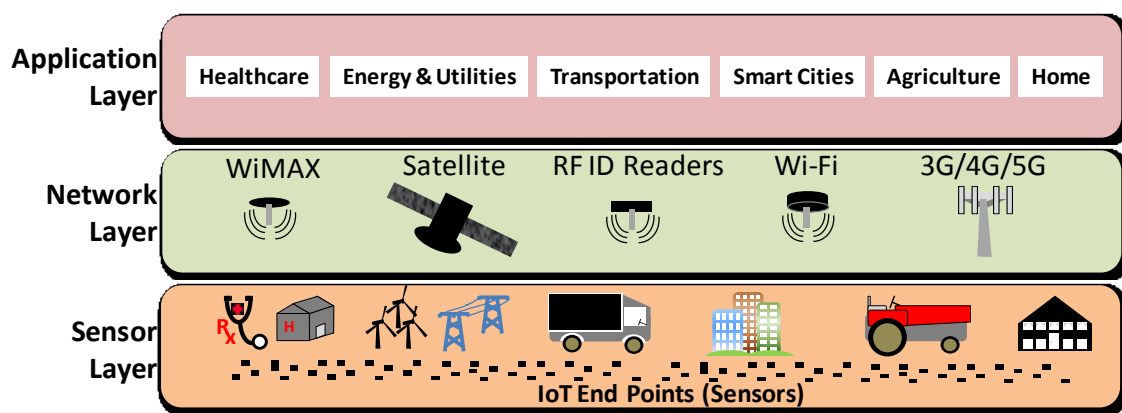


Fig. 16. IoT system concept showing the sensor layer, network layer which includes satellite systems, and application layer.

The second opportunity motivator is to meet the connectivity need for internet-of-things (IoT) devices and networks. It is projected that IoT connected end point devices will grow to 25.6 billion units by 2020 [67]. Most of these devices will transfer their data through at least one radio frequency network layer device before being routed to the application layer. From a simplified system level perspective, this arrangement of connectivity is illustrated in Fig. 16. At the sensor level, multiple IoT end points can be aggregated together using gateways that will communicate data back and forth with the network layer. Note from the figure that satellite based connectivity is one of the possible solutions at the network layer. In fact, satellite based IoT type solutions are deployed now for industrial machine to machine (M2M) data communication [68, 69]. In addition, some workers have analyzed the ways to improve IoT device gateways using

satellite links and an optimum protocol [70, 71]. In [72] IoT connectivity through gateways has been analyzed with satellites as one of several access methods for networking. This approach is attractive since the gateway device aggregates the information from multiple IoT end points and then packages it for transport to the network layer as illustrated in Fig. 17. A similar approach is taken in [73] where satellites play the same role as Wi-Fi, 4G, and 5G in the network layer. The internet of space (IoS) is proposed in [74] where it is estimated that satellites will play a role in IoT devices for urban, rural, and remote end points. This need for connectivity includes Supervisory Control and Data Acquisition (SCADA) devices which are used in remote monitor and control applications. This need for data connectivity to IoT devices and gateway points provides an opportunity for satellite based solutions.

While consumer internet and IoT connectivity are the main opportunities considered in this article, there are others which provide additional motivation for developing a solution. An example is the delivery of connectivity for corporate enterprise applications such as oil and gas platforms. These systems are often in remote locations and yet require monitoring for security and operational reasons. This is one of the customer groups identified for use of the ViaSat-3

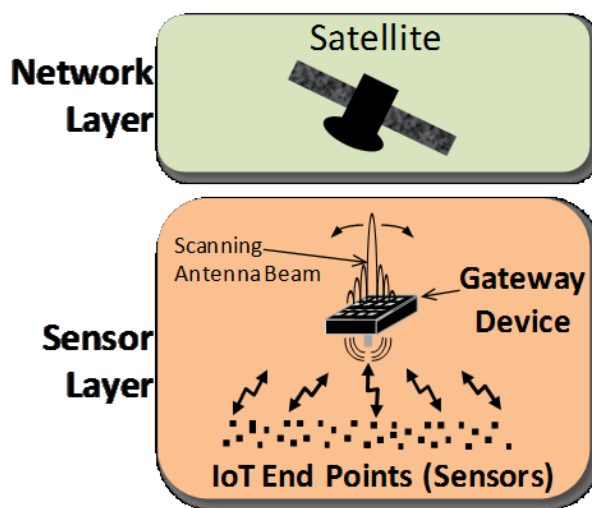


Fig. 17. A gateway device aggregates the information to/from multiple IoT end points and forwards it to the network layer which may be a satellite.

terabit per second satellite planned for launch in 2019 [75]. There are many other industrial connectivity opportunities. Consider, for instance, the connectivity opportunities that the GE Predix platform is projected to create [76]. Another opportunity motivator is commercial airliner in-flight high speed internet. The Bureau of Transportation reported that in 2015 there were nearly 900 million passengers on USA-based flights (both domestic and international) [77]. Existing systems have been deployed to provide services to this market which demonstrate the validity of this opportunity [63]. Depending upon the airline, the in-flight internet access is used by 7-40% of flyers. These in-flight internet services can use satellites for their connectivity. This type of solution will require more complicated terminals in the aircraft. Specifically, it will require antennas that can mechanically or electronically scan in two dimensions to remain connected to the satellite. While this could be a profitable application of the system it is not analyzed in this work.

There are also technical motivations for investigating HTS solutions. In particular, advances in certain technologies now make it possible to develop consumer ground station solutions at price points not previously possible. The point of this article is to show that using elliptical orbit satellites (such as Molniya orbits) combined with recent advancements in integrated circuit (IC) semiconductor technology and reductions in antenna cost (driven by lower cost microwave dielectric materials), it is possible to develop a baseline concept for an affordable HTS solution. The solution will serve as an alternative to geostationary (GEO) and low earth orbital (LEO) satellite systems.

5.2 Needs Analysis

One of the early steps in engineering of a new system is performance of a needs analysis. The goals of the needs analysis are to [78]:

- Show that a potential market for the new system exists.
- Show that existing systems have deficiencies that a new system can address or that technology advancements can result in new capabilities that are attractive to customers.
- Demonstrate that a solution that meets the need(s) is feasible.

This section will examine these three items. The main output from the needs analysis is a set of operational requirements which refer to the capabilities of the system as a whole.

5.3 Potential Market Analysis

The potential market for the new system is analyzed using a simple income model. While the purpose of this paper is not to present a detailed financial analysis of the potential markets for the baseline concept solution, a simplified market analysis is presented for the two main opportunity motivators from Section I, which are urban internet users and IoT connectivity. Since economic data is available from USA government and industry reports, the potential market analysis is purposely limited to only the USA market. However, this analysis can easily be expanded to other geographic markets.

A summary of the potential market analysis is shown in Table 6. For rural internet usage, the FCC Broad Band Progress report shows that 34 million in the USA are without high speed service [64]. If we assume that each connection will be shared by three individuals, then there are 11 million potential high speed internet users in rural areas. The report also reveals that the adoption rate when broad band is available is approximately 30%. If we assume a broad band service fee of \$30 per month, then the annual potential market in the US is \$1.19B.

Table 6. Total Potential Market For Two Opportunities Identified

RURAL INTERNET USAGE		IoT Data Usage	
Potential Users (B)	0.011	End Points Deployed (B)	25.6
Adoption	30%	Adoption	5%
Monthly Fee	\$30	Fee/Day/End Point	\$0.005
Revenue/Month	\$99M	Revenue/Day/End Point	\$6.4M
Revenue/Year	\$1.19B	Revenue/Year	\$2.336B

The table also shows the simplified market analysis for IoT connectivity through satellites. As stated earlier, industry projections are that 25.6B IoT end points will be in service by the year 2020 [67] [12]. If 10% of those units will have data transferred through satellites for a fee of \$0.005 per day (\$0.15/month), then the revenue per day is \$6.4M or \$2.336B per year.

There are several potential points of discussion on the market analysis. For instance, the IoT market analysis uses an assumption of \$0.005 dollars per day of access. That estimate is a highly discounted and based upon cost for M2M messaging based systems [79]. Costs for M2M connectivity vary from a fixed monthly fee of \$13/month to \$60/month plus airtime costs of \$0.0015 to \$0.12 per byte. As further verification of our calculation, the NSR report on M2M and IoT via Satellite projects the total market size to be approximately \$2B by the year 2021 [80, 81]. As can be seen in this simplified model, the revenue is linear with fee. This same type of simplification exists in the model for rural internet. In particular, the monthly fee is assumed to be \$30. This is a discounted value based on the FCC Broad Band Progress report that “monthly service price offerings as low as \$50” [64]. If this monthly fee is used instead, then the annual revenue estimate is \$1.98B instead of \$1.19B as shown in the table. Therefore, the value in the table can be considered to be a more conservative estimate. Despite the simplifications and

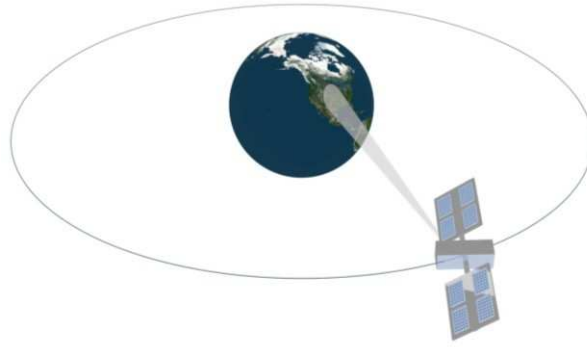


Fig. 18. Illustration of a geostationary satellite showing that the satellite remains pointed at the same location on earth throughout its orbit.

conservative income estimates in the financial model, it is useful for serving its purpose which is to show that a viable market exists for the system.

5.4 Reasons the New System Is Attractive To Customers

The needs analysis must show that existing solutions have deficiencies that a new system can address or that technology advancements can result in new capabilities that are attractive to customers. This will be achieved by considering the existing solutions and their limitations.

Consider the existing solutions. For instance, Ku-Band and Ka-Band geostationary satellites are being used now for internet delivery. Additional solutions are planned with even greater bandwidth. Consider, for instance, the ViaSat-3 satellite which is planned to provide over 1 Terabit per second of network capacity [82]. A geostationary satellite is illustrated in Fig. 18 which shows the satellite in ‘fixed’ orbit so it always points to the same location on the face of the earth.

There are existing and planned satellite communications systems that operate at Ku and Ka-Band. Ku-Band is the frequency range from 12-18GHz and is widely used for satellite television services. Ka-Band is the frequency range from 26.5-40GHz and is used for commercial satellite and military applications depending upon the particular frequencies in that



Fig. 19. An image that should be familiar to most people since it is of a satellite TV dish pointed to a geosynchronous satellite.

range [83]. One benefit of using geostationary satellites for this type of system is the consumer ground station antenna can be aligned once so that it points to the same location in the sky. This is because a geostationary satellite remains pointed at the same position on earth despite the earth's rotation. This is a big benefit since it means that relatively simple and low cost antenna technology can be used for the consumer ground terminal. An example is the now ubiquitous reflector dish and low noise block (LNB) mounted on homes and apartment balconies. Fig. 19 should be a familiar sight to most everyone since it shows a satellite TV dish.

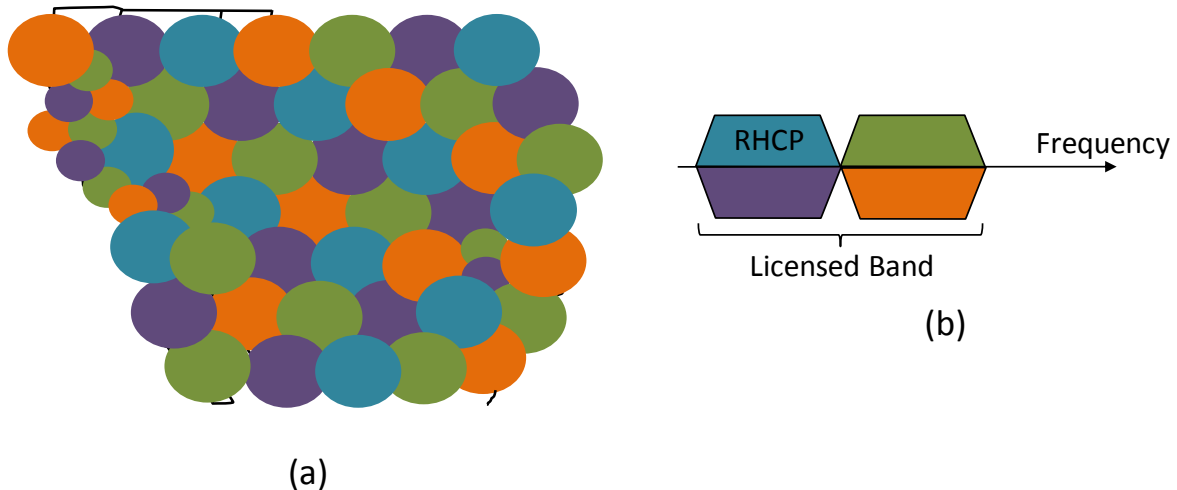


Fig. 20. Example of frequency re-use where (a) multiple antenna beams provide coverage of a portion of North America using (b) frequency and polarization diversity.

Research for increasing the data bandwidth of geosynchronous or geostationary satellite systems has focused in three main areas [84, 85, 86]. First is high spectral efficient waveforms. For instance, in [87] M-ary modulation for $M=16, 32,$ and 64 are compared in the presence of channel non-linearity due to high power amplifier performance for terabit/second satellite systems. M-ary is a modulation scheme commonly proposed for communication satellites which uses multiple simultaneous bits often with quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM) [88, 89, 90].

The second area of research for geostationary HTS satellites is frequency re-use which means multiple smaller antenna beams are arranged to provide the required coverage. Fig. 20(a) shows a portion of North America (South West USA and Northern Mexico) and a simplified coverage layout with multiple antenna beams of various beam widths. The baseline concept is to use a digital beam forming antenna on the satellite to allow for dynamic beam steering and beam shape control. In the figure, the antenna beams operate in one of two bands and either right hand circular polarization (RHCP) or left hand circular polarization (LHCP) as shown in Fig. 20(b). This arrangement is proposed in [91] to increase frequency re-use. It is also proposed in [92] and [87] except that the multiple-beam user links operate at Ka-Band and gateways operate at other bands such as Q/V band. This approach is attractive because of the wide frequency bands but suffers from attenuation and system cost related to the higher operating frequencies (high frequency components and systems are more costly for the satellite and ground terminal). Another proposed solution in [93] relies on large ground station antennas in dry climates and terahertz operating frequency (300-1086GHz) to achieve greater than one terabit per second of data transfer between ground stations and a geosynchronous (or possibly LEO) satellite. A drawback of this approach is the restriction of the ground terminals to dry climates. The

proposed solution investigated in this work operates in Ku-Band and with frequency reuse, but can be applied to other operating bands as well.

The third area of research for HTS satellites is in the satellite orbit type. As already mentioned, many proposed HTS systems and existing communication satellites use geostationary satellites (at altitudes of 35,786 km). An alternative is medium earth orbit (MEO) satellite systems (orbit altitudes between 2,000 to 35,000 km). An example of MEO satellites is the global positioning system (GPS) with an altitude of 20,200 km. Another alternative is a low earth orbit (LEO) satellite system (orbit altitudes between 160 to 2,000 km). Globalstar satellites are at an altitude of 1,414km and are an example of a LEO system. An important benefit of LEO and MEO satellites is the shorter latency due to the transmission path up to and down from the satellite [94]. The orbit type is part of the alternatives to be considered for HTS satellites.

One of the challenges with MEO and LEO satellites is the complexity of the antenna on the satellite and, more importantly, the consumer ground station. The challenge is achieving a low cost ground terminal since it must track the LEO satellites as they crisscross the sky as described in [95]. This is a challenge since the tracking must be in two dimensions which can be cost prohibitive as discussed in [96]. In particular, scanned arrays are needed which can be either mechanically or electronically scanned [97]. Because of the reliability issues with mechanical scanning, electronic scanning of the antenna beam must be used. In [98] algorithms for tracking LEO satellites using adaptive antennas are considered. However, in that investigation, simple cross-dipole antennas are used which do not meet the system level link budget requirements for high data rates and consumer grade connectivity needs. An alternative is to use two dimensional electronically scanned antenna arrays.

One difficulty with two dimensional electronically scanned consumer ground antennas for tracking LEO satellites is the complexity of the phase shifting elements required to achieve electronic scanning. This is illustrated in Fig. 21 which shows phase shifters located at each antenna element in the phased array. This means the number of phase shifter ICs required for the ground station for a LEO system is proportional to the number of antenna elements. For an antenna with 20 x 20 antenna elements, the number of required phase shifters is 400. This can be reduced if each phase shifter feeds multiple antenna elements. For instance, in a 20 x 20 element array, if each phase shifter feeds 4 elements, then the number of phase shifters is reduced to 100.

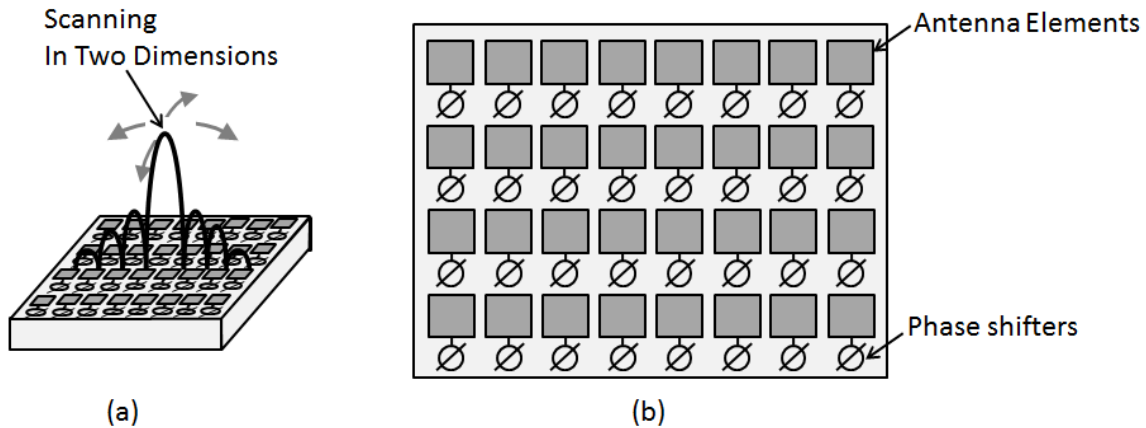


Fig. 21. Simplified illustration of (a) two dimensional beam steering array with (b) phase shifters at each antenna element to enable the beam steering.

If each phase shifter cost \$5 (US), then the cost of the phase shifters alone can be as high as \$500. This means the cost to the consumer would be \$1000-\$1500 for each antenna and this only accounts for the cost of the phase shifters. When the rest of the ground terminal costs are taken into account, the price tag to the consumer will be much higher. If low cost semiconductor technology such as Si-CMOS devices are used, then the concern is the impact of higher noise figure on the system [99]. While there are some cost reduction methods that can be used as mentioned in [97], it remains unproven if these cost reduction methods will achieve their goals.

Next, the needs analysis will consider technology advancements that make a new system attractive to customers.

5.5 An Alternative Solution With Attractive Features

While existing geostationary satellites and proposed LEO satellite constellations are viable solutions (with significant unknowns relative to the cost of LEO ground stations), an alternative exists with attractive features. The solution is to use elliptical (in either high apogee or low apogee) orbit satellites constellation with single axis electronic scanning arrays for the consumer ground station. This work focuses on Molniya orbit solutions with high apogee orbits, though low apogee elliptical orbits are an attractive solution and are included here as a viable solution too because of their lower latency and lower path loss. A few of the reasons for the attractiveness of elliptical orbits are:

Feature 1: It overcomes the requirement for 2D scanning that is needed for LEO satellite constellations. This is an important advantage since it means that the consumer ground station will be significantly lower cost. This reason will be explored in more detail below.

Feature 2: There are a limited number of available geostationary slots for new geostationary satellites and alternatives are necessary to support future HTS needs. As mentioned in [100, 101] the concern is not physical interference between satellites, but rather interference between geostationary satellite signals. The Molniya system avoids this concern since the orbital path is not near geostationary satellite orbits so signal interference is reduced.

Feature 3: The potential spectrum bandwidth available for elliptical orbit satellites such as Molniya and low apogee elliptical means that they can support HTS service even at Ku-band and lower frequency bands. This means that Ka-band will not be needed and lower cost electronics and antennas can be used on the satellite and on the consumer ground station. This significant is

Table 7. Bandwidth Granted By FCC In Virtual Geo satellite Request [60]

F_{Low} (MHz)	F_{High} (MHz)	Bandwidth (MHz)
3700	4200	500
5925	6725	800
10700	12700	2000
12750	13250	500
13800	14500	700
	Total =	4500

demonstrated by the FCC allowing 4.5GHz of bandwidth to Virtual Geosatellite, LLC [60] in C and Ku-Band as shown in Table 7. The benefit to customers is increase internet speed.

These benefits make elliptic orbit satellite solutions such the Molniya and low apogee elliptic orbits an attractive alternative. We will now describe the Molniya orbit in more detail in the next section.

5.6 Molniya Orbit and Ground Station Pointing Requirement

Elliptic orbit satellites follow an elliptic orbit path around the earth. A Molniya orbit is a type of elliptic orbit and is named after a series of Russian communication satellites that were launched starting in 1965. Those satellites used a highly elliptic orbit which is shown in Fig. 22. Note from the figure the major parameters used to describe a satellite in an elliptic orbit around the earth. The definitions are:

apogee = the point at which the orbit distance is largest.

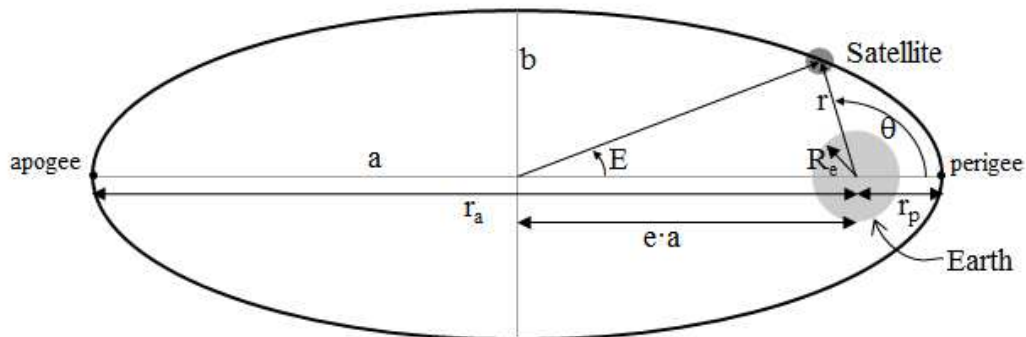


Fig. 22. Elliptic orbit of a satellite around the earth illustrating the main orbital parameters.

perigee = the point at which the orbit distance is smallest.

a = semi-major axis = distance from perigee to apogee.

b = semi-minor axis

e = eccentricity

r = distance from the center of Earth and the satellite

θ = angle between the lines from Earth center to perigee and Earth center to the satellite

r_a = distance from Earth center to apogee

r_p = distance from Earth center to perigee

E = angle between the lines from the center of the ellipse to perigee and to the satellite

R_e = radius of Earth

Molniya orbits can be configured with one or multiple satellites. For instance, the orbits for one, three and five satellites are shown in Fig. 23(a), (b), and (c), respectfully. Note the height of the orbit at apogee compared to perigee. A key feature of Molniya satellites is that each orbit is 12 hours so that the satellite completes two complete orbits per 24 rotation of the earth. This can be seen from the ground tracks for the case of 5 satellites is shown in Fig. 23(d). It is important to notice from the figure that the ground paths of the satellites follow a nearly north-to-south path in the center of North America during apogee in the first 12 hours and in the center of Asia (India, Russia, and part of China) during apogee in the second 12 hour period. Because of the high eccentricity, and Kepler's second law which teaches us that the satellite sweeps out equal areas during equal intervals, the time spent at or near apogee is approximately 8 hours of the 12 hour orbit.

