3-2005

Modeling and Simulation of Commercial Satellite Imagery Processes

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THESIS

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MODELING AND SIMULATION OF COMMERCIAL SATELLITE IMAGERY PROCESSES

THESIS

Presented to the Faculty

Department of Aeronautics and Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science (Space Systems)

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March 2005

AFIT/GSS/ENY/05-M04

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Abstract

The purpose of this research was to develop a general, statistical model of order-to-delivery times for commercial satellite imagery. The research looked at the current four satellites providers with 3-meter or better imagers in the context of a generalized model of commercial imaging satellite operations. Existing methods use orbit analysis tools to determine imaging time of a specified target based on defined satellite position and times but can only develop shortest and longest times to an imaging opportunity. To address the general question of the time to deliver an image for non-specific targets, this research develops a process model using Arena simulation software and random targets within large defined regions. Analysis of delivery times conducted on the output reveals dependencies on collective satellite coverage, prediction of weather over the target area, number of collection requests in the system and the computer and communications resources of the satellite operator.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor Dr. Rich Cobb for his advise and support during the preparation of this thesis, and Dr. John Miller without whose support with Arena this effort would not have been possible. Dr. Chris Colliver, the sponsor of this research, also deserves credit for his patience with me as I tried several iterations of technical approach to not-quite-what-he-was-asking before we found the common ground that I could work on and that he was interested in knowing.

I am also grateful to Mr. Pierre Izard of DigitalGlobe for lending his time helping me understand processes, develop reasonable inputs and assess the output of the model.

Most of all I am grateful to my wife, for so very much.

David A. Shultz

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MODELING AND SIMULATION OF THE COMMERCIAL SATELLITE IMAGERY PROCESSES

I. Introduction

Overview

Modern commercial satellite imaging has moved the satellite remote sensing industry into new areas of application such as insurance assessment, community planning, disaster relief and, most significantly for this research, intelligence. With four commercial entities with advertised resolutions better than 3 meters, governments or non-governmental actors can purchase images with resolutions equal to, or better than, the military reconnaissance satellites of world powers. But there are two determinants of intelligence value to the user: the first is the clarity of objects in the image, driven by the resolution offered by the satellite payload; the second is the timeliness of the image, driven by a number of considerations and explored in this research.

The four high resolution satellites are Quickbird 2, Ikonos 2, Orbview 3, and EROS A1. Quickbird 2, owned and operated by DigitalGlobe of Longmont, Colorado, is capable of 60 cm panchromatic imagery. (A note on resolution; throughout this paper, resolution is used in the sense of ground sample distance, or equivalently, meters per pixel.) The threat potential of imagery of this resolution is so significant that government licenses authorizing operations of Quickbird 2 specifically prohibit release of high-resolution images less than 24 hours after it is taken (Quickbird Product Release). While Ikonos 2 and Orbview 3 are both capable of 1-meter resolution, versus the 0.6-meters of Quickbird 2, they both operate under other conditions, such as shutter control, imposed by the U.S. (Licensing, 2005). However, EROS A1 and other imagers on-orbit or planned will not be operated by U.S. entities and so will not be subject to U.S. imposed limitations.

Future plans for the commercial operators include full-fledged constellations of two, three, or more imagers. The Indian Space Research Organization (ISRO) operated IRS satellite project includes several satellites with 1 to 5.8-meter capability (Appendix B) while the Israel based ImageSat International has similar plans for 8 satellites, all with 1-meter resolution (Bar-Lev, 2001). The France based SPOT Image satellites, with two operational satellites on orbit (the 4th and 5th of the series), plan to maintain that number while upgrading resolutions and are experimenting with geosynchronous relay satellites to further improve the uplink-image-downlink cycle times. While a typical sensor has a revisit interval of 3 to 5 days (including off-axis capability), each new satellite increases the opportunities to image a particular target quickly, and a constellation of three or more satellites almost assures access to any location within 24 hours in a typical low-earth-orbit remote sensing scenario with a mid-morning, sun-synchronous satellite flyover time.

Problem Statement

The National Air and Space Intelligence Center "assesses current and projected foreign aerospace capabilities and intentions… and evaluates evolving technologies of potential adversaries." (NASIC, 1996). Determining the timeliness of commercial imagery accessible by these "potential adversaries" is obviously a necessary part of assessing their capabilities. The question is also relevant to any friendly party wishing to assess a natural disaster, a man-made disaster, or any other urgent need for information.

The question this research set out to address is, "What is the shortest time, in general, it takes to receive an image of a general target?" The question, as addressed, concerns itself only with commercial, not military, imaging satellite systems, and assumes a visible light, panchromatic image with one of two resolution ranges. While the broadest interpretation of the question does not address satellite resolution or a particular image type (e.g. Visible panchromatic, infrared (IR), IR and visible multi-spectral, Synthetic Aperture Radar (SAR), etc.), I chose to narrow the scope of the research in order to limit the permutations possible with resolution and image type. Further justification is provided by the great preponderance of visible light sensors on commercial systems rather than SAR or infrared (other than near-IR on many multispectral capable sensors).

The specification of a "general" time to image a range of possible targets is extremely significant. The are a number of programs available (such as Analytical Graphics Inc.'s Satellite Tool Kit or the Aerospace Corporation's Satellite Orbit Analysis Program) that would allow the user to designate a start time, satellite, uplink station, target, and downlink station and determine how much time would pass between start time and downlink opportunity. However this method presupposes a particular satellite position at the start time and a specific target for the analysis. This is not an appropriate approach to the general time, general target, and general satellite problem.

A second question, on the tail of the primary question of time, asks what aspects in the request-to-delivery process are the most significant to the total process duration. The attempt is made to answer this both in term of total time involved and greatest contributors to variability in total time to delivery. As the results will demonstrate, even this simplification leads to different answers under various conditions and targets.

A more complete description of timeliness in the U.S. military intelligence process can be found in Pawling (2004), whose thesis defense I attended, and provided my introduction to the use of Rockwell's Arena environment as a means of addressing the processes I deal with in this research (see also Miller, 2004).

Objective

The objective of this research is twofold: First, to develop an Arena model of commercial satellite operations sufficient in detail to answer the questions of timeliness posed in the previous paragraphs; second, to make the model sufficiently flexible to allow future exploration of alternate variations on satellite or ground architectures for satellite imagers. In other words, to design a model that not only answers the questions originally asked, but also enables discovery of the next generations of questions and their solutions.

II. Literature Review

Process Descriptions

The processes of commercial satellite imaging operations are not usually discussed outside of the individual company channels for reasons of proprietary advantage (Erikson, 2004). While the company or satellite user guides discuss services offered, they offer only the broadest sense of internal process. Time, the figure of interest in this study, is addressed in company literature as a "promised-by" value for the purpose of setting prices with a steep premium for short turn requirements.

The exceptions are the two ACS Defense studies (Zesiger, 2000 & 2001) conducted for NASIC that were given to me at the beginning of my research. The reason for the company data included in those reports was the government purpose of the research and the limited distribution of the report. Nevertheless, without revealing the details of any particular company, Zesiger developed a generalized process that the companies use to take in requirements and eventually return the customers' images. The actual progression of actions and the labels of the intermediate stages may go by different names for any given company and the steps may be combined or broken out more than in the model, but it serves as a useful framework on which to build (Figure 1).

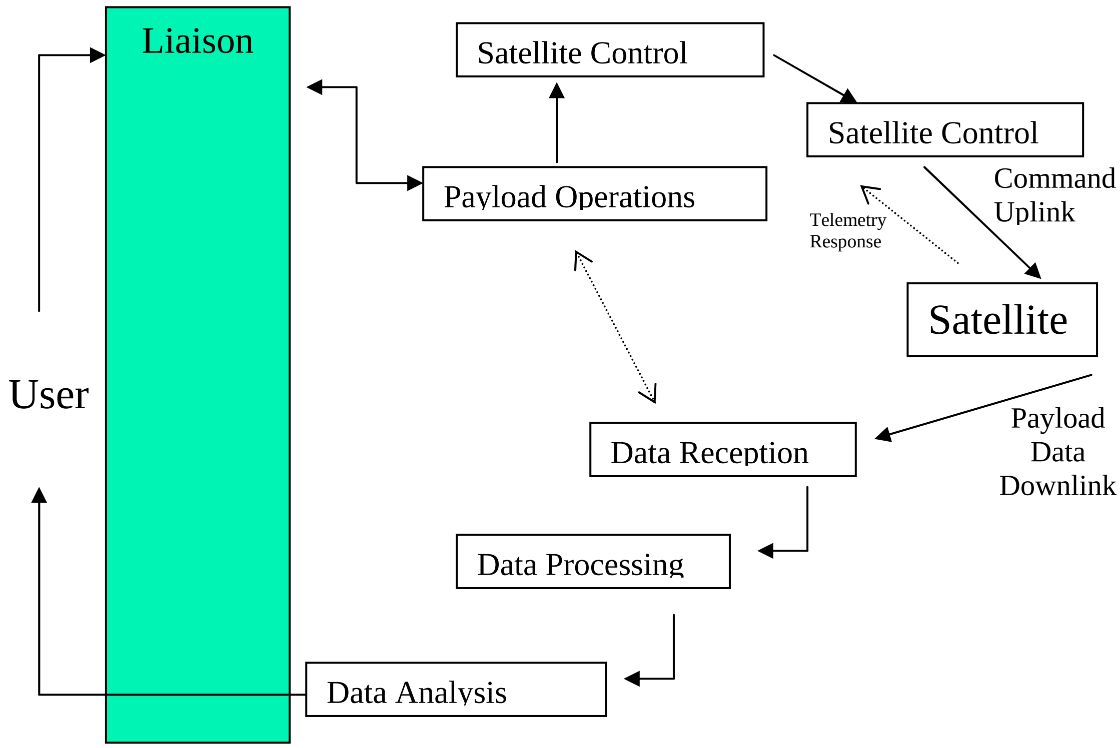


Figure 1. Commercial Satellite Remote Sensing Process (adapted from Zesiger, 2001)

Zesiger Model Overview

Given the importance of the Zesiger (2001) generalized model to this research, the following summary is provided.

1. User contacts satellite operator's customer liaison to determine the following.
    a. Target area and type
    b. Range of dates for desired imaging
    c. Maximum acceptable cloud cover
    d. Image viewing angle limits (and direction)
    e. Type of sensor to be used (a company may have access to more than just electro-optical imagers)
    f. Type of data delivery (mail, courier, FTP data transfer)
    g. Level of processing (see Table 1)
    h. Required timeliness (varies by vendor from 2 levels to 5)
2. The liaison forwards the initial order request to the Payload Operations Center (POC) for analysis, study and acquisition plan proposal.
3. The liaison contacts the user with the POC proposal for user approval. If the proposal is accepted, payment is arranged.
4. The plan is forwarded to the Satellite Control Center (SCC) where it is tested for feasibility and satellite command generation. Note that the command includes the

information needed by the satellite to image the target and how to download, or store and download later, the resulting sensor data.

5. Commands are forwarded to the Satellite Control Site (SCS) for uplink when the satellite is in view.
6. The satellite receives the commands.
7. The sensor collects the data and downlinks it at the programmed time to a Data Reception Site (DRS).
8. The DRS forwards the data to a Data Processing Site (DPS) for processing.
9. Processed data is sent to a Data Analysis Element (DAE) if this was ordered by the customer.
10. The final product is delivered to the user in the manner agreed.

It is important to note that the Zesiger model was developed as a precursor to a target, satellite and ground system specific predictor, thus the inclusion of options 1a-h in the model. As previously noted (see the **Problem Statement**), it is not the intent of this research to fix these particulars. The process steps described above are those used as the first level of processes for the model developed in this research.

Using the Zesiger methodology, a user generates a request to one company with all the particulars at a certain start time, t_0. Steps 1 to 4 are performed by the satellite company for a duration of time, d_1, then the orbit calculator determines the times of the next uplink opportunity after t_0+d_1 based on satellite ephemeris, antenna locations and limits, minimum duration and SCS policies (some companies only command once daily, some when required from several possible locations (Zesiger, 2000)). After uplink, a period of time will pass before imaging can occur, d_{image}, followed by a calculation of downlink opportunity similar to the uplink calculation. Steps 7 through 9 take various amounts of time based on company resources and the particular processing and analysis options selected by the user, d_{proc} and delivery options $d_{deliver}$. The total duration of the operation is then calculated by adding the minimum and maximum durations to the start time, as shown below.

$$\min(Duration_{Total}) = t_0 + \min(d_{up}) + \min(d_{image}) + \min(d_{down}) + \min(d_{proc}) + \min(d_{deliver})$$
$$\max(Duration_{Total}) = t_0 + \max(d_{up}) + \max(d_{image}) + \max(d_{down}) + \max(d_{proc}) + \max(d_{deliver})$$

If the Zesiger calculation were repeated with the same start time and user selections the answer range would be the same in each instance. Each satellite and satellite operator would also have different, but unchanging, answers for each case, even if the satellites were otherwise identical, based on orbital position at t_0.

Pawling Model Overview

Pawling (2004) modeled the U.S. military intelligence process as described in numerous military publications. The model assesses time from determination of a need, through collection, processing and exploitation, analysis and production, dissemination and integration, and communications between each stage. Each request had Arena attributes such as a "need by time," quality required (1 to 5), information source (1 of 13) and priority (1 to 5). These attributes and others determined which steps that requirement had to pass through to be complete. At any stage if the "need by time" had been exceeded the request was eliminated and counted as unsatisfied.

The high level of specificity of Pawling's model to the U.S. military and to processes beyond the scope of the question guiding this research made the model itself inappropriate. On the other hand, the use of Arena to address the question of time through a tasking system is fundamental to the approach taken here.

III. Methodology

Overview

The selected approach for this research is similar to the Zesiger (2000, 2001) model, but different in two significant ways. First, in order to answer the "time-to-deliver" question for a non-specific satellite, large numbers of targets for imaging are generated in a quasi-random fashion. Each "Request For Image" (RFI) passes through the stages based on the Zesiger process beginning with Customer Service. Targets are then collected by the satellites according to an approximation of their shared orbital characteristics and determined time over target and coverage density within the longitudinal span of each pass. Collection is further limited by a constraint representative of on-board storage capacity and other operational limits before passing through a series of steps for downlinking, processing, and delivery.

Second, I employ the satellites cooperatively within a family corresponding to resolution capability rather than individually assess each satellite against each target. This is done primarily because developing a model for each satellite and company would require an extended period of time to gain access to the detailed, proprietary information of each company with the final model and results limited to government entities. On the positive side, by treating the satellites as a constellation the results are comparable, but not identical, to such future architectures as the eight satellite constellation planned by ImageSat International (Bar-Lev, 2001). Alternately, one could posit a customer who determines, before ordering, which company could meet his requirement first and places his order only with that company.

Arena Simulation Software

Arena is a visual, drag-and-drop, high-level process simulation environment based on the SIMIAN simulation language and developed by Rockwell Software. Models are created using ready made process blocks with configurable parameters for delay or decision with simple or complex rules. Process steps involving queues are assigned resources used to complete the step, and the software allows complex configurations that support limits on resources or the times they are available as well as the order in which items are completed (Kelton, 2004). Values for duration of processing time or delay can be generated by several distributions with user specified parameters. All modeling for this research was done in the Arena environment. Rather than use Arena's built in analysis tools, however, analysis was performed using Microsoft Excel spreadsheets.

Arena was selected for its relatively approachable learning curve, the intuitive nature of the models, and its availability at AFIT. As a drag-and-drop modeler, it is relatively easy to get started and behavior of each block easy to modify using the property interfaces. More complex behavior of resources, queue priority, and file input and output were then developed with the assistance of the built in help and the use of the Kelton (2004) text. When the model is built, it reflects a traditional flowchart structure easy to comprehend and explain. Finally, there were Arena licenses and experience available within the institution.

Assumptions and Justifications

Driven by the principal question, “What is the shortest time, in general, it takes to receive an image of a general target?” and the interests of the research sponsor in the capabilities of customers with more resources and interpretation experience than typical businesses, several assumptions are made for the purpose of modeling the shortest time to deliver.

#1. Certain regions of the world are imaged more than others.

Regions of greater development and wealth will have greater demand for imagery for government studies, research both public and private, and business related purposes. Regions of international concern, such as persistent conflict or unrest, especially when a major government is involved, such as the Middle East, will generate demand for imagery. While short term interest may arise in a region, typically for a natural disaster, the period of interest is generally much shorter than the simulation times used and they are, by definition, unpredictable in location, so are not modeled.

#2. The high resolution satellites, and the associated ground segments, are treated as complete, cooperative constellations.

As discussed in the overview to this section, attempting to separate each company’s resources would force the models and results to be handled as proprietary. What this assumption implies is that a user’s request, no matter the time of day, goes to any arbitrary, open customer service department for processing and, when complete, to an open satellite control center.

At first glance the always open assumption seems too easy: In fact it is fairly realistic. To illustrate let’s take the example of Space Imaging. While the company’s

U.S. control center is located in Colorado, it has several partner locations around the world that have autonomous commanding and downloading capabilities that also take in customer requests for imaging in those regions. So if a user in the U.S. had a midnight requirement for an image of Asia or the Middle East, that user could place a call, or visit the website, of the regional partner (who would be open for business) to place the order.

A glance at the downlink sites of three of the four high resolution systems and the medium resolution SPOT system demonstrates the large number of opportunities for image reception by both groups. Aggregating the sites into a single cooperative system is also not so significant because the companies themselves are aware of the imaging demands of the regions and respond (this is assumption #1). Note the duplication of sites in Pacific Asia, Southeastern Asia, the Middle East, Europe, and the U.S. (Figures 2 - 4). Having made the case for treatment of the ground assets into one system, it is simple to extend the argument to treat the satellites as one system.

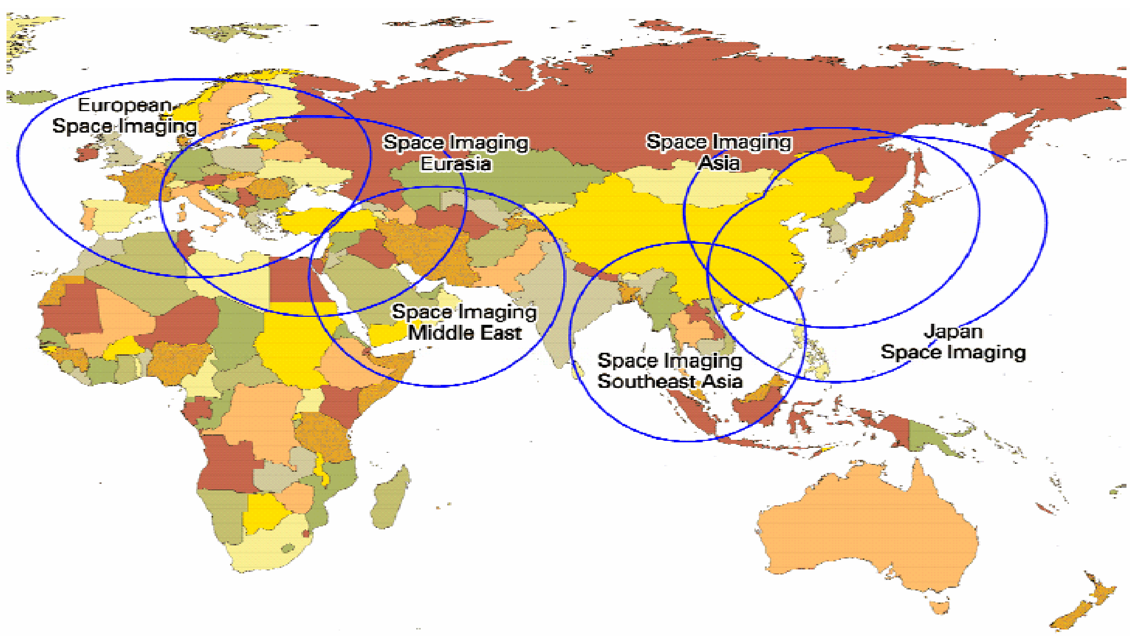


Figure 2. Space Imaging Receive Sites (Ikonos Guide, 2004). U.S. Station in Colorado.

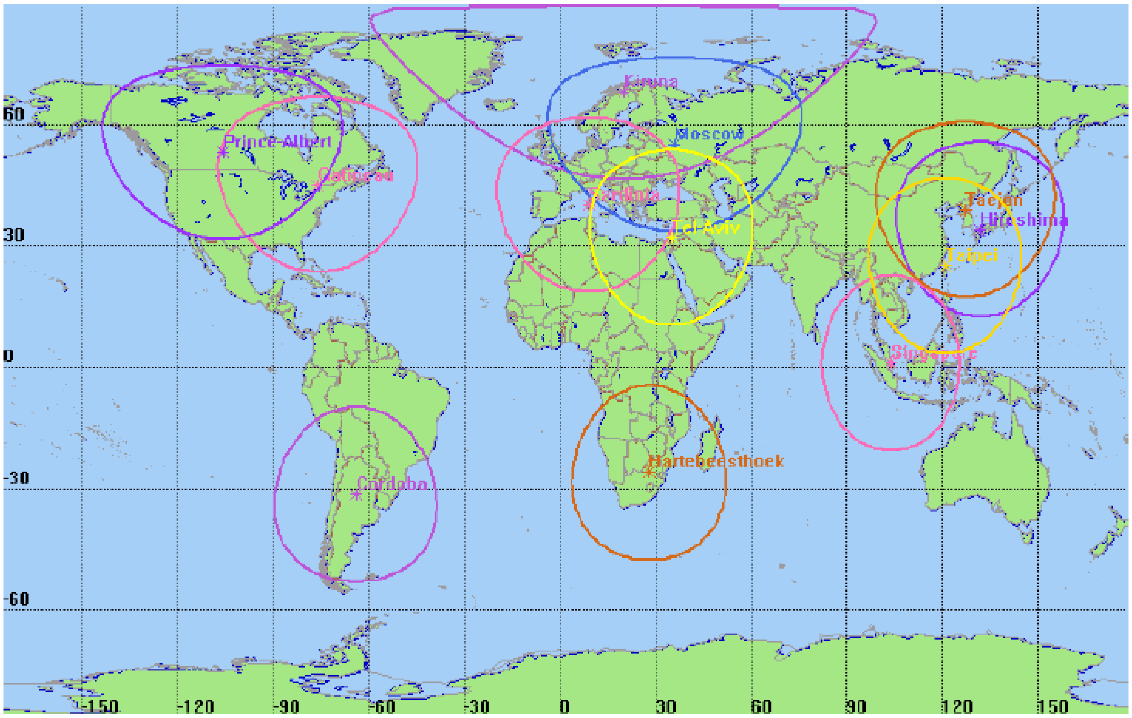


Figure 3. ImageSat Receive Sites (Bar-Lev, 2001)

