Integrity Applications Incorporated

The Space Situational Awareness Cost (SSA) Model

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2016 ICEAA Conference

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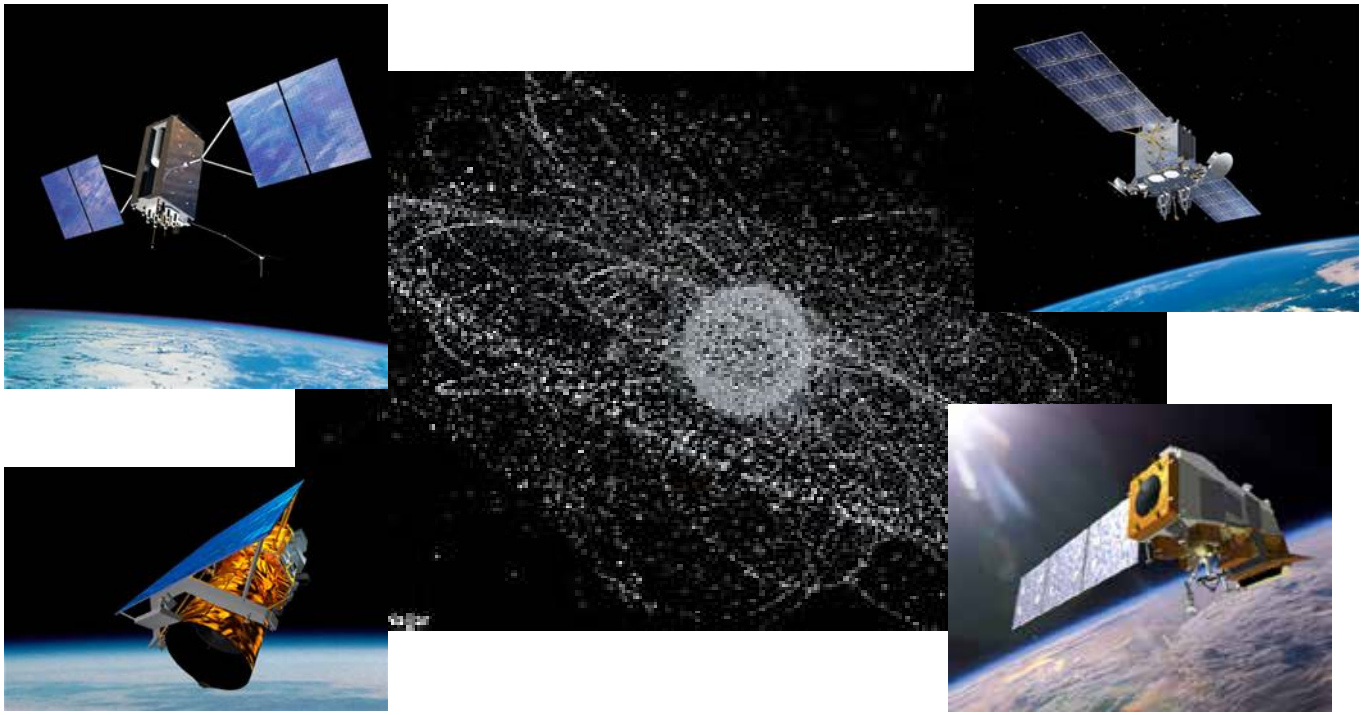
Introduction

- 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.



