Development of Multiple Parameter-based Cost Model for Small Earth Observation Satellite

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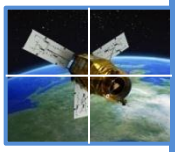
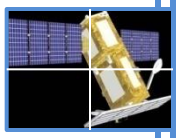
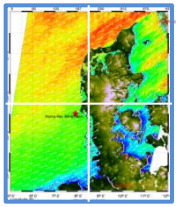
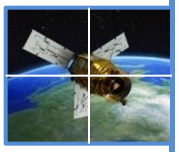
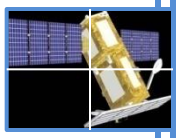
Introduction

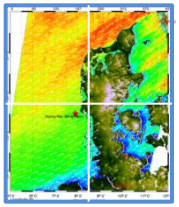





- Many countries are interested in developing earth-observation satellites
- Much cost saving possible using low-altitude, high-maneuverability small satellites
  - Shorter development period
  - Can be used both strategically and tactically
- Accurate development cost estimate is important at beginning to ensure program success

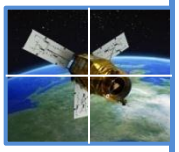
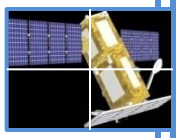
Cost Model Development Steps

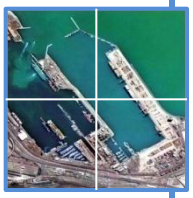
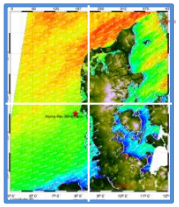





- Electro-optical and SAR satellite data was collected for this research
  - EO satellite mass range: 100 – 1000 kg
  - SAR satellite mass range: ~ 5000 kg
  - 100+ satellites in database, 26 EO and 8 SAR satellites selected for study
- Defined System Complexity Index by combining various parameters, using established database
- Cost model developed by incorporating correction factors depending on reliability requirements

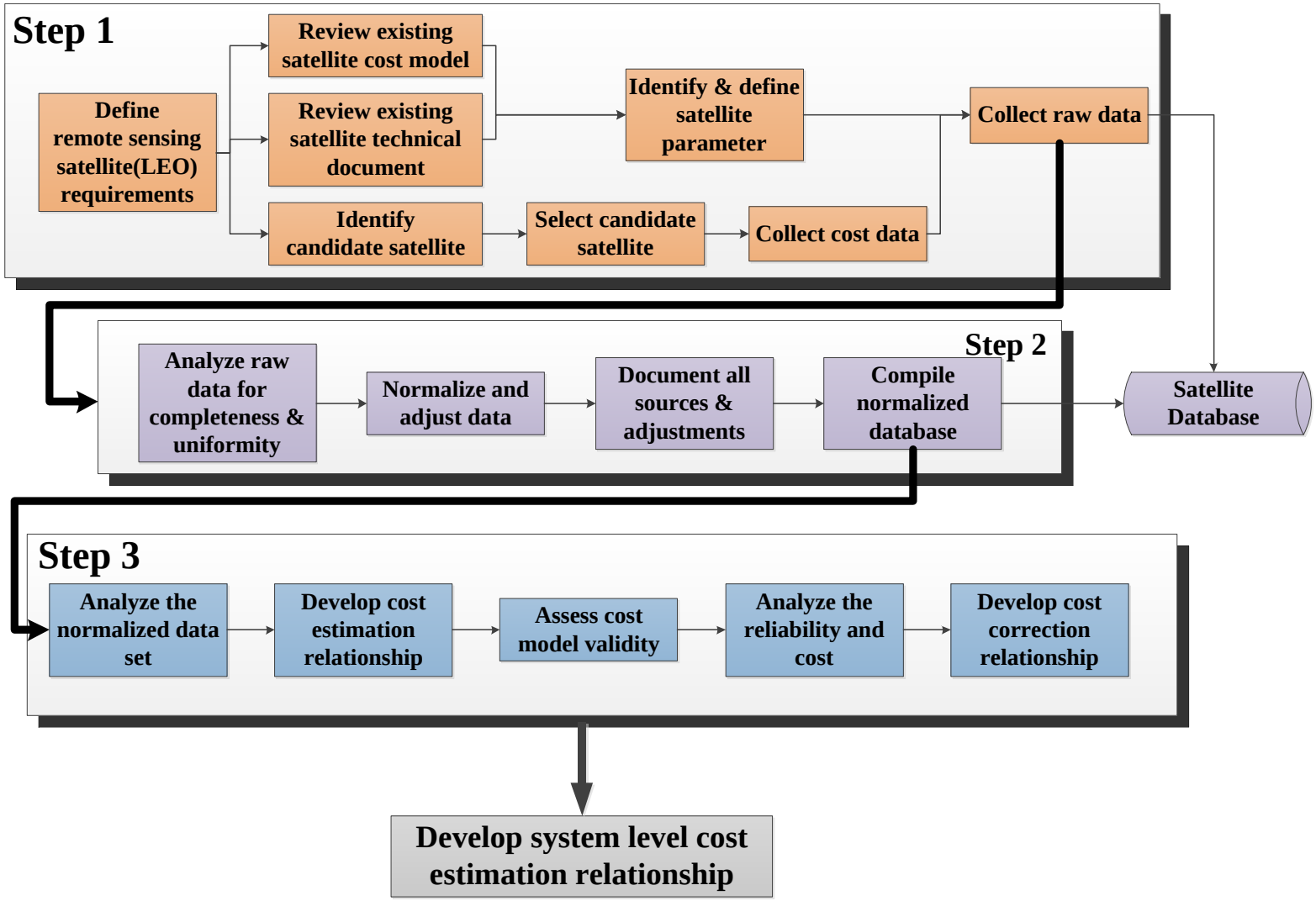
Development Procedure

- Step 1
  - Define Main Parameters for Cost Estimation and Collect Satellite Data – Cost, programmatic, and technical data from previously flown LEO observation satellites were collected.
- Step 2
  - Evaluate and Normalize Satellite Data – The collected instrument data were normalized to scale uniformity, ensure completeness of costs, and correct for known bias and inconsistencies.
- Step 3
  - Develop and Validate Cost Estimation Relationship – Statistical techniques were applied to the normalized data to drive System Complexity Index and establish Cost Estimating Relationships

