



VPL

A cost model for Earth- and Mars-orbit
navigation & communication
constellations

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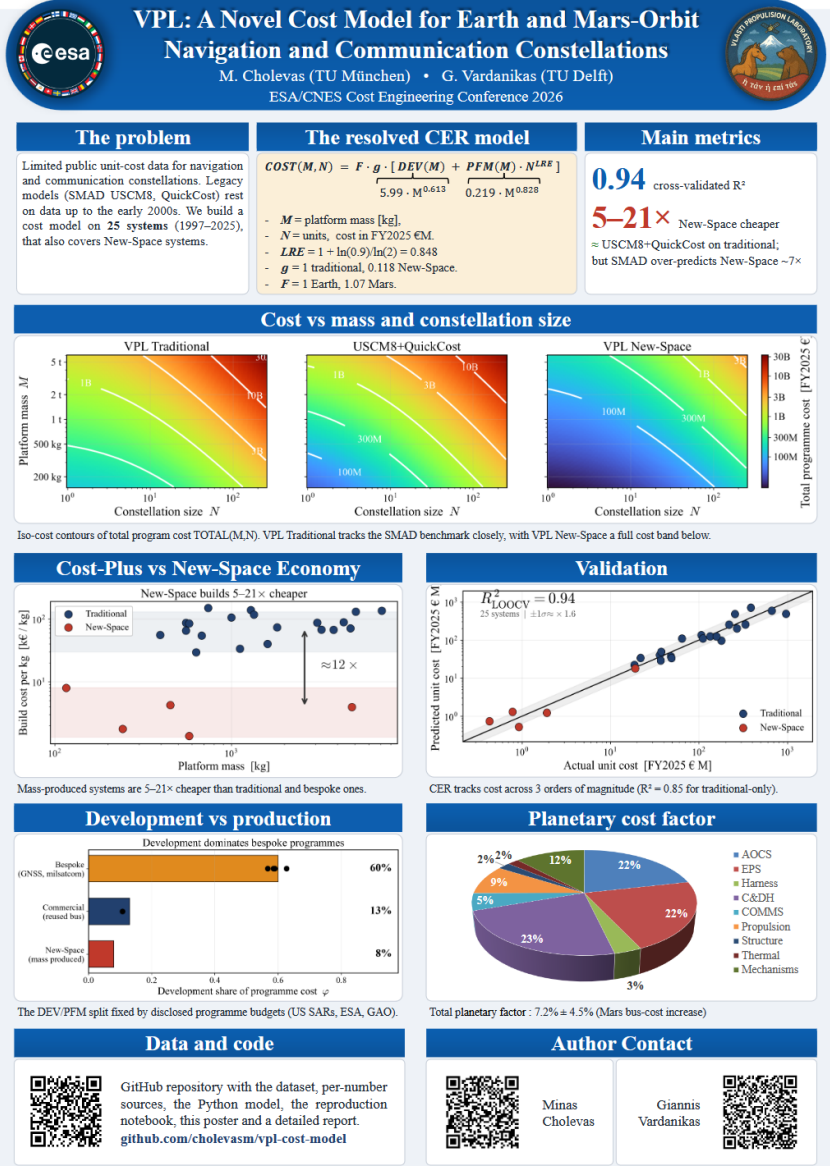
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Winners · 2025 ESA/CNES Cost Engineering Challenge

Poster Presentation



Mass and count in. Programme cost out.

$$\text{TOTAL} = F \cdot g \cdot [\text{DEV} + \text{PROD}]$$

$$\text{DEV}(M) = 5.99 M^{0.613}$$

$$\text{PROD}(M, N) = 0.219 M^{0.828} \cdot N^{0.848}$$

$g = 1$ traditional · 0.120 New-Space

$F = 1$ Earth · 1.07 Mars

0.945

leave-one-out R^2
over 25 constellations

M platform wet mass [kg]

N number of satellites

AVG average unit cost = TOTAL / N

TOTAL programme cost = DEV + PROD

DEV development (one-time)

PFM first (proto-flight) unit

PROD all N units = PFM · N^{LRE}

Price a Mars constellation from its mass and size



ESA/CNES Cost Engineering Challenge 2025
Mars-orbit navigation & communication
constellation