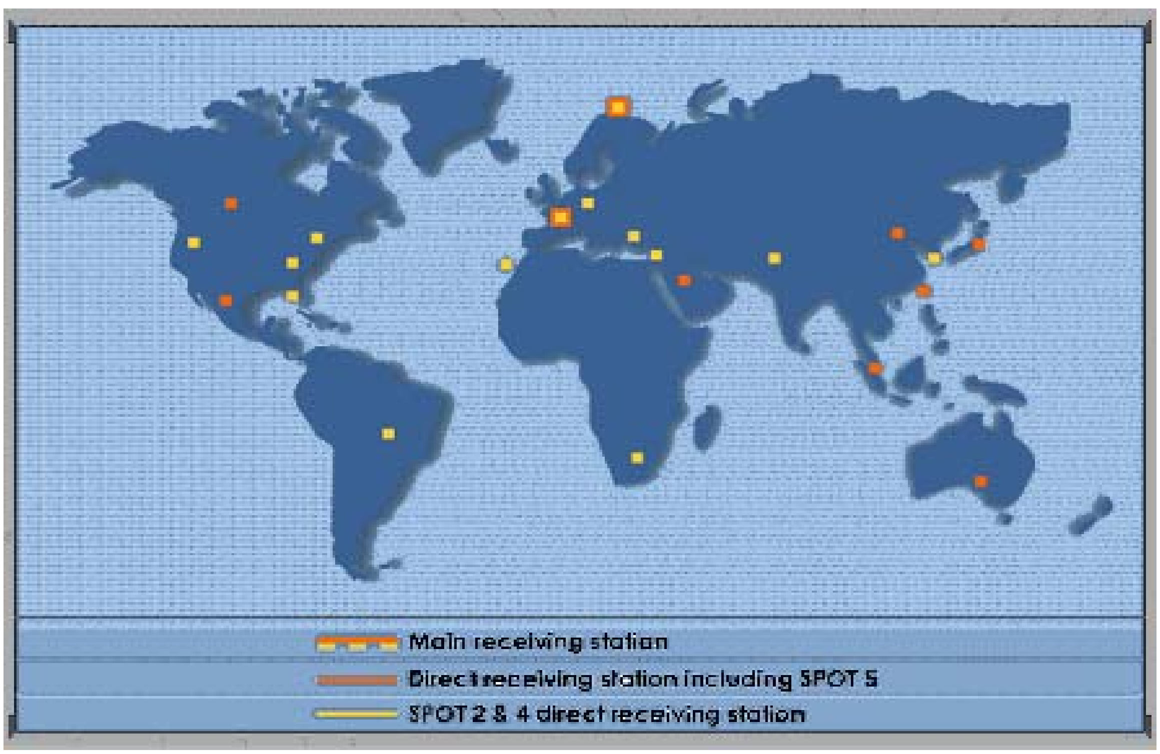


Figure 4. SPOT Image Receive Sites (Imagery Acquisition, 2004)

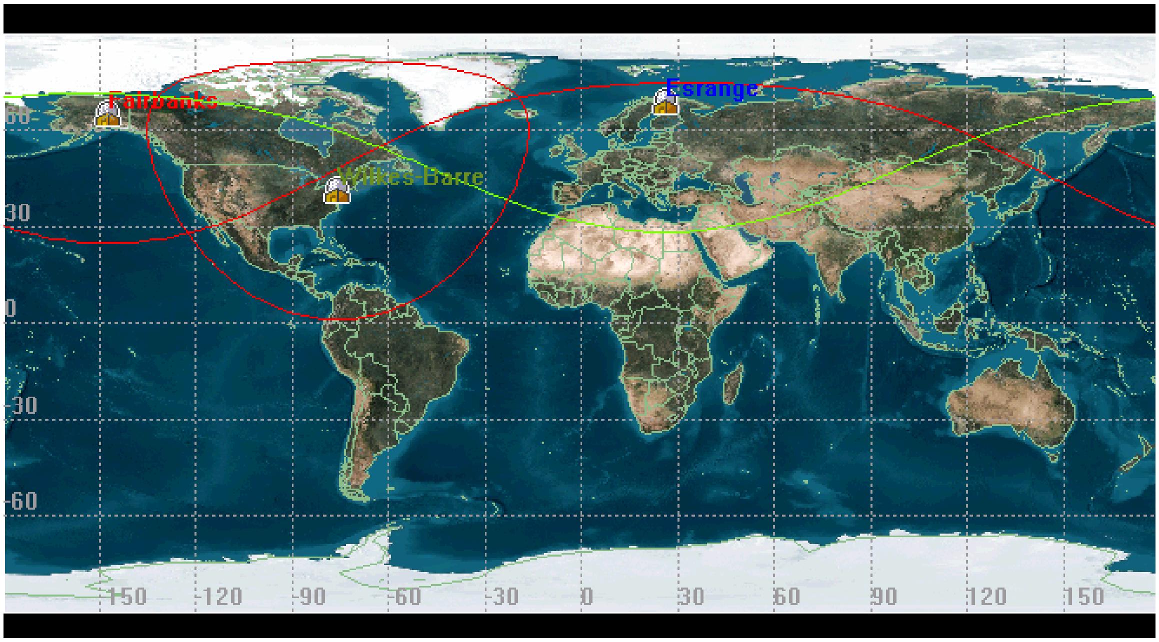


Figure 5. DigitalGlobe Receive Sites (Derived from QuickBird Product Guide, 2004)

Figure 5 illustrates an interesting departure from the rest by DigitalGlobe. By putting three sites in northern locations they ensure satellite contact on every pass. This is partly a resource issue, but business and legal issues are also factors. By virtue of the U.S. government 0.6-meter license that DigitalGlobe operates under, no image can be released with resolution better than “the international average high resolution,” currently about 1.8 meter, within 24 hours of the imaging event. By not taking the business route that Space Imaging has with many international, autonomous “Regional Affiliates” DigitalGlobe maintains the necessary control over image distribution (Izard, 2005).

Regarding the orbits of the satellites, it is partly due to weather and partly a business decision to put electro-optical remote sensing satellites in their chosen orbits. A visible light sensor images during daylight, gathering the reflected sunlight from the Earth’s surface, but weather is also driven by sunlight, and clouds generally build during the course of a day. It is therefore desirable to have the satellite pass over a region in the morning. However, the long shadows of early morning are not desirable, while the near absence of shadows at noon make interpretation more difficult, so the difference is often cut with flyovers between 0930 and 1100 hours local time.

The physics of gravity governs the motion of satellites in their orbits and, except in certain special orbits, satellites will not continue to arrive at the same time every day. One of these special orbits is the sun-synchronous, and these orbits are used universally by the commercial remote sensing systems. However just because two satellites share a local time of descending node (LTDN), an orbital mechanics term for the local, not Greenwich Mean Time (GMT), time the satellite passes from north to south over the equator, does not mean they are in the same orbit otherwise, nor does it mean they have passed over exactly the same ground. In general, a single satellite in a typical low earth, sun-synchronous orbit will have a revisit interval (a term meaning the period of time before a satellite can view the same area again) of 1 to 5 days.

Revisit interval is tied to target latitude, satellite altitude, and the degree to which the satellite's sensor can look to the sides. The larger area of low latitude earth compared to higher latitudes means longer revisit intervals for equatorial regions versus mid- or high-latitude regions. Satellites at higher altitudes can view greater lateral distances on earth using identical sensors than those closer. Some satellites (see Appendix B) have a greater ability to turn their sensors to the side (Wertz, 1999). All these factors determine how frequently a given sensor can view a particular target.

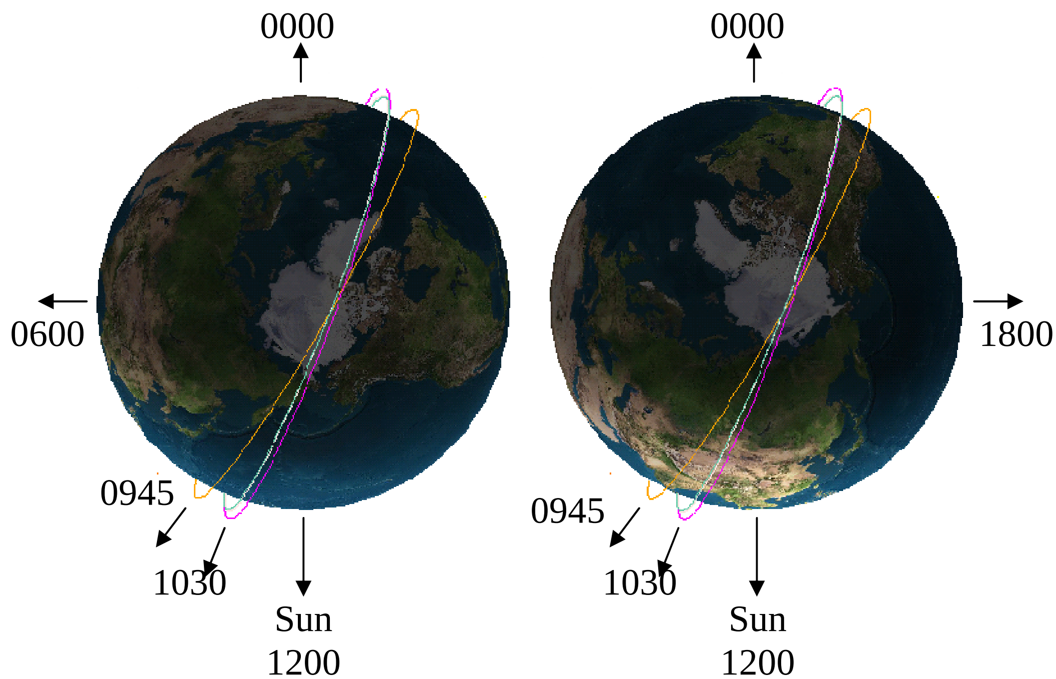


Figure 6. Sun-synchronous Orbits of High-Resolution Satellites (0000 and 0500 GMT)

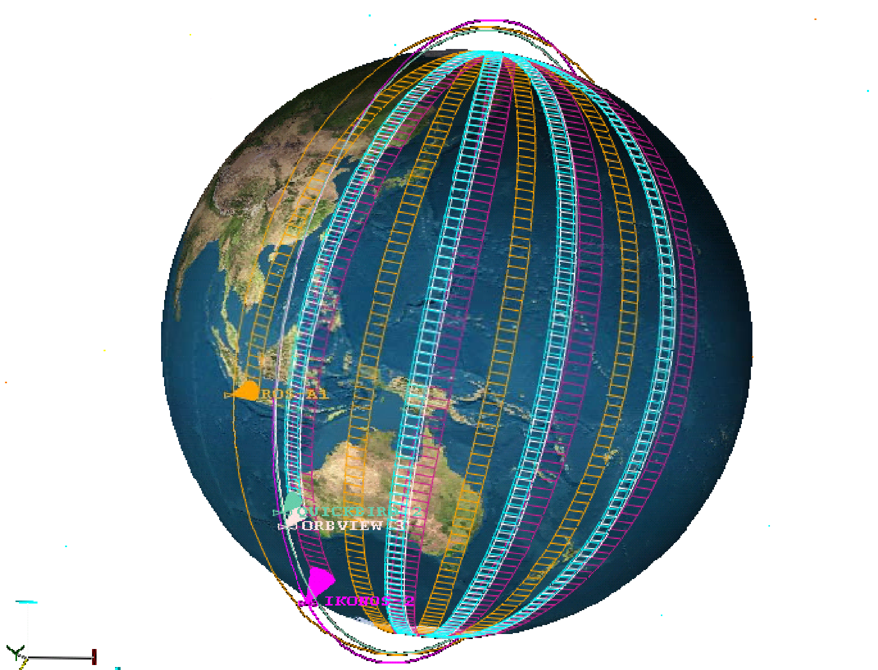


Figure 7. Four Passes Of High-Resolution Satellites (Assuming 20 Degree Look Angle).

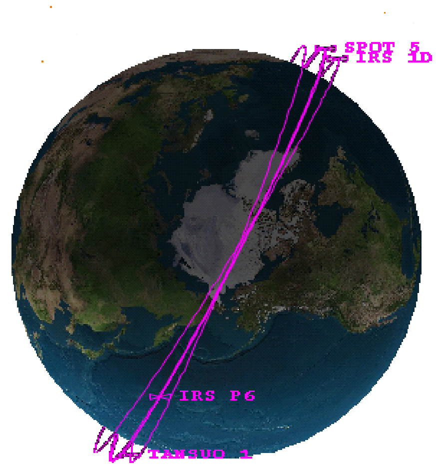


Figure 8. Sun-synchronous Orbits for Medium-Resolution Satellites

Because most imaging is conducted at mid-latitudes and because the current satellites are in non-identical, sun-synchronous orbits, this research assumes that the high resolution satellite constellation used for this study has a single imaging opportunity every day with a cumulative probability of capturing any given image that is 100 percent by the fourth day. This is not quite the ideal situation that would be created by a single entity that could carefully spread the satellites to "fill-in" any coverage gaps such as the planned ImageSat constellation already referenced. The process of determining the coverage distribution used in this study is described in Appendix C.

#3. **The users of interest for this study require only minimal image processing.**

The satellite companies offer image processing services ranging from none at all (raw from the satellite) all the way to complex multispectral analysis of large areas consisting of mosaics of individual multispectral and panchromatic images combined with elevation data and registered to absolute ground coordinates accurate to a few meters. The available options are described by processing levels as shown in Table 1. Note that the names of the levels can vary with vendor and may also include sublevels.

Table 1. Image Processing Levels (Zesiger, 2001).

Level	Description
1	Radiometrically corrected images with no geometric correction applied except chip offset removal.
2	Radiometrically corrected images which are geometrically corrected to the accuracy of the support data.
3	Radiometrically corrected images which are geometrically corrected to the accuracy of ground control points visible in the imagery.
4	Radiometrically corrected images which are orthorectified to correct for terrain variations with or without ground control points.
5	Digital terrain data extracted from stereo imagery.
6a	Pan-sharpened multispectral imagery (with Level 1, 2, 3, or 4 geometric processing applied).
6b	Band ratio multispectral imagery (with Level 1, 2, 3, or 4 geometric processing applied).
7	Image mosaics produced from multiple small images (with Level 2, 3, or 4 geometric processing applied and Level 6a or 6b processing optionally applied).

For the purpose of this research, images will only be processed to level 2 for the following reasons. First, the actors of concern are assumed to have higher levels of processing capability and image analysis professionals as required by their needs. If the analysis is being done by the user’s resources, this obviates the need to model such activities by the image provider. It is entirely reasonable that the non-major world powers (as well as large non-government actors) are perfectly capable of maintaining the hardware and expertise required to exploit the commercial imagery they purchase. It would also be extremely unreliable to include a figure for the duration of analysis across such a range of users, purposes and capabilities in what is intended to be an estimate of the shortest time to delivery of a generic image. Second, for many uses of timely intelligence, it is sufficient to know only coarse details: presence or absence of troops or supplies at a location; numbers of troops or supplies; roads used by forces; and other such basic tactical or operational level details. Third, and finally, by assuming only the most basic level of processing the model outputs times of delivery that are the quickest; thus addressing the basic question of the research.

This assumption is a significant point of departure between the Pawling (2004) model and my own. This is a completely logical difference: Pawling set out to model the U.S. military intelligence cycle including sub-processes for requirement determination, collection, analysis, exploitation, and dissemination to the originating user by the larger intelligence activity. This research is focused on the use of commercial capabilities to meet the collection requirements of agencies (not necessarily a national intelligence organization) with internal, but wildly disparate, resources to accomplish the other aspects of their "intelligence cycles." Completely parallel arguments to this one for image processing explain the absence of the other stages of the intelligence cycle modeled by Pawling (2004) from this study.

#4. The satellite operators attempt to predict cloud cover over the target before scheduling the imaging to take place.

Spot Image, the operators of the SPOT constellation of satellites and DigitalGlobe, in their respective web pages and user's guide, state that they use weather data to anticipate if prospective targets will be clear or clouded prior to scheduling them for imaging by their satellites. Given the price commanded by an image, it seems likely that other companies would make the attempt to avoid missing a clear, and profitable, shot rather than take a picture of clouds. DigitalGlobe also has a policy of refunding partial payment or reshooting images with more than 20 percent cloud cover, unless the customer has specified, and paid for, a clearer shot (Quickbird Product Guide, 2004).

#5. Customer requests are for point targets, satisfied by a single image.

This assumption is simply a limitation of the model as implemented. It is not clear what proportion of satellite operations are truly single image versus those requiring multiple images. Of intelligence type requests, certainly mapping operations are not single images, nor tasks where only approximate locations of interest are known and searching is required. On the other hand, where a lower time limit is desired on the possibility of reconnaissance, the single shot assumption is useful.

#6. Only two levels of user specified priority are used.

Actually, each satellite operator has different tiers of promised acquisition and turn-around for images, ranging from two to five (Zesiger, 2001, and system user guides). Essentially, the more quickly (or the narrower the imaging window) you want an image, the more it will cost. This turns out not to be mere profiteering by the vendor, but a real burden on the personnel at each stage, and on delivery times of the lower tier orders based on resources. While Arena supports up to 5 levels of priority, the assumption reflects the desire to get at a fastest time to deliver information to a user who is assumed to have large resources. This is also consistent with assumption #3. Based on these arguments, it is most appropriate to the problem to go with the fewest levels of priority.

Discussion of Model

With the assumptions laid out and explained, the design of the model is more easily explained. Convenience dictates discussing the model in sections and logically there are three major categories of activity. First the Request and Customer Service section (outlined in blue in Figure 9), then the SCC Processing and Collection section (outlined in purple), and, last, the Post-Imaging section (outlined in green). I will discuss the design and operation of the model and those settings required for understanding, but for complete details of the settings for each block in the Arena model see Appendix A of this document.

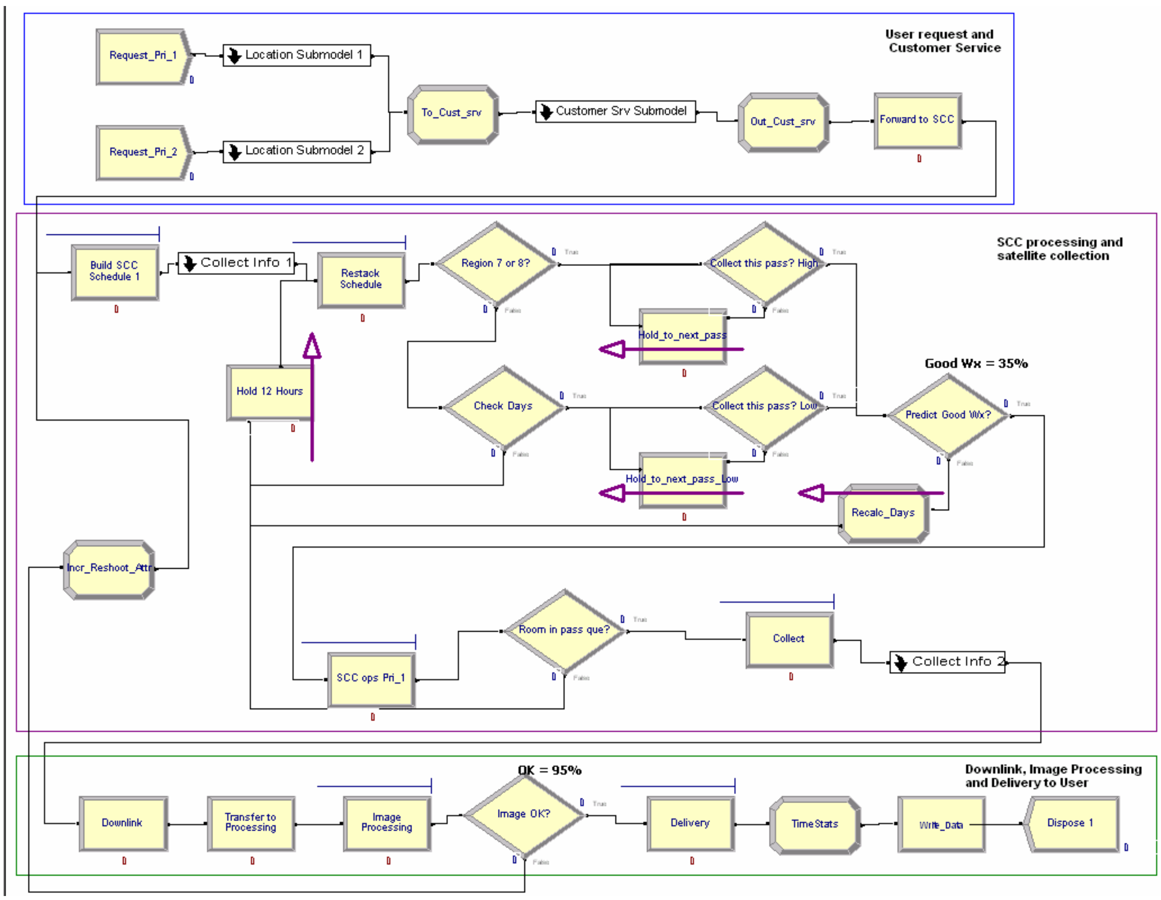


Figure 9. The Commercial Satellite Imagery Operations and Processing Model

As mentioned in the earlier description of Arena, it is possible to select from a large number of possible distributions for process times so it is worth discussing the choices made for this model. There are actually two distributions used: the triangular and the exponential. The triangular distribution is used here, given the lack of real world data from the satellite operators from which true distributions could be developed, as the default choice (Kelton, 2004, p164-165). A triangular distribution is described by three parameters: a minimum, a most likely and a maximum value. It behaves in most cases like a normal distribution but without the possibility of values beyond the minimum and maximum. This makes a lot of sense for a managed process because there won't be values shorter than the minimum, and the managers of the real process won't allow RFIs to linger longer than a maximum amount of time in a given stage: Both of these not-allowed situations would occur with a normal distribution. Keep in mind that the preceding discussion applies a single process block, and is not necessarily true for the overall model behavior.

The second distribution used (for the generation of RFIs) is the exponential and requires a little more explanation. The arrival of customers, or phone calls, or any number of other events, **in a given time period** is generally a Poisson distribution (Sachs, 1984). However, Arena's parameters for creation of RFIs (*entities*, in general) are for the **time between one arrival and the next**: this distribution for a Poisson arrival distribution is an exponential distribution with a mean that is the inverse of the mean of the Poisson distribution (Walpole, 1985). More discussion of these distributions can be found in the references, and many other statistics texts.

Request and Customer Service.

The first activity in the model is to create Requests for Imagery (RFI). This is accomplished using a **create** block with a distribution (with parameters) to govern the creation. Two blocks create priority 1 and priority 2 RFIs respectively. While the distribution used in both is exponential, the parameters differ between priority 1 and 2 as well as differing between the run cases. The baseline case sets the means to 1 every 120 minutes and 1 every 6 minutes (a 1:20 ratio) for priority 1 and 2 RFIs respectively. The loads and the priority 1 vs. 2 ratios are varied for different cases. Note that Arena will support other distributions and even schedules during which no orders would be taken; these would be appropriate for modeling a single operator with non-24hr service hours.

Each RFI created goes next to a *Location Submodel* (Figure 10), which are both identical, where it is assigned an attribute called *region* that takes integer values from 1 to 8 according to a discrete distribution built in order to create eight regions on the globe (Figure 11) with ranges of latitude and longitude assigned in the next series of blocks, named *LatLong#*. The RFIs are assigned the *region* attribute according to the weights in Table 2, then directed to the appropriate *LatLong#* **assign** block by the simple logic in the **decision** block named *Region1*.

