

COST MODELING OF SATELLITE CONSTELLATIONS

Assessing the Impact of Optical Inter-Satellite Links

Galileo
Kompetenzzentrum

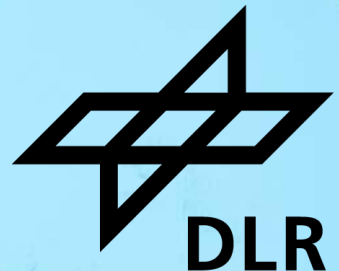
FOR A PRECISE, SECURE & SUSTAINABLE FUTURE

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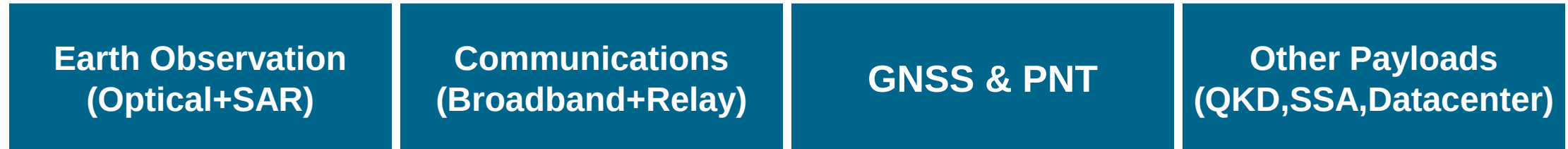
INTRODUCTION

Almost all satellites are part of a larger constellation



- More than **16'000 active** satellites in orbit -> most are part of a **constellation**

Constellations Applications



Future large Constellations

- **ESA projects:** IRIS2, LEO-PNT, (Galileo 2nd Gen)
- **Commercial:** Amazon LEO, Constellation as a service

Optical Inter Satellite Link (OISL) terminals are a hot-topic

“Enable high-capacity laser communication and routing directly between satellites”

- Advantages against RF-links:
 - Higher datarates
 - Secure communications
 - Lower SWaP for same performance
 - No frequency congestion
- Improve data sovereignty
- Constant TT&C access

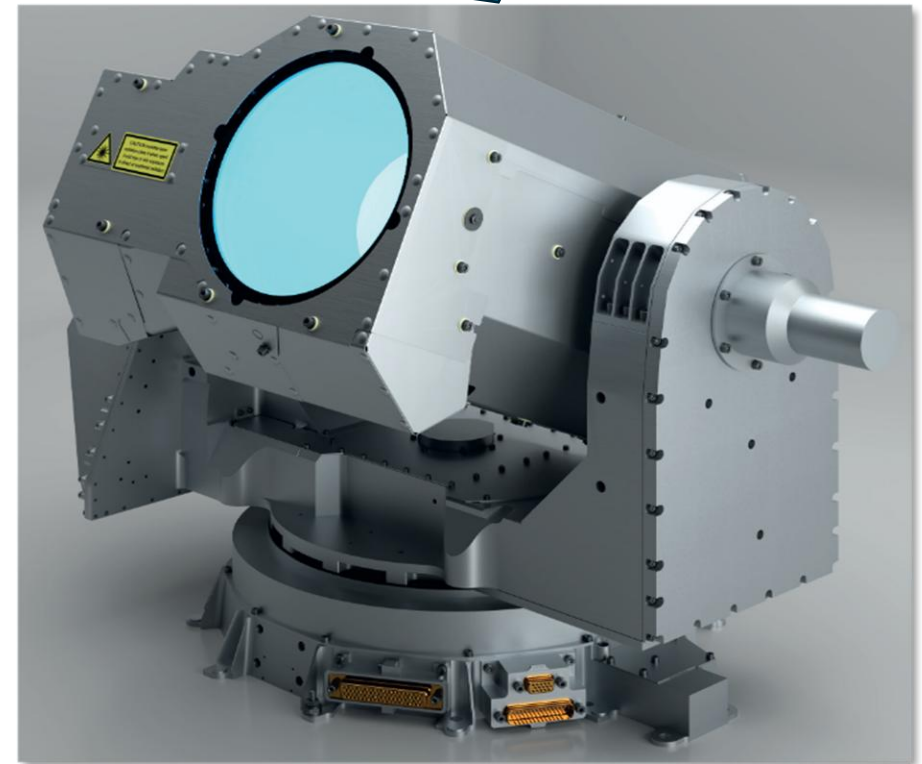


Image Source: Tesat-Spacecom GmbH & Co. KG
[SCOT135 Datasheet]

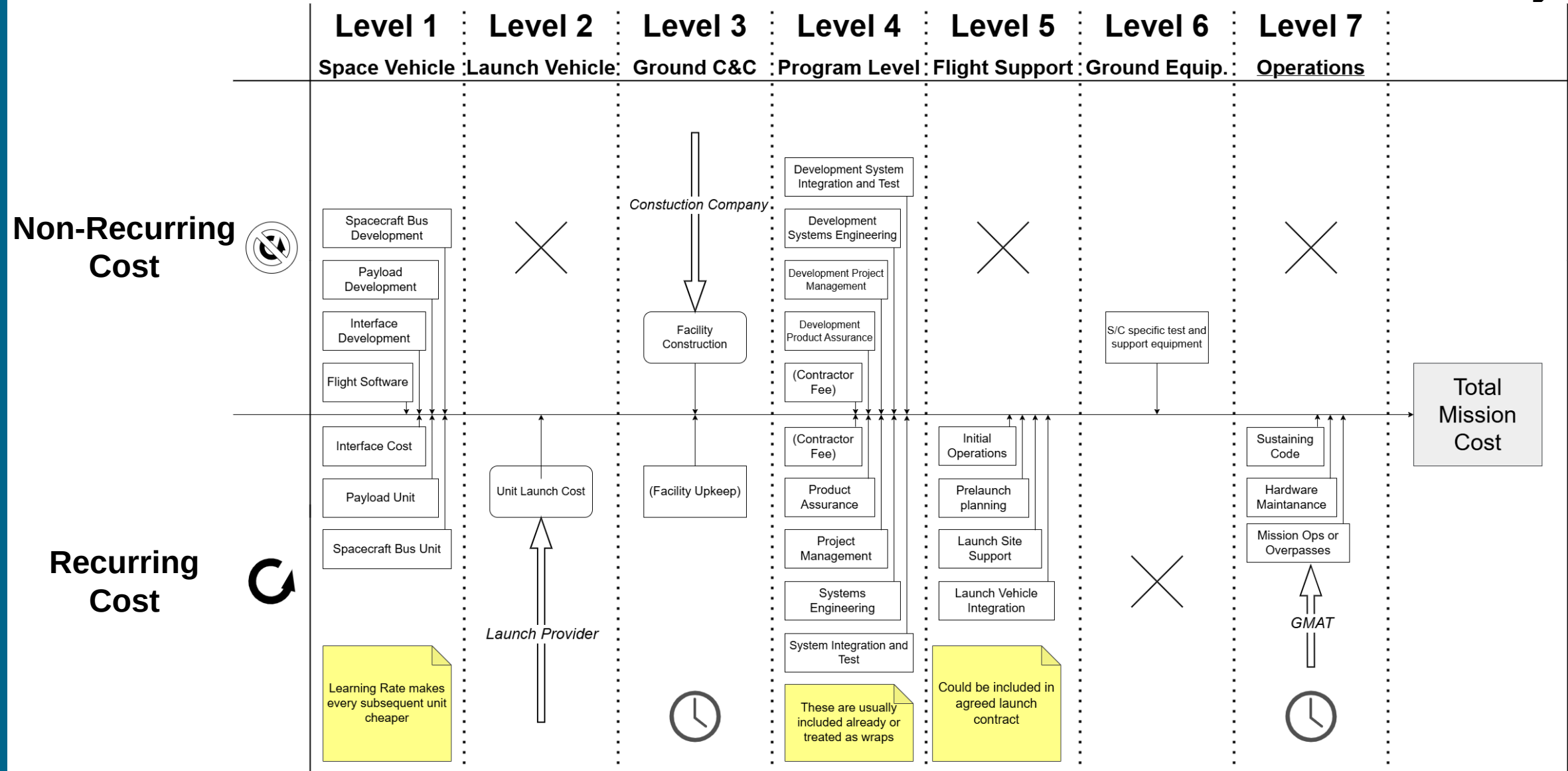


- How do open-literature cost models hold up today?
- How do different architectures differ with respect to cost?
- Size vs. Latency vs. Cost!



- How much do they cost?
- What is currently feasible?
- What are the performance improvements?