Development Procedure



Definition of Main Parameter

- Study of Previous Cost Model
  - Objective : to develop reliable cost model by first studying previous cost models, then analyzing short comings

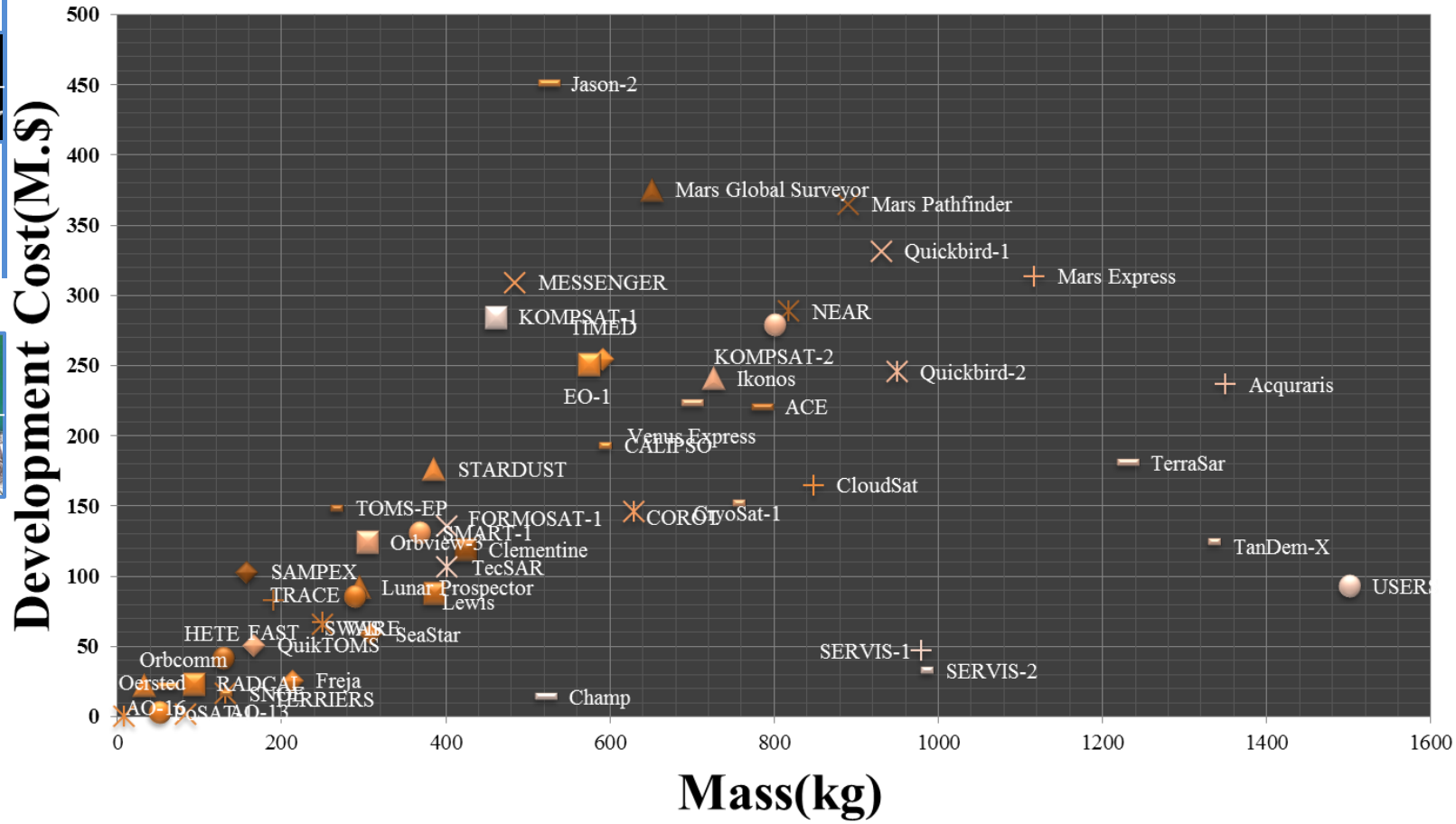
USCM | **SSCM** | **QuickCost** | **Price-H** | **SEER-H**

Mass-based cost models

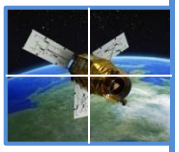
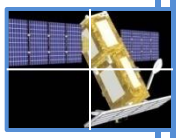
- Majority of cost models are mass-based
  - Additional parameters are added to increase accuracy

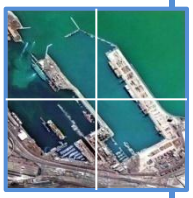
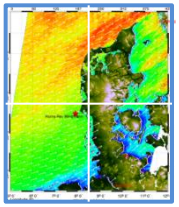
Definition of Main Parameter

