THE SPACE SITUATIONAL AWARENESS (SSA) COST MODEL: ENABLING SSA ARCHITECTURE ANALYSIS OF ALTERNATIVES

James Smirnoff, Brennen Woodruff, Ryan Welch, and Geoff Pierce
Integrity Applications Incorporated
15020 Conference Center Drive, Suite 100
Chantilly, VA 20151

ABSTRACT:
This paper describes a new tool called the Space Situational Awareness (SSA) Cost Model which provides an objective and data-driven framework to estimate the cost of ground-based electro-optical components of future SSA architectures. Cost estimates from the SSA Cost Model complement technical performance estimates provided by the existing Space Surveillance Architecture Rapid Analyzer (SARA) tool. Together, the IAI developed SSA Cost Model and SARA tools enable informed SSA analysis of alternatives (AoA) and architecture trade studies.

Keywords: Space Situational Awareness, SSA, Commercial off-the-shelf, COTS, cost analysis, analysis of alternatives, AOA, cost model, cost estimating relationship, CER, SARA, telescope, radar, trade studies

1. INTRODUCTION

Today there are over a thousand operating satellites orbiting the earth providing a variety of critical functions such as communications, navigation, weather sensing, reconnaissance, and astronomy. And, with the ever growing capability and popularity of smaller CubeSats, the number of satellites in orbit will only continue to grow. As the capabilities of satellites become more vital and the space environment becomes more crowded, Space Situational Awareness (SSA) is increasingly important.

There are a variety of ways to achieve SSA including space-based sensors such as the Space Based Space Surveillance (SBSS) Pathfinder satellite, ground-based radar sensors like those planned for the US Air Force Space Fence, passive RF sensors that track satellites based on the RF signals that they emit, and ground based electro-optical telescopes.

Among the many options for government agencies as they define the electro-optical telescope components of a future SSA architecture are various custom developed telescopes, a vast array of smaller aperture commercial-off-the-shelf (COTS) telescope options, and even commercially provided SSA.

2. SCOPE:

The SSA Cost Model estimates the cost of developing, procuring, and operating ground based electro-optical telescope systems for the purpose of facilitating architecture trade studies.

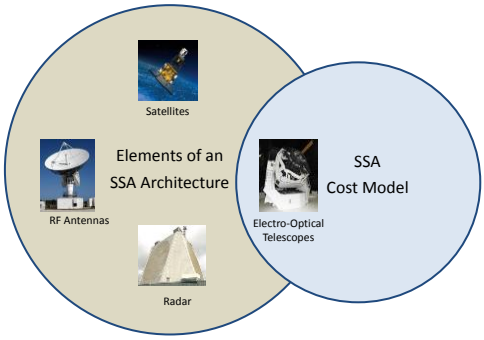


Figure 1: SSA Cost Model Sensor Types

Other ground based SSA sensors such as passive RF or radar sensors are not including in this model though it is extensible to accommodate them in a future version. Also not included in the scope of the SSA Cost Model are any space-based SSA sensors. Options for government agencies as they define the electro-optical telescope components

of a future SSA architecture are custom developed telescopes, smaller aperture commercial-off-the-shelf (COTS) telescopes, and commercially provided SSA.

An example of a large custom developed telescope is the DARPA funded Space Surveillance Telescope (SST). This telescope employs a 3.5 meter aperture primary mirror along with an array of charge-coupled device (CCD) sensors arranged on a curved focal plane array.

Figure 2: DARPA Space Surveillance Telescope

Commercial off-the-shelf (COTS) telescopes, while much smaller and less exquisitely designed, still provide an increasingly effective Space Situational Awareness (SSA) capability as part of an overall architecture.

Figure 3: Example of a COTS Based Telescope Assembly

Telescopes up to one meter in aperture are commercially available and can be paired with a camera for astrophotography and stored inside a stationary or portable dome enclosure.

A third choice for an SSA architecture or one that could supplement existing capability is to purchase SSA capability as a service from a commercial provider. One example of such a provider is ExoAnalytic Solutions. ExoAnalytic Solutions offers the services of telescopes in the continental United States (CONUS) or outside the continental United States (OCONUS) on a nightly basis for a fee. They also offer COTS software that enables remote telescope operation and image processing as well as analysis software to facilitate detection, tracking, and characterization or captured images.

Figure 4: ExoAnalytic Solutions ESPOC Command Center

3. BACKGROUND

There are several existing published works identifying methods for estimating space telescopes. Most notable are the articles written by NASA Marshal Space Flight Center (MSFC) Senior Optical Physicist, Dr. H. Phillip Stahl. In 2005, Dr. Stahl wrote an article in Optical Engineering, the flagship journal of the International Society for Optics and Photonics (SPIE), titled "Multivariable parametric cost model for ground optical telescope assembly". In the article, Dr. Stahl described his models for estimating large aperture optical telescope assemblies and he settles on two models: a multivariate model containing several variables, and a nearly as powerful univariate model which estimates the cost of an optical telescope assembly as a function of the primary mirror aperture diameter.

