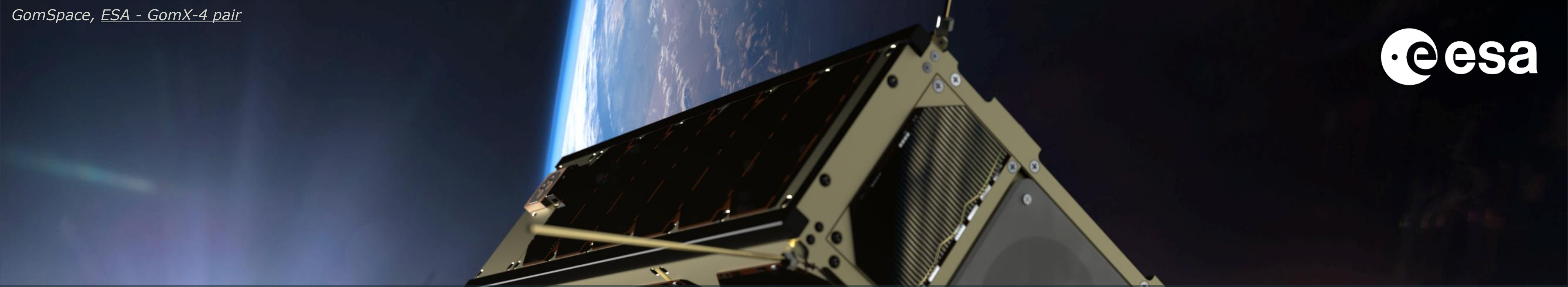

GomSpace, ESA - GomX-4 pair

Multivariate Modelling for End-to-End Cost Estimates in financially sustainable CubeSat Projects: the CubEM approach

SCEC
SPACE COST ENGINEERING CONFERENCE
3-4 October 2024
Toulouse
France

Authors:

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Giulia Cambone (ESA)

European Space Agency
Agence spatiale européenne

→ THE EUROPEAN SPACE AGENCY

An ESA perspective – why we need CubEM

CubEM – CubeSat Estimating Model

Lights on New Space – gaining more and more traction

Cheap, standard, COTS, fast procurements, New Space approach → Need for a tailored model

Interplanetary
Miniaturised Asteroid Remote Geophysical Observers (M-Argo)
Rendezvous with an asteroid (shape, mass, surface)

Moon
Lunar Meteoroid Impacts Observer (LUMIO)
Observe meteoroid impacts on the lunar far side (meteoroid flux in the Earth Moon system)

IOD
OPS-SAT – flying laboratory
Test and validate new techniques in mission control and on-board satellite systems

Telecomm/IOD
GOMX-3
Demonstrate aircraft ADS-B signal reception and geostationary telecommunication

Earth Observation
Φ-sat – artificial intelligence for EO
Filtering out less than perfect images so that only usable data are returned to Earth

Navigation
Passive REflecTomeTry and dosimetry (PRETTY)
GNSS reflectometry from in orbit as well as radiation measurements

Educational
Fly Your Satellite! (FYS)
Educational programme for university and other tertiary education student teams

Some Examples

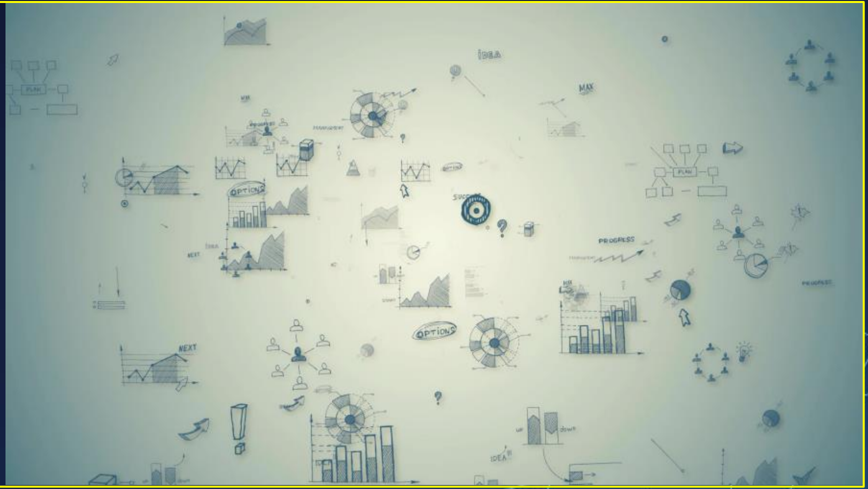
Web URLs:
- ESA - CubeSats
- ESA - M-Argo: Journey of a suitcase-sized asteroid explorer
- ESA - LUMIO – New CubeSat Illuminating Lunar Impacts
- ESA - OPS-SAT
- ESA - Φ-sat
- ESA - PRETTY CubeSat
- ESA - Fly Your Satellite! – Vega Maiden Flight Teams

CubEM – Purpose and Applicability

Purpose: preliminary New Space mission estimates

Applicability:

- Early phases
- Concurrent engineering
- Project trades
- Cost drivers' identification



CubEM – Scope of Estimate

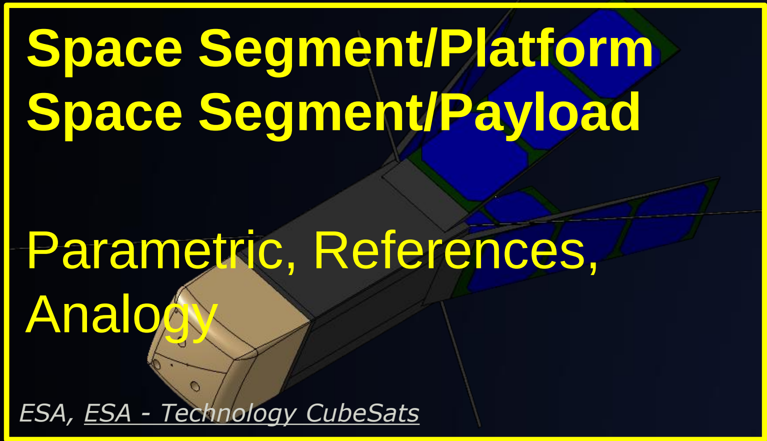
- **CubEM**
  - **Space Segment**
    - **System Level activities**
      - Project Office
        - *Management*
        - *Engineering*
        - *Product Assurance*
      - AIV/T
      - GSE
    - **Platform**
    - **Payload**
    - **Contingency**
  - **Launch Segment**
  - **Ground Segment & Operations**
  - **User and Data Segment**

PFM → FM1 → FMR

N.B: The modelling of the User and Data segment (applications, user data retrieval, downstream) is still under investigation.
Need to collect a representative set of data.