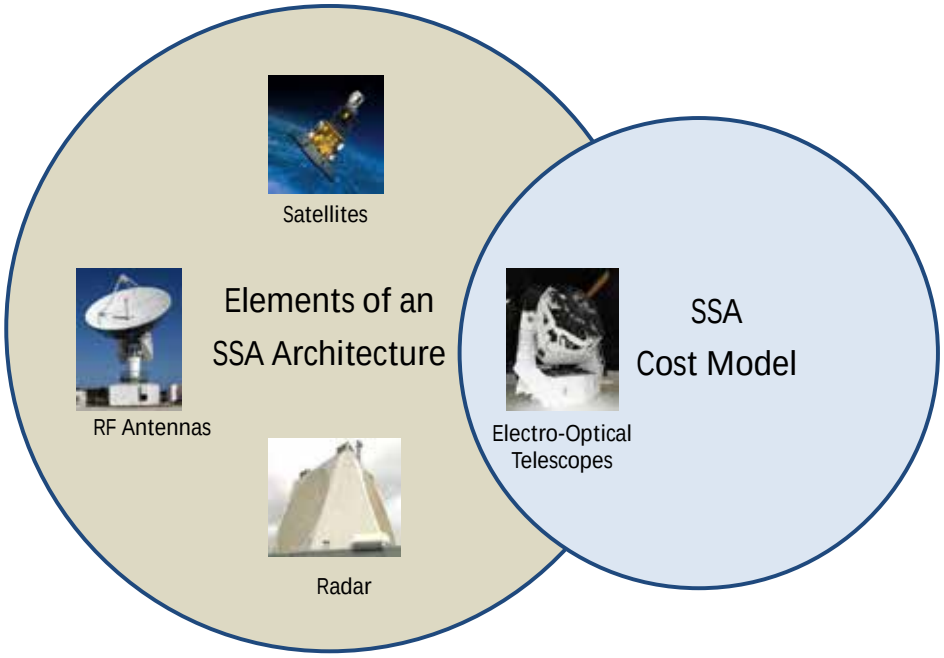
Introduction

- As the capabilities of satellites become more vital and the space environment becomes more crowded, Space Situational Awareness (SSA) is increasingly important.

And, with the ever growing capability and popularity of smaller CubeSats, the number of satellites in orbit will only continue to grow.

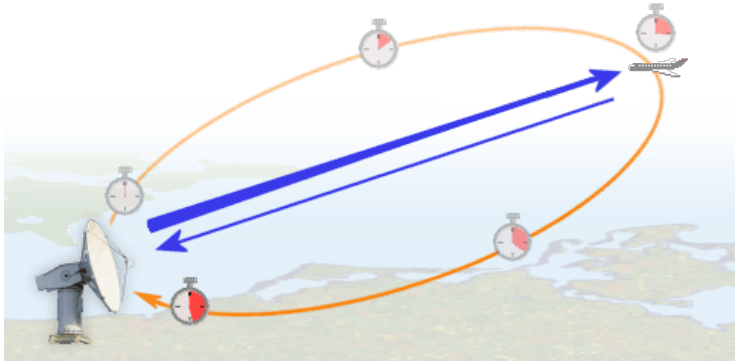
Scope

- 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.



Scope

Radar – **Ra**dio **D**etection **A**nd **R**anging

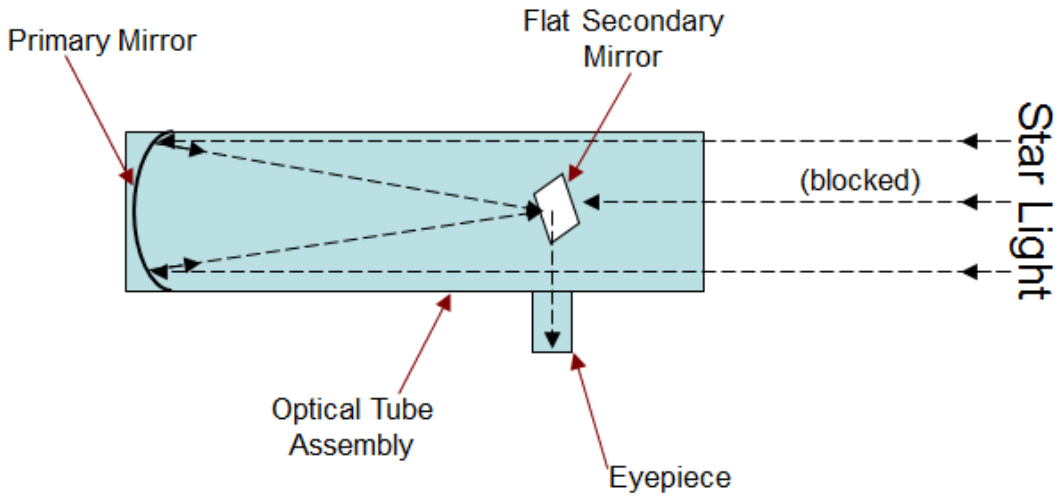


- Emits Radio waves at a specific frequency
- Uses reflected energy to characterize objects
- Advantages: Actively measures distance, motion, and can track many objects
- Disadvantages: Expensive, Large, Complex

Radar is not included in the current SSA Cost Model

Scope

- Ground-Based Electro-Optical Telescopes collect electromagnetic (EM) radiation emitted or reflected by an object and focus it into an image using lenses or mirrors



- Advantages:
  - Ability to cover large areas quickly
  - Creates images that can be used for object characterization
- Disadvantages:
  - Challenging to use for Low Earth Orbit (LEO) observations
  - Impacted by weather conditions (e.g. cloud cover)

Scope

- 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.