Candidate Independent Variable
Aperture Diameter of Primary Mirror
Primary Mirror Operating Temperature
OTA assembly weight
Areal density of the primary mirror
Lightweighting percentage
Number of curved optical elements
Number of duplicate segments
Unique prescriptions
Optical facesheet material
Axis factor (on-axis or off-axis)
Support structure material
Year of development
Period of development
Design Life (months)

Figure 5: Candidate Independent Variables Identified by Stahl

A 2012 SPIE Astronomical Telescopes and Instrumentation article also primarily authored by Dr. Stahl updates the 2005 ground optical telescope assembly model with new data and changes the functional form to add a leading constant.

$$Ground\ OTA\ Cost = 2(D)^{1.4}$$

Where:

- OTA is Optical Telescope Assembly including the primary mirror, secondary mirror, auxiliary optics, and support structure
- D is the Diameter of the Primary Mirror in Meters

Figure 6: Stahl's 2012 Large Aperture Ground Telescope Cost Model

This is the model that used in the SSA Cost Model for large aperture custom developed telescopes even though a few other older journal articles suggest a model with a somewhat higher exponent. We made this choice based on the 2010 article titled "Survey of cost models for space telescopes". This article includes a comprehensive overview of attempts by various authors to derive parametric estimates of telescope costs and the limitations of each model.

An example of another model is presented in Van Belle et al.'s 2004 Astronomical Telescopes and Instrumentation article titled "The scaling relationship between telescope cost and aperture size for very large telescopes." In this article, the authors find that cost scales to aperture size "as the 2.8 power…." but the exponent is lower (~2.46) if the data set is limited to newer telescopes. This article also discusses telescope operating costs and finds that they range from 5% to 30% of initial observatory construction cost.

Year	Title	Authors	Aperture Diameter Exponent
1997	Telescope costs and cost reduction	Schmidt-Kaler et al.	1.7-3.0
2003	Estimating the cost of extremely large telescopes	Stepp et al.	2.7
2003	Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters	NASA Near-Earth Object Science Definition Team	1.4
2004	The scaling relationship between telescope cost and aperture size for very large telescopes	Van Belle et al.	2.46-2.8
2005	Multivariable parametric cost model for ground optical telescope assembly	Stahl et al.	1.8
2012	Update on multi-variable parametric cost models for ground and space telescopes	Stahl et al.	1.4

Figure 7: Summary of Telescope Cost Model Aperture Diameter Exponents

Besides just describing methods for estimating the optical telescope assembly, existing published works also discussed other aspects of telescope and observatory cost. As one example, Schmidt-Kaler et al. in their 1997 article titled "Telescope costs and cost reduction" studied 60 telescopes of various sizes and types and found that facility costs are typically 20 percent to 50 percent of the cost of the telescope. And, with regard to operating costs, Stepp et al. found that "…for most telescopes in the 4m to 10m class, operating costs range between 3% - 6% of the construction cost of the facility."

Another informative research article is the 2003 NASA "Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters". This is a lengthy report which primarily focuses on the dangers of near earth objects striking the earth and the probability and consequences of such an event. However, it does describe a few candidate space and ground architectures for monitoring near earth objects and estimates the cost of each option. In describing the methods for estimating each option, the article presents several methodologies for facility preparation costs, operations and sustainment, and software.

4. SSA COST MODEL

To shape the estimate of SSA architecture costs in the SSA cost model, we defined elements of cost and organized them into a work-breakdown structure (WBS). The first major element of cost is the electro-optical telescope assembly which consists of either a COTS or custom developed optical telescope connected to a camera. The second major element of cost we estimated is Facility Preparation and Development which includes the effort to prepare and develop a location to operate an SSA asset. The third major element of cost or WBS element is Operations and Sustainment. This WBS element captures the software and equipment required to operate each SSA asset in a given candidate architecture. Finally WBS 1.4 captures the cost of commercially provided SSA capability if applicable to the chosen architecture.

WBS Number	WBS Title	WBS Description
1	**Ground-Based SSA Architecture**	This WBS element is the parent/summing element for all estimated elements of cost for a candidate SSA architecture. Major WBS level two elements are the Electo-Optical (EO) Telescope Assembly, Facility Preparation and Development, Operations and Sustainment, and Commercially Provided SSA.
1.1	**Electro-Optical (EO) Telescope Assembly**	Each EO Telescope assembly WBS element consists of an Optical Telescope connected to a Camera.
1.1.1	Optical Telescope	This WBS element accounts for the telescope and its mount.
1.1.1.1	COTS Optical Telescope	This WBS element consists of a commercially bought optical telescope through a retailer.
1.1.1.2	Custom-Developed Optical Telescope	The Custom-Developed Optical Telescope consists of the constructed primary mirror as well as secondary mirrors and auxillary optics as applicable and the Support Structure for the telescope.
1.1.2	Camera	This WBS element consists of the camera required for astrophotography.
1.2	**Facility Preparation and Development**	This WBS element includes the effort to prepare and develop a location to operate an SSA asset.
1.3	**Operations and Sustainment**	This WBS element captures the software and equipment required to operate each SSA asset in a given candidate architecture.
1.3.1	Data Storage	This WBS element is the effort and equipment required to store the data collected by SSA assets.
1.3.2	Software for Data Processing	This WBS element consists of the labor and equipment needed to process the images captured by each SSA asset in a candidate architecture.
1.3.3	Software for Data Analysis	This WBS element accounts for the software necessary to detect, track, and characterize objects.
1.3.4	Equipment Refreshment	This WBS element consists of the process and purchases necessary for replacing broken/overused equipment. The equipment that may need to be replaced includes the EO telescope, the camera, the dome structure, and various equipment associated with the command center (laptop/desktop, etc.)
1.4	**Commercially Provided SSA**	This WBS element consists of the nightly fee involved to use commercially provided telescopes temporarily to perform SSA

Figure 8: SSA Cost Model WBS Elements and Description

Below is a table describing the estimating methods we employed for each element of SSA architecture cost. For large custom developed telescopes, we leveraged the work of Dr. H. Philip Stahl, a recognized optics expert from NASA who published several papers on telescope cost estimating methods. For COTS telescopes and COTS cameras, we collected data and developed our own parametric cost estimating relationships (CERs). For other elements of cost such as Facility Preparation and Development, Operations and Sustainment, and Commercially Provided SSA, we employed analogy based methods.

WBS Number	WBS Title	Estimating Methodologies
1	**Ground-Based SSA Architecture**	*Summing Element*
1.1	**Electro-Optical (EO) Telescope Assembly**	*Summing Element*
1.1.1	Optical Telescope	*Summing Element*
1.1.1.1	COTS Optical Telescope	**CER** derived from vendor quotes
1.1.1.2	Custom-Developed Optical Telescope	**CER** proposed in Stahl - "Update on Multivariable Parametric Cost Models for Ground and Space Telescopes"
1.1.2	Camera	**CER** derived from vendor quotes
1.2	**Facility Preparation and Development**	**CER** based on telescope size proposed by the NASA NEO study for Custom Facility and **Analogy** to various services for COTS Facility
1.3	**Operations and Sustainment**	*Summing Element*
1.3.1	Data Storage	**Analogy** scaled to vendor quotes
1.3.2	Software for Data Processing	**Analogy** scaled to ExoAnalytic Solutions ESpOC Software
1.3.3	Software for Data Analysis	**Analogy** scaled to ExoAnalytic Solutions SpaceFront Software
1.3.4	Equipment Refreshment	**Analogy** scaled to vendor quotes
1.4	**Commercially Provided SSA**	**Analogy** scaled to leading commercial provider ExoAnalytic

Figure 9: Overview of SSA Cost Model Methods

4.1 COTS Telescope Cost Estimating Relationship (CER)

To estimate the cost of commercial off-the-shelf (COTS) telescopes, we collected data on the cost and technical characteristics of over fifty commercially available telescopes ranging in price from less than a thousand dollars for a small reflective telescope to several hundred thousand dollars for a complex observatory class one meter telescope. The full dataset is listed in Appendix 1.

Figure 10: Left: Celestron Advanced VX 11 Schmidt-Cassegrain Telescope (280mm Aperture)
Right: PlaneWave CDK700 Alt-Az Telescope (700mm Aperture)

In addition to cost, technical characteristics such as Aperture Size, Focal Ratio, Weight, Mount type, and Highest Useful magnification were also collected. Since the COTS telescopes are all one meter in diameter or less, the aperture size is shown in millimeters.

	Min	Median	Max
Price (dollars)	699	5,000	650,000
Aperture Size (mm)	254	356	1,000
Focal Ratio	2.2	6.6	11.0
Weight (lbs)	28	126	1,200
Magnification	300	300	841

Figure 11: Summary of COTS Telescope Data

Using multivariate regression techniques, we then developed candidate parametric models to predict the cost of the COTS telescope. The most parsimonious model with the greatest explanatory power was a model that estimated the cost of a COTS telescope as a linear function of its aperture size (millimeters) with an added factor if the aperture was greater than a half a meter:

$$COTS\ Telescope\ Cost\ (\$) = 12.95(Aperture\ Size(mm) + 19{,}175(Aperture > 500mm)$$

From the regression statistics shown below, we observe that this model is highly statistically significant and accounts for more than 70% of the variation in COTS telescope costs.

Regression Statistics	
Multiple R	0.85
R Square	0.72
Adjusted R Square	0.70
Standard Error	9235.82
Observations	51

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	1.09E+10	5.46E+09	64.03	2.85E-14
Residual	49	4.18E+09	8.53E+07		
Total	51	1.51E+10			

Parameters	*Coefficients*	*Standard Error*	*T-Statistic*	*P-Value*	*Lower 95%*	*Upper 95%*
Aperture Size (mm)	12.95	4.61	2.81	0.007	3.68	22.22
Large (aperture > .5)?	19174.91	3738.35	5.13	0.000	11662.42	26687.40

Figure 12: COTS Telescope CER Regression Statistics

4.2 COTS Camera Cost Estimating Relationship

Similar to the model development approach for COTS telescopes, for COTS cameras we collected data on 56 commercially available cameras with varying technical specifications. Then we used multivariate regression techniques to develop a parametric model that estimates the cost of a camera as a function of those technical parameters. The full dataset is listed in Appendix 2.

The technical parameters collected in addition to the cost included image sensor type, sensor area, sensitivity to light, measures of lens design, and frame rate.

	Min	Median	Max
Price (dollars)	295	999	27,500
Sensor Area (mm)	116	368	2,324
Max ISO Sensitivity	800	12,800	204,800
Frame Rate	2	5	14

Figure 13: Summary of COTS Camera Data

Despite many more complicated models with higher R^2, the model with the best combination of simplicity and explanatory power estimates the cost of a camera as a linear function of the sensor area and whether or not the image sensor type is a charge-coupled device (CCD). Specifically the COTS Camera CER is:

$$COTS\ Camera\ Cost\ (\$) = 3.71(\text{Sensor Area (mm)}) + 9861.44(\text{CCD})$$

From the regression statistics shown below, we observe that this model is highly statistically significant and accounts for more than 78% of the variation in COTS telescope costs.

Regression Statistics	
Multiple R	0.90
R Square	0.80
Adjusted R Square	0.78
Standard Error	2511.54
Observations	56

	df	SS	MS	F	Significance F
Regression	2	1.39E+09	6.97E+08	110.52	1.23E-19
Residual	54	3.41E+08	6.31E+06		
Total	56	1.73E+09			

Parameters	Coefficients	Standard Error	T-Statistic	P-value	Lower 95%	Upper 95%
CCD?	9861.44	1460.49	6.75	0.000	6933.34	12789.54
Sensor Area (mm)	3.71	0.63	5.87	0.000	2.44	4.97

Figure 14: COTS Camera CER Regression Statistics

4.3 Model Framework

The first tab of the MS Excel based SSA Cost model is the model inputs tab. This is where a user can define multiple candidate SSA architectures comprised of one or many COTS or custom developed electro-optical (EO) telescopes. Candidate architectures can also be defined as including commercially provided SSA. Calculations are performed on the tabs with titles matching those of the WBS level 2 elements of cost (e.g. EO Telescope Assembly and Operations and Sustainment). Also included for reference in the model are summaries of the analytical work that went into developing the COTS Telescope and COTS Camera CERs.

Additionally, the complete WBS description is included along with a summary of the methods used to estimate each element of cost. Another important tab in the model includes the Risk Implementation Areas tab which describes how risk and uncertainty distributions were applied within the model. Of course, there is also a tab called Summary Output which depicts the cost estimate for each architecture in various ways.

The table below is a complete listing of the tabs in the model and their purpose:

Tab Name	Description
Model Inputs	Enter information here to obtain an estimate of multiple SSA architecture costs.
Summary Output	Summary costs and summary charts for the SSA architectures described in the Model Inputs tab.
Electro-Optical (EO) Telescope Assembly	Uses information from the Inputs tab to estimate the cost of the Electro-Optical (EO) Telescope Assembly
Facility Prep & Development	Uses information from the Inputs tab to estimate the cost of the Facility.
Operations & Sustainment	Uses information from the inputs tab to estimate the cost of Operations.
Commercially Provided SSA	Uses information from the Inputs tab to estimate the cost of SSA performed by a Commercial Provider.
WBS Description and Methods	The estimating Work Break Down Structure (WBS). Names and decriptions of elements of cost being estimated and a summary description of cost estimating methods for each.
COTS Telescope Model	Displays the CER developed for COTS Telescopes.
COTS Camera Model	Displays the CER developed for COTS Cameras.
Custom Telescopes CER	Summary description of the CER developed by Stahl in "Update on Multivariable Parametric Cost Models for Ground and Space Telescopes"
ExoAnalytic PriceList	Displays the pricelist from which the commercial services estimate was derived.
Risk Implementation Areas	Areas of the model in which risk and uncertainty was applied and their distributions.
Correlation Matrix	Displays the correlation matrix for @Risk Calculations.
Ground Rules and Assumptions	Model Ground Rules and Assumptions so that it is clear what is being estimated and what is being excluded.
Literature Review and Notes	Summary descriptions and notes from articles on Ground Based Telescope costs including heuristics and rules of thumb for estimating elements of cost relevant to this tool.
Change Log	Documentation of changes made to the model.
Possible Model Add-Ins	Shows the possible future add-ins to the model.
Acronym List	Glossary of acronyms used in this spreadsheet.

Figure 15: SSA Cost Model Tab Names and Descriptions

4.4 Using the SSA Cost Model

To use the SSA Cost Model, simply navigate to the Model Inputs tab, specify candidate architectures, then run Monte Carlo simulation using the MS Excel add-in @Risk, and review the results in the Summary Output tab. Below is an example architecture from the model.