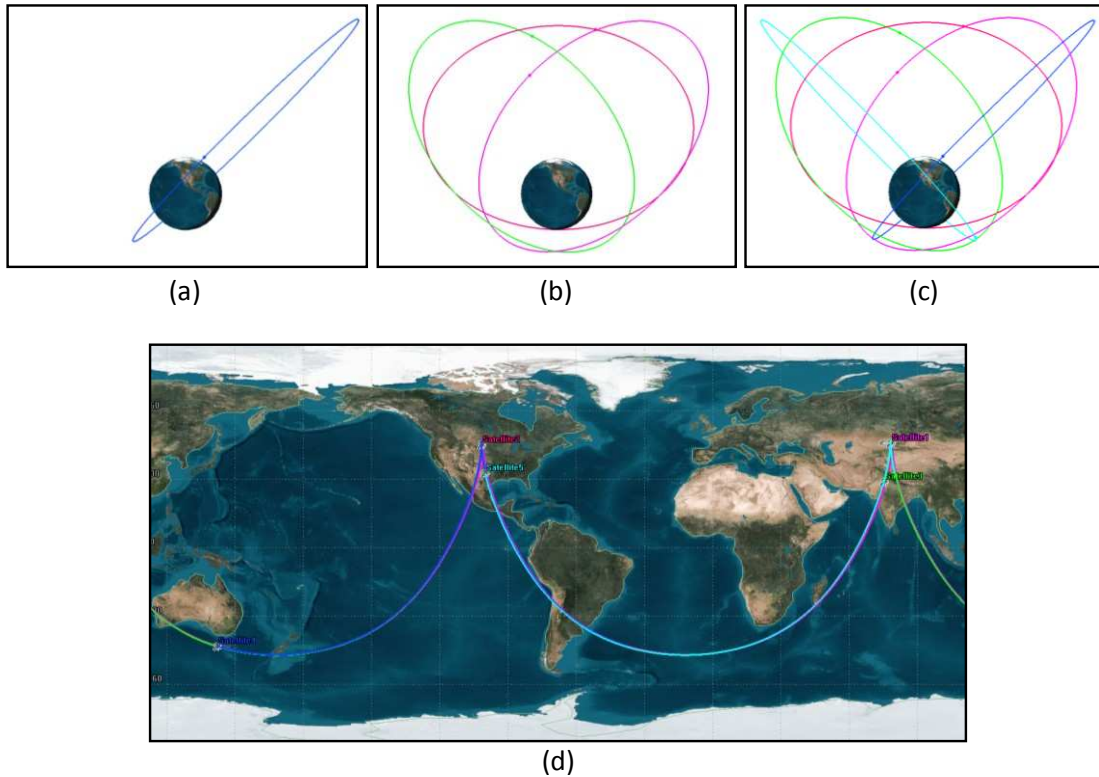


Fig. 23. The Molniya orbits for (a) one, three, and five satellites, and (b) the ground tracks for the case of five satellites (images generated using System Tool Kit (STK) software from Analytical Graphics, Inc.).

Since each satellite follows a nearly straight path (in longitude), Earth locations to the east and west of it will have access to the satellite. This can be seen in Fig. 24(a) which plots the access that a point in Boston, MA, USA will have as a function of time. Note that the satellite constellation provides continual access over the 24 hour period. An important feature, as mentioned earlier, is the elevation angle from the ground location to the satellite will appear to be nearly constant as a function time while the satellite is near apogee. In other words, a user on the eastern side of the ground track will view the satellites as passing at a nearly constant elevation when the user is looking westward. A user on the western side of the ground track will view the satellites as passing at a nearly constant elevation when the user is looking eastward. This is illustrated in Fig. 24(b) which shows that the elevation angle varies from approximately

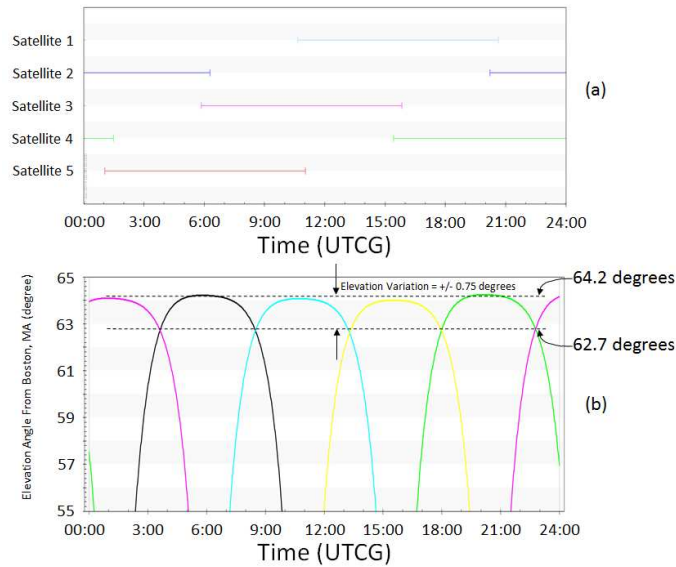


Fig. 24. The 5 satellite constellation provides (a) complete coverage as seen from Boston, MA, and (b) a variation of approximately +/-0.75 degrees in elevation. (graphs generated using System Tool Kit (STK) software from Analytical Graphics, Inc.).

62.7 to 64.2 degrees for a total variation of approximately +/- 0.75 degrees. This is an important result since this provides the specification for the antenna beam width and pointing accuracy requirement. This means that the antenna can be set to a fixed elevation and as long as the antenna beam width is properly designed so that the satellite remains in the consumer ground station antenna beam width as it varies slightly in elevation. This arrangement will ensure the constellation of satellites will be continually in the consumer ground antenna beam width. The simulations were performed with the following orbital parameters for the Satellite:

- Semimajor Axis: 26,553.4 km
- Eccentricity: 0.56
- Inclination: 47 degrees
- Argument of Perigee: 270 degrees
- RAAN: 153 degree (for Satellite 1)

- True Anomaly: 0 degrees

At this inclination, the Argument of Perigee will be perturbed over time. This will require fuel burn to keep the satellite at the correct Argument of Perigee. Other inclinations such as a critical inclination of 63.4 degrees can also be used which will overcome the perturbation of the Argument of Perigee.

5.7 Consumer Ground Station

One benefit of the tight variation in elevation is that a simple ground station can be used. This is because the ground station will scan electronically in only one direction since the elevation setting will be fixed during installation. Fig. 25(a) is a simplified illustration showing the concept of an array antenna. Fig. 25(b) shows one dimensional line array elements each with a single phase shifter attached. The line arrays are combined to create the 2 dimensional array. This is a significant improvement over what is required for LEO satellites since the number of required phase shifters in the consumer ground station is reduced. For instance, for an array with 20 x 20 elements, only 20 phase shifters are required which is much lower cost than the 100 to 400 required for the ground station in a LEO system as previously.

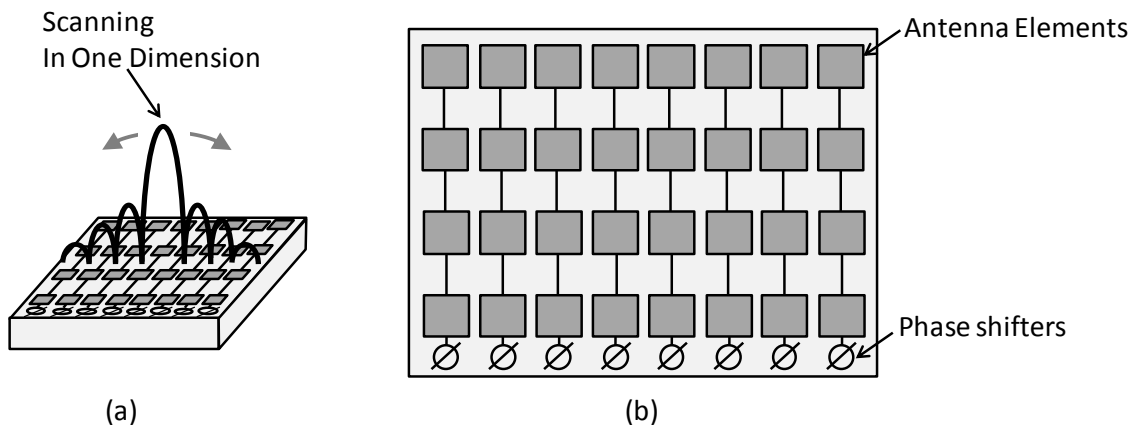


Fig. 25. Illustration of the (a) one-dimensional scanning array with (b) phase shifters at each column of antenna elements to enable the beam single dimension beam steering.

Part of the reason fewer phase shifters is a benefit is they are high performance and costly semiconductor components. As part of the systems engineering evaluation, a trade study was conducted to determine the candidate semiconductor for the phase shifter. The candidate technologies are silicon complementary metal-oxide-semiconductor (Si-CMOS), silicon germanium (SiGe), gallium arsenide (GaAs), and indium phosphide (InP). The trade study analyzed seven criteria for selecting the semiconductor material. The selection criteria along with a description are:

1) Integration Complexity: The phase shifter requires a high level of circuit complexity. This is because it contains many different types of circuits such as low noise amplifiers, high power amplifiers, operational amplifiers, digital control circuits, analog to digital converters, and temperature compensation circuits. The functionality of these circuits contribute to the overall function and performance of the system. As a result, this criteria is important since it has a direct impact on the customer need for high availability and data rate on both up and down link.

2) Relative Cost: The active circuits that form the integrated circuit are fabricated onto semiconductor wafers. There are two important factors impacting the relative cost of semiconductor wafers. The first is the raw material cost. The second is the volume of wafers produced per year which is normally reported in units of million square inches (MSI). As more wafers are produced, the cost of each wafer will be lower. Therefore, semiconductors with lower raw material cost and high production volume will result in lower cost integrated circuits. This has an important impact on the customer need for a low cost solution.

3) Production Capacity: This is the capacity of semiconductor foundries to fabricate the integrated circuits onto the raw wafers. This is an important selection criteria since the volume of finished wafers required to meet the demand for consumer ground stations must not be a

significant percentage of the world wide capacity. Otherwise, the cost of the foundry processing will increase and the ability to meet demand will be impacted. This has an important impact on the customer need for a low cost solution.

4) Output Power (TX): The transmit (TX) output power of the semiconductor material directly impacts the effective isotropic radiated power (EIRP) of the consumer base station. This, in turn, is a major determining factor for the up-link (ground to satellite) link budget. This translates into an impact on the customer need for uplink data connection speed.

5) Receive IP3: The receiver third order intercept (IP3) must be high enough that it will achieve the required dynamic range. IP3 determines the high side of the dynamic range of the receiver. In other words, it sets the maximum signal level that can enter the receiver without the signal being distorted. This includes not only the desired signal from the satellite, but also any other undesired signals that are at or near the same operating frequency of the receiver. This is important for cases of possible interfering signals which may overwhelm the receiver. This translates into an impact on the customer need for a high level of availability of the system.

6) Receive Noise Figure: The receive noise figure, like IP3, impacts the minimum signal the receiver in the consumer ground station can distinguish. It sets the noise floor and the lower end of the dynamic range. The receiver noise figure determines the G/T of the consumer ground station which will be discussed in Section V. This translates into an impact on the customer need for a high level of availability of the system and on the maximum data rate of the system.

DC Power Consumption: This is a factor for thermal reasons. Integrated circuits which consume more electric power also generate more heat. The heat degrades the performance and lifetime of the integrated circuits. Therefore, lower DC power consumption translates, in general, to more reliable electronics. This impacts the customer need for a reliable system. Given these seven

selection criteria, a trade study was conducted to determine the semiconductor material that should be selected for the phase shifters used in the consumer ground station. The trade study spreadsheet is shown in Fig. 26. Note that there is a clear distinction between the silicon based materials (Si-CMOS and SiGe) and GaAs and InP with Si based solutions being preferred.

Criteria	Si-CMOS	SiGe	GaAs	InP
Integration Complexity	5	5	3	1
Relative Cost	5	5	3	1
Production Capacity	5	5	3	1
Output Power (TX)	3	3	5	5
Receive IP3	3	3	5	5
Receive Noise Figure	1	3	5	5
DC Power Consumption	5	5	3	1

Key	
5	= High
3	= Medium
1	= Low

Criteria	Weighting	Si-CMOS		SiGe		GaAs		InP	
		Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)
Integration Complexity	2	5	10	5	10	3	6	1	2
Relative Cost	2	5	10	5	10	3	6	1	2
Production Capacity	2	5	10	5	10	3	6	1	2
Output Power (TX)	1	3	3	3	3	5	5	5	5
Receive IP3	1	3	3	3	3	5	5	5	5
Receive Noise Figure	1	1	1	3	3	5	5	5	5
DC Power Consumption	1	5	5	5	5	3	3	1	1
	10		42		44		36		22

Fig. 26. Trade study result shows that Si based semiconductors are preferred to GaAs and InP solutions.

Each of the criteria is given a weighting, W_k , which is related to its importance to the mission of the system. Each of the energy generation options is assigned a value, V_k , for its ability to achieve each of the criteria. If this is done, then the score for each option is given by:

$$Score = \sum_{k=1}^n W_k V_k \quad (7)$$

Where n = the number of criteria, which is seven in our case. The trade study was implemented in a spread sheet.

The justification for the assigned values for a few of the criteria will now be discussed. For integration complexity in Si-CMOS and SiGe semiconductor processes, it is easier to include functions such as operational amplifiers, digital control circuits, analog to digital converters, and temperature compensation circuits as compared to GaAs and InP. This is mainly due to factors

such as the available transistor types and number of metal layers available in the foundry processes. For these reasons, Si-CMOS and SiGe scored higher than GaAs and InP.

The relative cost of the raw material and cost of the semiconductor wafers varies. The active circuits that form the integrated circuit are fabricated onto semiconductor wafers. The cost of Silicon is low compared to GaAs and InP due in large to the fact that it is the second highest concentration element (at 27.7%) on the earth's crust. Also, the volume of silicon wafers produced is much higher than for GaAs or InP. For instance, the volume of Si wafers produced in 2016 will be nearly 11,000 million square inches (MSI) compared to approximately 150 MSI for GaAs [102, 103]. For these reasons, Si-CMOS and SiGe scored a higher value than GaAs and InP.

Despite the performance limitations of Si-CMOS and SiGe compared to GaAs and InP, they are the better choice as the semiconductor material. The relative weighting score between them is very close with SiGe having a slightly higher score due to better noise figure performance. An advanced development effort should be conducted so that major subsystems simulated and/or fabricated with Si-CMOS and SiGe can be compared to make a final choice between the semiconductor material.

The criteria of output power, IP3, and noise figure are better for GaA and InP since they are wider band gap materials and have better electron transport compared to Si-CMOS and SiGe. Work on comparing Si-CMOS and SiGe demonstrates that SiGe has the performance edge over Si-CMOS for noise figure, IP3, and output power [104, 105]. As a result, SiGe scores better than Si-CMOS but lower than GaAs and InP on these performance criteria.

Also, in [106] key performance parameters such as noise figure, gain, 1 dB compression point, and IP3 for low noise amplifiers are compared for SiGe and GaAs. An important finding is

that SiGe is able to achieve approximately 1.4dB of noise figure at 12GHz. The output power of SiGe for the uplink will stretch its performance limits. However, output power levels of SiGe at Ku-band have been demonstrated at 24.45dBm [107] and 850mW was demonstrated at 10.5GHz [108]. Similar performance levels for SiGe will be used in the system level link budget analysis which will show the feasibility of its usefulness for consumer ground stations.

The design of antenna for the ground station must account for multiple, often competing, requirements. Three of the requirements that will be addressed here are:

1. It must be capable of providing the required gain to close the link with the satellite.
2. Have a wide enough beam width that the satellite will remain within the main beam through the required portion of the orbit.
3. Scan electronically without introducing grating lobes.

To determine the ability of the ground station antenna to achieve these requirements, we must first consider the antenna as an array of radiating elements. This is depicted in Fig. 27. Note that there are M columns of line arrays each with N elements for a total of MxN elements. Thus,

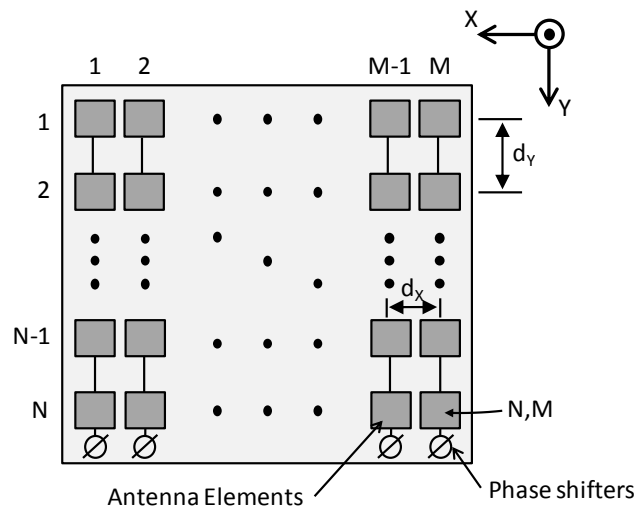


Fig. 27. Ground station antenna represented as an array of antenna elements with M columns and N rows.

for an array for $M=20$ and $N=20$, there will be 400 elements. Also notice that there are M elements spaced apart in the x -direction by d_x and N elements spaced apart in the y -direction by d_y .

Given the configuration in the figure, the antenna will create a beam in the far field with a beam width as defined in Fig. 28. In the direction broadside to the antenna, the antenna 3dB beam width in degrees can be approximated using

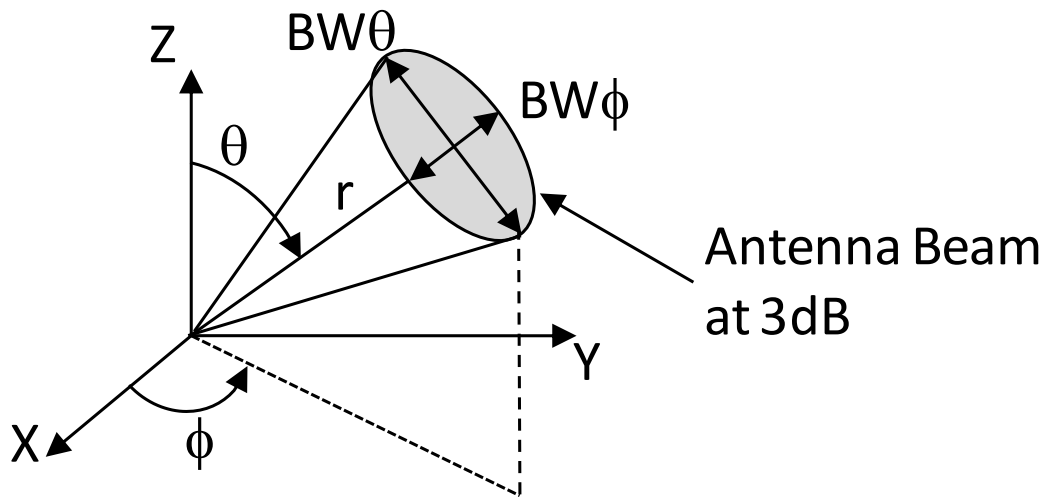


Fig. 28. Antenna beam width in the far field.

$$BW_{\theta} = 50.76^{\circ} \sqrt{\frac{\lambda}{Nd_y}} \quad (8)$$

and

$$BW_{\phi} = 50.76^{\circ} \sqrt{\frac{\lambda}{Md_x}} \quad (9)$$

Where, λ = the wavelength at the operating frequency. Using (8) and (9), the magnitude of the directivity can be approximate by

$$D(\theta, \phi) = \frac{16}{\sin(BW_\theta)\sin(BW_\phi)}. \quad (10)$$

If the efficiency of the antenna is given by ϵ_{eff} , then the gain of the antenna in dB can be calculated using

$$G(dB) = 10 \log_{10}(\epsilon_{eff} D). \quad (11)$$

Assuming the center of the band to be 11.7GHz, antenna efficiency of 65%, the number of elements in array are $N=20$, $M=20$, element spacing of $d_x=15.38\text{mm}$ (0.6λ), $d_y=23.07\text{mm}$ (0.9λ), the calculated antenna parameters are

$$BW_\theta = 2.8^\circ, BW_\phi = 4.23^\circ, \text{Gain} = 34.57\text{dB}.$$

Note that the element spacing is much wider in the y-direction since the antenna will not be scanning along that axis, but the element spacing is just above a half-wavelength in the x-direction since that is the direction the antenna will be scanning. This arrangement minimizes the presence of grating lobes as the antenna is scanned. Since the beam width in the non-scanned direction is 2.8° , this will ensure that the satellites remain in the antenna's main beam as they vary by $\pm 0.75^\circ$ in their north-south ground track as discussed above.

This level of investigation into the antenna design demonstrates the feasibility. It is suggested that an advanced design effort is in order to further demonstrate either through detailed simulations or, preferably, through testing that the antenna design concept will achieve the gain, beam width, and grating lobe free scanning that is required.

5.8 Cost of the Ground Station

The cost of the ground station can be analyzed by considering the two main contributors to the cost. The first is the cost of the antenna circuit board. It is a printed circuit board (PCB) but cannot be fabricated using standard PCB material such as FR-4. Rather, it must be fabricated

using high quality laminates with low losses at the frequency range of the satellite signals. This is critical to the proper operation of the antenna otherwise a large portion of the signal will be absorbed by the PCB material rendering the system unusable. Until recently, the cost of the high quality laminates has been prohibitive since they use Polytetrafluoroethylene (PTFE) materials which have been relatively high cost in the past. However, the cost of PTFE based low loss microwave laminates are \$58 to \$80 per square meter in high volume [109] [54]. This means that a 0.6 m² antenna will have approximately \$35 of antenna PCB board cost. As production volumes increase, there will likely be additional cost savings.

The other main cost contributor to the ground station is the cost of the integrated circuit phase shifters and amplifiers. Since the trade study in the last section showed SiGe as the preferred semiconductor material, the cost analysis will be based on it. Fig. 29 shows the cost per die for the phase shifter integrated circuit with the associated control electronics and amplifiers. At a wafer cost of \$2500 on a 200mm SiGe fabrication line, the cost of each integrated circuit is approximately \$3.13 each, and on a 250mm wafer, the cost is approximately \$1.81 before

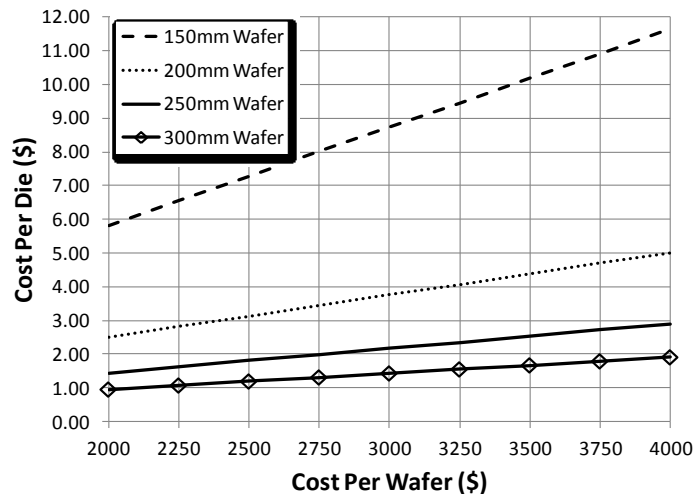


Fig. 29. The cost per phase shifter integrated circuit as a function of wafer cost and wafer size (assumes a die size of 5x5mm, 80% yield, and unpackaged die).

packaging. For an array of 20 line arrays, the total die cost will be approximately \$36 to \$63. As the semiconductor industry moves to 300mm wafers, the cost of the die will drop to approximately \$1.19 each for a total die cost per array of \$26.