- Mass-based cost models generally demonstrate high accuracy
  - Increase in mass generally correlate to increase in caost



Shortcomings of Mass-based Models

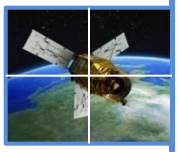
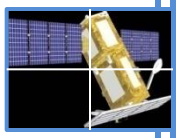



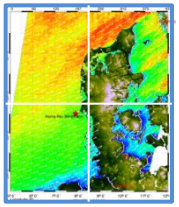
- Other factors that affect development costs show up as only small factor in mass-based cost estimation
- Decrease in mass can result in increase in cost
  - Claude R. Joyner II, 2011, Pros, Cons, and Alternatives to Weight Based Cost Estimating)
  - For given performance requirement, decrease in mass will require higher development cost
    - Mirrors and lens in EO satellite accounts for approx. 20% total mass

Previous Work

- There are studies in adapting parameters to overcome this shortcoming
  - Bearden – looked into development cost of deep-space exploration missions and low-cost exploration missions using complexity index
  - NASA – developed cost model specific for the observation satellite payloads to account for current trend of utilizing standardized modular satellite bus
  - SAIC, Aerospace Corporation – researched EO satellite cost modeling taking into consideration complexity index and developing organization (DoD, NASA, Europe)
  - Mettas – takes into consideration complexity of system according to reliability

Cost Model Development Steps



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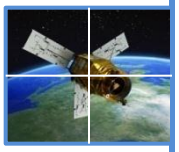
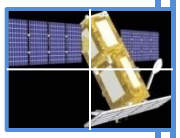
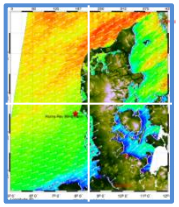
Evaluation of Satellite Data

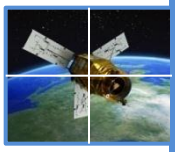
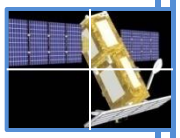



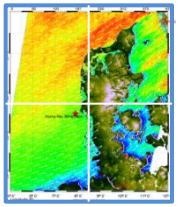


Evaluation of satellite data

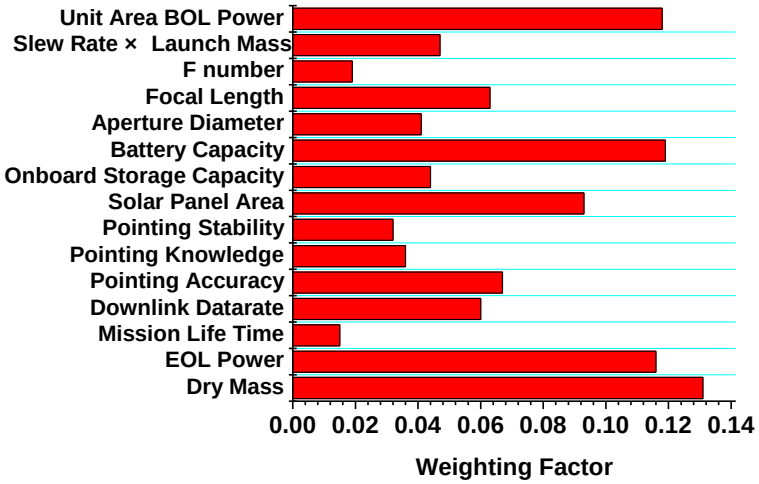
- KEOSCM(KAU Electro Optical Satellite Cost Model) is based on small satellite database
- Contains data of small satellites developed or in development as of Jan of 2012
- Hyperspectral Camera and Particle Detector satellites excluded
- Multispectral/Panchromatic Camera payload satellites included only
- In case of SAR satellites, only active SAR satellites are included
- Satellites with launch failures included
- Failed satellites due to malfunction have been excluded

Evaluation and Normalization of Satellite Data

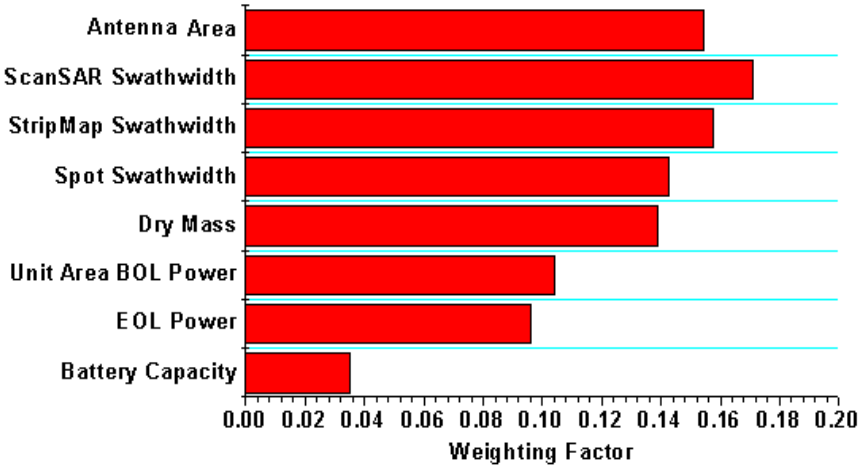





- Selection of parameters
  - Parameters that affect cost are selected from technical and statistical analysis
  - Each weighting is determined from Correlation Analysis
  - System complexity index is derived by combining complexity indexes of each selected parameter