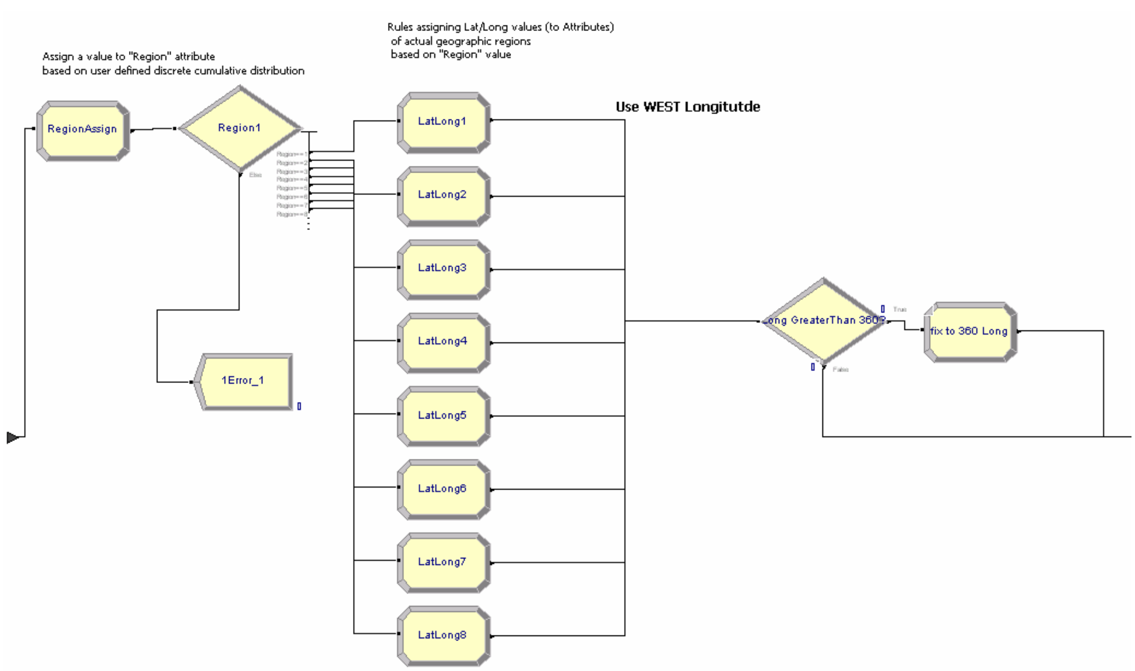


Figure 10. The *Location* Submodel.

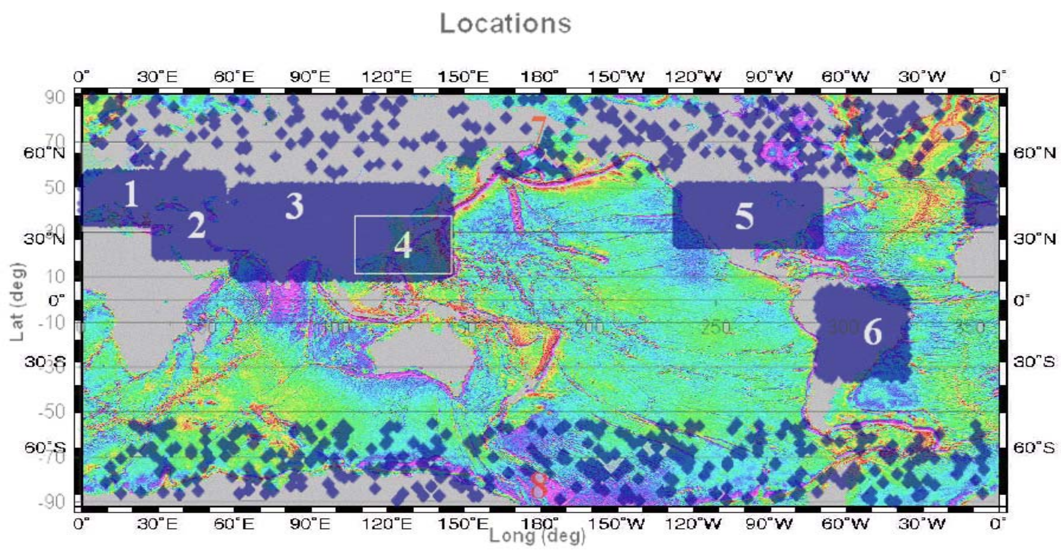


Figure 11. Map of Regions Used

Table 2. Regions and Weights.

Region attribute	**Geographical Region**	**Weight (%)**	**West Longitude (degrees)**	**Latitude (degrees)**
1	Europe	25	-10 to 305	35 to 55
2	Middle East	20	300 to 330	20 to 40
3	Asia	15	215 to 300	10 to 50
4	China	5	230 to 280	20 to 50
5	U.S.	30	70 to 125	25 to 50
6	Brazil	3	35 to 70	-35 to 5
7	Arctic	1.5	0 to 360	55 to 90
8	Antarctic	1.5	0 to 360	-90 to -55

Longitude in degrees West was used because it simplified the collection logic if it increased in the same direction as the sun moves across the Earth. More regions are possible and overlap is permissible (as with China and Asia in the definition above) they just become unwieldy and, as in this case, do not contribute to answering the research question.

The next decision and assign blocks ensure the longitude ranges are within 0 to 360. Values greater than 360 could occur due to the use of a sample range of 305 to 370 for Europe. This was done to keep the range in one block rather than two (0-10 and 305-360). These ranges are only intended to be approximate. The exact values are not significant to the results, though the total number of targets in a range of longitude may matter.

Returning now to the main model, the assign block *To_Cust_Srv* creates two significant attributes for each RFI that will store the simulation time at this point and select a probability of the target being imaged 1, 2, 3, or 4 days from creation. The *To_Cust_Srv* attribute value will keep the start time for the RFI as it progresses through the model: Like all the attributes used in the model, it will remain associated with the particular RFI and serve as a log of events and time for use in the analysis. The *Days_2_collect* attribute will be discussed with the SCC Processing and Collection section.

An item of Arena usage not mentioned before is that none of the create, assign, or decide operations performed on the RFIs have consumed any simulation time. That is about to change. The *Customer_Srv Submodel* (Figure 12) has six time consuming steps, though only five may be encountered. The first is the **process** block named *Contact*. This step represents the duration of the initial phone call by the customer to the customer liaison for the purpose of specifying the particulars of his desired image request. This is equivalent to step 1 of Zesiger (2001). Continuing to follow the Zesiger model, the next step is *Payload_Ops* for evaluation of the request. The next step, *Contact2*, (Zesiger step 3) involves the liaison calling (or writing) back to the customer with the actual image proposal as drafted by Payload Operations. There are two conditions dealt with by the two **decision** blocks here: the first is time lost if the liaison's attempt at communication does not result in immediate contact with the customer; the second is the chance that the customer will not approve the proposal and it will have to go back to Payload Operations for development of another proposal. The values used for the parameters of these operations are included in Appendix A. Note that these values remain fixed in all the cases examined in this study.

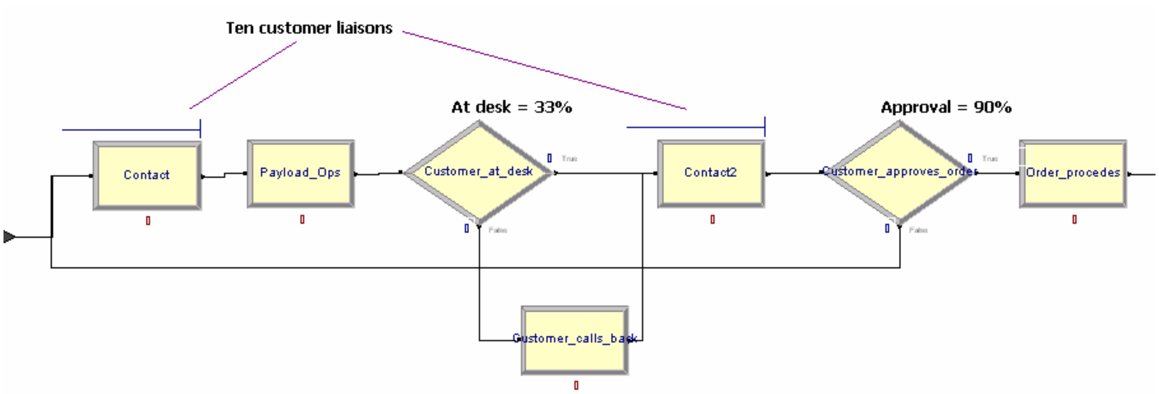


Figure 12. The *Customer_Srv* Submodel

The *Contact* step also uses an Arena capability logically called a **resource**. A **resource** is considered an asset that acts on items in the process queue until the processing activity is complete and the resource is freed to process the next item. In this case, a resource was defined and named *Customer_srv_rep*, that there are ten reps at all times and that processing an order requires one of these. Therefore, ten liaisons could be taking or verifying orders from ten customers simultaneously, additional customers would be put on hold, or their correspondence remain unread, until the resource was again available. The choice of ten is somewhat arbitrary for our hypothetical cooperative constellation.

The next two steps are fairly simple. The *Out_Cust_srv* block creates an attribute for each RFI that will store the simulation time at this point, equivalent to the *In_Cust_srv* entry. The last step in this part of the model is a simple delay (see Appendix A) that does not require a resource, but captures the time from the completion of liaison activity and the first look at the new order by the SCC Processing personnel. This could include transmission time if the SCC was not co-located with Payload Operation or the liaison activity. In the results, the contribution of this block will be counted against SCC processing time.

SCC Processing and Collection.

The next major section of the model has more complex logic to simulate the actions of both the ground processing decisions of the SCC operations and the collectable targets from the orbiting satellite. The process used here to simulate the results of SCC processing and satellite collection does not reflect the actual processes of SCC operation. In truth, the SCC would take a requirement and put it on something more like a calendar. If a user wanted an image of Tokyo, the SCC would put that request in a stack of requests that are obtainable by satellite #1 on pass #14 two days hence. When it was time to work that pass, the SCC would look at all the orders for that pass, try to satisfy the priority 1 requests then fill in the priority 2 requests while doing weather prediction for each potential target (see assumption #4). All that while ensuring the satellite on-board memory is not exceeded between downlink opportunities and that a target to the west of nadir followed by one to the east of nadir are not too close to allow the satellite to slew in time to take both.

Rather than try to mirror the actual chain of events in Arena, which would require many more variables and structures for every pass (up to 15 per day) for several days, what the earlier assignments of *Days_2_collect* accomplished is to associate when each RFI's target is collectable with each RFI based on a strictly empirical calculation based on coverage analysis like those in Figure 7 for a latitude of about 36 degrees North (see Appendix C). The implemented collection process then makes a series of relatively simple decisions that determine if the target is potentially collectable based on the probability of coverage from *Days_2_collect*; current simulation time relative to the target longitude; probability of clear weather over the target; and finally, if there is room in the pass schedule for another image.

The first block, *Build SCC Schedule 1* assigns a delay to the process to imitate the initial analysis time to properly align the RFI to a particular pass and rebuild the stack according to priority, weather, satellite memory, and other factors. This delay is drawn from a triangular distribution with minimum, most likely, and maximum of ½ hour, 3 hours, and 6 hours, respectively.

The *Collect Info 1* submodel is just a place to collect information about the numbers of priority 1 and 2 requests and what regions they fall in. It is mirrored by the *Collect Info 2* submodel at the end of the collection process in order to gather data on relative collection times among the categories of request and target region. The full details of these submodels are included in Appendix A.

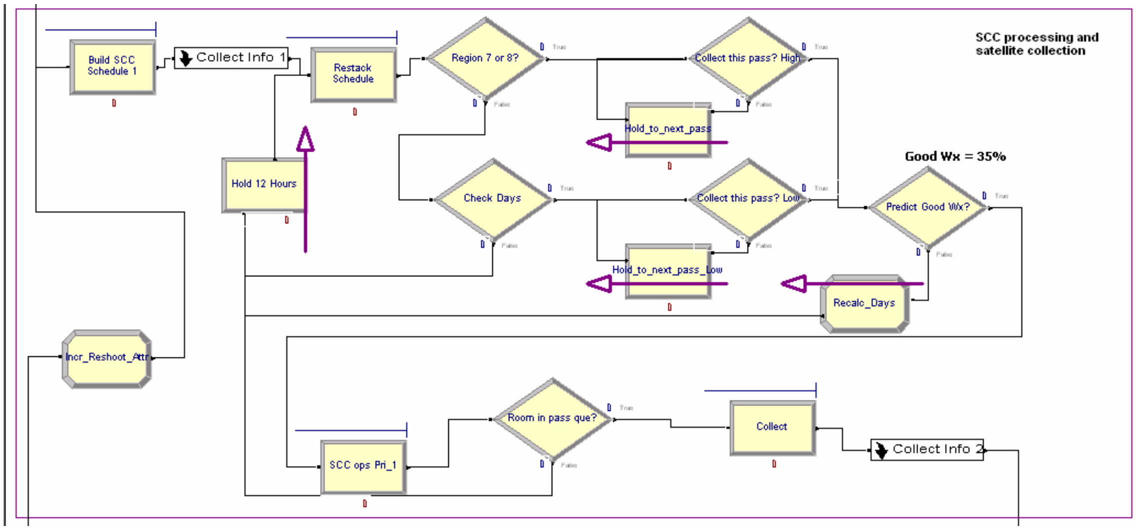


Figure 13. SCC Processing and Collection Section

The *Restack Schedule* **process** block is in place to keep priority 1 requirements first in the evaluation process and to slow the decision process so that rejected images aren't evaluated again right away. Likewise the **process** blocks named *Hold_to_next_pass*, *Hold_to_next_pass_Low*, and *Hold 12 Hours*, ensure that images rejected for longitude, weather, or because the satellite image limit for the pass is exceeded, isn't approved a few minutes later as an independent draw from the distribution. In the *weather* and *full pass queue* negative situations, the RFI is held for 12 hours, enough to miss the current daylight pass opportunity, but not enough to prevent a try on the next opportunity 24 hours later.

The six **decision** blocks that are next are the heart of the collection determination process that prove to be the single largest source of delay and variability for process times. The first determines if the RFI is polar, for which regions the coverage situation is based solely on opportunity because coverage density is all but total above 55 degrees. The second, more likely situation, incorporates two decisions based on the empirical *Days_2_image* cumulative coverage distribution (see Appendix C) and the current simulation time relative to the longitude of the targets relative to the approximate positions of the satellites.

The calculation of satellite position is based on the orbits of the four high resolution imagers (which is also very similar for the medium resolution imagers) and their sun-synchronous nature. Refer back to Figure 6 and note that the satellites are an angle ahead of the overhead sun determined by their LTDNs: For Ikonos 2, Orbview 3, and QuickBird 2, the LTDN is 1030. Therefore these satellites, when they cross the equator, are 1.5 hours, or 22.5 degrees longitude (15 degrees longitude per hour) ahead of the noon sun. Keeping in mind we are approximating for a time-to-deliver problem rather than a rigorous orbital solution, we can use the simulation time (*TNOW* in Arena) as GMT, which at zero corresponds to midnight--opposite the sun. So at time 0000, the satellites are 13.5 hours (202.5 degrees) ahead of GMT, and they will always be 13.5 hours ahead on their daylight passes over the Earth. The corresponding longitude offset for EROS A1, with a LTDN of 0945, is 14.25 hours.

To these values a small margin is added to account for the extended field of view of a satellite at a nominal altitude of 490 km (see Appendix A for exact values) and assuming a 20 degree slant angle (conservative for the imagers per the user guides). For the mid-latitude case, a margin of 2.3 degrees longitude (the calculated margin for 36 degrees latitude) was used that is conservative for the bulk of targets. The actual values vary from 1.88 at the equator to 3.28 at 55 degrees latitude (Wertz, 1999).

For polar imaging the field was widened to the equivalent of 0815 to 1200 in consideration of the small spacing of lines of longitude near the poles. The margin used for the polar case is 3.76, the value for 60 degrees latitude. Given that the value goes rapidly to 22 degrees of longitude in view at 85 degrees latitude, this is very conservative.

For a constellation of medium resolution satellites (see Appendix B) the reasoning as explained here would be the same. The span of possible collection for medium imagers is identical to that of the high. Where the high resolution satellites span LTDNs of 0945 to 1030, the medium resolution range is 1015 to 1100; 45 minutes for both. The only difference between the two constellations is the coverage distribution.

The next decisions are weather and capacity. The general approximation for cloud cover is that 67 percent (ISCCP, 2005) of the world is cloudy at any given moment with seasonal, diurnal, latitudinal, and other variations. If the weather prediction is poor, the *Days_to_collect* attribute is reset with another draw from the coverage distribution. The reason for resetting the attribute is that the satellite coverage does not repeat every 4 days; each satellite has its own cycle interval usually in the range of 10 to 16 days. This is the interval between exact ground trace repetition and the value that would be used for each satellite in a computation of single body coverage. Since the coverage was empirically derived over four day intervals, the distribution is the probability that a target will be in view of the sensor **in the next four days**. If an image is not taken for some reason, it is appropriate to calculate again the coverage odds. Finally, capacity is a limit on the number of images the imaging constellation can hold in storage on-board the satellite (more on this in Appendix C).

The purpose of *SCC ops Pri_1* is to hold RFIs until the pass is at hand. It does this by assigning a delay by the rule *1.6667 - AMOD(TNOW,1.6667)*, where AMOD is an Arena modulo function that returns a real remainder. What this accomplishes is to hold

RFIs for 100 minutes (1.6667 hours, approximately the period of the satellites) then release them at once to the next block that will limit their total number to 100 per pass.

The last block in this section is *Collect*. This is a simple process that uses four satellites (as **resources**) to shoot targets in 1 to 3 minutes each. This is slow enough that the queue can be emptied during a single daylight pass, but not so fast that it's never full (per the decision in the previous paragraphs).

<u>Downlink, Image Processing and Delivery</u>.

The last section of the model simulates the steps the image goes through after collection by the satellite as described by Zesiger (2001). *Downlink* must occur during the time the satellite is in view of the receive station. In many cases the downlink occurs near simultaneously with image acquisition, but even if no station is in view at the time of imaging, all the satellites have high transmission rates, on the order of tens of MB/sec to empty memory in the few (generally less than 14) minutes that the satellite will remain in view of the receive station. The next step, *Transfer to Processing*, can take much longer due to relatively slow communications (even a "fast" T1 line is only 1.544 MB/sec) that are available at some remote receive stations to connect to the processing centers and the large file sizes of the images. For example, a Quickbird 2 basic pan image can be 1600MB (Quickbird Guide, 2004). This contrasts with *Processing* itself, which is quite fast for the low level of processing assumed for this study; on the order of one to five seconds of computer time (Zesiger, 2001).

After basic processing (level 2 or equivalent radiometric and sensor correction level), the image can be examined for cloud cover in the image. If the cloud cover is greater than the minimum (20% for most systems per the company guides) the scene is usually reshot, at which point the RFI goes back to the SCC for collection. An **attribute** set by the *Incr_Reshoot_Attr* process tracks these RFIs.

The last process step is *Delivery*. Similar to *Transfer to Processing*, the length of time to complete delivery of the image is dependent on the bandwidth available to the company and the customer. All the major companies have a FTP (File Transfer Protocol) server for making images available to the customer. For our well resourced users (see assumption #3) this method of delivery is used exclusively. In fact, each company also employs physical delivery option on CD or digital tape that lessens the load on the FTP servers and bandwidth. To partially offset the larger load in the model, the delivery times for the very large images are relatively fast: a triangular distribution was used with minimum 10 min (T1 speed with 100MB file), most likely 30min (sharing the T1 with 3 users), and maximum 3 hours (dial-up modem). The remaining three blocks serve to collect data, write it to a file, and clean up the Arena entities.

Validation

The process of commercial imaging operations used to build the Arena model in this research was documented by the Zesiger (2001) study. More difficult was finding a way to penetrate the proprietary nature of the industry to make sure the demand for images was comparable to the modeled inputs. I was fortunate enough to have contact with DigitalGlobe during the development of the model and, while the result is nothing like what a constellation of four Quickbird satellites would look like, they were helpful in providing certain important load values (Wood, 2004 and Izard, 2005). In particular, the rate of output was also deemed of the expected order.

Verification

Verification of the model as producing accurate delivery times is not possible by virtue of the assumptions used in building the model. By using an aggregate of satellites rather than a true constellation and assuming only point targets rather than mosaic requests, the model departs substantially from existing constellation models and the real collection and delivery times of the existing single satellite operations of the current operators.

IV. Results

Overview

The nature of the simulation as a continuously running model that is sensitive to the number of RFIs in the collection process at any given time, suggests modeling single long runs for data generation rather than many short ones: Essentially, output during the period of time before the stages fill to a steady state (the ramp-up time) is not useful for analysis of throughput since it is not representative. In order to exclude data from the ramp-up period, the time series of the three main stages of the model and their total were examined for the period of time at which they seemed to stabilize.

As you can see in Figure 14, the total duration of orders stabilize after a few hundred hours (the coordinate axis is labeled in number of RFIs; the 4,126th RFI exited at 500 hours). The *Collection* portion of the program was, by far, the driving factor of total time: Customer service and processing times were fairly flat, quite small compared to collection, and quickly stabilized. The actual figure selected to exclude ramp-up time was 500 hours, in favor of caution, and verified for each separate case. A total of 2,500 hours of simulation time was run for 2,000 hours of data to be used in all future analysis. This consistently resulted in approximately twenty thousand RFIs completed through the entire system, a rate of 10.3 images per hour or 247 per day.

Arena could generate this much data for the model in under 2 minutes, if “batch mode” was selected. Simulations using the animated graphics feature, while handy for troubleshooting and flow checking, would take over 24 hours to generate the same 2,500 simulated time. The 2,000 hours generated 20,403 completed images for the baseline case and, during analysis with Microsoft Excel, was responsible for generating unrecoverable memory errors on a computer with 1GB of RAM, forcing some time-consuming workarounds and data sets no larger than 2,000 hours. Figures were also generated with the Excel program.

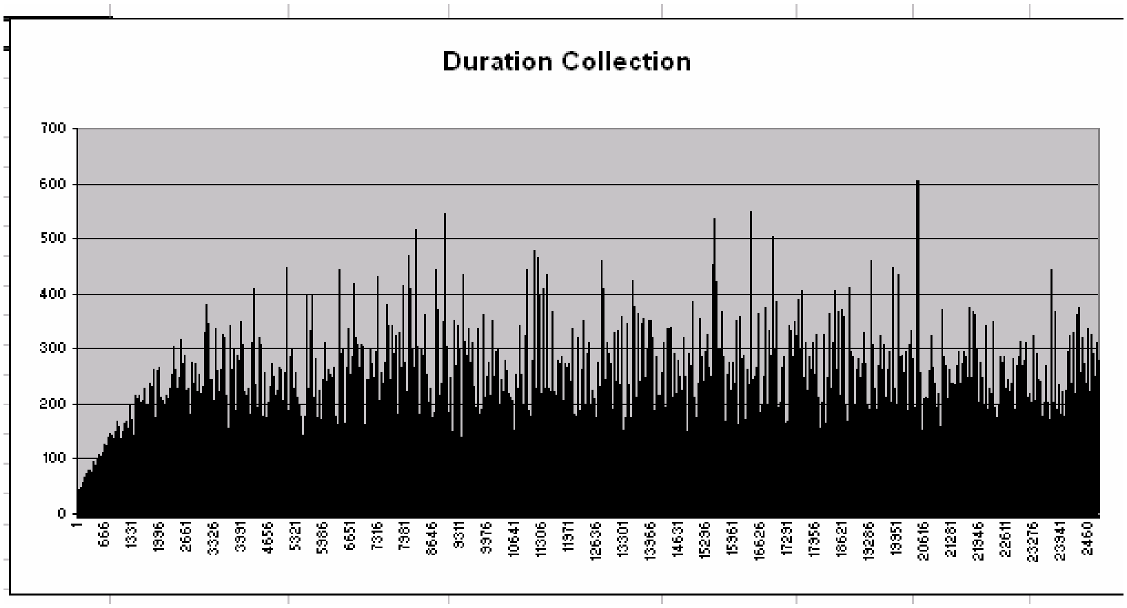


Figure 14. Baseline Time to Exit for Completed RFIs (in order complete)

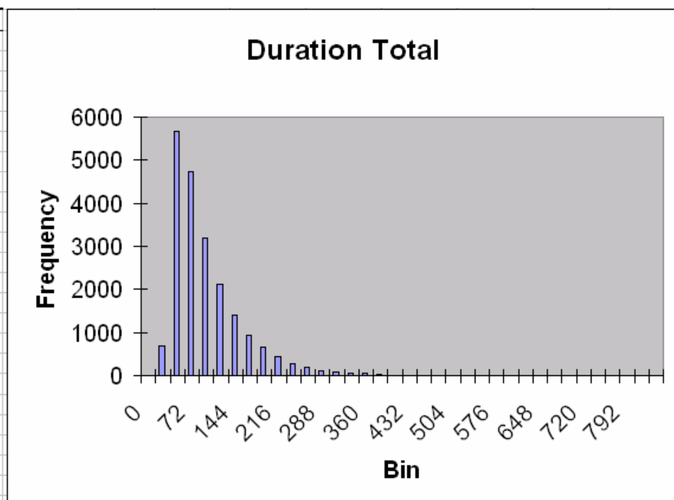
The simulation results are analyzed as a baseline case first, then used as a reference for several alternate cases of simulation with variations on the baseline model parameters. These case variations consist of two cases that explore the repercussions of demand for imaging certain locations more than others (see assumption #1), three that explore the consequences of business decisions by the operator, and one case that could be the result of either the environment or a business decision.