This analysis shows that the main cost drivers for the consumer base station, the antenna PCB and integrated circuit phase shifters, can be fabricated for a cost that is approximately \$61 (\$35 for the antenna and \$26 for the integrated circuits).

5.9 Link Budget

The purpose of this section is to show through modeling that it is possible to achieve uplink and downlink with acceptable margin using subsystems and components that are low risk. Low risk means that the required hardware components have been previously demonstrated in a relevant environment which is Technology Readiness Level (TRL) 5 or 6 [110] [55]. The key functional elements that affect the link are the:

- Effective Isotropic Radiated Power (EIRP) of the transmitter
- Losses (free-space and atmospheric)
- Channel bandwidth
- Receiver G/T

These four elements will be investigated and viable hardware solutions with low risk will be described. Prior to that, however, the block diagram of the satellite link must be described.

The block diagram of a link between a satellite and ground station is shown in Fig. 30. The downlink (satellite to ground terminal) is shown in Fig. 30(a) and the uplink (ground station to satellite) is shown in Fig. 30(b). For the downlink, the satellite operates as the transmitter (TX) with a high power amplifier and transmit antenna and the ground terminal operates as the receiver (RX) with a receive antenna and low noise amplifier. For the uplink, the arrangement is

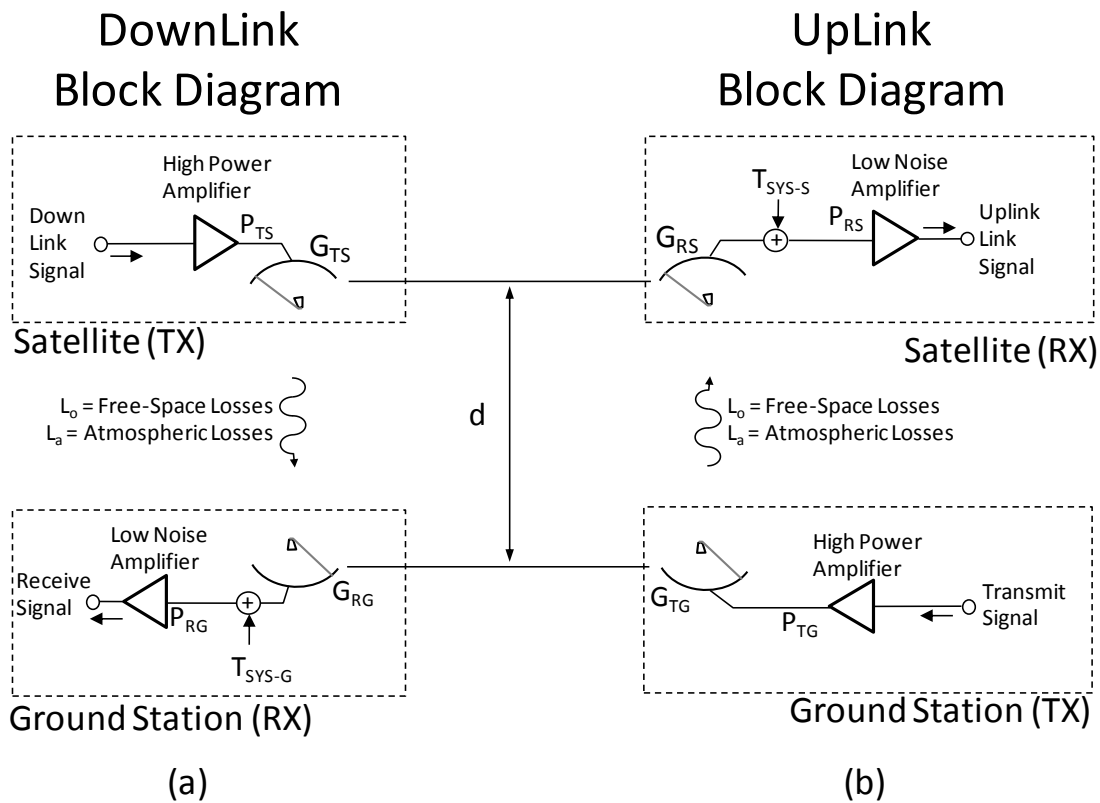


Fig. 30. Simplified block diagram of the satellite (a) downlink with the satellite as the transmitter (TX) and ground terminal as receiver (RX), and (b) uplink with the ground terminal as the TX and satellite as RX.

just the opposite with the ground terminal functioning as the TX with high power amplifier and transmit antenna and the satellite functioning as the RX with a receive antenna and low noise amplifier. It is also important to note that in the receive cases there is an added noise which is the system noise temperature. It accounts for all the system noise contributions such as from the low noise amplifier and antenna. The definitions for the elements in the block diagram are:

- G_{TS} = Satellite transmit antenna gain (downlink)
- P_{TS} = Satellite power amplifier out power (downlink)
- G_{RS} = Satellite receive antenna gain (uplink)
- P_{RS} = Satellite signal power received (uplink)
- T_{SYS-S} = Satellite receiver system noise power (uplink)

G_{RG} = Ground station receive antenna gain (downlink)

P_{RG} = Ground station signal power received (downlink)

T_{SYS-G} = Ground station receiver system noise power (downlink)

G_{TG} = Ground station transmit antenna gain (uplink)

P_{TG} = Ground station power amplifier out power (uplink)

d = distance between the satellite and ground terminal antenna

Between the satellite and the ground terminal free-space, L_o , and atmospheric losses, L_a , occur. Free-space losses are also called spreading losses and are defined by the IEEE Std 145-2013 as “the loss between two isotropic radiators in free space, expressed as a power ratio [111].” The atmospheric loss is due to attenuation from effects such as rain fade. The free-space loss is proportional to the square of the distance between the satellite and ground terminal and is given by [112]

$$L_o = \left(\frac{4\pi d}{\lambda} \right)^2 \quad (12)$$

Where:

λ = wavelength of the signal

The system noise temperature is has two components which are the noise temperature of the antenna, T_A , and the noise temperature of the receiver, T_{RX} which can be written as

$$T_{SYS} = T_A + T_{RX} \quad (13)$$

The noise temperature of the antenna is affected by where the antenna beam is pointed. If the antenna has low side lobes and is on the earth pointed up to cold clear sky then the noise temperature will be low. If the antenna is mounted on a satellite and is pointed toward the warm earth, then the noise temperature will be much higher. The noise figure (NF) of the receiver is

normally specified and includes the feed loss, L_F , plus the noise figure of the electronics, NF_{LNA} which can be written as

$$NF(dB) = NF_{LNA}(dB) + L_F(dB) \quad (14)$$

but the receiver noise temperature can be calculated from NF using

$$T_{RX} = T_{REF} \left(10^{NF(dB)/10} - 1 \right) \quad (15)$$

The system designer needs to know the signal to noise ratio (S/N) of the system being designed. This is because it provides a measure of quality (or capacity) of the communication channel based upon Shannon's channel capacity theorem

$$C = B \cdot \text{Log}_2(1 + S/N) \quad (16)$$

which gives the channel capacity in bits per second for a given system signal to noise ratio and channel bandwidth B . The signal to noise ratio for the uplink (consumer ground station to satellite) is calculated using

$$\left. \frac{S}{N} \right|_{\text{Satellite}} = P_{TG} G_{TG} \cdot \left(\frac{\lambda}{4\pi d} \right)^2 L_a \frac{1}{kB} \frac{G_{RS}}{T_{SYS-S}} \quad (17)$$

The first two terms relate to the ground station antenna and output power, the middle terms to the channel and losses, and the final term relates to the satellite receive antenna and system noise temperature. For the downlink (satellite to ground consumer station), the signal to noise ratio is given by

$$\left. \frac{S}{N} \right|_{\text{Ground Station}} = P_{TS} G_{TS} \cdot \left(\frac{\lambda}{4\pi d} \right)^2 L_a \frac{1}{kB} \frac{G_{RG}}{T_{SYS-G}} \quad (18)$$

It is normal to use the effective isotropic radiated power (*EIRP*) which is the product of the transmit power and transmit antenna gain. In this case

$$EIRP_S = \text{Satellite EIRP} = P_{TS} G_{TS} \quad (19)$$

$$EIRP_G = \text{Ground Station EIRP} = P_{TG} G_{TG} \quad (20)$$

Since satellites use digitally modulated and coded channels, it is more convenient to use energy per bit transmitted normalized to the power spectral density of the noise, or E_b/N_0 . It is related to signal to noise ratio by

$$\frac{E_b}{N_0} = \frac{S}{N} \frac{B}{R} \quad (21)$$

Where S/N is calculated from (11) or (12) depending upon whether the uplink or downlink are being analyzed, B is the channel bandwidth and R is the digital data rate. If satellite TV providers are used as a frame of reference for the required E_b/N_0 , then the required E_b/N_0 for the downlink (satellite to ground station) will be between 6.5 and 7.2dB without margin which provides a 10^{-10} bit error rate (BER) as described in [113]. For the work, we will use the E_b/N_0 requirement 6.85dB which is between these two values.

Using (11) and (12) requires the knowledge of the slant distance from the consumer ground station to the satellite. Simulations of the Molniya orbit using the same orbit parameters

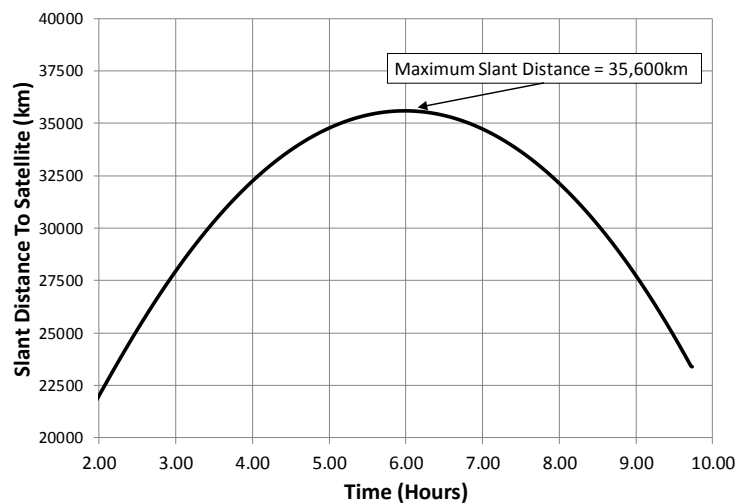


Fig. 31. Slant distance from Boston, MA to satellite shows the maximum at 35, 600km (simulations performed using System Tool Kit (STK) software from Analytical Graphics, Inc).

as for Fig. 23 and Fig. 24. The result is shown in Fig. 31 which shows the maximum slant range as 35,600km.

Referring back to Table 7, the downlink and uplink frequencies must be assigned to particular frequency bands. Since consumer internet access is non-symmetrical, with high download and low upload speeds, it makes sense to allocate the wider Ku-band at 10.7-12.7GHz to the downlink and the narrow Ku-Band from 13.8-14.5GHz to the uplink. One benefit of this

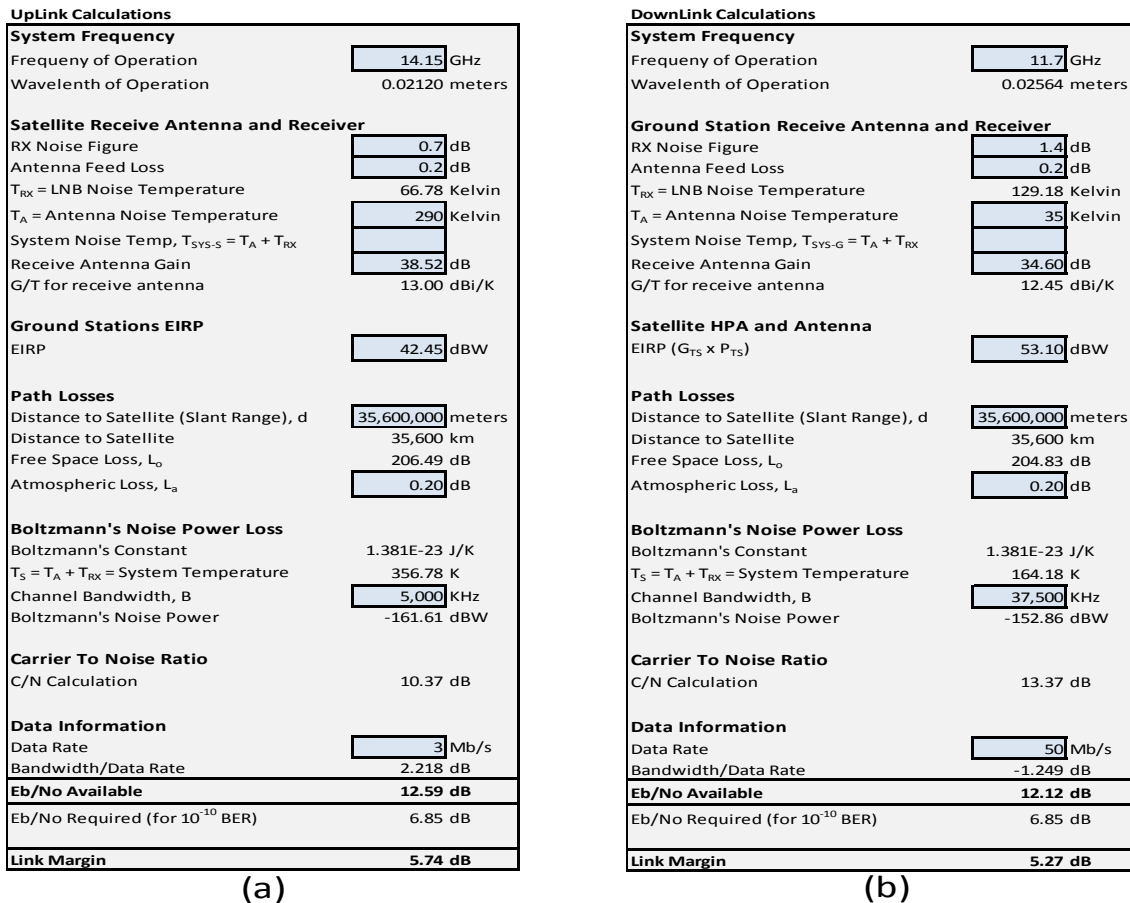


Fig. 32. Link budget calculations for (a) the uplink, and (b) the downlink.

arrangement is the separation of 1.1GHz between the up and down links which is helpful for isolation reasons. The rest of the spectrum (1.8GHz) in Table 2 can be allocated to providing access and control to the satellite. Based upon this frequency plan and (7), and (8), the link

analysis was performed. For the uplink, the center of the band was chosen at 14.15GHz and the link calculations spreadsheet results are shown in Fig. 32(a). It shows the calculated E_b/N_0 is 12.59dB which provides a link margin of 5.7dB beyond the goal of 6.85 dB. For the downlink, the center of the band was chosen at 11.7GHz and the link calculations spreadsheet results are shown in Fig. 32(b). It shows the calculated E_b/N_0 is 12.12dB which gives a link margin of 5.3dB beyond the goal of 6.85dB. This analysis is for a Molniya orbit satellite which has a more challenging link budget than a low apogee elliptic orbit since the Molniya orbit apogee is approximately the same distance as the radius of a GEO satellite. The point of the analysis is that it is possible to close the link with margin for the Molniya orbit. Based on this link budget there are a several requirements that are placed on the consumer ground terminal and satellite. First, the receive noise figure for the ground station on the downlink must be 1.4dB. As stated earlier, prior work in [107] [52] demonstrates the ability of SiGe to achieve this noise performance. Second, the ground station uplink transmit $EIRP$ is 42.45 dBW with an antenna gain of 34.6dB. This means that the ground station must have a transmit power of $42.45\text{dBW} - 34.6\text{dB} = 7.85\text{dBW}$ which is 6.1W. If there are twenty line arrays, then this means that each line array must produce 0.305W or 24.8dBm of transmit power. This level of output power from SiGe is within the range of demonstrated performance as discussed in Section III. Third, the satellite antenna gain is 38.52dB which can be achieved with an antenna diameter less than 1 meter. Fourth, the satellite receive noise figure is set to 0.7dB which means that the satellite G/T is required to be 13dB which may be a bit aggressive. However, next generation satellite performance is being extended to achieve the HTS goals so that this requirement should be carefully considered.

5.10 Conclusions and Recommendations

The conclusions of this work are that an operational need exists for HTS satellites and a feasible solution exists. These conclusions are supported by analysis in five areas. First, the needs analysis focused on consumer internet users in rural and remote areas and connectivity for IoT end points and access points. A simple financial model showed that these needs provide a financial incentive for development of a solution. Recent technical advances in SiGe integrated circuit technology and cost reductions in circuit board materials for antennas provide additional incentive for the new system.

Second, several alternatives for the system solution were considered including geostationary, low Earth orbital (LEO), and Molniya orbit satellite constellations. The analysis considered the whole system including the consumer ground station. The Molniya orbit solution was chosen because of the available bandwidth at C-Band and Ku-Band which overcomes the spectrum crowding of geosynchronous satellites and because of the lower cost consumer ground station compared to LEO solutions.

Third, the Molniya solution was investigated in detail to ensure that a feasible system level solution exists. Orbital dynamics were considered and it was shown that a constellation of five satellites can provide continuous coverage for the USA and parts of Asia. It was also shown that the elevation, as seen from the ground station, has a variation of only +/- 0.75 degrees which is within the main beam of the consumer ground station.

The fourth investigation in this work that supports the conclusions is the consumer ground terminal. It was analyzed from a cost and available technology perspective. It was found that the cost of the key integrated circuit, the phase shifter, is affordable now and will become more affordable as industry migrates from 200mm to 250mm and 300mm wafers. Fifth, the link

budget was analyzed and it was found that the link can be closed with approximately 5dB of margin for both up and down links. The work in these five areas supports the conclusions that there is an operational need for the new system and that a feasible solution is exists.

Additional work should be performed on this system in at least six different areas. First, the overall system affordability should be investigated in more detail. Specifically, the cost of developing and deploying the constellation versus the financial benefit must be analyzed. Second, a more extensive analysis of Molniya orbit satellite elevation as a function of orbit parameters over the desired coverage area should be conducted. In fact, the trade space of orbit parameters should be examined to minimize the elevation variation at all points in the desired coverage area. Third, an advanced development effort was suggested in the analysis to aid in choosing between the use of SiGe or Si-CMOS for the phase shifter. This is important since there are cost advantages for choosing Si-CMOS over SiGe but there are unanswered questions with the ability of Si-CMOS to meet the noise figure and output power levels required. Fourth, an additional advanced development effort is suggested for the antenna for supporting circular polarization. Fifth, there are certain benefits that a low apogee elliptical orbit offers over a Molniya orbit and yet both benefit from wide available bandwidth. Therefore, a further refinement in this analysis is to optimize the type of elliptical orbit with variables such as apogee and inclination being important trade parameters. Sixth, a comparison of the capital cost for developing a global GEO versus elliptic orbit system should be compared. Of course, there are many other areas of work that can and should be conducted to further this system concept toward implementation.

5.11 Assessment As A SoS

This is another example of a complex system that is not a SoS. The reasons are that each of the elements lack independence management and operational independence. One entity manages the subsystems and the subsystems need each other in order to provide a useful function.

6. Description and System Architecting of The MSDD System

The fifth and final system to be considered as a possible SoS is a Multi-Spectral Drone Detection (MSDD) system for installation in airports.⁵ The system uses multiple independent sensors and some are separately developed and separately managed. By themselves, the sensor provides a significant function and value meeting customer needs that is separate from the MSDD. When the sensor outputs are combined, they can provide functionality the individual systems were never intended to provide. Also, several of sensors are pre-existing and have their own sources of funding for deployment, maintenance, operation, and management. As can be seen from this description, the MSDD system may be a viable candidate to be considered a valid SoS.

This chapter is concerned with describing the MSDD and the development of the baseline concept. First the problem of drone detection is described and examples are given which justify the need for the system in general. Then the specific need for airport protection is described. Second, a survey of prior work is performed which demonstrates that existing solutions have



Fig. 33. Threat of drones against public venues, government buildings, military targets, and nuclear power plant.

⁵ From R. Sturdivant, E.K.P. Chong, “Systems engineering baseline concept of a multispectral drone detection solution for airports,” *IEEE Access* (submitted).

deficiencies. Third, a baseline solution is developed using the SAI method described in Chapter 1. The result is a feasible baseline design that is capable of meeting the need. This chapter concludes with a summary and suggestion for additional work.

6.1 Problem Description and Significance

There is growing concern that drones will be used as military weapons, as shown in Fig. 33 against civilian and military targets. Recent events illustrate the existence of significant vulnerability. Take, for instance, the accidental landing of a remotely controlled drone on the U.S.A. White House Lawn. The crashed drone, shown in Fig. 34, was about 2 feet in diameter. The drone was flown by a government employee from his apartment balcony. The problem is the owner of the drone was intoxicated while flying it. He claims to have lost control at approximately 3AM while flying it for recreational purposes. Though Secret Service officers on duty at the time claim to have seen it, the radars installed around the white house were not able to detect the drone since it was “too small and flying too low to be detected by radar” [114]. The reason is that the installed radar systems around the white house were designed to detect larger fast moving objects like planes and missiles. A small drone is either not seen at all by these radars, or it is mistaken as a bird and ignored. Though this was an innocuous event, it reveals a



Fig. 34. Image of the drone that crash landed on the south lawn of the US White House.

serious vulnerability that exists. If the White House is not protected against these types of drones that could be weaponized with explosives, chemical, biological, or nuclear weapons, then other sites such as power generators, nuclear power plants, schools, and government buildings must be at even greater risk.

Another example of the threat is that a man landed a drone with radioactive material on the roof of the private residence of the Japanese Prime Minister [115]. The perpetrator of the incident, a 40 year old man, said he purposely landed the drone where he did as a protest against the Japanese government's nuclear energy policy.

In another example, two men were arrested by German police over a plot to use a model plane as part of a terror plot. The report said, "They are suspected of having sought to acquire information and equipment necessary to carry out 'radical Islamist explosive attacks using remote controlled airplanes,' according to a statement on the website of Germany's Federal Public Prosecutors' Office" [116].

These examples demonstrate the reality of the threat, but an objection to this is that only limited amount of damage can be caused by a single drone. While this objection underestimates the damage that 1-2kg of C4 explosives can inflict, it also misses the fact that drone attacks can be perpetrated simultaneously using multiple drones. Consider, for instance, students at the Naval Postgraduate School in Monterey, CA demonstrated that a swarm of 50 drones can be controlled by one operator [117]. This type of swarm attack poses a threat much greater than a single drone. As a result, the threat from drones is real and solutions must be developed.

The concern in this work is specifically for the treat to airports which is taken seriously. For instance, the FAA has reported that there are more than 100 sightings of unauthorized drones at airports each month [118]. As a response to the threat posed by drones to airports, the FAA

developed its Pathfinder Program. The purpose of this program is to evaluate procedures and technologies design to identify unauthorized UAS operations in and around airports [119]. As part of that program, the FAA has recently signed cooperative research and development agreements with three different companies. Therefore, this is an area of active research and solutions are still being developed. This chapter focuses on the development of a baseline concept for a SoS for the detection of drones at airports.

Table 8. Drone categories used in this work (based upon [120]).