1 FY2010 dollars, legacy programmes

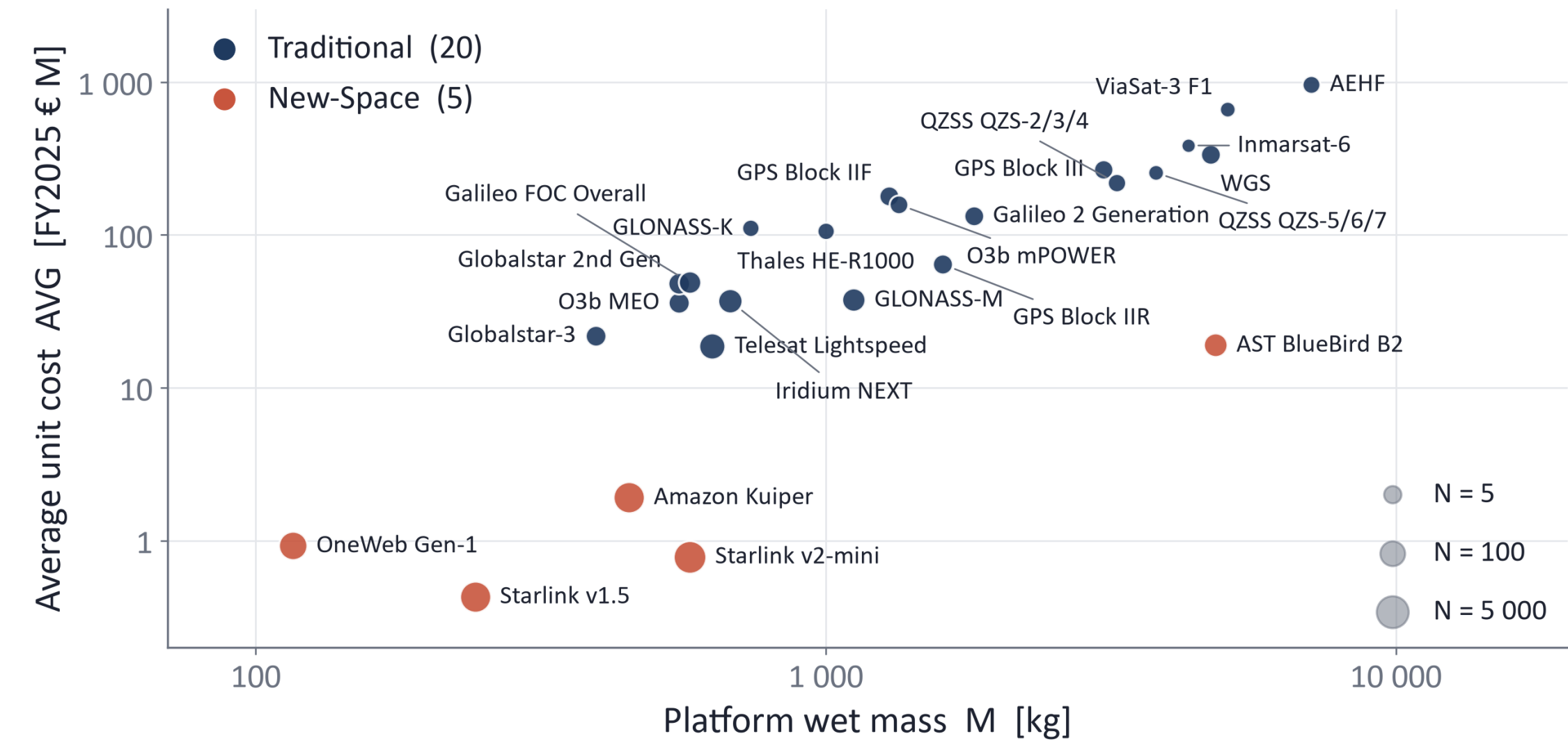
Live Calc

Table 11-8. USCM8 Non-recurring Subsystem CERs in FY2010 Thousands of Dollars. These CERs predict the cost of development plus one qualification unit. See Tables 11-34 and 11-37 for application of these CERs.

