



**CREATING A LINEAR MODEL TO OPTIMIZE SATELLITE
COMMUNICATION BANDWIDTH UTILIZATION**

Graduate Research Project

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Abstract

The purpose of this paper is to develop a model to maximize the efficiency with which satellite communications (SATCOM) resources are used. The paper begins by presenting background information on the problem, including the utility of SATCOM, a description of how SATCOM works and identifying SATCOM systems in use. The paper then examines the current process for assigning SATCOM resources and identifies a shortcoming that may be improved by the model presented. Once the problem is fully described, a technique known as linear modeling is introduced as a potential means to increase efficiency of resource utilization. The paper then presents an example of a linear model that could be expanded for implementation and used for actual problem analysis. The final section of the paper describes areas that require further study and additional steps that must be taken to convert the concept presented in this paper to an actual model suitable for use.

To my wife, daughter and son

Acknowledgments

This paper would not have been possible without the help and support of many people. While I benefited from the knowledge and encouragement of more people than I could mention in one page, there are some specific individuals who I must single out and thank for their support.

First is Lt Col David Denhard, who not only served as my advisor, but also taught me much about operations research over the past year. I am extremely grateful for his insight, counsel and attitude of “Don’t write a GRP to fill an academic square; write a paper that will be useful to someone.”

Lt Col Rick Folks and Maj Matt Lupone at JCS/J6SC were kind enough to propose and sponsor my topic. MSgt Mark Shields at the Regional SATCOM Support Center at MacDill AFB spent much time educating me on SATCOM and the apportionment and allocation process. I give them my thanks.

Last, and most important, is thanks to my family. To my two children who are too young to understand the pursuit of advanced knowledge, but old enough to know Daddy had to spend time working on this paper; they are the light of my life. To my friend and my wife; for her support and encouragement through the paper process and the entire year at AFIT, I will be eternally grateful.

David A. Stone

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CREATING A LINEAR MODEL TO OPTIMIZE SATELLITE COMMUNICATION BANDWIDTH UTILIZATION

I. Introduction

Communications is one the most fundamental requirements for conducting affairs of state and military operations at any level. Since the earliest days of warfare, combatants have relied on communications to coordinate their actions and maximize their warfighting capability. Today, one of the most important means of communications is through satellites. Satellite communications (SATCOM) allow real time communications to literally every spot on the earth.

Military Utility for SATCOM

As SATCOM technology has matured, our military operations have become so reliant on SATCOM that it is now an irreplaceable element of our operations. This increased reliance means the demand for SATCOM will continue to grow at an exponential rate. SATCOM plays a critical role at every level of military operations—strategic, operational and tactical. Figure 1 depicts the growth in demand for SATCOM in recent conflicts and Figure 2 depicts the projected growth.

At the strategic level, SATCOM allows our military and civilian leaders to communicate around the globe. Not only do these leaders rely on SATCOM for voice communications, they use it for machine-to-machine communications, video teleconferences, to transmit imagery and intelligence, to maintain global situation awareness and much more.

	Operations Desert Shield/Storm	Operation Noble Anvil	Operation Enduring Freedom	Operation Iraqi Freedom
Total SATCOM Used (Mbps)	100	250	750	2,400
Total Force Engaged	500,000	51,000	55,000	235,000
Number of 5,000 Military Member Force Increments	100	10.2	11	47
SATCOM Used per 5,000 Military Members (Mbps)	1	24.5	68.2	51.1

Figure 1. Historical Demand for SATCOM (Rayermann, 2003-2004)

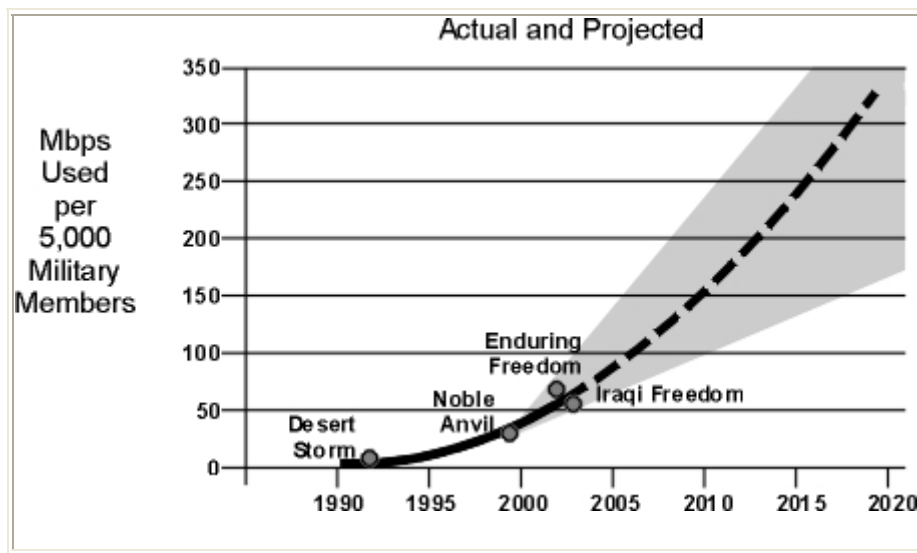


Figure 2. Projected Growth of SATCOM Demand (Rayermann, 2003-2004)

SATCOM is an integral element in allowing forces and capabilities located around the world to support operations in a particular region. For example, during

Operation DESERT STORM, SATCOM was a critical link in the missile defense network. With missile warning ground sites located in the Continental United States (CONUS), SATCOM allowed prompt warning of Iraqi missile launches. This information was critical to warning coalition forces and the civilian population of attack.

At the operational level, SATCOM allows us to integrate forces well beyond the range of line of sight communications. SATCOM is a critical enabler of the Air Force's Global Strike mission. An example of this is the ability to dynamically re-task a B-2 bomber mission which has departed the United States on a bombing mission in Europe or Southwest Asia. SATCOM allows us to update the crew with intelligence and, if required, change targets and mission timing.

In the Global War on Terror, Unmanned Aerial Vehicles (UAVs) have become an indispensable tool in conducting surveillance and limited attacks. The nature of the UAV requires long distance, large bandwidth communications to both fly the UAV and receive the live video imagery from it. SATCOM provides the link to conduct these operations from the CONUS, thereby significantly increasing the capability and security of fielded American forces while allowing UAV operators to remain far from the hostile area.

At the tactical level, SATCOM allows communications between ground troops on or even beyond the front lines and the Command and Control (C2) echelon. For example, the PRC-117 provides a UHF SATCOM capability in a man-portable backpack and is an integral piece of equipment for special operations forces and is rapidly gaining favor with conventional forces as well. SATCOM provides a vital communications link to these troops, particularly in mountainous areas such as Afghanistan, where line of sight

is extremely limited. SATCOM also provides a capability for secure, data burst communications for Special Operations Forces who cannot risk exposing their location.

These examples provide just a small sample of the importance of SATCOM to military operations. Equally as important, they also show a trend in increasing reliance and need for SATCOM. That trend will continue and demand for bandwidth will continue to grow rapidly.

Problem statement

The current demand for military SATCOM bandwidth is more than three times the existing capacity (Lupone, 2006). Currently, when a new request for bandwidth is approved, planners must often rearrange frequency assignment and may have to “bump” a lower priority user from the satellite in order to accommodate the higher priority request. Planners use a process of trial and error to determine how to re-arrange SATCOM bandwidth allocations to accommodate the new requirement while making the most efficient use of SATCOM bandwidth and minimizing impact to users (Shields, 2006a). This “trial and error” technique may not yield the optimum spread of assignment, resulting in wasted bandwidth and potentially bumping a user unnecessarily.

Additionally, the current allocation process looks only at the requested frequency spectrum to assign the requested bandwidth. There is no consideration of shifting users who have the capability to exploit another frequency spectrum to optimize use of all available bandwidth (Shields, 2006a).

The purpose of this paper is to develop a means to optimize SATCOM satellite bandwidth utilization, specifically with respect to considering the possibility of switching

users between frequency spectra, including commercial SATCOM, to maximize the number of requirements filled.