Architecture 1

Description	Mixture of COTS/Custom Sensors and Commercially Provided SSA						
Sensor Name	EO Telescope 1	EO Telescope 2	EO Telescope 3	EO Telescope 4	EO Telescope 5	Commercial SSA 1	Commercial SSA 2
Location	Site 2	Site 2	Site 3	Site 4	Site 4		
Start of Operation (Year)	2015	2015	2015	2015	2015	2015	2015
End of Operation (Year)	2020	2030	2030	2030	2030	2030	2030
SSA Capabilities Obtained from Commercial Provider?	No	No	No	No	No	Yes	Yes
CONUS or OCONUS Commercial Service?						OCONUS	OCONUS
Number of Nights Per Year of Commercial Service						100	100
COTS or Custom Sensor?	COTS	COTS	Custom	Custom	Custom		
Aperture Diameter of Primary Mirror (mm)	500	1,000	3,000	3,000	3,000		
Sensor Area (mm) of Camera	1,000						
CCD Camera?	Yes						
Include Facility Costs?	Yes	Yes	Yes	Yes	Yes		
Include Data Storage?	Yes	Yes	Yes	Yes	Yes	No	No
Number of Hours Per Night for Stored Data	12	12	12	12	12		
Number of Days for Keeping Raw Data	30	30	30	30	30		
Number of Days for Keeping Processed Data	365	365	365	365	365		
Include Software to Operate Telescope and Process Images?	Yes	Yes	Yes	Yes	Yes		

Include Software to Enable Data Analysis (Entire Architecture)?	Yes

Figure 16: Example SSA Architecture entered in Inputs tab of SSA Cost Model

For each sensor in each architecture, the analyst identifies attributes such as the start and end year of operations, the size of the telescope and whether or not the telescope is COTS or Custom Developed. There is also a choice to elect commercially provided SSA employing either a CONUS or OCONUS telescope. The analyst can also decide whether or not to include Facility or Data Storage costs. If Data Storage costs are included, the model allows the user to customize the number of hours per night of stored data and the number of days to keep raw and processed images. Finally, there is an option to include or exclude the cost of analysis software. Up to five architectures can be built and compared at one time and this is easily extendable to accommodate more if needed.

4.5 Risk and Uncertainty Analysis

Because there is uncertainty surrounding many aspects of any SSA architecture, the SSA Cost Model does not treat the cost estimate as a deterministic value but rather as a distribution of likely costs. To accomplish this, we characterized areas of uncertainty with probability distributions and then used Monte Carlo simulation to obtain the range of likely costs for each architecture.

In all, we modeled 24 areas of uncertainty. One example of uncertainty is our estimate of cost for COTS telescopes and COTS Cameras. Each of these estimates are based off a CER that had a standard percent error (SPE) associated with it. In other words, the CER did not perfectly predict the historical costs so we don't expect it to perfectly predict future costs. In these two cases, we modeled the error of the estimates as lognormally distributed with a mean equal to the CER predicted value and a standard deviation equal to the CER predicted value multiplied by the CER SPE.

Other examples of error in the model that we treated probabilistically include the cost per terabyte of data storage, and the sizes of the raw and processed images captured by the SSA sensors.

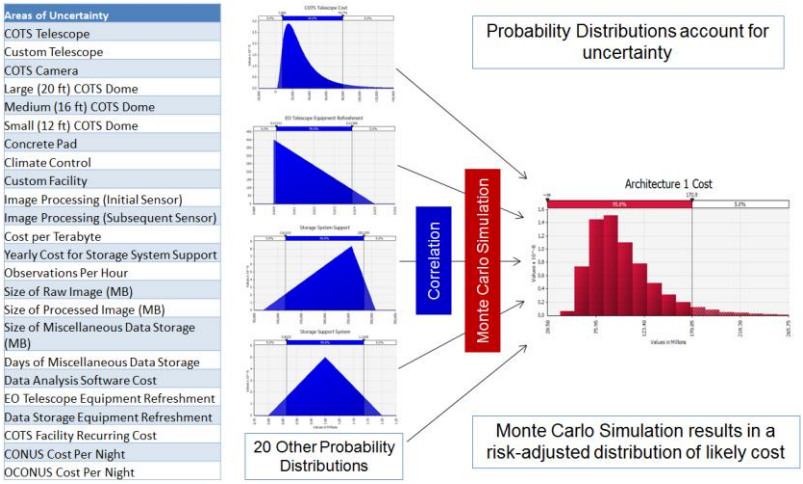
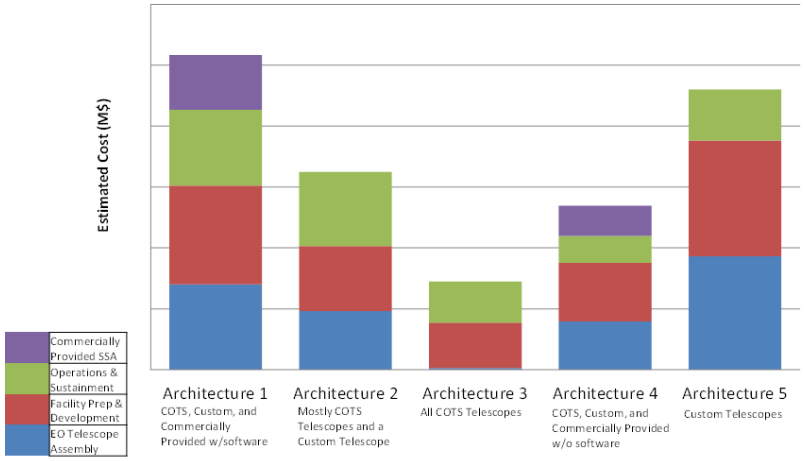


Figure 17: Summary of SSA Cost Model Areas of Uncertainty

4.6 SSA Cost Model Output

After each architecture is defined and Monte Carlo simulation is performed, the SSA Cost Model portrays the cost of each architecture in a variety of ways on the Summary Output tab. Below is an example of model output which shows the estimated cost of each of five notional architectures consisting of a mix of COTS telescopes, custom developed telescopes, and commercially provided SSA. The costs are portrayed in a stacked column chart by major element of cost for easy comparison.