Parameters and Weighting Factor for EO Sat



Parameters and Weighting Factor for SAR Sat

Definition of Main Parameter

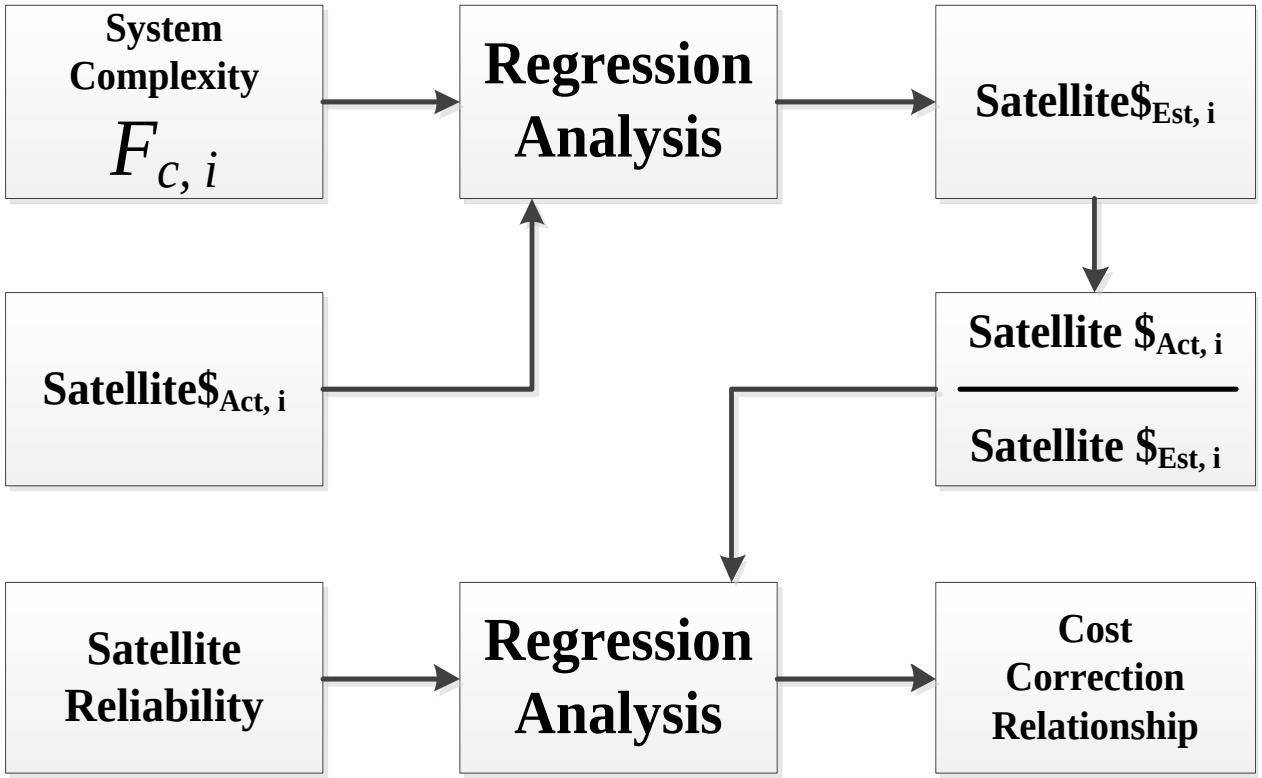
- Proposed cost model utilizes complexity index and reliability factors
- Complexity Index (F_C)
  - Index proposed by Bearden
  - Describes technical and programmatic complexity
  - Can describe technical complexity
    - Was not expressed in mass-based models
  - Calculated using "Percent Rank" statistical tool
    - Ranked data is expressed in percentile
    - Values between data is determined by linear interpolation