Case 0: Baseline Model

The baseline model is the most reflective of model parameters based on discussion with DigitalGlobe and extrapolated to the assumption environment described previously. As the baseline, it will also serve as the point of departure for the other exploratory changes and comparisons of behavior. Appendix A fully documents the parameters, settings and other configuration items of this version of the model.

The time series in Figure 14 is obviously uneven and warrants some explanation. First of all, the “bursty” nature of the time data is exactly what should be expected from a model that is simulating satellite access to ground targets: Opportunities to image the target can *only* occur once a day, at best, for the mid-latitude targets that make up 97 percent of the RFIs. Therefore, an opportunity lost does not reoccur for another 24 hours. Given the coverage situation for the high resolution satellites, there is a 41 percent chance that one day will become two days or more. This is in addition to the 65 percent chance of cloudy weather over your target (also see Figure 16 for collection times only).

Bin	*Frequency*
0	0
24	695
48	5657
72	4732
96	3190
120	2127
144	1395
168	930
192	648
216	440
240	274
264	194
288	116
312	82
336	56
360	44
384	28
408	12
432	12
456	8
480	6
504	2
528	1
552	0
576	2
600	1
624	0



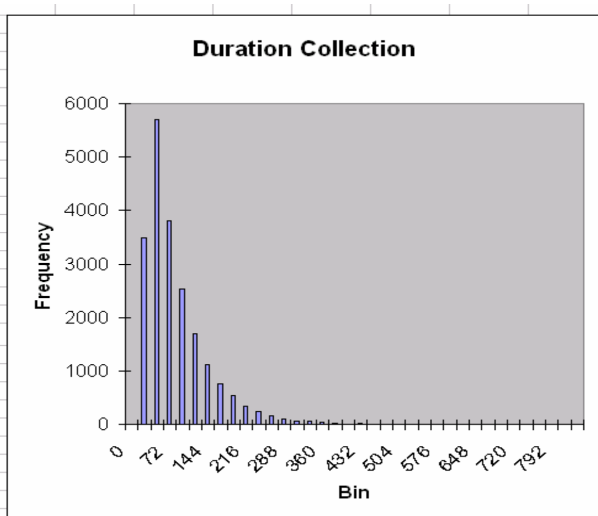
Column1	
Mean	85.32067528
Standard Error	0.41767349
Median	67.472218
Mode	61.904001
Standard Deviation	60.0244907
Sample Variance	3602.939484
Kurtosis	6.280787719
Skewness	1.975267513
Range	825.542648
Minimum	4.123022
Maximum	829.66567
Sum	1762127.907
Count	20653
Largest(5000)	110.322327
Smallest(5000)	42.488289
Confidence Level(95.0%)	0.818673169

Figure 15. Baseline Histogram of Duration Total

The consequence of the uneven time to exit values is that many standard statistical measures are not useful. For example, the average total duration is 84.1 hours, not an unreasonable value at first glance, but the standard deviation is 59.5, that is 71% of the average and highlights the discrete, widely spaced events that make up the sample. A look at some histograms of the data (Figures 15, 16, and 17) reveal that a more useful metric for this data will be the median (Sachs, 1984) as the data is highly skewed to the right by repeated attempts to collect. Note that the confidence interval reported by the Excel program in the figures assumes a normal distribution; not accurate for the skewed data of the simulation: Nor is the mode appropriate for real-valued data.

Regarding the differences between priority 1 and 2 RFI times in the process (see Figure 17), there were no significant differences revealed in the average or median baseline simulation results. What was significant was the much longer maximum times priority 2 RFIs spent in the system (Figure 18). This is a logical result given the relative scarcity of Priority 1 targets (1 for every 20) and their placement at the head of every queue (except the *Collect* block, which sorts by latitude-high to low).

Bin	*Frequency*
0	0
24	3490
48	5696
72	3799
96	2538
120	1699
144	1124
168	749
192	540
216	329
240	233
264	160
288	96
312	59
336	51
360	31
384	23
408	9
432	10
456	7
480	4
504	1
528	1
552	1
576	1
600	1
624	0
648	0
672	0



	Column1
Mean	72.22623695
Standard Error	0.415331309
Median	54.210923
Mode	163.107575
Standard Deviation	59.68789229
Sample Variance	3562.644486
Kurtosis	6.51046532
Skewness	2.018265242
Range	824.064112
Minimum	0.16455
Maximum	824.228662
Sum	1491688.472
Count	20653
Largest(5000)	97.337933
Smallest(5000)	29.422943
Confidence Level(95.0%)	0.814082308

Figure 16. Baseline Histogram of Collection Times

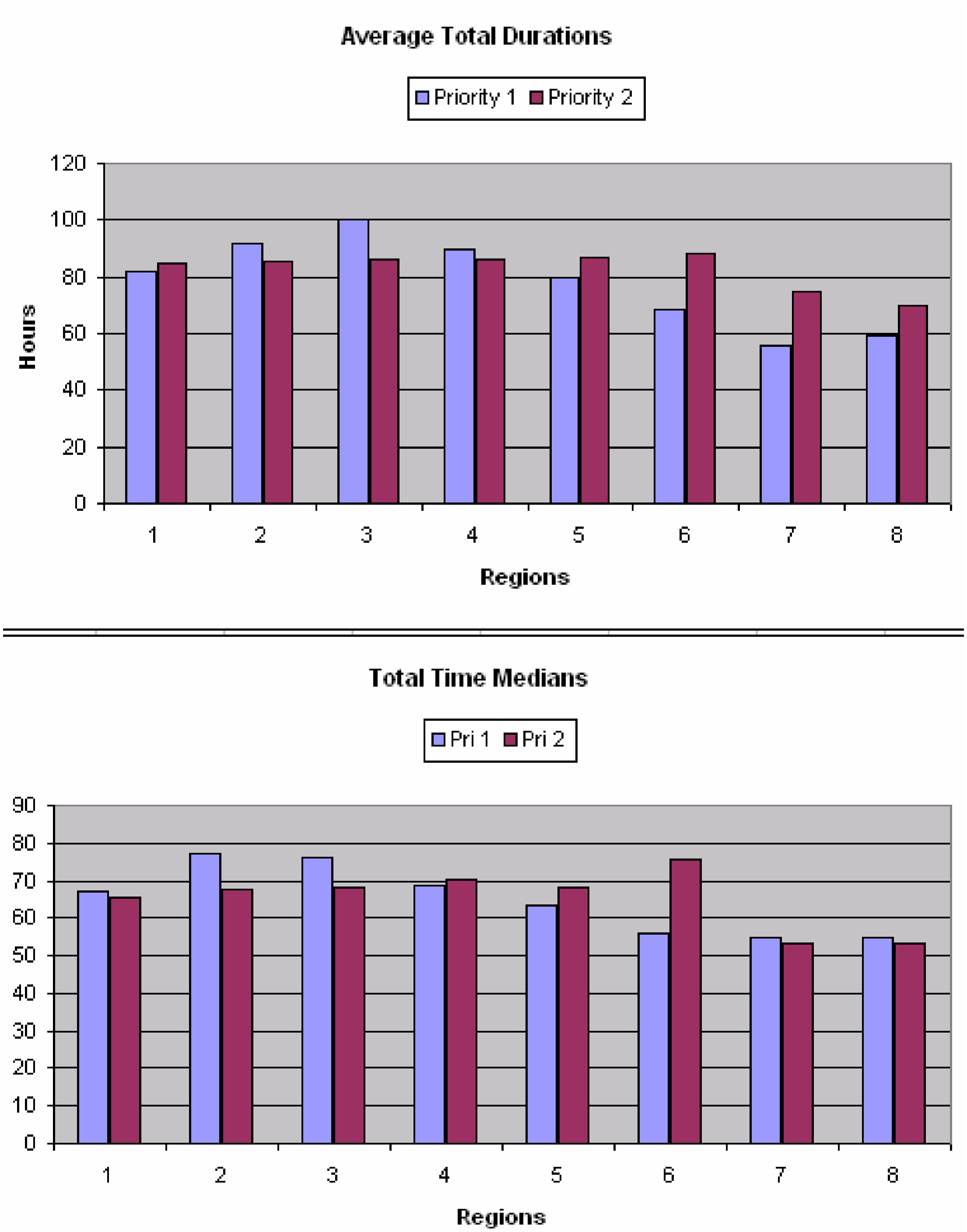


Figure 17. Baseline Average and Median Duration Totals for Priority 1 and 2 RFIs.

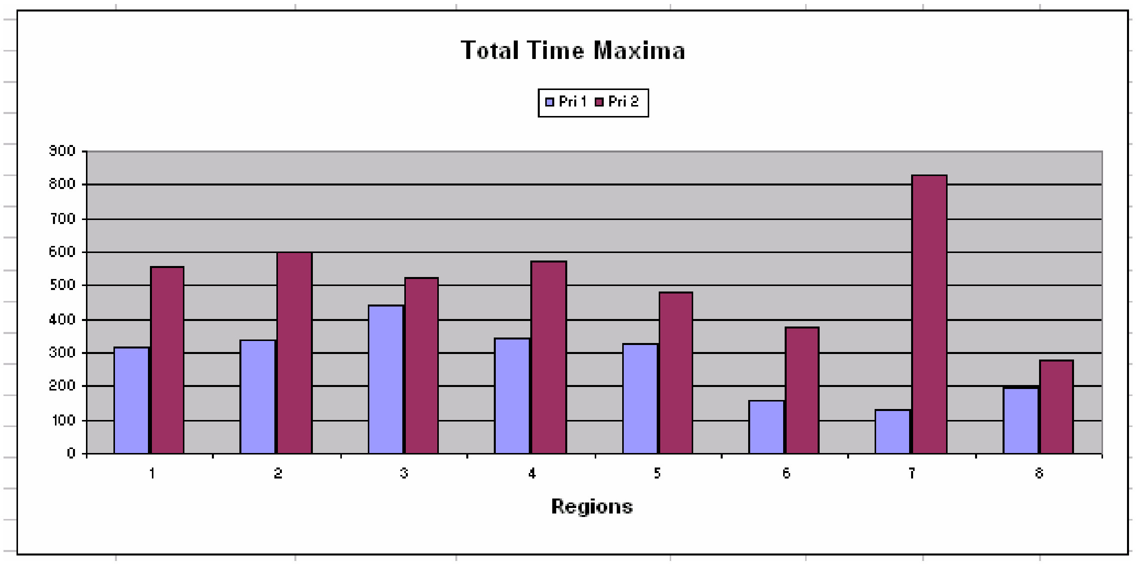


Figure 18. Baseline Maxima for Duration Total by Region.

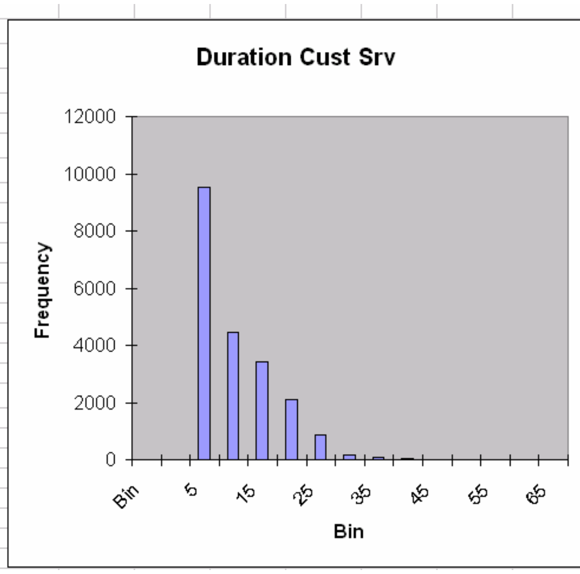
The lack of significant difference in the medians suggests the collection model used requires higher loads than in the baseline conditions to bump off priority 2 targets in large numbers or that the model does not operate sufficiently close to capacity to exercise more frequently the prioritization of priority 1 targets. Examination of the animated baseline run does, in fact, show that the *Room in Pass que* limit was never exceeded. This potential will be examined in Case 1 (no weather prediction) as 65 percent more RFIs will reach the queue without a weather decision, and in Case 4 with higher rates of RFIs.

The fact that the model does not run close to its capacity is a positive. Given the essential question of the research to find shortest times, running the model close to its maximum throughput would be counterproductive. Of course, we are not only interested in shortest possible times, but also shortest general time. The result above indicate that median is a better single descriptor of general expected time (60 to 70 hours) than average for this data, but the maxima may be best for observing certain effects.

Region 6, 7, and 8 data were the only sets subject to any significant variability (especially priority 1) between runs with identical parameters, due to their smaller sample sizes of 3 percent for region 6 and half that for regions 7 and 8. Given the additional investment required to combine data from runs, it was decided not to pursue better characterization. This decision was further justified by the absence of actual environmental factors in the model that make the model itself unreasonably optimistic about imaging the poles. These factors include the assumption that imaging occurs around times of equinox, providing daylight to both poles and the assumption that polar cloud cover is about the same as the worldwide average rather than much higher, as is the case in truth (ISCCP, 2005). Finally, the interest of the research question is fundamentally for non-polar latitudes.

Other steps in the Baseline process are customer service and post-collection processing (Figure 19 and 20). Both of these times are very small compared to the duration of time spent in collection, but for the very fastest total times, these small periods may still be significant. The impact of processing resources will also be explored in Cases 3 and 4.

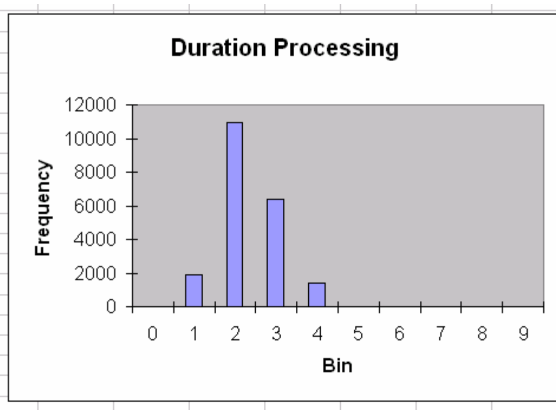
Bin	Frequency
0	0
5	9529
10	4462
15	3414
20	2101
25	876
30	145
35	71
40	39
45	12
50	2
55	1
60	1
65	0



Column1	
Mean	7.684381148
Standard Error	0.046794425
Median	5.81263
Mode	1.471654
Standard Deviation	6.724897819
Sample Variance	45.22425067
Kurtosis	1.330230429
Skewness	1.130805043
Range	57.421413
Minimum	0.411057
Maximum	57.83247
Sum	158705.5238
Count	20653
Largest(5000)	12.271266
Smallest(5000)	1.691393
Confidence Level(95.0%)	0.091720785

Figure 19. Baseline Duration of Customer Service Activity

Bin	Frequency
0	0
1	1868
2	10955
3	6389
4	1410
5	31
6	0
7	0
8	0
9	0
ıre	



Column1	
Mean	1.849873627
Standard Error	0.004796637
Median	1.752207
Mode	1.317109
Standard Deviation	0.689332015
Sample Variance	0.475178626
Kurtosis	-0.348772728
Skewness	0.523040801
Range	4.134015
Minimum	0.40822
Maximum	4.542235
Sum	38205.44001
Count	20653
Largest(5000)	2.341029
Smallest(5000)	1.292697
Confidence Level(95.0%)	0.009401789

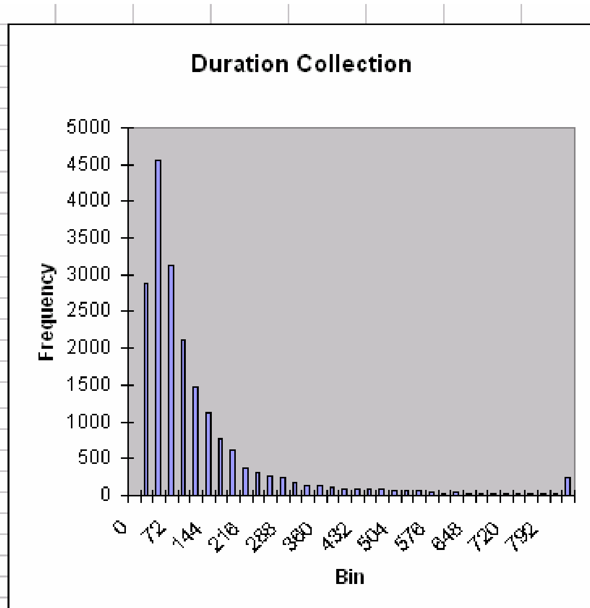
Figure 20. Baseline Duration of Post-collection Processing

Case 1: No Attempt to Predict Weather Over Target

In this case the *PredictGoodWx* decision in the SCC Processing and Satellite Collection section of the model is set to 100 percent. Thus, all collectable targets will make it to the *Room in pass que* decision. All targets in the *Collect* process will be processed, then downlinked, then computer processed to level 2 before being evaluated for quality. At this stage the value for the *Image OK* decision, in the last section of the model, was changed to 35 percent in order to reject the 65 percent of images that were taken of clouds. All of these failed RFIs must then be sent back through collection for re-imaging.

Obviously there is a large price the operator must pay for effectively having to take 65 percent of images more than once. This penalty shows in the effective number of images per hour for this case: 9.77 per hour; 13 fewer per day; 1060 fewer for the 2000 hours sampled. In addition, Figure 21 shows the costs in ability to deliver timely images to customers by the large number of RFIs above 836 hours (34.8 days), the limit of the histogram.

Bin	*Frequency*
0	0
24	2888
48	4560
72	3126
96	2115
120	1469
144	1128
168	772
192	623
216	369
240	306
264	275
288	239
312	184
336	133
360	128
384	105
408	86
432	97
456	78
480	78
504	74
528	56
552	59
576	39
600	33
624	45
648	30
672	20
696	29
720	16
744	27
768	23
792	18
816	14
More	248



Column1	
Mean	116.7468829
Standard Error	1.170043623
Median	64.01766
Mode	39.012685
Standard Deviation	163.3458005
Sample Variance	26681.85053
Kurtosis	22.58118729
Skewness	4.079357349
Range	1811.32993
Minimum	0.200254
Maximum	1811.530184
Sum	2275396.748
Count	19490
Largest(5000)	126.657836
Smallest(5000)	33.400043
Confidence Level(95.0%)	2.293383626

Figure 21. CASE 1 Histogram of Duration Collection

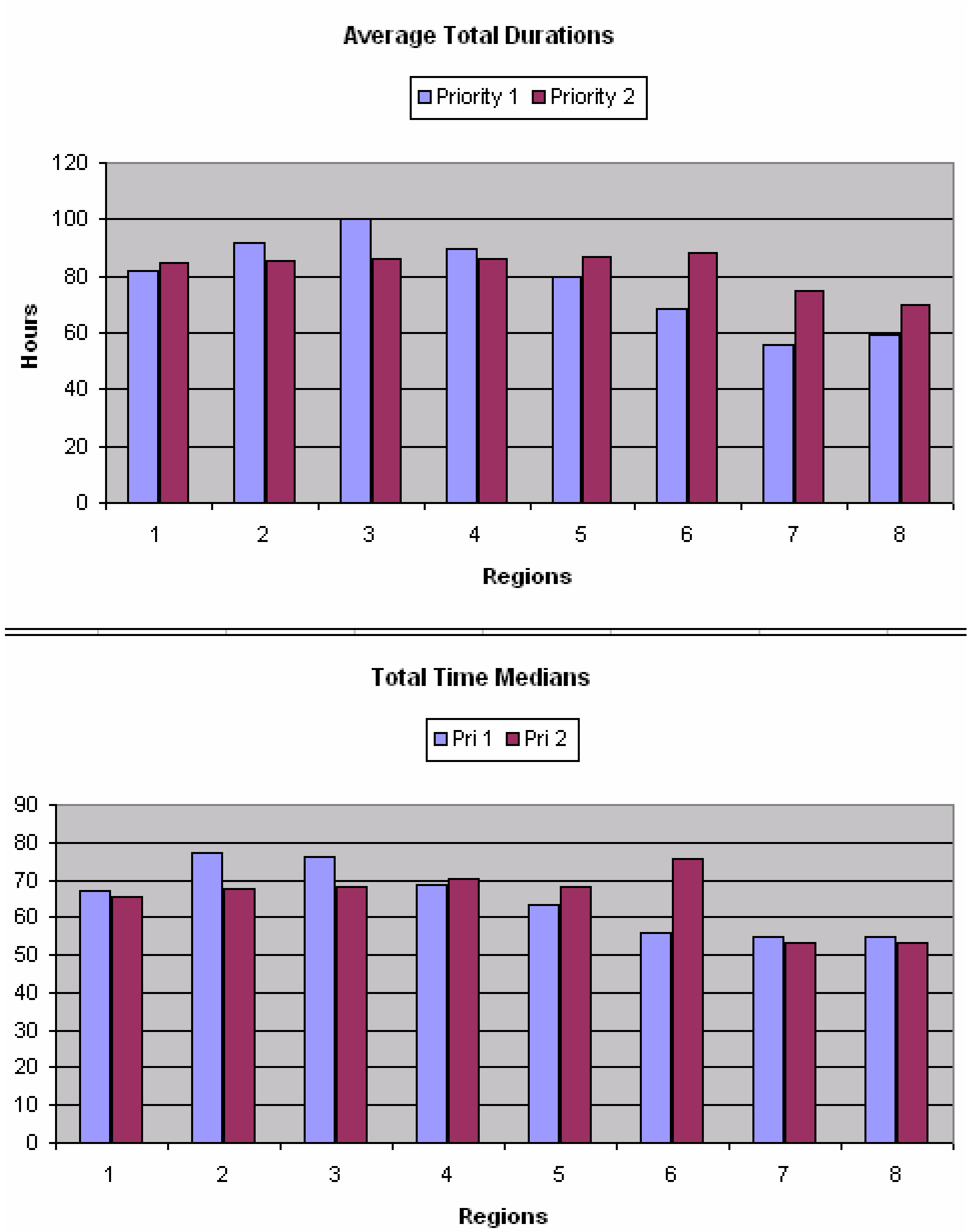


Figure 22. CASE 1: Average and Median Duration Total

In spite of the expectation of extreme behavior in the 2000 hours, the average and median values (Figure 22) for total time in the system are not appreciably different from the baseline case: Another view of the data is in order. Looking at the time series in Figure 23 (items appear in the order they exit the system), it is apparent that the process is exhibiting signs of runaway behavior: Extreme times are becoming more extreme and this also shows up in the maximum values (Figure 24).