4. RECOMMENDATIONS FOR FUTURE WORK:

The SSA Cost Model is a useful tool for estimating the cost of candidate SSA architectures but it is currently limited to electro-optical telescopes. A future version of the model could incorporate other ground based SSA sensors such as passive RF and radar sensors and even space-based SSA sensors.

Also, to be able to make architecture design decisions, we also need to understand the capability that a given architecture provides. The Integrity Applications Incorporated (IAI) developed Space Surveillance Architecture Rapid Analyzer (SARA) is a modeling tool that simulates sensor performance to estimate level of object characterization achieved over time.

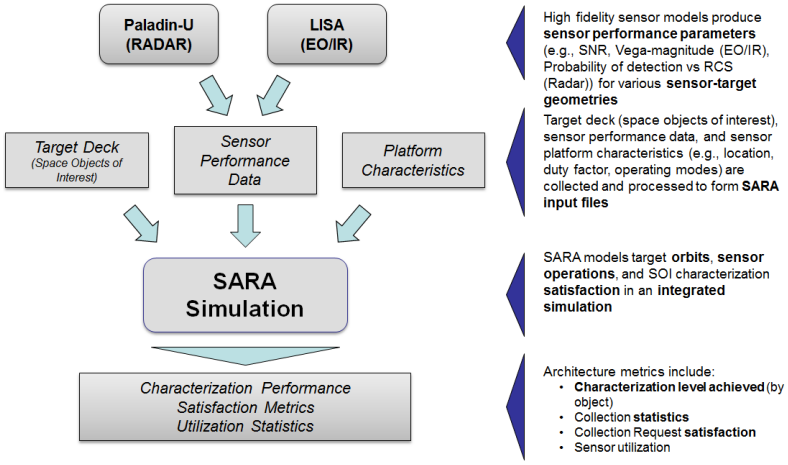


Figure 18: Space Surveillance Architecture Rapid Analyzer (SARA) Overview

A future effort to fully integrate the SSA Cost Model with the SARA tool would provide an analyst with a single tool to both characterize the performance of a candidate SSA architecture and estimate its cost.

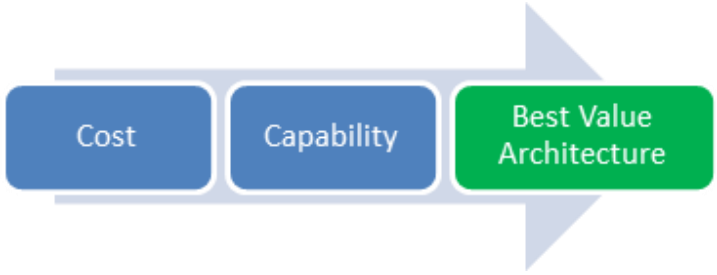


Figure 19: Value of Combining SSA Cost Model and SARA Tool

REFERENCES

[1] Stahl, H. Philip, et al. "Multivariable parametric cost model for ground optical telescope assembly." *Optical Engineering* 44.8 (2005): 083001-083001.

[2] Stahl, H. Philip, et al. "Update on multivariable parametric cost models for ground and space telescopes." *SPIE Astronomical Telescopes+ Instrumentation*. International Society for Optics and Photonics, 2012.

[3] MIT Multidiscipline System Design Optimization (MSDO) Presentation, 2004
NASA Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters, August 2003

[4] McGraw, John T., and Mark R. Ackermann. "A 1.2-m Deployable, Transportable Space Surveillance Telescope Designed to Meet AF Space Situational Awareness Needs." *Proceedings of the 2007 AMOS Technical Conference E*. Vol. 4. 2007.

[5] DARPA Space Surveillance Telescope Overview, www.darpa.mil/program/space-surveillance-telescope

[6] Van Belle, Gerard T., Aden B. Meinel, and Marjorie P. Meinel. "The scaling relationship between telescope cost and aperture size for very large telescopes." *SPIE Astronomical Telescopes+ Instrumentation*. International Society for Optics and Photonics, 2004.

[7] Stepp, Larry M., Larry G. Daggert, and Paul E. Gillett. "Estimating the cost of extremely large telescopes." *Astronomical Telescopes and Instrumentation*. International Society for Optics and Photonics, 2003.

[8] Schmidt-Kaler, Theodor, and Peter Rucks. "Telescope costs and cost reduction." *Optical Telescopes of Today and Tomorrow*. International Society for Optics and Photonics, 1997.