System Complexity Index ← $F_C = \sum w_i f_i$ → Parameter Complexity Index

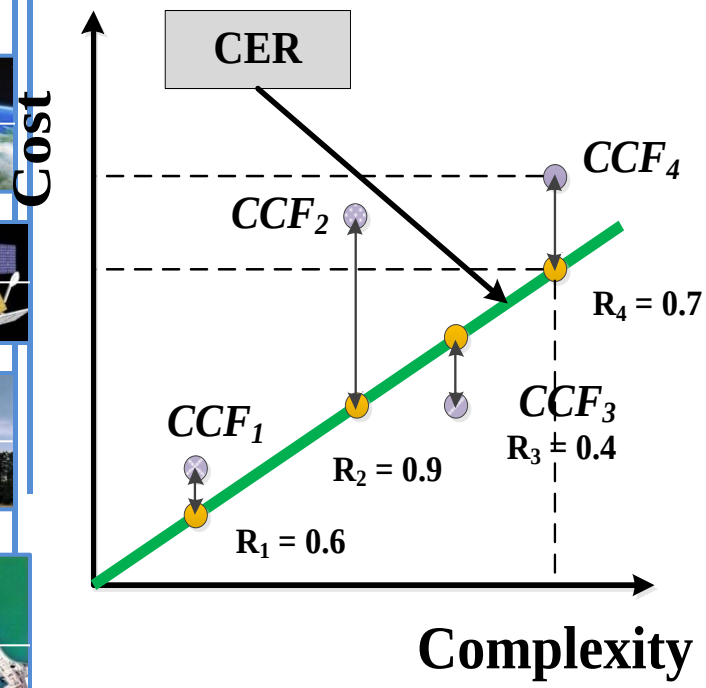
w_i ↓ Weighting Factor

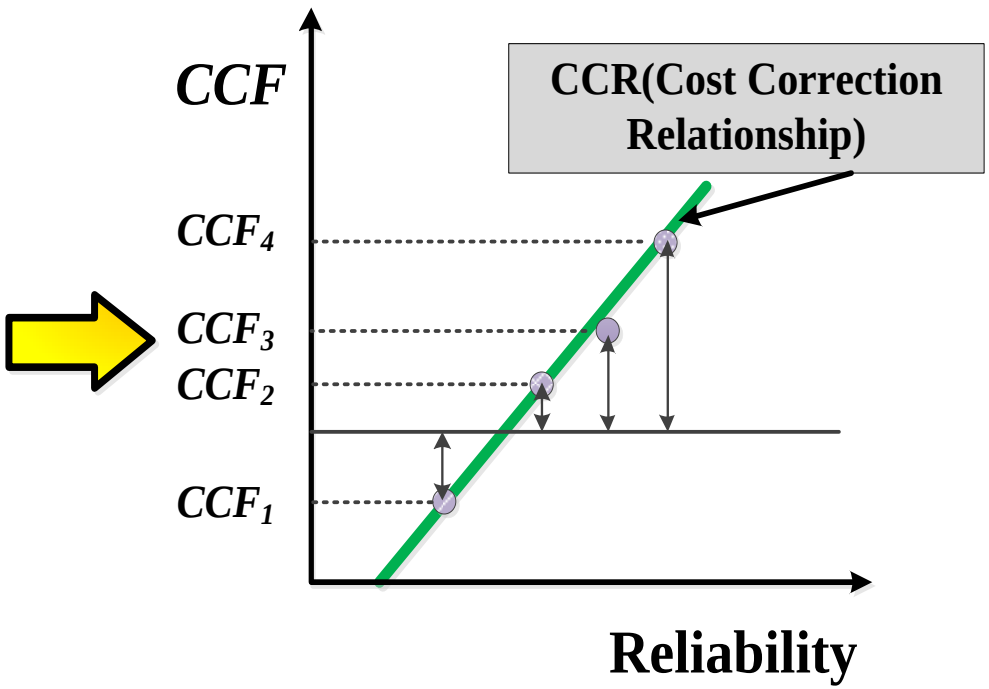
Definition of Main Parameter

- Cost Correction Relationship
  - Derived based on reliability model by Mettas and methods described by TRANSCOST
  - Cost estimation method proposed by Covert has been applied



Definition of Main Parameter



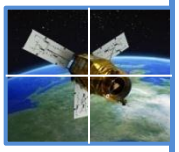
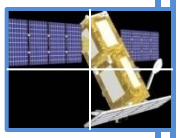


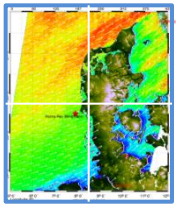
$$CER = f_{CER}(C)$$

$$CCR = f_{CCF}(R)$$

$$\boxed{Final\ \ CER = f_{CER}(C)\, f_{CCF}(R)}$$

Normalization of Satellite Data



Normalization of Cost Data

- The satellite cost data carries a different monetary value depending on the point in time of the satellite cost evaluation.
- As an example, if the cost of a satellite is evaluated in the far past, the cost value at a later time will be higher, and the inflation must be taken into consideration.
- In addition, the different values of the international monetary units must be taken into consideration in normalizing the cost data
- Accordingly, the cost data was normalized to FY2012 values using NASA New Inflation, and in case of international development, the exchange rate at that time is factored in for conversion to USD.

Development of Cost Model

- CER for EO Satellite
  - For EO satellites, cost estimation derivation was divided into High Cost Traditional Satellite and Low Cost Small Satellite

$$y = a \cdot e^{bx}$$

HCTS Data
Regression Analysis

→

HCTS
Cost Estimation
Relationship

→

Fix
Parameter "b"