CubEM – Methodology

Phases C/D



Space Segment/Platform
Space Segment/Payload

Parametric, References, Analogy

ESA, ESA - Technology CubeSats

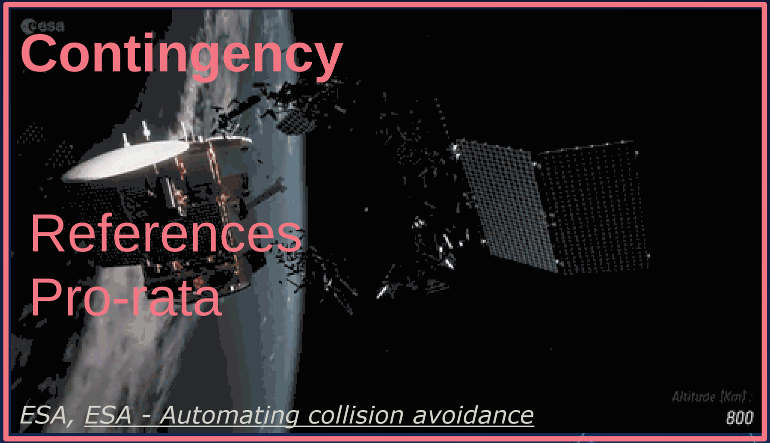
Phases B2/CD/E1

Space Segment/ System Level activities

Cost-to-cost

ESA, ESA - Advanced manufacturing

Phases B2/CD/E1



Contingency

References
Pro-rata

ESA, ESA - Automating collision avoidance

Phase E1

Launch Segment

References
Pro-rata

ESA / CNES / Arianespace, ESA - Vega-C launch in slow motion

Phase E2

Ground Segment & Operations

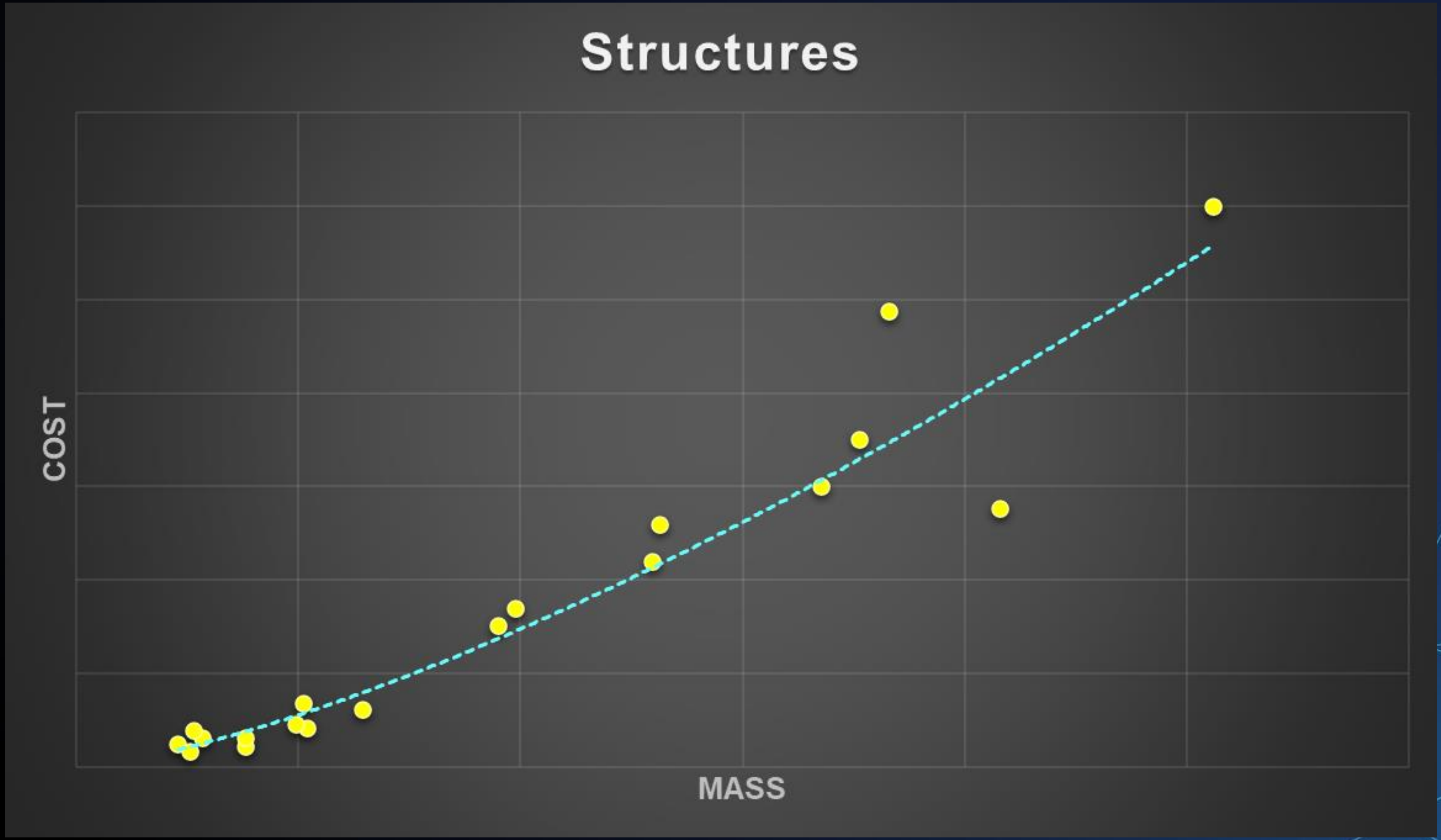
References, Analogy

Parametric: Cost Estimating Relationships (mathematical functions)
Cost-to-cost: Cost of one component based on cost of another
Pro-rata: In proportion
References, Analogy: Need to account for deltas, as good as source

Space Segment / Platform and Payload Production

Parametric Method: CubEM provides estimates down to Equipment Level

Cost Estimating Relationships (CERs)



CER: *a mathematical formula where a dependent variable (cost) is expressed as a function of one (single-variate) or more (multi-variate) independent cost-driving parameters (e.g. mass, power)*

$$Cost = a + b \cdot Mass^{C_1}$$

a = intercept
b = characteristics of the product
c1 = cost discount when mass increases

…more than one cost driver?

Space Segment / Platform and Payload Development

Cost Factors for development models

- Normalized for 1FM
- CubEM derives them from Standard satellites'
- Still needed to apply **CERs** for production cost

Additional MAIT effort at Equipment Level

FM1 = 1	Reference
PFM > FM1	It is the effort to procure FM1 plus qualification tests plus refurbishment.
QM < PFM QM > FM1	A flight-representative QM is the effort to procure FM1 plus qualification tests.
EM expected below of FM1	The EM is not flight representative, it excludes hi-rel parts, it might be a partial model, it might be a down scaled model.
SM = QM	This is true for flight-representative structures.
SM < FM1	In case of PFM approach the SM may count for qualification tests and refurbishment only.
SM much below FM1	Mass dummies
FM2 to FMn < FM1	Effect of learning curve

Typical models at equipment level:

- Bread Boards (BB)
- Structural Model (SM) or Structural Thermal Model (STM)
- Engineering Model (EM)
- Engineering Qualification Model (EQM)
- Qualification Model (QM)
- Proto Flight Model (PFM)
- Flight Model (FM)
- Spares

If:

1EM = a · 1FM

1QM = b · 1FM

HW Matrix of component = 1EM + 1QM + 1FM

Cost of component = (a + b + 1) · **cost of 1FM**

ESA/Science Office, ESA - Hera deploying CubeSats

Space Segment / Platform and Payload modelling

Production cost from CER

HW/SW — Data collection & normalization

CER — Building a relationship

Eq. 1FM — Equipment 1FM CER output

Equipment Level

Development cost from Cost Factors

Eq. 1FM·(a+b+…+1) — Applying cost factors to all Equipment

1st Satellite — Based on Model Philosophy

Sat. FM1 — 1st Recurring Sat (cost factors = 0)

Sat. FMR — Learning Curve

Satellite Level

Space Segment / Platform - CER formulation and cost-drivers

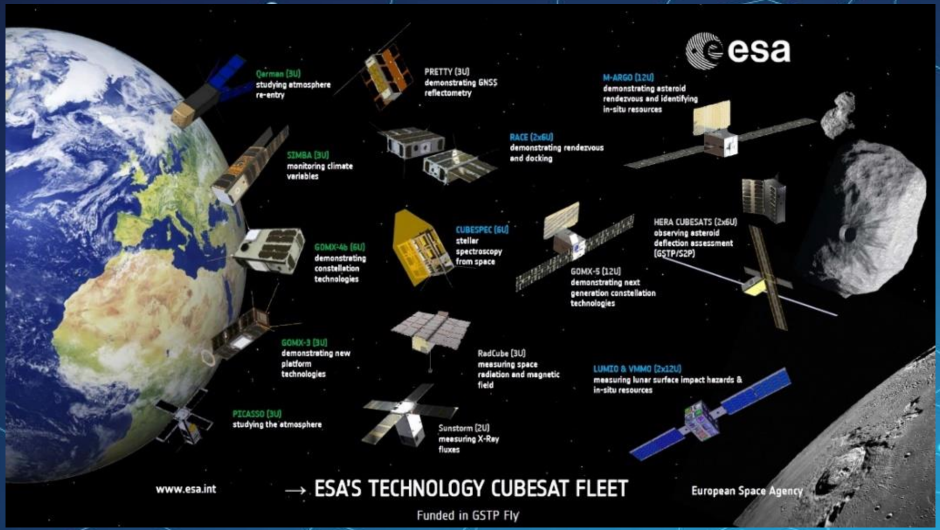
$$Cost = a + b \cdot X_1^{c1} \cdot X_2^{c2} \cdot \ldots \cdot X_m^{cm} \cdot d_1^{x_{m+1}} \cdot d_2^{x_{m+2}} \cdot \ldots \cdot d_n^{x_n}$$