Significance of the Study

This study was conducted at the request of JCS/J6CS to seek a more efficient means of allocating SATCOM bandwidth and assigning frequency spectra to meet requirements. This study did not create a “finished product” model that can be immediately implemented, but rather a small scale “proof of concept” that can be transformed into a full scale model packaged in a user friendly format.

The utility of a completed, full-scale model will be two-fold. First, the model serves as a guide and check on current allocation. It does not, however, provide an absolute solution for allocation and assignment. Second, sensitivity analysis of the computed solution can be used to identify choke points and binding constraints in fulfilling SATCOM requirements. This information can be used to identify sectors where capability to operate in other spectra could provide the most overall benefit.

Assumptions

In order to simplify data gathering and development of the model concept, the communications requirements of the Unified Combatant Commander (UCC) and the entire bandwidth apportioned to him are all assumed to be in the same region / field of view. This assumption was made at the direction of JCS/J6CS. The model can be modified to eliminate this assumption and include regional limitations within the UCC area of responsibility, if required.

The model also assumes there is sufficient bandwidth to fill at least priority 1 and priority 2 requirements. This assumption was made to simplify the weighting coefficients in the objective function of the model. This assumption is realistic because it is unlikely there will ever be such a large demand by priority 1 and priority 2 requirements as to completely use all SATCOM bandwidth. In the event this occurs, the model can be modified to reflect that situation.

In order to simplify calculations used in the model's objective function, it is assumed that no single requirement is so large that more than nine requirements in the next lower priority tier can be filled using the same resources required to fill the single higher priority requirement. If this assumption becomes invalid, the difference in the value of weighting coefficients of succeeding priorities must be increased. The increase must be by a factor greater than the number of requirements in the next lower priority that can be filled using the same resources required by the single larger requirement. For example, if 14 priority 3B requirements could be filled using the same amount of resources required to fill a single priority 3A requirement, the difference between the weights for priority 3A and 3B must be increased by an amount greater than a factor of 14. If this is not done, the model can generate an incorrect solution.

Limitations

The greatest limitation of the research and model presented in this paper is with respect to the input data for bandwidth needed to satisfy requirements. *Currently, requirements in the SATCOM Database (SDB) are expressed in terms of data rate. Available resources are expressed in terms of actual bandwidth available.* For the model

presented in this paper to work, requirements and available resources must be expressed using the same unit of measure. While this conversion is technically possible, the number of variables associated with doing so make it a cumbersome process. Some of the variables, including the user equipment type, are not determined until the user submits a request to activate the requirement. This creates a challenge to using the model for modeling future situations using only SDB data. In order to implement the modeling concept, an efficient means of conversion must be developed.

Structure of Paper

This paper is organized in a “standard” research paper format with five chapters. Chapter 2 provides a review of relevant literature and information to provide a foundation for the research and model, as well as framing for the remainder of the paper. Chapter 3 provides a description of the process and methodology used to arrive at the solution presented. It includes a basic primer on linear programming as well as the specifics on how the final model was created. Chapter 4 presents an analysis of the results of the model concept. Because actual data from the SATCOM database is classified, it was not used. Instead, representative unclassified data was used to develop the model. Chapter 5 provides a conclusion to this study, including recommendations for implementation and areas for further research.

II. Review of Relevant Literature and Research

Definitions

Allocation – The operational real-time assignment of SATCOM communications payload resources to an approved user for use in activating a communications link or network (CJCSI 6250.01B, 2004).

Apportionment – Formal assignment of a portion of a SATCOM systems communications payload for the exclusive use of a UCC or national user, subject to reapportionment by USSTRATCOM in response to emergent requirements (CJCSI 6250.01B, 2004).

Bandwidth – A measure of frequency range, measured in hertz (Wikipedia, 10 May 2006).

Data Rate - The amount of digital data that is moved from one place to another in a given time, usually in a second's time. The data transfer rate can be viewed as the speed of travel of a given amount of data from one place to another. In general, the greater the bandwidth of a given path, the higher the data transfer rate (SearchEnterpriseVoice.com, 2005).

Defense Information Systems Agency (DISA) – Serves as the focal point for SATCOM systems architectural engineering for the Department of Defense and is responsible for maintaining the SDB. (CJCSI 6250.01B, 2004)

Defense Satellite Communication System (DSCS) – Primary satellite used by the DoD for SHF communications. Characterized by high data rate capability and relative protection against interception and jamming (Muolo, et al., 1993).

Electromagnetic Spectrum (also *Frequency Spectrum* or *Spectrum*) - The range of electromagnetic radiation that is emitted, reflected, or transmitted (Wikipedia, 2006a).

Extremely-High Frequency (EHF) – The portion of the electromagnetic frequency spectrum between 30 GHz and 300 GHz (Wikipedia, 2006a). The primary military uplink frequency in the EHF range is in the area of 44GHz (MILSTAR Fact Sheet, 2005).

Field of View (FOV) – The portion of the earth that is within the line of sight of the satellite. The FOV of a geosynchronous satellite is approximately one-third of the earth's surface.

Geosynchronous – An orbital path with a period of 24 hours, which allows a satellite to remain above the same point on the earth as the earth rotates about its axis (Wikipedia, 2006b).

MILSTAR – Primary satellite used by the DoD for EHF SATCOM. MILSTAR is a joint service satellite communications system that provides secure, jam resistant, worldwide communications to meet essential wartime requirements for high priority military users. The multi-satellite constellation links command authorities with a wide variety of resources, including ships, submarines, aircraft and ground stations. The operational MILSTAR satellite constellation consists of five satellites positioned around the Earth in geosynchronous orbits. (MILSTAR Fact Sheet, 2005)

Multi-Band SATCOM Terminal (MST) – A satellite terminal capable of transmitting and receiving in multiple frequency spectra, such as UHF, SHF and EHF.

SATCOM Database (SDB) – A comprehensive database containing current and future military SATCOM requirements. Unified Combatant Commanders, DoD Services

and other US Government Agencies desiring use of military SATCOM must reflect their requirements for military owned satellite services as well as all commercial, allied and civil satellite services (CJCSI 6250.01B, 2004).

Satellite Communications (SATCOM) - Electronic communication using a communication satellite to relay the signal from a transmitting user to one or multiple receiving users (National Communications System Technology and Standards Division, 1996). Information transmitted may include voice, imagery, video and machine-to-machine communications.

Super-High Frequency (SHF) – The portion of the electromagnetic frequency spectrum between 3 GHz and 30 GHz. Military SHF SATCOM typically ranges from 7.9 GHz to 8.4 GHz. (FM 24-24, 1994)

Ultra-High Frequency (UHF) – The portion of the electromagnetic frequency spectrum between 300 MHz and 3 GHz (Wikipedia, 10 May 2006).

Unified Combatant Command (UCC) – A command with a broad continuing mission under a single commander and composed of significant assigned components of two or more military departments that is established and so designated by the President, through the Secretary of Defense with the advice and assistance of the Chairman of the Joint Chiefs of Staff (JP1-02, 2006).

UFO / FLTSAT - Primary satellite constellation used by the DoD for UHF SATCOM. UFO / FLTSAT is operated by the Navy to provide narrow band, mobile communications for military and civilian leadership communications (Boeing, n.d.).

How SATCOM Works

In their simplest forms, radio waves are electronic emissions that travel in a straight line. The challenge of using radio waves for global communications is bending those straight paths of travel around the curvature of the earth. While some radio frequencies can be “bounced” off layers of the atmosphere, those frequencies have other traits that make them less than desirable for high capacity, global communications. A solution to bending the signal around the world is to “bounce” it off some object that can reflect it around the curvature of the earth. Satellites provide such an object (Figure 3).

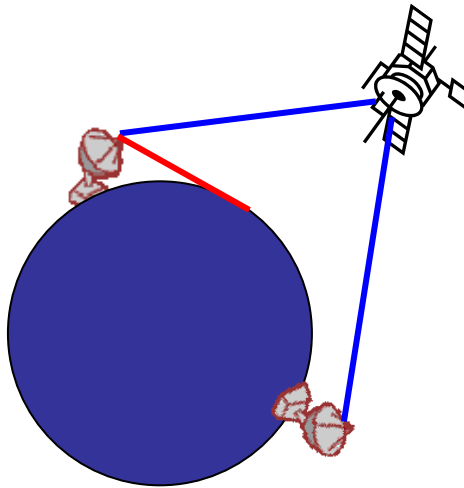


Figure 3. How SATCOM Works

The critical element of using a satellite for communications is the Field of View (FOV) of the satellite, which refers to the portion of the earth that is within the line of sight of the satellite. In order to use the satellite directly, the user must be within the satellite's FOV.