Drone Category	Mission Radius	Payload
Nano	100-500 m	<0.2 kg
Micro	5 km	0.2–0.5 kg
Mini	25 km	0.5-10 kg
Small	50-100 km	5-50 kg
Tactical	200 km	25-200 kg

6.2 Drone Categories and Survey of Prior Work

There are at least five categories of drones [120] and some of their critical characteristics are summarized in Table 8. The first type is called the nano drone with a maximum mission radius of 100-500 m and a payload of less than 0.2 kg. The second type is the micro drone which weights less than 2 kg with a maximum mission radius of 5 km and a maximum payload of 0.2-0.5 kg. The third type is a mini drone with a maximum mission radius of 25 km and a maximum payload of 0.5 to 10 kg. The fourth type is a small drone with a maximum mission radius of 50-100 km and a maximum payload of 5-50 kg. The fifth type is the tactical drone with a maximum mission radius of 200 km and a maximum payload of 25-200 kg. The focus of this work is on mini drones and larger because their payload capacity means they can carry explosives that can cause significant damage.

The majority of the prior work on drone detection can be divided into three main types with some examples of overlap. The first type is detection using sound. For instance, in [121]

audio classification of drones was performed using data mining techniques. They used a Hidden Markov Model for phenome analysis and consumer quadcopters were used in their experimentation. They found that data clustering similar objects and drone flight states helped speed up the analysis and improve classification of detected drones. Another example of sound detection is in [122] which used correlation methods and audio fingerprinting methods. The audio fingerprinting method leverages consumer mobile phone applications which recognize songs. These apps sample a portion of a song, create a spectrogram, and compute similarities to stored songs in a database. Their result showed the correlation method provided higher scores for detection. Another investigation [123] compares various correlation methods experimentally. For instance, the Spearman and Kendal rank-correlations were used but were not able to show sufficient differences between sound sources. However, Pearson and cross-correlation showed acceptable discrimination between sound sources.

The second type of system uses cameras for the detection of drones. In [124], for instance, a moving camera is used to track the movement of a drone and uses a regression-based approach. They achieved object-centric learning-based motion stabilization and were able to classify targets in spatio-temporal image cubes. A completely different approach is taken in [125] which uses ‘humans-as-sensors’ by using a smart phone application and leveraging data captured on personal smart phones. While this method is interesting, it requires cooperation of users and is prone to misuse since the application is distributed to users.

The third type uses RADAR to detect drones. For instance, in [126] the system is based on a 35GHz FMCW radar with 0.02 to 2.0 Watts of peak transmitted power and is used to detect when a drone passes a ‘barrier.’ The results show that the drone was detected at ranges as far as approximately 50 meters and velocities as high as approximately 3.5 m/s. Another example is in

[127] which uses an antenna array operating at L-Band with approximately 10kW of transmit power. However, the range of radar systems for drone detection is limited due to the small radar cross section (RCS) of the drones. Also radar return signal clutter makes it even more difficult to distinguish drone targets at airports. Nevertheless, prior work demonstrates that it is possible to detect drones with radar.

In addition to the three main types of systems, other workers have been proposed to combine multiple sensors. For instance, in [128] several possible detection methods are considered including audio, video, thermal, RADAR, and radio frequency detection. The demonstrated system uses video and audio detection and an RF gun to disable the drone. The audio method uses a template matching method and the video method uses an absolute difference method between consecutive frames to detect color and motion. The results show that motion was detected as long as the drone occupied a threshold minimum number of pixels.

However, these approaches do not leverage the benefits of a SoS approach for drone detection. These examples demonstrate varying levels of performance but take a narrow view on integrating sensor functions for the purpose of detecting drones. Furthermore, the prior work fails to utilize existing sensors and instead propose the development of custom sensors tailored specially to drone detection. Moreover, the approval process for deployment of new sensors at airports is long and expensive. This means that if a new system is developed, it could take many years before it is actually deployed.

Because of these challenge, an alternative is to take a bigger perspective—A SoS perspective and consider how multiple systems can be used together to meet the need. This approach will assess methods to sustain value delivery over time, system value propositions, non-functional requirements, customer/user needs, already existing systems, possible new

systems, and architecture alternatives. This type of SoS approach is expected to be more responsive to changes in the operational environment and increase the likelihood of the system meeting customer needs. The ability to adapt is important for this system since drone technology is still maturing and expanding. The SoS approach has the potential to provide a viable solution and the first step is the development of a feasible baseline concept.

6.3 Concept Development Using The SAI Method

The approach taken here for concept development is the SAI method. As discussed in Chapter 1, it is an eight step process which results in a feasible baseline system that is expected to meet customer needs. Each of the eight steps will now be analyzed.

As described in Fig. 2 in Chapter 1, the eight steps start with an operational needs description which is a statement of the operational goals of the SoS. For the drone detection SoS, it is “the main operational goal of the MSDD SoS is to provide information to enhance protection of airport assets against attack by drones.” The attributes needed for the system are derived from this statement.

6.3.1 Step 1: Determine Value Proposition and Constraints

This step requires the identification, understanding, and documentation of overall SoS architecture value propositions. This step in the process can be broken down into six sub steps.

a) **Develop Value Proposition Statement:** During this step, the value proposition is explored and written down. The value proposition for the MSDD system is that it will provide the information necessary to protect key airport assets. The value of this lies in the assets that are at risk. A few of the assets that are vulnerable to drone attack are [129]:

- Passengers and visitors
- Aircraft (with or without passengers aboard)

- Cargo and mail terminals
- Airport traffic control tower
- Parking garages
- Fuel Facilities
- Airline buildings
- Airport information systems
- Electric power supply facilities

The value of the systems is that it provides information needed for the protection of these key assets.

b) **Identify and Assess Constituent Systems:** The goal of this step is to determine possible assets that may be combined to form the SoS. This includes new systems and already existing systems that have relevant capability and availability. It is important that this step not prematurely eliminate systems from consideration so the focus is upon generating an exhaustive list which will be culled later.

In the case of airport, the existing assets are a combination of technology and human assets. Some of the assets exist now and are found at many airports. The list of existing assets are:

- i. **Surface Movement Radar (SMR):** These radar systems detect aircraft and vehicles and plot their location in real time on a map displayed on a computer screen. An example system is the Airport Surface Detection Equipment, Model X (ASDE-X) developed and sold by SAAB-Sensis [130]. The system consists of a radar, multilateration technology, and satellites to enable air traffic controllers to track the ground movement aircraft and

vehicles. The system has been deployed in 35 airports in the U.S.A [131]. Similar systems have been deployed at other major airports worldwide.

- ii. **Video Surveillance (Visual Imaging):** Most airports have video surveillance for security. The video cameras are distributed around the airport and the video feeds are available for security.
- iii. **Airport Security Personnel:** Airports have ground patrols actively providing security for the airport. They are an asset that can be used for the detection of drones.
- iv. **Air Traffic Controllers:** Air traffic controllers have access to multiple airport sensor outputs and can be used as an asset in the detection of drones.

In addition to existing assets, new sensors can be developed and deployed to detect drones. They are:

- v. **Audio Sensors:** Audio sensors can be used to detect drones. Most airports do not have audio sensors appropriate for drone detection so that this type of sensor would have to be developed and deployed.
- vi. **Infrared (Thermographic) Cameras:** These cameras have the benefit of being able to detect objects that generate heat and can operate at night time. This is because the sensor detects heat signature in the infrared range. Since drones generate heat at their motors and in their electronics, the heat signature can be detected.
- vii. **LIDAR (Light Detection and Ranging):** This can be used for optical imaging in the ultraviolet, visible, or near infrared spectrum.
- viii. **Millimeter-wave (mmW) Radar:** In addition to the existing radar sensors, other sensors can be developed that have attractive capability. For instance, millimeter-wave radars can be used for target tracking since they can have very narrow antenna beam widths. Also,

the target size and features are larger compared to the wavelength at mmW frequencies. An example is a 35GHz FMCW radar proposed for drone detection in [132].

ix. **Low Cost Radar:** An option for the radar sensor is to use multiple smaller radars with less capability than the SMR radar. A benefit of using smaller radars is they can provide coverage in areas that a single SMR cannot achieve. For instance, the SMR coverage will be shadowed by buildings, trees, and other obstructions. In these instances, low cost radars can be distributed throughout the airport to augment the capabilities of the SMR. In other cases, such as smaller airports with lower operating budget, low cost radar can provide the capability the SMR replacement capability.

c) **List Key Organization and Policy Constraints Limiting Architectures:** organizational and policy constraints that limit potential SoS architectures: There are two key organizations who will have policy influence on the solution. The first is the airport authority. For the Long Beach airport, the authority is the Airport Advisory Commission and the airport management. The role of the advisory committee is to guide the overall airport mission and long term planning. The airport management are concerned with execution of the airport purpose.

The second organization is international and national regulatory groups. At the international level, the International Civil Aviation Organization (ICAO) has recognized the need for protection against unlawful use of drones around airports. In fact, a recent report from them state that drones introduce, “new considerations with regard to fulfilling safety-related responsibilities such as incorporation of technologies for detect and avoid, command and control, communications with [air traffic control]ATC, and prevention of unintended or unlawful interference.” [133] In Europe, the European Civil Aviation Conference (ECAC) provides international rules about airport safety. In the U.S.A., the Federal Aviation Administration

(FAA), Transportation Security Administration (TSA), and Department of Homeland Security (DHS) provide leadership at a national level to provide a safe and efficient airport system. Other government agencies with interest in these systems are the national and international communication commissions such as the Federal Communications Commission (FCC) in the USA. They have regulatory control over any radar systems because they will be generating electromagnetic radiation in the spectrum under their control. These national and international groups have interest in airport security.

Since these groups recognize the threat of drones they are actively involved in investigating solutions. This is a key benefit since it means that they are motivated to be actively involved.

d) **List Key Physical and Geographic Constraints:** The emphasis is on physical and geographic constraints that limit potential SoS architectures. The main physical and geographical constraint for this type of system is that it must be contained within the airport property borders. Fig. 35 illustrates a typical airport layout.

e) **Identify and Classify Stakeholders:** During this step it is important to

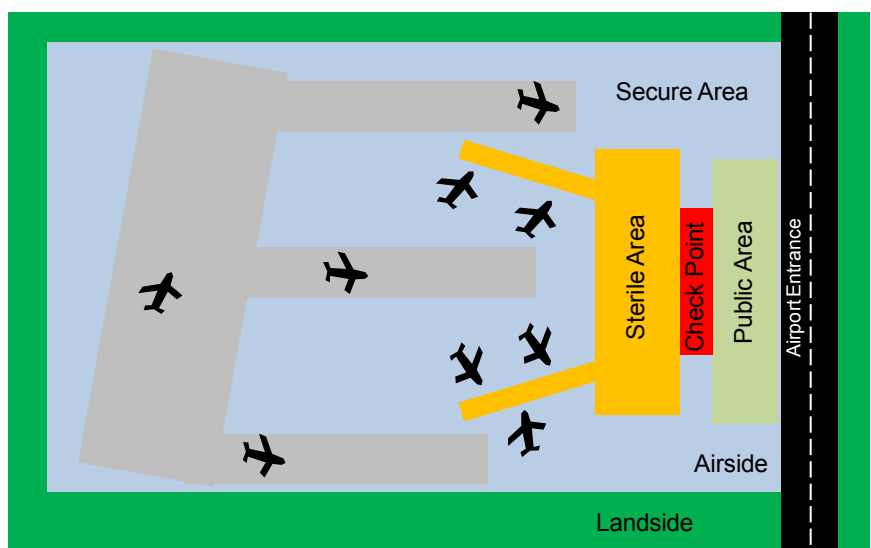


Fig. 35. Typical layout of an airport.

distinguish between stakeholder types. For this work, we have identified government agencies, airport personnel, airport users, airlines, and airline passengers as system stakeholders. Government officials include the F.A.A. and the Department of Homeland Security in the U.S.A.

Airport employees are often organized into a structure similar to Fig. 36. The employees who will be most actively involved in executing on airport security are the Facilities and Operations groups. The Airport Director is responsible for developing airport policy and the administration of airport activities. The airport employees and executive team are important stakeholders.

Each airport supports a number of different airlines, cargo carriers, private plane groups, and government agencies. These user groups depend upon reliable airport access and so they have an interest in airport security as external stakeholders.

Another stakeholder group is airline passengers. This group is concerned with airport and air plane security, efficient operation of the airport (to limit time spent at the airport), and airport cost that affects their airline ticket.

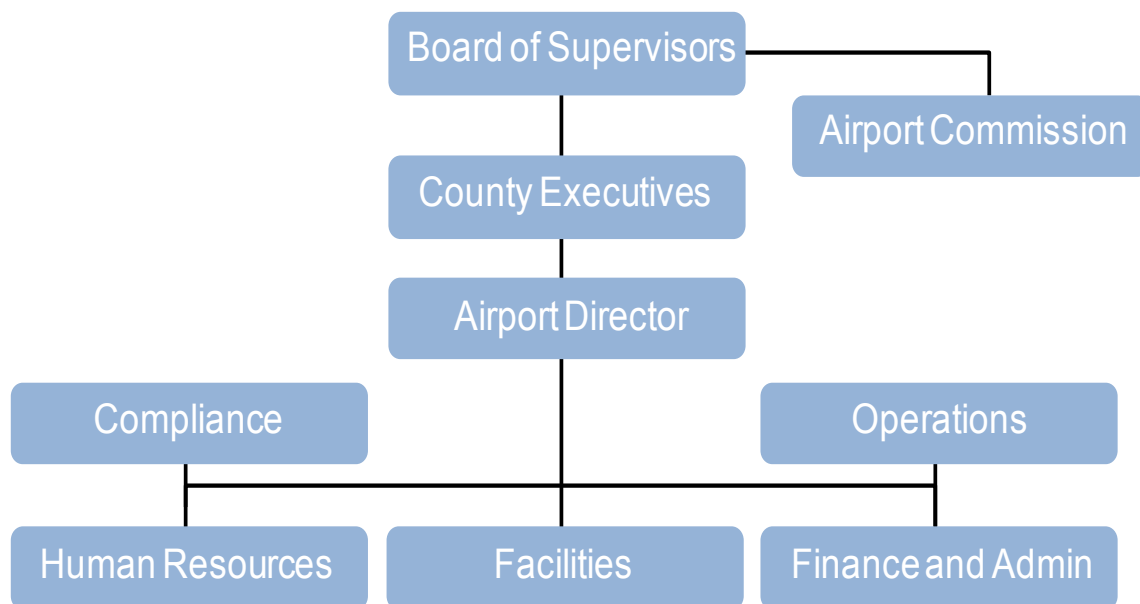


Fig. 36. Typical airport organizational chart.

f) **Elicit Stakeholder Value and Design Space Preferences:** For the purposes of this work, stakeholder value and design space preferences have been obtained through surveys of stakeholders and experts. For this work, the stakeholder groups surveyed is airport operations and safety personnel. Informal interviews were conducted to determine their value and design space preferences. In addition, a team of engineers, sensor technology experts, and retired sensor company executives was gathered to develop value and design space preferences. The results from each group are summarized in Table 9.

Informal interviews with airport operations and safety personnel at four airports were conducted. The purpose of the conversations was to illicit stakeholder value and design space preferences. The identities of the interviewees and the airports are not being revealed in this report to respect the privacy of the conversations. There are several important results from those conversations. The first is that it is very clear that airports are well aware of the threat posed by drones and they are actively working with local groups, private industry, and federal agencies to understand the threat and to develop ways to respond. For instance, one of the airports has agreed to be a beta test site for a drone detection system developed by a technology startup company. In addition, that same airport is part of a local organization that is being developed to study drone use in their county and local cities. Second, airports operations and safety organizations desire the ability to provide drone detection, but they are not thinking about thwarting drone attacks. A common thought is that the airports do not have the charter of disabling or destroying drones that pose a threat. Third, a common theme was that optical systems are perceived as too costly and ineffective. Prior experience with custom optical detection systems has left airport personnel with the opinion that the value offered by them does not justify their expense. That said, the idea of using their existing optical camera's as part of a SoS solution had not been considered and

they were open to such a solution. However, the logistics of implementation were unclear. Fourth, there is a uniform desire for highly accurate detection and low false detections. Fifth, there is a desire to provide a comprehensive security solution but no real plan to achieve it. The threat posed by drones was acknowledged, but airport personnel are not empowered due to budget and regulatory reasons to implement large scale change. Sixth, all of the personnel interviewed were only working on methods to manage local drone users. In other words, the current activities on drones at airports is on providing licenses or other authorization to local drone users and development of rules for drone use. These results are summarized in Table 9 and though the results provide insight into airport operations and security personnel value and design space preferences, it is with a relative small sample size. Therefore, a more extensive survey should be conducted.

Table 9. Summary of airport stakeholder value and design space preferences

#	Description	Value-Space Preference	Design-Space Preference
1	Aware of the threat & new technology	Recognize the value to airport security and operations to detect drone	Open to new technologies and willing to be beta test site
2	Not considering thwarting methods	Value of thwarting or disabling drones is not a high value	No design space preferences for drone thwarting
3	Custom optical detection is too costly	Custom optical drone detection systems do not provide enough value	Prefer a concept that does not use custom optical detection systems
4	Desire accurate detection of drones	High value attached to accurate detection	Important objective is high accuracy.
5	Systems must be deployed within the regulatory environment	High value placed on solutions that are deployed within the regulatory boundaries	Concept must be capable of being approved by existing regulatory organizations
6	Existing activities focused on drone user regulation/management	High value placed on management of local drone users	Design should accommodate drone management systems

A team of engineers, sensor technology experts, and retired sensor company executives contributed to the value delivery and design space exploration. Because of the background of the team, the result of the meeting focused more on design space explorations. This result is valuable since it confirms the list of available constituent systems. The main output is the ranking of the

anticipated value delivery from the possible constituent systems as shown in Table 10. The column in the table for ‘Already Deployed At Airports (Y/N)?’ means that the system has been deployed at major airports. System that have not been deployed will need to be developed. The other output was a list of SoS ilities that will be important to maintain system value delivery. The ilities are incorporated into Table 12.

Table 10. Ranking of the anticipated value delivery for each of the identified constituent sensor systems based on the team brainstorming.

Value Delivery Ranking	Already Deployed at Airports? (Y/N)	System Name	Justification For Ranking
1	Y	Surface Movement Radar (SMR)	Provides sensing in adverse weather conditions.
2	N	Low Cost Short Range Radar	Provides coverage in shadowed areas (behind buildings) of the airport that the SMR system cannot sense.
3	Y	Video Surveillance (Visual Imaging)	Provides data useful for detection using video signal processing.
4	N	Radar Sensors at millimeter-wave (mmWave) frequencies	If wide band millimeter-wave radar is used, it can provide additional information about the target.
5	N	LIDAR	Provides additional optical imaging
6	N	Infrared Cameras	Provides thermal imaging which other sensors do not.
7	Y	Human Observation: Airport personnel and air traffic controllers.	Provides data useful for detection and for visual confirmation by human operators.
8	N	Audio Sensors	Provides information that can further distinguish drones from other targets

There are a few results of this step in the SAI method. One result is it provides insight into expectations of stakeholders. This is important since expectations can drive system non-functional requirements. Another result is that it provides insight into possible existing solutions and systems that stakeholders may have knowledge of. In addition, this step aids in defining the problem scope. Finally, this step can also identify external forces and even their impact to system value delivery.

6.3.2 Step 2: Identify Potential Perturbations

For the MDSS there are many perturbations that can interfere with value delivery over system lifetime for most systems. The perturbations are changes in the system's design, context, or stakeholder needs which can put value delivery at risk. One output from this step is a table of perturbations which categorizes each according to type, space, origin, intention, nature, consequence, and effect. The purpose of this step is to identify and categorization them so that they can be used in later steps to develop ilities and approaches to maintain value delivery over time.

Table 10 is a taxonomy of identified perturbations to the MSDD system. The perturbations are found from interviews with domain experts and team brainstorming activity. The table provides a way to organize and compare them.

Each is categorized according to seven descriptors. The first is type which can be a *shift* which is a long term change in context or stakeholder needs, a *disturbance* which is a short term change that requires action for resolution, or a *disruption* which is a transient effect that requires no action for resolution. A shift means the SoS is not likely to return to its prior state while disturbances or disruptions are temporary. The second category is the space which is the design itself, the context of operation, or the needs of the stakeholders. It is where the perturbation is occurring. The third is origin which refers to the source of the perturbation which can be internal to the SoS or one of its systems, external to them, or either. The fourth is the intentionality of the perturbation which can be yes, no, or either. The fifth is nature and should not be confused with the fourth. Nature refers to agency behind the perturbation which can be natural or artificial. A perturbation can be artificial (created by humans) and still be intentional or unintentional. However, all natural ones are unintentional. The sixth is the consequence which is a rating of

positive, negative, or either. It is what follows from by the perturbation. The effect is produced by the cause (the perturbation). It is a description of the changes that occur to value delivery resulting from the perturbation. The idea behind this step is that knowledge of perturbations helps SoS architects develop systems that avoid, mitigate, and recover from them.

Table 11. Taxonomy of perturbations to the MSDD SoS.

Perturbation	Type	Space	Origin	Intentional	Nature	Consequence	Effect
Weather	Disruption	Context	External	No	Natural	Negative	Reduced Detection
Regulations	Shift	Context	External	Either	Artificial	Either	Various
Response Time	Disturbance	Design	Internal	Either	Artificial	Either	Change in Value
System Maintenance	Disruption	Context	Internal	Yes	Artificial	Negative	Temporary Value Loss
Attack	Disturbance	Context	External	Yes	Artificial	Negative	Change in Value
Communication Disruption	Disruption	Design	External/ Internal	Either	Artificial or Natural	Negative	Temporary Value Loss
System Decommissioned	Shift	Design	Internal	Yes	Artificial	Negative	Change in Value
Incompatible Upgrades	Shift or Disturbance	Design	Design	Yes	Artificial	Negative	Change in Value
Drone Types Change	Shift	Needs	External	Yes/No	Artificial	Negative	Change in Value

Weather: The weather can impact the performance of sensors. For instance, optical systems are essentially disabled by fog. Weather can also impact the performance of radar systems. It also impacts the ability of human observers to detect drones. Therefore, weather can negatively impact value delivery.

Response Time: The response time is combination of the time required for the SoS to identify a possible drone threat and the time required for drone thwarting systems to be deployed. If the response time is too slow, this will impact effectiveness and other metrics. The SoS response time of the individual systems is out of the control of the SoS, and yet changes in their individual response times affects the SoS. The response time of the system may also improve over time due

to added capabilities to the system. Therefore, understanding and accounting for response time changes is important for value delivery sustainment over the SoS life cycle.

System Maintenance: The systems must be maintained properly. For instance, optical glass covering visual sensors must be periodically cleaned to maintain high resolution images. Since the MSDD is a SoS, the maintenance of each of the systems is out of the control of the SoS itself. Therefore, value delivery of the MSDD SoS depends upon proper maintenance of each system.

Attack: An attack is a willful act meant to disrupt the performance of one or more of the systems. The attack can be a random act of vandalism or an intentional act meant to disrupt the system. The attack can be physical or non-physical. An attack can affect value delivery.

Communication Disruption: Changes in communication status covers events that eliminate or diminish the ability of the system to transfer data (such as sensor data). There are multiple possible causes such as lightning strikes, equipment failure, to name a few. Proper operation of the communication functions in the SoS is essential for value delivery.

System Decommissioned: If one of the systems in the SoS is decommissioned by its operators, then there will be shift in SoS value deliver.

Incompatible Upgrades To Systems: If one of the systems in the SoS is upgraded and its outputs or functioning is incompatible with the SoS, then this will require the SoS to adapt to maintain value delivery or it will impact value delivery.

Drone Type Changes: As technology changes, the types of drones available will change. As a result, value delivery of the SoS may be impacted if it cannot adapt to changes in technology.

6.3.3 Step 3: Identify Initial Desired Ilities

In this step, a list of potential ilities is identified that promote the long-term behavior of the SoS. Iility development is important since they are used in subsequent steps in SoS architecting. They directly impact the priority of system functionality.

In this work, the potential ilities are developed in two ways. First, they are gathered from direct expressions and implied requests from stakeholders. During interviews in Step 1, stakeholders explicitly stated desired ilities. They also expressed them indirectly using language that implies certain ilities. Second, the perturbation analysis in Step 2 revealed ilities. Together these two methods are used to generate system ilities.

Table 12. List of potential ilities with their description (definition) and the basis for being included as an ility for the MSDD SoS [134].

Iility	Description (Definition)	Basis
Compatibility	Functions in conjunction with existing drone management systems	Driven by stakeholder survey
Functionality	The ability of the SoS to maintain value delivery over the system life cycle by preserving system functions.	Driven by definition of a SoS Driven by perturbations
Reliability	Provides accurate detection of drones in with low failure rate and low maintenance requirement.	Driven by stakeholder survey
Evolvability	The system must be adaptable to changes in drone technology, regulations, and airport physical changes	Drive by brainstorming sessions Driven by perturbations
Quality	The SoS is well constructed to achieve the desired functions.	Driven by stakeholder survey Drive by brainstorming sessions
Flexibility	The ability to change or adapt to new circumstances.	Driven by stakeholder survey Drive by brainstorming sessions Driven by perturbations
Resilience	The degree to which the SoS can recover quickly from a major disruption while maintaining a high degree of value sustainment.	Drive by brainstorming sessions Driven by perturbations
Adaptability	The capacity of SoS changes to be driven by the external environment. Reconfigurations of the system are driven by external changes.	Drive by brainstorming sessions Driven by perturbations
Interoperability	This is the capacity of the constituent parts of the SoS to work together as a whole.	Driven by definition of a SoS
Agility	The capacity to change quickly.	Drive by brainstorming sessions and perturbations.

Table 12 summarizes the list of potential alternatives. It also shows the source of the alternative whether it is stakeholder driven, team brainstorming session driven, or perturbation driven.

6.3.4 Step 4: Generate Initial Architecture Alternatives

The purpose of this step is to generate value-driven (values from Step 1) alternatives for the SoS architecture. The alternative definitions will include design variables and operational variables and may include basic concepts of operation. Fig. 37 shows the matrix of alternatives. Referring back to Table 10, it lists the eight available systems that can be used in the SoS. In theory, if we assume that the SoS will consist of 3 of the systems, then there are 56 combinations of possible SoS alternatives using combinatorial mathematics.

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \quad (22)$$

Where n is the number of things available which is 8 possible systems for the SoS and k is the number of things selected which is the actual number of systems that make up the SoS. This means that (22) can be used to determine the number of combinations of systems that can be generated given the number of systems out of the available 8 systems that will be used to construct the SoS.

	Surface Movement Radar (SMR)	Low Cost Short Range Radar	Visual Imaging	mmW Radar	LIDAR	Infrared Cameras	Human Observation	Audio Sensors
Surface Movement Radar (SMR)	■							
Low Cost Short Range Radar	■	■						
Visual Imaging	■	■	■					
mmWave Radar	■	■	■	■				
LIDAR	■	■	■	■	■			
Infrared Cameras	■	■	■	■	■	■		
Human Observation	■	■	■	■	■	■	■	
Audio Sensors	■	■	■	■	■	■	■	■

Fig. 37. Matrix of possible SoS combinations given the available systems.

One option for reducing the number of possible combinations is to restrict the SoS to systems that already exist and are deployed. If this is done and all available sensors are used, then one SoS architecture is the SMR + Visual Imaging + Human Observation. As mentioned earlier, state of the art SMR systems have been deployed in the U.S.A. and at major airports worldwide, visual imaging systems exist at airports as part of existing security systems, and human observation exists in the form of airport security and air traffic control operators. This combination of systems will be called Option 1 for the SoS.

Another option for selecting architectures for the MSDD system is based upon their ranking. Referring back to Table 9, it lists the available systems ranked on effectiveness. If the first four systems are selected, then this can provide another option. It will consist of Surface Movement Radar (SMR) + Low Cost Short Range Radar + Video Surveillance (Visual Imaging) + mmWave Radar. This approach will be called Option 2 for the SoS.

Another option is to combine Option 1, the already deployed sensors, with the top ranked option that is not already deployed. This results in a SoS consisting of Surface Movement Radar (SMR) + Video Surveillance (Visual Imaging) + Human Observation + Low Cost Short Range Radar. This combination will be called Option 3 for the SoS.

Another option is to add infrared sensing to Option 3. In this case the sensors involved would be Surface Movement Radar (SMR) + Video Surveillance (Visual Imaging) + Human Observation + Low Cost Short Range Radar. The benefit, of course, is the detection capability of infrared cameras. This combination will be called Option 4 for the SoS.

All four of the options identified share a few common features for their concept of operations. First, each of the SoS options will require a method for interconnecting the systems. This will require software for integrating the sensor outputs. The software will need to be

flexible in its interfaces and data formats so that new systems can be added. Second, the SoS will require a control room for monitoring the results. It may be that the system is integrated with existing FAA control room systems. Third, the SoS will require personnel for monitoring the fused sensor output which also may be FAA personnel such as air traffic control. All the options identified so far share these common features for the fusion of their data and management.

6.3.5 Step 5: Generate Ility-Driving Options

This step is concerned with the generation and selection of options that can be added to architecture alternatives to achieve desired ilities. In other words, options at the system level must be developed that will enable the achievement of the ilities identified in step 3. The procedure in this step is the ilities will be grouped together according to common themes and then options in the system to achieve the ilities will be generated.

Reliability and Quality: The first grouping of ilities is reliability and quality. They are concerned with how the system is produced, engineered and maintained. Reliability can be measured such as failure rate per year, or mean time to failure. It is the probability that the system will continue to deliver value to the customer over some period of time. Quality is more difficult to measure since it is based upon more subjective criteria. It characterizes the level of superiority and excellence of the system. One criterion used to determine quality of a system is based upon its reliability. Quality can also mean the level to which the system is fabricated to its required standards. In other words, quality can mean that the product is produced in fashion that all the manufacturing requirements such as tolerance are achieved. The baseline concept must include methods for determining the reliability of the SoS and a way to maintain quality.

The concept for achieving quality can be challenging for a SoS that uses existing systems. This is because the quality of the existing systems is not under its control. However, what can be

controlled for quality is the fusion of the various systems that make up the SoS. The fusion is enabled through software, interfaces (both hardware and software), and computing hardware. Therefore, these parts of the SoS must be developed and produced using standards to yield a quality product. Furthermore, any systems that are produced under the control, budget, and management of the SoS will be designed and manufactured to the quality levels that are necessary. In these two ways, the SoS can achieve quality.

Achieving reliability in the SoS is also dependent upon the reliability of the existing systems, systems developed under the control of the SoS, and the fusion of all sensor data. As with quality, the reliability of new systems and of the fusion hardware/software is under the control of the SoS. Therefore, those items will be developed, managed, and maintained to achieve the required reliability.

Interoperability and Compatibility: Interoperability refers to the ability of the data from constituent systems of the SoS to be fused together so that the required functionality is achieved. Therefore, it refers to connectivity within the SoS. Interoperability is part of the definition of a SoS and will therefore be achieved by definition.

Compatibility is different and refers to the ability of the SoS to function in conjunction with systems outside the SoS such as other drone management systems like the FAA UAS Rule (Part 107) and the FAA Pathfinder program. One concept for how this can function is that detected drones can be checked against the drone flying scheduled in the FAA or local database. A drawback of this approach is that nothing keeps a malicious group from registering a drone, scheduling it for a flight near an airport, and using it for attack on the airport. Nevertheless, as external systems are developed, the SoS must be compatible with them.

Resilience, Agility, Evolvability, Flexibility, Adaptability: These five ilities all describe the SoS in terms of its ability to change dynamically in response to external factors. The external factors create perturbations to the system as described in step 2. The system must respond to them to maintain value delivery.

Resilience and Agility both refer to how rapidly the system can respond to changes. The nuance of resilience is that it means the system can not only respond quickly, but that the SoS can maintain value delivery during the time it takes to adapt. In other words, the act of adaption of a system to changes rarely occurs instantaneously but instead requires some finite amount of time. During the time of adaption the SoS has the capacity to continue value delivery.

Evolvability and adaptability both refer to the capacity of the SoS to change, reconfigure, or modify. The slight nuance of evolvability is that the changes are external to the system. Adaptability, on the other hand, includes the capacity to change due to internal or external perturbations.

Flexibility is a high level ility which exists above resilience, agility, evolvability, and adaptability. Simply stated it is the capacity of the system to change in reaction to perturbations.

The concept of operation for these change ilities is that the SoS includes the capacity for the individual systems to provide extended functionality when one of the other systems are non-operational or provide are providing reduced functionality. For instance, if the SMR radar is down for repairs or maintenance, then the lower cost radars distributed through the airport must provide functionality that maintains value delivery of the SoS. On this approach, the SoS is developed in a fashion that there is overlap between the capabilities of the constituent systems which allows the system respond to change.

Functionality: This is the capacity of the SoS to maintain value delivery over the system life cycle by preserving system functions.

6.3.6 Step 6: Evaluate Potential Alternatives

This is the modeling of various alternatives (generated in Step 4) in terms of relevant metrics. Example metrics are value (attributes and cost), and ility metrics. For this analysis, each of the individual systems will be considered first, then the four options for the SoS will be evaluated.

a) Review of Individual Systems

Surface Movement Radar (SMR): Airport air traffic controllers use SMR to track the movement of aircraft and vehicles on the ground at airports [135]. An example system is the radar that is part of the ASDE-X and its next generation called the SR-3 both sold by Sensis SAAB. The radar is part of a multilateration system that includes sensors and transponders. Fig. 38 shows the computer display from the ASDE-x system. The range of the radar is approximately 12,000 feet, but it operates to an altitude of 200 feet above ground.

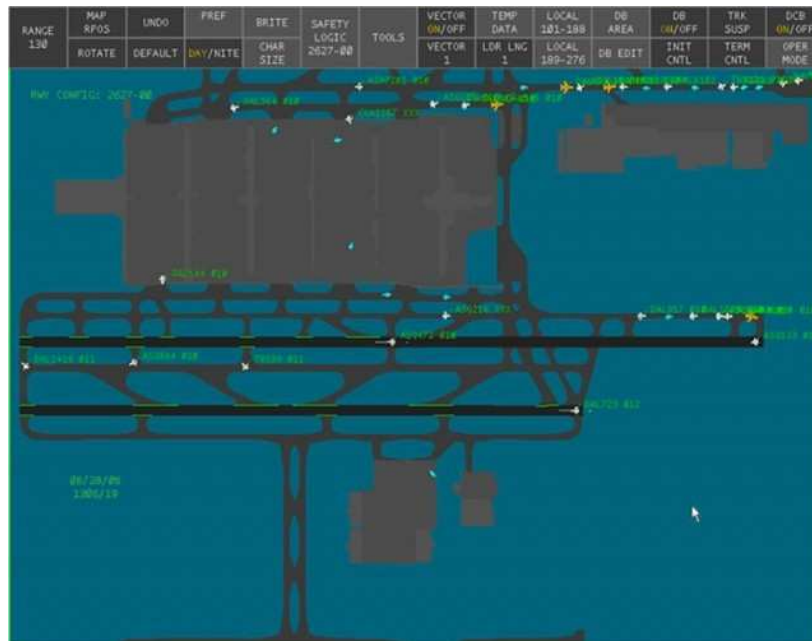


Fig. 38. ASDE-X system computer display showing ground traffic at Hartsfield-Jackson Atlanta International Airport (public domain image).

The ASDE-X antenna creates a fan beam pattern with a horizontal beam width of 0.35 degree and vertical beam width of 10 degrees. It operates at a frequency of 9.0 to 9.2GHz and the antenna provides 37dB of gain. The antenna is mechanically scanned at a rate of 60Hz and it is approximately 6.5 meters long (L), 1.0 meter wide (W), and 0.5 meters high (H) as shown in Fig. 39.

The ADSE-X radar is intended to detect rather large targets with radar cross section in the range of 0.5 meters at a range of approximately 4-5 km with guaranteed performance during rain fade conditions.

Low Cost Short Range Radar: Typical systems are based upon FMCW radar, but some may be pulsed Doppler. An example is the A2000 from Spotter RF which is specifically designed for the detection of drones and provides detection up to 1.0 km [136]. It is small at approximate 0.25 m square and 6.6 cm thick.



Fig. 39. Image of a typical antenna type used in the ASDE-X system (from: <https://www.chl.nl/antennasAntennefamiliesAntennaSGE.html>)

One alternative is to distribute Low Cost Short Range Radars in the coverage area which is an approach taken in [137]. The system uses optical fiber links between the radar transmitter and receiver which reduces leakage, distortion, and propagation losses. The demonstration showed that it was possible to link distributed radars with fiber optics. A similar approach was taken in [138] which used multiple receivers to create a multistatic radar for the purpose of detecting drones. These examples demonstrate the usefulness of distributing multiple radars for drone detection.

Video Surveillance (Visual Imaging): Visual imaging can be used for detection of drones. There are multiple variations of optical cameras such as fixed cameras, pan tilt zoom (PZT), and wide band cameras. An example of a camera system that offers 180 degree imaging at 30 frames per second is the MEGApix PANO 48MP Camera from Digital Watchdog (<http://digital-watchdog.com/>) which is shown in Fig. 39. One of the benefits of this system is



Fig. 40. Image of the MEGApix PANO 48MP camera (Image Source: Digital Watchdog, <http://digital-watchdog.com/>).

that it provides continuous camera coverage of large areas which is an advantage over PZT cameras which must rotate to from one sector to another. Also, with two MEGApix units installed, this system is able to deliver 96 mega pixels of video for continuous coverage over 360 degree.

Radar Sensors at millimeter-wave (mmWave) frequencies: Millimeter-wave radar sensors have several attractive benefits. First, the bandwidth available is much greater than for microwave and lower frequency radars. This is important since a wide band waveform can be use to obtain additional target information. Second, the antennas can be small for the same gain and beam width. This is a benefit for installation since the antennas will be lighter and will be more aesthetically appealing at the airport. Third, small UAVs are a larger portion of a wavelength or multiple wavelengths in dimension so that they will scatter more energy. These benefits make mmWave radars an attractive option.

However, they do have some drawbacks. First, components and subsystems are more expensive at mmWave frequencies. This situation is starting to change due to the explosion of high data rate back haul and satellite systems which use components in the 20-80GHz range. Nevertheless, mmWave radars are more expensive. Second, it is more challenging to generate high power levels at these frequencies. This is another reason that high power radars can be expensive at mmWave. Third, atmospheric attenuation is higher in these frequency bands. As a result more of the signal is absorbed by the atmosphere than at lower frequencies. Although these are important drawbacks, the benefits of mmWave radars make the an attractive option for drone detection.

An example system is described in [139] which describes a 35GHz FMCW system designed for drone detection. The systems were analyzed for velocity detection in the range of 15

to 37.5 m/s. The presented measured results were for short ranges (<100m), but the result does demonstrate the usefulness of mmWave radar for drone detection.

LIDAR: This is a combination of the words light and radar. The idea behind this technology is that light energy can be used in the same way as radio wave. Since the wavelength of light is so small, it can create high resolution images. Fig. 41 shows a LIDAR image of the Marching Bear Mound Group in Iowa.

The idea behind using LIDAR is that it is a possible sensor to provide high resolution images for the detection of drones. Low cost LIDAR sensors are being developed. For instance, LeddarTech (<http://leddartech.com/>) is developing low cost LIDAR systems for use on drones and other application. The goal is for these low cost drones to be used for autonomous vehicles. However, this same technology can be used to detect drones. Also, low cost LIDARs are being developed by Infineon for use in self driving cars through the acquisition of LidarExpertise located in the Netherlands [140]. Though the present cost of LIDAR systems may make them a

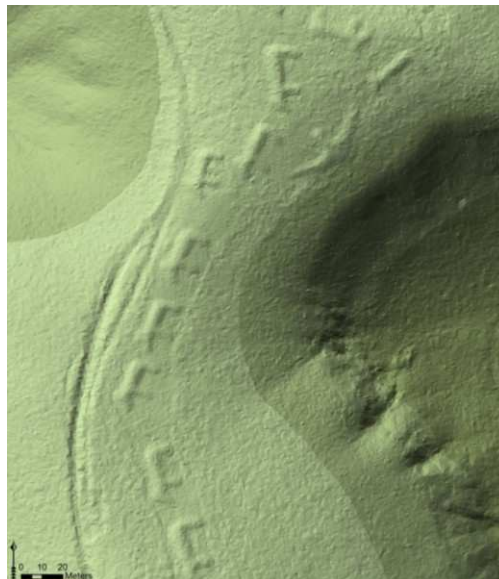


Fig. 41. LIDAR image of the Marching Bear Mound Group in Iowa (public domain image from the U.S. Department of the Interior).

challenge for low cost drone detection systems, the cost is expected to be reduced significantly in the near future.

Infrared Cameras: These cameras have the ability to detect targets at night and use radiation from target in the infrared spectrum. An example system is the infrared sensors from HGH Infrared Systems (<http://www.hgh-infrared.com/>) with an image of their Cyclope systems tracking a drone in Fig. 42. Their cameras can detect drone sized target to several km. Their system can cover a 360 degrees field of view. In addition, signal processing has been developed for the simultaneous detection and tracking of targets.

Human Observation (Airport personnel and air traffic controllers): Human observers can be used to perform rapid assessment and classification of potential drone targets. A benefit is that this resource already exists at the airports. A drawback is that human observation can be unpredictable and not always accurate.



Fig. 42. Infrared camera image of a drone taken using the Cyclope system from HGH Infrared (<http://www.hgh-infrared.com/News/Press/Eyes-on-the-Horizon>)

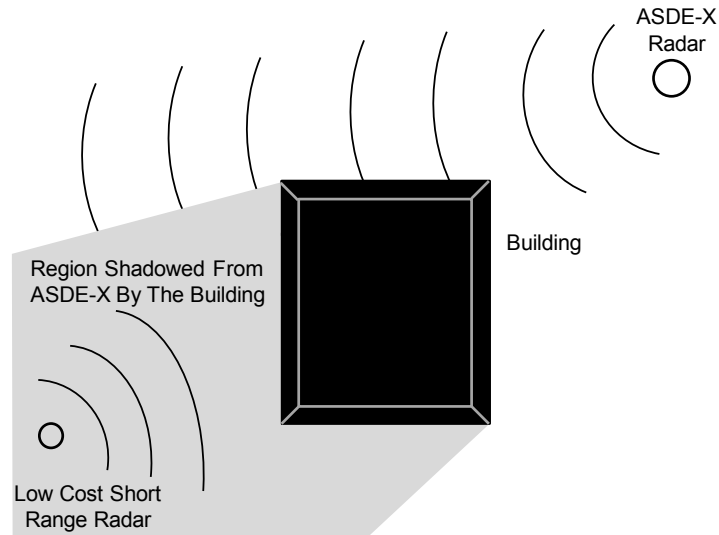


Fig. 43. The ASDE-X radar provides coverage to several km, but its radar signal can be shadowed by airport buildings and structures. Low cost and short range radars can operate in those areas to improve the coverage area.

Audio Sensors: Audio sensors have the potential of detecting drones. One of the concerns is that airports are noisy environments so the effectiveness of audio sensors is questionable. An advanced development effort may be necessary to assess their effectiveness.

b) Evaluate Alternative SoS Options

With a better understanding of the individual systems, it is possible to evaluate the SoS alternatives. Table 13 shows the four options previously identified. A benefit of Option 1 is that it uses only systems that already exist. This is important since it means that the SoS can be deployed without development of any new systems. The focus of the SoS development will then be on interconnection and integration of the outputs from the sensors, analysis of the results, operation system, and associated management and maintenance.

One of the concerns for the concept of operations of Option 1 is that the SMR will have shadow areas in the airport due to buildings and other airport infrastructure. This is illustrated in Figure 43. If this occurs, then the drone can fly in a path behind the building and avoid detection

by the ASDE-X system. This is because the SMR signal is scattered by the building anything in the shadowed area will not be detected.

Table 13. SoS options with list of benefits and drawbacks.

Option Name	Systems	Benefits	Drawbacks
Option 1	<ul style="list-style-type: none"> • SMR (such as ASDE-X) • Visual Imaging • Human Observation. 	<ul style="list-style-type: none"> • Existing Systems • Lower deployment cost 	<ul style="list-style-type: none"> • Limit radar altitude coverage • Limited SoS redundancy
Option 2	<ul style="list-style-type: none"> • SMR (such as ASDE-X) • Low Cost Short Range Radar • Visual Imaging • mmWave Radar 	<ul style="list-style-type: none"> • Detection probability • Large coverage area • Improved altitude coverage 	<ul style="list-style-type: none"> • mmW radar is expensive • Two new systems
Option 3	<ul style="list-style-type: none"> • SMR (such as ASDE-X) • Visual Imaging • Human Observation • Low Cost Short Range Radar 	<ul style="list-style-type: none"> • Detection probability • Large coverage area • Improved altitude coverage • Ease of integration 	<ul style="list-style-type: none"> • One new system
Option 4	<ul style="list-style-type: none"> • SMR (such as ASDE-X) • Visual Imaging • Human Observation • Low Cost Short Range Radar • InfraRed 	<ul style="list-style-type: none"> • Improved nighttime detection • High SoS redundancy 	<ul style="list-style-type: none"> • Two new systems • Integration complexity

Options 2-4 overcome this limitation by using low cost short range radar as illustrated in the figure. An approach to overcome this limitation is for the low cost short range radar to be placed in the shadow areas of the airport as shown in the figure. This will allow for increased detection of drones. Furthermore, if the data from ASDE-X radar is unavailable, the SoS can still deliver value by detecting drones using the the low cost short range radars. Furthermore, the altitude of detection for the low cost short range radar can be much higher (up to 500m-2km) than the 200 feet specified for the ASDE-X system.

The mmWave radar as part of Option 2 is also a back-up system and provides detection that the SMR radar cannot. The concept of operation is the mmW radar can operate if the data output from the ASDE-X is unavailable for whatever reason such as maintenance or data interruptions. Also, the shorter wavelength of the mmW radar means that it has the potential to detect smaller drones since the drone will be larger compared to the operating wavelength.

A drawback of Option 2 is that it requires two new systems to be deployed beyond the already existing ones. This requires development funds for the prototype development and increases the recurring cost of each system deployed. It also means that there is more sensor information being generated that needs to be connected, analyzed, and used. This adds more complication to the system compared to Option 1 and Option 3.

Option 3 also has the benefit of the low cost short range radar to enhance drone detection coverage compared to Option 1. However, it does not include the mmWave radar which reduces functionality compared to Option 2. One obvious benefit is the reduced prototype development and lower recurring cost compared to Option 2 since the human observer used in Option 3 are already existing. Theoretically, additional training and reporting of findings is required. Therefore, Option 3 can be considered a compromise of cost and functionality between Options 1 and 2.

Option 4 has the benefits of Option 3, but with the addition of an infrared sensor. The concept of operations for the infrared sensor is it's an enhancement to the optical sensors. They provide the ability to extend optical sensing into night time and to detect the heat generated by the motor, battery, and electronics in the drone. This provides an additional layer of functionality and capability to the system.

6.3.7 Step 7: Analyze Architecture Alternatives

This is the deep analysis of data generated in Step 6 for the purpose of developing understandings of the possible trade-offs that exist with the alternative SoS architectures.