Generic life-cycle overview developed for this research



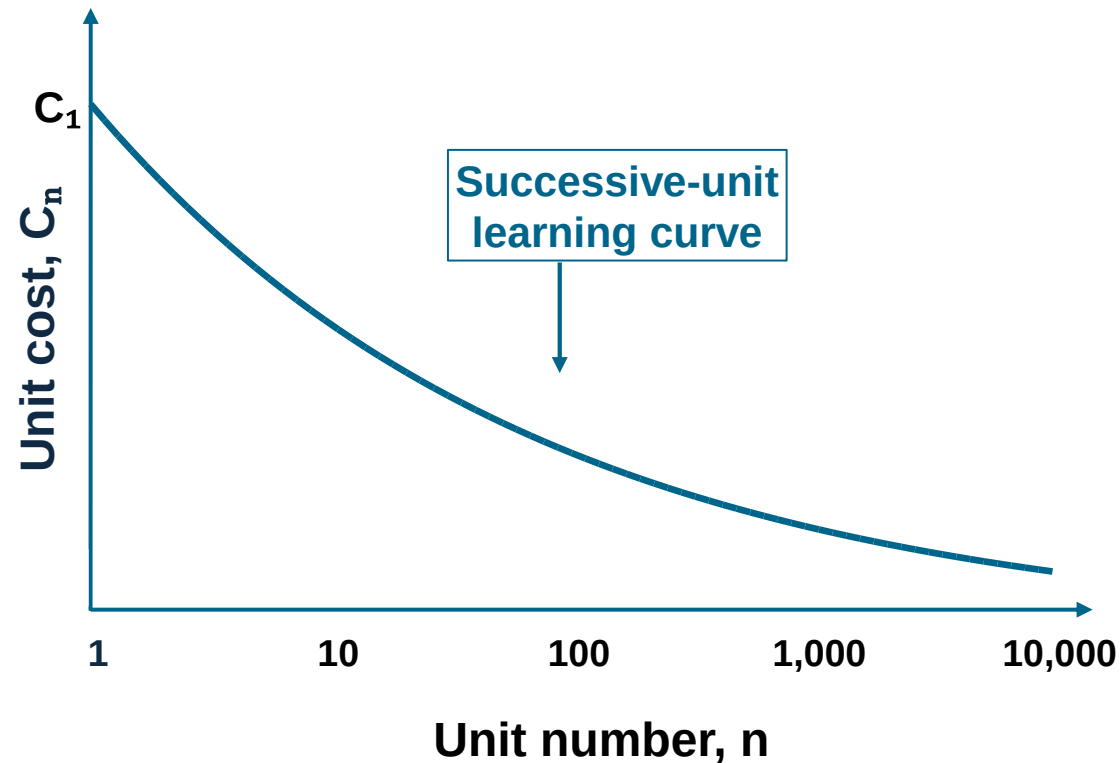
Introduction – Model synthesis

- Collected data is not sufficient for entirely new cost models

Used Model	USCM	SSCM	QuickCost	KEOSCM
Reference Year	2002	2008	2010	2012
Mass Range	100–7,500 kg	20–400 kg	80–15,000 kg	100–1,000 kg
Cost Output / Scope	Development + Recurring Unit Cost	Protoflight Cost	Protoflight Cost	Unit Cost
Notes	Oldest model	Early small-spacecraft model	NASA-focused	Literature-derived

Tab. 1 Comparison of public cost models used as baseline.

Introduction – Learning Curve



As cumulative production increases, recurring unit cost decreases due to learning and process improvement.

Successive-unit learning-curve formula

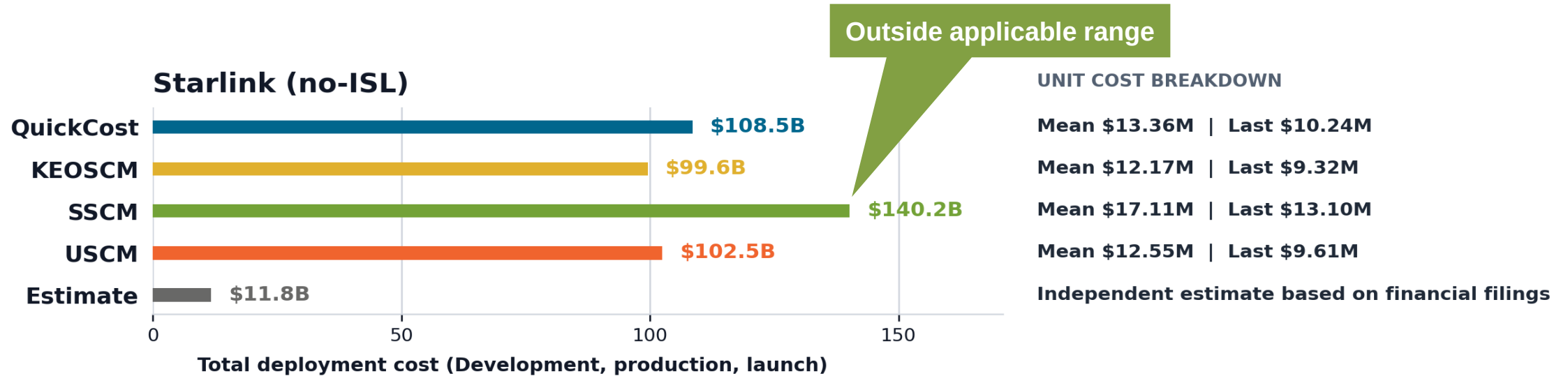
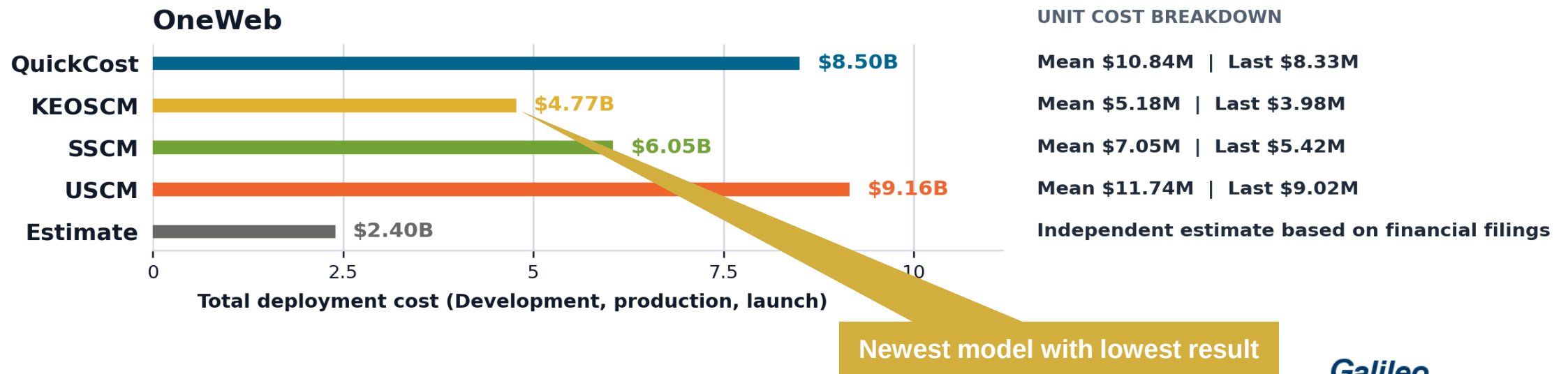
$$C_n = C_1 n^{\frac{\ln(S)}{\ln(2)}}$$

where S is the learning-curve factor

Number of units, N	Learning curve factor, S
$1 < N < 10$	0.95
$10 \leq N < 50$	0.9
$50 < N$	0.85

Tab. 2 Learning Curve factors as found in:
X. Wang and S. Zhang (2021) Cost Analysis for Mass Customized
Production of Satellites Based on Modularity