Scope

- 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.

- 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.

Scope

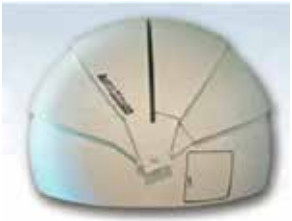
- A third choice for an SSA architecture or one that could supplement existing capability is to purchase SSA capability as a service from a commercial provider.

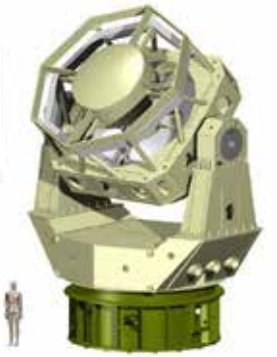
SSA Cost Model Features

- Estimate and compare the cost of up to five architectures at once
- Each architecture can consist of up to 12 sensors at multiple sites
- Choice of Commercial-off-the-shelf (COTS) or custom developed electro-optical telescope assemblies or a third option to purchase commercially provided Space Situational Awareness (SSA) capabilities
- Developed in MS Excel
- Implements Palisade @Risk to capture 24 areas of cost uncertainty

Major Elements of Cost

Element of Cost	Description
EO Telescope Assembly	An optical telescope connected to a camera.
Facility Prep & Development	The preparation and development of a facility to operate an SSA asset.
Operations & Sustainment	The software and equipment required to operate each SSA asset and store its data.
Commercially Provided SSA	The cost to procure SSA services from a commercial provider.





Extendable to Radar and Passive RF Sensors

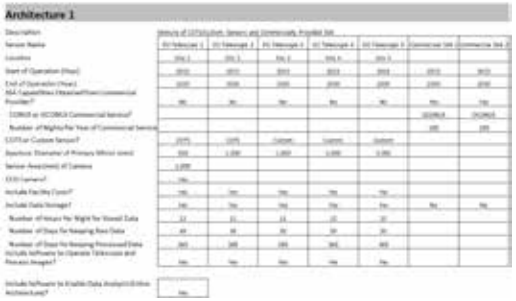
Using the SSA Cost Model

1. Describe each Architecture

Architecture Description	Sensor Name	Sensor Location
Start of Operation	End of Operation	Commercial SSA
COTS	Custom	Aperture Diameter
Camera Type	Camera Sensor Area	Include Facilities?
Include Data Storage?	Hours per night of Operation	Days of Raw Data Storage
Days of Processed Data Storage	Include Operating SW?	Include Data Analysis Software?

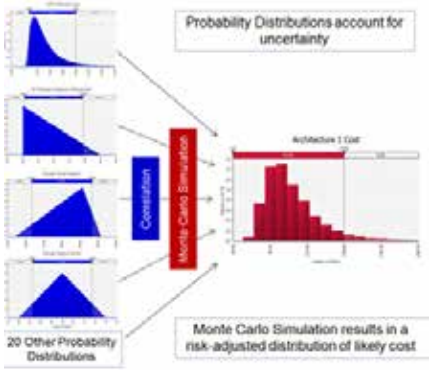
2. Model Generates Point Estimates

- EO Telescope Assembly
- Facility Prep & Development
- Operations & Sustainment
- Commercially Provided SSA



3. Perform Risk Analysis

- Monte Carlo Simulation using the Palisade @Risk Tool
- 24 Areas of Cost Uncertainty
- 10,000 Trials
- Results in a risk-adjusted distribution of likely cost



Inputs Example

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

Methods Summary

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

Custom Telescope Methods

- There are several existing published works identifying methods for estimating ground-based telescopes.