Radar Drone Detection and The RCS Concern: One of the concerns for detecting drones using radar is their small radar cross section (RCS) and this is a concern for all four options. This is because radar cross section is dependent upon the size, material, shape, and

movement of the target. Smaller targets have a smaller RCS and are more difficult to detect. Targets fabricated of mostly metal have larger RCS while plastic targets have a smaller RCS. Targets with smooth edges and rounded corners have a lower RCS. The fundamental reason for these characteristics of targets is that RCS is due to the reflection of the radar signal off the target. Given as an equation, RCS in dimensions of area is given by

$$RCS = \lim_{r \rightarrow \infty} \left(4\pi r^2 \frac{|E_s|^2}{|E_i|^2} \right) \quad (23)$$

Where E_s is the scattered field off the target, E_i is the incident field from the radar, and r is the range from the radar to the target as illustrated in Fig. 44. Often, the RCS of targets is given in log format which is calculated as $\sigma = 10 \log(RCS)$ with units of dBsm (decibels square meter) with RCS is given in square meters.

The RCS of drone targets has been investigated by several workers. For instance, in [141] small consumer drones are measured in an antenna chamber at 12-15GHz and at 3-6GHz. The results show that the RCS varies from approximately -3 to -24dBsm depending upon the drone type, orientation of the drone, and frequency. The results also showed that there was approximately a 10dB increase in RCS at 12-15 GHz compared to 3-6GHz operating frequency.

Another investigation into drone detection in [142] used both simulation and measurement to determine the RCS of micro-drones and specifically the effect of blade rotation on RCS. The work examined RCS as a function of radar signal polarization, frequency, and drone blade movement. They showed that the RCS of just the blade on a drone varies by 30-50dB depending upon the polarization of the transmit and receive radar signal and the frequency of operation.

Drone Detection And The Radar Equation: Using the measured RCS numbers from [141], it is possible to calculate the signal to noise ratio for a low cost microwave radar. The calculations use the radar equation which is given by:

$$SNR = \frac{P_r G_p}{k_B T_s B_n} = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4} \frac{G_p}{k_B T_s B_n} \quad (24)$$

Where:

- P_r = received power (W)
- P_t = transmit power (W)
- G_r = gain of receive antenna
- G_t = gain of transmit antenna
- σ = radar cross section of the target (dBsm)
- λ = wavelength of operation (m)
- R = range to target (m)
- G_p = processing gain (such as pulse compression gain)
- k_B = Boltzmann's constant = 1.38×10^{-23} (Joules/K)
- T_s = total noise (background and system noise)
- B_n = receiver bandwidth (Hz)

The SNR for a short range drone detection radar was calculated. The calculations assume an operating frequency of 9GHz, a peak output power of 1000 W, antenna gain of 30dB on

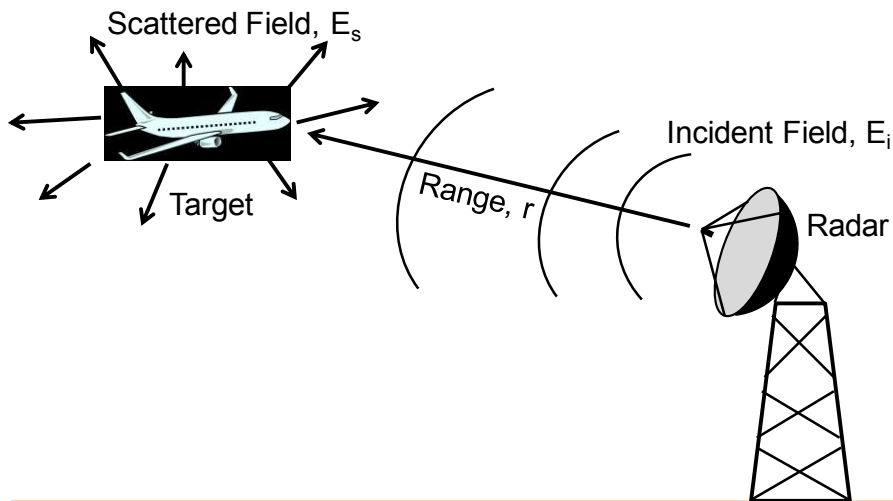


Fig. 44. The radar transmits an incident electric field (E_i) toward the target at a range (r) which causes a scattered field (E_s) off the target.

transmit and receive, a noise figure of 2dB, and 0dB of processing gain. The results are shown in Fig. 45 for a range of drone RCS from -30 to 0 dBsm.

From this analysis, if the minimum signal to noise ratio for reliable detection is taken to be 13.4 dB [143, 144] to achieve a probability of detection of 95% and a probability of false alarm of 10^{-6} , then for the design described, it is possible to detect drones with an RCS of at least -25 dBsm to a maximum range of 1 km.

6.3.8 Step 8: Trade-off And Select “Best” Architecture With Ilities

This step uses the analysis results from Step 7 and a quality function deployment (QFD) method based on ilities decisions about the preferred architecture. The output from this final step is the baseline solution that will be carried forward into the next phases of the system lifecycle such as advanced development, detailed design, etc.

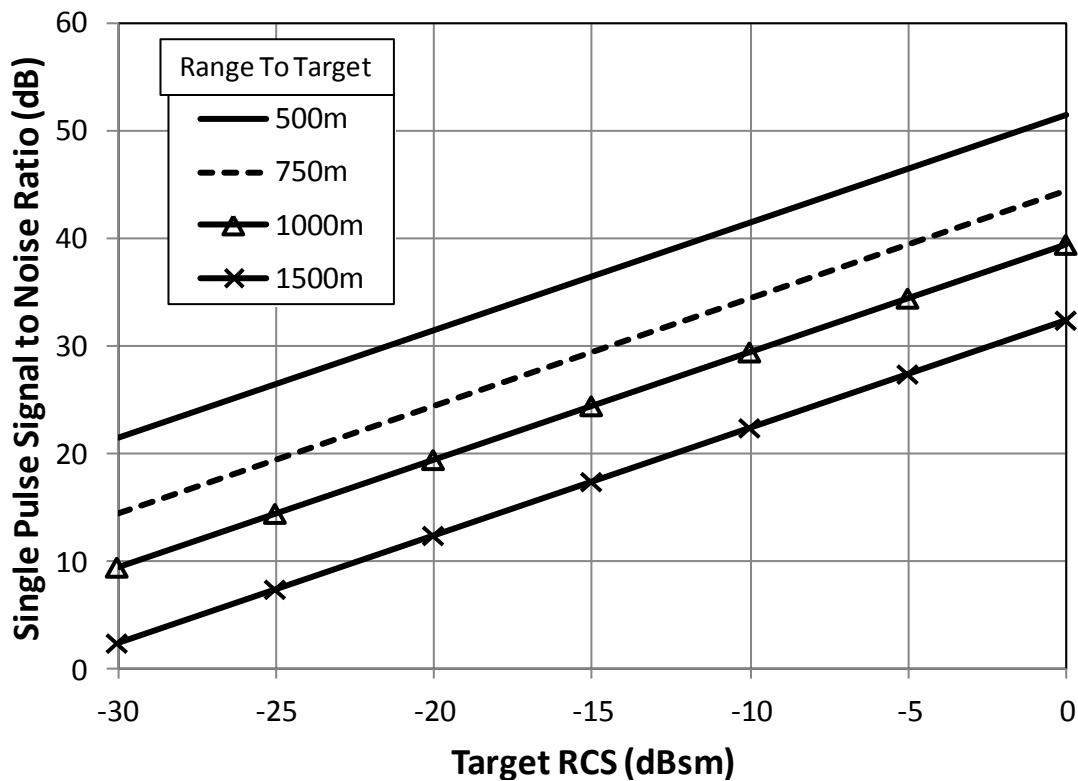


Fig. 45. Calculated single pulse signal to noise ratio as a function of target RCS and range to the target.

The approach in this section is a modification to the SAI since it usesilities in a QFD to choose the best SoS option. The approach is based upon work in [145] which used a QFD style decision matrix with ilities as the criteria. The same approach is taken here were the SoS ilities are used as the criteria for choosing the SoS option. Fig 46 shows the QFD. Based upon the QFD matrix, the baseline solution should be Option 2 which is the SMR + Low Cost Short Range Radar + Visual Imaging + mmWave Radar option with a score of 68.

The next highest rated is Option 4 with a score of 58 and there are two primary reasons that it received a lower score. First, it will have lower reliability than the other options since there are more systems in the SoS. True enough that the increase number of systems means that the SoS will continue to deliver value if one is unavailable. However, the resilience of the system takes this capability into account. Reliability, in this case, is measure of the full SoS and the likelihood of one system being unavailable increases as the number of systems increases. Second, is the compatibility of the systems that comprise the SoS is lower as the number of systems increases. Since Option 4 contains the largest number of systems, it received a lower compatibility rating. For these reasons, Option 4 was rate as second.

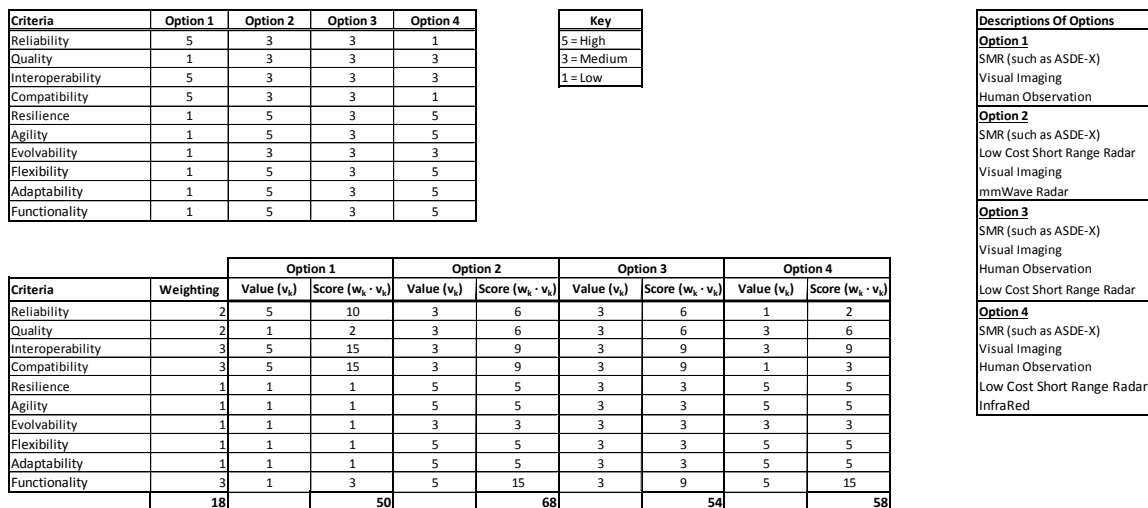


Fig. 46. The QFD decision matrix for choosing the SoS option as the baseline.

6.4 Chapter Conclusions and Assessment as a SoS

This chapter examined a SoS solution for drone detection. Drones pose a serious threat to infrastructure such as government buildings, bridges, and nuclear power plants. Airports are also vulnerable and this chapter developed a concept for a drone detection SoS for airports. The SAI method was used for the analysis and baseline selection. The process resulted in selecting Option 2.

The chapter also served as an example of how a SoS is different from complex systems. One of the main differences, as discussed in Chapter 1, is that the individual systems are independently managed. For this SoS, the SMR and Visual Imaging systems are already existing at the airports and are under separate management. The SMR is managed by the FAA and the Visual Imaging systems are managed by local airport security. The Low Cost Short Range Radar and the mmWave Radar, if developed and deployed, may have their own management or may be under the control of the SoS.

One improvement in this work is that other stakeholders could also be surveyed. Because of the cost involved in a more comprehensive survey and access to stakeholders, only airport personnel and system experts were surveyed. However, a more comprehensive survey would also involve more airport stakeholders such as management, human resources, airport operations, airport security, FAA air traffic controllers, and system suppliers.

This MSDD system should be considered a SoS for at least three reasons. First, it fits the definition of a SoS developed in Chapter 1 which is repeated below:

A system of systems is a product of a system engineering process that contains one or more systems for which significant aspects of the integration and life cycle development

of the component system(s) are beyond the managerial control or influence of the larger system.

As already mentioned, The MSDD system has the SMR and visual image systems which are not under the managerial control of the SoS. The main sensor in the SoS is the SMR so it qualifies as a ‘significant aspect’ as required by the definition. Second, several of the systems are developed and engineering independent of the SoS and for its own purposes. Again, the SMR and visual imaging systems meet this criteria. Third, the systems are geographically distributed. It is true enough that they all located at nor near the airport, but they are distributed throughout the airport. In fact, the video system is a distributed system with sensor located a various places on the airport property. For these reasons, the MSDD is rightly considered a SoS.

7. Advanced Development: Short Range Radar Technology

This chapter describes the advanced engineering development activity for a Low Cost Short Range Radar sensor system.⁶ Since the development is taken to the point of a prototype system, the results in this chapter include not only the systems engineering but also detailed development of the key subsystems and components. For instance, a significant portion of the chapter is dedicated to the development of the X-band antennas used, the FMCW transceiver, and the data analysis results. The purpose of the prototype is to show a scaled down version of the Low Cost Short Range Radar operating in CW Doppler mode at reduced power levels. This mode of operation is different than the pulsed FMCW mode that the actual system may actually use. Also, the actual radar transceiver is rather simple but the demonstrated antenna components are a unique contribution. Together, they demonstrate that a Low Cost Short Range Radar is well within the realm of low risk technology.

7.1 Microwave Radar System Description

The radar transceiver hardware is very simple and a block diagram of it is shown in Fig. 47. Note that the output frequency is 9.224-9.552GHz. The real system will likely be in the range of 9.0-9.2GHz. Also, the output power is only +10dBm (10mW) which is much lower than real system which calls for a baseline output power of 1kW. All of the components were purchased on the used and second hand market to control the cost of the demonstration. Though many simplification have been made to the system, a high power system can be demonstrated if a high power amplifier is added just prior to the transmit antenna and receive protection is added such as a limiter.

⁶ © [2016] IEEE. Reprinted, with permission, from R. Sturdivant, E.K.P. Chong, “Dielectric Notch Radiator Antennas with Integrated Filtering For 5G and IoT Access,” in *IEEE Radio and Wireless Symposium, Phoenix, AZ*, January 15-18, 2017.

The system oscillator is a voltage controlled oscillator which is driven by a waveform generator. The particular oscillator was chosen for its cost and linear voltage-frequency transfer characteristics. The output frequency range from the oscillator is 4.612-4.776GHz and it is filtered to reduce harmonic content from the oscillator. Filter has attenuators before and after since the impedance match of filter is not optimum. The signal is then fed to an amplifier which increases the signal level to approximately +12dBm before it is fed into the frequency multiplier where it is converted into an X-band signal. The signal is then sent to a band pass filter fabricated using air cavities and then to the buffer amplifier. The signal is then sent to the high power amplifier where its output signal level is +14dBm. The radar signal is then split to the transmit antenna and to the receiver mixer local oscillator. The receive signal is passed through a

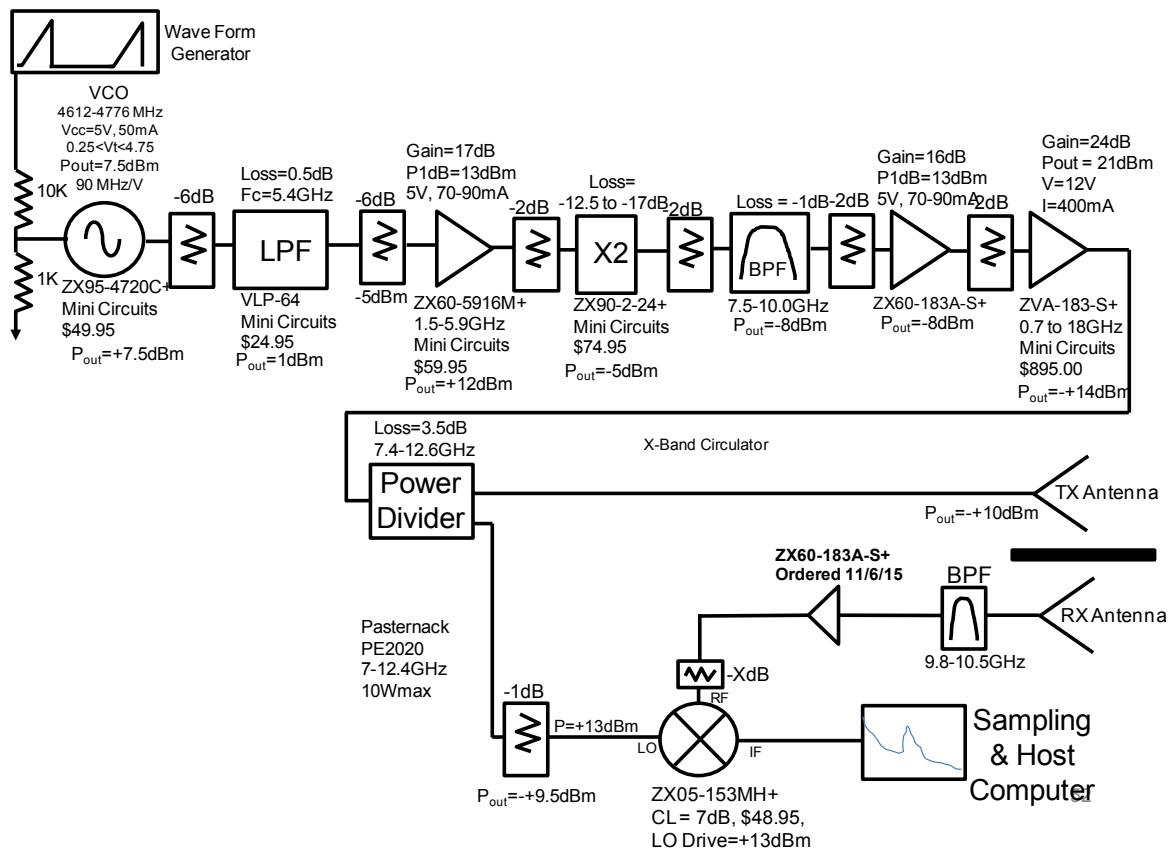


Fig. 47. Block diagram of the FMCW transceiver prototype hardware.

band pass filter as a pre-selector and then to the low noise amplifier. The mixer creates a difference signal between the transmit and received radar signals. The difference frequencies are then amplified, filtered, sampled, and then processed by the host system.

A simplified explanation of the operation of FMCW radar is shown in Fig. 48. Since the transmit signal is frequency ramp, the receive signal from a target will be also. The receive signal is delayed from the transmit signal by the amount of time it takes to propagate to the target and back to the transmitter. If the frequency ramp is linear, then the difference in frequency is proportional to the distance to the target which can be calculated as

$$\text{Target Distance} = \frac{c\Delta t}{2} \tag{25}$$

Where:

c = speed of light = 3×10^8 m/s

Δt = delay between transmit and receive signals

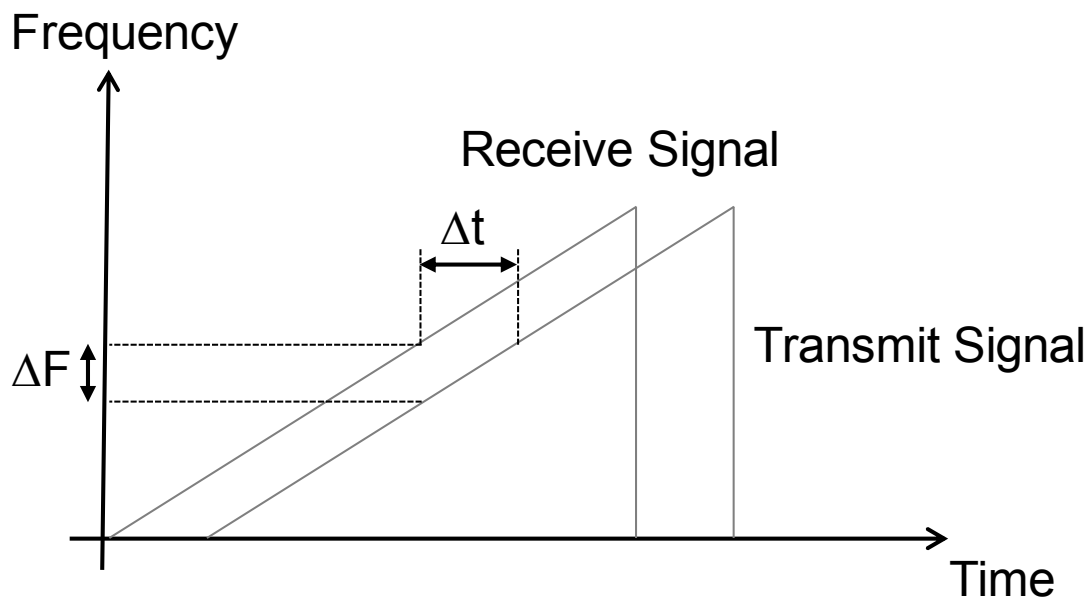


Fig. 48. A simplified illustration of the operation of FMCW radar with the transmit and receive signals mixing to create the difference frequency which is proportional to target distance.

Radar Box



Inside Radar Box



Fig. 49. Image of the FMCW radar transceiver hardware.

The hardware was fabricated and an image of it is shown in Fig. 49. The hardware components are fabricated in small metal packages with SMA connectors and DC bias points where required. Complete transceiver (except for the waveform generator) was assembled into a standard metal enclosure as shown in the figure.

7.2 Antenna Detailed Design

The purpose of the antenna in a radar system is to convert the electrical signals in the electronic hardware into traveling electromagnetic waves. For the microwave radar used in the drone detection system, two types of antennas were used. The first type is a horn antenna and an illustration is shown in Fig. 50. It can be readily noticed that the horn antenna is named as such



Fig. 50. Image of a horn antenna used in the prototype testing.

since it physically looks similar to a horned instrument, like a trumpet. This type of antenna provides performance that is desirable for this system such as excellent gain. Because horn antennas were available for the prototyping of the hardware, they were chosen as the baseline for the experimental system.

A different type of antenna was also developed as a Plan B. The Plan B antenna is a dielectric notch antenna (DNR) and it was chosen since it has features that the baseline antenna does not such as small size, lower cost, and lower mass. However, the technology used in the DNR antenna was not proven when the baseline needed to be selected. Therefore, the DNR antenna was carried forward as an advanced development activity and considered as an alternative for the antenna if proven worthy through technology demonstration.

7.3 Advanced Development Of The Dielectric Notch Radiator

Tapered slot antennas (TSA) have been used for many decades. Possibly the most familiar form of a TSA is the Vivaldi antenna [146]. This type of antenna has found extensive use in antenna array systems [147,148]. Numerical methods have been used for their design such as the TLM method [149] and FDTD method [150]. However, one limitation of Vivaldi type TSA antennas is they are electrically large, up to several wavelengths long [151] as illustrated in Fig. 51(a) which can limit their application where size is a concern.

An alternative TSA to the Vivaldi is the dielectric notch radiator (DNR) antenna [152, 153] (the notch refers to the physical appearance of the antenna, and should be confused with a notch filter). It has the same positive benefits of the Vivaldi TSA, but it is much shorter. In fact, it can be fabricated with the taper section being less than a half wave length long. Prior work has been done on compact versions of Vivaldi antennas. In [154], for instance, a compact Vivaldi antenna was realized, but size compaction was achieved by embedding the antenna in a dielectric. The dielectric loading increases the size, weight, and cost of the antenna which limits the types of applications that can use it. Another example is shown in Fig. 51(b) which is similar to the DNR and is referred to here as the ZHG after the authors of the paper describing it [155]. One drawback of the ZHG antenna is it uses slot line sections with abrupt bends. This can result in undesired parasitic radiation especially at higher frequencies. In contrast to this prior work, the DNR, shown in Fig. 51(c), uses a smooth radius for the slot line section which minimizes the undesired radiation. Also, it avoids the need for dielectric loading for compaction.