↓

LCSS Data
Regression
Analysis

←

LCSS
Cost Estimation
Relationship

←

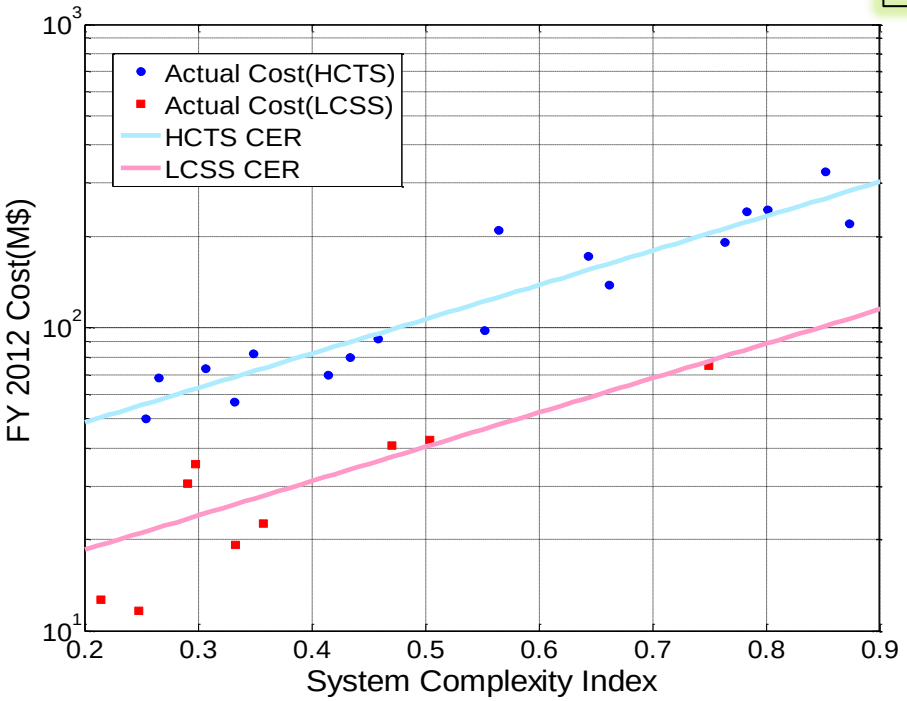
Derive
Adjustment Factor
f_{LCSS}

$$y = a \cdot e^{bx} \cdot f_{LCSS} \qquad y = c \cdot e^{bx}$$

Procedure for Derivation of Adjustment Factor

Development of Cost Model

- Cost Estimation Relationship (CER) derivation results



$$f_{CER_{HCTS}}(F_C) = 28.986 \times e^{2.606 \times F_C}$$

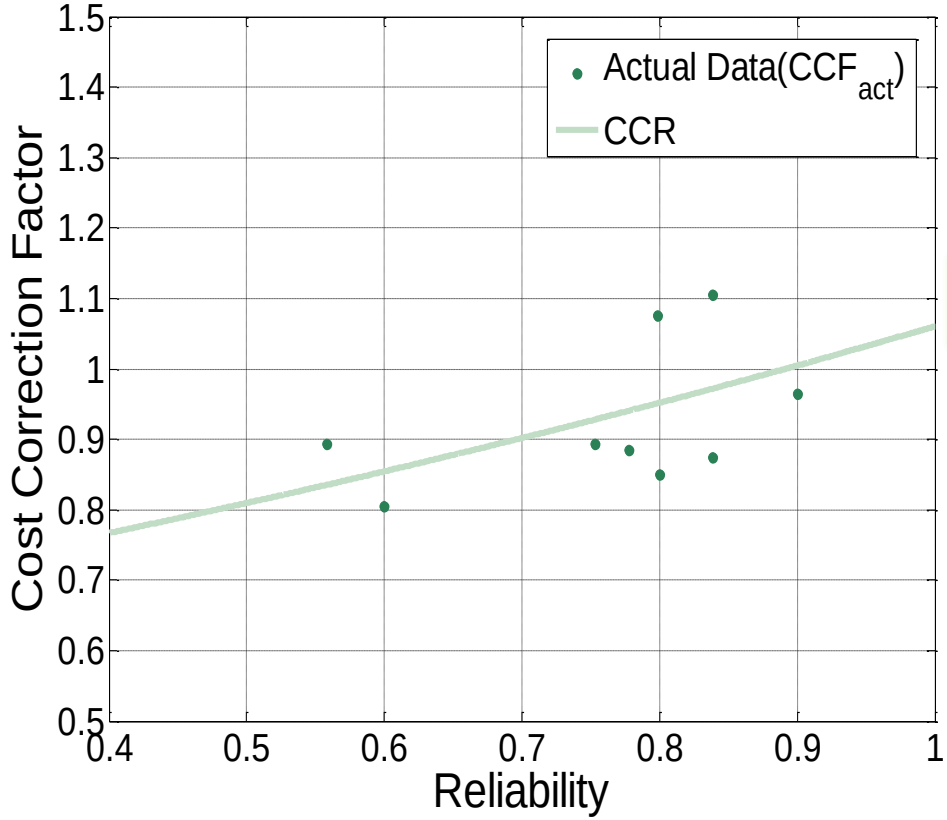
Item	Value
R^2	0.699
SE	33%
F value	19.543
p value	0.003