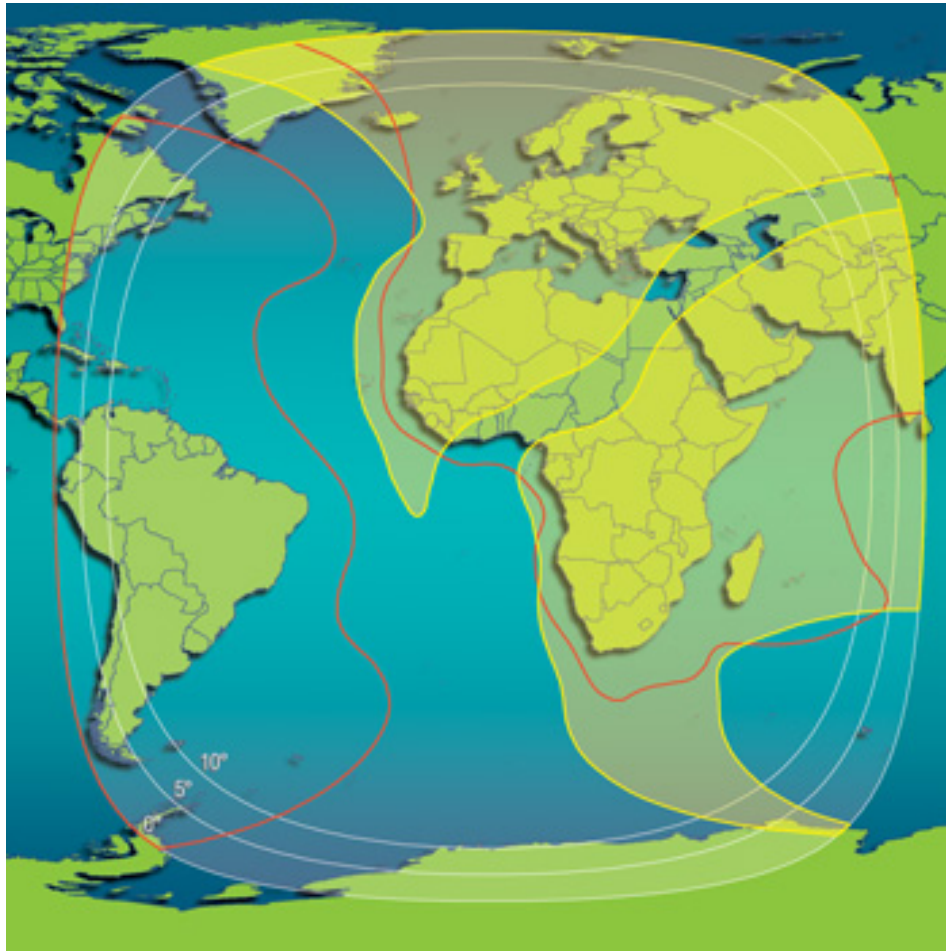


Figure 4. Geostationary Satellite Field of View (Intelsat, n.d.)

As general rule, communications satellites are in geostationary orbits, meaning they remain above the same point on the earth, ensuring the FOV continuously covers the same geographic region. While there are some SATCOM systems that use other orbits, they will not be discussed in this paper.

The FOV for a geostationary satellite is approximately 1/3 of the earth, as depicted the “0” ring in Figure 4. In general, any user within the FOV can communicate

with any other user in the same FOV by bouncing a signal off the satellite. If communications beyond the FOV is required, the signal must be relayed from one satellite to another. This can be accomplished either by downlinking the signal to an intermediate relay station which would then send the signal up to a second satellite to be received, or by relaying the signal directly from one satellite to another using a technique called “cross linking.” Cross linking technology is still relatively new and few satellites currently have this capability (Boeing, n.d.)

Early communication satellites were little more than electronic relays for signals. They received the signal from a user and simply retransmitted that signal back down to earth where another user could receive it. Today, technology has become far more sophisticated and satellites are able to serve as an electronic switchboard with the ability to direct communications to specific users and specific regions of the FOV. Uplink and downlink beams can be electronically shaped and steered and access to the satellite can be limited to authorized users (Wikipedia, 2006b).

SATCOM Transmissions

The ultimate goal of SATCOM is to allow the users to transmit information to one or many other users. The data rate for a transmission is the speed at which information can be passed and is often expressed in kilobits per second (kbps). Figure 5 depicts a general categorization of data rates.

Data Rates

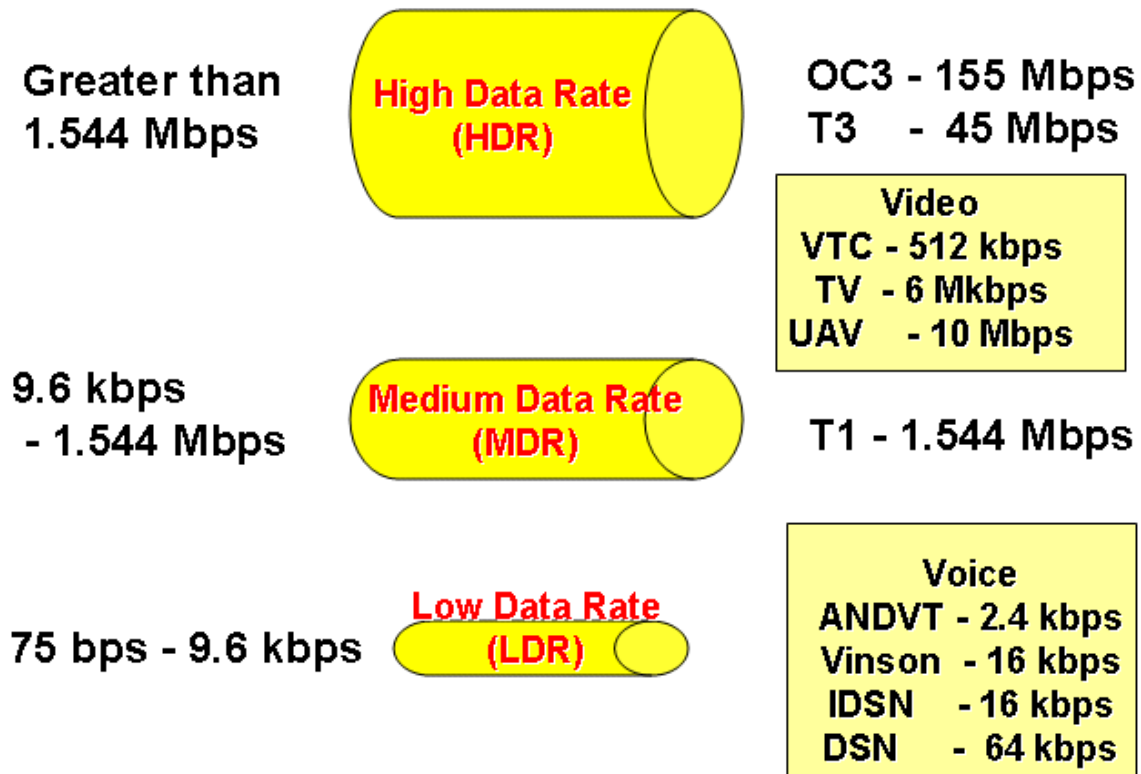


Figure 5. Data Rates (Global Security Bandwidth, n.d.)

Numerous factors impact the effective data rate of a transmission stream; three of the primary factors are frequency, bandwidth and modulation scheme. If a transmission is thought of as a water pipe, data rate can be thought of as the total volume of water that passes through the pipe in a given amount of time. The two ways to increase that volume are to move the water faster and use a bigger pipe (Gallagher, 1996).

Just as with terrestrial radio transmissions, SATCOM radio transmissions are electronically deconflicted to prevent users from interfering with each other's signals.