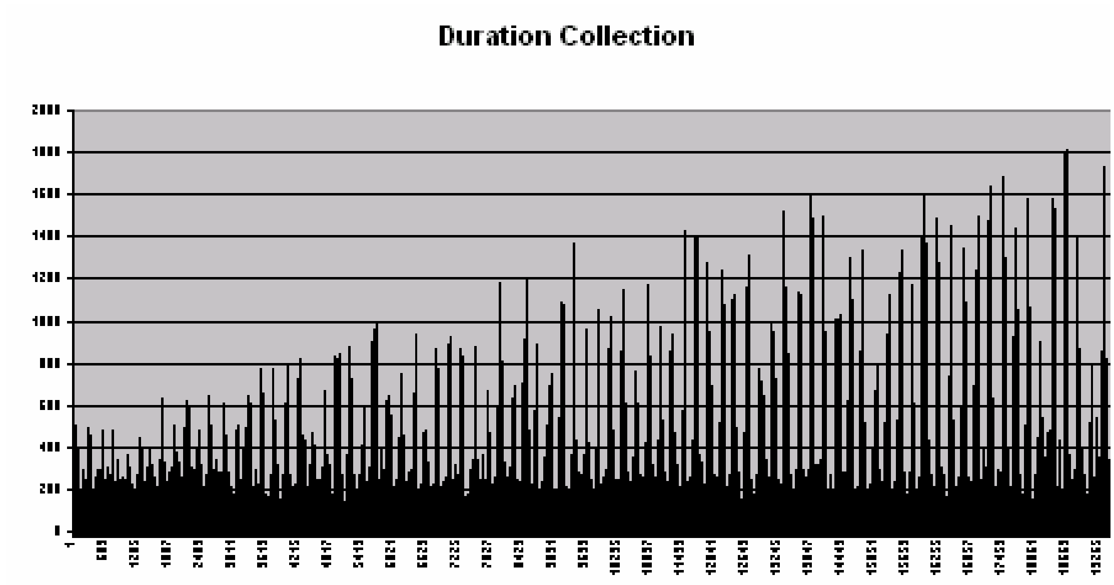


Figure 23. CASE 1: Time Series of Duration Collection

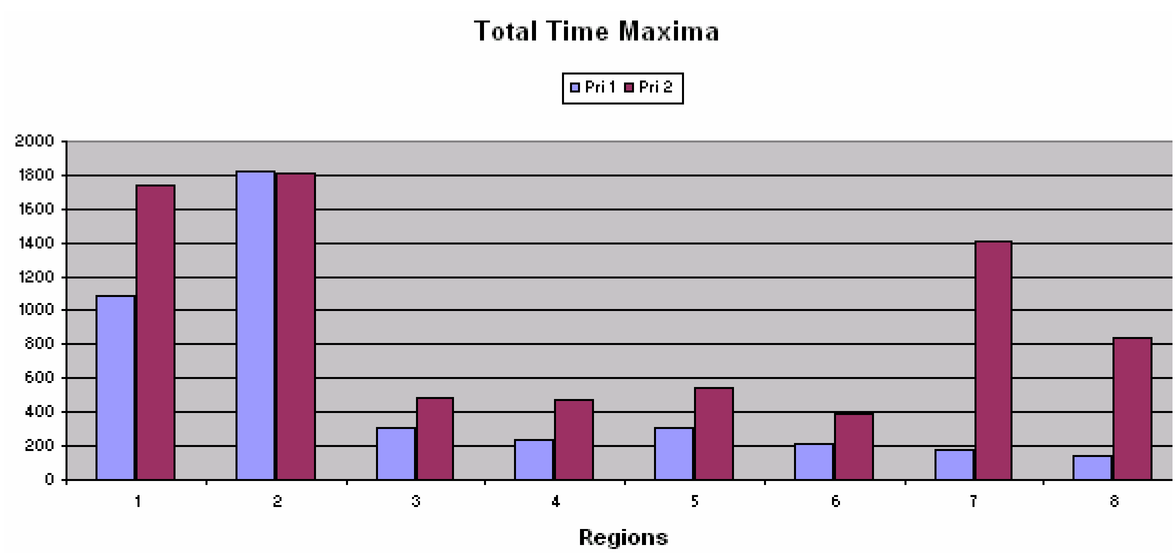


Figure 24. CASE 1: Maximum Duration Totals by Region

The companies that are involved in commercial imagery are aware of the weather problem. The first, and earliest available, solution was to have extra capacity to deal with weather, as well as surge demand. More recently, weather forecasting has become a business driven requirement for the industry. Both QuickBird and SPOT user guides (2004) highlight the fact that weather forecasting is done to help the customer get a usable image, but it also serves a purpose in SCC pass planning, and it is reasonable to assume other operators are doing the same.

The lack of impact on average or median times in Case 1 further makes the case that the model is capable of very high throughput. The total images per hour for Case 1, while lower than baseline, was still high enough that lots of images were being completed, but it would be much more difficult for the operator to assure a given image would be complete in a short period, a necessity for priority 1 customers.

Case 2: Greater Overlap of Regions in Longitude

For this case, changes were made to the assignment of latitude and longitude corresponding to the geographic regions used by the model. The changes were made with the purpose of creating more situations where a single imaging pass would cover regions with a more equal number of RFIs for each region (see Figure 25). This is a matter of environment the system must operate in, and may change in response to world events.

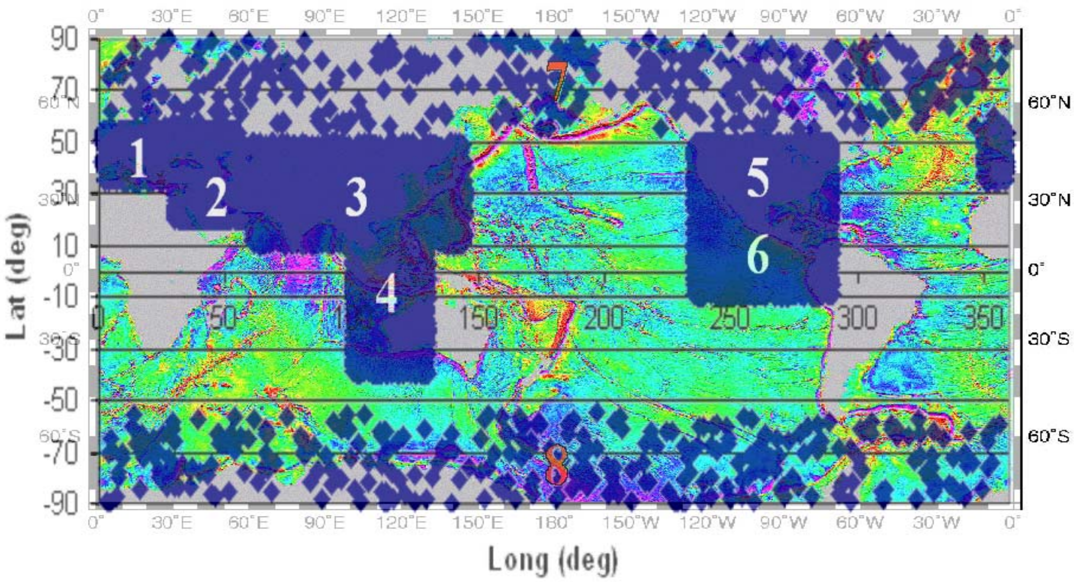


Figure 25. CASE 2: Map of Overlapping Regions.

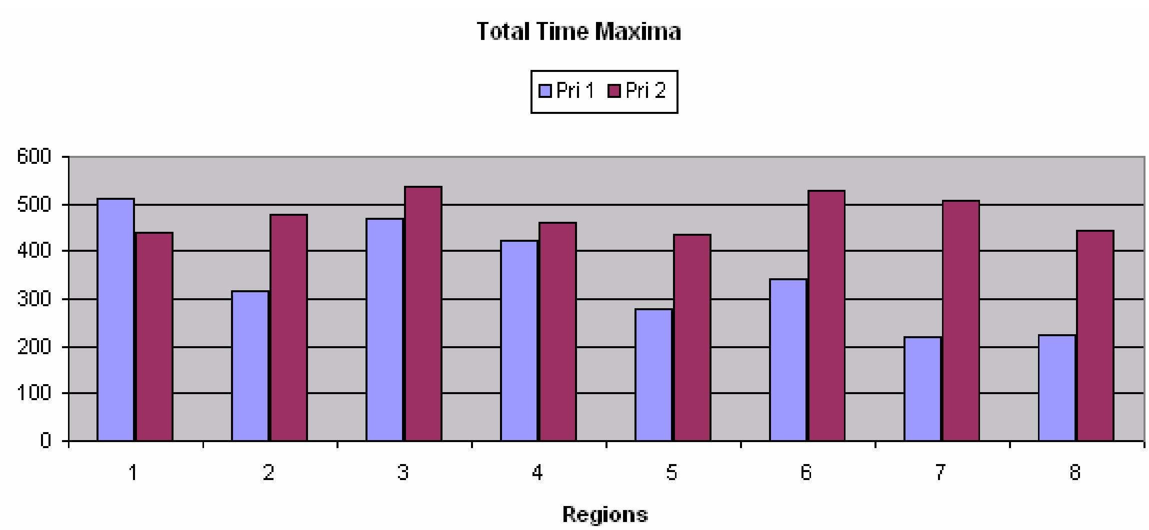
In addition to changing the arrangement of the regions, the frequencies of their occurrence in the target pool was changed from the baseline model (see Table 2) to make them more even and ensure greater conflict for imaging. The new weights are listed in Table 3. The altered cumulative distribution for the *RegionAssign* block is included in Appendix A.

Table 3. CASE 2: Altered Regions and Weights.

Region attribute	**Geographical Region (approx)**	**Weight (%)**	**West Longitude (degrees)**	**Latitude (degrees)**
1	Europe	20	-10 to 305	35 to 55
2	Middle East	20	300 to 330	20 to 40
3	Asia	13	215 to 300	10 to 50
4	Indonesia and Australia	12	230 to 260	-40 to 10
5	U.S.	20	70 to 125	25 to 50
6	Central America	12	70 to 125	-10 to 25

7	Arctic	1.5	0 to 360	55 to 90
8	Antarctic	1.5	0 to 360	-90 to -55

The apparent results of these alterations were fairly slight. There is some increase in the median times of region 5 and 6 where there was no prior overlap, but this may also be due to the more equal weights between the two locations (Figure 26). These results further indicate that there is excess capacity in the imaging system.



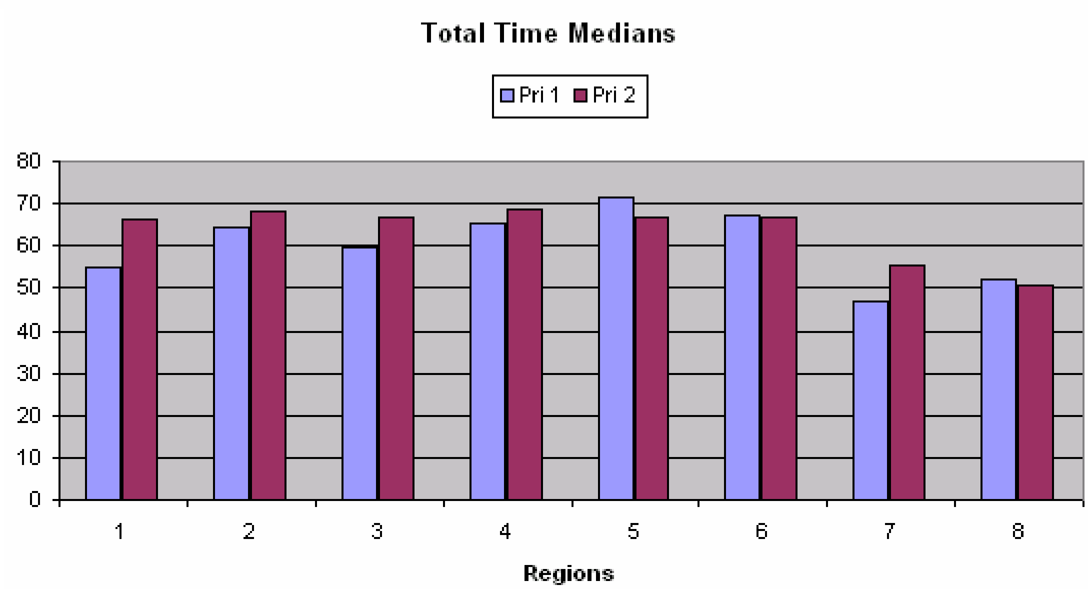


Figure 26. CASE 2: Maxima and Median Duration Totals by Region

An additional observation to make on this point involves two significant attributes of the model itself. First is the random assignment of latitude and longitude to target within a region. Not only is this is rarely the case in truth (mapping is the counter-example); it de-emphasizes the potential for conflict between two targets. For example, targets may be too far apart (e.g. on opposite sides of the satellite's ground track) for both to be imaged even though both are individually obtainable. Second, and more significant, is the assumption that the four satellite constellation can take 100 images every 100 minutes with no mechanism for prioritizing by region. In practice, more images are taken of regions that can afford to buy them.

Case 3: Fewer Post-collection Processing Resources

This case decreases the computer resources assigned to *Image Processing* at the data processing site and the resources assigned to image *Delivery* were also decreased. This second **resources** are called bandwidth in the model and can be considered the limit on the rate at which the bits of the FTP file can travel from the satellite operator to the customer. The parameters (see Appendix A) were calculated based on the speed a 100 MB image can travel on a T1 line (1.544 Mbps) for the minimum of the triangular distribution, versus a 44 Kbps modem for the maximum time, with a 3-way shared T1 for the expected value. For the baseline case, 40 of these resources (10 per vendor) are available to each of the cooperative ground system. For this case, both sets of resources were decreased by 25 percent.

This situation was suggested early in the development of the model when apparently effective collection parameters were still generating runaway behavior in the total times. Eventually the subtle reliance on the ground systems was discovered. Essentially, the ground systems used the extended periods between productive passes to work off the backlog generated by the heavy imaging passes. If the resources are not enough to get through the backlog before the next wave of images arrives, the backlog gets bigger and bigger with every day. In practice it is the total bandwidth in and out of locations that will matter, breaking the capacity into 40 pieces is just modeling convenience. The issue of how robustly to equip the ground system is a basic question of the business model: Too much resource costs more money than necessary if it doesn't bring advantage; too little will bog down under demand and not allow timely products. This is seen in the comparison of time series between baseline and this case (Figure 27). The increased jaggedness of the Case 3 data (on the right) is symptomatic of periods of overload (though not continuing overload).

This situation can occur in practice when remote receive stations experience demand they are not resourced to handle. These remote stations were connected by commercial modems no more capable than household 56 K models (Zesiger, 2001). When they received more than a few images day after day, they would have to be skipped by employing satellite storage until they could download collected image data to another site.

Baseline Duration Processing   Case 3 Duration Processing

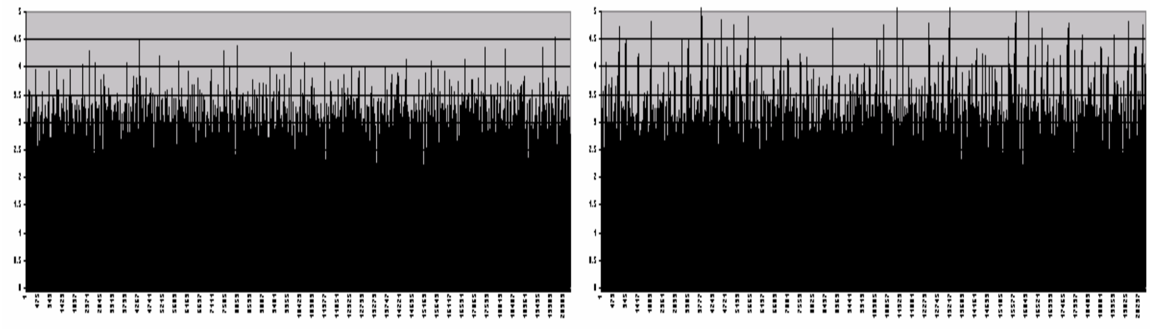


Figure 27. CASE 3: Time Series Duration Processing

Also significant to the post-collection processing is the effect it has on the total times of priority 1 and 2 RFIs. Since the priority 1s are handled first in processing they suffer no degradation (at least in small proportions) in the last stage. However, priority 2 RFIs end up staying in the system somewhat longer than previously (Figure 28).

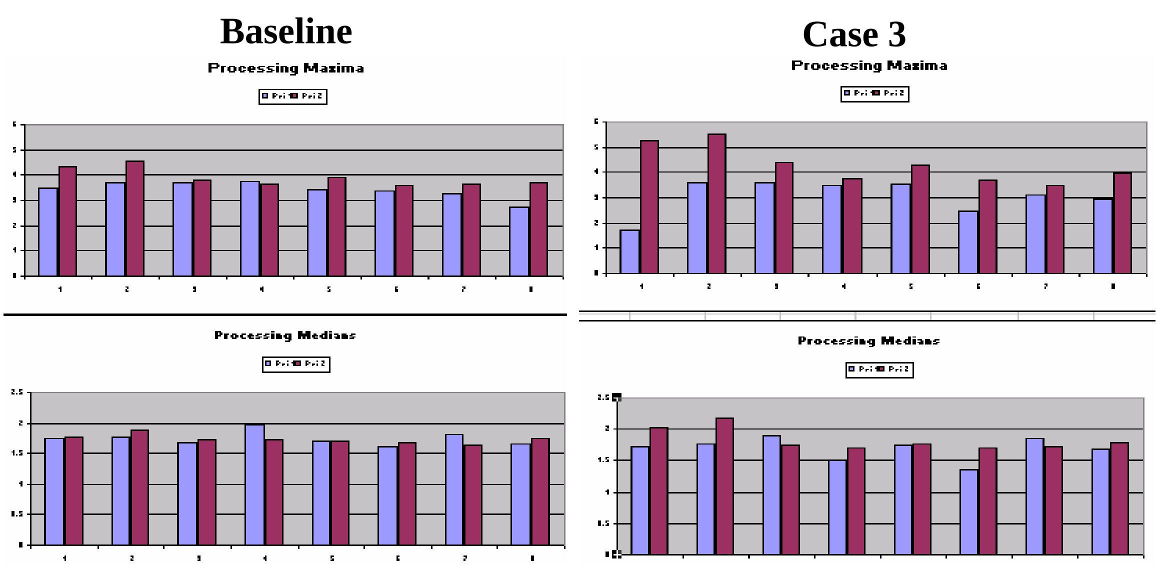


Figure 28. Baseline vs. CASE 3 Processing Maxima and Medians

Case 4: More Priority 1 RFIs

Case 4 increases the number, and thus the proportion, of priority 1 RFIs in the system by a factor of 2. The total number amounted to 1171 more data points over the 2000 hours, or about 1 extra RFI for every 2 hours. The actual counts for this run were 938 more priority 1s and 67 fewer priority 2s. The primary effect of the extra priority RFIs was an increase in the priority 1 maxima of about 50 to 100 hours. The effect on priority 2 total times is also apparent, and more certain given the much larger sample sizes (Figure 29).

The point of this case is to emphasize the statement made in the assumptions (assumption #6) that high priority treatment should be costly for good business reasons. If there are too many high priority RFIs in the system the differential is diluted for all high priority customers. At this load and processing capacity there was no noted effect on time required to process priority 2 orders.

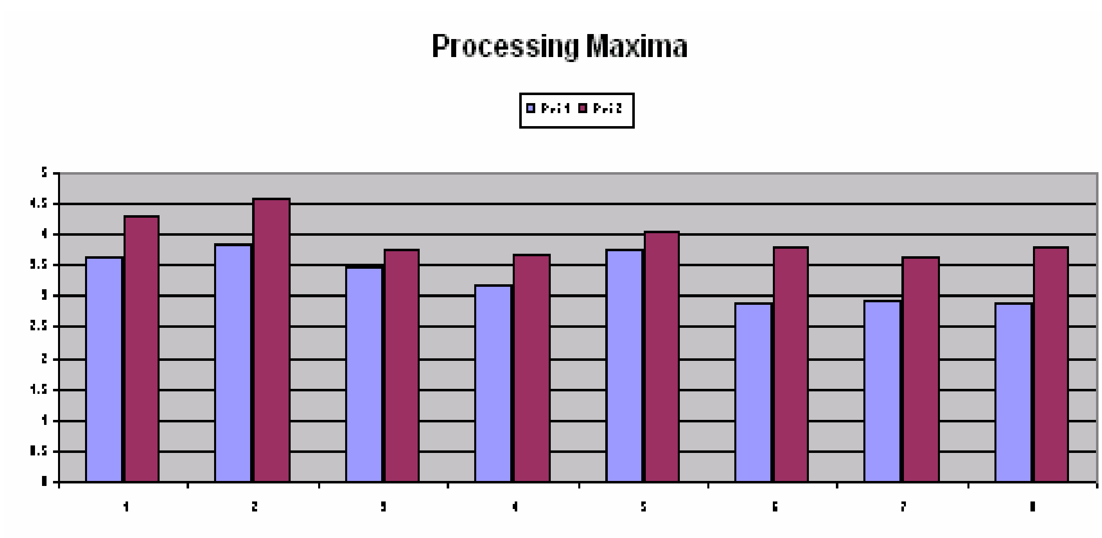


Figure 29. CASE 4: Duration of Processing Maxima by Region

Case 5: First-In-First-Out Processing

In conversation with DigitalGlobe (Wood, 2004) it was noted that when a customer buys priority one service that the preferential treatment goes all the way to delivery. By changing the processing priorities of the two resourced processes in the post-imaging section of the model to First-In-First-Out (FIFO) it was with the intention of measuring the difference this would make in the last stage. In contrast, no difference was noted (Figure 30). At higher loads in the delivery process, this would inevitably slow orders, but that point was not reached in this case.

One very significant factor that differs between this modeled result and a similar occurrence in the industry is the level of processing assumed in model. By limiting consideration to level 2 processing (see Table 1) in the quest for the fastest delivery answer, the model forgoes consideration of processing levels that take hours of processing time, rather than minutes, and may require additional imaging as well.

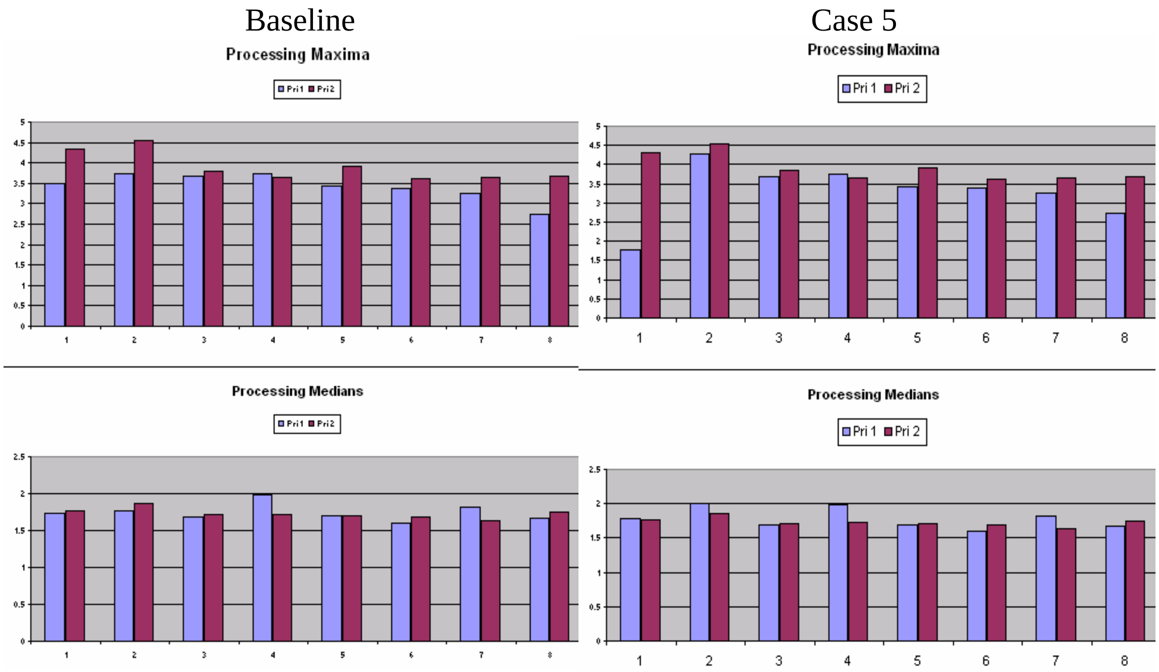


Figure 30. Baseline vs. CASE 5 Processing Maxima and Medians

Case 6: Uniform, Worldwide Target Distribution

Case 6 explores the system operation under essentially continuous load. There is no consideration to ocean areas versus continental, and, for the purpose of analysis, all the world between 55 degrees latitude North and South, is region 1. There is predictably little difference between the resulting duration data and the overall averages for the baseline case (Figure 31). Again it is the maxima that primarily distinguish between the levels of priority.

This case is classified an environmental condition that would have to be allowed for if the satellite operator saw their niche as large area coverage. This is not the case for the high resolution imagery industry, but would be appropriate for certain medium and most low resolution systems and products. Synthetic Aperture Radar (SAR) systems

(RADARSAT and the future RADARSAT 2) perform in a mix of modes including medium and low resolution operation for the express purpose of larger area terrain elevation mapping missions as well as being in demand for polar images of sea ice that could pose hazards to shipping and fishing vessels. A further requirement for worldwide operations is a worldwide data receive architecture. The last was assumed for the aggregate model of satellite operations, but represents a real problem for a single system operator.

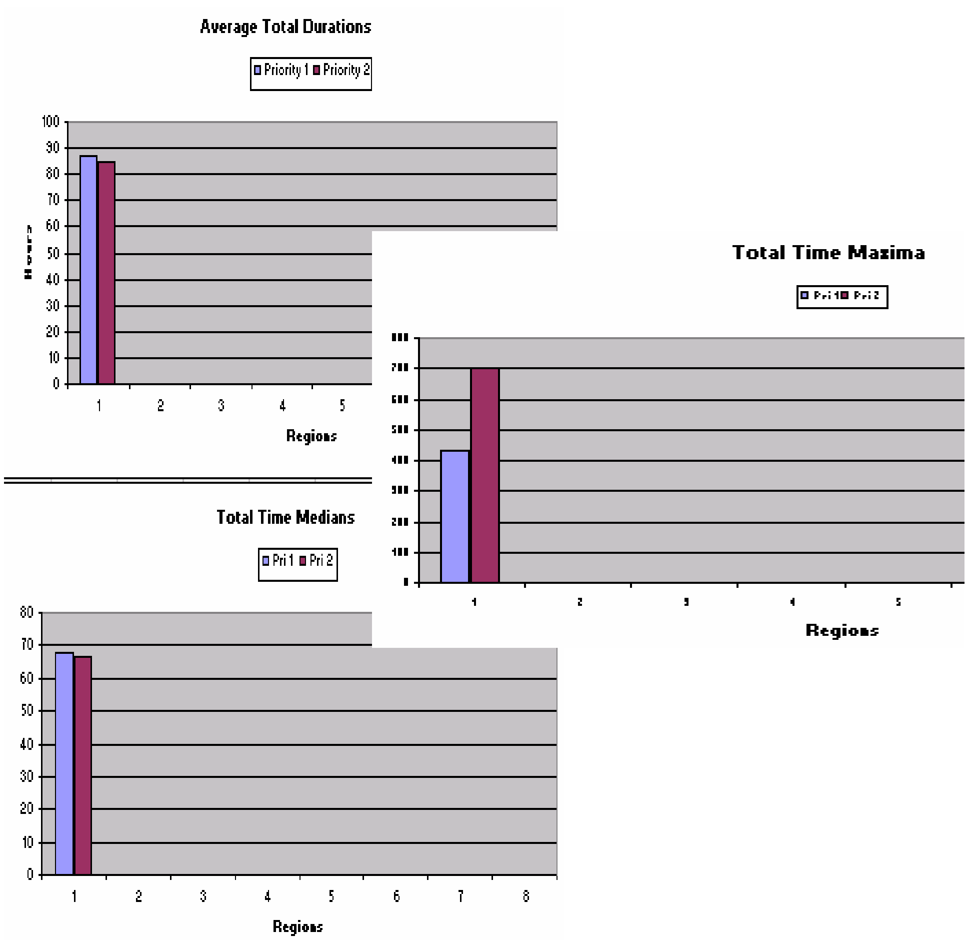


Figure 31. CASE 6: Total Duration Average, Maxima, and Median

Summary of Cases

Looking back through the total time results of the seven cases (Figure 32) it is apparent that only the decision to not attempt to predict weather over the target area significantly impacted the turn times of the image orders (only the first 144 hours is shown). Region 5 was used for the comparison in the figure due to its large number of RFIs for all cases and its involvement in Case 2's increased region overlap. The slight increase in RFIs for Case 4 results is attributed to the larger number of total RFIs, as there was no change in other parameters. This result for case 4 also serves to highlight the capacity of the model to handle more orders than were present in these cases. In fact, an attempt was made to determine the model's RFI ceiling, but an entity limit in the Arena software was reached before any RFI ceiling was observed.

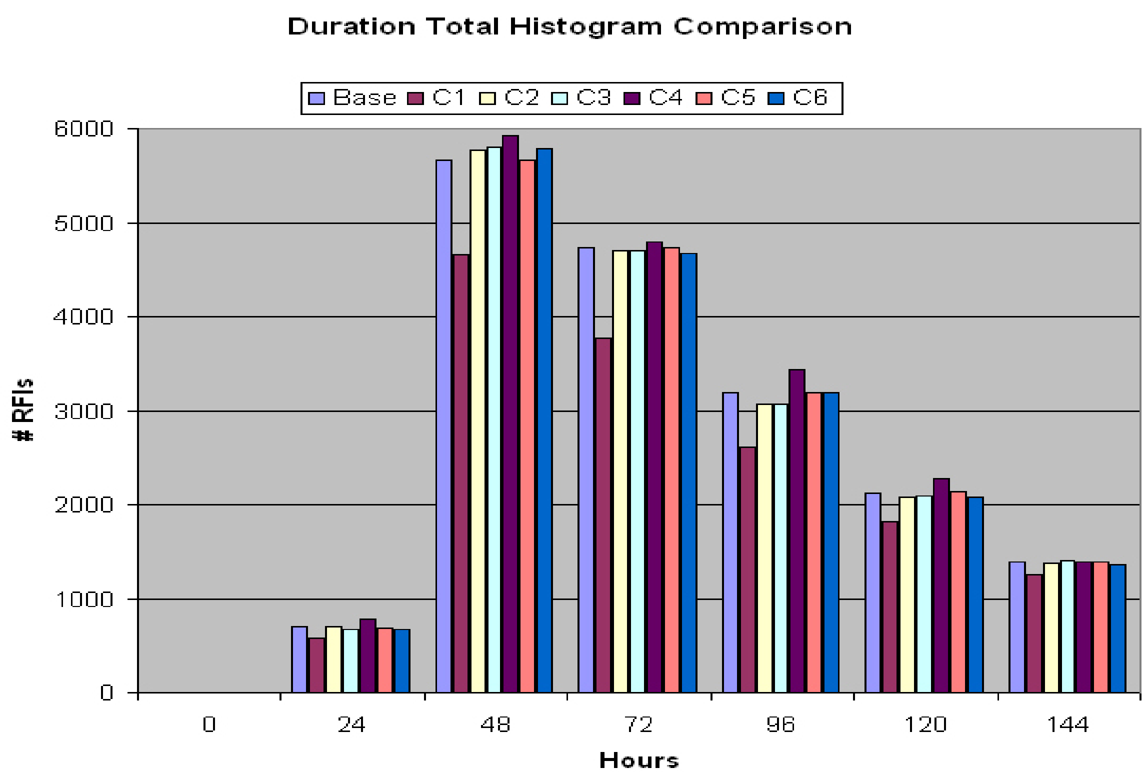


Figure 32. Region 5 Duration Totals For All Cases

Another way of looking at the histogram data for the cases is shown in Figure 33. This is a plot of the 5000th largest (counted back from the maximum) and 5000th smallest (counted up from the minimum) duration totals for each of the Cases and including all the regions. This figure also demonstrates the tendency of the total time data to skew rightward in Case 1, as weather forces reshooting images, and in Case 2, which was not previously noted, as a consequence of greater overlap of regions. However, the turn time of the fastest 5000 RFIs is only slightly impacted in all the cases.

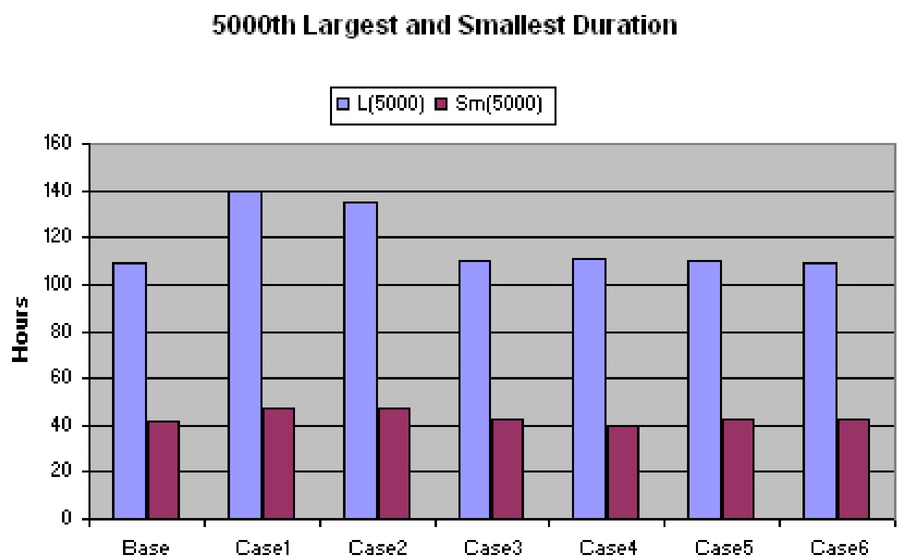


Figure 33. 5000th Largest and Smallest Duration Totals

Looking at a case-wise summary (again using region 5) of the three basic statistics used (Figure 34), the same result is not as clearly observed as Case 1 did not generate large spikes in maxima for Region 5. In fact, Figure 34 highlights the small range of eight hours or less for the case averages and medians. Note the y-axis scale is different for figure 34 than previous graphs for the individual cases.

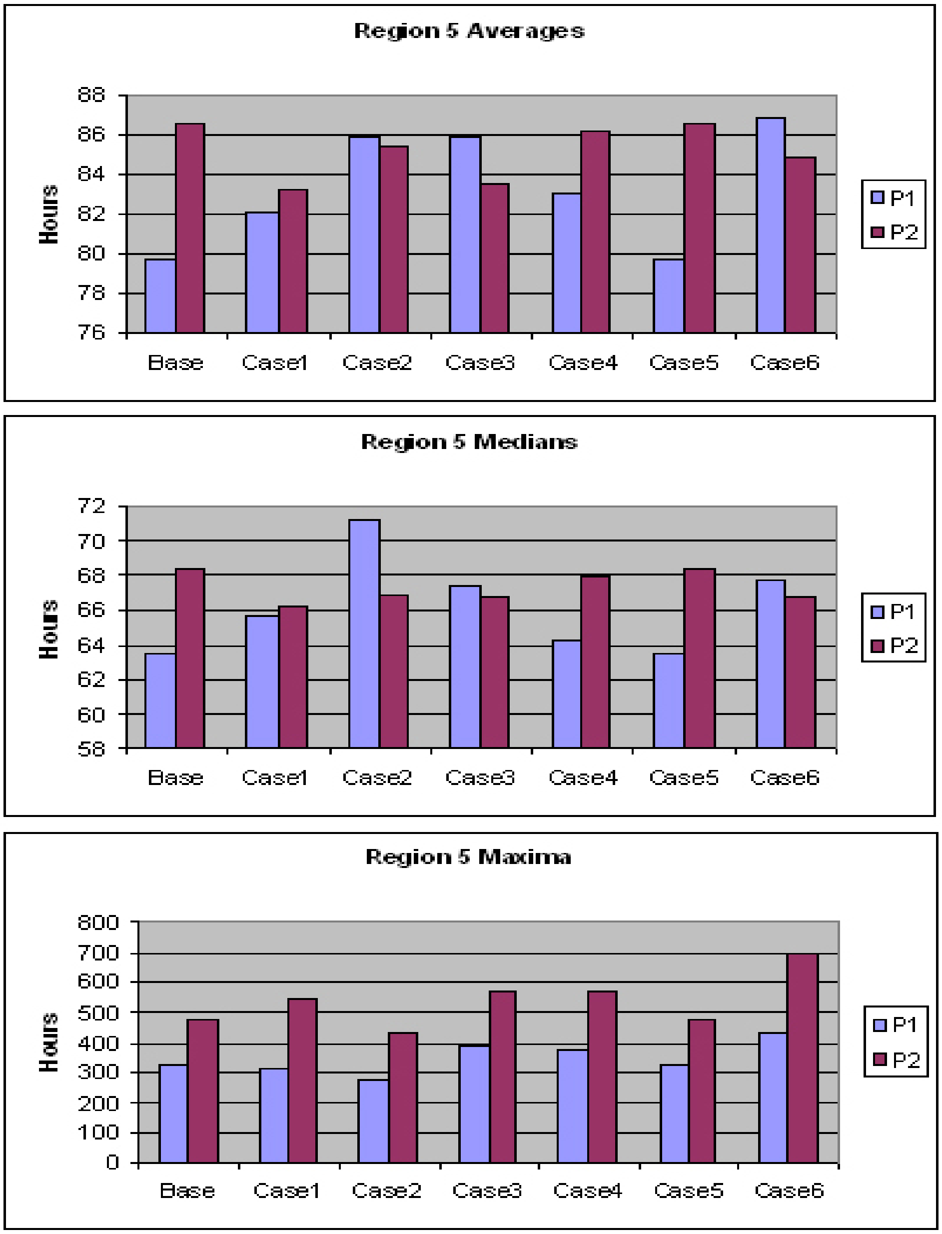


Figure 34. Region 5 Average, Median, and Maxima for All Cases

V. Conclusions

Summary

The basic question this research set out to answer was to estimate the shortest time, in general, it takes to receive an image of a general target. The most general answer is a median of 60 to 70 hours if the baseline assumptions are accurate for the situation. Significantly, the 5000^{th} lowest sample of about 20,000 (1/4 of the orders) was only 41.8 hours, with 700 below 24 hours (3.4%). For prediction of a particular image order, environmental factors dominate. The single most important additional information you can have is an accurate cloud forecast of the target location. Weather is generally even more important (67%) than the satellite coverage (60%), though uncertainty in weather forecasts will always be far greater than satellite positions.

The model built to answer the question proved robust enough to explore variations on the environment and the assumptions that went into its baseline results, and much more could be done. Questions of varied load, computer and bandwidth resources, weather impacts, and longitudinal demand were easily altered in the model with the capability to do more as analysis capability allows. The coverage technique allows general questions of access over time to be answered without reliance on moment to moment calculations by dedicated programs with learning curves every bit as steep as Arena.

Limitations of the model are its aggregate system assumptions and lack of an easy to use analysis tool. While it was a deliberate move to examine all the imaging satellites collectively, it would require changing a host of parameters to make the model a tool for assessing the pluses and minuses of a particular system or system change, nor would many of the other assumptions hold true for a single system. Analysis tools are essential for any simulation model intended to generate results in response to its users' questions: without them a model may not be worth using for the task. In retrospect, Excel was not the best tool to answer many of the questions that could be posed to the model.

Future Research

There are three main directions for furthering the model. The first is the satellite collection model. Separate models for each satellite could be developed with specific orbit, viewing ability, and targeting logic to better emulate actual satellite operations' specific and limiting factors. These could operate simultaneously on an RFI with the first to turn it around providing the what-is-the-fastest answer. If extended to include different ground models (e.g. DigitalGlobe's polar stations, or the more common basing in high demand areas) the model could provide even more detailed results to general and even particular questions of coverage or accessibility.

The second area addresses the single target limitation. By not allowing the model to handle multiple images per order/product, the model underestimates a great deal of the demand on the satellite's sensor. According to DigitalGlobe (Izard, 2005) point targets are the exception to the usual order. Not only does this result in the model underestimating demand on the sensor, it also dramatically under-represents the demands on the operators' computer processing capabilities and the personnel who use them, since the multi-shot tasks consume vastly more of these resources than level 2 processing of a single image.

The third problem has already been discussed somewhat; the problem of an analysis tool. While this model used a text file output for processing, Arena generates a richer Access database output file. A strong programmer could build better visualization and statistical tools using either of these outputs than used in this study. The motivation to do so is in the promise of the other two approaches to have a more flexible, realistic, and powerful tool to assess imaging space and ground systems for responsiveness.

Appendix A – Arena Model Configuration

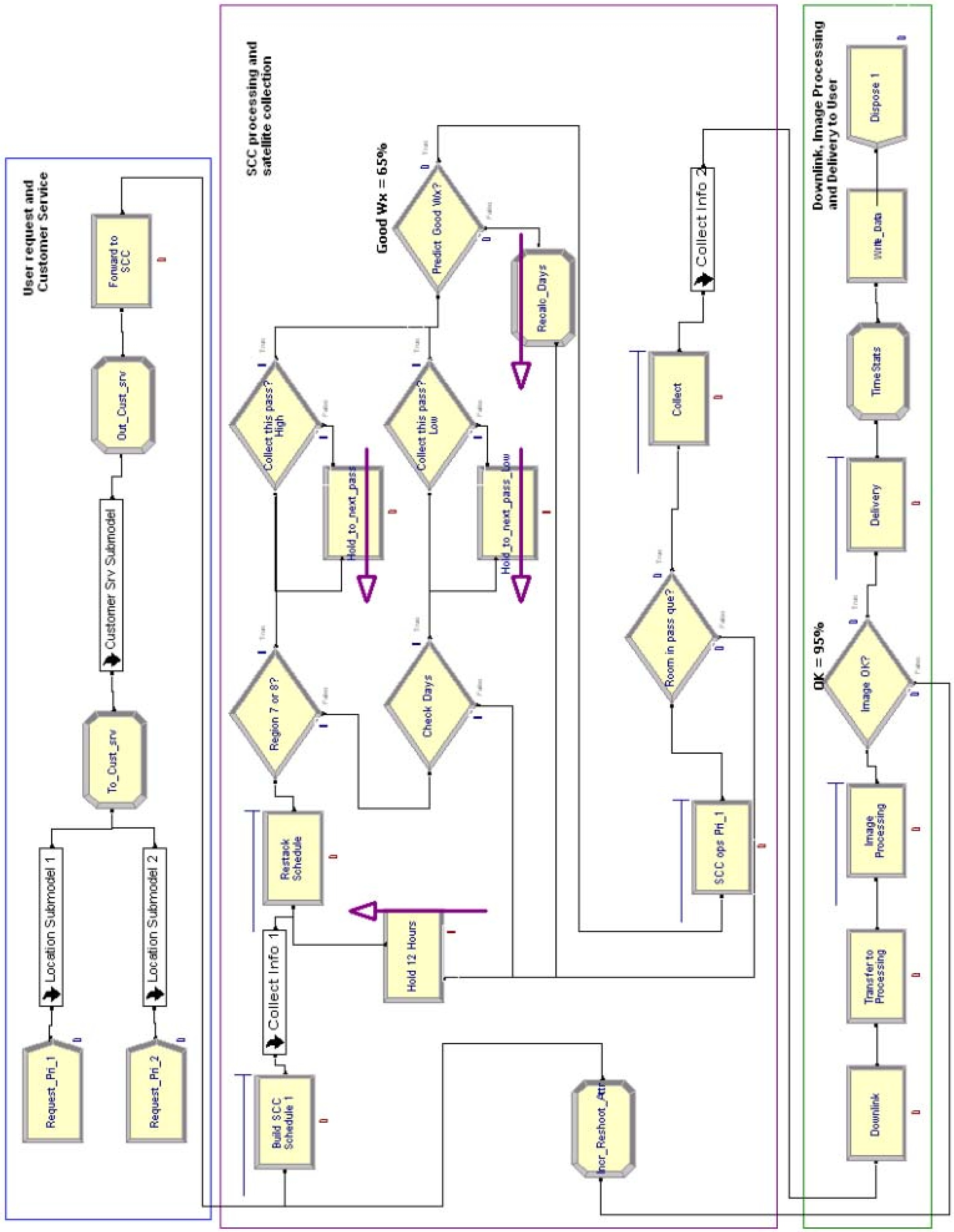


Figure A1. The Complete Arena Model

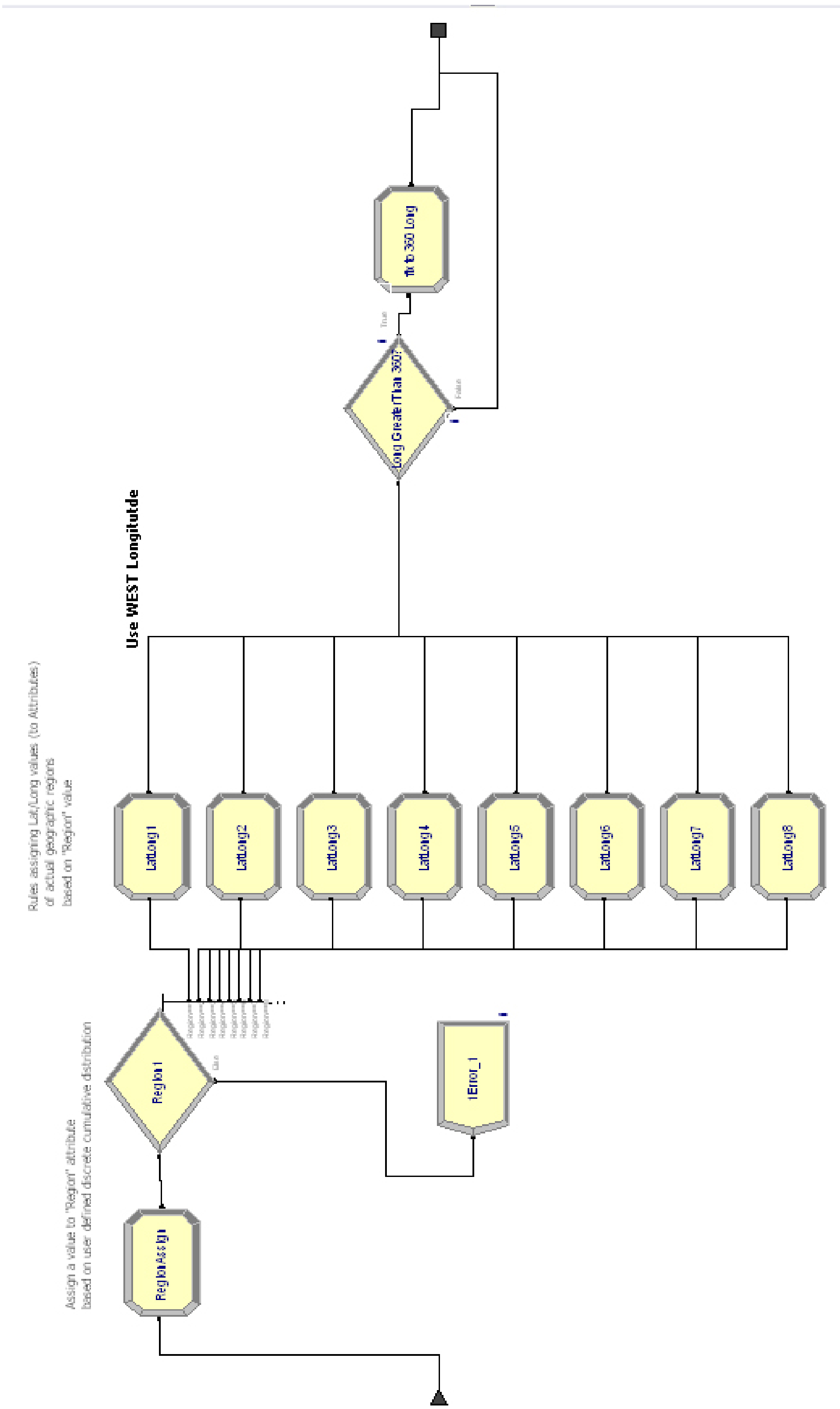


Figure A2. Location Submodel 1 and 2

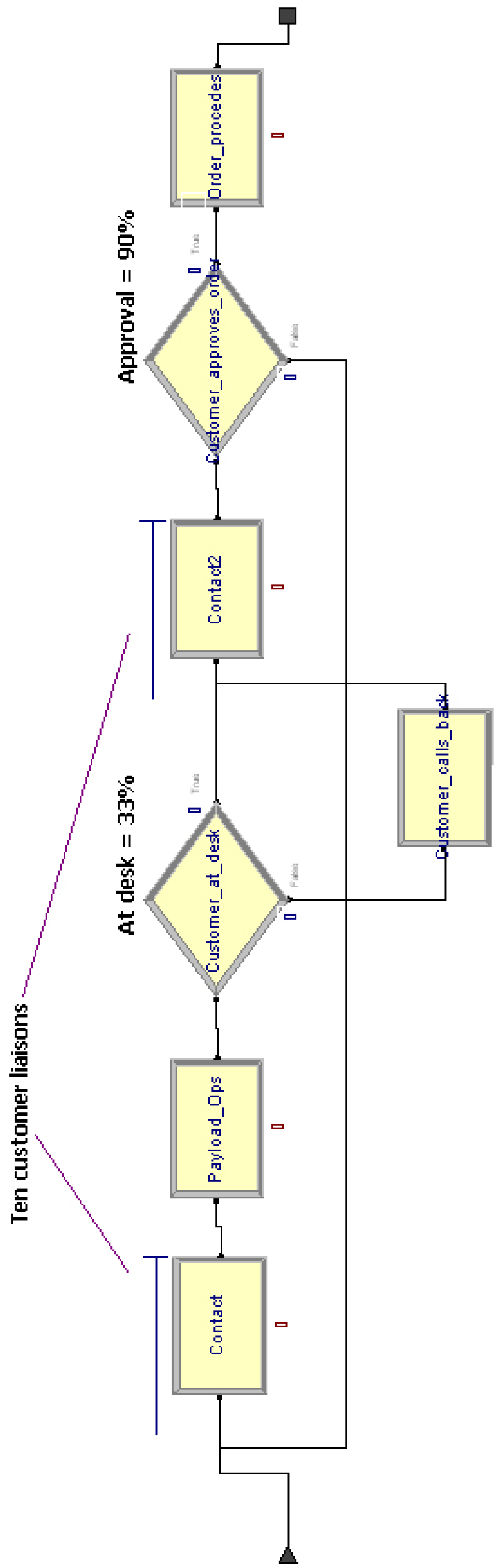


Figure A3. Customer Service Submodel

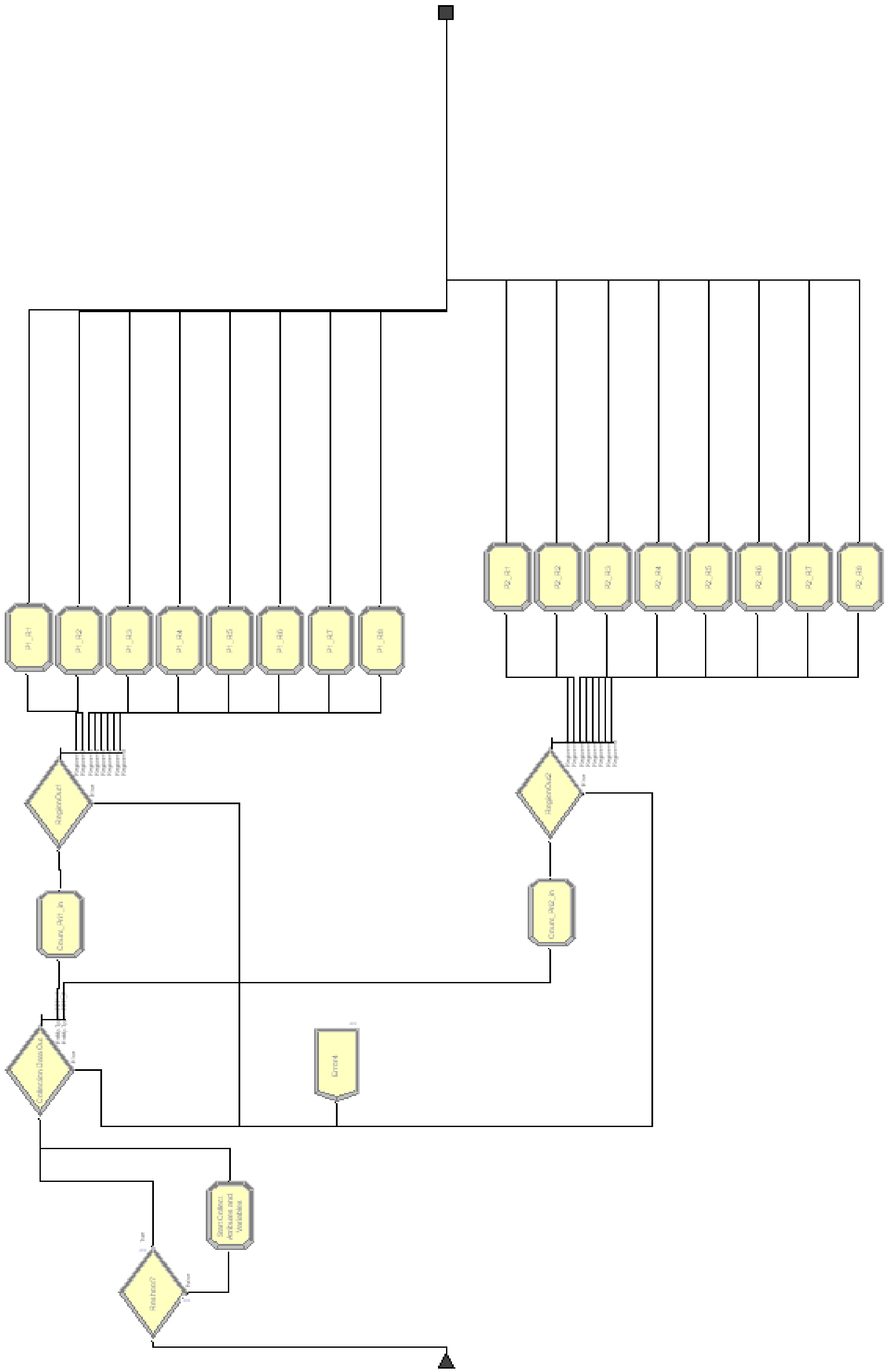


Figure A4. Collect Info 1 Submodel

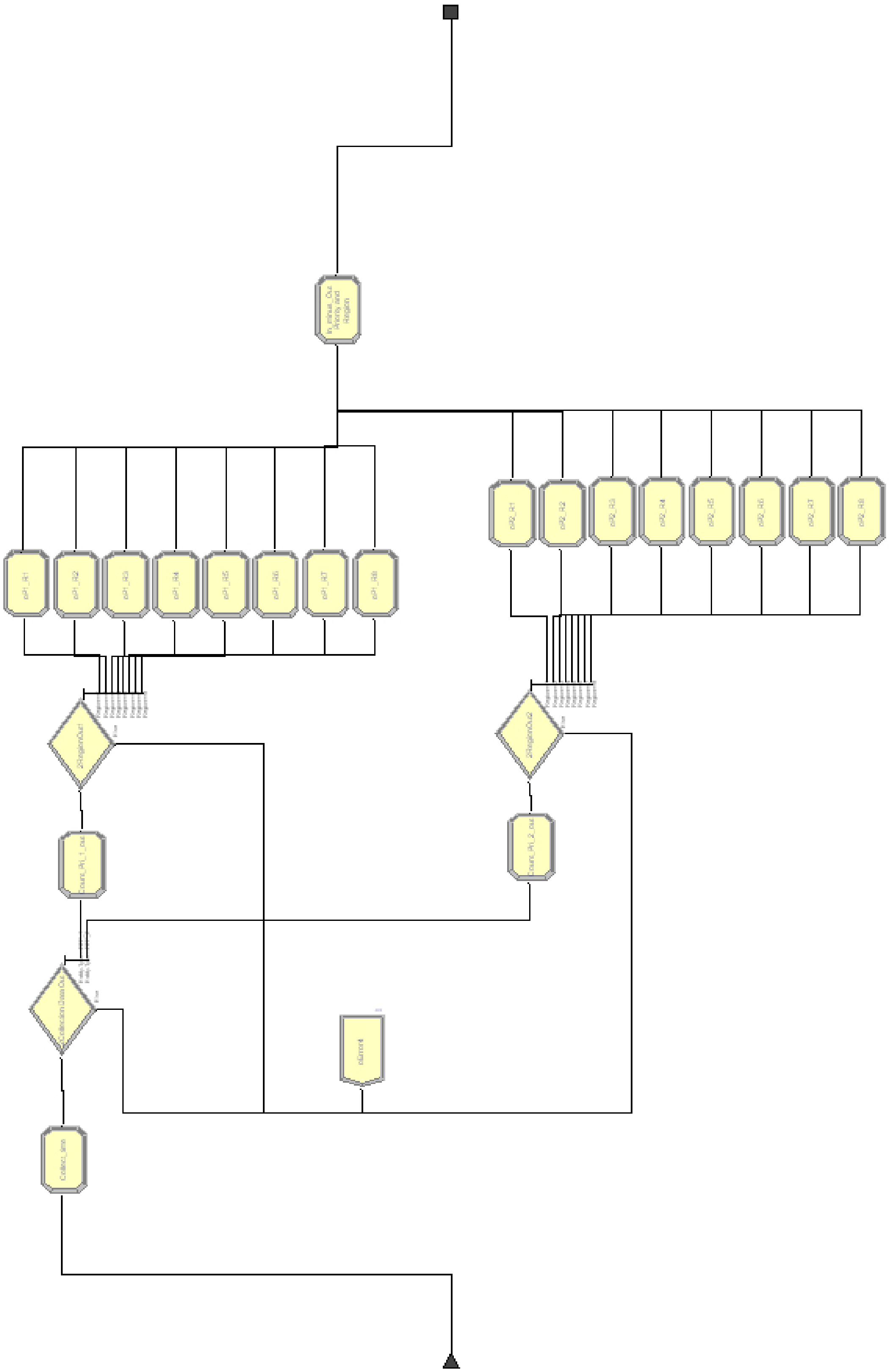


Figure A5. Collect Info 2 Submodel

Block Name	**Type**	**Parameters**
Request_Pri_1	Create	Entity Type: RFP_1 Time Between Arrivals: Type=Random (Expo); Value=2 hr Entities per Arrival=1; Max Arrivals=Infinite; First Creation=0 *Value=1 hr for CASE 4*
Request_Pri_2	Create	Entity Type: RFP_2 Time Between Arrivals: Type=Random (Expo); Value=0.1 hr Entities per Arrival=1; Max Arrivals=Infinite; First Creation=0
Location Submodel 1 and 2		
RegionAssign	Assign	Assignments: Type=Attribute, Name=Region, Value=DISC(.25,1, .45,2, .6,3, .65,4, .95,5, .97,6, .985,7, 1.0,8): *Altered to DISC(.2,1, .4,2 .53,3, .65,4, .85,5, .97,6, .985,7, 1,8) for CASE 2* *Altered to Value=1 for CASE 6*
Region1	Decide	Type=N-way by Condition Conditions: IF Attribute NAMED Region == 1 IF Attribute NAMED Region == 2 IF Attribute NAMED Region == 3 IF Attribute NAMED Region == 4 IF Attribute NAMED Region == 5 IF Attribute NAMED Region == 6 IF Attribute NAMED Region == 7 IF Attribute NAMED Region == 8
LatLong1	Assign	Type=Attribute, Name=Long, Value=unif(305,370) Type=Attribute, Name=Lat, Value=unif(35,55) Type=Attribute, Name=Pri_Region, Value=51 Pri_Region attribute not used in current analysis *CASE 6: Long=unif(0,360), Lat=unif(-55,55)*
LatLong2	Assign	Type=Attribute, Name=Long, Value=unif(300,330) Type=Attribute, Name=Lat, Value=unif(20,40) Type=Attribute, Name=Pri_Region, Value=52 Pri_Region attribute not used in current analysis
LatLong3	Assign	Type=Attribute, Name=Long, Value=unif(215,300) Type=Attribute, Name=Lat, Value=unif(10,50) Type=Attribute, Name=Pri_Region, Value=53 Pri_Region attribute not used in current analysis

Block Name	Type	Parameters
LatLong4	Assign	Type=Attribute, Name=Long, Value=unif(230,280) Type=Attribute, Name=Lat, Value=unif(20,50) Type=Attribute, Name=Pri_Region, Value=54 Pri_Region attribute not used in current analysis *Altered for CASE 2, see page 46.*
LatLong5	Assign	Type=Attribute, Name=Long, Value=unif(70,125) Type=Attribute, Name=Lat, Value=unif(25,50) Type=Attribute, Name=Pri_Region, Value=55 Pri_Region attribute not used in current analysis
LatLong6	Assign	Type=Attribute, Name=Long, Value=unif(35,70) Type=Attribute, Name=Lat, Value=unif(-35,5) Type=Attribute, Name=Pri_Region, Value=56 Pri_Region attribute not used in current analysis *Altered for CASE 2, see page 46.*
LatLong7	Assign	Type=Attribute, Name=Long, Value=unif(0,360) Type=Attribute, Name=Lat, Value=unif(55,90) Type=Attribute, Name=Pri_Region, Value=57 Pri_Region attribute not used in current analysis
LatLong8	Assign	Type=Attribute, Name=Long, Value=unif(0,360) Type=Attribute, Name=Lat, Value=unif(-90,-55) Type=Attribute, Name=Pri_Region, Value=58 Pri_Region attribute not used in current analysis
Long Greater Than 360?	Decide	Type=2-way by Condition IF Attribute NAMED Long > 360
Fix to 360 Long	Assign	Type=Attribute, Name=Long, Value=Long-360
To_Cust_srv	Assign	Assignments: Type=Attribute, Name=Days_2_collect, Value=DISC(0.589,1, 0.786,2, 0.911,3, 1.0,4); Type=Attribute, Name=Reshoot, Value=0; Type=Attribute, Name=ToCustSrv, Value=TNOW; Type=Attribute, Name=Long15, Value=Long/15
Customer Srv Submodel 1		
Contact	Process	Action: Seize Delay Release, Priority Medium(2), Resources: Cust_srv_rep, Quantity=1 Delay Type=Triangular, Hours, Value Added Min=.05; Value=.0833, Max=.1667
Payload_Ops	Process	Action: Delay Delay Type: Triangular, Hours, Value Added Min=.1667, Value=1, Max=2
Customer_at _desk	Decide	Type=2-way by Chance, Percent True=33

Block Name	Type	Parameters
Contact2	Process	Action: Seize Delay Release, Priority Medium(2), Resources: Cust_srv_rep, Quantity=1 Delay Type=Triangular, Hours, Value Added Min=.0333; Value=.05, Max=.1667
Customer_calls _back	Process	Action: Delay Delay Type: Triangular, Hours, Value Added Min=.0833, Value=.75, Max=24
Customer _approves _order	Decide	Type=2-way by Chance, Percent True=90
Order_procedes	Process	Action: Delay Delay Type: Triangular, Hours, Value Added Min=.05, Value=.0833, Max=.1667
Out_Cust_srv	Assign	Assignments: Type=Attribute, Name=OutCustSrv, Value=TNOW;
Forward to SCC	Process	Action: Delay Delay Type: Triangular, Hours, Value Added Min=.01, Value=.1667, Max=1
Build SCC Schedule 1	Process	Action: Seize Delay Release, Priority Medium(2), Resources: SCC Scheduler, Quantity=1 Delay Type=Triangular, Hours, Value Added Min=.5; Value=3, Max=6
Collect Info 1 Submodel		
Reshoot?	Decide	Type=2-way by Condition IF Attribute NAMED Reshoot > 0.5
Start Collect Atributes and Variables	Assign	Type=Attribute, Name=Start_collect, Value=TNOW
Collection Data Out	Decide	Type=N-way by Condition Conditions: IF Entity Type NAMED RFP_1 IF Entity Type NAMED RFP_2
Count_Pri1_in	Assign	Type=Variable, Name=P1_all_in_collect, Value= P1_all_in_collect + 1 (Used for debugging and animated run)
RegionOut1	Decide	Type=N-way by Condition Conditions: IF Attribute NAMED Region == 1 IF Attribute NAMED Region == 2 IF Attribute NAMED Region == 3 IF Attribute NAMED Region == 4 IF Attribute NAMED Region == 5 IF Attribute NAMED Region == 6 IF Attribute NAMED Region == 7 IF Attribute NAMED Region == 8

Block Name	**Type**	**Parameters**
P1_R1	Assign	Type=Variable, Name=P1_R1_in_collect, Value= P1_R1_in_collect + 1 (Used for debugging and animated run)
P1_R2	Assign	Type=Variable, Name=P1_R2_in_collect, Value= P1_R2_in_collect + 1 (Used for debugging and animated run)
P1_R3	Assign	Type=Variable, Name=P1_R3_in_collect, Value= P1_R3_in_collect + 1 (Used for debugging and animated run)
P1_R4	Assign	Type=Variable, Name=P1_R4_in_collect, Value= P1_R4_in_collect + 1 (Used for debugging and animated run)
P1_R5	Assign	Type=Variable, Name=P1_R5_in_collect, Value= P1_R5_in_collect + 1 (Used for debugging and animated run)
P1_R6	Assign	Type=Variable, Name=P1_R6_in_collect, Value= P1_R6_in_collect + 1 (Used for debugging and animated run)
P1_R7	Assign	Type=Variable, Name=P1_R7_in_collect, Value= P1_R7_in_collect + 1 (Used for debugging and animated run)
P1_R8	Assign	Type=Variable, Name=P1_R8_in_collect, Value= P1_R8_in_collect + 1 (Used for debugging and animated run)
Count_Pri2_in	Assign	Type=Variable, Name=P2_all_in_collect, Value= P2_all_in_collect + 1 (Used for debugging and animated run)
RegionOut2	Decide	Type=N-way by Condition Conditions: IF Attribute NAMED Region == 1 IF Attribute NAMED Region == 2 IF Attribute NAMED Region == 3 IF Attribute NAMED Region == 4 IF Attribute NAMED Region == 5 IF Attribute NAMED Region == 6 IF Attribute NAMED Region == 7 IF Attribute NAMED Region == 8
P2_R1	Assign	Type=Variable, Name=P2_R1_in_collect, Value= P2_R1_in_collect + 1 (Used for debugging and animated run)
P2_R2	Assign	Type=Variable, Name=P2_R2_in_collect, Value= P2_R2_in_collect + 1 (Used for debugging and animated run)

P2_R3	Assign	Type=Variable, Name=P2_R3_in_collect, Value= P2_R3_in_collect + 1 (Used for debugging and animated run)
Block Name	**Type**	**Parameters**
P2_R4	Assign	Type=Variable, Name=P2_R4_in_collect, Value= P2_R4_in_collect + 1 (Used for debugging and animated run)
P2_R5	Assign	Type=Variable, Name=P2_R5_in_collect, Value= P2_R5_in_collect + 1 (Used for debugging and animated run)
P2_R6	Assign	Type=Variable, Name=P2_R6_in_collect, Value= P2_R6_in_collect + 1 (Used for debugging and animated run)
P2_R7	Assign	Type=Variable, Name=P2_R7_in_collect, Value= P2_R7_in_collect + 1 (Used for debugging and animated run)
P2_R8	Assign	Type=Variable, Name=P2_R8_in_collect, Value= P2_R8_in_collect + 1 (Used for debugging and animated run)
Restack Schedule	Process	Action: Seize Delay Release, Priority Medium(2), Resources: Stacker, Quantity=1 Delay Type=Constant, Hours, Value Added, Value=.05
Region 7 or 8?	Decide	Type=2-way by Condition IF Attribute NAMED Region => 7
Collect this pass? High	Decide	Type=2-way by Condition IF Expression: ((AMOD(TNOW+16, 24) >= Long15) && (AMOD(TNOW=11.75, 24) <= Long15))
Hold_to_next_pass	Process	Action: Delay Delay Type: Constant, Hours, Value Added Value=.25
Check Days	Decide	Type=2-way by Condition IF Attribute: Days_2_collect < (MOD(TNOW-Start_collect, 96) + 1)
Collect this pass? Low	Decide	Type=2-way by Condition IF Expression: ((AMOD(TNOW+14.403, 24) >= Long15) && (AMOD(TNOW=13.347, 24) <= Long15))
Hold_to_next_pass _Low	Process	Action: Delay Delay Type: Constant, Hours, Value Added Value=.25
Predict Good Wx?	Decide	Type=2-way by Chance, Percent True=35: *Percent True=100 for CASE 1.*
Recalc_Days	Assign	Assignments: Type=Attribute, Name=Days_2_collect, Value=DISC(0.589,1, 0.786,2, 0.911,3, 1.0,4)