	CubEM CERs	2nd Input	3rd Input
AODCS&GNC	**ADCS boards CubEM CER**	**Thickness [mm]**	
AODCS&GNC	**Earth/Nadir Sensors CubEM CER**		
AODCS&GNC	**Gyros CubEM CER**		
AODCS&GNC	**Magnetometers CubEM CER**		
AODCS&GNC	**Magnetorquers CubEM CER**	**Mag moment [Am2]**	
AODCS&GNC	**Reaction Wheels CubEM CER**	**Momentum [mNms]**	**Dimensions [mm3]**
AODCS&GNC	**Star Trackers CubEM CER**	**Cross Boresight ["]**	
AODCS&GNC	**Sun Sensors CubEM CER**		
Communications	**GNSS/UHF antennas CubEM CER**		
Communications	**S-/X-/K-band antennas CubEM CER**	**S-band [Yes, No]**	
Communications	**TxRx CubEM CER**		
OBDH	**OBCs CubEM CER**		
Power	**Power Systems CubEM CER**	**Capacity [Wh]**	
Power	**PCDUs CubEM CER**		
Power	**Solar Panels CubEM CER**	**Deployable [Yes, No]**	
Propulsion	**Propulsion Systems CubEM CER**	**Electrical [Yes, No]**	
Structure	**CubeSat Deployers CubEM CER**		
Structure	**CubeSat Structures CubEM CER**		
Structure	**Harness CubEM CER**		
Structure	**Mechanisms CubEM CER**		
Other	**CubeSat Platforms CubEM CER**		
Payload	**Hypersp. Optical Cameras CubEM CER**	**Lens [mm]**	
Payload	**Not Hypersp. Optical Cameras CubEM CER**	**Dimensions [mm3]**	

Other than the **Mass (1st Input)** – they are: Quantitative Variables or Categorical Variables

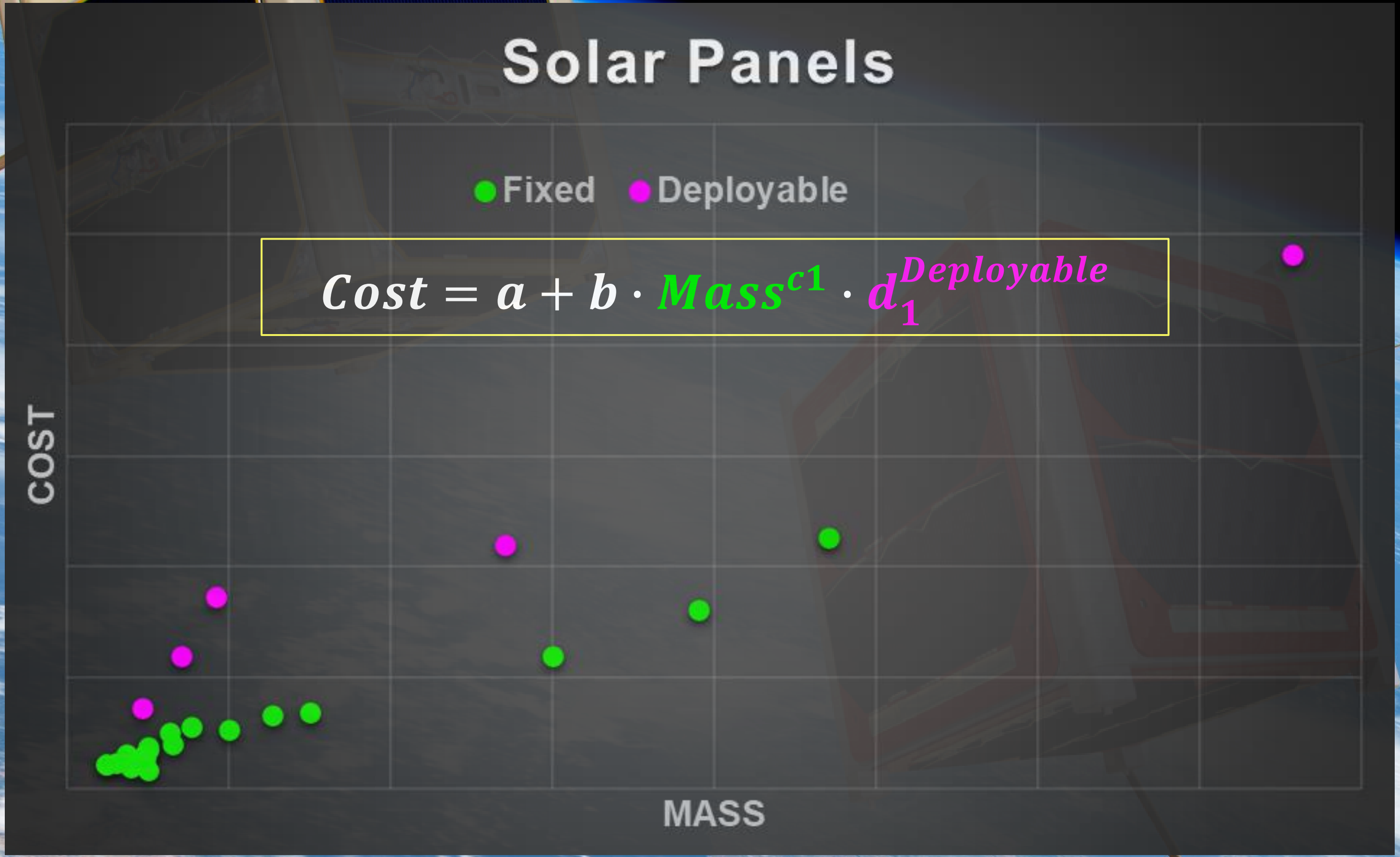
CubEM database: COTS
- *www.cubesatshop.com*
- High TRL (TRL ≥ 8)
- Normalized to 1FM (Flight Model)

ESA, ESA - Technology CubeSats



ESA/Medialab, ESA - Fly Your Satellite! CubeSats phoned home

Space Segment / Platform - Multi-variate CER example



…But how to retrieve CER parameters?

a, b, c1, d1,..

Space Segment / Platform - ZMPE method

ZMPE = Zero Percentage Bias Minimum Percentage Error

<u>A constrained minimization process:</u> model accurate (1.) and unbiased (2.)

1. *Minimum Percentage Error*:

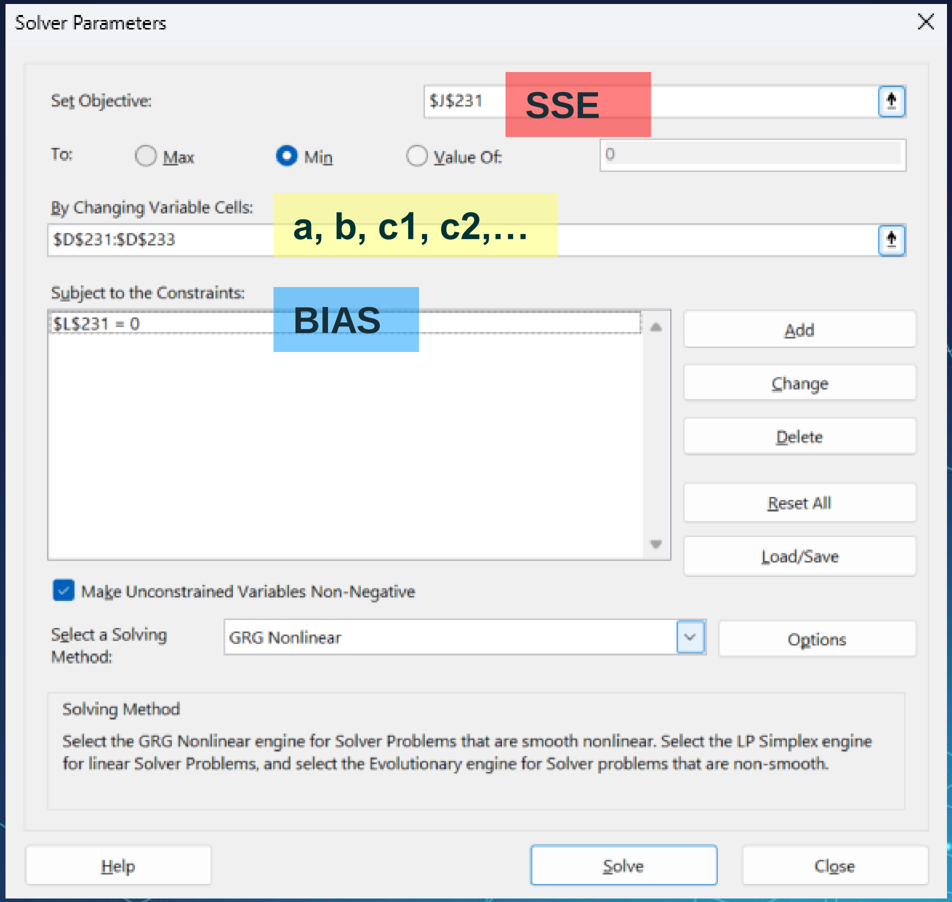
   minimize SSE $\sum_i \left(\frac{y_i - \hat{y}}{\hat{y}}\right)^2$

2. *Minimum Percentage Bias*:

   subject to constraint $\text{BIAS} = \sum_i \left(\frac{y_i - \hat{y}}{\hat{y}}\right) = 0$

$$y_i = \textit{actual values}$$
$$\hat{y} = \textit{estimated values} = a + b \cdot X_1^{c1} \cdot X_2^{c2} \cdot \ldots$$

CER Developement Handbook.pdf (army.mil)



CubEM uses the Excel solver

Is the CER a good fit?