Much like a common FM radio where different radio stations are assigned different frequencies, SATCOM users are assigned a specific frequency and bandwidth to use for communication.

Frequency refers to the number of cycles per second at which a radio wave is oscillating (National Communications System Technology and Standards Division, 1996). A radio receiver can be tuned to receive a specific frequency and filter out all others. By separating the frequencies assigned to different users, we can prevent different users' signals from interfering with each other. Frequencies are assigned based on a center frequency from which the user may deviate a specified amount up and down. For example, an FM radio station may be assigned the frequency of 91.5 Megahertz (MHz) as a center frequency but may then vary its range ± 0.10 MHz, from 91.4 to 91.6 MHz.

Bandwidth refers to the range of frequency assigned to a specific user. In our example above, the FM radio station was assigned .20 MHz of bandwidth. Bandwidth can be thought of as the diameter of our water pipe. Just as a larger diameter pipe can carry more water, a larger bandwidth can carry more information.

In addition to increasing the diameter of our pipe, we can also increase our total water flow by increasing the speed at which it travels through the pipe. The modulation scheme does not lend itself as neatly to the water pipe example, but the impact of a more advanced modulation scheme is "water" can move through the pipe at a quicker speed. The two most important factors in determining which modulation schemes can be used are frequency and user equipment type (Shields, 2006b).

As a general rule, higher frequency spectra allow transmission of information more quickly than lower frequency spectra because they allow more complex modulation schemes. The difference in data rate within a frequency spectrum is negligible, but the difference from one spectrum to another (e.g. between UHF and SHF) is appreciable. Important factors in user equipment type are the transmitters and receivers, as well as antenna size.

In order to avoid the intricacies related to operating in varying frequencies, communications requirements are often expressed in terms of required data rate. When fulfilling requirements, the required data rate is then converted to a frequency, a bandwidth and a modulation scheme that provide the required data rate.

Military SATCOM Frequency Ranges, Systems and Utility

By convention, the radio frequency (RF) spectrum is divided into general classifications based on the specific frequency range. Appendix 1 shows the division of the entire RF spectrum. The three frequency ranges currently used by military SATCOM are: UHF, SHF and EHF.

Each of the frequency ranges used has a unique set of advantages and disadvantages which are a direct result of the physical properties of the frequency. In order to efficiently and effectively use SATCOM, it is important to understand the inherent capabilities and limitations of each range and use them to our advantage.

UHF has the lowest frequency and the narrowest bandwidth. These two factors make use of UHF for high capacity communications impractical. Additionally, UHF is a very mature technology and it has been used for a long time. As a result, the UHF spectrum

is extremely crowded and there is little room for large bandwidth signals. Additionally, the characteristics of UHF do not lend it to complex modulation schemes.

While UHF is not useful for high capacity communications, its signal is not very directional. This non-directional nature means the transmitted signal will spread over nearly the entire FOV of the satellite and does not require the receiving antenna to point specifically at the satellite to receive the signal. Additionally, reception does not require a large satellite dish. These characteristics make UHF excellent for mobile users such as aircraft, ground troops and ships that can neither carry a large satellite dish, nor point accurately at the satellite (Boeing, n.d.)

Military UHF SATCOM is provided by a constellation of satellites UHF Follow-on / Fleet Satellite Communications System (UFO/FLTSAT). The UFO/FLTSAT system is operated by the US Navy and consists of 11 satellites spaced around the earth. The newest UFO satellites each provide a total of 555 kHz of bandwidth (Boeing, n.d.).

SHF is the next highest frequency range and is primarily used for high capacity, secure communications. The higher frequency of SHF and the greater available bandwidth make it extremely useful for long distance, high capacity communications. The greater available bandwidth allows users to “pad” their signal with encryption, which requires additional bandwidth, to make their communications secure from interception. The wide bandwidth also allows for techniques such as “frequency hopping” to make signals impervious to jamming.

Like UHF, SHF has limitations which restrict its use for some functions. One of the greatest limitations is SHF requires a large satellite dish antenna to make use of its

high capacity. Additionally, it requires fairly accurate antenna pointing. These two factors make use of SHF impractical for many mobile users.

The Defense Satellite Communications System (DSCS) is the primary military satellite operating in the SHF range. The Air Force currently operates 13 DSCS satellites spaced around the world (Goodman, 2004). Each satellite uses six super high frequency transponder channels capable of providing secure voice and high rate data communications. DSCS uplink frequencies range from 7.9 to 8.4 GHz, providing a total of .5 GHz of bandwidth per satellite (MILSATCOM Joint Program Office, n.d.). The greater bandwidth combined with the ability to use more complex modulation schemes gives DSCS far more capacity than that provided by UFO/FLTSAT.

EHF is the highest of the military SATCOM frequency ranges and is the most recent technology. The EHF bandwidth is approximately four times the width of the SHF bandwidth, which provides great utility and flexibility of use. The EHF spectrum combines many of the advantages UHF and SHF. It provides the secure, jam resistant communications often associated with DSCS with the mobility that UHF allows (MILSTAR Fact Sheet, 2005).

The MILSTAR satellite provides DoD EHF SATCOM capability and consists of five satellites positioned around the earth which provide worldwide communications to meet essential wartime requirements for high priority military users. MILSTAR uplink frequencies range from approximately 43 – 45 GHz (MILSTAR Fact Sheet, 2005). The combination of larger bandwidth, higher frequency and advanced technology give each MILSTAR satellite a total capacity of approximately 40 Mbps (Goodman, 2004).

Commercial SATCOM

While the military SATCOM systems are extremely capable, the bandwidth they provide is not sufficient to meet all of the DoD's SATCOM needs. In order to meet SATCOM requirements, the military relies on commercially available SATCOM to augment military systems.

Commercial SATCOM is readily available and provides a critical gap-filler for requirements DoD systems cannot fill, but there are some limitations. The greatest concern of using commercial SATCOM for military purposes is its security and susceptibility to jamming. As general rule, commercial systems are not designed to continue operating in a hostile environment where enemy forces may attempt to intercept or jam signals. Additionally, the United States must always be concerned with the willingness of commercial vendors to allow use of their systems for combat operations. As with any commercially procured service, cost is also an issue.

SATCOM Terminals

In order to communicate over SATCOM, the user uses a SATCOM terminal to transmit and receive data. Each frequency spectrum requires a specific type of terminal, including antenna, in order to be compatible. Additionally, some satellites require use of a terminal unique to that particular SATCOM system. In order to provide improved flexibility and reduce the amount of equipment required, multi-band SATCOM terminals (MSTs) have been developed. As the name implies, MSTs are terminals that are compatible with multiple frequency spectrums.

MSTs add some flexibility, but there are limitations. Due to the unique wave forms and significant differences in frequency, there are no MSTs that are compatible with MILSTAR. Currently, MSTs are available that operate in a combination of military UHF or SHF, plus common civilian SATCOM spectra. It is important to note that users may have multi-band capability through use of multiple SATCOM terminals, particularly non-mobile or ship-borne users who are not overly constrained by space or weight limitations.

CJCS Guidance

The Chairman of the Joint Chiefs of Staff (CJCS) has overall responsibility for management of DoD SATCOM assets. Day to day oversight and responsibility for ensuring effective and efficient use of the resources is delegated to the Commander, US Strategic Command (CDRUSSTRATCOM) (CJCSI 6250.01B, 2004).

CJCS Instructions (CJCSI) are high level directives published by the Chairman of the Joint Chiefs of Staff which provide direction for a broad spectrum of issues to the US military. CJCSI 6250.01B, "Satellite Communications," dated 28 May 04 establishes procedures for use of SATCOM. CJCSI 6250.01B covers a broad range of topics regarding SATCOM, including the procedures for dividing bandwidth among users to meet requirements. The three relevant issues are: priority, apportionment and allocation.

The Appendix to Enclosure D of CJCSI 6250.01B delineates SATCOM prioritization. There are seven general levels of priority, some of which are further subdivided into more discrete elements. The prioritization scheme follows a logical pattern of precedence where the functions of greatest importance to national security rank the

highest and those requirements with less bearing on national security rank lower. The entire listing can be found in Appendix 2 of this paper.