ACRYONYM LIST

Acronym	Description
CCD	Charge-Coupled Device
CER	Cost Estimating Relationship
CONUS	Continental United States
COTS	Commercial Off the Shelf
EO	Electro Optical
OCONUS	Outside the Continental United States
SARA	Space Surveillance Architecture Rapid Analysis
SSA	Space Situational Awareness
SST	DARPA developed Space Surveillance Telescope
WBS	Work Breakdown Structure

Apendix 1: COTS Telescope Dataset

Telescope Name	Price	Aperture Size (mm)	Focal Ratio	Overall Weight (lbs)	Highest Useful Magnification
Celestron 11" CPC Deluxe HD	3799.00	280	10.0	93.0	661
Celestron 14" EdgeHD OTA	5799.00	356	11.0	46.0	
Celestron Advanced VX 11	2699.00	280	10.0	95.0	661
Celestron C11-A XLT OTA	2449.00	280	10.0	27.5	660
Celestron C-14-A OTA	4999.00	356	11.0	45.0	
Celestron CGE Pro 1100	6999.00	280	10.0	204.0	300
Celestron CGE Pro 1400	8999.00	356	10.0		
Celestron CGE Pro HD 14" EdgeHD	9999.00	356	10.0	240.0	841
Celestron CGEM 1100 Computerized	3399.00	280	10.0	120.0	300
Celestron CGEM DX 1100	3699.00	280	10.0	145.0	661
Celestron CGEM DX 1100 EdgeHD	4399.00	280	10.0	145.0	661
Celestron CGEM DX 1400	6299.00	356	10.0	185.0	841
Celestron CGEM DX 1400 HD	6999.00	356	10.9	185.0	841
Celestron CPC 1100 StarBright XLT	2999.00	280		125.6	660
Celestron CPC 1100 XLT GoTo	2999.00	300	10.0	84.0	300
Celestron EdgeHD 1100 CGE Pro	7999.00	280	10.0	204.0	300
Celestron EdgeHD 1100 CGEM	3999.00	280	10.0	120.0	300
Celestron EdgeHD 1100 OTA	3399.00	280	10.0		
Celestron Rowe-Achermann	4999.95	280	2.2	122.0	
Levenhuk Ra 300N Dob	879.95	300			
Meade 12" LX200-ACF	4499.00	305	10.0		
Meade 12" LX850-ACF OTA	9999.00	406	8.0		
Meade 14" LX600-ACF	8499.00	356	8.0		
Meade 16" LightBridge Truss Tube	1999.00	406	4.5	128.0	
Meade 16" LX200-ACF	15999.00	406	10.0		
Meade MAX ACF	35999.00	508	8.0		
Obsession 20" F/4 Classic	9495.00	508	4.0		
Obsession 20" F/5 Classic	7695.00	508	5.0		
Obsession 25" F/4 Classic	14995.00	635	4.0		
Orion Atlas 10 EQ-G	2048.66	254	4.7	117.0	300
Orion SkyQuest XT10i IntelliScope	789.99	254	4.7	55.3	300
Orion SkyQuest XT12g	1799.99	305	4.9	101.8	300
Orion SkyQuest XT12i	1235.99	305	4.9	83.0	300
Orion SkyQuest XX12g GoTo Truss Tube	2199.99	305	4.9	128.8	300
Orion SkyQuest XX12i IntelliScope Truss	1399.99	305	4.9	83.5	300
Orion SkyQuest XX14g	2799.99	356	4.6	158.0	300
Orion SkyQuest XX14i Truss Tube	1979.99	356	4.6	120.0	300
Orion SkyQuest XX16g GoTo Truss Tube	3699.99	406	4.4	195.0	800
PlaneWave CDK1000	650000.00	1000	6.0		
PlaneWave CDK20 OTA	32500.00	508	6.8	140.0	
PlaneWave CDK24 OTA	50000.00	588	6.8	240.0	
PlaneWave CDK700	200000.00	700	6.6	1200.0	
PlaneWave PW20-RC OTA	46000.00	508	6.8	140.0	
PlaneWave PW24-RC OTA	65000.00	588	6.5	240.0	
Renegade 22" F/3.2	12495.00	539	3.2		
Renegade 25" F/3.1	14750.00	635	3.1		
SkyWatcher 12" Collapsible Truss	1049.00	305	4.9		720
SkyWatcher 16" GoTo Collapsible	3655.00	406	4.4		812
Webster C28 F/3.3	20399.00	711	3.3		
Webster C28 F/4.1	18199.00	711	4.1		
Webster C30	24100.00	762	3.3		
Webster C32	27199.00	813	3.6		
Zhumell Z12 Deluxe	699.00	305	4.9	75.0	