Space Segment / Platform - Assessing CER's quality

CERs quality metrics

SSE $= \sum_i \left(\frac{y_i - \hat{y}}{\hat{y}}\right)^2$ Estimated values deviating from actuals (accuracy)

BIAS $= \sum_i \left(\frac{y_i - \hat{y}}{\hat{y}}\right)$ BIAS > 0 overestimation, BIAS < 0 underestimation

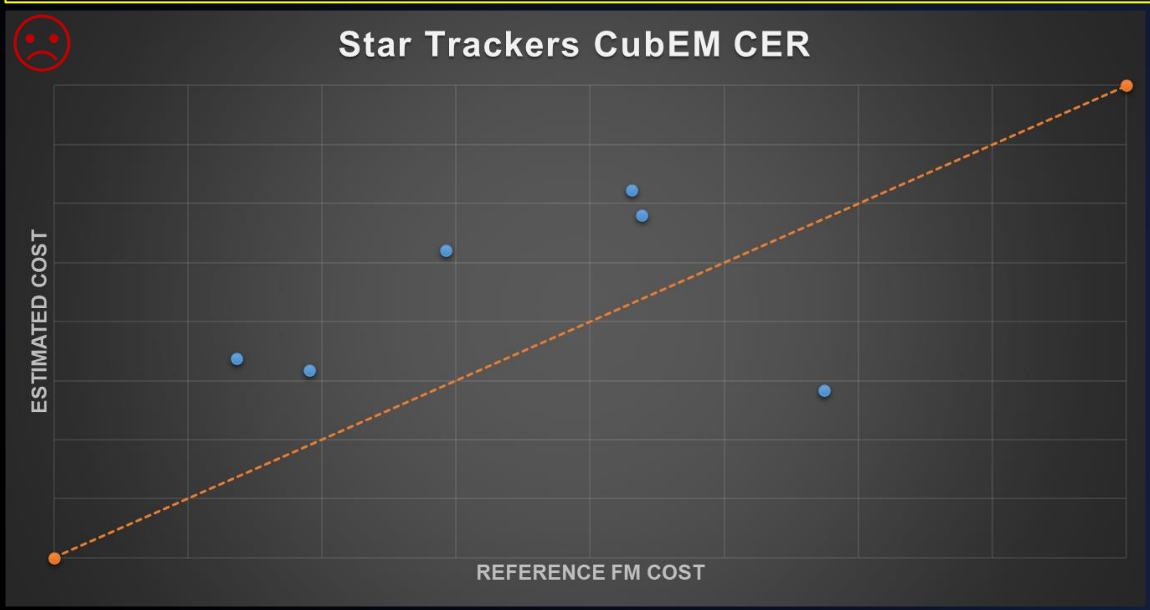
$R^2 = 1 - \frac{(y_i - \hat{y})^2}{(y_i - \langle y \rangle)^2}$ Cost drivers as good predictors ($0 \le R^2 \le 1$)

We aim at:

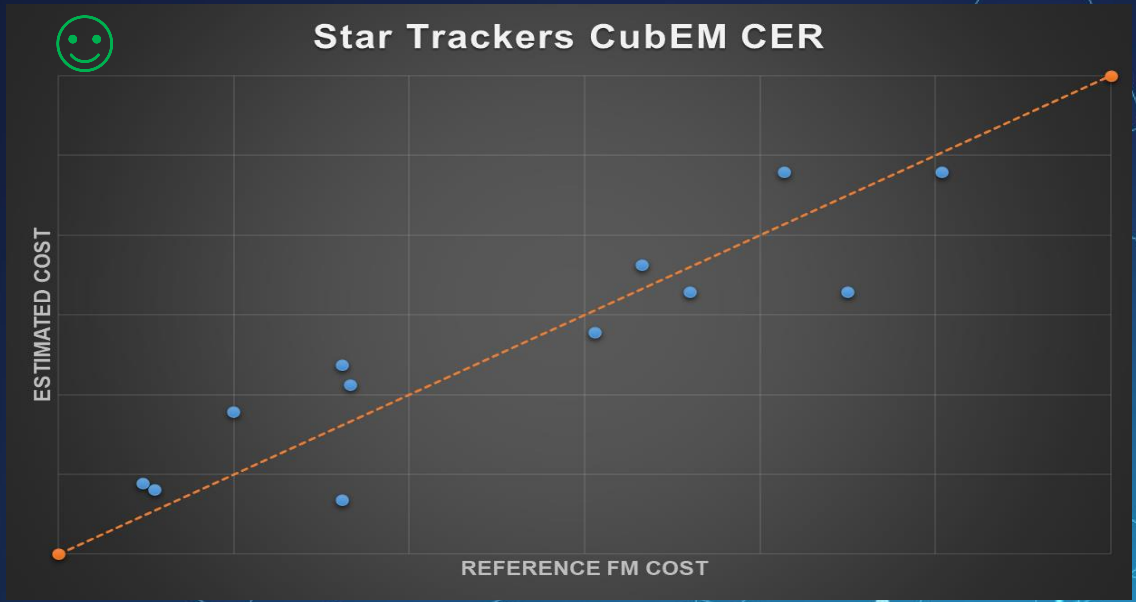
Min(SSE)

BIAS = 0

$R^2 \sim 1$



R2	R2 "close" to 0	SSE	"High" SSE	BIAS	
	0.41724		2.83791		0.00000



R2	R2 "close" to 1	SSE	"Low" SSE	BIAS	
	0.89629		0.42426		0.00000

Example values

Space Segment / Platform - CER database example

Sun Sensors CubEM	Cost [€]	EC	Cost [€] EC 2004	Mass [g]	ŷ	((yi-ŷ)/ŷ)2	(yi-ŷ)/ŷ	(yi-ŷ)2	(yi-<y>)2
Sun Sensor 1	7,000	2021	5,396	10	3,905	0.1459601629	0.3820473308	2,225,213	3,088,479
Sun Sensor 2	9,000	2021	6,938	20	5,808	0.0378936924	0.1946630228	1,278,051	10,884,659
Sun Sensor 3	1,300	2021	1,002	3	1,798	0.1958785342	- 0.4425816695	633,138	6,952,066
Sun Sensor 4	3,200	2021	2,467	12	1,850	0.1110286078	0.3332095554	380,124	1,373,543
Sun Sensor 5	8,000	2021	6,167	30	4,133	0.2423159034	0.4922559328	4,138,684	6,392,295
Sun Sensor 6	9,000	2021	6,938	40	7,234	0.0016744505	- 0.0409200503	87,626	10,884,659
Sun Sensor 7	2,000	2021	1,542	7	1,820	0.0233995865	- 0.1529692340	77,528	4,397,630
Sun Sensor 8	11,000	2021	8,480	45	7,234	0.0296558802	0.1722088274	1,551,934	23,435,035
Sun Sensor 9	2,500	2021	1,927	20	2,435	0.0435507090	- 0.2086880663	258,325	2,929,598
Sun Sensor 10	3,300	2024	2,194	15	2,435	0.0098709571	- 0.0993526905	58,551	2,088,955
Sun Sensor 11	5,000	2024	3,324	2	1,795	0.7246318760	0.8512531210	2,335,496	99,433
Sun Sensor 12	500	2024	332	1	1,778	0.6611006883	- 0.8130809851	2,090,036	10,932,849
Sun Sensor 13	900	2024	598	5	1,802	0.4462842489	- 0.6680450950	1,449,411	9,245,281

	CER parameters		Quantity	Inputs	R2	SSE	BIAS	SSE bis	SST
	a =	100.000			0.82132	2.67325	0.00000	16564116	92704481
	b =	10.000							
Technical variable	c1 =	1.000	Mass [g]	25		Input			
			Chosen EC =	2004		Output			
			Stand-alone Estimate	350		= a + b * Mass ^ c1			

Example values

Space Segment / Platform - Improving CER's quality

esa

Improving quality:

Remove clear outliers

Re-check actual data sheet (<u>your data may be wrong</u>! – third-party resellers)