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

Custom Telescope Methods

The most complete treatment of ground based telescope cost estimating methods are the articles written by NASA Marshal Space Flight Center (MSFC) Senior Optical Physicist, Dr. H. Phillip Stahl.

Single Variable Model

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

Where:

- OTA is Optical Telescope Assembly including the primary mirror, secondary mirror, auxiliary optics, and support structure
- OTA cost is in BY00$M
- D is the Diameter of the Primary Mirror in Meters

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)

COTS Telescope 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.

	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

COTS Telescope CER

- 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:

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

Camera CER

- 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.

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

	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

	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

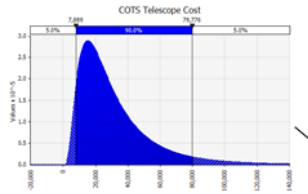
CMOS vs. CCD Cameras

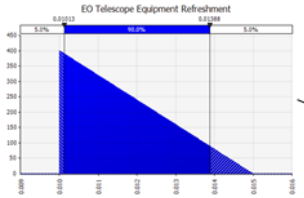
- Complementary Metal-Oxide-Semiconductor (CMOS) Camera
  - Rolling Shutter Effect

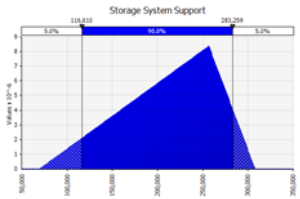
- Charge Coupled Device (CCD) Camera

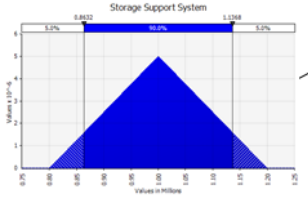
Risk and Uncertainty Analysis

Areas of Uncertainty
COTS Telescope
Custom Telescope
COTS Camera
Large (20 ft) COTS Dome
Medium (16 ft) COTS Dome
Small (12 ft) COTS Dome
Concrete Pad
Climate Control
Custom Facility
Image Processing (Initial Sensor)
Image Processing (Subsequent Sensor)
Cost per Terabyte
Yearly Cost for Storage System Support
Observations Per Hour
Size of Raw Image (MB)
Size of Processed Image (MB)
Size of Miscellaneous Data Storage (MB)
Days of Miscellaneous Data Storage
Data Analysis Software Cost
EO Telescope Equipment Refreshment
Data Storage Equipment Refreshment
COTS Facility Recurring Cost
CONUS Cost Per Night
OCONUS Cost Per Night