$$f_{CER_{LCCS}}(F_C) = 11 \times e^{2.606 \times F_C}$$

Item	Value
R^2	0.699
SE	33%
F value	19.543
p value	0.003

Reliability Factor

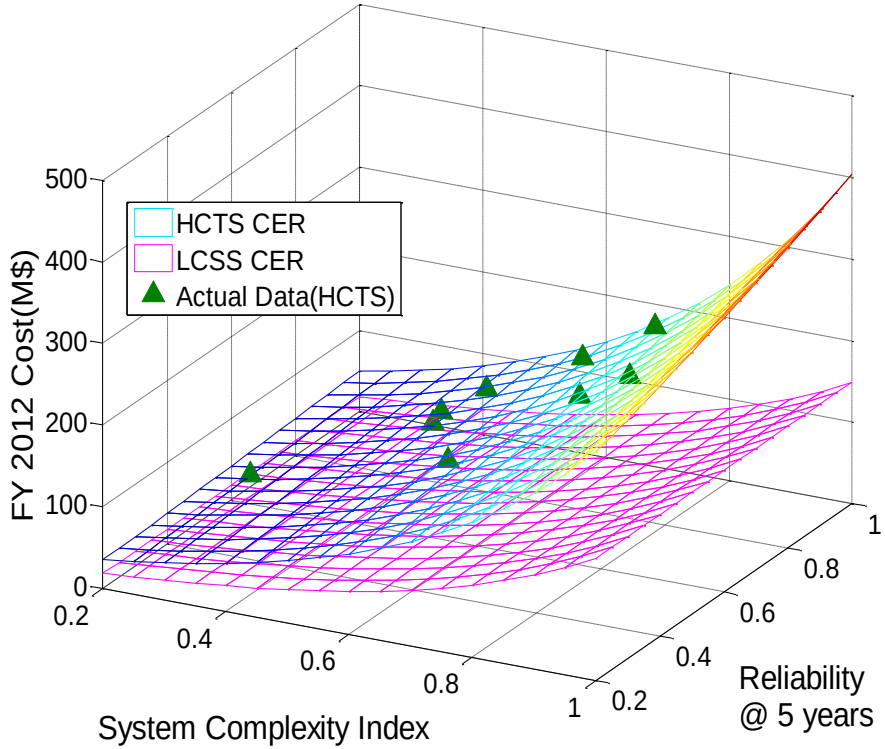
- Cost Correction Relationship



$$f_{CCF}(\mathrm{R}) = 0.618 \times e^{0.54 \times \mathrm{R}}$$

Item	Value
R^2	0.206
SE	10%
F value	2.824
p value	0.148

Development of Cost Model

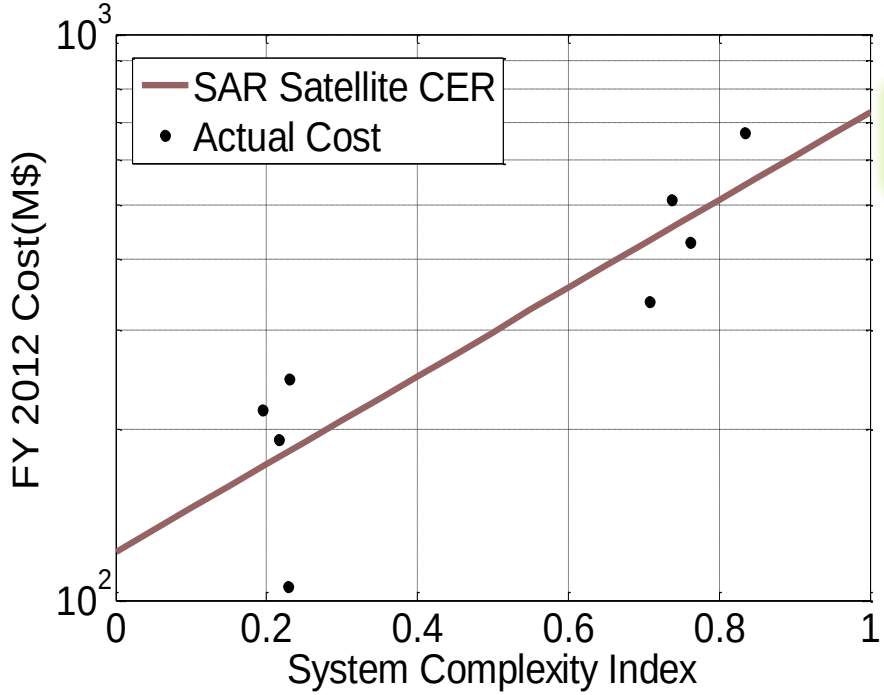


$$f_{CER}(F_C, f_{LCSS}) = 28.986 \times e^{2.606 \times F_C} \times f_{LCSS}$$

- $f_{LCSS} = 1$ @ *HCTS Satellite*
- $f_{LCSS} = 0.379$ @ *LCSS Satellite*

Development of Cost Model

- CER for SAR Satellite



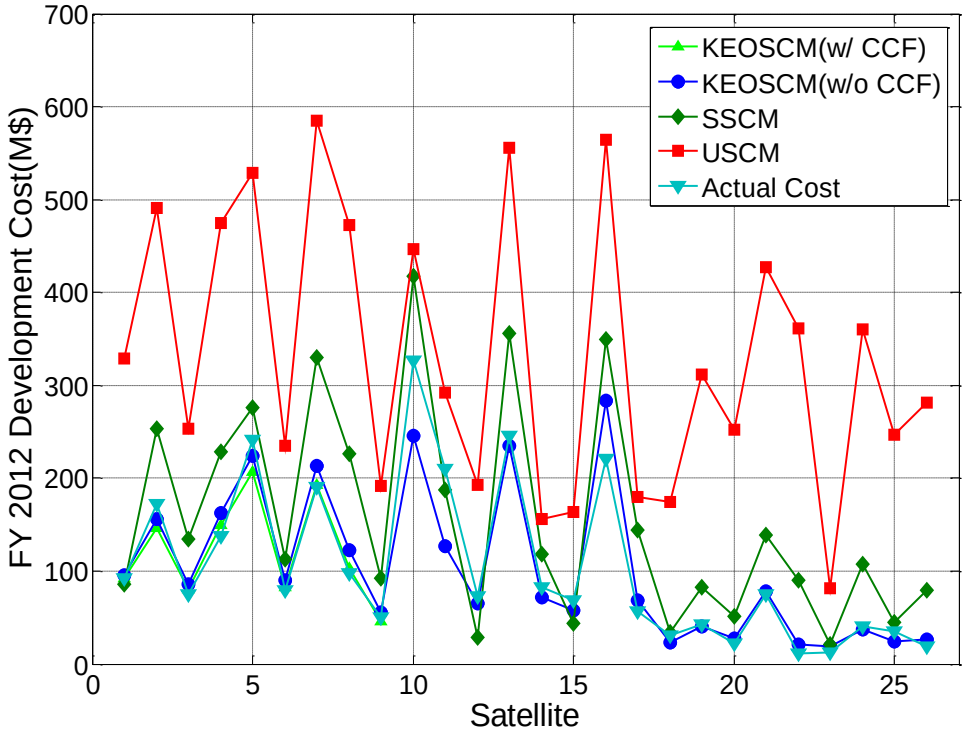
$$f_{CER}(F_C) = 121.74 \times e^{1.788 \times F_C}$$