SME-SMAD WBS Element (Non-recurring subsystem)	CER Y = non-recurring cost in FY2010 thousands of dollars for development plus one qualification unit.	Cost Driver(s)	Cost Driver Input Range	SEE
1.1 Spacecraft				
1.1 Spacecraft Bus (alternate CER when no component information is available)	Y = 108 X1	X1 = Spacecraft Weight (kg)	114–5,127 kg	47%
1.1.1/1.1.2 Structure and Thermal Control	Y = 646 X1 ^{0.684}	X1 = Structure + Thermal Weight (kg)	59–501 kg	22%
1.1.3 Attitude Determination & Control System (ADCS)	Y = 324 X1	X1 = ADCS Weight (kg)	35–524 kg	44%
1.1.4 Electrical Power System (EPS)	Y = 64.3 X1	X1 = EPS Weight (kg)	47–1,065 kg	41%
1.1.5 Propulsion (Reaction Control)	Y = 20.0 X1 ^{0.485}	X1 = Total RCS tank volume (cubic centimeters)	Not given	35%
1.1.6 Telemetry, Tracking, & Command (TT&C)	Y = 26,916	Y = Average TT&C Cost (since there is no statistical)	CER based on S- Band telemetry	Not given

Recommended tool: SMAD, USCM8 cost models (Table 11-8)

25 constellations, 1997–2025, every input sourced



VPL v1: split the unit cost with an assumed share

$$\text{DEV} + \text{PFM} \cdot N^{\text{LRE}} = \text{AVG} \cdot N^{\text{TLRE}}$$

a Total Learning Rate Exponent, DEV shared equally by every unit

$$\lambda = \text{PFM} / (\text{DEV} + \text{PFM})$$

assumed linear in N: 0.35 at N = 5 → 0.15 at N = 198

$$\text{LR} = 0.9$$

fixed manufacturing learning rate

→ solve for DEV and PFM from M, N and AVG

0.62

leave-one-out R^2
of the v1 CER

$\lambda(N)$ was chosen,
not fitted to data.

VPL v2: fit the whole programme cost, keep N in the model

$$\begin{aligned}\text{TOTAL}(M, N) &= F \cdot g \cdot [\text{DEV}(M) + \text{PROD}(M, N)] \\ &= F \cdot g \cdot [\text{DEV}(M) + \text{PFM}(M) \cdot N^{\text{LRE}}] \\ &= F \cdot g \cdot [d M^p + q M^r \cdot N^{1 + \ln(lr) / \ln 2}]\end{aligned}$$