Using $S=0.85$, No ops cost



Approach for improving cost estimates

1. Review data from different constellations

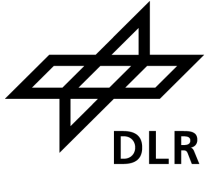
2. Add mass-scale production model

3. Review available OISL terminals

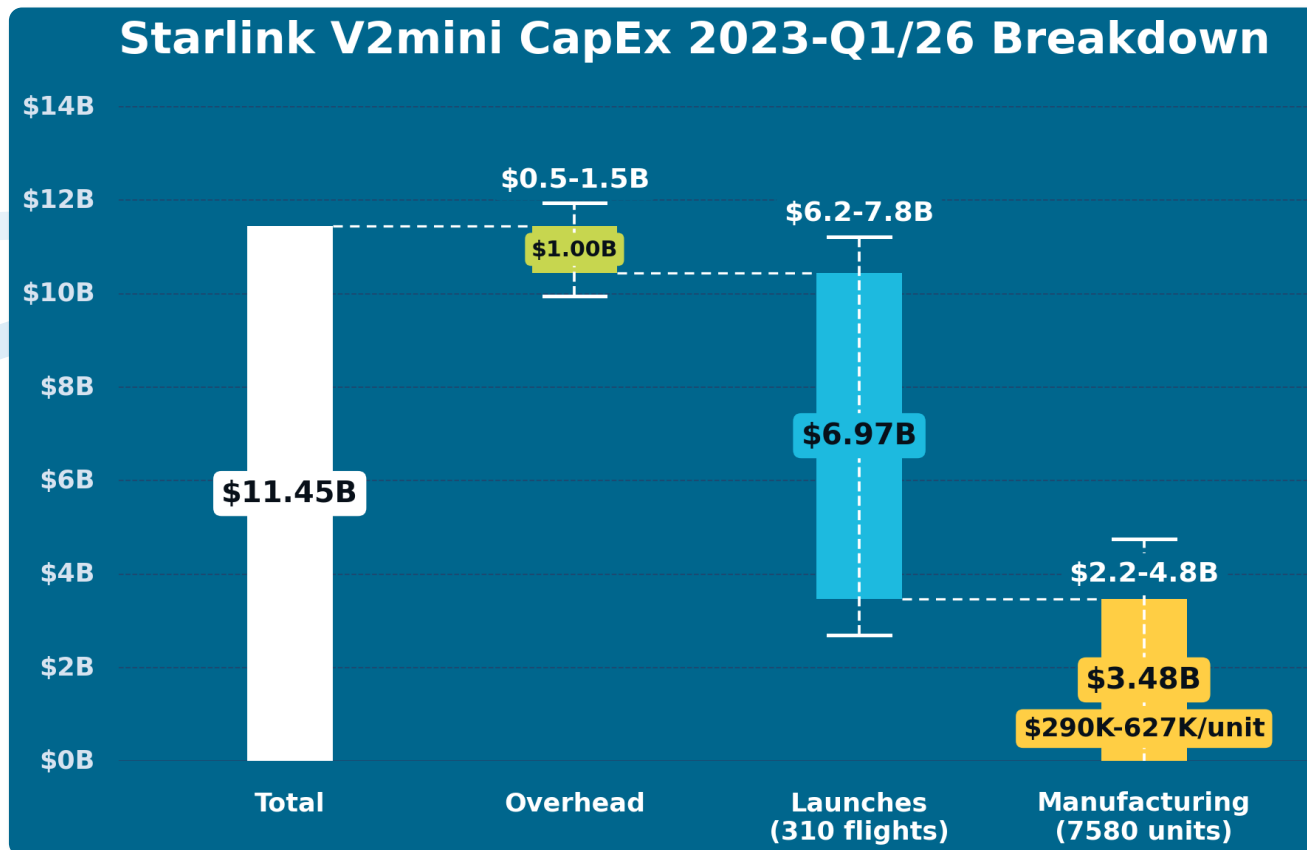
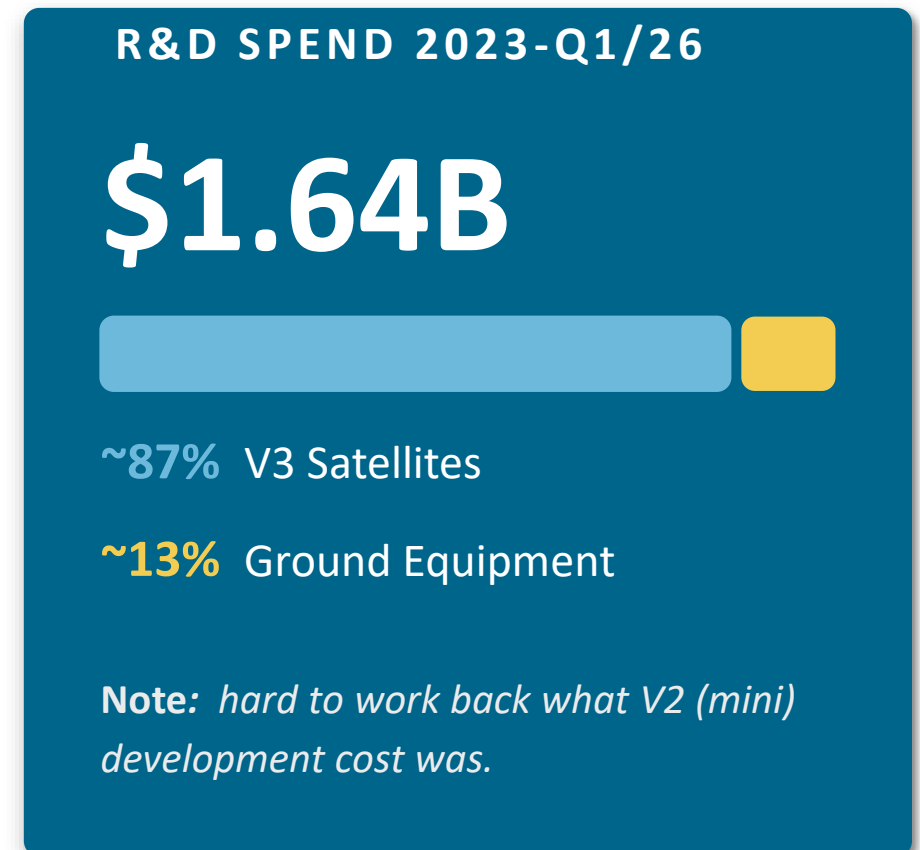
4. Apply OISL production model

REVIEW

Example: Starlink gives us great clues



- SEC filing detail financials split into Space, **Connectivity** and AI (2023-Q1/26)
- Corresponds roughly to the first **V2mini** launch



Starship has the potential to revolutionize constellations

Status Quo

- Launches represent largest cost factor

Prospect

- Targets lower launch cost, with $\sim 4\times$ Falcon 9's expendable LEO payload capacity (100 vs. 23 t)

Risk

- Gap between SpaceX and European competitors could grow even bigger

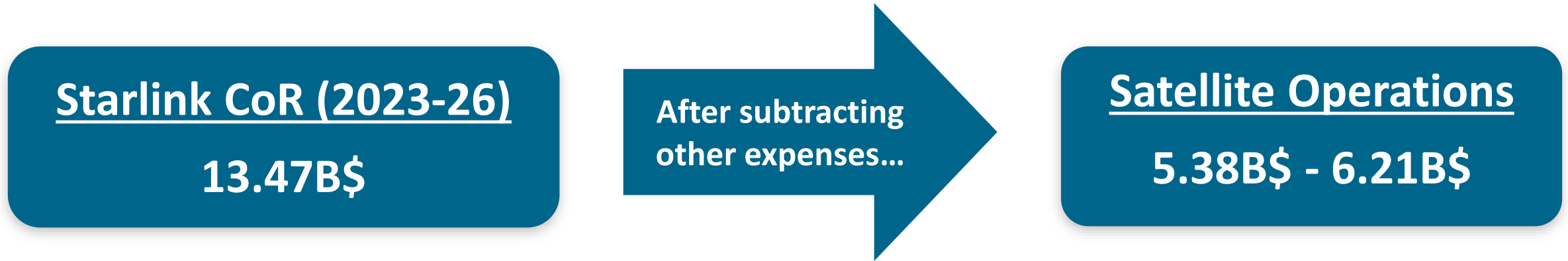
But...

- No one knows what one Starship launch will end up costing...

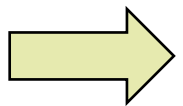


Image Credit: Space Exploration Technologies Corp. [Form S-1].

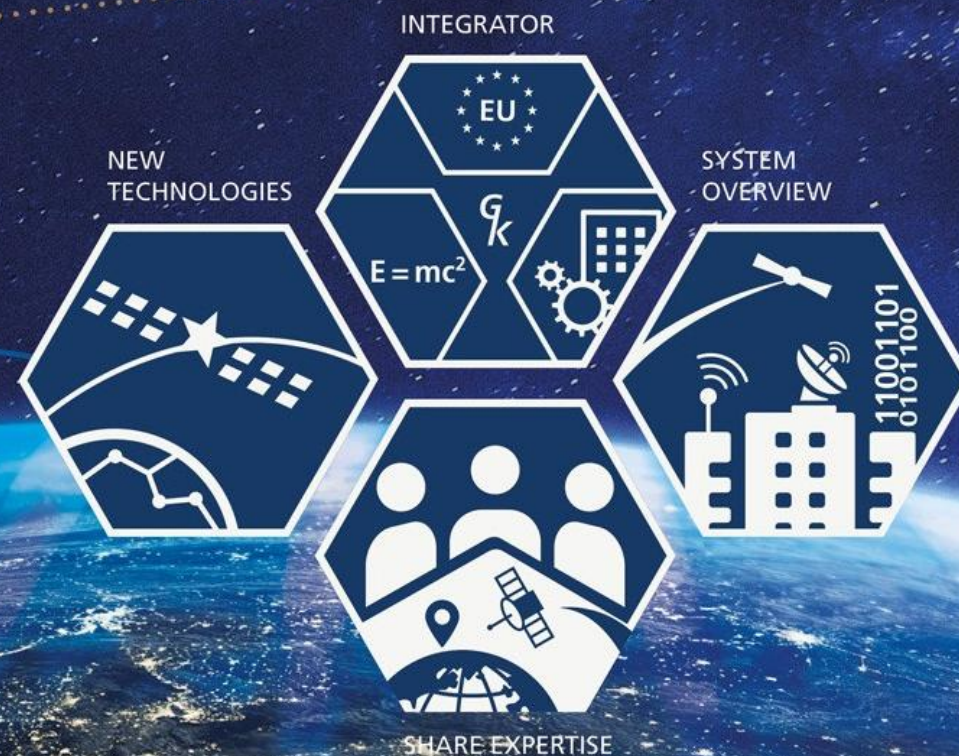
Recurring operating costs can be inferred similarly



- Ground Ops vs Other Ops Share: *estimated* **55%** vs. **45%**
- Average of **1.93B\$/year** or very roughly **255k\$/satellite/year**