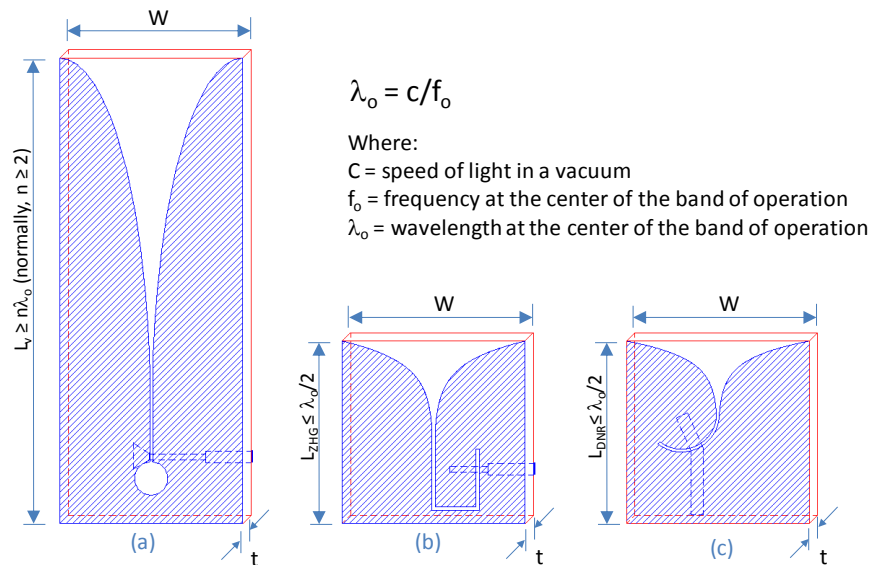


Fig. 51. Examples of tapered slot antennas include the (a) Vivaldi which is several wavelengths long, or (b) ZHG which is approximately a half wavelength long, and (c) DNR which is approximately a half wavelength long.

This section describes the DNR and how the risk in using it as part of the system was reduced. The approach was to demonstrate the DNR antenna commercial wireless and radar. Specifically, a DNR solution was developed for 5G and IoT applications. An antenna designed and fabricated to cover LTE band numbers 12 and 25, and 2.4GHz Wi-Fi band. These are popular bands for 5G and IoT applications. The antenna was integrated with diplexer filters which separate out the bands of interest. A version of the DNR antenna was also developed to cover X-band which is the operating frequency of the drone detection radar system. The test results of the antenna are shown for the element as well as a line array of four elements.

7.4 DNR Design Procedure

The design of the DNR involves five steps which are described below. As will be seen, this work uses exponential tapers, though a significant amount of work has been demonstrated for other taper types such as Chebyshev transformer method [156], and an optimum taper [157]. The five step design procedure is:

Step1-Calculate Antenna Element Width, W , and Length, L : The width of the antenna, W , is illustrated in Fig. 52. There are two antenna requirements that impact the choice

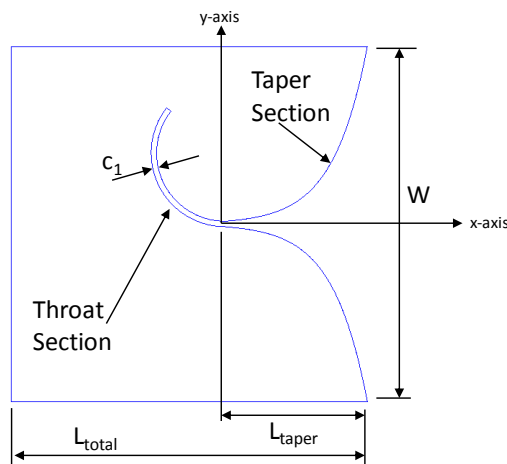


Fig. 52. Definition of the physical features of the DNR antenna.

of W . First, if the antenna element is going to be used in an array that will be scanned, then the width of the element must be chosen to avoid the presence of grating lobes [158]. Second, the width is chosen based upon the lowest operating frequency of the antenna.

The width of the antenna can be approximated as a half wavelength at the lowest operating frequency. This can be written as

$$W = \frac{\lambda_{f_{\min}}}{2} = \frac{c/\sqrt{\epsilon_{\text{reff}}}}{2f_{\min}} \quad (26)$$

Where:

c = speed of light in a vacuum (meter/second)

ϵ_{reff} = effective dielectric constant of the tapered slot line at the radiating end of the antenna.

f_{\min} = minimum frequency in the operating bandwidth, BW , and $BW = f_{\max} - f_{\min}$ (Hertz)

The width of the tapered slot at the radiating end of the antenna is equal to the antenna width. In this case, for moderate dielectric constant materials ($\epsilon_r \sim 4$), the value of the effective dielectric constant, ϵ_{reff} , approaches unity. As an example, if this approximation for ϵ_{reff} is assumed, and a minimum operating frequency of 9GHz is used, and using (26), then the width of the DNR antenna is found to be

$$W = \frac{c/\sqrt{\epsilon_{\text{reff}}}}{2f_{\min}} = \frac{3 \times 10^8 \text{ (m/s)} / \sqrt{1}}{2 \cdot 9 \times 10^9 \text{ (1/s)}} = 16.67 \text{ mm}.$$

Because of the approximation of ϵ_{reff} , the actual achieved f_{\min} will be lower. If a more accurate estimate of ϵ_{reff} is needed, then it can be calculated using [159]. Alternatively, a simple to calculate estimate of ϵ_{reff} which can be used even for higher dielectric constant substrates is to use

$$\epsilon_{\text{eff}} \approx \frac{(1 + \epsilon_r)}{2} \quad (27)$$

This equation over estimates ϵ_{reff} since it assumes that the half space is filled with the dielectric.

The length of the taper section of the antenna is chosen by the designer. The taper section is chosen as a fraction of the length (which is assumed here to be equal to W) by a scaling constant, K , which will fall in the range of 0.4-0.7 for most designs. The taper section length can be written as

$$L_{Tapper} = K \cdot W . \quad (28)$$

Continuing the previous example, if K is set to 0.4, then the length of the antenna operating at $f_{min} = 9\text{GHz}$ is found to be 6.67mm.

Step 2-Choose the throat width: The width of the slot line throat is determined by a few factors. First, for fabrication of the circuit board, there will be a limit on the narrowest line the fabricator is able to achieve. If printed circuit board is used, then a practical limit on the minimum width is in the range of 0.125mm to 0.250mm (for most fabricators), though small widths can be fabricated. Second, the optimum performance of the transition from microstrip to slot line depends upon the width of the slot so it must be chosen along with other features to maximize the desired performance of the antenna. Third, the width of the throat impacts performance at the maximum frequency. The designer must balance these requirements in choosing the throat width.

Step3-Calculate the Tapper Dimensions: As previously mentioned, this work uses an exponential taper. The derivation of the taper design equations follow an approach similar to that used in [160, 161] except this work extends the derivation so that the coefficients in the equation for the exponential taper can be calculated directly from the known physical features. The equation giving the taper dimensions is

$$y(x) = c_1 e^{Rx} + c_2 \quad (29)$$

Where:

y = the dimension in the y-direction (meter)

x = the dimension in the x-direction (meter)

c_1 = Slot line width in the throat section of the DNR = beginning width of the tapered slot line (meter)

R = opening rate (1/meter)

c_2 = a constant, often set to zero (meter)

If we let $C_2 = 0$ and (29) is evaluated at the radiation end of the taper where $y = W/2$ and $x = L_{taper}$, then solve for R which gives

$$R = \frac{\ln\left(\frac{W}{2c_1}\right)}{L_{taper}} \quad (30)$$

and keeping in mind that c_1 is the width of the slot line at the beginning of the taper at $y = 0$. This means that the coefficients in (29) can be calculated from the design constraints and values obtained in the previous steps.

Step 4-Optimize Microstrip to Slot Line Transition: This step is related to Step2 and may actually be performed in conjunction with it. It is the optimization of the dimensions of the microstrip line and the slot to achieve optimum performance. There has been extensive prior work in this area [162, 163, 164]. The approach in this work is to perform an optimization in HFSS [165] with minimum antenna port return loss as the optimization goal.

Step 5-Matching Circuits (as needed): The last step in the design of the antenna element is to include matching circuitry, if needed. Techniques such as quarter wave transformers can be used.

7.5 X-Band Antenna Element And Array

An X-band DNR antenna element was developed using Rogers 4003 ($\epsilon_r=3.55$) with a thickness of 0.5mm. The system that will use this antenna has a lower operating frequency of

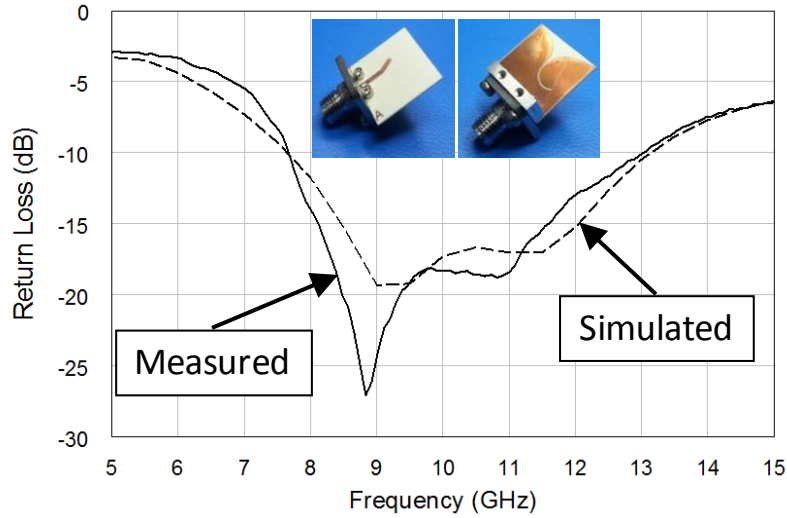


Fig. 53. X-band antenna simulation and measured data.

9GHz. If the simplifying assumption that $\epsilon_{\text{reff}}=1$ is used, then the width, W , of the antenna is found from (26) to be 16.67mm as calculated above which was rounded down to 16.5mm. It is assumed that the overall length of the antenna is equal to its width, W . For the length of the taper section, the scaling constant, K , is assumed to be 0.4. This means that the taper section will be 40% of the overall antenna length. This yields the length of the taper section, L_{taper} , to be 6.67mm as calculated above which will be rounded down to 6.6mm.

The taper dimensions were calculated using (29) and the length of the throat and

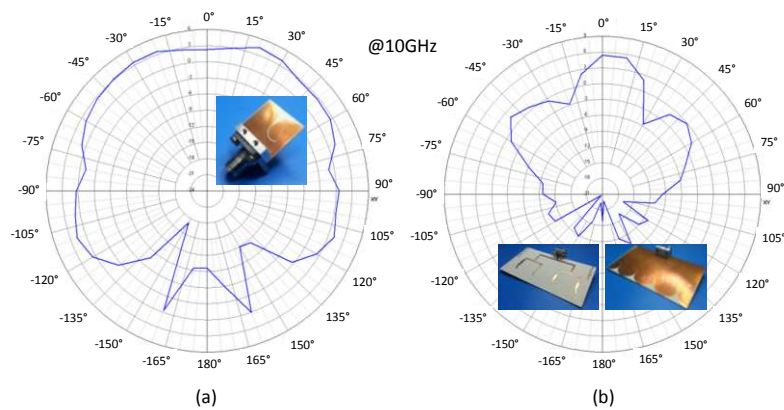


Fig. 54. Measured gain at 10GHz for (a) single element and (b) a four element array.

dimensions of the microstrip to slotline transition were optimized in HFSS. The antenna was fabricated and a comparison between the simulated and measured return loss is shown in Fig. 53. Note the agreement between the measured and simulated performance. The single element measured antenna gain is shown in Fig. 54(a). Note how that the maximum gain is approximately 3dB. A four element array was also designed, and fabricated. The measured gain for the four element array is shown in Fig. 54(b) as approximately 6dB.

7.6 5G and IoT Antenna With Integrated Diplexer Filtering

This section describes a broadband (0.7 to 2.5 GHz) antenna used to cover 5G and IoT bands. The use of mobile bands for IoT communication is being deployed now [166]. Attractive bands include LTE band numbers 12 and 17. IoT device access using Wi-Fi bands has been investigated [167, 168] and using Zigbee below 1GHz [169]. The system described here demonstrates a wide band DNR combining either mobile phone bands with Wi-Fi bands or Zibee 915MHz with Wi-Fi bands into a compact antenna.

A simplified block diagram is shown in Fig. 55. Note the +45 degree polarization and the -45 degree polarization ports. Also note that the signal is separated using a diplexer formed by a low pass and high pass filter. The low pass filter connects to the LTE bands and the high pass

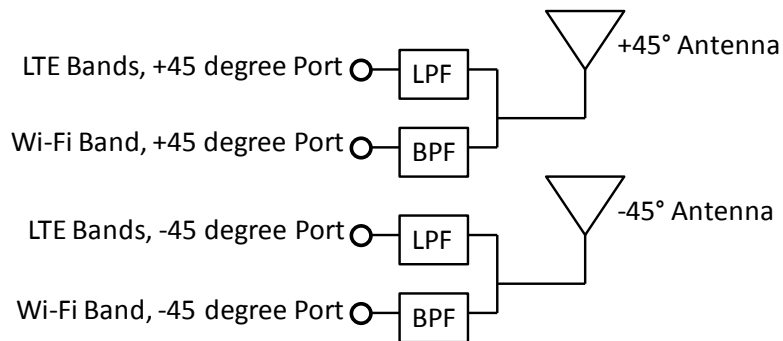


Fig. 55. Simplified block diagram of the 5G and IoT antenna solution.

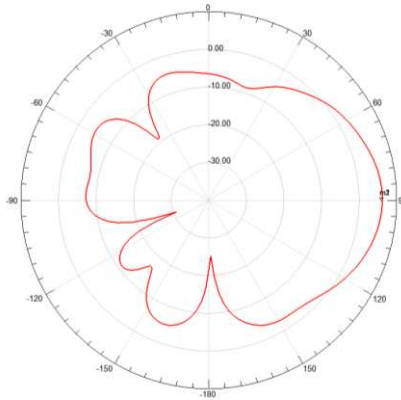


Fig. 56. Antenna simulated gain is 6.1dB at 2.4GHz.

filter connects to the Wi-Fi bands. This arrangement allows for dual polarization on each of the bands.

The antenna was designed using the same 5 step design procedure outline above. The substrate type was chosen to be FR-4 at a thickness of 0.762mm. The effective dielectric constant was estimated to be 2.5 and the width, W , of the antenna was found using (1) to be 137mm., the length of the taper section, L_{taper} , was found to be 68.6mm using a value of $K=0.5$ in (3), the total length, L_{total} , was set equal to W , and c_1 was chosen to be 0.762mm for ease of manufacturing. From this the opening rate was calculated using (5) to be 0.0656/mm.

The antenna was designed and the transition from microstrip to slotline in the antenna was optimized using HFSS. The simulated antenna gain is shown in Fig. 56.

7.7 Technology Demonstration Summary of DNR Antenna

This work described the benefits and design procedure for a DNR antenna. Two examples were presented. One for the case of a X-band antenna appropriate for use in radar systems A simple 4 element array was also described. The second example antenna covered 0.7 to 2.6GHz and a diplexer was used to separate the LTE bands (useful for 5G communication) or Zibee bands from the Wi-Fi bands (useful for IoT communication).

7.8 Radar Demonstration In CW Doppler Mode

A simple demonstration of the Low Cost Radar was conducted in CW Doppler mode. This test was conducted using cars as the target to demonstrate functionality of the radar. Fig. 56 shows a plot of the detected signal. Note how the target shows the speed of the vehicle at approximately 35 miles/hour.

7.9 Chapter Conclusions

The purpose of this chapter is to present some of the advanced development effort used to show the feasibility of part of the SoS. The low cost radar consists of many different subsystems and this chapter demonstrated the antenna technology, a simplified radar transceiver, and the data capture and display within MatLab.

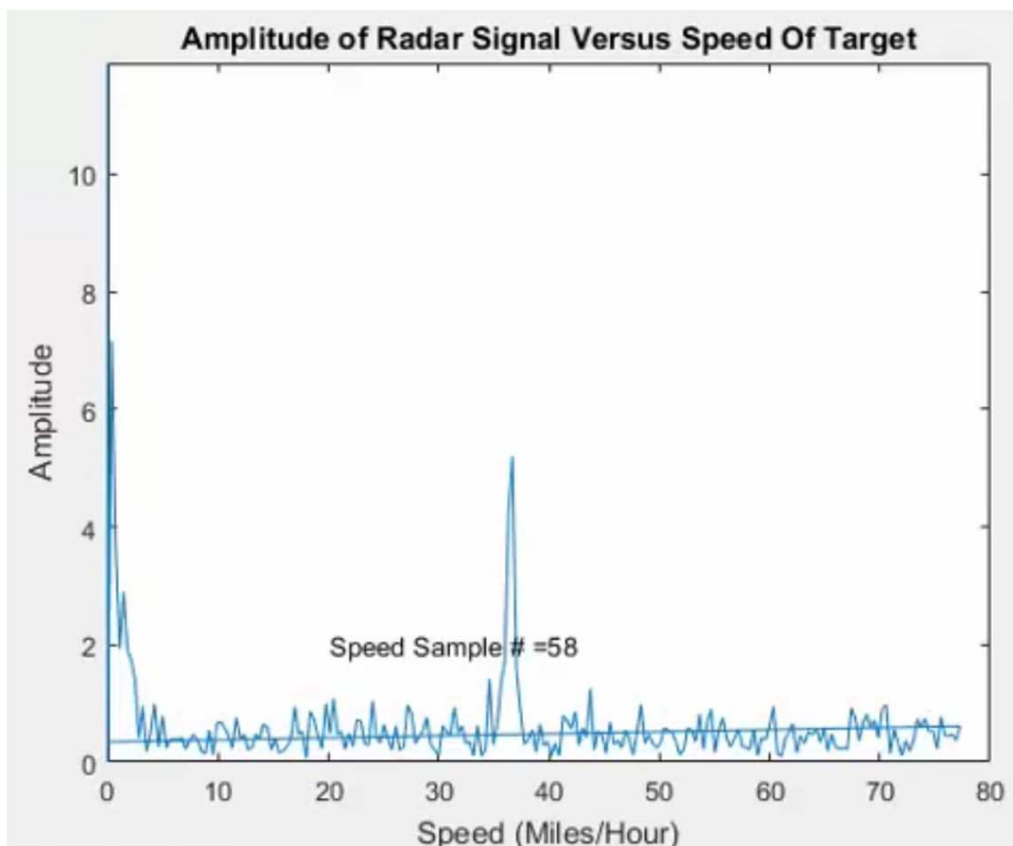


Fig. 57. Measured data from the low cost radar operating in CW Doppler model using vehicles as targets.

8. Emergence in Systems of Systems

Emergence can be a useful concept for describing system level and emergent behavior has been described as one of the characteristics of SoS as mentioned in Chapter 1 and discussed in [170]. Emergence is able to capture effects that are widely recognized as real and relevant that occur, often unexpectedly, at the higher levels of systems. A few examples of systems with phenomena that have been regarded in prior work as emergent are:

Simple Rules Based Computer Simulations: For instance, John Conway's Game of Life computer simulation uses four simple rules relating to neighboring cells [171]. When the computer simulation executes, higher level phenomena occur which are the result of the interactions of individual cells. Another example is flocking behavior in computer simulations which use simple behavioral rules in relation to nearest neighbors. The flocking behavior has been described as emergent [172, 173, 174].

Corporate Organizational Systems: Corporate level competence was analyzed as a system in [175] to find the cooperation mechanism which leads changes in capabilities. These modifications to corporate level competence have been considered emergent.

Radar Systems: When air defense systems are integrated together, they can exhibit characteristics that are best explained as emergent [176]. Interactions between various radars are possible because of a network of interconnected communications. Network wide emergent behavior is observed such as optimized firing and target engagement strategies.

Economic Systems: Examples such as international trade patterns, prices, goods, technologies, and markets are regarded as potentially emergent processes in economics [177]. It has also been argued that some macroeconomic phenomena supervene on micro interactions

between microeconomic phenomena [178]. Emergence has also been used to explain economic capital patterns [179].

Health Care Provider Organizations: When the UK National Health Service (NHS) made changes to its directives regarding patient wait times, unexpected system wide behavior occurred at hospitals [180]. The result was undesirable and caused negative effects for many patients. The organizational behavior was considered emergent.

These are just a few examples of how emergence has been used to explain phenomena in complex systems.

Multiple workers have developed methods for modeling emergence in complex systems. One method uses complex events in a multi-level agent based simulation [181, 182, 183]. Another uses reconstructability analysis to validate emergence [184]. A good survey of approaches to modeling emergence can be found in [185] which compare their benefits and drawbacks.

In addition, several workers have developed methods for detecting emergence. For instance, a taxonomy of emergent behavior is developed in [186] which can be used to classify emergence so it can be recognized. A method for detecting emergence using the level of interaction is described in [187]. A similar method in [188] uses interaction statistics as a way to detect emergence. In [189] the authors develop a set of four core characteristics of emergence and three additional features as a way of detecting emergence in the context of capital formation in economics. The four conditions are:

- 1) Material realization (emergent patterns are realized in physical structures and processes);
- 2) Coherence (pattern is not a mere aggregate but a systemic whole);

- 3) non-distributivity (pattern possesses global properties absent from its parts);
- 4) Structure dependence (systemic properties depend upon connective structure).The detection of emergence remains an active area of research [190].

However, these models of emergence and techniques for detecting it do not include causation that can occur from emergent phenomena down to parts of the system. Or, when prior work does mention downward causation, it is included as part of a model without any description of the functioning of the downward causation or examples of it. As a result, a significant class of emergent causation is ignored.

Therefore, the goals of this work are to develop a conceptual model of downward causation from emergent phenomena, describe the necessary and sufficient conditions for weak emergence using downward causation, and show that this method is useful for detecting emergence by showing examples. In fact, on the proposed approach, only those phenomena with confirmed downward causation possess the sufficient condition for emergence. All other phenomena thought to be emergent are either rejected as non-emergent or classified as potentially emergent.

Of course, downward causation is not new to the study of emergence. It is commonly used in philosophical discussions of emergence as in [191, 192] but when it is used in philosophical discussion it is usually associated with strong emergence. This limitation in prior philosophical work of only allowing downward causation for strong emergence limits the causal tool kit available to systems engineers.

Downward causation has also been used in the description of systems as in [193] but, again, in association with strong emergence. Strong emergence, if it exists, is regarded by some as being restricted to consciousness as in [19]. Downward causation has also been proposed as

part of sociology investigations to explain small group dynamics such as musical ensembles and group conversations [194]. Though downward causation has been analyzed in philosophy and sociology, a conceptual model of weak emergence with downward causation has not been developed for systems engineering. Also, it has not been shown to be useful in distinguishing emergence from non-emergence.

This work is divided into six sections. Section II describes the reductionist method used in science so that it can be compared to emergence. The comparison helps with grasping the fundamental ideas behind emergence. With this backdrop, a model for emergence is provided in Section III which includes the necessary and sufficient conditions for phenomena to be considered emergent. Section IV describes how black box modeling is applied to emergence modeling. Section V illustrates how the necessary and sufficient conditions are applied in specific cases. This work concludes in Section VI with a summary and recommendations.

8.1 Scientific Investigation and Emergence

Before beginning the discussion of emergence, it is instructive to describe the dominate method of scientific investigation which is often called scientific reductionism. This approach assumes that everything can be reduced, decomposed, or disassembled to constituent parts. It is illustrated in Fig. 58.

Note how analysis starts with the physical system or object being studied which is decomposed or disassembled into its lower level constituent parts. The goal is to understand functioning of lower level parts so operation of the complete system or object can be known. The process of disassembly and study of resulting parts continues until the level of required detail is achieved or limits of disassembly are reached.

