From *Tsiolkovsky* to P_{70}.

Anatomy of a €733M decision.

> *"A spacecraft's life-cycle cost is not estimated — it is argued, line by line, from a rocket equation to a confidence percentile."*

A WALKTHROUGH IN 7 STAGES

How does a **1 928 kg** communications spacecraft in a lunar halo orbit end up with a **€733M** committed budget? This poster traces the full cost-engineering chain on a single fictitious mission — from the rocket equation taught in year 2 of an aerospace degree, all the way to the **Agency Baseline Commitment** at the 70th percentile of a Monte Carlo distribution.

Methodology USCM8 parametric CERs (Wertz, New SMAD 2011) · NASA Cost Estimating Handbook v4.0 (2015)
Base year FY2025 EUR constant · **Architecture** 1 PFM (L2) + 1 RFM (L1) + 1 Ground Spare

/01 Why park a satellite at L1 and L2?

The Earth–Moon Lagrange points are **quasi-stable gravitational saddles**. A halo orbit around L2 sees the lunar far side continuously; from L1 it sees the near side and Earth at the same time. One **1 985 kg** backbone replaces a constellation of **≥4 lunar low-orbit relays**.



Dry mass per satellite	1 928 kg
Wet mass (incl. Xe propellant)	1 985 kg
Payload (Ka + FSO + Nav)	598 kg
EPS power BOL	8 kW

RELAYS REPLACED
≥4 LLO → 1 LBN
A single halo node replaces a low-lunar constellation

STATION-KEEPING
70 m/s/yr → 8 m/s/yr
~10× lower Δv than a low-lunar relay

Ref Wertz, New SMAD §18.6 · ARTEMIS-P1/P2 (Folta & Woodard 2010)

/02 The equation everyone knows

$$\Delta v = I_{sp} \cdot g_0 \cdot \ln(m_0 / m_f)$$

With Δv = **520 m/s** (incl. 30% margin per NASA CEH §2.3.2), a Hall thruster I_{sp} = **1 900 s** trims propellant from **344 kg** (chemical) down to just **57 kg**. The 287 kg saved become payload mass — where the cost story really starts.

Δv station-keeping	50 m/s
Δv repositioning L1↔L2	150 m/s
Δv disposal (EOL)	50 m/s
Insertion + TCM	150 m/s
Margin (NASA CEH §2.3.2)	+30%

Mass-to-cost coupling: every kg you don't burn becomes payload mass *that can be priced by a CER*.

Ref Tsiolkovsky 1903 · Safran PPS-5000 datasheet (2019)

/03 From kilograms to euros

Parametric Cost Estimating Relationships (CERs) turn the mass budget into money:

$$Y = a \cdot X^b$$

The USCM8 model calibrates **a** and **b** on **47 historical missions**. Example for ADCS non-recurring:

$$Y_{NR} = 324 \cdot m_{ADCS} \quad [\$K]$$

96 kg of attitude hardware → **€38.7M** gross before heritage adjustment.

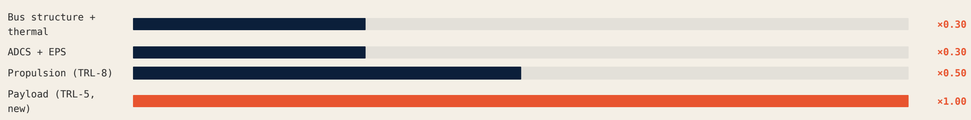
Structure + Thermal (520 kg)	€57.2M
ADCS (96 kg)	€38.7M
EPS (405 kg)	€32.4M
TT&C (constant CER)	€33.5M
Payload (analogy, 598 kg)	€140.0M

Power law → non-linear scaling. b < 1 in most CERs means a 30% mass cut saves only ~12% in cost.

Ref New SMAD Tables 11-8, 11-9 (pp. 298–299)

/04 Heritage & the learning curve

A brand-new subsystem costs 100% of its CER. A flight-proven one costs ~30%. Heritage multipliers (New SMAD Table 11-4) reflect what fraction of design, qualification and testing can be reused.



For the lot of 3 units (PFM + RFM + Spare), Wright's learning curve compresses recurring cost:

$$\text{Total Lot} = T_1 \cdot N^{1 + \ln S / \ln 2}, \quad S = 0.95$$

With T_1 = **€185M** and N = 3, the lot costs **€512M** — a 7.6% saving vs. three identical first units.

Heritage saving on NRE	−€166M
Learning-curve saving on lot	−€43M

Ref New SMAD Table 11-4 (p. 296) · USCM8 Eq. 11-6 (p. 316)

/05 The deterministic baseline: €666M

Aggregated by NASA CEH WBS Level 2 (Fig. 4, p. 7), three units plus 5-year operations plus contractor fee land on a point estimate of **€666M FY2025 constant**. That number is *not* the committed budget — it is the median of an unknown distribution. It says nothing about how confident we are that the project will land at or below it.

PFM (NRE + qual.)	€253.1M
RFM (Wright, N=2)	€166.4M
Ground Spare (N=3)	€160.4M
Contractor fee (10%)	€58.0M
Operations 5y (NPV 3%)	€28.5M
LCC baseline (P0)	**€666.4M**

3 units
FLIGHT MODEL + REDUNDANT + SPARE

× 1.245
K_{conv}: FY2010 USD → FY2025 EUR (DOD INFLATION × EUR/USD = 0.92)

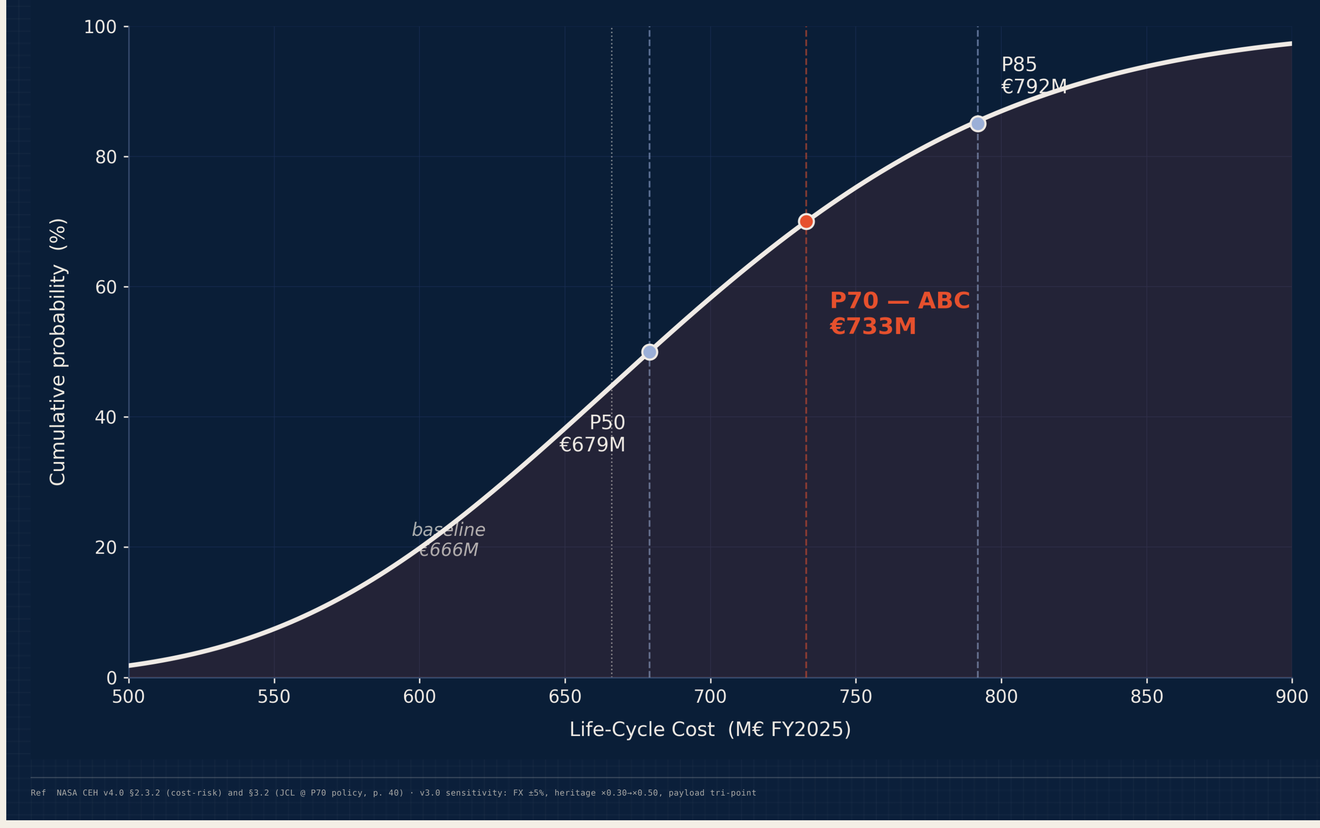
Ref NASA CEH v4.0 §2.3.1 · New SMAD Table 11-31 (inflation chain)

/06 Where the €733M committed budget really comes from

V3.0 FINAL

Each subsystem CER carries a Standard Error of Estimate (SEE). Sampling each as a lognormal and adding 6 discrete risks (Bernoulli × Triangular) **100 000 times** produces the cost-confidence S-curve. NASA policy mandates committing at the **70th percentile** (the Agency Baseline Commitment, CEH §3.2 p. 40); the gap between baseline and P70 is the **Unallocated Future Expense**:

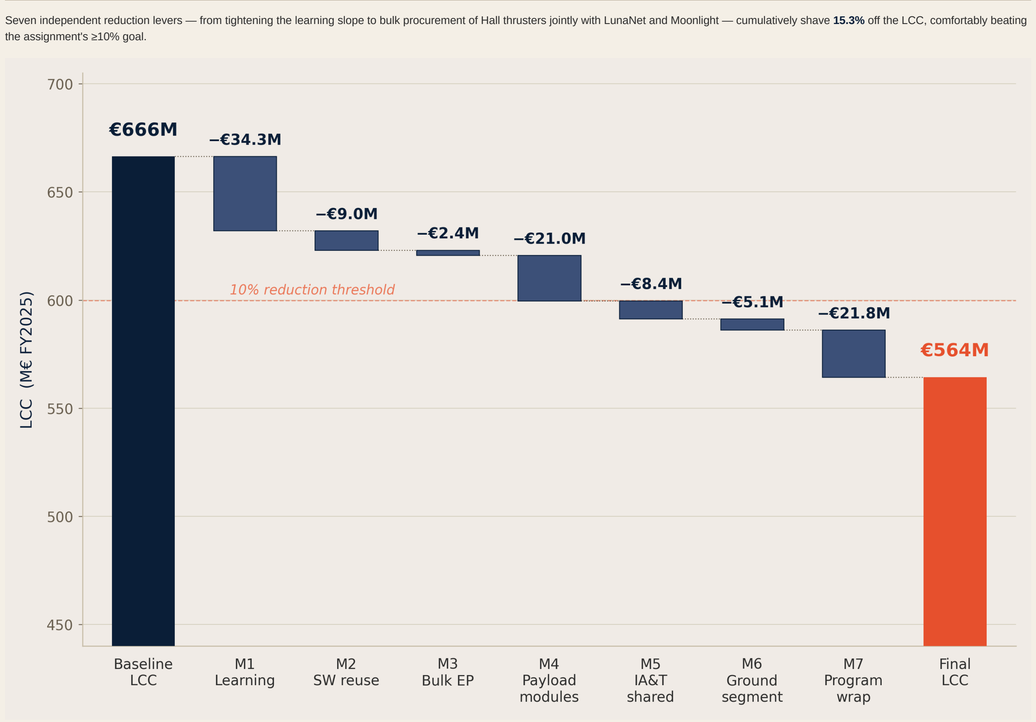
$$\text{UFE @ P70} = €733M - €666M = €66.5M$$



Ref NASA CEH v4.0 §2.3.2 (cost-risk) and §3.2 (JCL @ P70 policy, p. 40) · v3.0 sensitivity: FX ±5%, heritage ×0.30–×0.50, payload tri-point

/07 Beating the assignment target

Seven independent reduction levers — from tightening the learning slope to bulk procurement of Hall thrusters jointly with LunaNet and Moonlight — cumulatively shave **15.3%** off the LCC, comfortably beating the assignment's ≥10% goal.



M1 Learning slope 0.95→0.90	−€34.3M	**M2** Moonlight SW reuse	−€9.0M
M4 Standard payload modules	−€21.0M	**M5** IA&T shared w/ Gateway	−€8.4M
M3 Bulk Hall procurement	−€2.4M	**M6** Single-string ground seg.	−€5.1M
M7 Reduced program wrap 8→5%	+ total committed:		€564M

Ref NASA CEH v4.0 §4.2 (Trade Studies) · ESA Moonlight industry day 2024

So what did we learn?

✓ **ESTIMATING IS ARGUMENTATION**
Every number is traceable to a specific page of New SMAD or NASA CEH v4.0. No magic.

✓ **P70 IS POLICY, NOT A GUESS**
The 70th percentile is the **NASA Agency Baseline Commitment**, written into CEH v4.0 §3.2.

€ **HIDDEN LEVERS EXIST EVERYWHERE**
Tightening the learning slope, sharing IA&T with Gateway, and bulk-buying thrusters with Moonlight cut **15.3%** off the LCC — without removing a single requirement.

✓ **MASS DRIVES COST — NON-LINEARLY**
Power-law CERs mean a 30% mass cut saves only ≈12% in cost. Payload complexity dominates.

! **THE RISK IS THE PAYLOAD**
89% of total cost variance comes from one TRL-5 element. Pre-PDR testbed: **2.7× ROI**.

→ **THE BIGGER PICTURE**
Cost engineering is the **quiet discipline** that lets ESA commit to missions five years in advance: the bridge between systems engineers and the project manager.

> *The €733M is not a forecast. It is the smallest budget that a rational Agency can **honestly** commit to **in public.***

NASA CEH v4.0 §3.2 (p. 40) – "It is policy that the JCL value be at 70 percent for the Agency Baseline Commitment (ABC), with a Management Agreement (MA) value of at least 50 percent."

Heritage cost engineering meets New Space

What if the LBN were built by a New Space prime instead of a traditional ESA contractor? Rough order-of-magnitude reference points from comparable systems:

APPROACH	LCC EST.	VS. LBN
Heritage *(this work)*	€666M	–
New Space prime (est.)	€220–300M	~0.4×
CubeSat constellation	€90–140M	~0.2×

Trade-off — lower cost is bought with higher risk acceptance, shorter mission life, and reduced redundancy. ***Cost reduction is never free.***

Why is space cost engineering different?

No serial production.
Three units, not three million. Parametric CERs replace cost accounting.

Mass and cost are coupled.
A kilogram saved in propellant becomes a kilogram available for revenue-bearing payload.

No field repair.
Failure modes are committed at launch. P70 commitment exists because P50 isn't safe enough.

End-to-end traceability →

Mass distribution New SMAD Table A-8 (p. 952) · **Δv & propellant** New SMAD §18.6 · **CERs NRE** Table 11-8 (p. 298) · **CERs Recurring** Table 11-9 (p. 299) · **Learning curve** Eq. 11-6 (p. 316) · **Inflation chain** Table 11-31 (p. 316) · **Heritage factors** Table 11-4 (p. 296)
NASA CEH v4.0: **WBS L2** Fig. 4 (p. 7) · **GR&A** §2.2.1 (pp. 11–14) · **Cost-risk & UFE** §2.3.2 (pp. 27–28) · **JCL @ P70 ABC** §3.2 (p. 40) · **Sensitivity** §4.1 (p. 42) · **Time-phasing** §2.3.1 (p. 26)