Operating costs between \$200-600k/satellite/year across constellations



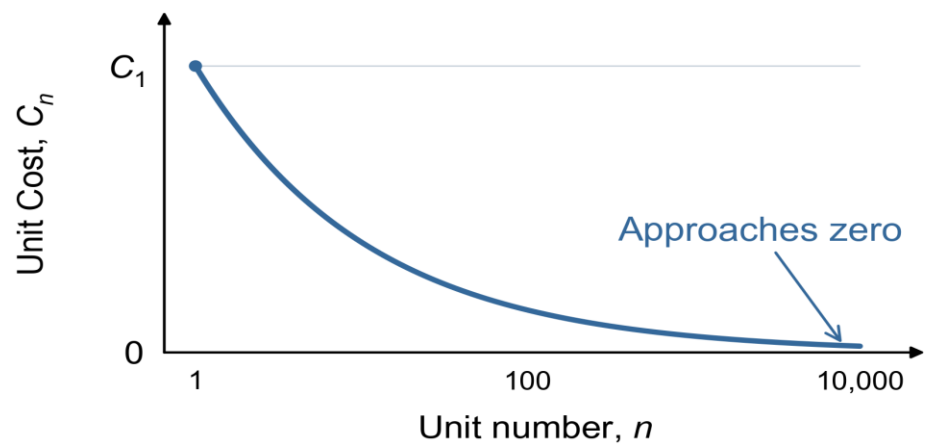
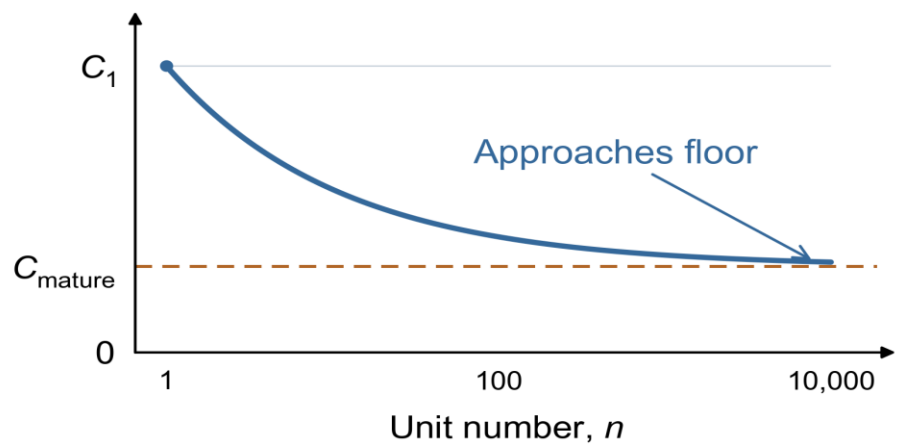
MODELLING

Corrections from the data



$$C_n = C_1 n^{\frac{\ln(S)}{\ln(2)}}$$
→

$$C_n = C_{\text{mature}} + (C_1 - C_{\text{mature}})n^{\frac{\ln(S)}{\ln(2)}}$$



- Approach independent of used Cost Model

with:
$$C_{\text{mature}} = C_{\text{ref}} \left(\frac{M_{\text{bus}}}{M_{\text{ref}}} \right)^{\alpha_{\text{bus}}}$$

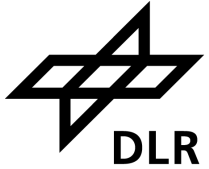
Coefficient	Value
Reference mass: M_{ref}	140 kg
Bus-mass coefficient: α_{bus}	0.7094
Reference Cost: C_{ref}	\$90,352

Tab. 3: Optimal regression parameters from constellation data

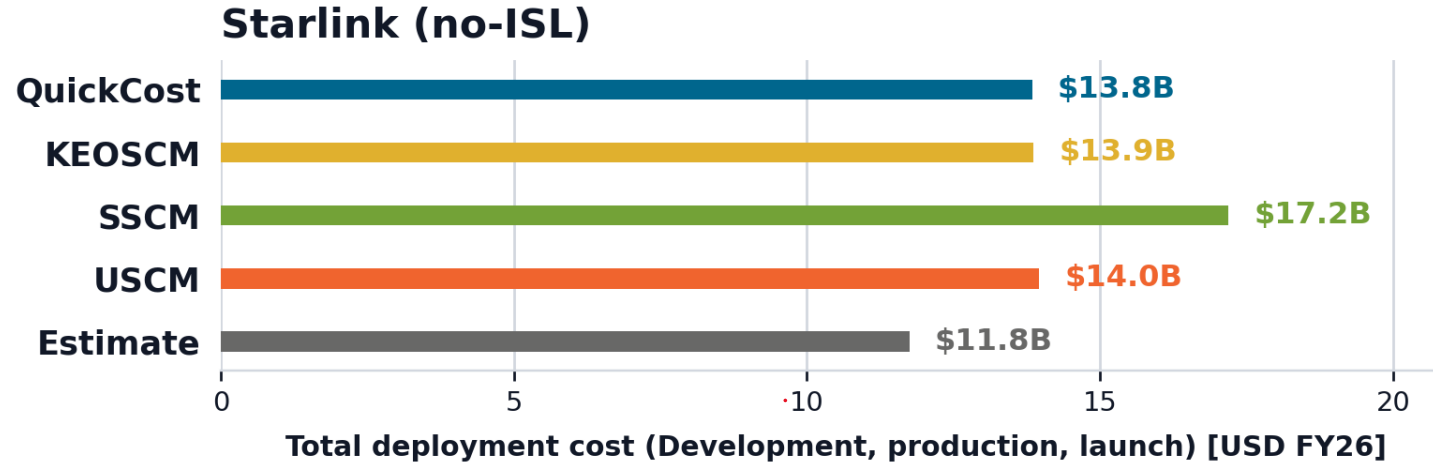
Constellation	Bus mass	Predicted floor
OneWeb	140 kg	\$90,352
Starlink V2 Mini (nOISL)	558 kg	\$240,980
EnduroSat	500 kg	\$222,929

Tab. 4: Example floor costs for select constellations

New Cost Estimates (Using LC=0.6388, No ops cost)