Apportionment refers to the distribution of a “block” of resources to a particular user for deliberate planning. In the case of SATCOM, blocks of bandwidth are apportioned to each of the UCCs based on guidance from the Secretary of Defense, as well as the current world situation. Apportionment is used for deliberate planning and may be changed based on a dynamic world situation (CJCSI 6250.01B, 2004).

Allocation refers to the real-time assignment of bandwidth to users for actual use. Where apportionment is done in blocks of bandwidth, allocation is concerned with assigning a combination of frequency and bandwidth to provide the required data rate. SATCOM is not allocated if a requirement is not validated and included in the SDB (CJCSI 6250.01B, 2004).

All military SATCOM requirements and non-military requirements for use of military SATCOM are maintained in the SATCOM Database (SDB). The SDB contains specific information for each requirement and is used to allocate SATCOM. Before a requirement is entered into the SDB, it must be validated. The SDB is maintained for the JCS by DISA (CJCSI 6250.01B, 2004).

USSTRATCOM is appointed as the SATCOM Operational Manager (SOM). As the SOM, USSTRATCOM is responsible for day-to-day management of SATCOM, including resource allocation. USSTRATCOM operates three Regional SATCOM Support Centers (RSSCs) and one Global SATCOM Support Center (GSSC). The SSCs are responsible for conducting planning and implementing the allocation process in

accordance with USSTRATCOM and JCS directives (CJCSI 6250.01B, 2004). The SSCs do not serve as decision authorities; they are only responsible for implementing standing guidance.

The SSCs are operated by the 614th Space Communications Squadron, which falls under USSTRATCOM. As the name implies, the RSSCs are responsible for supporting regional combatant commanders. The GSSC supports the UCCs whose mission is global in nature and not limited to one particular region of the world (Shields, 2006a).

Current Process

The SDB contains over 3,200 requirements (Lupone, 23 January 2006). At any given time, many of the requirements in the SDB are inactive. An inactive requirement is a requirement that has been validated but that the user does not currently require use of, so no resources are allocated to it.

When a customer needs to activate a link, they send a request to the SSC. The request includes the SDB requirement number, terminal type, location desired, spectrum requested and data rate required. When the SSC receives the request, it is given to the section within the SSC that is responsible for the requested spectrum. The spectrum manager ensures the requirement is a validated SDB requirement. They then determine whether or not the requesting UCC has any apportioned bandwidth available to fulfill the request. If bandwidth is available, the requirement is filled. If bandwidth is not available, the manager may try to “borrow” bandwidth from another UCC. If that is not successful, the manager uses priorities to determine which requirements should be filled. If the new requirement has sufficient priority, it will receive the required bandwidth and

the lowest priority currently on the satellite will lose its assigned bandwidth (Shields, 2006a).

Under the current process for SATCOM allocation, there is no consideration given to fulfilling a requirement in a different frequency spectrum than requested. In many cases, using a different spectrum is not feasible due to limitations imposed by user equipment. Even in cases where an alternate spectrum may be feasible (e.g. with MSTs), the option is not considered. Additionally, during the process of “bumping” a lower priority user off the satellite to fulfill a new, higher priority request, there is no consideration given to moving some other user who can operate in a different spectrum off of the filled satellite to another spectrum to avoid completely usurping a currently filled requirement (Shields, 2006a).

Existing Solutions

A comprehensive literature review of the World Wide Web and library resources found no unclassified research conducted on the current allocation process. During an interview conducted with Dr. Paul Chappell, a contractor supporting CJCS/J6, he stated his company has conducted reviews on a case-by-case basis to look for more efficient ways to satisfy requirements by switching users between spectra, but those efforts were conducted using a “brute force” method and no models were ever developed (Chapell, 2006).

III. Research Methodology and Model Design

Optimizing allocation of SATCOM bandwidth presents a classic case of maximizing use of limited resources. Optimization of limited resources is a common problem analyzed by the Operations Research community and mathematical programming, particularly linear programming, is a standard means of developing a solution model.

Linear Programming

Linear programming provides an excellent method to model frequency spectrum assignment by using a series of mathematical equations to solve for the most efficient assignment of spectra. Linear programming is appropriate for this model because the problem can be broken into specific elements that must be satisfied. Additionally, the problem is based on definite factors; not probabilities.

In order to create an effective linear model, an overall goal or objective must be developed. An example of a goal would be to maximize the number of user requests satisfied. The goal is expressed as an “objective function,” which the linear program seeks to maximize or minimize.

Once the goal is established, a set of decision variables that capture the capabilities, limitations and needs of the users and available resources must be developed. The decision variables are then be used to quantify the characteristics of each requirement. An example of a decision variable is data rate required. A user with an EHF only terminal may require 5 kbps on an EHF satellite. A second user with an MST may require either 5 kbps on an SHF satellite *or* a commercial satellite.

After decision variables are developed, constraints as related to the decision variables must be identified. A simple example of this would be available bandwidth. While the demand for data rate and bandwidth may be unlimited, the availability of resources is strictly limited to the systems available.

Because requirements must be filled completely (i.e. cannot allocate only 80% of the required data rate), a specific linear programming technique called “integer programming” must be used. Every requirement has a variable assigned to it denoting its “fill” status. If the model fills the requirement, the value assigned to the variable is 1 and the objective function receives credit for filling that function. If the requirement is not filled, the variable receives a value of 0 and the objective function does not receive any credit for filling the requirement.

The decision variables and constraints can be combined to form a series of mathematical equations that collectively represent every constraint and requirement, as well as the overall goal. Linear programming software is available as part of Microsoft® Excel as well as numerous other commercial off the shelf programs. Using linear programming software, one can easily solve all equations within the set constraints to identify the solution that achieves the overall goal: maximizing the number of user requests satisfied.

While the mathematical nature of linear programming tends to present a fairly clear-cut solution, the decision maker may have additional considerations not captured in the model. In addition to providing a mathematical solution, linear programming allows for sensitivity analysis to determine how each decision variable and constraint within the

model is affecting the solution. For example, the sensitivity analysis may reveal that a small number of MSTs available within a particular user group is a limiting factor in bandwidth allocation. This analysis could be used to support procuring more MSTs.

Data collection

The greatest challenge of data collection for the actual model is identifying those requirements which might be filled in a spectrum other than what is requested. CJCS/J6 conducted this type of review to determine where commercial SATCOM would be a viable alternative, but no such study has been conducted to evaluate possible alternatives within the military SATCOM spectra.

The second challenge for data collection is expressing requirements in terms of a common unit of measure. The SDB expresses requirements in terms of data rate (bps), but allocation is conducted in terms of bandwidth. Currently, the SSC translates the data rate requirements into bandwidth during the allocation process. For the proposed model, the available resources (i.e. bandwidth) must be expressed using the same units of measure as the requirements to allow mathematical expression of the constraint on available resources.

The overall objective function of maximizing the number of requirements satisfied was provided by CJCS/J6. Relevant factors and constraints in the model were developed in a joint effort between the author, CJCS/J6 and contractors supporting J6.

Model Development

The first step in developing the model was to clearly express an objective function to reflect the goal of satisfying the maximum number of users possible. The objective equation is:

$$T = P_1X_{11} + P_1X_{12} + P_1X_{13} + P_1X_{14} + \dots + P_nX_{n1} + P_nX_{n2} + P_nX_{n3} + P_nX_{n4}$$

The objective is to maximize the value of T by changing the values of X_{nm} while observing defined constraints. It is important to note that T represents a relative score that is the sum of the weights of the filled requirements; it is not the number of requirements filled.

X_{nm} is a “use flag” variable that indicates whether or not the requirement is filled. If the requirement is filled, X_{nm} takes on a value of 1. If it is not filled, the value is 0. The subscript n is simply the requirement number. The subscript m takes on the value of 1, 2, 3 or 4 and indicates the frequency spectrum for the particular requirement. A value of 1 indicates UHF; 2 indicates SHF; 3 indicates EHF; and 4 indicates commercial SATCOM.

In order to simplify model building and record keeping, every requirement will have a UHF, SHF, EHF *and* commercial component in the value function. To preclude assigning a spectrum which will not fulfill the requirement, the possible value of the use flag X_{nm} is limited to zero for cases where requirement n cannot be filled in spectrum m .

P_n denotes the priority score for the particular requirement. As discussed earlier, requirements for higher priority requests must be accommodated before bandwidth can

be assigned to any lower priority users. In order to mathematically force the model to follow the priority scheme, the coefficients for each requirement are weighted in the objective equation.

The model is predicated on assumption of sufficient capacity to fill all priority 1 and priority 2 requirements at a minimum, so a constraint was constructed to automatically fill those requirements *a priori*. Beginning with priority 3, each level of priority is assigned a weighting score to be used by the objective function. Because the objective is to attain the highest possible score for T , the model fills the highest priority requirements first. Each priority weight is less than the preceding priority by a factor of ten, which mathematically precludes filling multiple lower priority requirements in favor of a single higher priority requirement. In the event a single requirement is so large that more than nine requirements in the next lower priority could be filled using the same resources required to fill the single higher priority requirement, the model will generate an incorrect solution. A full listing of priority descriptions and coefficient scores is found in Appendix 2.

With the objective function fully developed, constraints are then constructed to reflect the limitations and requirements of the system. Constraints include available bandwidth, observing priorities and other functions to ensure the model properly fills requirements.

The most fundamental constraint is available resources. For military SATCOM, the resource is available bandwidth and is broken into three spectra: UHF, SHF and EHF.

Each spectrum requires a single equation to represent the available bandwidth and the bandwidth used. It is expressed as:

$$U_1X_{11} + U_2X_{21} + U_3X_{31} + U_4X_{41} + \dots + U_nX_{n1} \leq U_{Avail}$$

In this example, the U_n represents the amount of bandwidth each requirement would require in the UHF spectrum. X_{n1} continues to indicate whether or not the particular requirement is filled, just as in the objective function. In cases where a requirement cannot be filled by UHF, the value of the “use flag” X_{n1} is limited to 0 in the solution. By adding the required bandwidth of each requirement filled in the UHF spectrum and constraining the sum to be “less than or equal to” the total available bandwidth, the model is prevented from assigning more resources than are available. In cases where the requirement is not fulfilled by assigning UHF bandwidth, the value of that X_{n1} is set to 0, and the bandwidth requirement is not counted against the running total of resource capacity available. Similar equations are created for SHF and EHF.

Assignment of commercial SATCOM is modeled in the same way as MILSATCOM but because funds to purchase commercial SATCOM are limited, assignment of commercial SATCOM is constrained by cost. Similar to the process for the data rate constraints, a cost is assigned to each possible use of commercial SATCOM. If the model fills the requirement using commercial SATCOM, the cost for that requirement is added to a running total cost. The running total cost is constrained to not exceed a specified budget and any possible solution that would exceed the budget is rejected by the model.

In determining whether a requirement can be filled in a particular spectrum, factors beyond physical capability must be considered. For example, even if a user has an MST that is capable of using commercial SATCOM, the user may also require anti-jam capability not offered by commercial SATCOM. In such a case, that requirements use flag for commercial SATCOM is limited to 0, indicating that commercial SATCOM cannot be used to fulfill the requirement.

A second type of constraint was created to prevent the model from filling a single requirement in more than one spectrum. This is accomplished by the equations:

$$X_{n1} + X_{n2} + X_{n3} + X_{n4} = 1 \text{ (Priority 1 \& 2)}$$

or

$$X_{n1} + X_{n2} + X_{n3} + X_{n4} \leq 1 \text{ (Priority 3 and lower)}$$

By limiting the sum of the four portions of the requirement (UHF, SHF, EHF and Commercial) to 1, only one “use flag” for each requirement can take on a value of 1, thereby limiting the model to filling only one of the four spectrum requirements.

Recalling the assumption of sufficient bandwidth to fill all priority 1 and 2 requirements, the model is forced to fill those requirements *a priori* by setting the constraint equal to 1 (i.e., forces the model to set one of the “use flags” equal to 1).

For all priority 3 and lower requirements, the expression is forced to be “less than or equal to” 1, allowing the latitude to leave some requirements unfilled. Unlike priorities 1 and 2, resources may be exhausted before all requirements are filled at some level of priority. The absolute requirement to equal 1, as described in the previous

paragraph, forces the model to fill *all* requirements within the priority level, which would prevent the model from reaching a solution.

Based on the assumptions specified above, no other constraints are required for the model. The relative “straight-forward” nature of linear programming makes adding complexity, such as specifying particular regions, a fairly simple prospect if required.

IV. Results

Final Model

As described in the previous chapter, the model presented in this paper does not provide an actual solution to or analysis of a particular Combatant Commander's bandwidth allocation. Instead, the model presents a framework that can be populated with scenario specific data and constraints to provide real world analysis. An example of a model is presented in Appendix 3 and Appendix 4.

As shown in Appendix 3, the example was limited to 12 requirements with varying priorities and data rate requirements. The CJCSI 6250.01B priority is listed in the table for each requirement and the corresponding weight from Appendix 2 is included. The columns marked UHF, SHF, EHF and Commercial indicate the feasibility of filling the requirement within the indicated spectrum and the capacity requirement. For simplicity, the example model used required data rate in terms of kbps for all requirements. The numbers in the example are purely notional.

The example input data was entered into a linear equation that was created using commercially available linear programming software. The objective was to maximize the number of requirements satisfied while observing priorities. The output is shown in Appendix 4. While the output data may appear to be somewhat esoteric, the following paragraphs will clarify it.

Under "Variables," the "Req't (#/Spectrum)" row identifies the requirement number and spectrum, similar to the convention described for the "use flag" in the previous chapter but with the X_{nm} omitted. The number to the left of the slash reflects

the requirement number n and the number to the right of the slash indicates the spectrum m . The actual value of X_{nm} in the optimized objective solution is indicated in the row labeled “Use Flag” immediately below “Req’t.”

The two rows immediately below the value reflect the upper and lower limits on the value of X . Because the model uses a binary system, the value must always be either 1 or 0. In cases where it is feasible to fill a requirement in a particular spectrum, the upper bound of the value is 1. In cases where it is not feasible to fill a requirement in a particular spectrum, the upper bound is set at 0, thereby precluding the model from filling the requirement in that spectrum. For example, requirement 1/1, 1/2 and 1/4 have an upper bound of 0, which means requirement 1 cannot be filled in the UHF, SHF or commercial spectra. The upper bound for 1/3 allows the model to fill requirement 1 in the EHF spectrum.

The section labeled “Constraints” provides the limitations on the solutions. The first four constraints, named “UHF,” “SHF,” “EHF” and “Com,” reflect resource limitations. The column labeled “Limit” indicates the total data capacity available. In the example, the total UHF capacity is limited to 200 kbps and cost of commercial SATCOM was limited to 3,500. For the sake of simplicity, the example used data rate capacity for the first three constraints and cost for the Commercial spectrum. As discussed earlier, the unit of measure used for the actual model may vary from constraint to constraint, but must remain constant within a particular constraint. The “Actual” column indicates the actual amount of the resource used in the computed solution. In this example, the optimal solution used 192 kbps of the UHF capacity. The data rate

throughput for each requirement is identified on the respective spectrum's constraint row under the requirement. For example, reading across the EHF constraint line, the reader finds 512 listed under Req't 1/3. This indicates requirement 1 requires 512 kbps throughput in the EHF spectrum.

The constraints governing how the model fills requirements are listed below the resource constraints. Requirement 1 has priority 2A, which is a "must fill" so the model forces the sum of the fill flags for this requirement to equal 1. For requirements with priority lower than 2, the model may not fill them so the constraint is set as "less than or equal to" 1. The value listed in the "Actual" column indicates whether or not a requirement was filled as part of the optimal solution. In this example, requirements 3 and 11 were not filled, as indicated by the 0 in the "Actual" column. The particular spectrum used to fill each requirement is reflected in the "Use Flag" row in the "Variables" section.