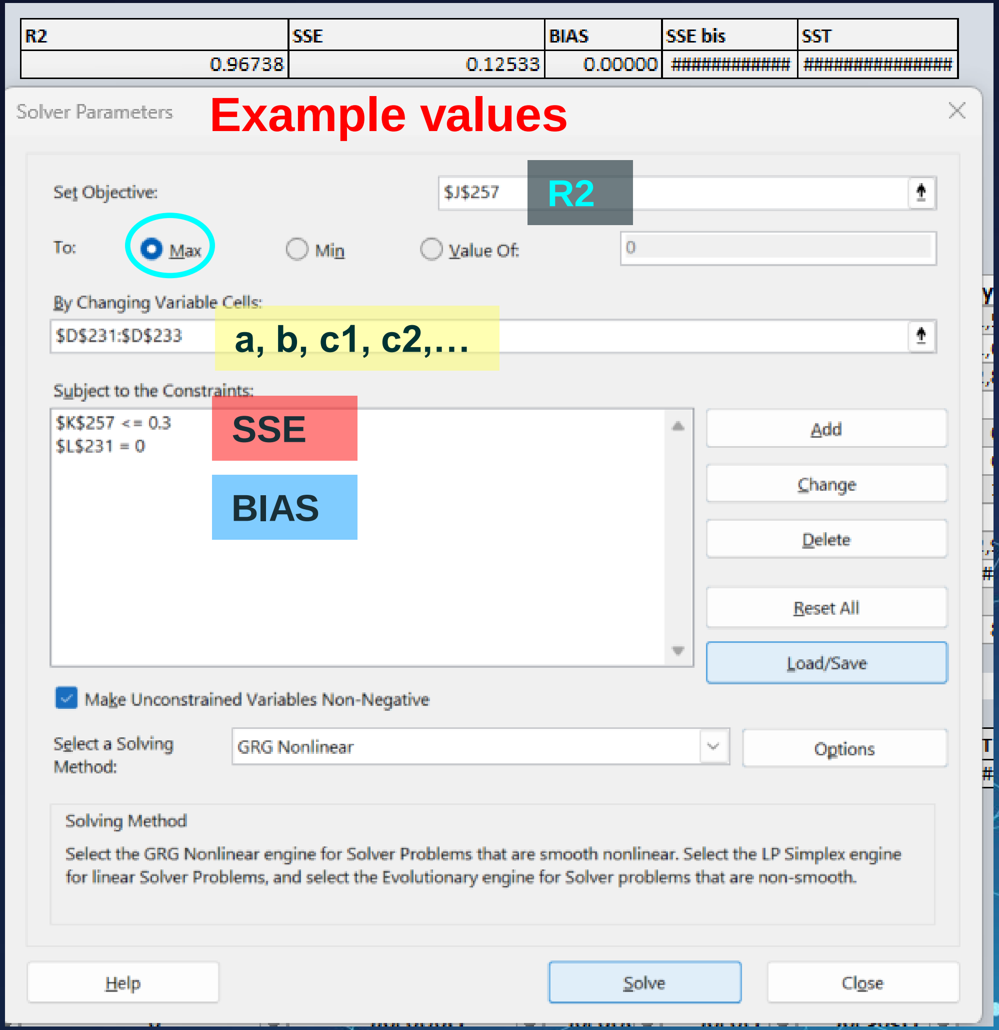
Remove points if assumptions (e.g. cost up to PFM, very low TRL, batch order…)

Expand data set (RFQs, re-check of online sources)

+

Change solver objective…

$SSE \downarrow$
$R^2 \uparrow$



Space Segment / Platform - Remarks

Selection of Cost drivers:
- Scatter plots analysis
- Physics and logic
- Specs easy to retrieve!

Data gathering:
Remove noise (e.g. engineering, harness, delivery…)

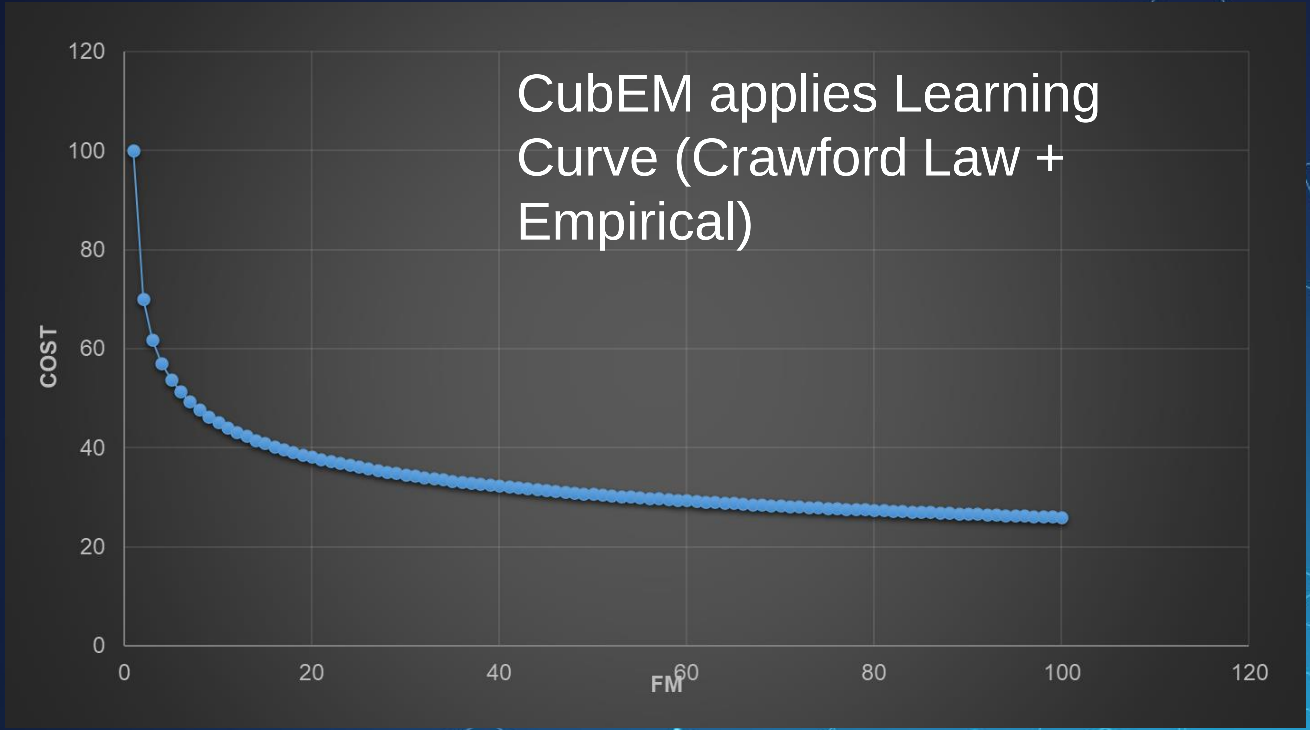
Data gathering:
Discounts for batch purchases – company image (ROM 5-15%)

Less is more

CER parameters	
a =	449.0360882
b =	41.1587
c1 =	0.5743374
c2 =	0.5351528

CER parameters	
a =	449.0360882
b =	41.1587
c1 =	0.5743374
c2 =	0.0535152

Example values



Space Segment / Payload - Tailored to each mission

Camera	Not LEO (Moon)
Camera	Earth Observation
Camera	Earth Observation
Camera	ADR
Camera	Earth Observation
Camera	Earth Observation
Cryocooler	Earth Observation
GNSS-R	Earth Observation
GNSS-R	IOD IOV
GNSS-R	Earth Observation
Internet of Things 5G	IOD IOV
Langmuir Probe	Earth Observation
Laser Communication Terminal	Earth Observation
LiDar	ADR
Magnetometer	Earth Observation
Magnetometer	Earth Observation
Magnetometer	Earth Observation
Mass spectrometer	Earth Observation/IOD IOV
Radiation Monitor	Earth Observation
Radiometer	Earth Observation
Receiver	IOD IOV
Receiver	Earth Observation/IOD IOV
SAR	Earth Observation/IOD IOV
Spectrometer	Earth Observation/IOD IOV
Spectrometer	Earth Observation/IOD IOV
Spectrometer + Telescope	Earth Observation
Telescope	Earth Observation
Telescope	Earth Observation/IOD IOV
Telescope	Earth Observation/IOD IOV

Analogy & accounting for deltas (size, complexity)

- Experience helps
- Is reference applicable?
- Low TRL

CubEM does not provide a standard method for payload estimation: Manual Input

Payload models could be built with larger dataset, proper drivers should be identified (e.g. power)