Statistic Analysis Results

Item	Value
R^2	0.730
SE	31%
F value	19.94
p value	0.0043

Verification of Cost Model

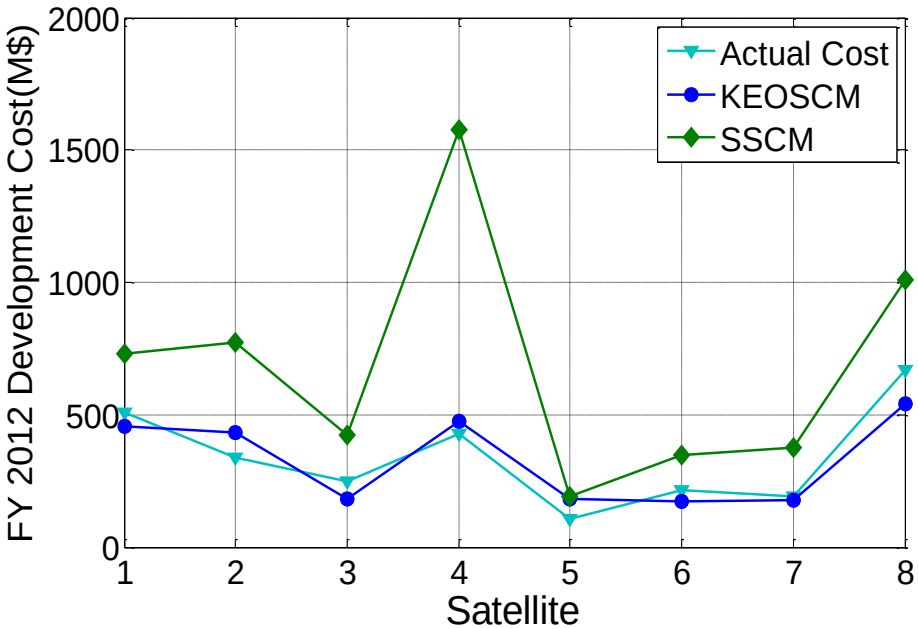
- Different types of verification methods applied
  - Cost estimation results compared to actual satellite data used
  - Resulting error comparison with other cost models
  - Application to other EO satellite in development



Cost Model	Difference
KEOSCM(w/o CCF)	21%
KEOSCM(w/ CCF)	7%
SSCM	98%
USCM	460%

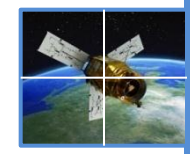
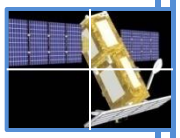
Verification of Cost Model

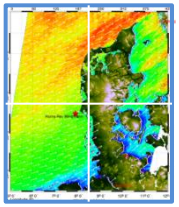
- SAR satellite verification result



Cost Model	Difference
KEOSCM	24%
SSCM	100%

Application of KEOSCM



- Application to current satellite in development
- EO satellite specification

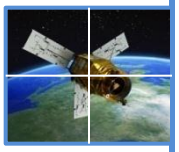
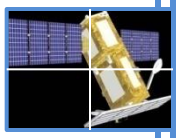
Factors	Values
Launch Mass	537.96 kg
Dry Mass	517.84 kg
Mission Life Time	5 years
EOL Power	1203 W
Downlink Data Rate	576 Mbps
Pointing Accuracy	0.0024 deg
Pointing Knowledge	0.002 deg
Pointing Stability	0.0002 deg/s
Slew Rate	2 deg/s
Solar Panel Area	3 m^2
Onboard Memory Capacity	300 Gbits
Battery Capacity	30.1 Ah
Aperture Diameter	0.87 m
Focal Length	8.8 m
F Number	10.09
Reliability	0.7 @ 5 years

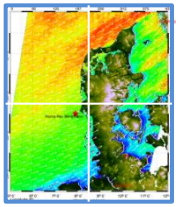
SCI
(System Complexity Index) : 0.765

LCSS Concept Development Cost
→$81M

HCTS Concept Development Cost
→ $192M

Application of KEOSCM



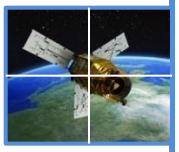
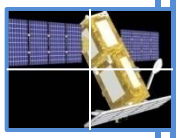
- SAR satellite specification

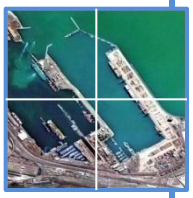
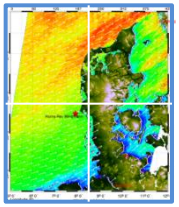
Factors	Values
Launch Mass	954 kg
Dry Mass	918 kg
Mission Life Time	5 years
EOL Power	4497 W
Downlink Data Rate	238 Mbps
Pointing Accuracy	0.024 deg
Pointing Knowledge	0.002 deg
Pointing Stability	0.0005 deg/s
Slew Rate	1 deg/s
Solar Panel Area	19.4 m^2
Onboard Memory Capacity	15.7 Gbits
Battery Capacity	114 Ah
ScanSAR Swathwidth	500 km
StripMap Swathwidth	30 km
Spot Swathwidth	15 km
ScanSAR Resolution	50 m
StripMap Resolution	2 m
Spot Resolution	1 m

SCI
(System Complexity Index) : 0.529

Development Cost
→$313M

Conclusion

- KEOSCM was developed to enable cost estimation according to given mission
  - Developed targeting EO and SAR payload satellites
- Multiple-parameter methodology was employed to overcome shortcomings of mass-based cost models
- When applied to satellites in database, result showed much higher accuracy compared to previous cost models
  - EO satellites: approx. 7% error
  - SAR satellties: approx. 24% error
- Authors plan to continuously update database as more data becomes available
- Team is currently also looking into conceptual design tools, and plan to integrate cost model and design tools to develop a complete, integrated conceptual design tool

Thank you. Questions?

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