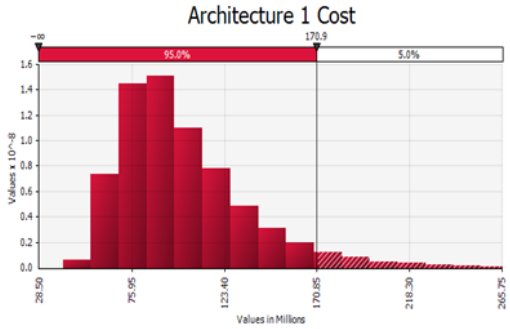


20 Other Probability Distributions

Correlation

Monte Carlo Simulation

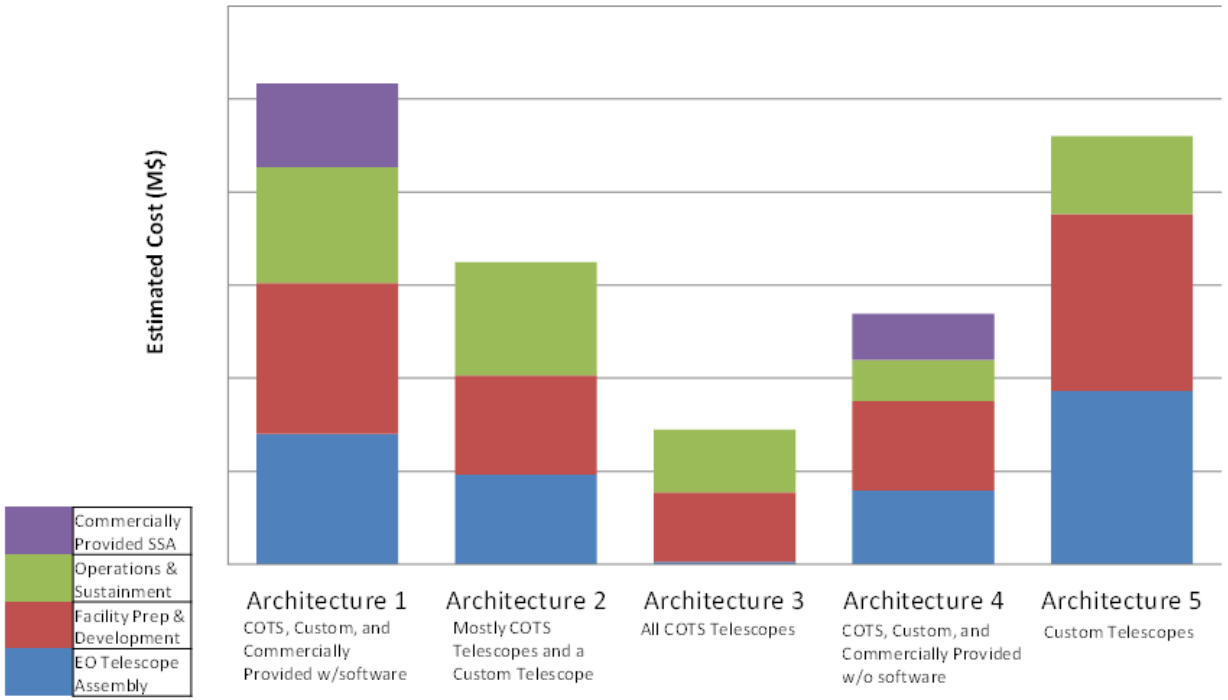
Probability Distributions account for uncertainty



Monte Carlo Simulation results in a risk-adjusted distribution of likely cost

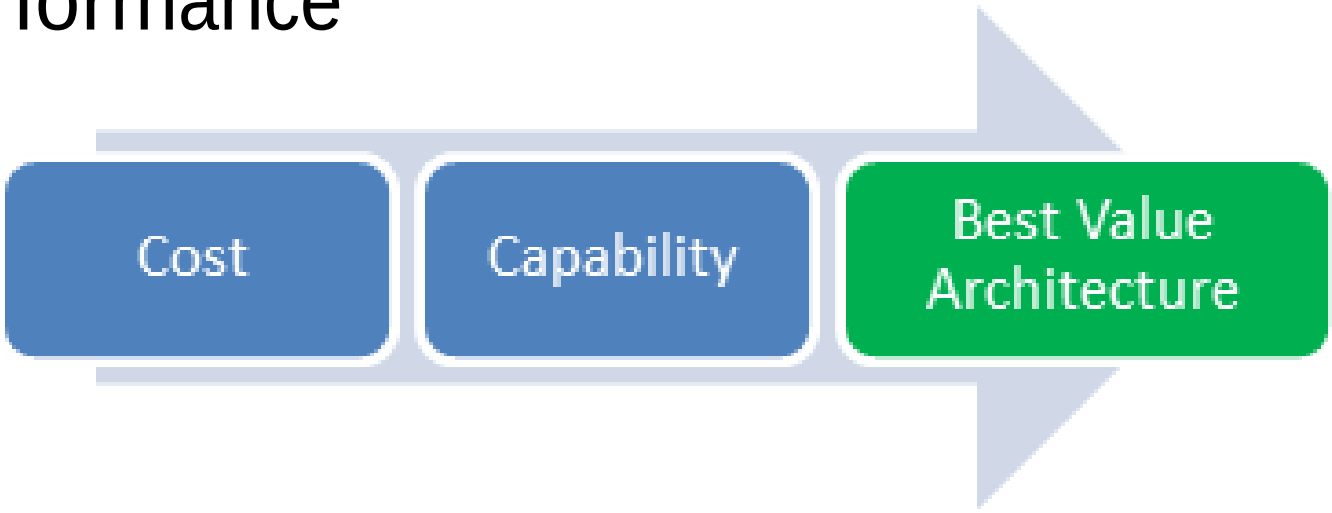
SSA Cost Model Output

- 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:



Next Steps

- Expand to Radar and RF Sensors
- Refine Estimating Methods
- Model Validation
- Pair with a tool that estimates sensor performance



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.

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Backup Slides

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.

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.