CubEM layout Equipment Level

CubEM Estimating Project	Example values				+ 1EM + 1PFM € EC2025	+ 1EM + 1PFM + 3FMs € EC2025
Equipment name	Unit Quantity	Unit Mass [kg]	Selected CubEM CER	Other Estimating Method	1st Satellite cost Phase C/D	All Satellites cost Phase C/D
Platform					**615,000**	**1,358,000**
AODCS&GNC					**131,000**	**299,000**
Eq 6	1	0.3	Magnetometers CubEM CER		108,000	238,000
Eq 19	2	0.05	Gyros CubEM CER		23,000	61,000
Eq 32	1	1		Comment on estimating methc	-	-
Communications					**77,000**	**153,000**
Eq 2	1	0.5	GNSS/UHF antennas CubEM CER		56,000	99,000
Eq 17	2	0.05	S-/X-/K-band antennas CubEM CER		9,000	23,000
Eq 22	2	0.05		Comment on estimating methc	12,000	31,000
OBDH					**35,000**	**93,000**
Eq 16	2	0.05	OBCs CubEM CER		35,000	93,000
Power					**250,000**	**531,000**
Eq 18	2	0.05	Power Systems CubEM CER		12,000	31,000
Eq 23	2	0.34	PCDUs CubEM CER		75,000	201,000
Equipment test	1	1.3	Solar Panels CubEM CER		163,000	299,000
Propulsion					**10,000**	**23,000**
Eq 38	1	0.05	Propulsion Systems CubEM CER		10,000	23,000
Structure					**78,000**	**177,000**
Eq 7	1	0.05	CubeSat Deployers CubEM CER		51,000	112,000
Eq 33	1	0.05		Comment on estimating methc	25,000	60,000
Eq 34	1	0.05	CubeSat Structures CubEM CER		2,000	5,000
Thermal					**34,000**	**82,000**
Eq 28	1	0.05		Comment on estimating methc	34,000	82,000
Eq 29	1	0.05		Comment on estimating methc	-	-
Payload					**322,000**	**757,000**
Eq 9	1	0.05	Hypersp. Optical Cameras CubEM CER		30,000	73,000
Eq 14	2	0.012	Not Hypersp. Optical Cameras CubEM CER		29,000	77,000
Eq 15	2	0.05		Comment on estimating methc	263,000	607,000

CubEM layout Equipment Level

CubEM Estimating Project **Example values**

Equipment name	TRL of Equipment	x BB	x SM	x STM	x EM	x EQM	x QM	x FM	x PFM	x SP
Platform		1st Satellite(s) Hardware Matrix at Equipment Level								
AODCS&GNC										
Eq 6			1 SM		1 EM				1 PFM	
Eq 19					1 EM			1 FM	1 PFM	
Eq 32					1 EM				1 PFM	
Communications										
Eq 2					1 EM	2 EQM			1 PFM	
Eq 17					1 EM			1 FM	1 PFM	
Eq 22					1 EM			1 FM	1 PFM	
OBDH										
Eq 16					1 EM			1 FM	1 PFM	
Power										
Eq 18					1 EM			1 FM	1 PFM	
Eq 23					1 EM			1 FM	1 PFM	
Equipment test					1 EM		1 QM		1 PFM	
Propulsion										
Eq 38					1 EM				1 PFM	
Structure										
Eq 7			1 SM		1 EM				1 PFM	
Eq 33					1 EM				1 PFM	
Eq 34					1 EM				1 PFM	
Thermal										
Eq 28					1 EM				1 PFM	
Eq 29					1 EM				1 PFM	
Payload										
Eq 9					1 EM				1 PFM	
Eq 14					1 EM			1 FM	1 PFM	
Eq 15					1 EM	1 EQM		1 FM	1 PFM	

Space Segment / System Level activities - CubEM approach

Cost-to-cost relationships: estimating the cost of one component/phase of a project based on the cost of another component/phase

System / (HW/SW) depends on Model Philosophy at System Level: normalization needed

System Level from HW/SW

HW/SW C/D

Hardware and Software

System / (HW/SW)

Cost-to-cost

System C/D

Phase C/D

System Phases B2/E1 from Phase C/D

System C/D

System Level

System C/D / System B2,E1

Cost-to-cost

System B2,E1

Phases B2,E1

Space Segment / System Level activities - CubEM approach

Cost-to-cost need tuning and validation

PO, AIV/T, GSE from System

System C/D — System Level

PO, AIV/T, GSE / (HW/SW) — Cost-to-cost

PO,AIV/T, GSE C/D

Phase C/D

Mgmt, Eng, PA from PO

PO C/D — Project Office

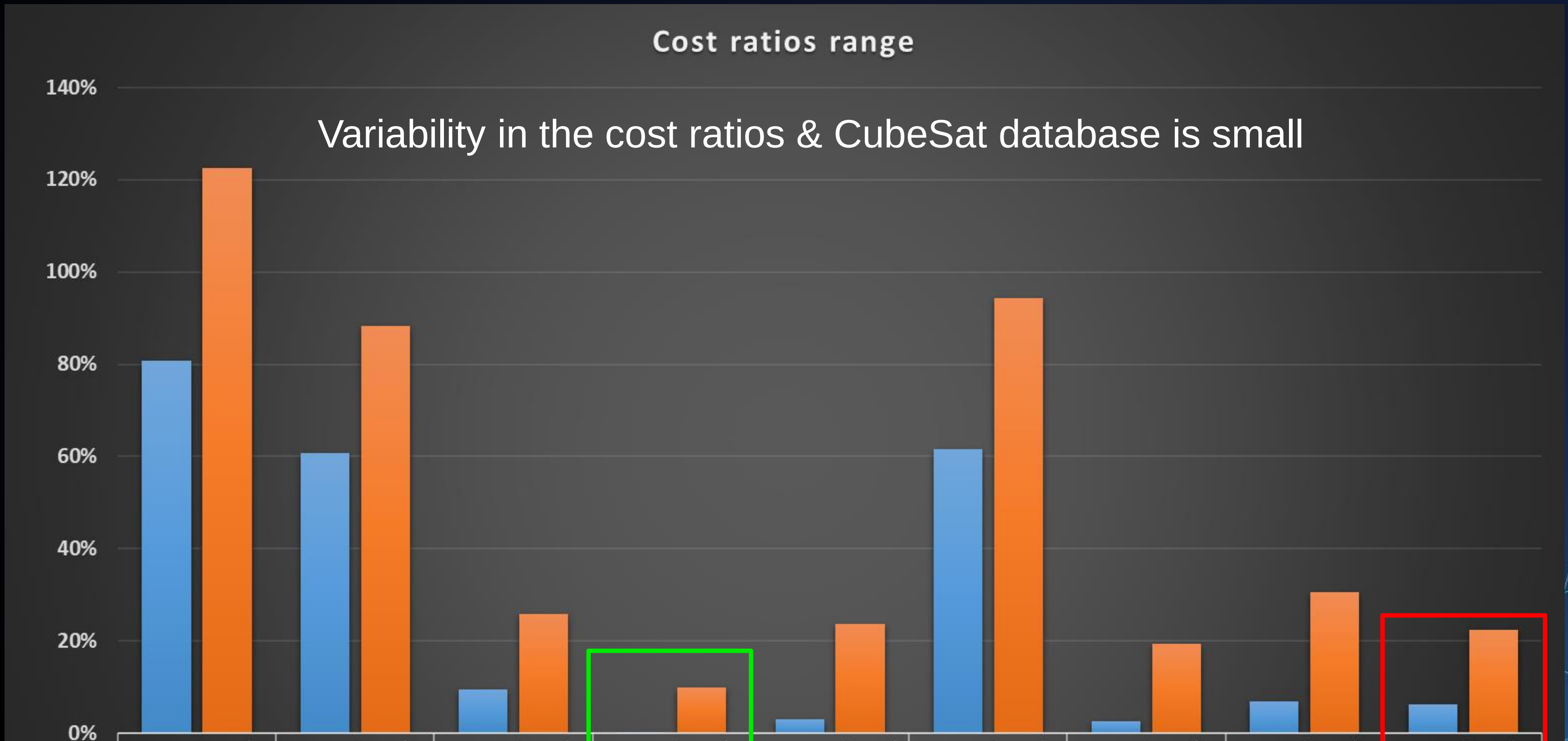
Mgmt, Eng, PA / PO — Cost-to-cost

Mgmt, Eng, PA C/D

Phase C/D

Recurring Sats = x% FM1

Space Segment / System Level activities - Take aways



	Sys_PhCD / (Pf+Pl)	PO_PhCD / Sys_PhCD	AIV_PhCD / Sys_PhCD	GSE_PhCD / Sys_PhCD	Mgmt_PhCD / PO_PhCD	Eng_PhCD / PO_PhCD	PA_PhCD / PO_PhCD	Sys_PhB2 / Sys_PhCD	Sys_PhE1 / Sys_PhCD
MIN	81%	61%	10%	0%	3%	62%	3%	7%	6%
MAX	123%	88%	26%	10%	24%	94%	19%	31%	22%