While the utility of computing the optimal solution is obvious, the model is also useful to determine which constraints are "binding" or limiting the ability to fulfill more requirements. In the example, the two requirements which went unfilled both required UHF. The optimal solution used 192 kbps of the available 200 kbps in the UHF spectrum. Additionally, the actual value of SHF capacity used was nearly all of the 2200 kbps available in that spectrum, so SHF would not have provided a useful alternative even if it had been a feasible alternative. EHF and commercial, however, have "slack," meaning there is a significant amount of those resources still available for use. The model shows if it had been feasible to fill more requirements in either EHF or

commercial, it may have been possible to fill requirements 3 and 11. Using this type of information, an organization may identify areas where funds could best be spent to increase the number of requirements that can be filled.

Validation and Verification

Validity of the model was established by constructing the model objective and constraints in accordance with direction from CJCS/J6. A formal validation must be performed on the full scale model by a competent validation authority before the model is implemented.

In addition to the formal validation process, users must ensure the data input into the model is accurate. If the input data is not accurate, the solution presented by the model will likely be inaccurate and may not present the optimal solution. This includes, but is not limited to, the actual cost and budget for commercial SATCOM.

Linear programming is a well established and recognized technique for efficiently allocating resources. Its mathematical, and therefore, objective nature provides a solid foundation for verification of the model. An initial verification was conducted by running the model on a limited number of requirements to ensure it filled the requirements in order of priority and maximized the number requirements satisfied while not exceeding available data rate capacity. A formal verification must be performed on the full scale model by a competent verification authority before the model is implemented.

During the verification, the conditions described in the assumptions section regarding weighting factors must specifically be verified. This would be accomplished

by reviewing all requirements in the SDB to ensure no single requirement requires more resources than any nine requirements in the next lower priority grouping.

V. Conclusion

Areas for additional study

By far, the most important area for further study is a technique to transform the units of requirements (kbps) and units of resources into the same measure. From a modeling perspective, the specific unit used is unimportant, as long as the unit is the same for requirements and resources. Because the resource constraint for each spectrum is independent of the others, the unit used can vary from spectrum to spectrum. For example, just as the commercial SATCOM constraint uses a different unit (cost), MILSTAR requirements can be expressed in kbps while DSCS requirements are expressed in bandwidth. According to Dr. Paul Chapell of SAIC, it is technically possible to perform this transformation, but it is not routinely performed for all requirements (Chapell, 2006).

In addition to the technical areas for additional study, a concept for model use must also be developed. This concept must define appropriate uses for the model, as well as data input sources and limitations. Initial discussions with subject matter experts indicate the most likely application is long range planning and programming and future analysis in conjunction with DISA's currently on-going "Mix of Media" study (Chapell 2006; Folks, 2006).

Once the above challenges are resolved, the model must be packaged in a useable form for the intended users. While linear modeling is a basic technique for those schooled in operations research, it does not lend itself to ease of use for the average user. Additionally, the large number of requirements create more than four times that number

of equations on a spreadsheet. Inputting and managing these numbers would be tedious and fraught with errors, even for those trained in linear programming. Therefore, any fielded version of this model should have a graphical user interface that facilitates ease of use for the average planner. Like any other model used for real world decision making, the final model must be fully validated and verified to ensure accuracy of solution.

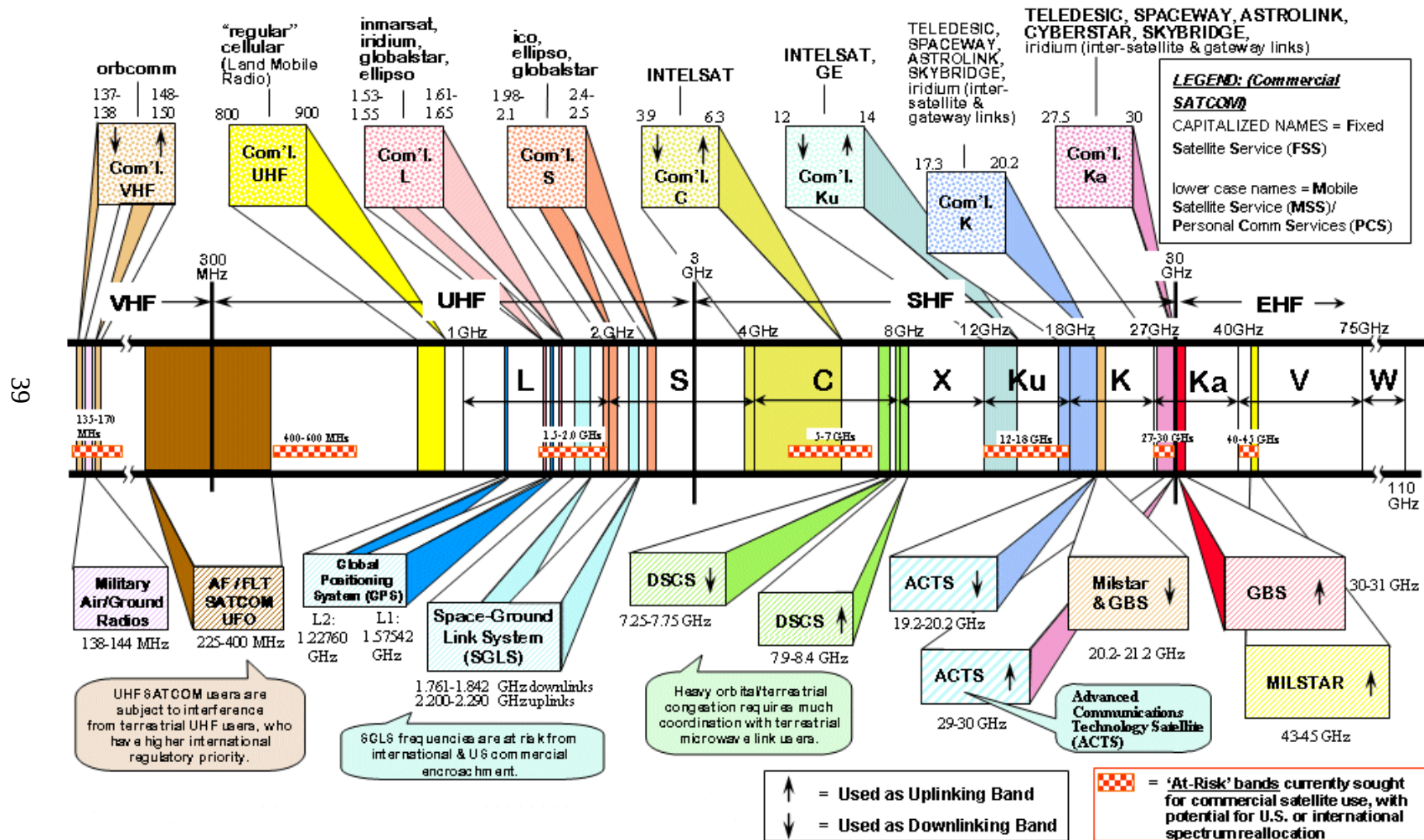
When fielded, it is imperative the users of the model fully understand the limitations and proper use of the model. The adage “all models are wrong; some are useful” applies to the model proposed in this paper. The model does not present an absolute solution to the problem, as there will likely be intangible and subjective factors that must be considered. Instead, the model should serve as a guide or starting point for decision making. Analysis of binding constraints can also be useful in identifying those factors which limit satisfaction of requirements.

Summary

SATCOM has become an integral piece of our military operations and is clearly an enabler for our global capabilities today and tomorrow. Our reliance on SATCOM continues to grow, but the available bandwidth is not keeping pace. Just as with any other valuable resource, limited availability of SATCOM bandwidth demands more efficient and effective use.

The concept presented in this paper provides a framework for creating a model to analyze utilization of bandwidth to optimize assignment. The flexible, scaleable nature of the framework allows model development for a wide variety of scenarios, ranging from extremely complex to simplistic and of any size.

Appendix 1– SATCOM Bandwidth (Global Security, n.d.)



Appendix 2 – Priority Criteria and Weighting Scores

	Score	Priority	User Category
		1	Strategic Order (essential to national survival)
1	*	1A	System Control/Orderwire
		1B	Executive Support
2	*	1B1	Presidential Support
3	*	1B2	Secretary of Defense Support
4	*	1B3	Secretary of State/Envoy and Emissary Support/Diplomatic Negotiations
5	*	1C	Strategic and Threat Warning/Intelligence
6	*	1D	National and Strategic Nuclear Force Direction Requirements
		2	Warfighting Requirements
7	*	2A	CJCS Support - Relates exclusively to the support provided to the Chairman and Vice Chairman of the Joint Chiefs of Staff in the execution of their duties and senior military advisors to the Secretary of Defense
8	*	2B	Unified Combatant Commander Operations - Relates exclusively to the efforts required of the UCC in peace and war to facilitate the execution of their functional or geographic mission. Includes combat service support.
9	*	2C	Joint Task Force (JTF) or Combined Task Force 9CTF) Operations - Tactical military operations associated with a particular joint or combined task force.
10	*	2D	Component Operations (Theater Forces) - Tactical military operations not associated with a task force
11	*	2E	Tactical Warning and Intelligence - Relates to the sensors, personnel and associated support that collect and disseminate time-sensitive intelligence to US combatants
12	*	2F	Homeland Security Operations - Related to non-DOD HLS support (as designated by USNORTHCOM) to prevent aggression against the United States and its territories.
13	*	2G	CJCS Sponsored select Exercises - Relates to a limited number of CJCS sponsored strategic C2 exercises.
14	*	2H	Counter-narcotics Operations

	Score	Priority	User Category
		3	Essential Non-warfighting Operational Support
15	10^(10)	3A	Humanitarian Support / Military Assistance to Civil Authorities Response to peacetime crises and disasters in continental United States and overseas
16	10^(9)	3B	Intelligence and Weather - For gathering information on strategic threats to the United States or for all combatant commands' AORs. Also supports weather collection efforts.
17	10^(8)	3C	Logistics - Supports the routine transit and processing of DOD materiel.
18	10^(7)	3D	Diplomatic Post Support - Relates to the protection of US diplomatic facilities and personnel overseas.
19	10^(6)	3E	Space Vehicle Support - Relates to launch and recovery support to space vehicles.
20	10^(5)	3F	Other operations Support - Combatant command and Service-specific and essential peacetime operations.
		4	Training
21	10^(4)	4A	Joint Forces Training (Multiple Categories) - Forces engaged in sanctioned joint training
22	10^(3)	4B	Combatant Command Sponsored /Pre-deployment Training - Specific training tasks associated with supported and supporting commands; imminent follow on deployment or operations in support of homeland security / defense.
23	10^(2)	4C	Major Command - Air Force, Major Command - Army, Echelon 2 Sponsored Training performed in the name of a Service's major command
24	10^(1)	4D	Unit Sponsored - Unit level training
		5	VIP Support
25	1	5A	Service Secretaries
26	10^(-1)	5B	Service Chiefs
27	10^(-2)	5C	Combatant Commander Travel
28	10^(-3)	5D	Other Travel

	Score	Priority	User Category
		6	RDT&E and General
29	10 ⁽⁻⁴⁾	6A	DOD-Sponsored Testing
30	10 ⁽⁻⁵⁾	6B	DOD-Sponsored Demonstrations
31	10 ⁽⁻⁶⁾	6C	DOD Administrative Support
32	10 ⁽⁻⁷⁾	6D	DOD Quality of Life Initiatives
		7	Miscellaneous
33	10 ⁽⁻⁸⁾	7A	Other Non-DOD Support
34	10 ⁽⁻⁹⁾	7B	Non-US Support as approved by the authorized organization
35	10 ⁽⁻¹⁰⁾	7C	Other

* Indicates no scored required because the model will be mathematically forced to the categories based on assumption of sufficient capacity to meet all of these priorities, at a minimum.

Appendix 3 – Sample Model Input Data

Requirement	Priority		UHF		SHF		EHF		Comm		
	Raw	Score	Feasible	Resources	Feasible	Resources	Feasible	Resources	Feasible	Resources	Cost
1	2A	*					1	512			
2	6B	1.00E-05			1	1544			1	1544	750
3	7A	1.00E-08			1	64			1	64	250
4	4D	1.00E+01	1	10000					1	10000	1000
5	4D	1.00E+01			1	512					
6	3F	1.00E+05			1	128			1	128	300
7	4A	1.00E+04	1	10000					1	10000	1000
8	5A	1.00E+00	1	512					1	512	500
9	3C	1.00E+08	1	64							
10	4B	1.00E+03	1	128							
11	7A	1.00E-08	1	512							
12	2E	*	1	128			1	128			
Total Required				21344		2248		640		22248	3800
Available				200		2400		1000			3500

* Indicates "must fill status"

Appendix 4 – Sample Model Output

Variables

Req't (#/Spectrum):

Use Flag:

Lower Bounds:

Upper Bounds:

Priority Score:

1/1	1/2	1/3	1/4	2/1	2/2	2/3	2/4	3/1	3/2
0	0	1	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	1	0	1	0	1

1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-08	1.0E-08
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Constraints

Num.	Name	Actual	Rel.	Limit
1	UHF	192	<=	200
2	SHF	2184	<=	2200
3	EHF	640	<=	10000
4	Com	2500	<=	3500
5	1	1	=	1
6	2	1	<=	1
7	3	0	<=	1
8	4	1	<=	1
9	5	1	<=	1
10	6	1	<=	1
11	7	1	<=	1
12	8	1	<=	1
13	9	1	<=	1
14	10	1	<=	1
15	11	0	<=	1
16	12	1	=	1

Linear Constraint Coefficients

[illegible]

3/3	3/4	4/1	4/2	4/3	4/4	5/1	5/2	5/3	5/4	6/1	6/2	6/3	6/4
0	0	0	0	0	1	0	1	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	1	0	0	1	0	1	0	0	0	1	0	1

1.0E-08	1.0E-08	1.0E+01	1.0E+01	1.0E+01	1.0E+01	1.0E+01	1.0E+01	1.0E+01	1.0E+01	1.0E+05	1.0E+05	1.0E+05	1.0E+05
---------	---------	---------	---------	---------	---------	---------	---------	---------	---------	---------	---------	---------	---------

0	0	10000	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	512	0	0	0	128	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	250	0	0	0	1000	0	0	0	0	0	0	0	300
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	1	1	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

7/1	7/2	7/3	7/4	8/1	8/2	8/3	8/4	9/1	9/2	9/3	9/4
0	0	0	1	0	0	0	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	0	0	1	1	0	0	0

1.0E+04	1.0E+04	1.0E+04	1.0E+04	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+08	1.0E+08	1.0E+08	1.0E+08
---------	---------	---------	---------	---------	---------	---------	---------	---------	---------	---------	---------

10000	0	0	0	512	0	0	0	64	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1000	0	0	0	500	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0

10/1	10/2	10/3	10/4	11/1	11/2	11/3	11/4	12/1	12/2	12/3	12/4
1	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	1	0	0	0	1	0	1	0

1.0E+03	1.0E+03	1.0E+03	1.0E+03	1.0E-08	1.0E-08	1.0E-08	1.0E-08	1.0E+00	1.0E+00	1.0E+00	1.0E+00
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128	0	0	0	512	0	0	0	128	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	128	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	1	1	1	1

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Vita

Major David Stone graduated from Auburn University, AL in 1991 and was awarded a Bachelor of Science in Criminal Justice. Upon graduation, Maj Stone was commissioned through the Air Force Reserve Officer Training Corps. Maj Stone's first assignment upon entering active duty was as a student at Undergraduate Space Training, where he became a space operations officer. Following Undergraduate Space Training, Maj Stone was assigned to the 4th Space Warning Squadron at Holloman AFB, NM. In 1996, Maj Stone attended Minuteman III ICBM qualification training and was assigned to the 90th Space Wing at Francis E. Warren AFB, WY. In 1999, Maj Stone became a student at the US Air Force Weapons School, Nellis AFB, NV. Immediately following graduation, he was assigned as an instructor at the Weapons School. In 2002, Maj Stone was assigned to HQ AFSPC, where he served as the Chief of Theater Integration, followed by assignment to the AFSPC Commander's Action Group. In 2005, Maj Stone entered the Graduate School of Engineering and Management, Air Force Institute of Technology, Wright-Patterson AFB, OH, where he is completing the Operational Analysis program. Upon graduation, Major Stone will attend the School of Advanced Air and Space Studies at Maxwell AFB, AL.

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