- Learning curve interval (63% - 66%) Mean: 63.88%; compared to 85% legacy



UNIT COST BREAKDOWN

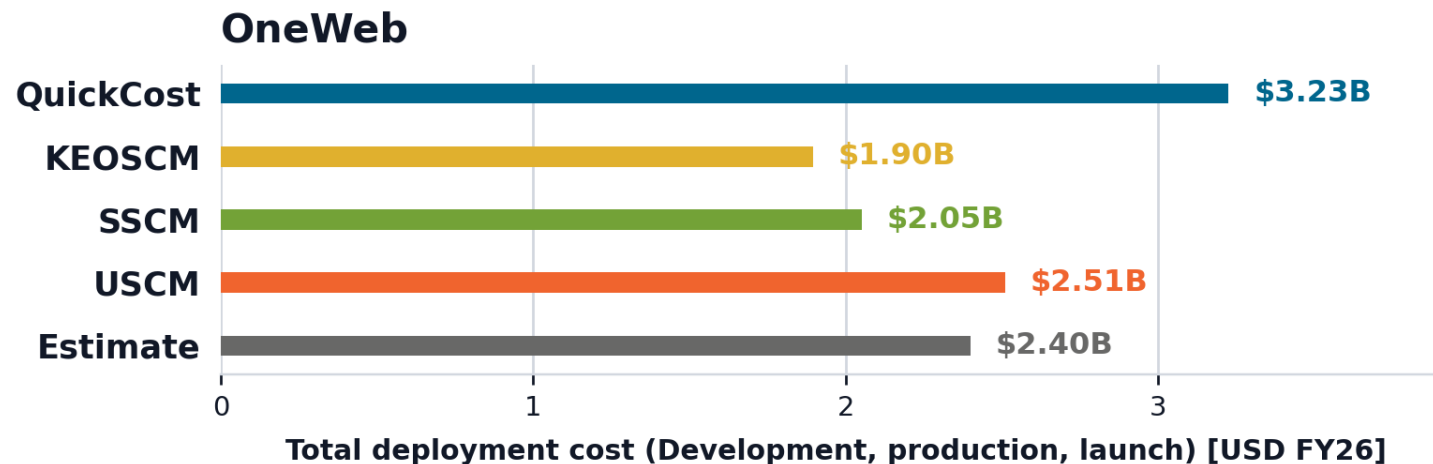
Mean \$0.87M | Last \$0.47M

Mean \$0.87M | Last \$0.46M

Mean \$0.96M | Last \$0.45M

Mean \$0.87M | Last \$0.47M

Independent estimate based on financial filings



UNIT COST BREAKDOWN

Mean \$2.87M | Last \$1.17M

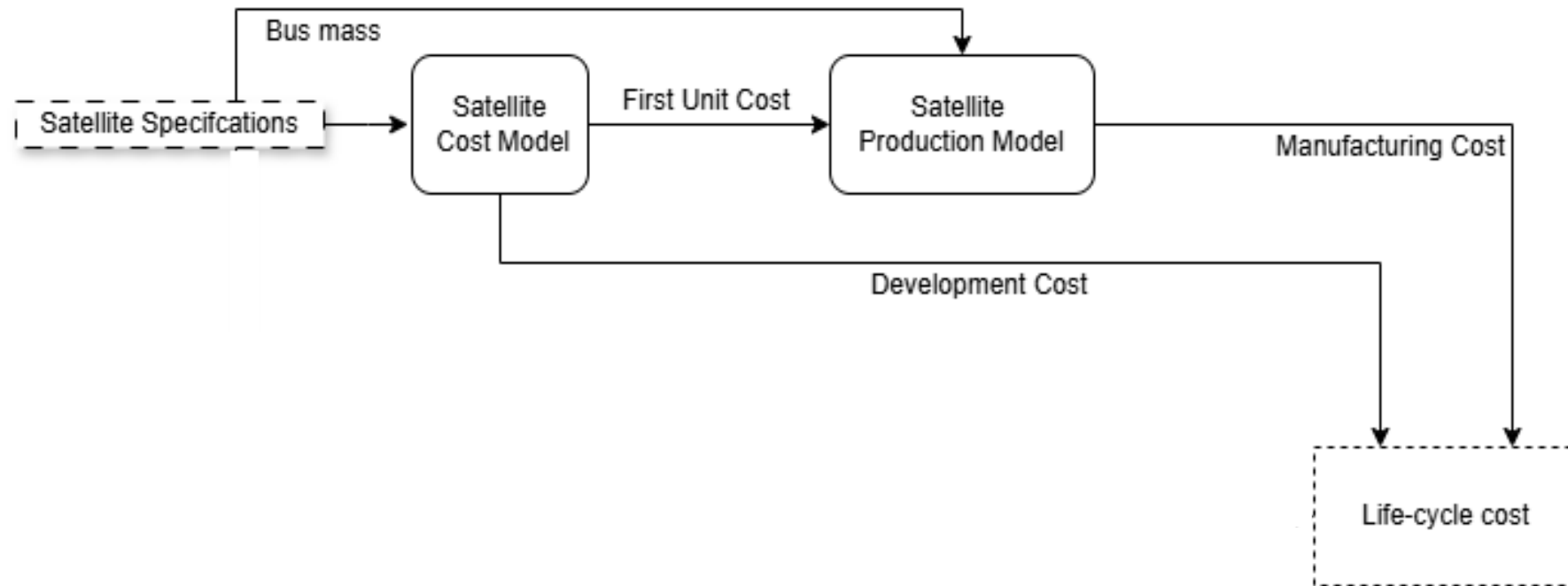
Mean \$0.91M | Last \$0.48M

Mean \$1.08M | Last \$0.48M

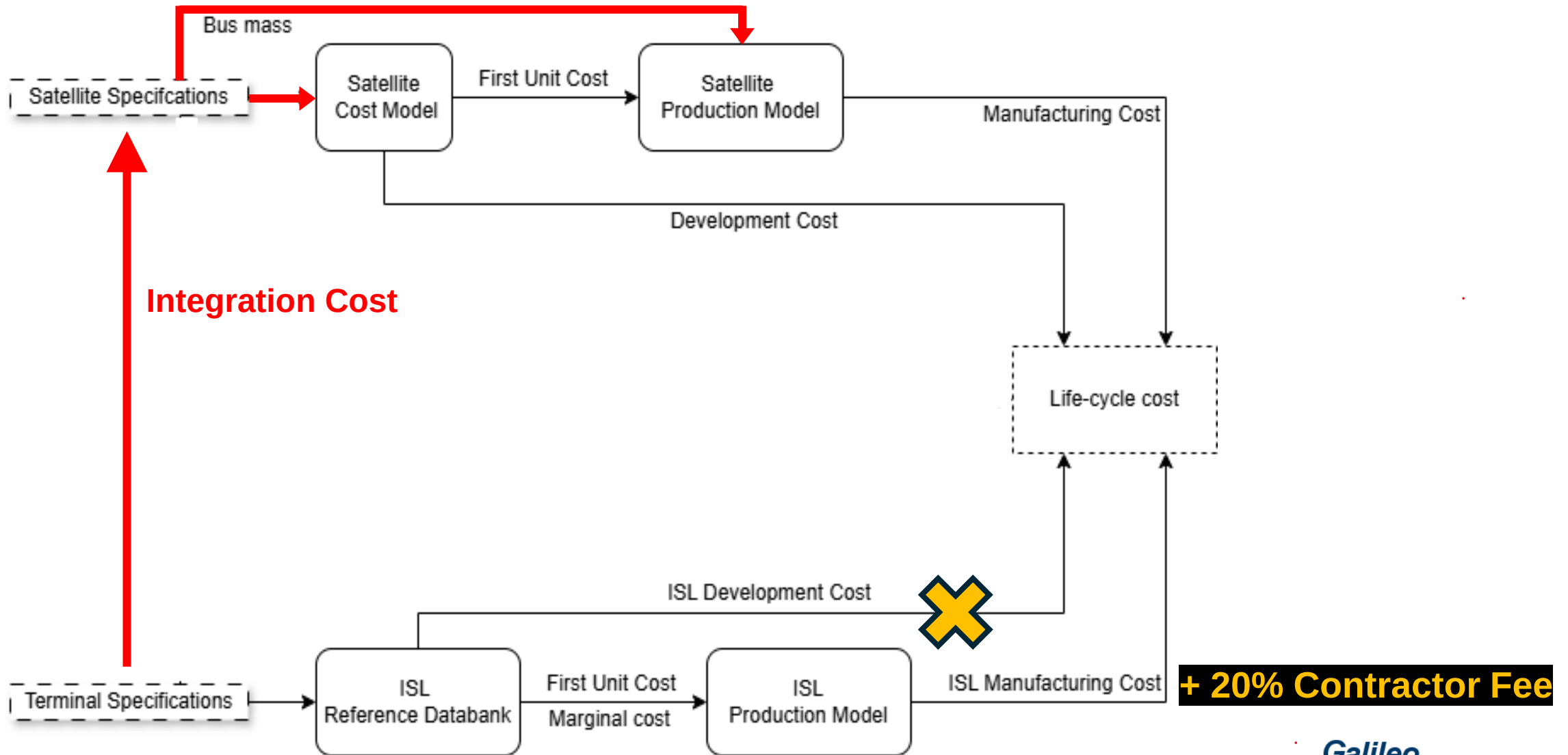
Mean \$1.74M | Last \$0.74M

Independent estimate based on financial filings

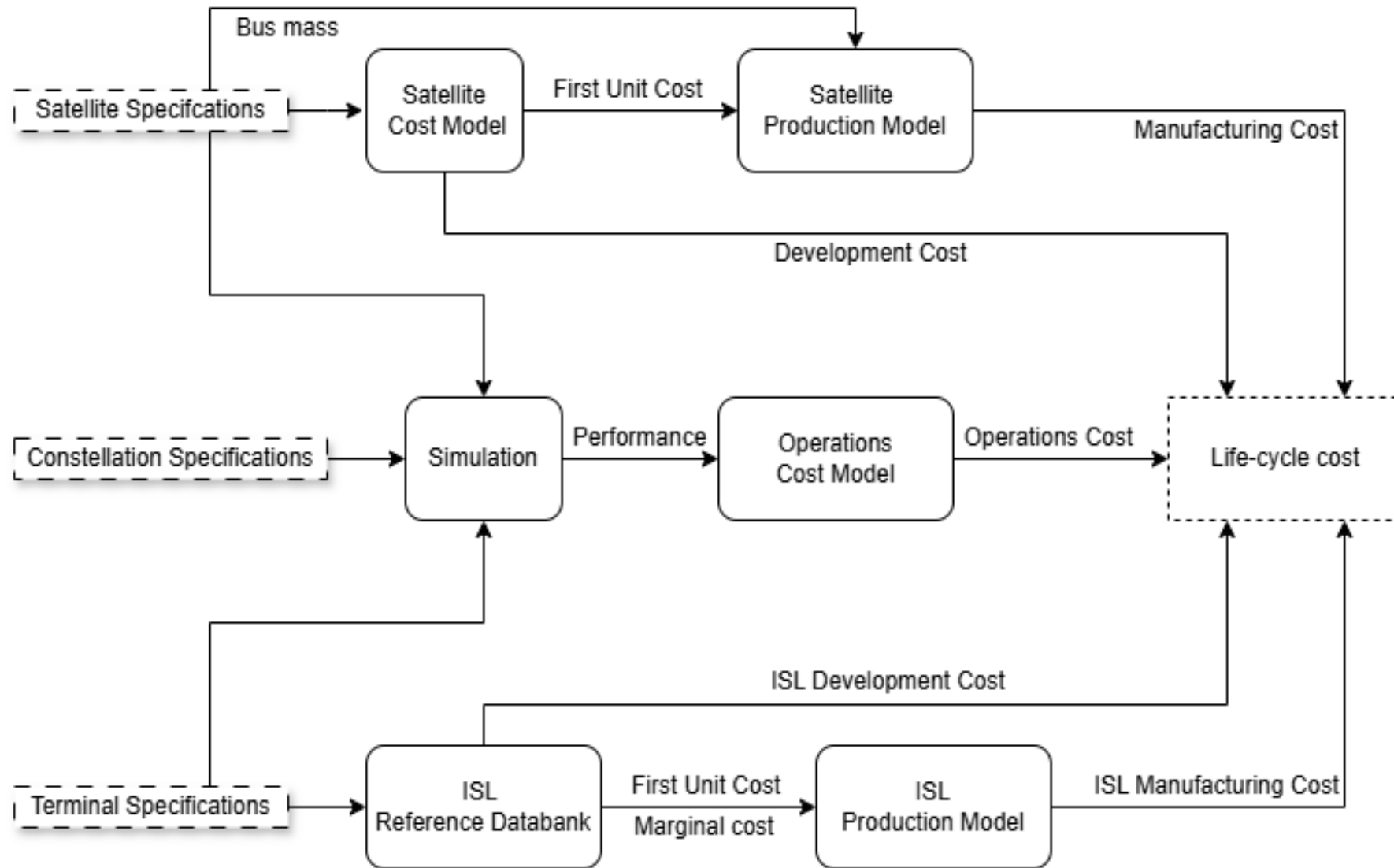
Terminal Choice feeds back into Cost models



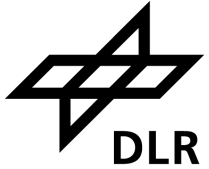
Terminal Choice feeds back into Cost models



Terminal Choice feeds back into Cost models



Available OISL terminal options

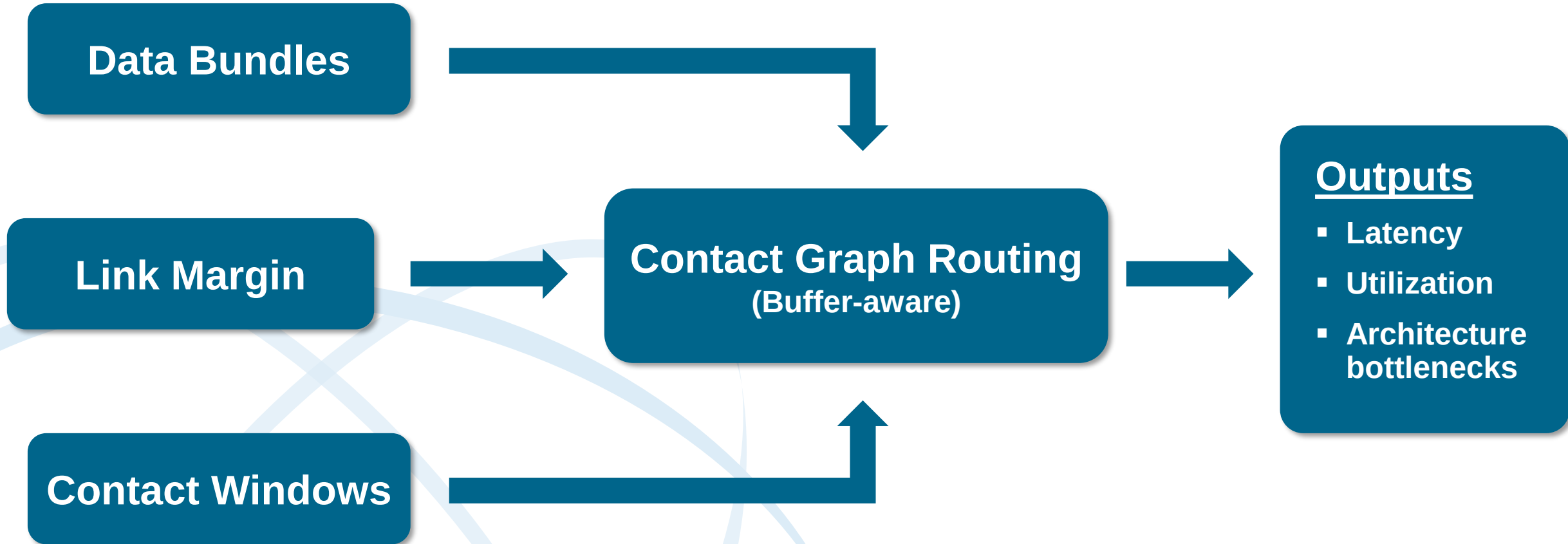


- Basis for comparison by analogy for SWaP + complexity increase

ISL Terminal	Rate/link	Range	Mass	Active power
CACI SkyLight 100M	100 Mbps	1,000 km	1.6 kg	35 W
TESAT SCOT30	1.25 Gbps	3,500 km	<6 kg	<60 W peak
CACI CrossBeam-ST2	2.5 Gbps	6,750 km	10 kg	75 W typ.
TESAT SCOT80 (*Dual EU)	2.5 Gbps/head* (up to 100Gbps coherent)	~8,000 km	11.9 kg/channel*	60–80 W/channel*
Starlink Estimated (3 terminals per sat)	up to 200 Gbps coherent	3000-5400km	7-15kg	50-100W

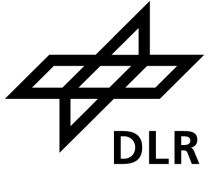
Tab. 4: optical-ISL terminals specifications of selected unique terminal options according to manufacturer datasheets. Ordered by specified datarate.

Modular Simulation Architecture

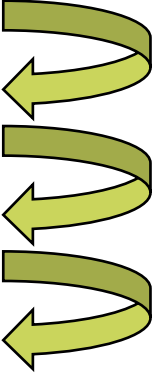


- Can also be used for optical-to-ground or RF-ISL and/or Relay Networks

Improvements vs. Cost in simple Example constellation

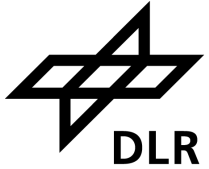


- **24** communication satellites in **2 LEO planes** with CACI CrossBeam-ST2 OISL
- **700kg** Spacecraft; Cost excluding Launch Cost  **Total: Avg. ~\$600M**

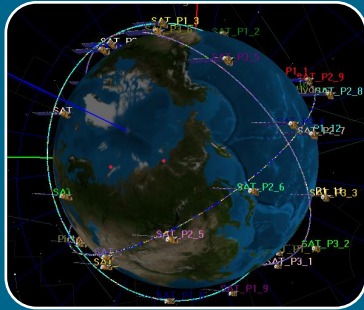
ISL terminals/sat	50th Percentile Latency	95th Percentile Latency	Cost Difference
0x	829.8s	4088.4s	 + \$47.53 to 63.35M + \$15.40 to 22.13M + \$14.75 to 18.61M
2x	65.4s	594.6s	
3x	25.2s	109.2s	
4x	24.6s	77.84s	

- Fixed Estrack ground station network (7 S-Band stations used)~

Some findings from the final model



- I. OneWeb same constellation but with ISL: **+\$240-440M**
- II. Starlink last unit cost without ISL: **~\$460k**  with ISL: **~\$620k**
- III. ISLs reduce the minimum number of GS for global coverage from **~30** to **1**
 **Operational savings depend on costs per ground station. Possibly tens of millions of dollars / year.**
- IV. How the **ground station network** can be changed to **save cost** is ongoing research / is explored in:
Kling, Ulrich Rolf (2023) Reducing Data Latency with Inter-Satellite Links in LEO Constellations: Trade-off Analysis and Impact on Concept of Operations.



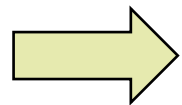
Constellation Cost Estimation

- Open-literature models hold up poorly for constellations
- Improved production approach provides easy tuning



Inter-Satellite Links

- OISL performance capabilities were shown
- OISL cost depends on datarate/range characteristic and also scales with production



Performance improvements over costs can be quantified for arbitrary constellations by our flexible evaluation framework

- Relay Networks
- Continue expanding reference data -> CubeSats don't fit the data yet
- Satellite reliability could be included as term
- Improve marginal cost estimate (take payload into account)

Contact

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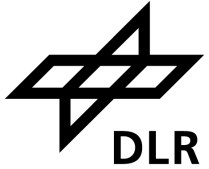
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BACKUP: Starlink CoR Breakdown



Starlink CoR (2023-25) = **\$13.47B**

(- \$4.768B) D&A = **\$8.70B**

(- \$0.35B) Share-based comp. = **\$8.37B**

(- \$0.4B) Warranty = **\$8B**

(- \$0.3B) Spectrum fees = **\$7.6B**

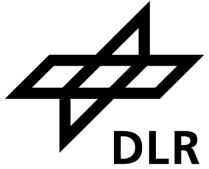
(- \$0.162B) Customer support = **\$7.45B**

(- \$1.245B/ \$2.075B) User terminal manufacturing = **\$6.21B/ \$5.38B**

⇒ This figure is left for ground station and satellite operations costs

⇒ Median of **\$1.93B/year** or very roughly **\$255k/satellite/year**

BACKUP: Constellations used for final modelling

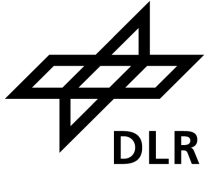


Constellation	Units	Spacecraft Mass	Application
Starlink V2 Mini	7,580	575 / 700 kg	Communications
OneWeb Initial Rollout	648	200 kg	Communications
Iridium NEXT	81	800 kg	Communications
Galileo FOC	34	~700 kg	GNSS
EnduroSat Product Line	-	8–500 kg bus	Any / General-purpose
DMC3 TripleSat	3	447 kg	Visual EO
BlackSky 2nd Gen	20	56 kg	Visual EO
ORBCOMM OG2	18	172 kg	Communications

Tab. A: Satellite Constellations with their main characteristics that were used for irreducible fraction regression..

- Constellations with insufficient technical/financial data were used as anecdotal references

BACKUP: Starlink v2mini technical specifications

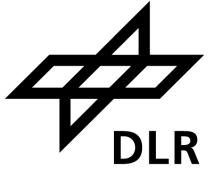


First V2mini launch in Feb-2026

- **3441** v2mini units launched | **4706** optimized v2mini units launched of
- **~700kg** Spacecraft dry mass | **575kg** Spacecraft dry mass
=> Both were lumped together in production cost model
- **~31kW** BoL Power; **96Gbps** class downlink

Model	First Unit Cost	Development
QuickCost	\$76.01M	\$190.03M Protoflight
KEOSCM	\$75.27M	None
SSCM	\$86.82M	\$239.84M Protoflight
USCM	\$75.96M	\$222.44M

BACKUP: OneWeb technical specifications

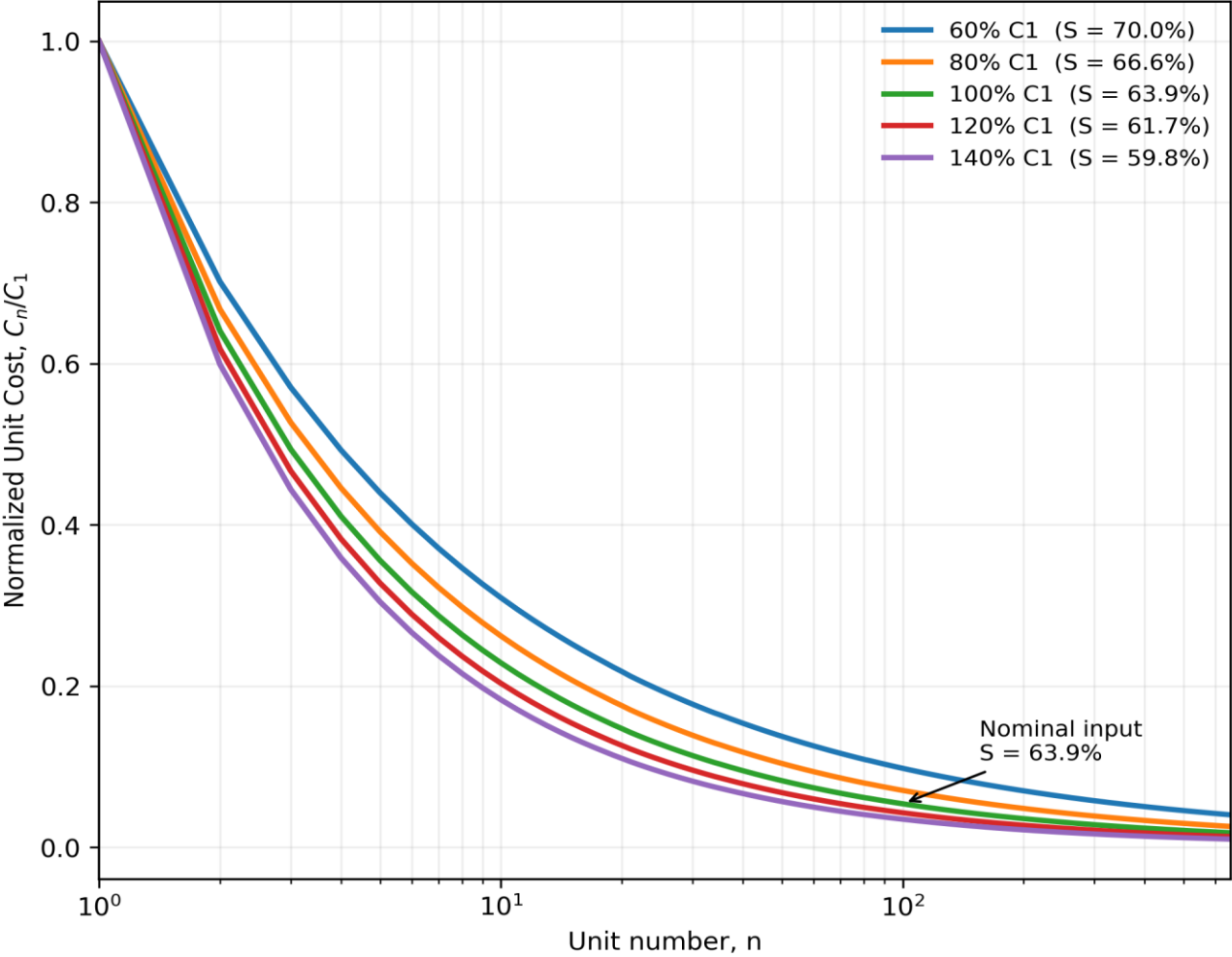
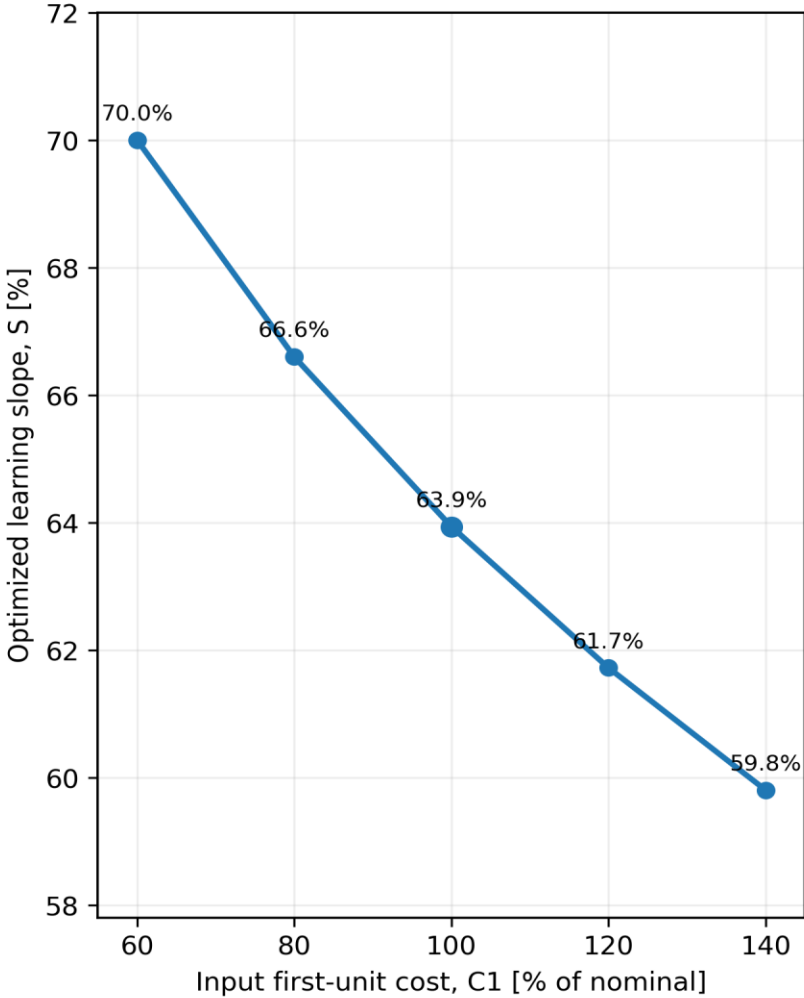


First unit launch in Feb. 2019

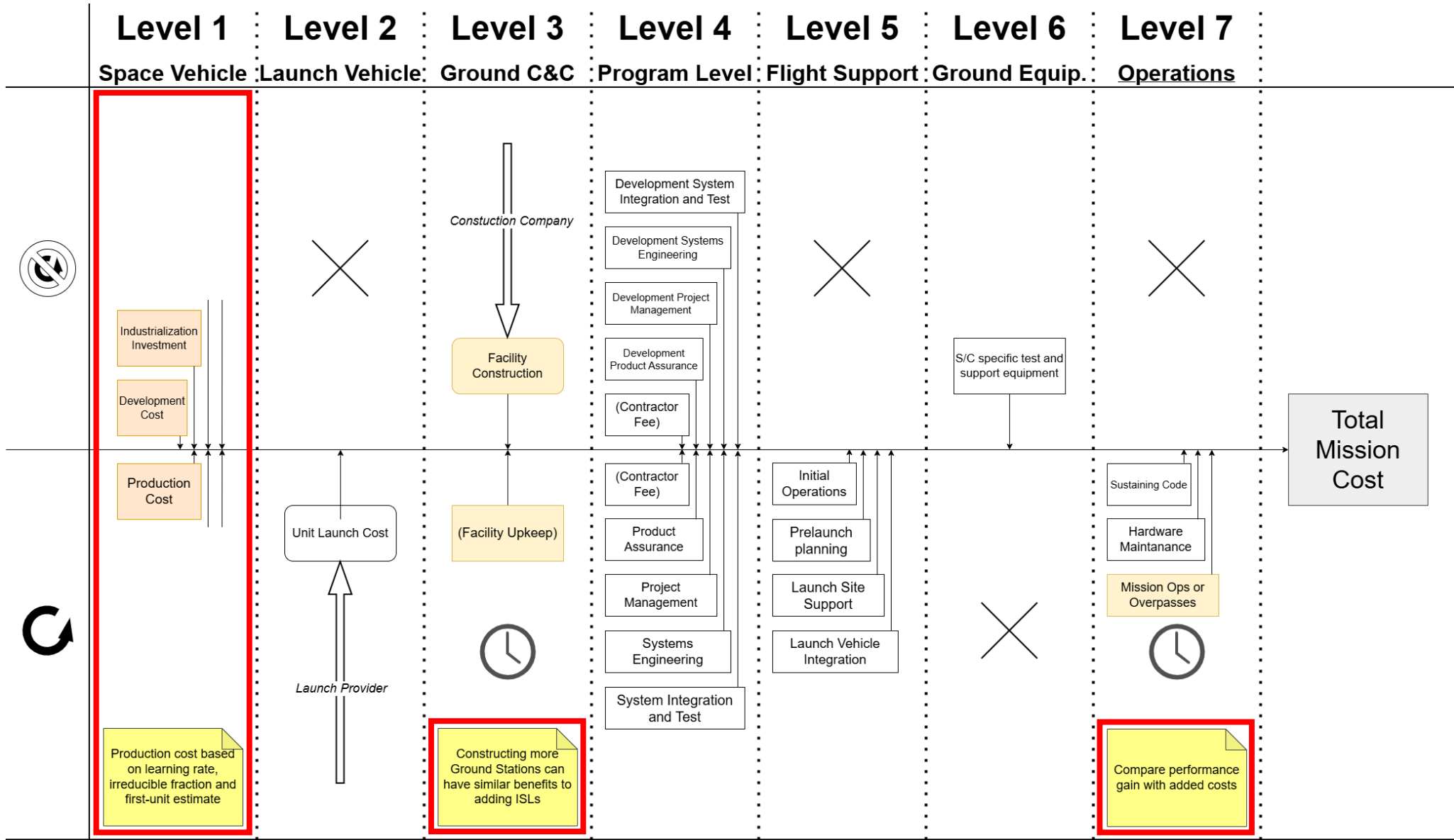
- **655 units** manufactured
- **~200kg** Spacecraft dry mass
- **~670W** BoL power; Payload makes up **60kg**