Alternative methods:
- If Manpower (FTEs) based

- need of a complexity correction
- number of Us not enough

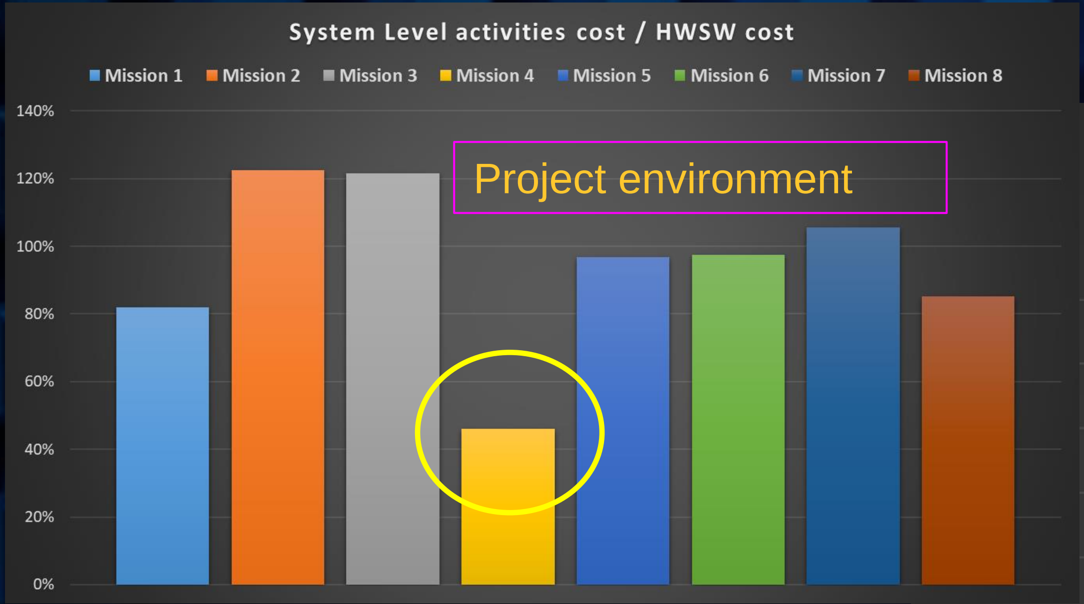
For CubEM database:

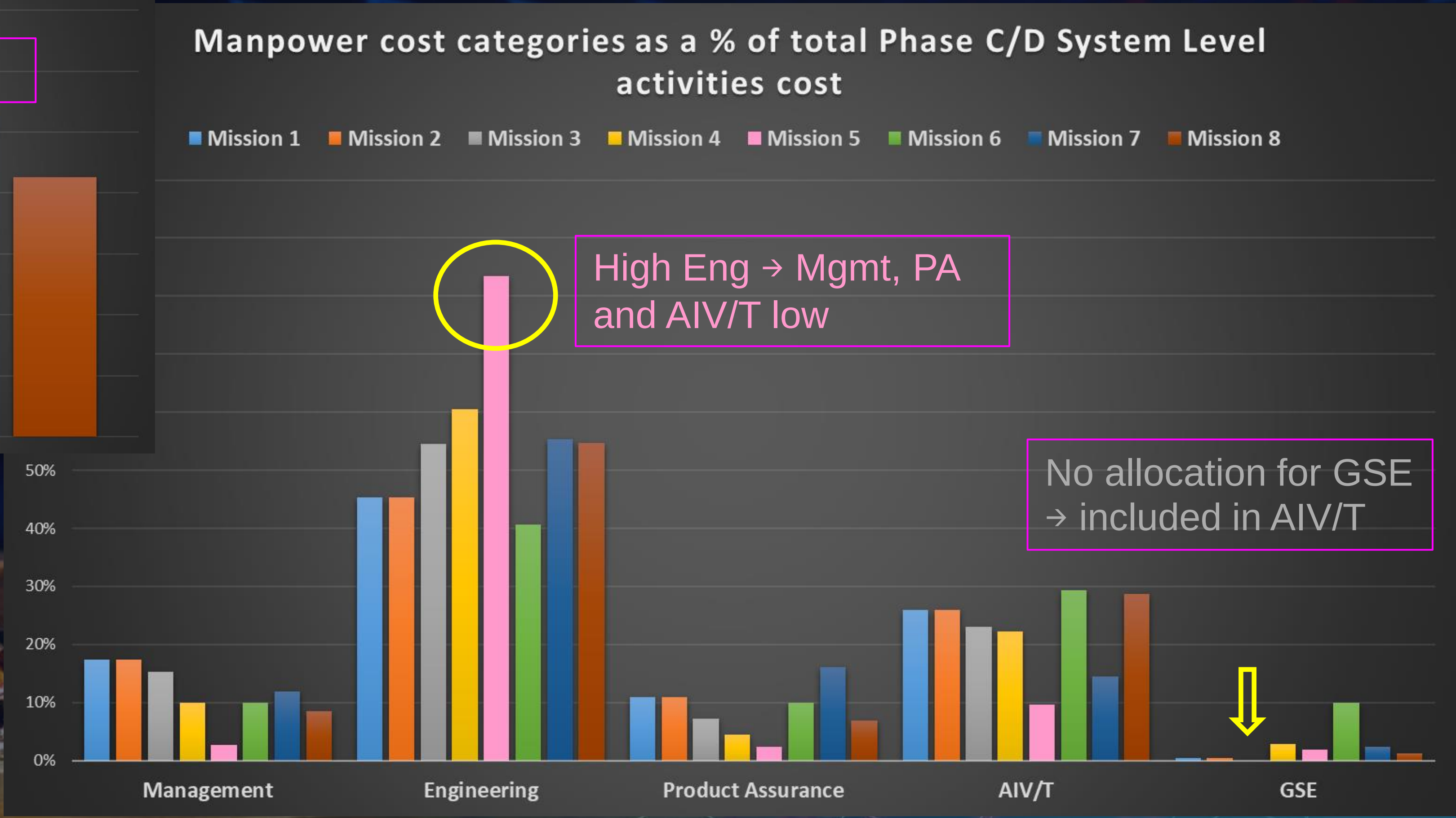
Average lower than for Standard large satellites: CubeSat modularity

Average higher than for Standard large satellites: CubeSat higher E1 over C/D

Space Segment / System Level activities – Limitations

Model limited by the available data set (small)





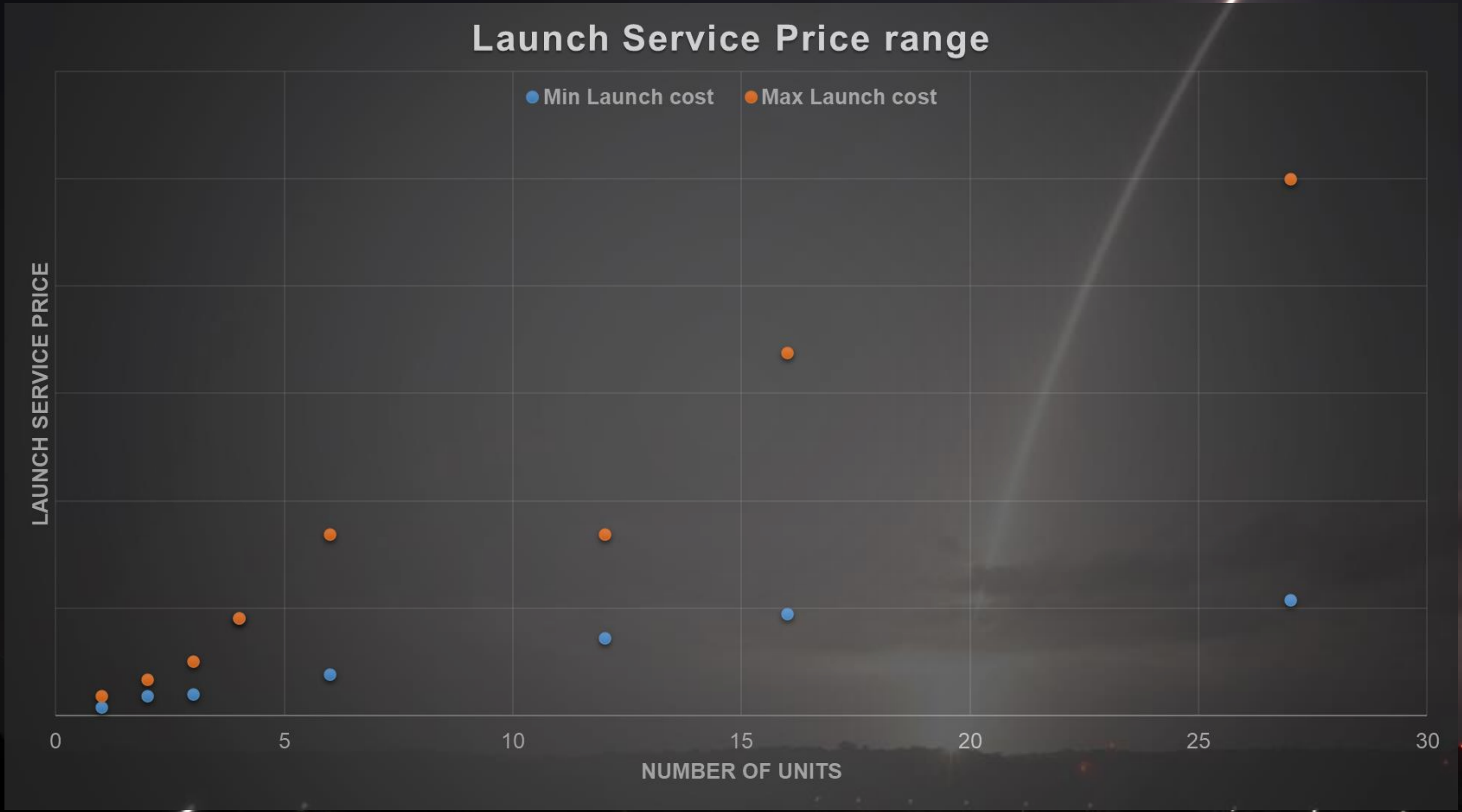
Financial data not always detailed

CubEM layout Space Segment Level

Estimate date: Q2 2024 *Cost Engineer: G.C.*	Phase B2	Phase C/D	Phase E1	TOTAL Ph B2/CD/E1/E2
CubEM Estimating Project	**Example values**			+ 1EM + 1PFM + 3FMs € EC2025
				All Satellites cost
Platform		**1,358,000**		**1,358,000**
AODCS&GNC		299,000		
Communications		153,000		
OBDH		93,000		
Power		531,000		
Propulsion		23,000		
Structure		177,000		
Thermal		82,000		
Payload		**757,000**		**757,000**
System Level	**215,000**	**1,679,000**	**155,000**	**2,049,000**
Project Office	147,000	1,147,000	106,000	
Management	29,000	229,000	21,000	
Engineering	102,000	793,000	73,000	
Product Assurance	16,000	125,000	12,000	
AIV/T & GSE	68,000	532,000	49,000	
AIV/T	47,000	366,000	34,000	
GSE	21,000	166,000	15,000	
Contingency	**49,000**	**873,000**	**36,000**	**958,000**
Space Segment	**264,000**	**4,667,000**	**191,000**	**5,122,000**

Launch Segment

Rideshare or Dedicated
Broker, Orbit specific requirements



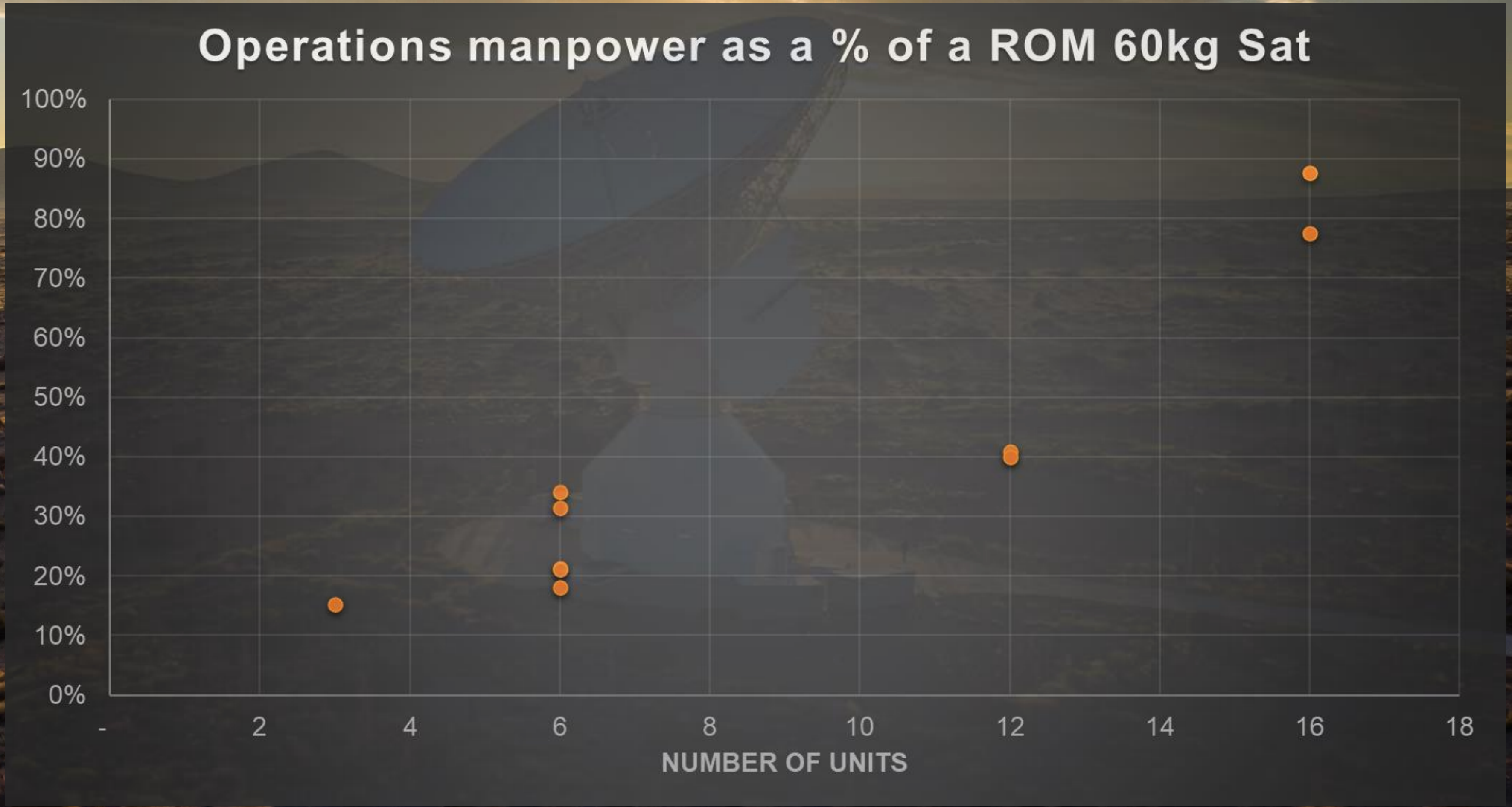
Remarks:
- Wider range for heavier sats
- CubeSats: price is quantized
- If micro-launcher needs maiden flight → can commit to mass/cost?

ESA–S. Corvaja, ESA - Sentinel-2C joins the Copernicus family in orbit

Ground Segment & Operations

Not trivial to link manpower assessment to Number of Units

References/Analogy (with care)
CubeSats have autonomy



Manpower ∝ CubeSat size, if size ∝ complexity

- autonomy, orbit, manoeuvres (e.g. CAMs), payload, etc.

CubEM: ops extra FMR as a % of 1st Sat

CubEM layout Grand Total Level

Estimate date: Q2 2024 *Cost Engineer: G.C.*	Phase B2	Phase C/D	Phase E1	Phase E2	TOTAL Ph B2/CD/E1/E2
CubEM Estimating Project	**Example values**				+ 1EM + 1PFM + 3FMs € EC2025
Platform		1,358,000			1,358,000
Payload		757,000			757,000
System Level	215,000	1,679,000	155,000		2,049,000
Contingency	49,000	873,000	36,000		958,000
Space Segment	264,000	4,667,000	191,000		5,122,000
Launch Segment			3,651,000		3,651,000
Launch Service Price			3,520,000		
Storage			131,000		
Ground Segment & Ops				2,017,000	2,017,000
Ground Station Manpower				865,000	
Ground Station Renting				1,152,000	
Grand Total					10,790,000

Future works

Depending on available data sources

- CERs for thermal subsystem and OBSW
- Larger payload database & (hopefully) CER
- Larger database for heavier components

- Extensive validation of System Level cost-to-cost
- Operations complexity assessment (manpower)
- **Modelling of the User and Data segment**

Conclusions

Platform Parametric approach:
- Minimal, early inputs & traceable results
- But time consuming and needs maintenance

Payload analogy and references approach:
- Experience needed
- Case-by-case basis

Launch Service Price References approach:
- Quotations depend on company image

System Level cost-to-cost approach:
- Importance of tuning and manual override
- Data need normalization and validation
- Larger dataset helps sound statistic

Contingency pro-rata approach:
- Early phases have higher allocation

Ground Segment & Operations analogy approach:
- Need to verify if references applicable

GomSpace, ESA - RACE double CubeSat mission

Thank you!

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