Unknowns

g, d, p, q, r, lr

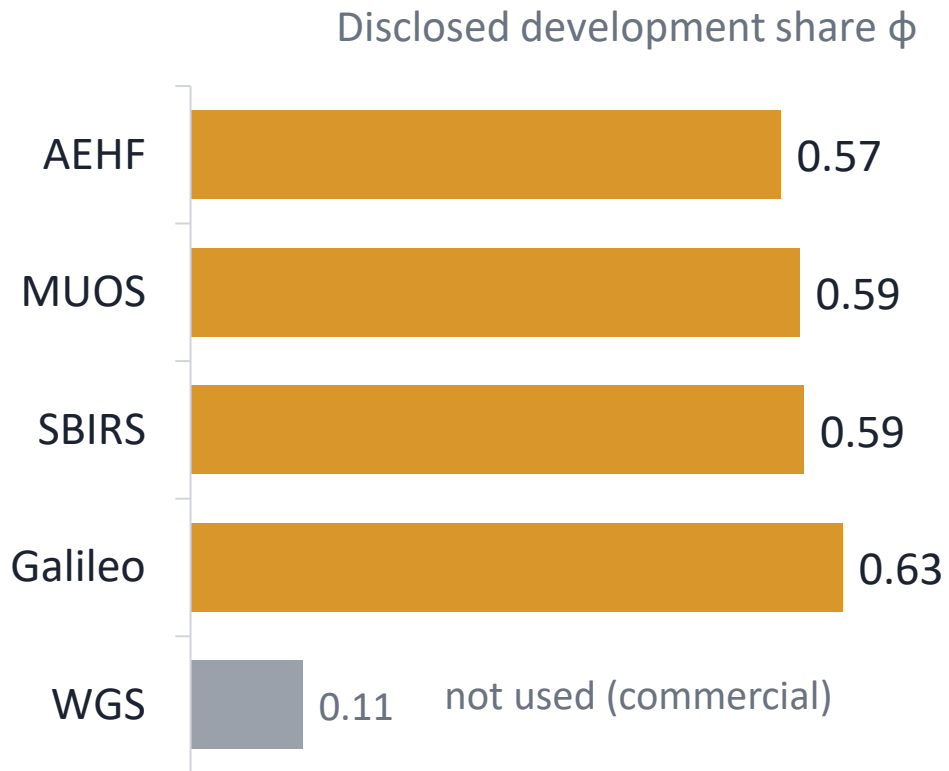
Assumed

$lr = 0.9$
 $\text{LRE} = 0.848$

Error, 25 systems, log space

$\log(\text{TOTAL} / N)$
 $- \log(\text{AVG})$

Unit costs alone cannot split DEV from PROD



Also fit the 4 bespoke programmes' shares:

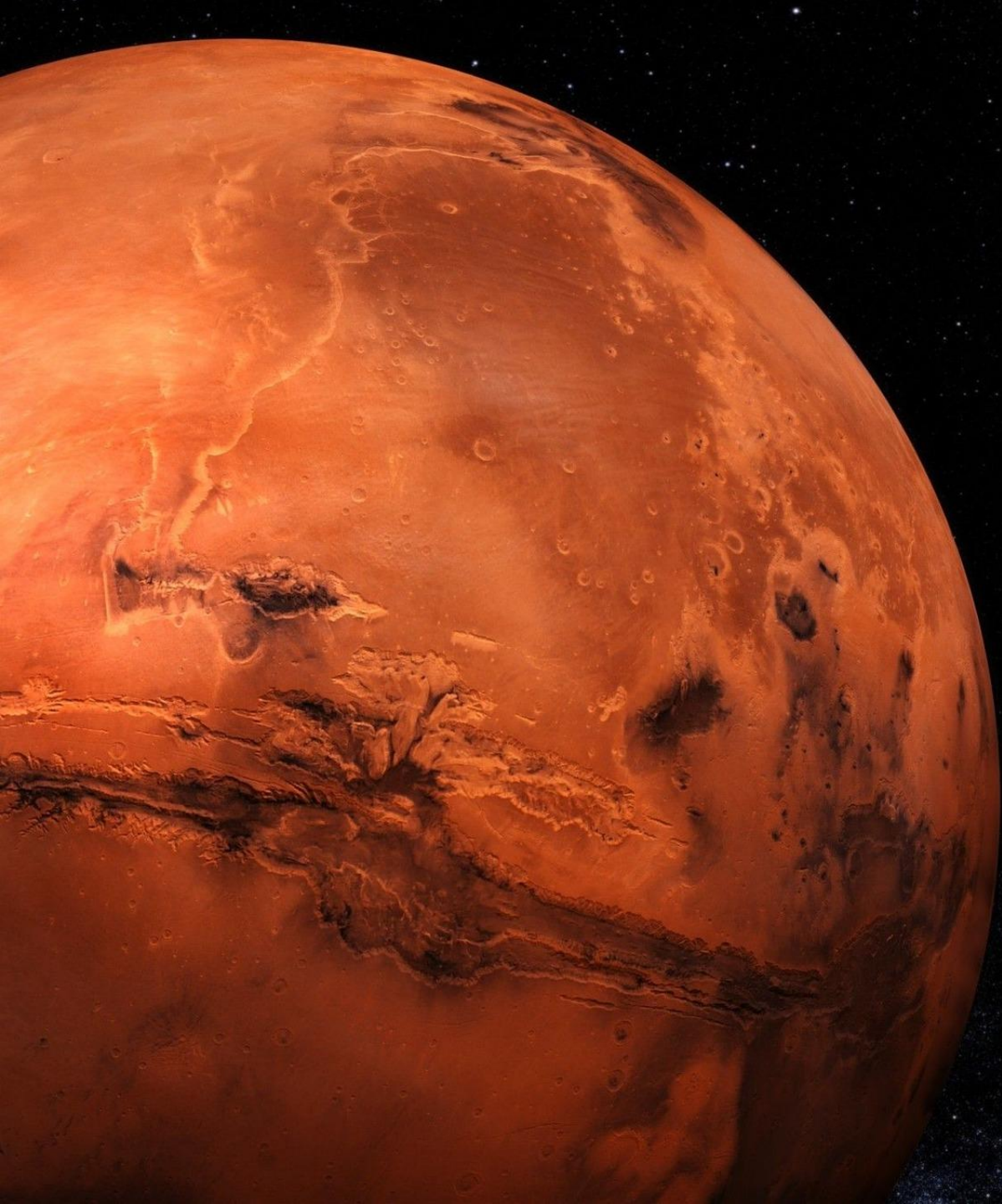
$$\text{DEV} / (\text{DEV} + \text{PFM} \cdot N^{\text{LRE}}) - \phi$$

weight $w = 0.5$

how much the fit cares about the 4 shares versus the 25 unit costs

Least squares $\rightarrow g, d, p, q, r$

Sources: US Selected Acquisition Reports (AEHF, MUOS, SBIRS, WGS); Galileo IOV/FOC budget



$$F = 1.07$$

Mars-orbit cost factor (Earth: $F = 1$)

$$F = 1 + \sum_i s_i \cdot \Delta_i$$

s_i subsystem share of bus cost

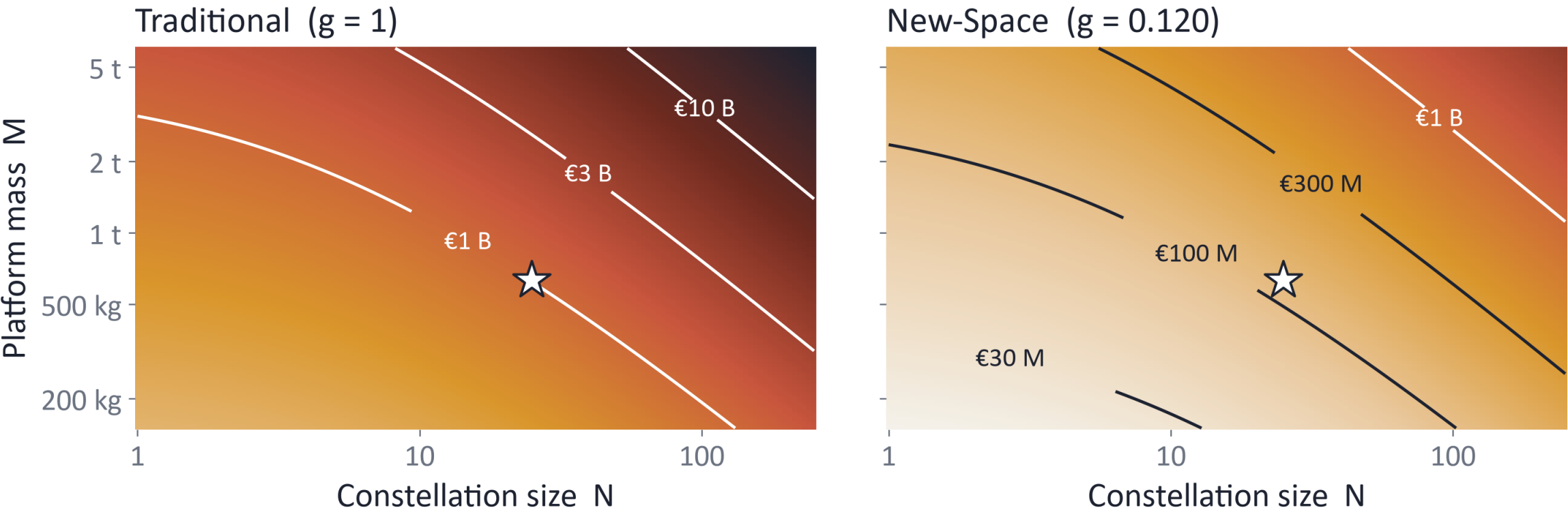
Δ_i Mars cost increase, from the literature

+7.2 % bus cost

$\sigma = 4.5$ % across subsystems · SMAD QuickCost: 1.29

$$\text{TOTAL} = F \cdot g \cdot [5.99 M^{0.613} + 0.219 M^{0.828} \cdot N^{0.848}]$$

$g = 1 \text{ traditional} \cdot 0.120 \text{ New-Space}$ $F = 1 \text{ Earth} \cdot 1.07 \text{ Mars}$



Lines: total programme cost, FY2025 €. ★ 2025 challenge bus: 630 kg × 25 satellites

It predicts systems it has never seen



fit on 24 · predict the 25th · repeat 25 times

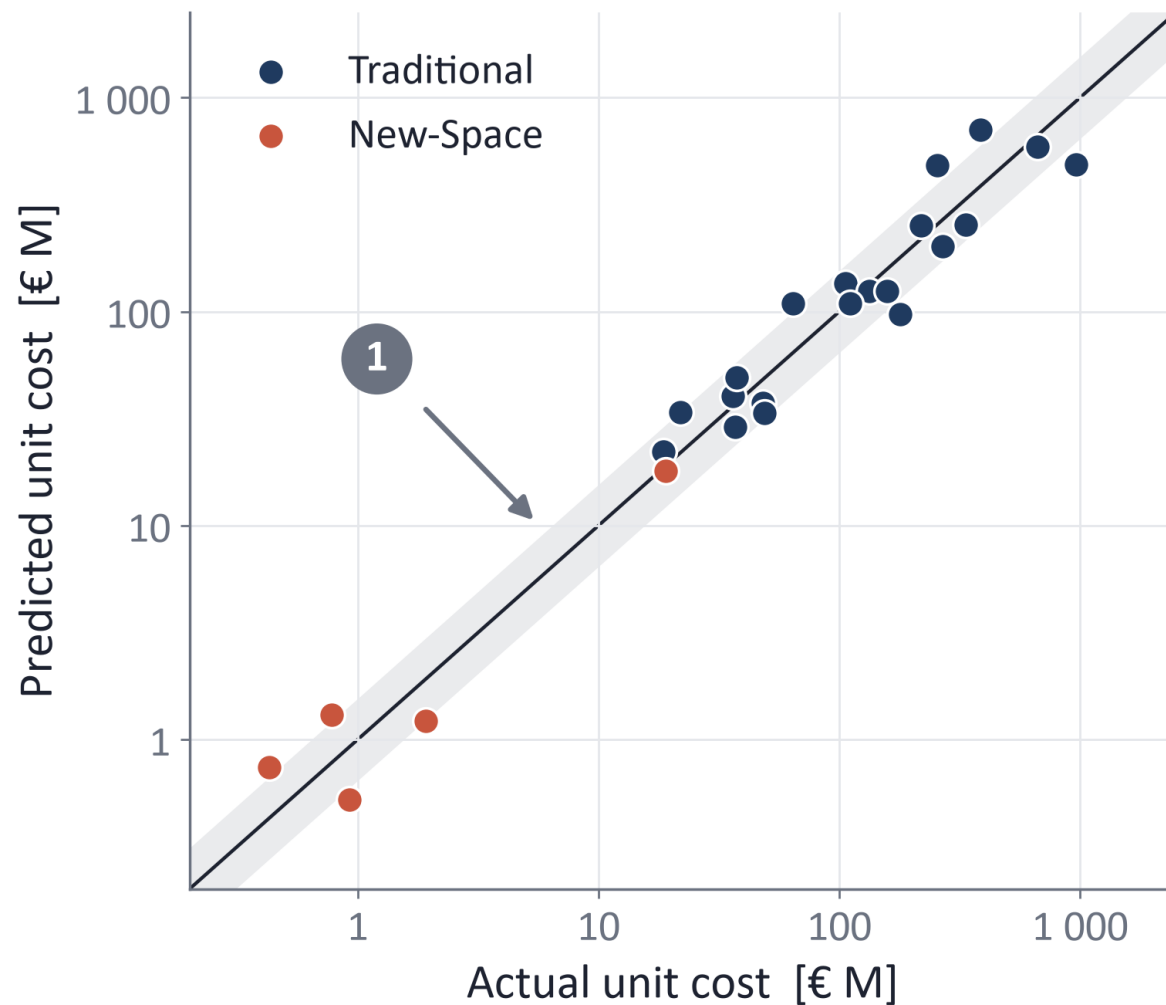
0.945

leave-one-out R^2 , 25 systems

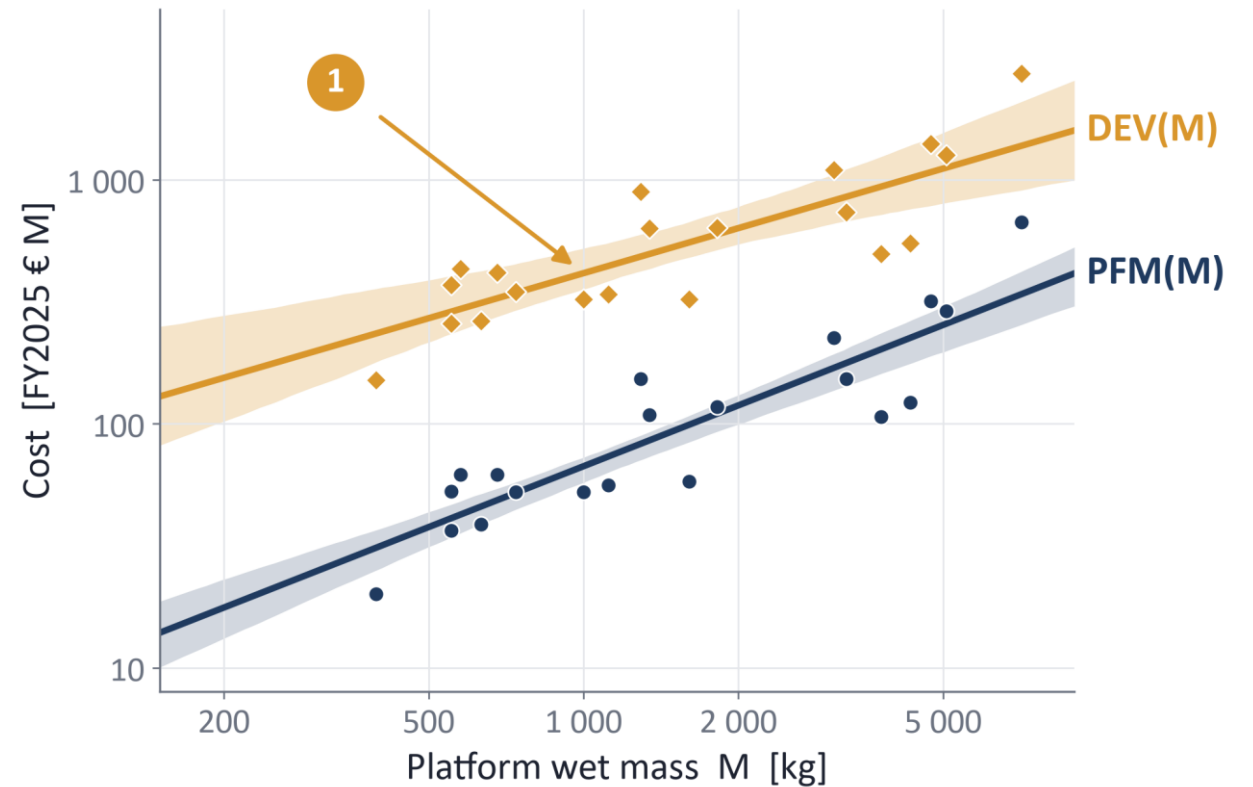
×1.55

1

1 σ prediction band



The development split is pinned, not guessed



Slightly ahead of SMAD, and where SMAD has no model

Median error · 20 traditional systems

24 %

VPL

31 %

SMAD USCM8 + QuickCost

R² · 20 traditional systems

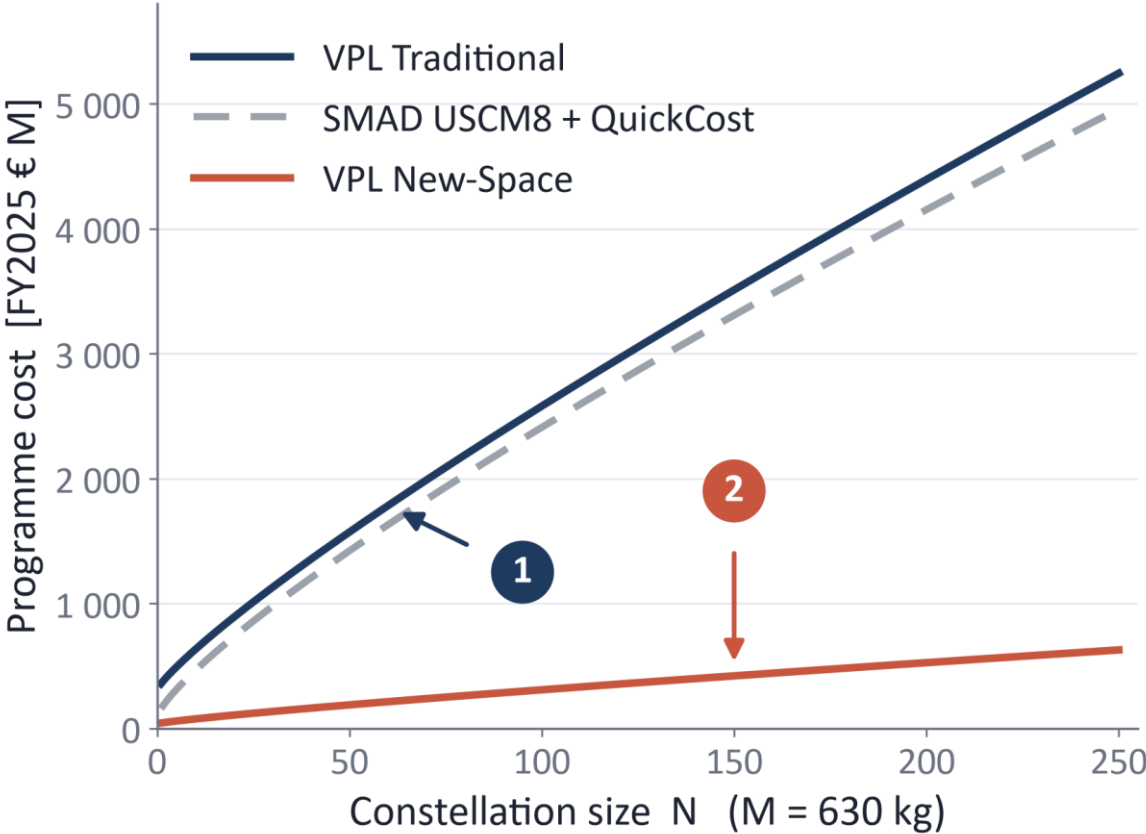
0.88

VPL

0.87

SMAD USCM8 + QuickCost

- 1 traditional cost sits above SMAD
- 2 New-Space ≈ 8× cheaper, no SMAD equivalent



Two open points

1 Only 5 New-Space systems,
and their unit costs are mostly analyst estimates.

2 The weight w of the DEV-share errors
in the least-squares fit is an open choice.

Contributions

$$\text{TOTAL} = F \cdot g \cdot [5.99 M^{0.613} + 0.219 M^{0.828} \cdot N^{0.848}]$$

- 1 A sourced modern dataset: 25 constellations, 1997–2025
- 2 A two-regime CER: traditional and New-Space, Earth and Mars orbit
- 3 A DEV / PROD split pinned by disclosed budgets
- 4 Leave-one-out $R^2 = 0.945$; ahead of SMAD on traditional systems



github.com/cholevasm/vpl-cost-model
data · sources · model · report



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Thank you!