Model	First Unit Cost	Development
QuickCost	\$70.02M	\$175.04M Protoflight
KEOSCM	\$17.81M	Not given
SSCM	\$24.78M	\$68.48M Protoflight
USCM	\$41.28M	\$116.33M

BACKUP: Sensitivity to first unit cost



Coming back to the life cycle overview



BACKUP: Typical OISL hardware specifications



<u>Aperture Diameter:</u>	20-135 mm
<u>Total Volume:</u>	1.5U to 30x30x50 cm³
<u>Transmitter Power:</u>	1-5 W
<u>Modulation Scheme:</u>	On-Off-Phase Keying or Coherent
<u>Acquisition Time:</u>	< 10-30 s
<u>Pointing Demands:</u>	Most terminals claim body-independent pointing!

BACKUP: OISL datarate drop-off with range

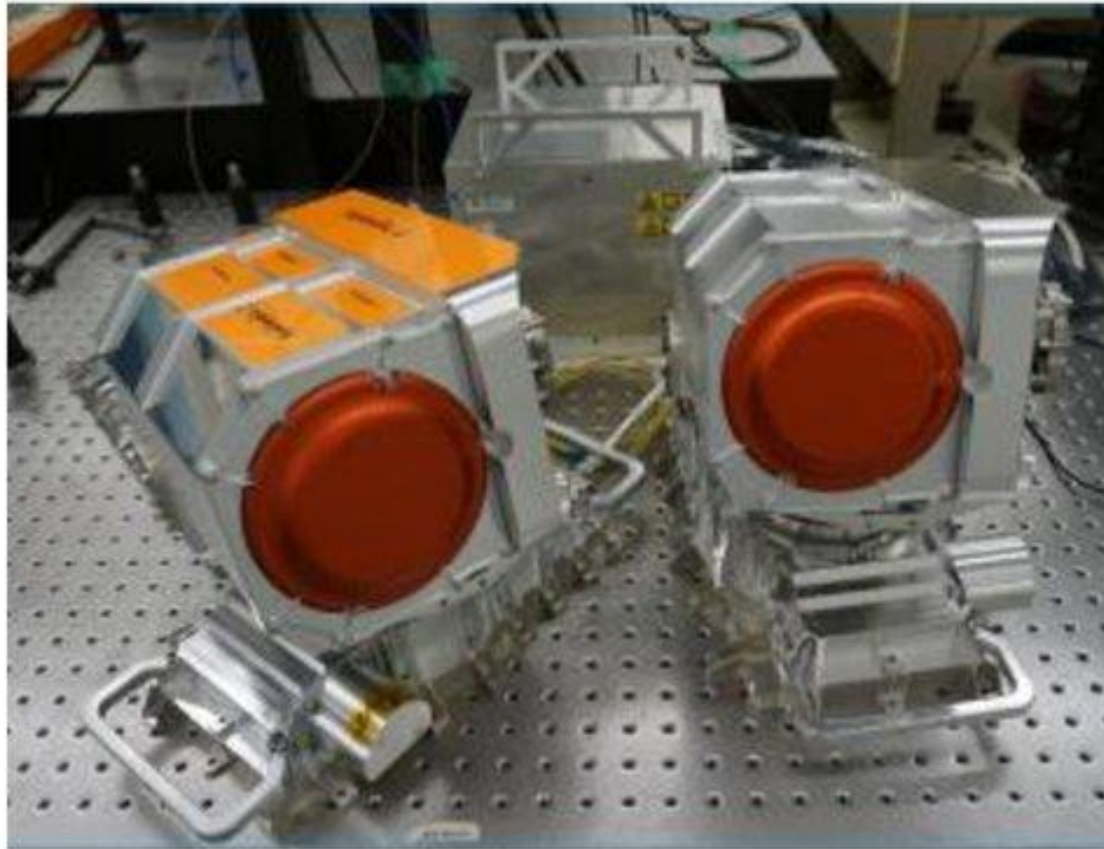
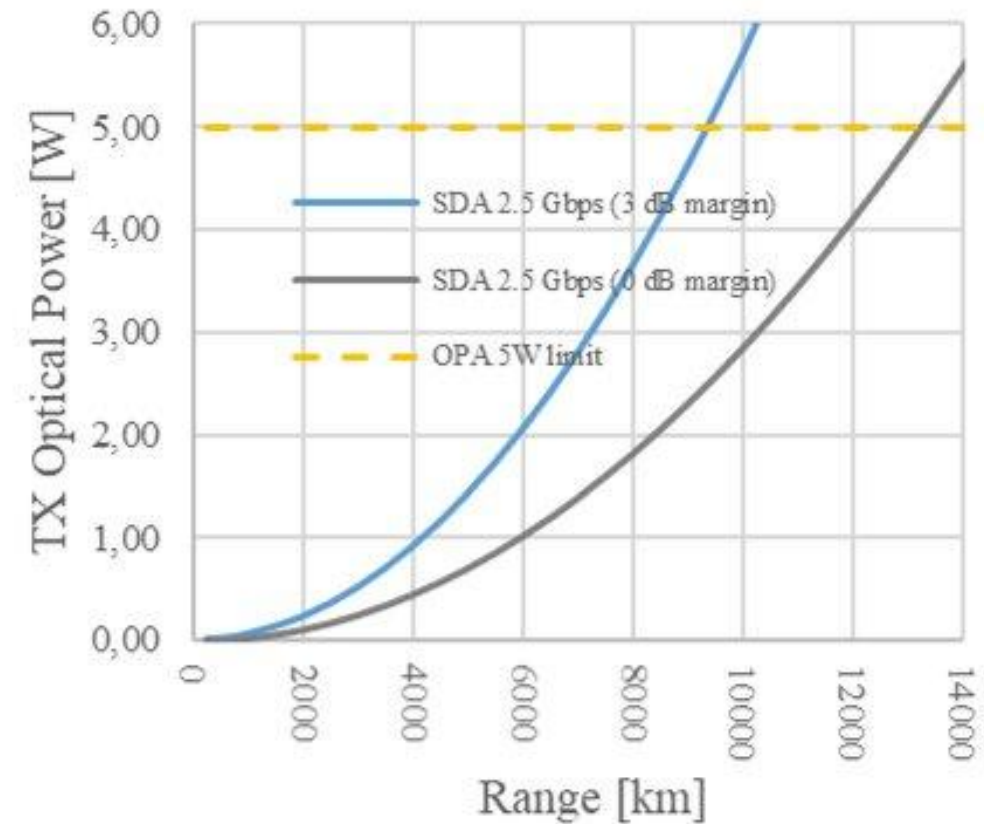


Fig. B “SCOT80 Release 3 Dual Terminal Assembly: One Dual Terminal Assembly consists of one Electronic Unit and two Optical Heads, resulting in two individual optical channels for operation (left)”

Taken from: [Mark Gregory, Frank Heine, Manuel Rank, et al. "Status on laser communication activities at Tesat-Spacecom", Proc. SPIE 13885, Free-Space Laser Communications XXXVIII, 138850A (5 Mar 2026); <https://doi.org/10.1117/12.3081815>]

BACKUP: Modelling Ops Cost



1. Classical modelling

- Cost per minute (of reserved contact window) for external provider
- Cost of building and operating/year of one groundstation (per antenna)

2. External Analogy

- Flat sum per satellite per year (\$200-600k / year)

3. Internal Analogy

- Internal operations cost data

=> Savings from automation and learning for constellations competes with higher routing and downlink demand for larger constellations.