Appendix 2: COTS Camera Dataset

Camera Name	Camera Body Price	CCD?	DSLR?	Sensor Area (mm)	Max ISO Sensitivity	Frame Rate (fps)
Canon EOS 5D Mark III DSLR	2499.00	0	1	864.00	25600	6.0
Canon EOS 5DS DSLR	3699.00	0	1	864.00	6400	5.0
Canon EOS 5DS R DSLR	3899.00	0	1	864.00	6400	5.0
Canon EOS 60D DSLR	649.00	0	1	332.27	6400	5.3
Canon EOS 6D DSLR	1399.00	0	1	855.62	25600	4.5
Canon EOS 70D DSLR	949.00	0	1	337.50	12800	7.0
Canon EOS 7D DSLR	749.00	0	1	332.27	6400	8.0
Canon EOS 7D Mark II DSLR	1499.00	0	1	336.00	16000	10.0
Canon EOS Rebel SL1 DSLR	399.00	0	1	332.27	12800	4.0
Canon EOS Rebel T5 DSLR	399.00	0	1	332.27	6400	3.0
Canon EOS Rebel T5i DSLR	649.00	0	1	332.27	12800	5.0
Canon EOS Rebel T6i DSLR	749.00	0	1	332.27	12800	5.0
Canon EOS Rebel T6s DSLR	849.00	0	1	332.27	12800	5.0
Canon EOS-1D C	7999.00	0	1	864.00	51200	
Canon EOS-1D X DSLR	5299.00	0	1	864.00	51200	14.0
Canon PowerShot G7 X	649.00	0	0		12800	
Fujifilm X100S	879.00	0	0	372.88	6400	
Fujifilm X100T	1299.00	0	0	368.16	6400	
Fujifilm X-T1 Mirrorless	1149.00	0	0	368.16	6400	8.0
Fujifilm X-T10 Mirrorless	799.95	0	0	368.16	6400	8.0
Hasselbad Stellar Special Edition	999.99	0	0	116.16	6400	
Leica C	615.12	0	0			
Leica D-LUX (Typ 109)	1051.60	0	0	224.90	12500	
Leica Q (Typ 116)	4250.00	0	0	864.00	50000	
Nikon COOLPIX P7800	499.95	0	0		1600	
Nikon D300S DSLR	1199.00	0	1	372.88	3200	7.0
Nikon D3200 DSLR	446.95	0	1	357.28	6400	4.0
Nikon D3300 DSLR w/18-55mm Lens	496.95	0	1	357.28	12800	5.0
Nikon D4S DSLR	5996.95	0	1	860.40	25600	11.0
Nikon D5200 DSLR	496.95	0	1	366.60	6400	5.0
Nikon D5300 DSLR	646.95	0	1	366.60	12800	5.0
Nikon D5500 DSLR	746.95	0	1	366.60	25600	5.0
Nikon D610 DSLR	1496.95	0	1	861.60	6400	6.0
Nikon D7100 DSLR	896.95	0	1	366.60	6400	6.0
Nikon D7200 DSLR	1196.95	0	1	366.60	25600	6.0
Nikon D750 DSLR	1996.95	0	1	861.60	12800	6.5
Nikon D810 DSLR	2996.95	0	1	861.60	12800	5.0
Nikon D810A DSLR	3796.95	0	1	861.60	12800	5.0
Nikon D90 DSLR w/18-105mm Lens	799.00	0	1		3200	4.5
Nikon Df DSLR	2746.95	0	1	860.40	12800	
Olympus OM-D E-M10 Mirrorless	449.00	0	0	224.90	25600	8.0
Olympus OM-D E-M5 Mark II	999.00	0	0		3200	
Olympus PEN E-PL6 Mirrorless	299.00	0	0	224.90	25600	8.0
Panasonic Lumix DMC-GH3 Mirrorless	697.99	0	0	224.90	12800	
Panasonic Lumix DMC-GH4	1497.99	0	0	224.90	25600	
Panasonic Lumix DMC-LX100	797.99	0	0		25600	
Panasonic Lumix DMC-ZS50	397.99	0	0		6400	
Pentax K-3 DSLR	749.00	0	1	366.60	51200	8.3
Pentax K-3 II DSLR	1096.95	0	1	366.60	51200	8.3
Pentax K-50 DSLR	295.00	0	1	372.09	51200	6.0
Ricoh GR	579.00	0	0		25600	
Sony Alpha a5100 Mirrorless	348.00	0	0	366.60	25600	6.0
Sony Alpha a58 DSLR w/18-55mm Lens	448.00	0	1	366.60	16000	8.0
Sony Alpha a6000 Mirrorless	548.00	0	0	366.60	25600	11.0
Sony Alpha a7 Mirrorless	998.00	0	0	855.62	25600	5.0
Sony Alpha a77II DSLR	898.00	0	1	366.60	25600	12.0
Sony Alpha a7II Mirrorless	1698.00	0	0	855.60	25600	5.0
Sony Alpha a7S Mirrorless	2498.00	0	0	855.62	102400	5.0
Sony Alpha a99 DSLR	1999.99	0	1		6400	10.0
Sony Cyber-Shot DSC-RX100 III	798.00	0	0	116.16	12800	

Camera Name	Camera Body Price	CCD?	DSLR?	Sensor Area (mm)	Max ISO Sensitivity	Frame Rate (fps)
Hasselblad H5D-40 DSLR	10995.00	1	1	1441.02	1600	
Hasselblad H5D-50 DSLR	27500.00	1	1	1801.97	800	
Leica S DSLR	18995.00	1	1	1350.00	1600	1.5
Leica S DSLR (Typ 007)	25400.00	0	1	1350.00	6400	3.5
Leica S-E DSLR (Typ 006)	14939.00	1	1	1350.00	1600	1.5
Mamiya 645DF+ DSLR	5990.00		1	2324.00		
Pentax 645D DSLR	4279.88	1	1	1452.00	1600	
Pentax 645Z DSLR	8065.00	0	1	1042.44	204800	3.0