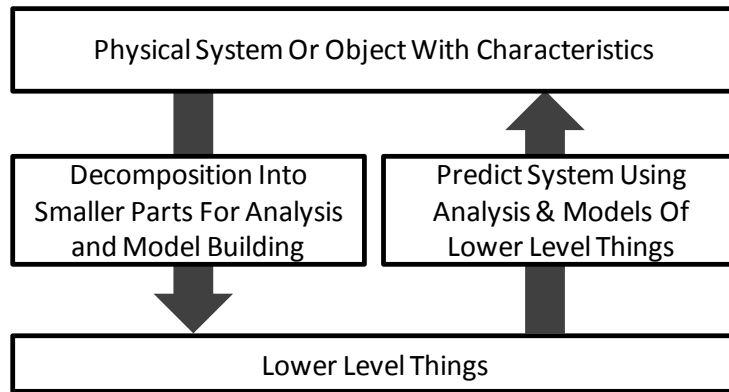


Fig. 58. Graphic showing the standard process of scientific investigation which is reductionism or disassembly of a system or object into its constituent parts. The parts are studied and models are developed which are used to predict or optimize system level performance.

Individual parts are studied and models of them are often developed. Detailed study of individual parts is where a significant amount of scientific investigation occurs. Particle physics, biochemistry, and DNA research are a few examples. The system is then reassembled and performance or activity of the complete system is then said to be determined by individual parts. This is the standard methodological approach used in scientific investigation.

An example is the study of biology where living systems are disassembled down to the level of cells, DNA, and biochemical reactions with the expectation of better understanding and predicting characteristics or properties of the complete biological system.

This method of analysis is powerful and has resulted in the growth of technological progress modern society currently enjoys.

Compare this with emergence which is the idea a complex system produces phenomena beyond what is achieved based solely on the system's individual parts. A useful way to explain this is the familiar phrase that 'the whole is greater than the sum of its parts.' Though this is an oversimplification (and can be misleading), it does point to the fact that a strict reductionist approach is not sufficient to capture all system level effects. If the system as a whole is represented by W and the individual parts by P_i , then this can be written as

$$W > \sum_i P_i . \tag{31}$$

One line of thinking takes emergence to be a function of interactions between parts and their external environment. If I_i and I_e are internal and external interactions which give rise to emergence, then (1) becomes

$$W = \sum_i P_i + E(I_i, I_e, P_i). \tag{2}$$

Where $E(I_i, I_e, P_i)$ is the emergent phenomena which is a function of the parts, and internal/external interactions. This means that

$$E(I_i, I_e, P_i) = W - \sum_i P_i . \tag{3}$$

While it is helpful to use reductionism as a means of comparison to emergence, this should not be thought to mean emergence is opposed to or is somehow incompatible with a methodological reduction approach to science. With these initial ideas in place, it is possible to describe the conceptual model of emergence.

Emergence can be described using the models shown in Fig. 59. For completeness, we start with descriptions of non-emergence and strong emergence followed by the necessary and sufficient conditions for something to be considered emergent.

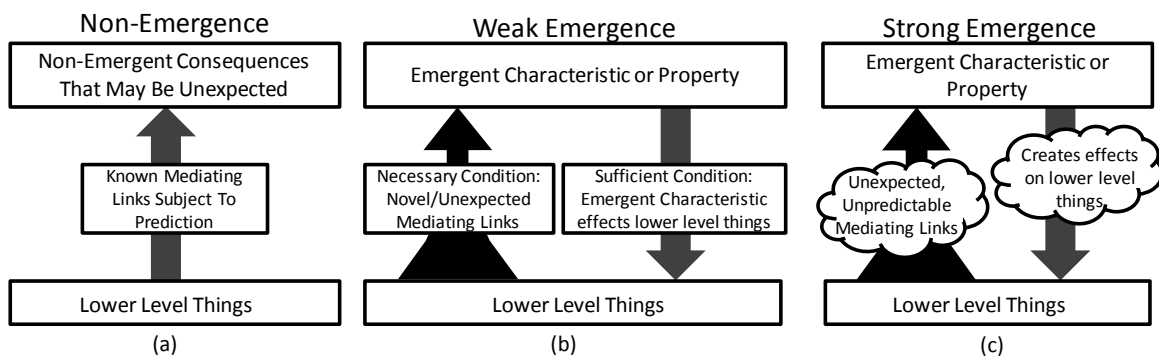


Fig. 59 The model of (a) non-emergent but unexpected consequences due to lower level things, and (b) weakly emergent characteristics with both necessary and sufficient conditions, and (c) strongly emergent characteristics due to unexpected and unpredictable mediating links which create effects on lower level things.

8.1.1 Non-Emergence

There are at least two cases where high-level phenomena appear to be emergent, but are not. The first case involves levels of explanation. Consider a rotating metal wheel. At the level of the molecules, their relative positions to each other are controlled by the interactions between them. However, at the level of the wheel, laws emerge that are not applicable to the relative position of each molecule in the wheel such as rotational inertia. Nevertheless, this does nothing to affect the application of reductionism in fully describing these types of higher level effects. The point is that systems can exhibit characteristics at the macro level that dependent upon micro level elements, but those phenomena are not emergent.

The second case involves unexpected phenomena that appear to ‘emerge’ from the system being observed but are actually predictable using reductionist methods. They may be beneficial or detrimental to the overall function of the system [21]. Nevertheless, they are unexpected since the causes are unknown to the individuals performing the observing, but may be known at the time to others and so they are subject to normal scientific analysis according to Fig. 58. Or, they may be unexpected at time t , but the system is studied with the valid expectation that in the near future at time $t + \Delta t$ the causes will become known and even predictable. This is because the causes are within the scope of existing scientific knowledge. A classic example of an unexpected, but non-emergent effect is the Tacoma Narrows Bridge which was at that time one of the world’s largest suspension bridges. It collapsed shortly after being completed due to unexpected resonances that resulted from high winds. The unexpected characteristic (such as mechanical bridge resonances in this example) can occur as a result of insufficient up front effort in predicting the possible system level states or as a result of unknown

mediating links that later become known. Because these causes and mediating link are known or within the present scope of being know, they are not emergent.

These two cases, levels of explanation and known mediating links, belong to the same group which are non-emergence phenomena and are illustrated in Fig. 59(a). As will be discussed in later sections, if either of these two types of explanation (or other purely reductionist explanations) account for the behavior, then it is not emergent. Therefore, the test for reductionism serves as one condition for emergence.

8.1.2 Strong Emergence

Strong emergence is illustrated in Figure 59(c) and is considered here for completeness. It shows the emergent characteristics being a result of lower level things but resulting from unexpected and unpredictable mediating links. In this class of emergence, mediating links are not just unknown now and may become known in the future. Rather, they cannot be known at all. For illustration purposes, imagine a Super Engineer (SE) who is presented with a system to analyze with unexpected phenomena. A SE is defined as a person who possesses all the scientific knowledge that is known about the physical world and is able to correctly apply that knowledge (not withstanding implications of the uncertainty principle which has been regarded as limiting deterministic knowledge) [195, 196]. For the case of strong emergence, the emergent phenomena will always be unexpected and unpredictable since the high level phenomena cannot be predicted, even in principle, from the lower level things. Even the SE will not be able to predict the emergent characteristics despite being granted access to the most power computing capability possible and the best possible scientific models. For this reason, and others, there is debate if strong emergence actually exists, with some regarding consciousness as the only known possible

example [197]. Since strong emergence cannot be predicted from lower level things, it is not developed any further.

8.2 Weak Emergence and The Necessary and Sufficient Conditions

Weakly emergent phenomena reside in the middle area between non-emergence and strong emergence as shown in Fig. 59(b) and so they share features of each. Unlike the non-emergent case, weakly emergent phenomena are rightly considered emergent. It is this class of emergence that is analyzed in the remainder of this work.

The emergent phenomena, in the weak emergence case, cannot be predicted using current known methods, but it is expected that they can be known and predicted, with acceptable accuracy, when sufficiently capable calculating methods are developed or new science is known. In other words, it is expected that further investigation (even if it is well in the future) will reveal the mediating links between the lower level things and widely accepted explanations are anticipated. Until then, the best that can be done for making predictions is to create abstract models such as regression (i.e. ‘curve-fit’) models (linear or non-linear) that are able to predict the physical result over some limited range of variables after extensive characterization (test and measurement), but the models do not represent a fundamental understanding of the operation of the system or lower level things. In this sense, the model is treated, at least in part, as a black box [198, 199].

In fact, if a fundamental understanding of the operation of the lower level things giving rise to the emergent phenomena exists, then the phenomena would no longer be considered emergent since that knowledge can be used to accurately model and predict. As a result, unexpectedness relative to the phenomena would be removed, emergence would no longer apply, and materialistic reductionism would be used.

However, for the case of weak emergence, sufficient understanding of the operation of the lower level things does not exist yet. Therefore, the phenomena are regarded as potentially emergent since mediating links are unknown, the phenomena are only ‘predictable’ after the fact using non-physical models, and methods such as levels of explanation and reductionism do not explain the phenomena.

Using these concepts, the phenomena can be tested to check for emergence using the necessary and sufficient conditions.

Necessary Condition for Emergence: A necessary condition for system level phenomena to be considered emergent is that the phenomena must be detectable and irreducible using known methods to the lower parts and interactions of the system. To be clear, in this case, the emergent phenomena itself is detectable. Also, by irreducible, it is meant that the phenomena must not be predictable using levels of explanation or reductionist methods. However, the phenomena are thought to be reducible at some point in the future (i.e., they are not strongly emergent).

Sufficient Condition for Emergence: A sufficient condition for phenomena to be considered emergent is they must exhibit detectable downward causation upon lower level parts and interactions of the system. In other words, they must do something to the system from which they emerge. Moreover, the effects of the emergent phenomena on other (normally, lower level) parts of the system can be detected.

If an emergence phenomenon is claimed to exist, but it or its effects are not detectable, then it is unclear why it is of interest to systems engineering and on what basis emergence is claimed.

8.3 Black Box Modeling Applied To Emergence

In this section, the modeling of weak emergence with downward causation is discussed. As will be seen, the activity turns out to be one of system identification or black box modeling. The goal of system identification is to build “mathematical models of dynamic systems from observed input-output data.” [200] The details of the internal workings of the system are unknown and the only knowledge is the inputs and outputs as illustrated in Fig. 60. In this section, black box modeling is applied to emergence.

The concept of black box modeling has been applied to describe both engineered and natural objects when knowledge of the internal operations are not known. An example is the act of reverse engineering of IBM personal computer Basic Input/Output System (BIOS) [201]. When engineers at Compaq Computer Corporation were tasked with reverse engineering the IBM BIOS, they treated it as an unknown black box and were only concerned with the inputs and outputs. Once the BIOS was fully characterized, a specification document was developed for it which fully described its input/output operation. A new team of engineers was assigned to develop a competing product that met the specifications. This is an example of how a physical system can be treated as a block box.

Another application of the concept of a black box is to describe models. That is, the model itself can be treated as a black box since, in some instances, the engineer is not concerned (in the practical senses) with the internal structure of the model only that the model provides

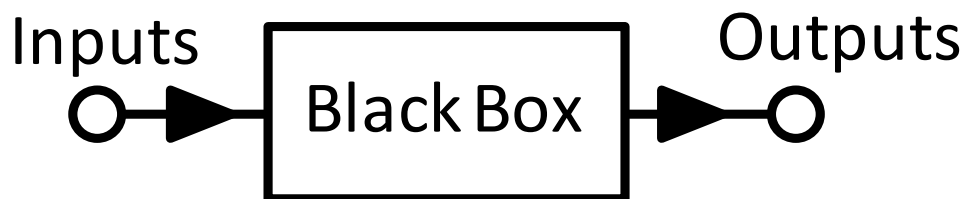


Fig. 60. A black box with input and outputs.

acceptably accurate output predictions given the input stimuli. In this case, the engineer possesses measured input/output data for a physical system and a model that has the potential to predict the operation of the physical system. The engineer will use the model (and likely optimize its variable parameters) to ‘match’ the measured data. The engineer is then able to use the model rather than the data itself. However, there may be little or no knowledge of the details of the model, and likely very little knowledge of the range over which the model is potentially valid. However, other sets of u_t and y_t can be used to increase the valid range.

Contrast the black box model with a model of a physical system that uses elements that are based upon well established scientific theories. Such a model can boast of having connectivity to other models and that its constituent parts have been verified by more fundamental measurements and theoretical models. Consider, for instance, the model of a transistor which can have non-linear elements which are based on more fundamental diode operation, semiconductor electron transport mechanisms, and capacitor charge effects. Such a model has known elements which are based upon well established science with a description that explains the interconnections of the model. A black box model lacks all this traceability since only input and output characteristics are of interest.

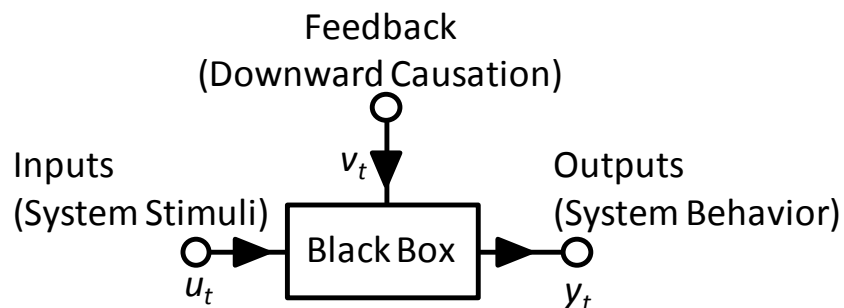


Fig. 61. Block diagram of the model for emergence where u_t are system stimuli, v_t are the downward causation modeled as feedback, y_t are the system behavioral outputs which includes emergent properties, and the black box models the system and unknown interactions which give rise to the emergent properties.

However, the basic black box model with an input and output is too simplistic to account for emergence. The model for emergence must also account for downward causation (downward stimuli) which are accounted for as feedback as illustrated in Fig. 61. In this case, the input stimuli are the known and downward causes have been identified. However, the exact interconnections within the model that give rise to the emergent behavior are unknown. Therefore, as mentioned earlier, the challenge for modeling emergent behavior then becomes a task of system identification. There are three steps in using the black box approach. First, a guess is made for the model and interconnections within the black box. A portion of the model may be based upon well established scientific components, elements, and connectivity representing the known parts of the system and used to capture the non-emergent system behavior. The model must also include elements and connectivity which are meant to account for the emergent system level behavior which is that part of the model which is guessed. Second, this is followed by an optimization of the black box model elements and interconnections given a set of inputs and feedback to minimize the error between the predicted outputs and the actual observed system behavior. Third, a check is made to determine if the error is acceptable and with particular concern if the emergent behavior has been predicted. Once an acceptable level of error has been achieved, the model can be used for further analysis.

Since the focus of this work is on the necessary and sufficient conditions for emergence, black box modeling of emergence is not developed further.

8.4 Application Of Necessary and Sufficient Conditions For Emergence

The process for filtering out non-emergent phenomena using the necessary and sufficient conditions is illustrated in Fig. 62. The *necessary condition* is used to determine if existing scientific methods can be used to explain the phenomena. In this work, this is tested by checking

if levels of explanation or materialistic reductionism can explain it. If they can, then the phenomena are considered non-emergent. If existing scientific methods cannot explain the phenomena, then it is considered potentially emergent. The *sufficient condition* for phenomena to be considered emergent is that they exhibit detectable downward causation on the lower level parts of the system. This process of filtering out non-emergent phenomena will be applied to a few examples.

The first example is the simple rules based computer simulations with John Conway's Game of Life. This system is a computer simulation of cells with simple rules for neighboring cells. Setting the initial conditions (inputs) and running the simulation generates results (outputs)

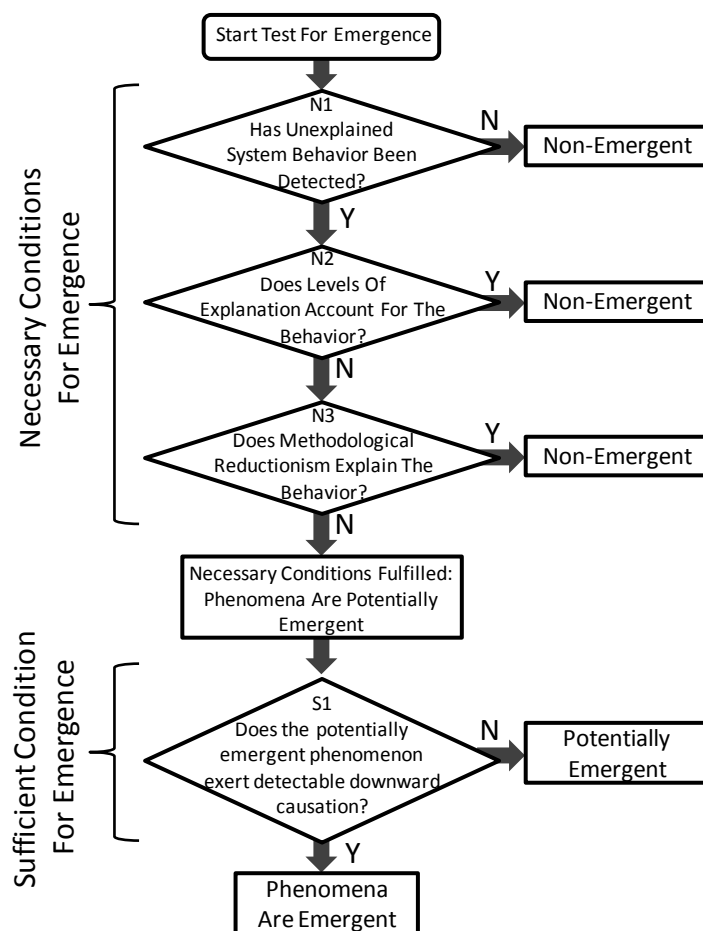


Fig. 62. Flow chart of the necessary and sufficient conditions for phenomena to be considered emergent.

which are initially unexpected. However, does this mean the behavior is emergent? Using the above test, the answer turns out to be no. The first reason is that all the behavior can be predicted using the rules of the systems and initial conditions [202]. In this way the seeming emergent property can be explained away by the micro level rules. It is true enough that some of the results may be unexpected such as the repeating gun, but once observed, the unexpected behavior is fully described by the rules of the game. This means that the simulation is subject to methodological reductionism so by the necessary conditions test, it is rejected as non-emergent.

The second example is radar systems for national air defense. When these systems are interconnected, unexpected system behavior results due to the interconnections. The unexpected behavior is a fused set of data into a single battle space picture with weapon systems centrally commanded to respond as necessary [203]. This ability results from the interconnection of the radar systems and weapon systems. However, is this behavior emergent? The answer is no because the system is engineered to perform in that fashion. True enough that the interactions between various systems provide capability that the individual systems cannot. Nevertheless, the interconnection effects can be predicted by properly analyzing the new behavior using well established methods [204, 205] so this behavior is rejected as non-emergent because of it can be explained using reductionism.

The third example is emergence in complex project systems. Large construction projects, for instance, are complex systems themselves which can exhibit emergent properties such as restorative capacity [206]. The restorative capacity of a system is its ability to recover quickly from disruptions caused by the complexity of the project [207]. Some projects have greater levels of restorative power and others have less of it. The study of the restorative properties in [31] is based upon a reductionist analysis which revealed that there are contributing factors (e.g.,

human skills, team building, timely decision making, etc.) which contribute to the restorative ability of complex projects. However, the reductionist analysis showed the contributing factors only partially explained restorative capacity and the best that can be hoped for is an optimization of an organizations complexity so it is congruent with the emergent properties. Stepping through the flow diagram in Fig 5 for the necessary conditions for emergence, we obtain:

Step N1: Has Unexplained System Behavior Been Detected? Yes, the behavior of restorative capacity has been identified.

Step N2: Does Levels Of Explanation Account For The Behavior? No, levels of explanation do not account for it since it is not part of a physical system with integrated constituent parts.

Step N3: Does Methodological Reductionism Explain The Behavior? No, methodological reductionism has identified contributing factors, but not enough to completely explain the behavior as described in [208].

At this point, the project system behavior of restorative capacity can be regarded as potentially emergent. Next is the sufficient condition for emergence:

Step S1: Does the potentially emergent phenomenon exert detectable downward causation? Yes, the phenomenon does exert detectable downward causation. The restorative capacity of the project system causes it to respond rapidly to disruptions to the system itself which is an effect that can be measured as the time it takes for the system to recover.

Therefore, the phenomenon of restorative capacity in complex project systems should be regarded as an emergent property of the system. Keep in mind that in the future, it may be possible for the behavior to be fully explained using reductionism which would move it to the

class of non-emergent behavior. However, until that occurs, the systems engineer is justified to regard it as emergent.

8.5 Conclusions

This work developed a conceptual model using emergence with downward causation. Methodological reduction approaches to scientific investigation were reviewed as a comparison to emergence in systems. Weak emergence was defined. Necessary and sufficient conditions for emergence were then developed and an algorithm was presented. Finally, the algorithm was applied to three different cases to determine the existence of emergence.

Not addressed in this work is the possibility, at least conceptually, for system level phenomena to be emergent, but not initially detectable. In this case, the emergent phenomenon exists but cannot be measured or noticed. In this case, the emergent phenomena cannot pass the first question in the emergence test algorithm in Fig. 62. As a result, it is possible for emergent phenomena to exist, but remain undetectable and the process developed here will reject them as non-emergent. However, this is hardly a significant issue since an undetectable property without detectable causation seems to be of little concern for systems engineering.

Further work may also be done on expanding the necessary conditions steps in the algorithm in Fig. 5. In this work, the step includes a test for using levels of explanation and methodological reductionism. However, more detail can be generated for the reductionism test. Also, the methods for applying the test can be fully developed. These types of expansions of this approach are beyond the scope of this work.

Further work can be done on developing methods to detect downward causation. In this work, it has been addressed by providing an example of how downward causation has been observed which is enough to establish the usefulness of this approach. However, additional work

should be done to establish methods for detecting downward causation from potentially emergent phenomena.

Other possible candidates for emergence are macro capital order phenomena [209] and adaptability of complex project systems [206]. For macro capital order, the degree of structural integration may be emergent. Specifically, the ability of streams of capital to coordinate and combine across firms appears to be difficult to explain using purely reductionist methods. For adaptability in complex systems, the capacity of a project system to reconfigure itself may fulfill the necessary and sufficient conditions. However, more work is required in both of these cases to determine if they meet the conditions to be considered emergent.

A possible concern for this approach is the definition of weak emergence used. On the definition used here, the expectation is that in the future, even very distant future, purely reductionist methods are expected to be developed that will explain away the weak emergent property. Therefore, by definition, the emergent property is only a construct for categorizing system level behavior that cannot be explained yet using reductionism. While this is true, it does not count against this approach. In fact, on this approach, the ability to recognize something as emergent in this sense is still useful to the systems engineer who can then adapt to account for it or use it to the benefit of the system as in the restorative capacity example given.

9. Summary and Conclusions On Complex Systems and SoS

This work is concerned with SoS. The purpose is to add rigor to the definition of a SoS and to provide examples of systems engineering applied complex systems that may appear to be candidate for being considered SoS. It was demonstrated that upon closer examination of these complex systems, they do not qualify as SoS. The systems that were considered are:

1. Pico Hydro Electric Power In The Nepal Himalayas
2. Systems Engineering of Hybrid Renewable Electric Power
3. Low cost AESAs for high volume consumer LEO satellite ground stations
4. Terabit Elliptic Orbit Satellite and Phased Array Ground Station for IoT Connectivity and Consumer Internet Access
5. Multispectral Drone Detection System

The progression of complex systems considered terminates in a drone detection systems for protecting airports. The SAI method was applied to develop the airport drone detection system. The result was the development of a baseline configuration that qualifies it to be considered a SoS.

Since emergence has been considered by some to be a characteristic of SoS, it was examined in Chapter 8. One of the nagging problems in emergence for systems engineering is how to detect emergence. Therefore, the necessary and sufficient conditions for emergence were developed and examples of their application were given.

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