Using the SSA Cost Model

Steps:

1. Navigate to the Model Inputs Tab
2. Build Candidate Architectures
3. Run the Monte Carlo Simulation using @Risk
4. Review the Results in the Summary Output Tab

Architecture 1

Description							
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		

Work Breakdown Structure

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

Risk Distributions

Areas for Risk Implementation	Distribution	Mean	Standard Deviation	Level of Certainty of Estimate For Triangular Dist.
Ground-Based SSA Architecture	*Summing Element*			
EO Telescope Assembly	*Summing Element*			
COTS Telescope	Log Normal	CER Result	CER Result*SPE	
Custom Telescope	Log Normal	CER Result	CER Result*SPE	
COTS Camera	Log Normal	CER Result	CER Result*SPE	
Facility Site Preparation	*Summing Element*			
COTS Facility	*Summing Element*			
Large (20 ft) COTS Dome	Triangular			High
Medium (16 ft) COTS Dome	Triangular			High
Small (12 ft) COTS Dome	Triangular			High
Concrete Pad	Triangular			Medium
Climate Control	Triangular			Medium
Custom Facility	Log Normal	CER Result	CER Result*SPE	
Operations	*Summing Element*			
Image Processor and Autonomous Sensor Control	*Summing Element*			
Cost for Initial Sensor Per Month	Triangular			Medium
Cost for Each Subsequent Sensor Per Month	Triangular			Medium
Data Storage	*Summing Element*			
Cost per Terabyte	Triangular			Custom
Cost for Storage System Support Per Year	Triangular			Custom
Number of Observations Per Hour	Triangular			High
Size of Raw Image (MB)	Triangular			Low
Size of Processed Image (MB)	Triangular			Low
Size of Other Miscellaneous Data Storage (MB)	Triangular			Low
Days of Miscellaneous Data Storage	Triangular			Low
Data Analyzer Per Year	Triangular			Medium
Equipment Refreshment	*Summing Element*			
EO Telescope Equipment Refreshment (Proportion Per Year)	Triangular			Custom
Data Storage Equipment Refreshment (Proportion Per Year)	Triangular			Medium
COTS Facility Recurring Cost (Proportion Per Year)	Triangular			Low
Commercial Services	*Summing Element*			
CONUS Cost Per Night	Triangular			Medium
OCONUS Cost Per Night	Triangular			Medium