Hold_12 Hours	Process	Action: Delay Delay Type: Constant, Hours, Value Added Value=12
Block Name	**Type**	**Parameters**
SCC ops Pri_1	Process	Action: Seize Delay Release, High(1), Resources: Priority, Quantity=1 Delay Type=Constant, Hours, Value Added, Value=1.6667-AMOD(TNOW,1.6667)
Room in pass que?	Decide	Type=2-way by Condition IF Expression: NQ(Collect.Queue) < 100
Collect	Process	Action: Seize Delay Release, Priority Medium(2), Resources: sensor, Quantity=1 Delay Type=Triangular, Hours, Value Added Min=.0167; Value=.03, Max=.05
Collect Info 2		
Collect_time	Assign	Type=Attribute, Name=Collect_time, Value=TNOW
2Collection Data Out	Decide	Type=N-way by Condition Conditions: IF Entity Type NAMED RFP_1 IF Entity Type NAMED RFP_2
Count_Pri_1_out	Assign	Type=Variable, Name=P1_all_out_collect, Value= P1_all_out_collect + 1 (Used for debugging and animated run)
2RegionOut1	Decide	Type=N-way by Condition Conditions: IF Attribute NAMED Region == 1 IF Attribute NAMED Region == 2 IF Attribute NAMED Region == 3 IF Attribute NAMED Region == 4 IF Attribute NAMED Region == 5 IF Attribute NAMED Region == 6 IF Attribute NAMED Region == 7 IF Attribute NAMED Region == 8
oP1_R1	Assign	Type=Variable, Name=P1_R1_out_collect, Value= P1_R1_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p1r1, Value=1
oP1_R2	Assign	Type=Variable, Name=P1_R2_out_collect, Value= P1_R2_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p1r2, Value=1
oP1_R3	Assign	Type=Variable, Name=P1_R3_out_collect, Value= P1_R3_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p1r3, Value=1

oP1_R4	Assign	Type=Variable, Name=P1_R4_out_collect, Value= P1_R4_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p1r4, Value=1
Block Name	**Type**	**Parameters**
oP1_R5	Assign	Type=Variable, Name=P1_R5_out_collect, Value= P1_R5_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p1r5, Value=1
oP1_R6	Assign	Type=Variable, Name=P1_R6_out_collect, Value= P1_R6_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p1r6, Value=1
oP1_R7	Assign	Type=Variable, Name=P1_R7_out_collect, Value= P1_R7_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p1r7, Value=1
oP1_R8	Assign	Type=Variable, Name=P1_R8_out_collect, Value= P1_R8_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p1r8, Value=1
Count_Pri2_out	Assign	Type=Variable, Name=P2_all_out_collect, Value= P2_all_out_collect + 1 (Used for debugging and animated run)
2RegionOut2	Decide	Type=N-way by Condition Conditions: IF Attribute NAMED Region == 1 IF Attribute NAMED Region == 2 IF Attribute NAMED Region == 3 IF Attribute NAMED Region == 4 IF Attribute NAMED Region == 5 IF Attribute NAMED Region == 6 IF Attribute NAMED Region == 7 IF Attribute NAMED Region == 8
oP2_R1	Assign	Type=Variable, Name=P2_R1_out_collect, Value= P2_R1_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p2r1, Value=1
oP2_R2	Assign	Type=Variable, Name=P2_R2_out_collect, Value= P2_R2_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p2r2, Value=1
oP2_R3	Assign	Type=Variable, Name=P2_R3_out_collect, Value= P2_R3_out_collect + 1 (Used for debugging and animated run)

		Type=Attribute, Name=p2r3, Value=1
oP2_R4	Assign	Type=Variable, Name=P2_R4_out_collect, Value= P2_R4_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p2r4, Value=1
Block Name	**Type**	**Parameters**
oP2_R5	Assign	Type=Variable, Name=P2_R5_ out _collect, Value= P2_R5_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p2r5, Value=1
oP2_R6	Assign	Type=Variable, Name=P2_R6_out_collect, Value= P2_R6_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p2r6, Value=1
oP2_R7	Assign	Type=Variable, Name=P2_R7_out_collect, Value= P2_R7_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p2r7, Value=1
oP2_R8	Assign	Type=Variable, Name=P2_R8_out_collect, Value= P2_R8_out_collect + 1 (Used for debugging and animated run) Type=Attribute, Name=p2r8, Value=1
In_minus_Out Priority and Region	Assign	Type=Variable, Name=P1_all_collect_que, Value=(P1_all_in_collect) – (P1_all_out_collect); Type=Variable, Name=P2_all_collect_que, Value=(P2_all_in_collect) – (P2_all_out_collect); Type=Variable, Name=P1_R1_collect_que, Value=(P1_R1_in_collect) – (P1_R1_out_collect); Type=Variable, Name=P1_R2_collect_que, Value=(P1_R2_in_collect) – (P1_R2_out_collect); Type=Variable, Name=P1_R3_collect_que, Value=(P1_R3_in_collect) – (P1_R3_out_collect); Type=Variable, Name=P1_R4_collect_que, Value=(P1_R4_in_collect) – (P1_R4_out_collect); Type=Variable, Name=P1_R5_collect_que, Value=(P1_R5_in_collect) – (P1_R5_out_collect); Type=Variable, Name=P1_R6_collect_que, Value=(P1_R6_in_collect) – (P1_R6_out_collect); Type=Variable, Name=P1_R7_collect_que, Value=(P1_R7_in_collect) – (P1_R7_out_collect); Type=Variable, Name=P1_R8_collect_que, Value=(P1_R8_in_collect) – (P1_R8_out_collect); Type=Variable, Name=P2_R1_collect_que,

		Value=(P2_R1_in_collect) – (P2_R1_out_collect); Type=Variable, Name=P2_R2_collect_que, Value=(P2_R2_in_collect) – (P2_R2_out_collect); Type=Variable, Name=P2_R3_collect_que, Value=(P2_R3_in_collect) – (P2_R3_out_collect); Type=Variable, Name=P2_R4_collect_que, Value=(P2_R4_in_collect) – (P2_R4_out_collect); Type=Variable, Name=P2_R5_collect_que, Value=(P2_R5_in_collect) – (P2_R5_out_collect); Type=Variable, Name=P2_R6_collect_que, Value=(P2_R6_in_collect) – (P2_R6_out_collect); Type=Variable, Name=P2_R7_collect_que, Value=(P2_R7_in_collect) – (P2_R7_out_collect); Type=Variable, Name=P2_R8_collect_que, Value=(P2_R8_in_collect) – (P2_R8_out_collect); Type=Variable, Name=R1_collect_que, Value=(P1_R1_collect_que) + (P2_R1_collect_que); Type=Variable, Name=R2_collect_que, Value=(P1_R2_collect_que) + (P2_R2_collect_que); Type=Variable, Name=R3_collect_que, Value=(P1_R3_collect_que) + (P2_R3_collect_que); Type=Variable, Name=R4_collect_que, Value=(P1_R4_collect_que) + (P2_R4_collect_que); Type=Variable, Name=R5_collect_que, Value=(P1_R5_collect_que) + (P2_R5_collect_que); Type=Variable, Name=R6_collect_que, Value=(P1_R6_collect_que) + (P2_R6_collect_que); Type=Variable, Name=R7_collect_que, Value=(P1_R7_collect_que) + (P2_R7_collect_que); Type=Variable, Name=R8_collect_que, Value=(P1_R8_collect_que) + (P2_R8_collect_que); **Note: All but attributes *p*r** only used for troubleshooting and animation.**
Incr_Reshoot_Attr	Assign	Assignments: Type=Attribute, Name=Days_2_collect, Value=DISC(0.589,1, 0.786,2, 0.911,3, 1.0,4) Assignments: Type=Attribute, Name=Reshoot, Value=Reshoot + 1
Downlink	Process	Action: Delay Delay Type=Triangular, Hours, Value Added Min=0; Value=.25, Max=.375
Transfer to Processing	Process	Action: Delay Delay Type=Triangular, Hours, Value Added Min=.029; Value=.125, Max=.75
Image Processing	Process	Action: Seize Delay Release, Priority Medium(2), Resources: Computer, Quantity=1

		Delay Type=Triangular, Hours, Value Added Min=.033; Value=.05, Max=.15
Image OK?	Decide	Type=2-way by Chance, Percent True=95 *Percent True=35 for CASE 1*.
Delivery	Process	Action: Seize Delay Release, Priority Medium(2), Resources: Bandwidth, Quantity=1 Delay Type=Triangular, Hours, Value Added Min=.1603; Value=.48, Max=3
Block Name	**Type**	**Parameters**
TimeStats	Assign	Assignments: Type=Variable, Name=Sim_time, Value=TNOW; Type=Attribute, Name=Deliver_time, Value=TNOW
Write_Data	Write to File	Arena File Name=Shultz_1 Assignments: Type=Other Other: IDENT, Entity.Type, Lat, Long, Region, Days_2_collect, ToCustSrv, OutCustSrv, Start_collect, Collect_time, Deliver_time, Reshoot, p1r1, p1r2, p1r3, p1r4, p1r5, p1r6, p1r7, p1r8, p2r2, p2r3, p2r4, p2r5, p2r6, p2r7, p2r8 **Note: These are the contents of the text output file in the order they appear here.**
Dispose 1	Dispose	Kills entities

Other Settings:

Queue – Basic Process

Name	Type	Attribute Name
Image Processing.Queue	Lowest Attribute Value	Entity.Type
Delivery.Queue	Lowest Attribute Value	Entity.Type
SCC ops Pri_1.Queue	Lowest Attribute Value	Entity.Type
Collect.Queue	Highest Attribute Value	Lat
Contact.Queue	Lowest Attribute Value	Entity.Type
Restack Schedule.Queue	Lowest Attribute Value	Entity.Type
Build SCC Schedule 1.Queue	Lowest Attribute Value	Entity.Type
Contact2.Queue	Lowest Attribute Value	Entity.Type

CASE 5 Alters ***Image Processing*** *and* ***Delivery*** *to First-in-First-out*

Resource – Basic Process

Name	Type	Capacity
Computer	Fixed Capacity	20
Bandwidth	Fixed Capacity	40
Sensor	Fixed Capacity	4
Priority	Fixed Capacity	Infinite
Cust_srv_rep	Fixed Capacity	10
Stacker	Fixed Capacity	Infinite
SCC scheduler	Fixed Capacity	Infinite

CASE 3 Alters the following:
Computer=15
Bandwidth=30

Variable – Basic Process

Name	Clear Option	Initial Values
All variables used	System	0

File – Advanced Process

Name	Access Type	Operating System File Name	Structure	End of File Action	Initialize Options	Comment
Shultz_1	Sequential File	<Path>\CASE-0_Shultz05.txt *(filename changed to reflect current Case)*	Free Format	Dispose	Hold	No

Appendix B – Remote Sensing Satellite List (2004)

Satellite Imagers with better than 35 meter resolution

Satellite	**Owner/Operator**	**Best Resolution**	**Revisit freq**	**Imaging time**	**NORAD SatCat#**	**Altitude (km)**	**Deg Off nadir**
Alsat-1	Algeria	30 m			27559	686	0
EROS A1	ImageSat (Int'l)	1.8 m ****	3 d	LTDN 0945	26631	480	45
Ikonos 2	Space Imaging	1 m ****	2.9 d		25919	680	26
IRS-1D	ISRO	5.8 m	5 d	LTDN 1030	24971		
IRS-P6	ISRO	5.8 m		LTDN 1030	28051	817	
Landsat 5	NOAA	30 m	16 d	LT?N 0945	14780		0
Landsat 7	NOAA	15 m	16 d	LTDN 1000	25682	705	0
Orbview 3	Orbimage	1 m ****	< 3 d	LTDN 1030	23838	470	45
QuickBird 2	DigitalGlobe (US)	.61 ****	3.5 d		26953	450	25
Radarsat 1	Canadian Space Agency (Canada)	8 m	< 5 d	LTDN 0600 LTAN 1800	23710	798	37-48 fine
SAC-C	Comision Nacional de Actividades Espaciales (Argentina)	30 m (only active over SA)			26620	702	
SPOT 4	SPOT Image	10 m	2.4 d *	LTDN 1030	25260	832	27
SPOT 5	SPOT Image	5 m	2.4 d *		27421		20
Tsinghua-1	Tsinghua University (China)	32 m	No data	No data	26385		
Ziyuan 1 (CBERS 1 or ZY-1)	Chinese Academy of Space Tech (Brazil/China)	19 m	3 d		25940	778	
Ziyuan 2 (10/00)	China	9 m ?	No data	No data	26481 or 27550 ?		
Ziyuan 3 (also ZY 1B or CBERS 2 10/03)	Chinese Academy of Space Tech (Brazil/China)	19 m			28057	778	
Tansuo 1		10 m			28220	600	

Satellite List and owner/operator from Aviation Week and Space Technology, 2004 Aerospace Source Book

* Other information from operator web sites and other various sources
**** Used in this study.

Alsat-1: http://www.spaceandtech.com/digest/flash2002/flash2002-093.shtml
Aqua:
EROS-A1: http://www.imagesatintl.com/aboutus/satellites/satellites.shtml#
http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/eros/erostek_e.html
EROS System – Satellite Orbit and Constellation Design; Dr Moshe Bar-Lev, Dr. Leonid Shcherbina, Mr. Vola Levin; 22nd Asian Concerence on Remote Sensing, 5-9 Nov 2001.
ERS-2: http://earth.esa.int/rootcollection/eeo4.10075/ERS1.5.html
IKONOS-2: http://www.spaceimaging.com/products/imagery.htm
IRS-1D: http://www.nrsa.gov.in/engnrsa/satellites/satellites.html
IRS-P3: http://www.nrsa.gov.in/engnrsa/satellites/satellites.html
IRS-P5/6: http://www.isro.org/rep2002/Links/Earth%20.htm
http://www.nrsa.gov.in/engnrsa/ebrochure/index.html
LANDSAT 7: http://landsat.gsfc.nasa.gov/project/satellite.html
LANDSAT 5: http://edc.usgs.gov/guides/landsat_tm.html
Oceansat (IRS-P4): http://www.nrsa.gov.in/engnrsa/satellites/irsp4.html
Orbview-1/2/3: http://www.orbimage.com/corp/orbimage_system/satellite.html
Quickbird 2: DigitalGlobe Product Guide at
http://www.digitalglobe.com/product/product_docs.shtml
Radarsat 1: http://www.rsi.ca/products/sensor/radarsat/radarsat1.asp
SAC-C: http://www.invap.net/space/index-e.html
SPOT 4/5: http://www.spotimage.fr/html/_167_224_229_.php
Tsinghua-1:
http://www.space.com/news/spaceagencies/microsat_china_001019.html
Ziyuan 1/2/3: http://www.spacetoday.org/China/ChinaSatellites.html
http://www.space.com/news/china_dod_040530.html
http://www.globalsecurity.org/space/world/china/zy-1.htm
Tansuo 1: http://www.spacedaily.com/news/china-00zzq.html

NORAD Satellite Catalog Number: http://celestrak.com/NORAD/elements/

Appendix C – Determination of Coverage Distribution

As discussed in the main section of the research, satellite coverage of ground areas by the four high resolution satellite sensors is empirically derived for use in this study. While it is a short exercise to determine coverage for a single satellite (Wertz 1999 discusses single satellite and constellation coverage methods), this is not the case at hand. The different orbital characteristics of the four satellites make it impossible to determine a single value for coverage; the satellites are constantly changing position with respect to each other.

Starting from an arbitrary day (2 Feb 2005), Aerospace Corporation's Satellite Orbital Analysis Program (SOAP) using then current ephemeris data, with the same epoch, for the four satellites of interest was configured to plot ground swaths for the sensors per this study's assumptions. The first four days' coverage was then sampled from the eastern edge of an EROS A1 pass to the eastern edge of the next along (approximately) the 36th parallel of the U.S. The swath paths are shown in Figure C1. The complete set of twelve swaths is included on the CD as a series of PowerPoint slides, "Swaths.ppt" and in the SOAP file, "Shultz_Hi_res_contour_SOAP-file.orb."

Coverage sampling was also accomplished for other periods of four days with disparate results. The first day's coverage can be as high as 75 percent, 2nd day 83 percent, and 100 percent by day three, but coverage for day one could be lower than half and completion by day four was more common across the eight samples.

Ultimately, the 0.589, 0.786, 0.911, 1.0 cumulative distribution was the one used for the Arena model. It was randomly selected by the arbitrary choice of start date; it was not an extreme case in the survey across eight 3 and 4-day samples; and there is no general solution possible.

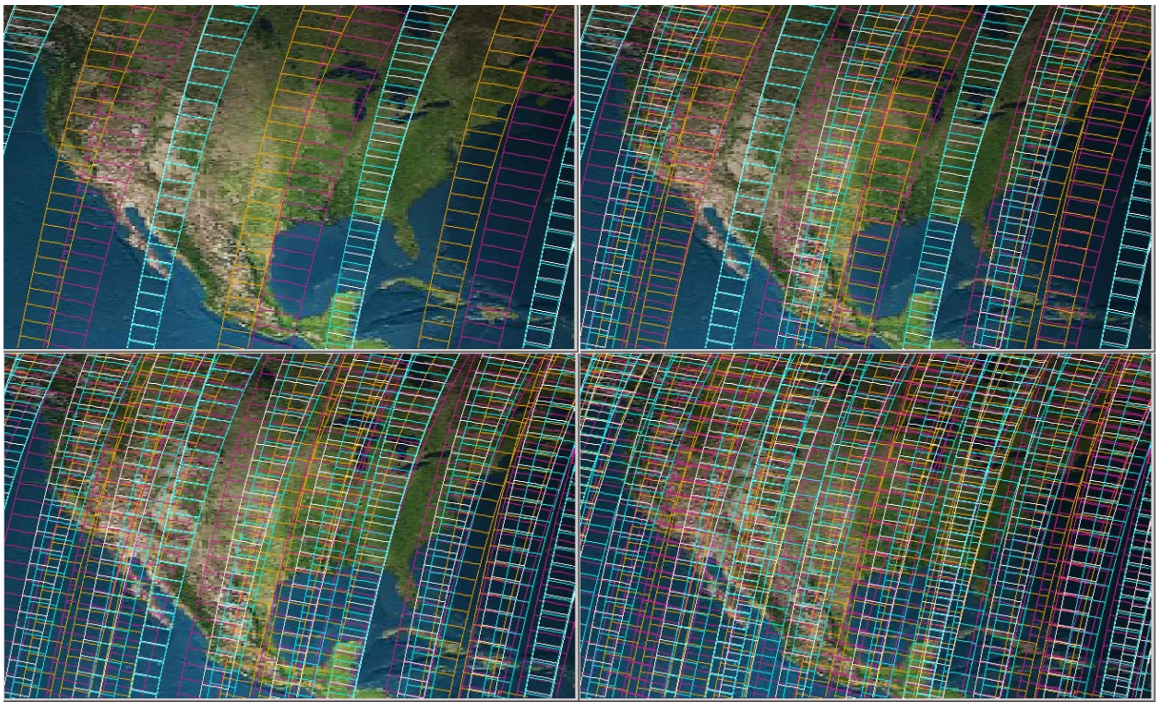


Figure C1. Sensor Coverage for Day 1, Days 1-2, Days 1-3, Days 1-4.
(Clockwise from top left)

Appendix D – Directory of CD-ROM

Baseline model
Arena model file: CASE-0_Shultz05.doe
Text output file: CASE-0_Shultz05.txt
Access output file: CASE-0_Shultz05.mdb
Excel analysis file: CASE-0_Shultz05.xls

Case 1: No Attempt to Predict Weather Over Target
Arena model file: CASE-1_Shultz05.doe
Text output file: CASE-1_Shultz05.txt
Access output file: CASE-1_Shultz05.mdb
Excel analysis file: CASE-1_Shultz05.xls

Case 2: Greater Overlap of Regions in Longitude
Arena model file: CASE-2_Shultz05.doe
Text output file: CASE-2_Shultz05.txt
Access output file: CASE-2_Shultz05.mdb
Excel analysis file: CASE-2_Shultz05.xls

Case 3: Fewer Post-collection Processing Resources
Arena model file: CASE-3_Shultz05.doe
Text output file: CASE-3_Shultz05.txt
Access output file: CASE-3_Shultz05.mdb
Excel analysis file: CASE-3_Shultz05.xls

Case 4: More Priority 1 RFIs
Arena model file: CASE-4_Shultz05.doe
Text output file: CASE-4_Shultz05.txt
Access output file: CASE-4_Shultz05.mdb
Excel analysis file: CASE-4_Shultz05.xls

Case 5: First-In-First-Out Processing
Arena model file: CASE-5_Shultz05.doe
Text output file: CASE-5_Shultz05.txt
Access output file: CASE-5_Shultz05.mdb
Excel analysis file: CASE-5_Shultz05.xls

Case 6: Uniform, Worldwide Target Distribution
Arena model file: CASE-6_Shultz05.doe
Text output file: CASE-6_Shultz05.txt
Access output file: CASE-6_Shultz05.mdb
Excel analysis file: CASE-6_Shultz05.xls

Other Support Files
SOAP constellation file Shultz_Hi_res_contour_SOAP-file.orb
Swath maps Swaths.ppt
Thesis document AFIT-GSS-ENY-05-M04.pdf

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NASIC Mission Statement. NASIC Public Affairs from National Management Association, NASIC Van Kuren Chapter website. http://www.dayton.net/nma/naic.html. 24 Jul 1996.

Licensing of Commercial Remote Sensing Satellite Systems. National Oceanic and Atmospheric Administion (NOAA). http://www.licensing.noaa.gov/faq.html. No date [2005]. NOTE: Each U.S.-based company has a separate license for each satellite capability increment.

OrbView-3 Commercial Satellite Imagery Product Catalog. Dulles, VA. OrbImage Inc. April 2004.

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1. Type of Product:	2. Operating System/Version:	3. New Product or Replacement:	4. Type of File:
CD-ROM	Any	New Product	Multiple: Arena, Excel, PDF, Text, Powerpoint, Access, SOAP

5. Language/Utility Program:

Multiple: Arena, Excel, PDF, Text, Powerpoint, Access, Satellite Orbit Analysis Program (SOAP)

6. # of Files/# of Products:	7. Character Set:	8. Disk Capacity:
31		640 MB
	9. Compatibility:	10. Disk Size:
		471 MB

11. Title:

Modeling and Simulation of Commercial Satellite Imagery Processes

12. Performing Organization:	13. Performing Report #:	14. Contract #:
Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB OH 45433-7765	AFIT/GSS/ENY/05-M04	
		15. Program Element #:

16. Sponsor/Monitor:	17. Sponsor/Monitor # Acronym:	19. Project #:
NASIC/SMS Attn: Dr. Chris Colliver 4180 Watson Way WPAFB OH 45433		
	18. Sponsor/Monitor #:	20. Task #:
		21. Work Unit #:

22. Date:	23. Classification of Product:
21 Mar 2005	UNCLASSIFIED
24. Security Classification Authority:	25. Declassification/Downgrade Schedule:

26. Distribution/Availability:

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

27. Abstract:

The purpose of this research was to develop a general, statistical model of order-to-delivery times for commercial satellite imagery. The research looked at the current four satellites providers with 3-meter or better imagers in the context of a generalized model of commercial imaging satellite operations. Existing methods use orbit analysis tools to determine imaging time of a specified target based on defined satellite position and times but can only develop shortest and longest times to an imaging opportunity. To address the general question of the time to deliver an image for non-specific targets, this research develops a process model using Arena simulation software and random targets within large defined regions. Analysis of delivery times conducted on the output reveals dependencies on collective satellite coverage, prediction of weather over the target area, number of collection requests in the system and the computer and communications resources of the satellite operator.

28. Classification of Abstract:	**29. Limitation of Abstract:**
UNCLASSIFIED	UU

30. Subject Terms:	**30a. Classification of Subject Terms:**
Satellite Imagery, Computer Simulation, Timeliness, Mathematical Models, Simulation	UNCLASSIFIED

31. Required Peripherals:

CD drive

32. # of Physical Records:	**33. # of Logical Records:**	**34. # of Tracks:**

35. Record Type:	**36. Color:**	**37. Recording System:**

38. Recording Density:	**39. Parity:**	**40. Playtime:**

41. Playback Speed:	**42. Video:**	**43. Text:**	**44. Still Photos:**	**45. Audio:**

46. Other:

47. Documentation/Supplemental Information:

48. Point of Contact and Telephone Number:

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
21-03-2005	**Master's Thesis**	Dec 2003 – Mar 2005

4. TITLE AND SUBTITLE

Modeling and Simulation of Commercial Satellite Imagery Processes

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Shultz, David A., Major, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)

Air Force Institute of Technology
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2950 Hobson Way
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GSS/ENY/05-M04

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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WPAFB OH 45433 DSN: 785-4129

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

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15. SUBJECT TERMS

Satellite Imagery, Computer Simulation, Timeliness, Mathematical Models, Simulation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
REPORT	ABSTRACT	c. THIS PAGE			Richard G. Cobb, PhD (ENY)
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