Risk Distribution Parameters

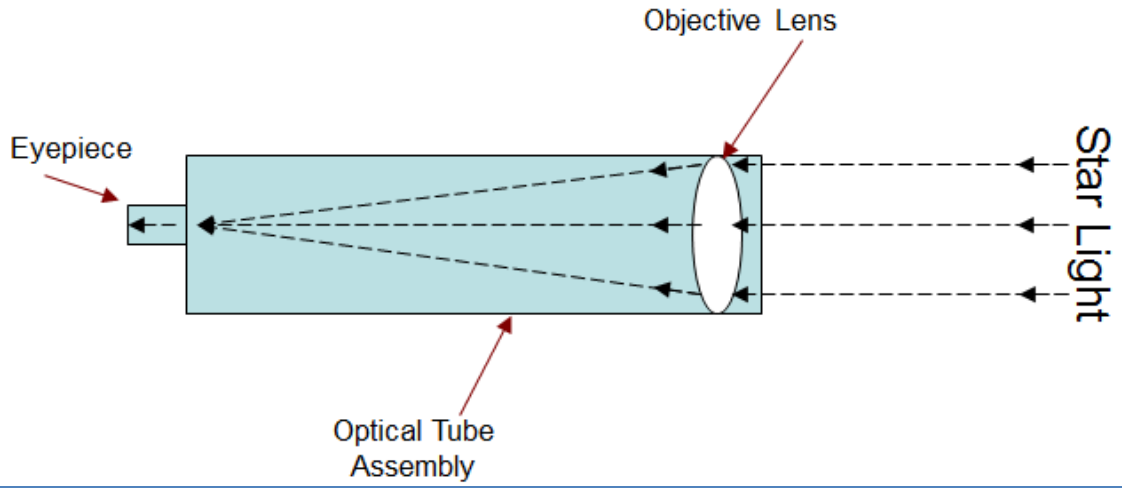
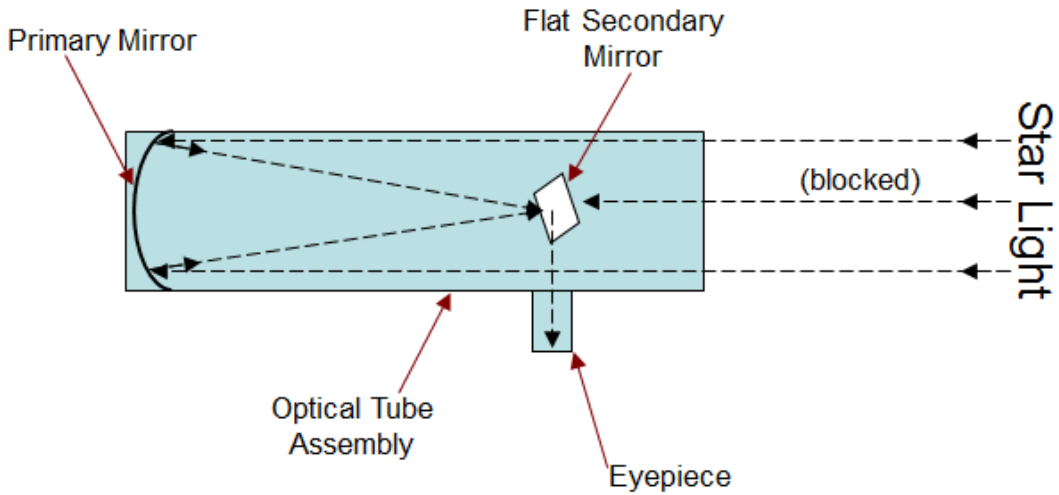
Areas for Risk Implementation	Level of Certainty of Estimate For Triangular Dist.	Custom Min	Custom Max	Min	Mode	Max	Triangular Risk Calculations
Ground-Based SSA Architecture							
EO Telescope Assembly							
COTS Telescope							
Custom Telescope							
COTS Camera							
Facility Site Preparation							
COTS Facility							
Large (20 ft) COTS Dome	High			68,703	76,337	83,971	76,337
Medium (16 ft) COTS Dome	High			44,779	49,754	54,729	49,754
Small (12 ft) COTS Dome	High			21,147	23,497	25,847	23,497
Concrete Pad	Medium			8,000	10,000	12,000	10,000
Climate Control	Medium			4,000	5,000	6,000	5,000
Custom Facility							
Operations							
Image Processor and Autonomous Sensor Control							
Cost for Initial Sensor Per Month	Medium			20,000	25,000	30,000	25,000
Cost for Each Subsequent Sensor Per Month	Medium			6,400	8,000	9,600	8,000
Data Storage							
Cost per Terabyte	Custom	787	2,250	787	1,875	2,250	1,637
Cost for Storage System Support Per Year	Custom	69,325	308,011	69,325	256,676	308,011	211,337
Number of Observations Per Hour	High			324	360	396	360
Size of Raw Image (MB)	Low			50	100	150	100
Size of Processed Image (MB)	Low			25	50	75	50
Size of Other Miscellaneous Data Storage (MB)	Low			3	5	8	5
Days of Miscellaneous Data Storage	Low			900	1800	2,700	1,800
Data Analyzer Per Year	Medium			800,000	1,000,000	1,200,000	1,000,000
Equipment Refreshment							
EO Telescope Equipment Refreshment (Proportion Per Year)	Custom	0.01	0.02	0.01	0.01	0.02	0.01
Data Storage Equipment Refreshment (Proportion Per Year)	Medium			0.02	0.03	0.04	0.03
COTS Facility Recurring Cost (Proportion Per Year)	Low			0.03	0.05	0.08	0.05
Commercial Services							
CONUS Cost Per Night	Medium			3,200	4,000	4,800	4,000
OCONUS Cost Per Night	Medium			4,800	6,000	7,200	6,000

Levels of Correlation

Level of Correlation	Correlation Value
High	0.75
Moderate	0.50
Low	0.25
Neg. Low	-0.25
Neg. Moderate	-0.50
Neg. High	-0.75
Neg. Perfect	-1

Basic Types of Optical Telescopes

- Refractor:



- Reflector: