A novel approach for mapping Earth observation needs into prospective CubeSat mission concepts
PhD Thesis Defense

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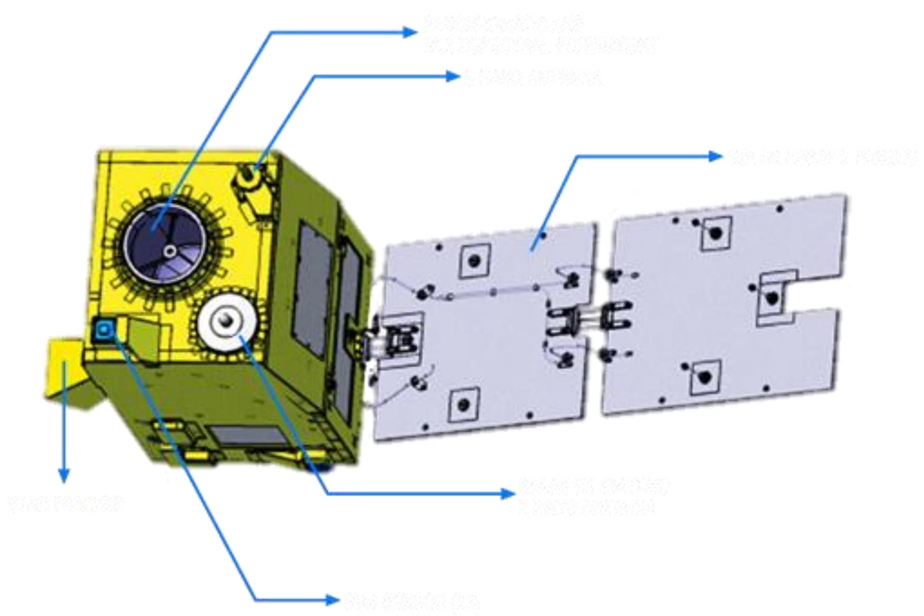
Don’t compare pears with apples

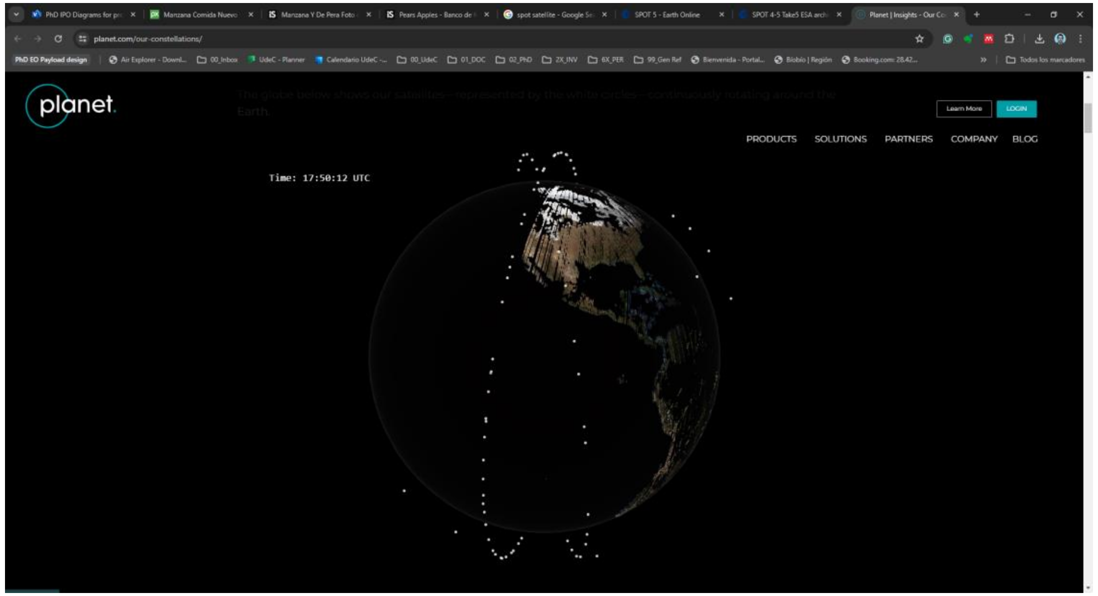
SSOT MS EO Chilean Satellite deployed 2011



- ~80 MUSD (FY2011) ->~146 MYSD (FY2024)*
- One 140 kg spacecraft (legacy Astrosat-100 bus)
  - 5.8 m res MS (3 bands VIS + 1 NIR)
  - ~1.4m res PAN
- Deployed by Soyuz from Kourou
- Small satellite by weight (< 180kg), not necessarily cost-effective

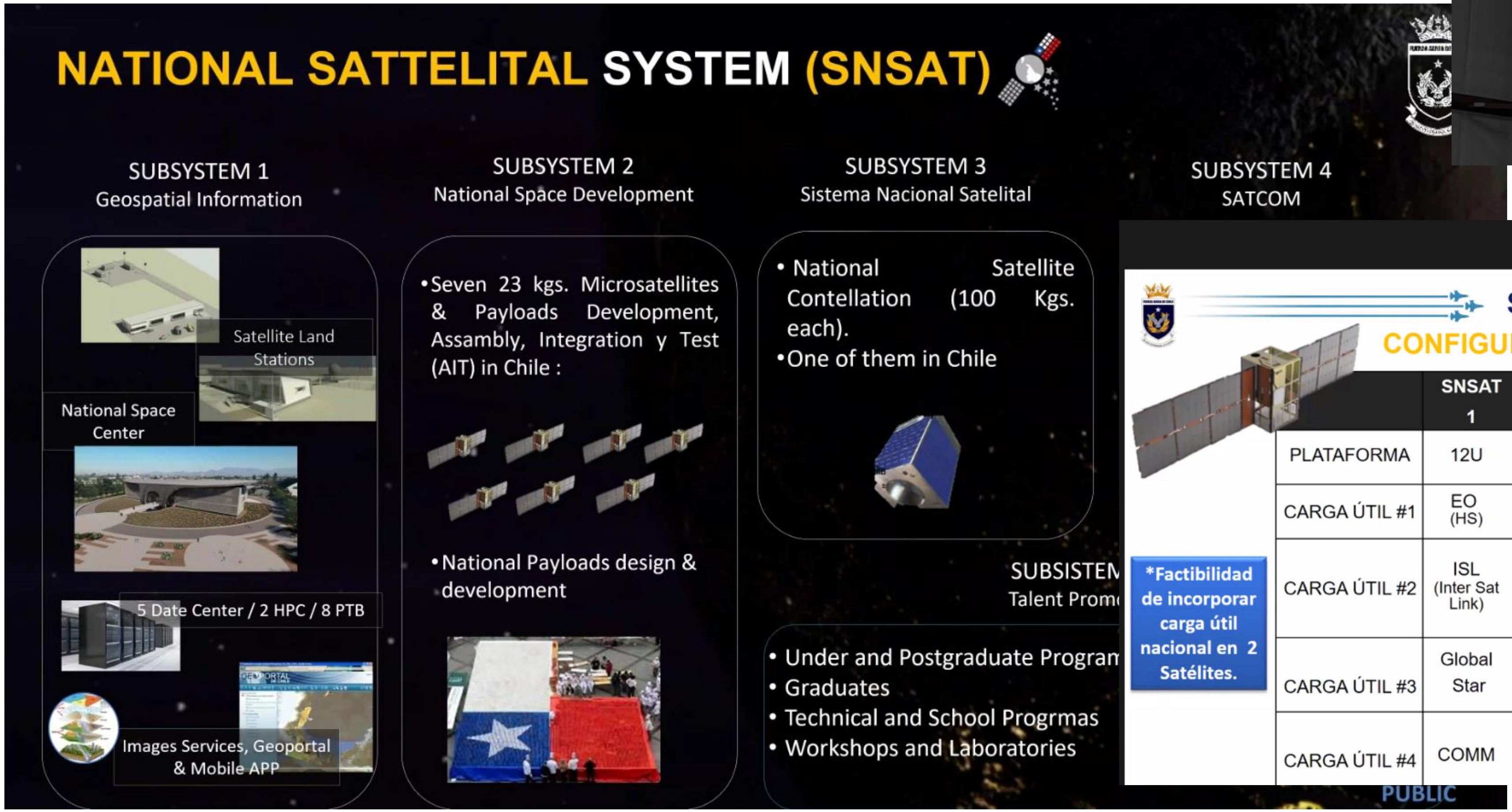
Planet founded 2010, DOVES 3 U CubeSats

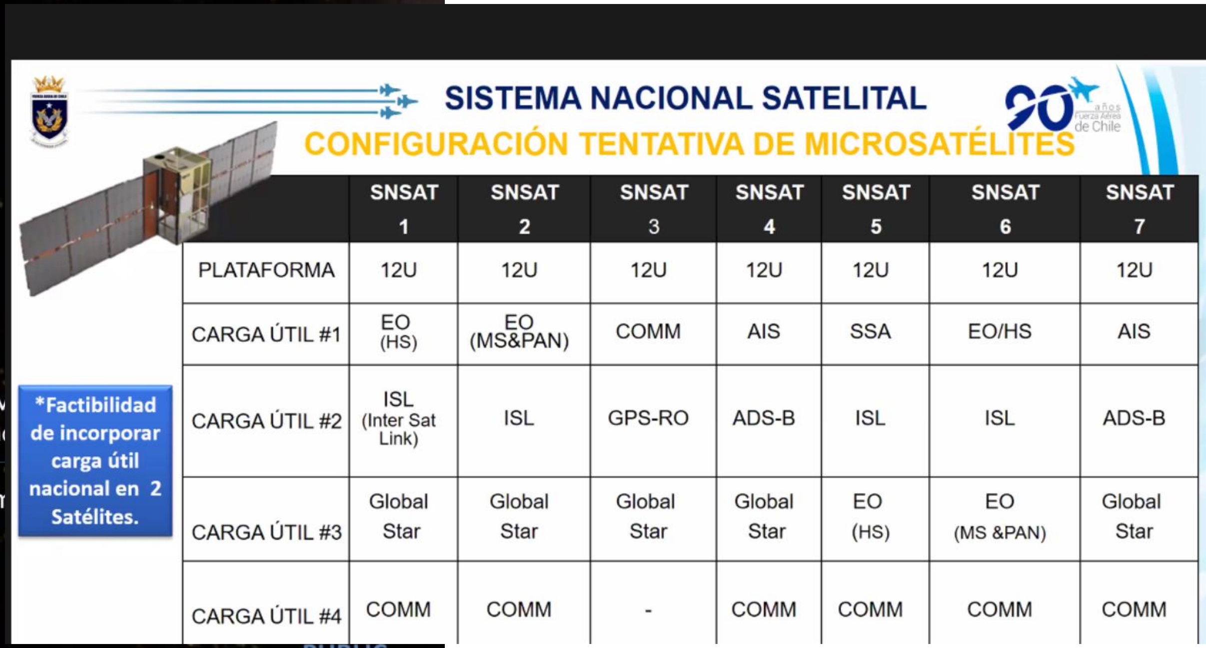
http://www.planet.com/our-constellations/



- ~150 active Spacecraft
- ~600 kUSD (FY2022) per satellite (Lopez et al. 2024)
- 3 to 5 m GSD
- Deployed since 2013 (592 to date (Nanosat.eu as of June 11th, 2024)

2021+ Chile SNSat program

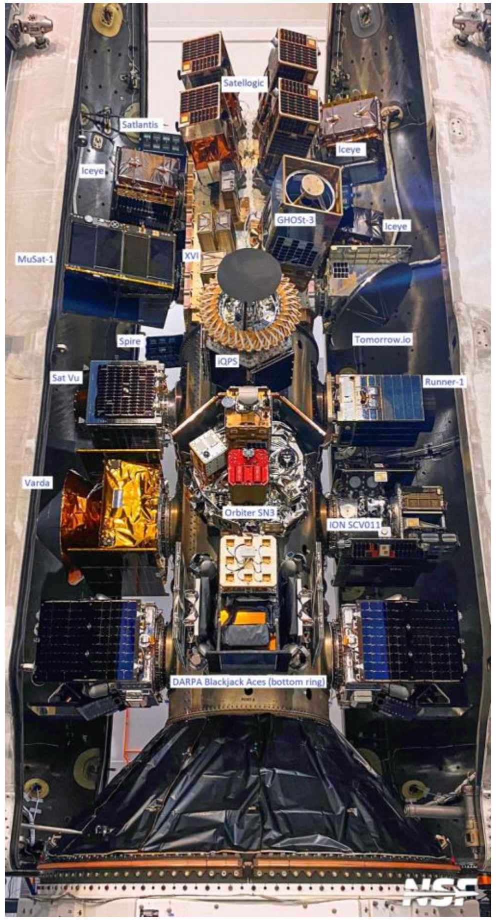




	SNSAT 1	SNSAT 2	SNSAT 3	SNSAT 4	SNSAT 5	SNSAT 6	SNSAT 7
PLATAFORMA	12U	12U	12U	12U	12U	12U	12U
CARGA ÚTIL #1	EO (HS)	EO (MS&PAN)	COMM	AIS	SSA	EO/HS	AIS
CARGA ÚTIL #2	ISL (Inter Sat Link)	ISL	GPS-RO	ADS-B	ISL	ISL	ADS-B
CARGA ÚTIL #3	Global Star	Global Star	Global Star	Global Star	EO (HS)	EO (MS &PAN)	Global Star
CARGA ÚTIL #4	COMM	COMM	-	COMM	COMM	COMM	COMM

Space-X Transporter-8 dedicated smallsat rideshare mission (June 12, 2023)

https://spacenews.com/spacex-launches-eighth-dedicated-smallsat-rideshare-mission/

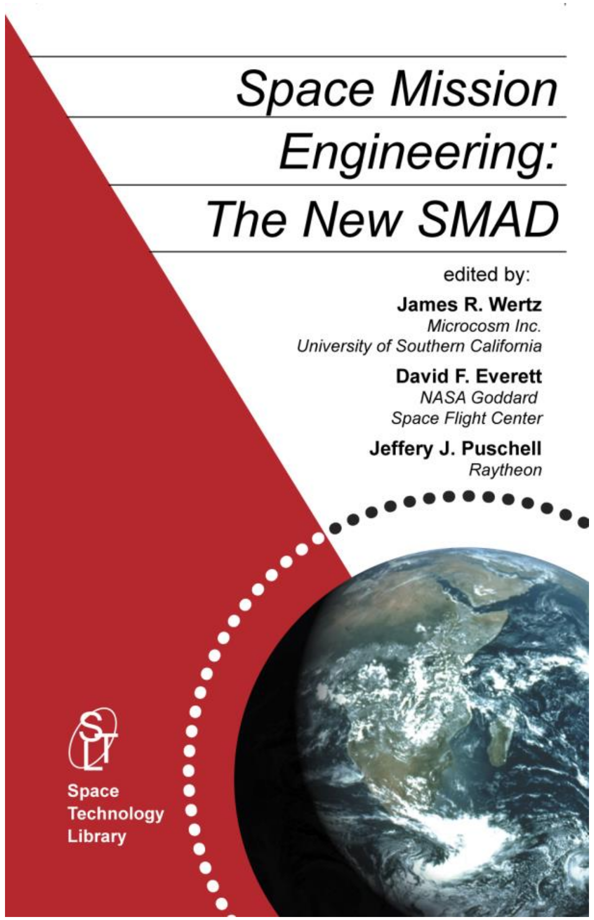


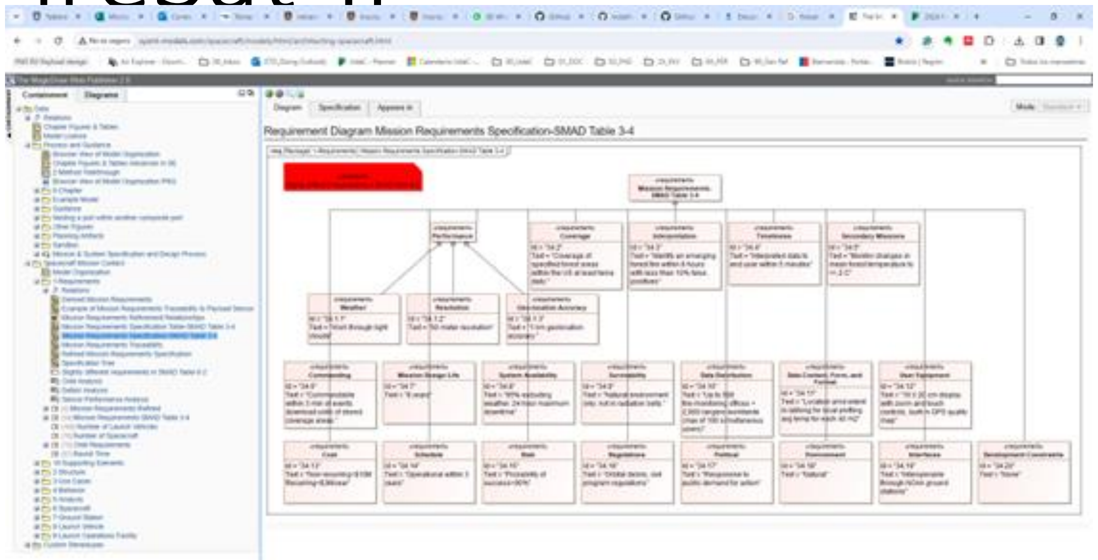
“Those who know how to count (most engineers) approach their design problems using analysis and optimization, powerful and precise tools derived from the scientific method and calculus. Those who do not (most architects) approach their qualitative problems using guidelines, abstractions, and pragmatics generated by lessons learned from experience — that is, heuristics”.

Eberhardt Rechtin

in “The art of systems architecture”, 2009

Case study inspired by FireSat-II



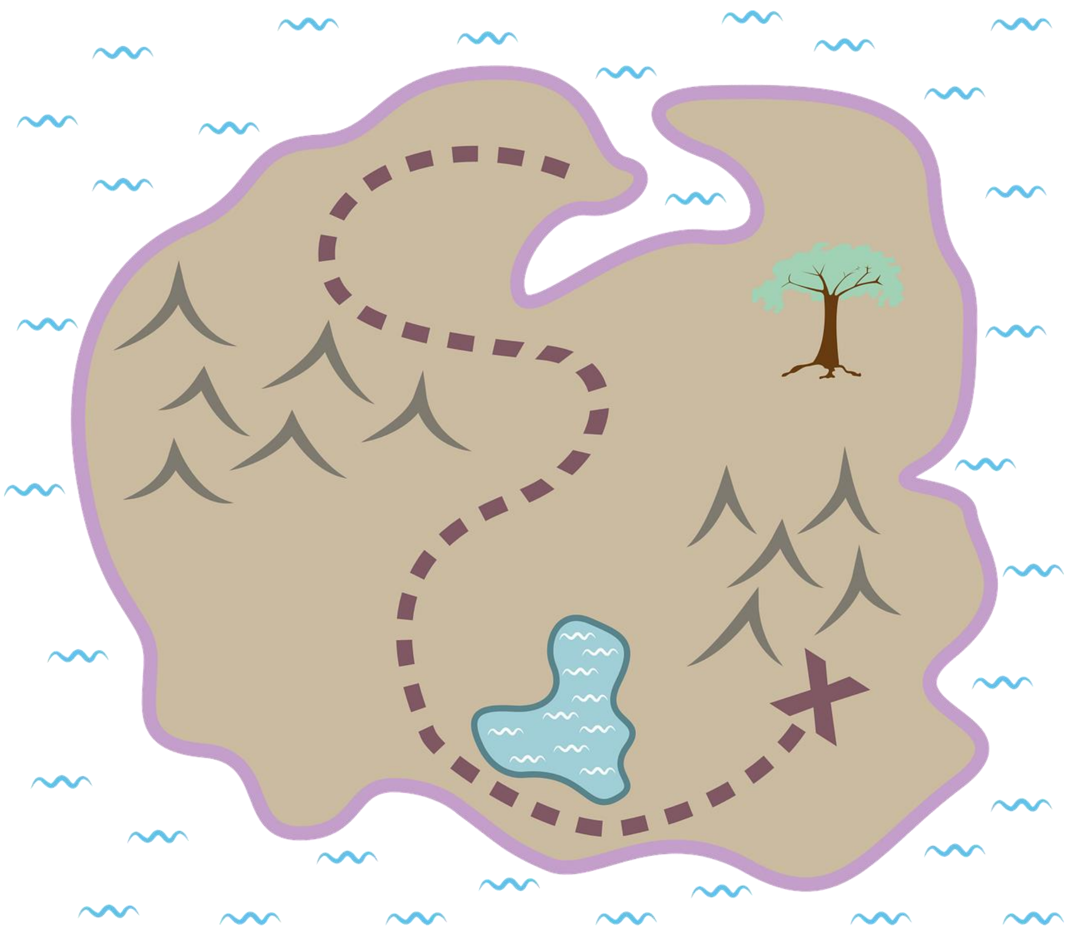


#	Id	Name	Text
1	34	Mission Requirements-SMAD Table 3-4	
2	34.1	Performance	
3	34.1.1	Weather	Work through light clouds
4	34.1.2	Resolution	50 meter resolution
5	34.1.3	Geo-location Accuracy	1 km geolocation accuracy
6	34.2	Coverage	Coverage of specified forest areas within the US at least twice daily.
7	34.3	Interpretation	Identify an emerging forest fire within 8 hours with less than 10% false positives
8	34.4	Timeliness	Interpreted data to end user within 5 minutes
9	34.5	Secondary Missions	Monitor changes in mean forest temperature to +/- 2 C
10	34.6	Commanding	Commandable within 3 min of events. download units of stored coverage areas.
11	34.7	Mission Design Life	8 years
12	34.8	System Availability	95% excluding weather. 24 hour maximum downtime
13	34.9	Survivability	Natural environment only. not in radiation belts.
14	34.10	Data Distribution	Up to 500 fire-monitoring offices + 2,000 rangers worldwide (max of 100 simultaneous users)
15	34.11	Data Content, Form, and Format	Location amd extent in lat/long for local plotting. avg temp for each 40 m2
16	34.12	User Equipment	10 X 20 cm display with zoom and touch controls, built-in GPS quality map
17	34.13	Cost	Non-recurring<$10M Recurring<$3M/year
18	34.14	Schedule	Operational within 3 years
19	34.15	Risk	Probability of success>90%
20	34.16	Regulations	Orbital debris, civil program regulations
21	34.17	Political	Responsive to public demand for action
22	34.18	Environment	Natural
23	34.19	Interfaces	Interoperable through NOAA ground stations
24	34.20	Development Constraints	None

1.- Introduction

1.- Introduction

- Present a novel approach for #mapping Earth observation needs into prospective nano-satellite mission concepts.
- By #concepts, we refer to scenarios where an initially feasible architecture concept, as for concept studies of a DSM based on CubeSats, can perform effectively and EO mission



https://pixabay.com/es/vectors/mapa-isla-mapa-del-tesoro-sendero-7367482/

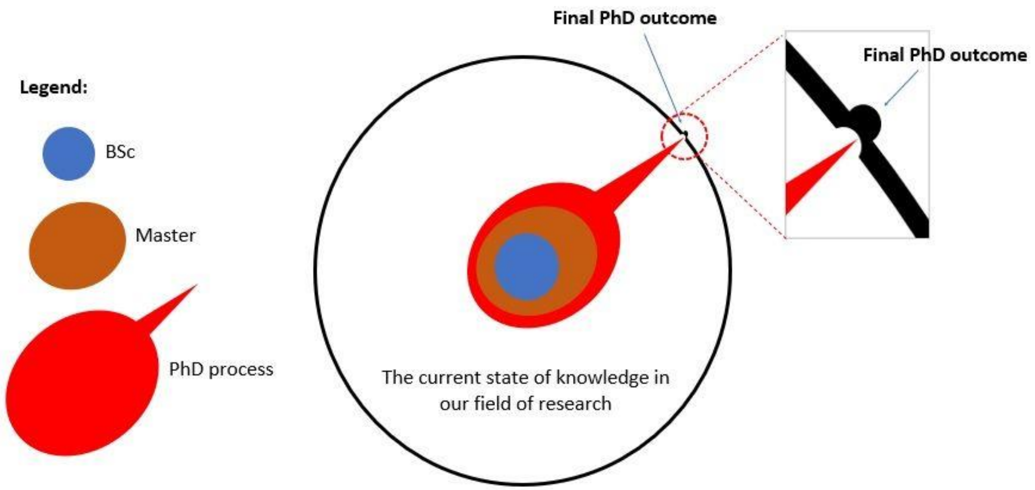
1.1 Conterxt

- a #CubeSat is a small satellite defined by a form factor and its interface to an orbital deployer
- The number of CubeSats has significantly risen since 2011, accounting for over 2000 satellites driven mainly by commercial player deploying their clusters, operating multiple spacecraft to fulfil a common goal.
- INPE's Small Satellite Division is interested in exploring CubeSat platforms as alternatives for attending their EO needs by taking advantage of the platforms and the philosophies for cost-effective access to space.

https://www.isispace.nl/product/3u-cubesat-bus/

1.2 Scope

- The scope of this work is CubeSat-based Distributed Spacecraft Missions in low Earth orbit for Earth observation missions in the visible and near-infrared spectrum. CubeSats play a relevant role in earth observation due to a combination of the standardised interface, reduced launch costs, shorter development times, and availability of commercial off-the-shelf (COTS) components.



https://www.wasyresearch.com/what-is-the-essence-of-phd/

Goals

- Get a better understanding of CubeSat distributed system cost-effective design philosophies -> <u>i.e. extract heuristics</u>
- <u>Provide support tools, and parametric models for the sizing </u>of CubeSat-based DSM architecture concepts (up to CML 3),
  - specifically systems engineering envelopes available for the payload design process (N_unitsits – Bus_Envelope).
  - Payload design is not in the scope, yet the envelope of the bus and cost will be valuable inputs for payload subject matter experts
- Supporting the <u>development of frequent missions </u>to counteract the space spiral
- Extend the application of this approach by:
  - **Constraining the search space**
  - Developing a heuristic
  - Communicating to developers
  - Propose future steps for generalizing to more applications (like IoT/telecoms)

1.3 Objectives – main objective

Develop a heuristic for the conceptual design of a CubeSat-based distributed spacecraft mission, which could eventually replace traditional low Earth orbit monolithic satellites.

1.3 Objectives – specific objectives

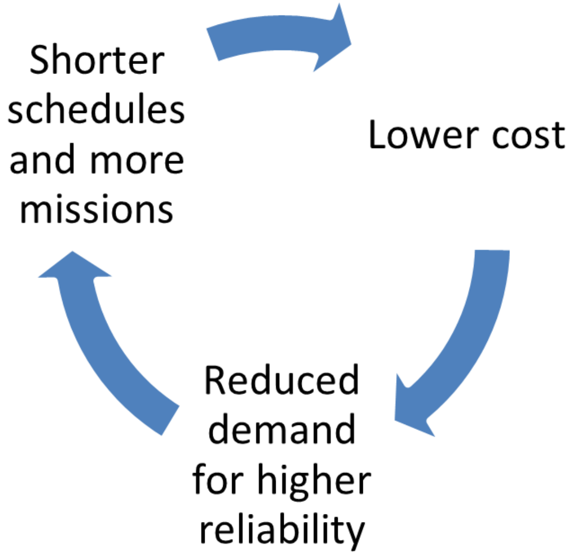
1. Identify three small satellites design practices and philosophies for achieving cost-effective space missions, specifically CubeSat ones.

2. Develop a test case of a CubeSat-based distributed spacecraft mission (DSM) architecture for FireSat II.

3. Integrate parametric sizing models (rough order of magnitude) for Earth Observation (optical) payloads in relevant orbits for CubeSat missions.

1. 4 Novelty, generality, and utility

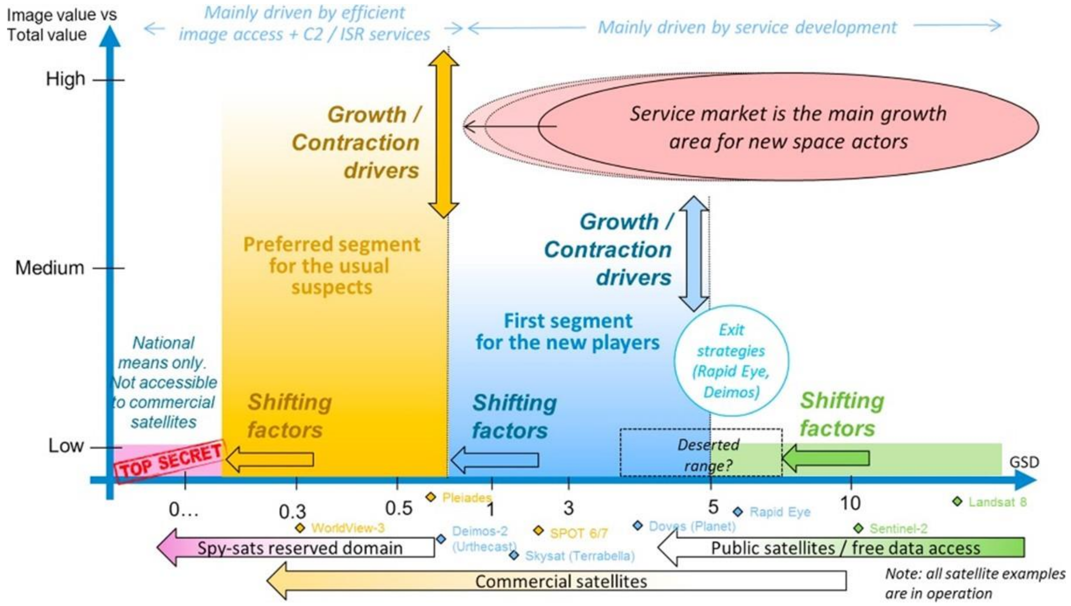
- There is a gap in data for LCC models for mass below 20 kg (Nag et al. 2014, Mrozinski 2019),
- CubeSats are “flexible” in their orbit
- strategy implemented here constrains the options to the one where CubeSats have been deployed in the past two decades due to the cost and availability of launch vehicles. This significantly simplifies the orbital trade space and imposes a margin or range requirement over the payload, the links, and other orbital-dependent parameters.
- Thus, this work contributes to the body of knowledge by **providing a heuristic, complimentary parametric models, and a set of constraints for the solution search space based on the analysis of previous missions, interviews with developers and mission design and analysis.**



2 FUNDAMENTAL CONCEPTS AND STATE OF THE ART

2.1 Earth observation trends

Figure 2-1 Earth observation market evolution. Source: (DENIS et a.l., 2017)



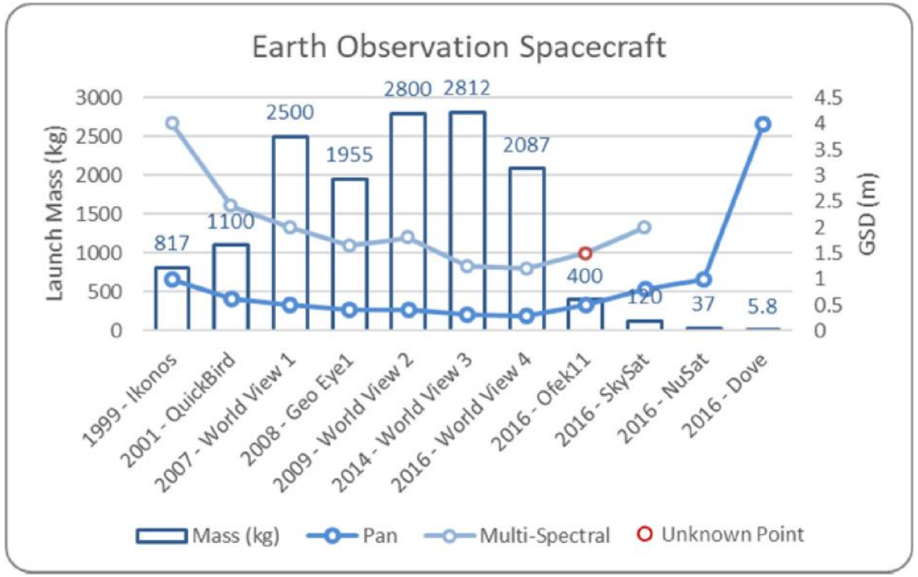


Figure 2-3 Earth observation spacecraft through the years. Source: (KOPACZ et al. 2020, fig.6)

2.2. Brazil’s Earth observation needs

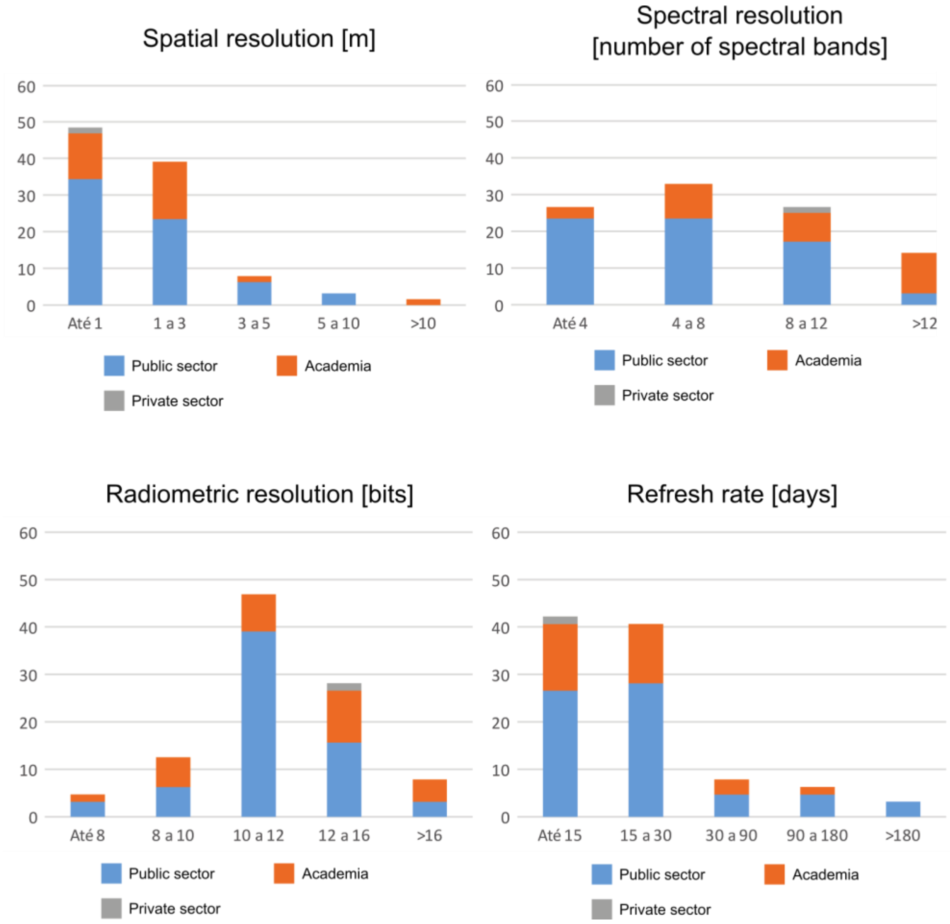


Figure 2-4 Optical Earth observation payload needs of the Brazilian space community for an optical high-resolution sensor. Source. (AEB 2019, p 50)

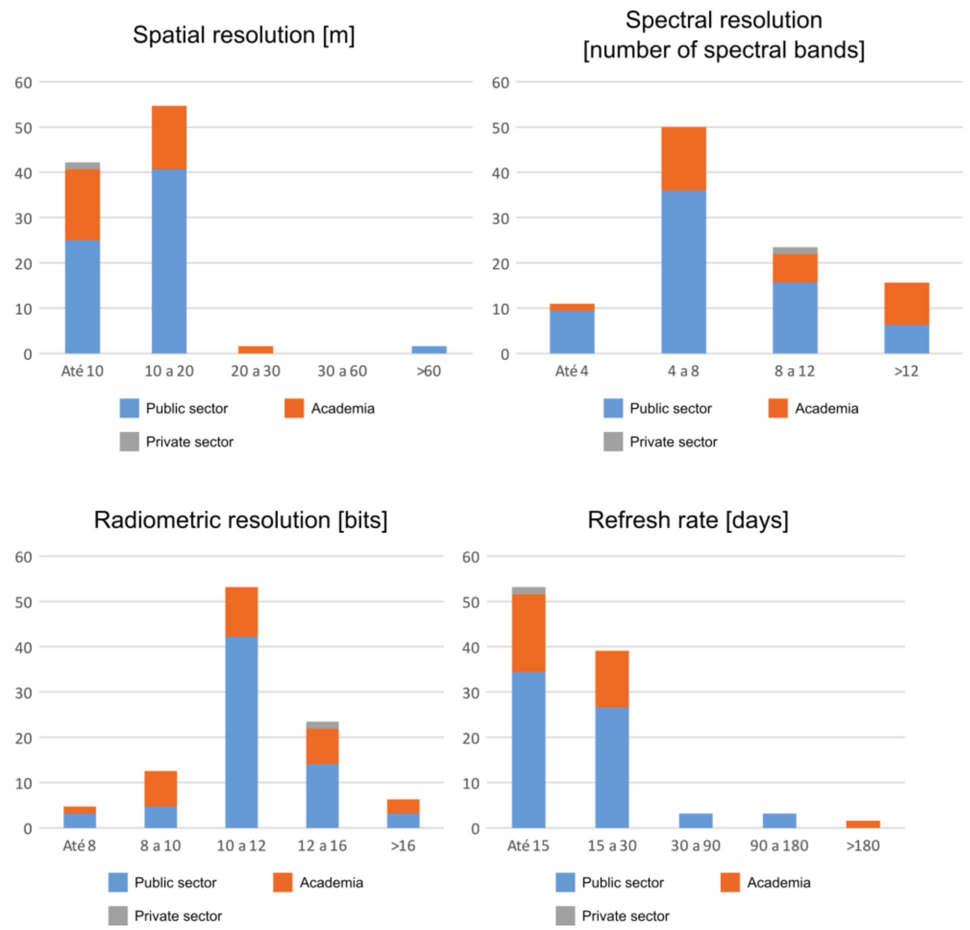


Figure 2-5 Optical earth observation payload needs of the Brazilian space community for an optical medium resolution sensor. Source: (AEB 2019, p 51)

“Catch up”?

How a Brazilian actor, such as INPE, can leverage the development of small satellites, especially CubeSats, to supply data in the spatial, radiometric, spectral, and temporal resolution required by the country’s organization?

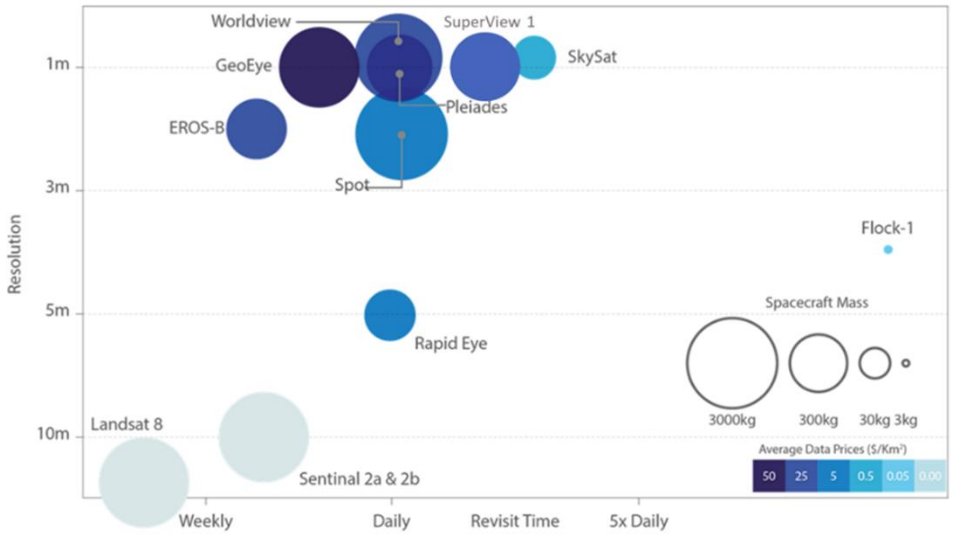


Figure 2-6 Ground Sample Distance, re-visit time, and price for Earth observations images. Note Flock-1 represents the first of Planet 3U CubeSats. Source: (ESA, 2020b)

2.3 Small satellites and CubeSats

Table 2-2 Extract of relevant satellite classes using mass and size as main attributes of identification.

Class Name	Mass (kg)	Subclass type	Mass (kg)		Size
		Light	[1000 - 3000[		Medium
Mini	[100 - 1000[	Heavy	[500 - 1000[		
		Intermediary	[180 - 500[		Small
		Light	[100 - 180[		
Micro	[10 - 100[	Heavy	[60 - 100[		
		Intermediary	[25 - 60[		
		Light		[10 - 25[	
		Cubesat	12U		
Nano	[1 - 10[			[8 - 10[	
			6U	[6 - 7.99[	
			3U	[3 - 3.99[	
			2U	[2 - 2.66[	
			1U	[1 - 1.33[	

Note small satellites in the scope of this thesis are highlighted in grey. Source: Adapted (A. S. BOTELHO; ADEMIR L., 2019, p. 68).

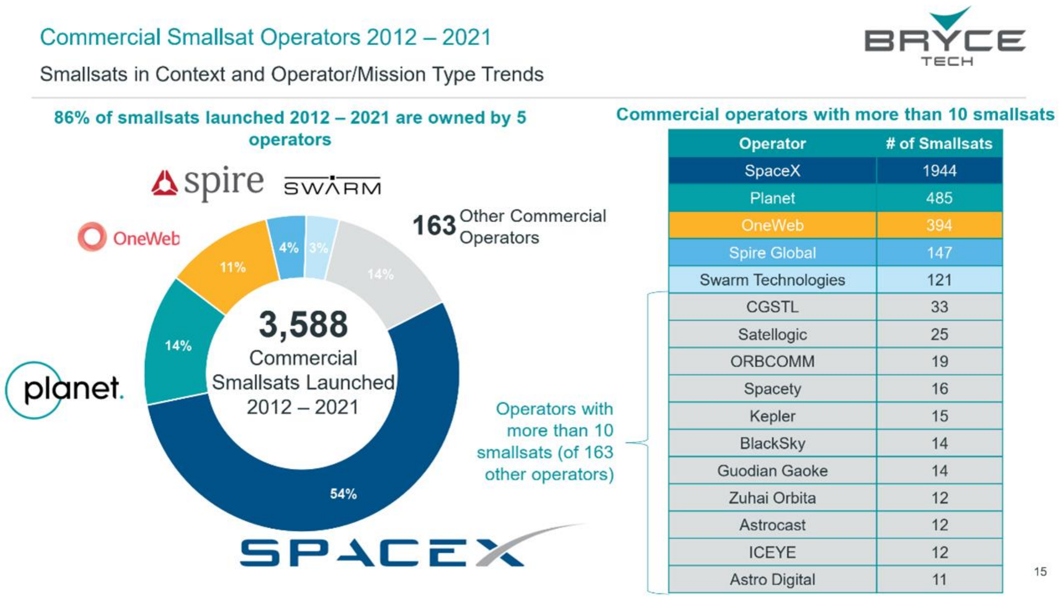


Figure 2-8 Commercial small sats (below 500 kg) launched between 2012 and 2021.
Source: (BRYCE SPACE AND TECHNOLOGY, 2022, p. 15).

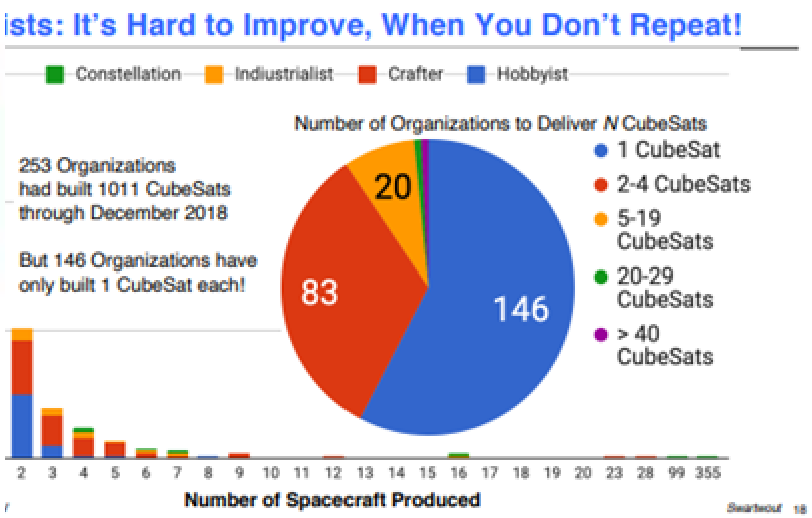
2.3. 3 CubeSat reliability and evolution

Figure 2-22 CubeSats success and failure rates. Source: (CERVONE et al., 2023, fig. 5)

Source: (SWARTWOUT, 2020a, p. 15).

lumber of spacecrafts per organization.

ellation; Orange: Industrialists; Red: Crafter; Blue: Hobbyist.



Source: (SWARTWOUT, 2020a, p. 18).

CubeSat capabilities

- Cubesat capabilities have increased significantly since the proposal of the standard in 1999, a set of surveys has been published looking into different aspects (BOUWMEESTER; GUO, 2010a; POGHOSYAN; GOLKAR, 2017a; SELVA; KREJCI, 2012; SWARTWOUT, 2013a)
- *"The dramatic increase in the number of CubeSat missions over the last few years combined with their short development times indicate that* ***surveys older than 3–4 years miss most of significant CubeSat developments."*** (POGHOSYAN; GOLKAR, 2017b)

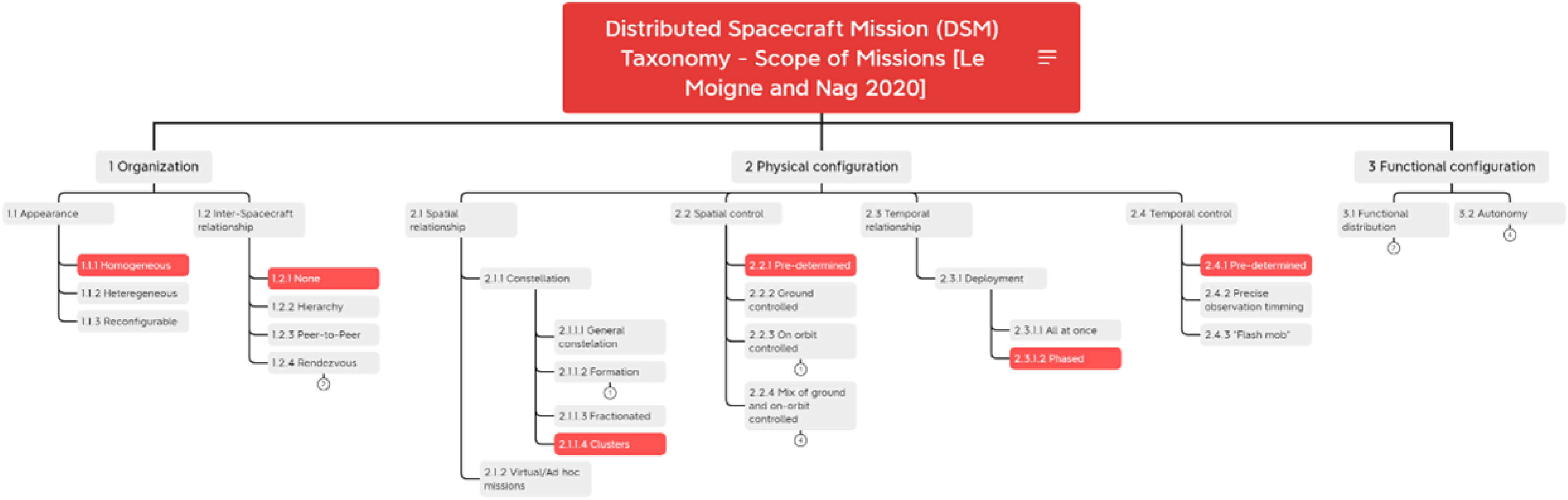
2.3.3 CubeSat reliability

- A positive trend was observed in the success rate from 2010 onwards (Swartwout 2013a).
- The sharp increase in the number of CubeSats deployed required more in-depth statistical analysis (such as Villela et al. (2019) and Swartwout's (2024) CubeSat census.
- NASA held a small satellite reliability initiative in 2017-2018, stating their concerns regarding the lack of data on CubeSat reliability

2.3.3 CubeSat reliability

- **The success rate or the reliability is not well documented yet, Bouwmeester et al. and Langer et al. (BOUWMEESTER; LANGER; GILL, 2017a; LANGER et al., 2017) deal with this and are relevant to assess the current capabilities of CubeSats, as their evolution cycle is faster than that of the traditional space industry.**
- Faure et al. (2017) discuss the high rate of infant mortality and attribute it to ground testing not being carried out sufficiently.
- Swartwout (2020a)
  - Systems engineer, mid-sized contractor: "more than 90% of the failures I see on the ground or in space are not parts-related"
  - Some characteristics and features for success
    - Process, process, process
    - Development schedule with significant functional testing and margin
    - Organisational robustness to staff turnover and mission failure

2.4 Distributed Satellite Systems (DSM)



2.4 Distributed Satellite Systems (DSM)

1 Organization	1.1 Appearance	**1.1.1 Homogeneous** Constellation or Formation	A DSM whose member spacecraft employ functionally identical bus, payload, and operational characteristics
	1.2 Inter-Spacecraft Relationships	1.2.1 None	This describes a DSM with no or no specific inter spacecraft relationships.
2 Physical Configuration	2.1 Spatial Relationship	2.1.1 Constellation	**2.1.1.4 Cluster** A collection of spacecraft that is not uniformly distributed over a particular spatial region, in contrast to a Walker constellation.
	2.2 Spatial Control	**2.2.1 Pre-Determined**	**This describes missions that do not have any specific spatial control, except the one predetermined before launch.**
	2.3 Temporal Relationship	2.3.1 Deployment	**2.3.1.2 Phased Deployment:** A phased deployment of a constellation is often employed for very large constellations or for mega-constellations. In this case, individual or groups of spacecraft are launched incrementally by design.
	2.4 Temporal Control	2.4.1 Pre-Determined:	This term characterizes missions for which the measurement acquisition is predetermined, and no specific temporal control is required after launch.

2.5.3 Concept Maturity Level (CML) Scale

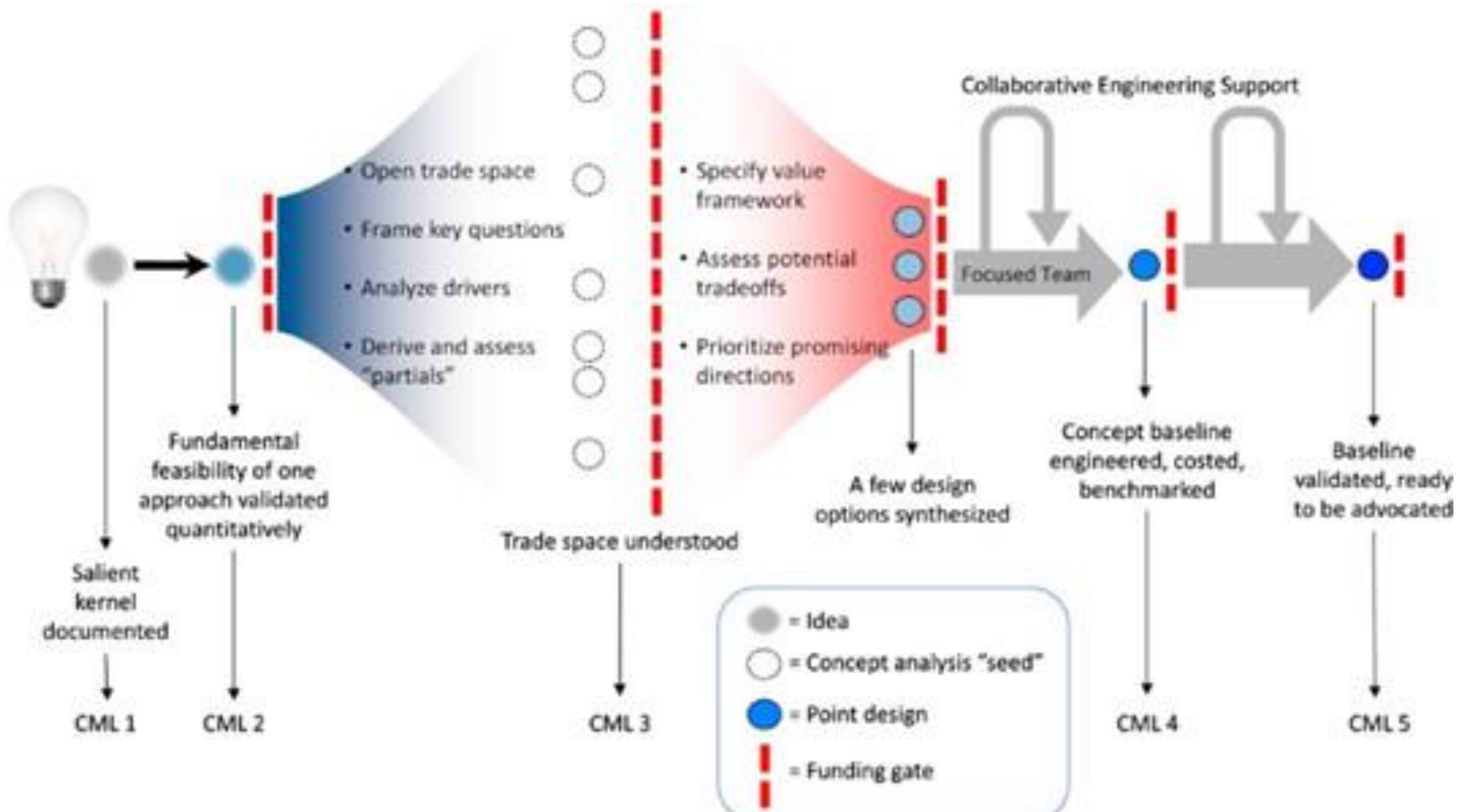


Figure 2 37 Concept maturity level idea evolution. Source: (SHERWOOD; MCCLEESE, 2013, fig. 5).

2.6 Reducing space mission cost

Figure 2 39 The space spiral significantly contributes to increasing costs and longer schedules. Source (WERTZ; EVERETT; PUSCHELL, 2011b, fig. 1–2)

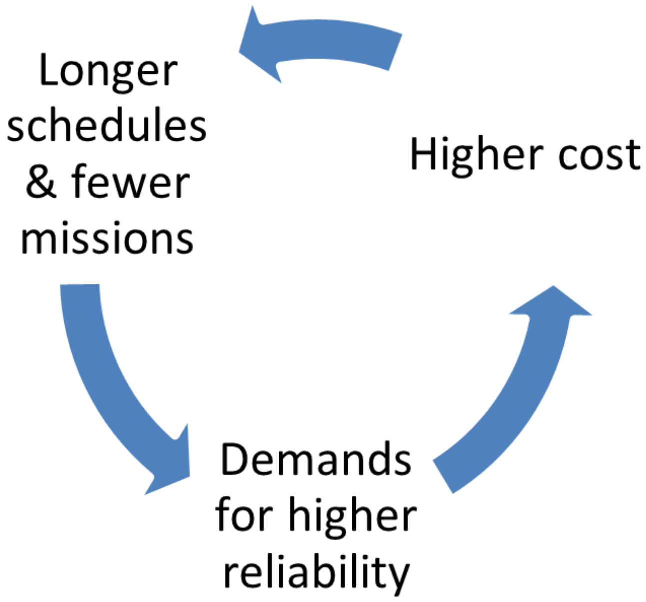
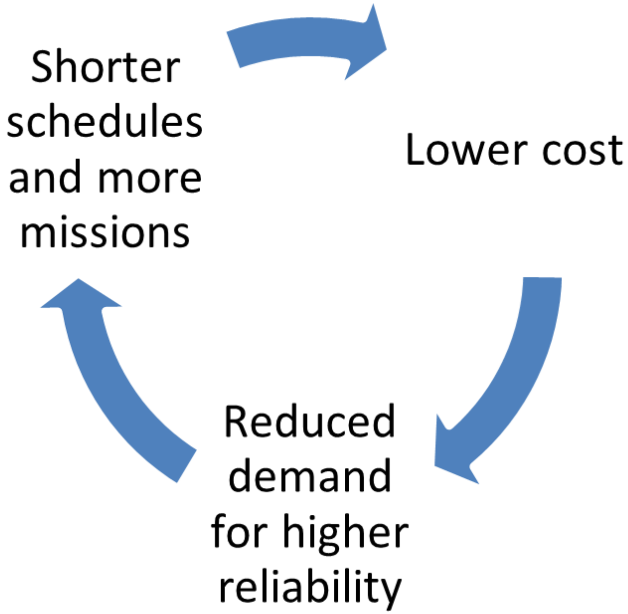
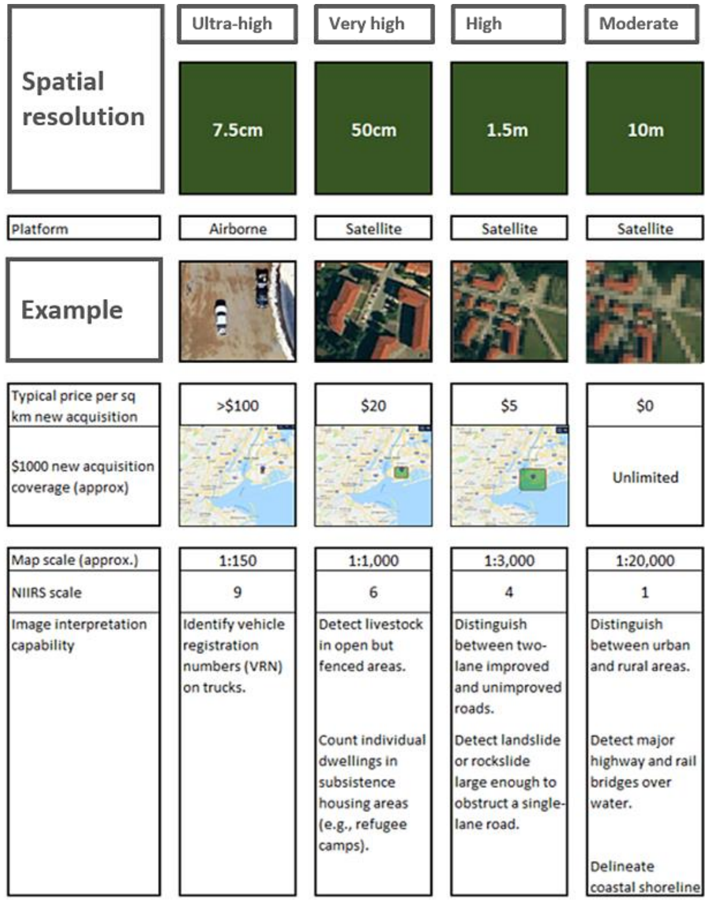


Figure 2 40 Principal methods for reducing costs and schedules. Source: (WERTZ; EVERETT; PUSCHELL, 2011b, fig. 13–5).



2.7 Earth observation payload design

- 2.7.1 Spatial resolution relations – **Can we observe the phenomenon of interest?**
- Relations are based on the work by Valenzuela & Reyes (2019b) regarding spatial resolution metrics. They assume nadir imaging and provide the basics for the performance comparison of different spacecraft.



Spatial resolution	Ultra-high 7.5cm	Very high 50cm	High 1.5m	Moderate 10m
Platform	Airborne	Satellite	Satellite	Satellite
Example				
Typical price per sq km new acquisition	>$100	$20	$5	$0
$1000 new acquisition coverage (approx)				Unlimited
Map scale (approx.)	1:150	1:1,000	1:3,000	1:20,000
NIIRS scale	9	6	4	1
Image interpretation capability	Identify vehicle registration numbers (VRN) on trucks.	Detect livestock in open but fenced areas. Count individual dwellings in subsistence housing areas (e.g., refugee camps).	Distinguish between two-lane improved and unimproved roads. Detect landslide or rockslide large enough to obstruct a single-lane road.	Distinguish between urban and rural areas. Detect major highway and rail bridges over water. Delineate coastal shoreline

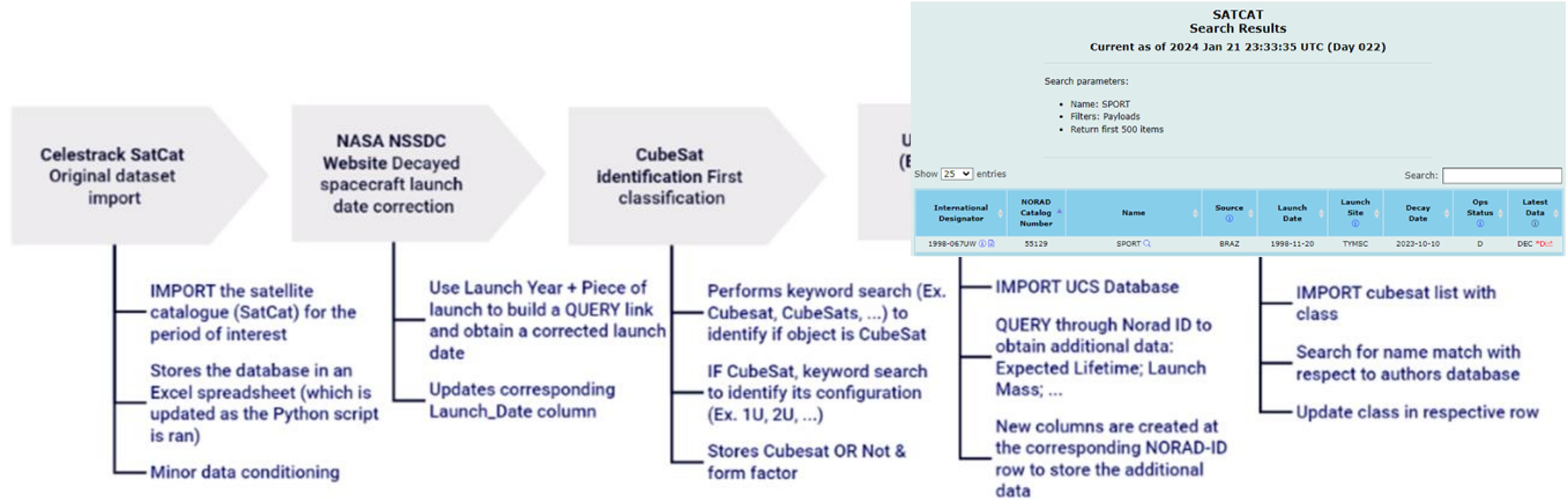
https://knowledgebase.geocento.com/knowledge/what-does-resolution-in-imagery-mean

2.8 Summary

- Small sats and CubeSats cannot be only defined by mass; their risk approach and design philosophies must be included
- Cost-effective is preferred over low-cost
- Existing cost models are very US and NASA-centric
- CSRM promises to be a relevant tool as a baseline for point design (i.e. CML 4 onwards)
- CML scale served as an inspiration
- The main difference between the approach towards mission design identified in literature was the extensive trade space exploration. The approach in this thesis looks to constrain the solution search trade space to reduce the cycle time (i.e. fast delivery) and achieve cost-effective concepts.

3 CubeSat cost-effective design practices and principles

3.1 CubeSat classification over two decades
3.1.2 Automated data-gatering tool developement



SATCAT
Search Results
Current as of 2024 Jan 21 23:33:35 UTC (Day 022)

Search parameters:

- Name: SPORT
- Filters: Payloads
- Return first 500 items

Show 25 entries Search:

International Designator	NORAD Catalog Number	Name	Source	Launch Date	Launch Site	Decay Date	Ops Status	Latest Data
1998-067UW	55129	SPORT	BRAZ	1998-11-20	TYMSC	2023-10-10	D	DEC

3.1.4 CubeSat clasification results - highlihgts

Fig 3-7

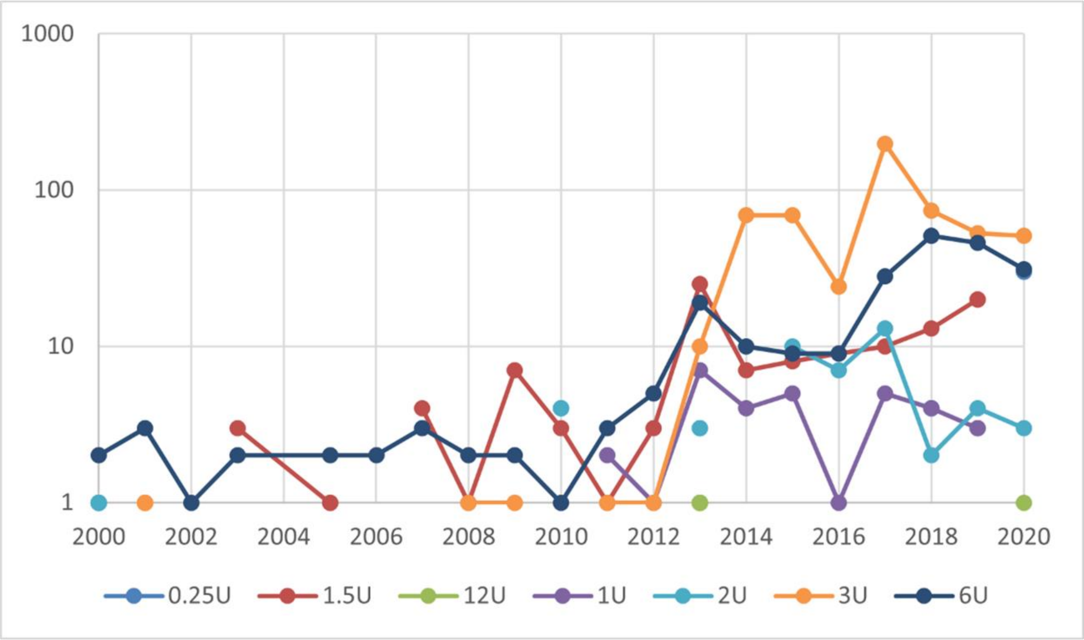
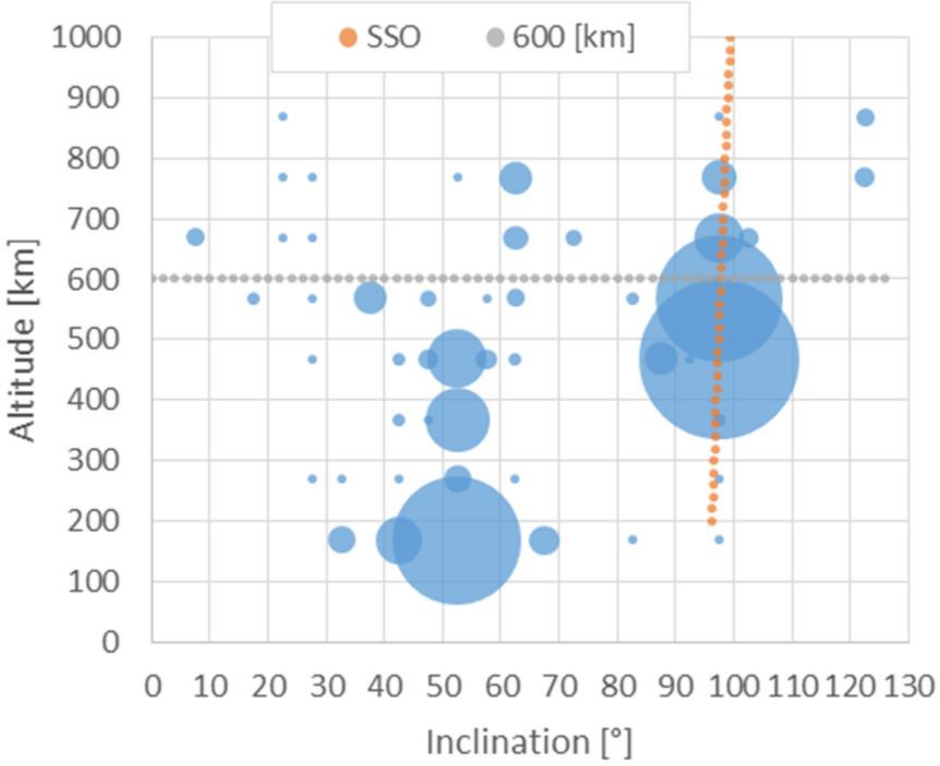


Fig 3-8



3.1.4.2 Life-Cycle Cost estimation / Planet

- Data on investment rounds was available for Planet and Spire 3U
- It assumes all to be non-recurrent costs, and that all the investment is used to grow the cluster
- Includes investments in the ground segment
  - Planet 45 ground stations
  - Spire 30+ ground stations

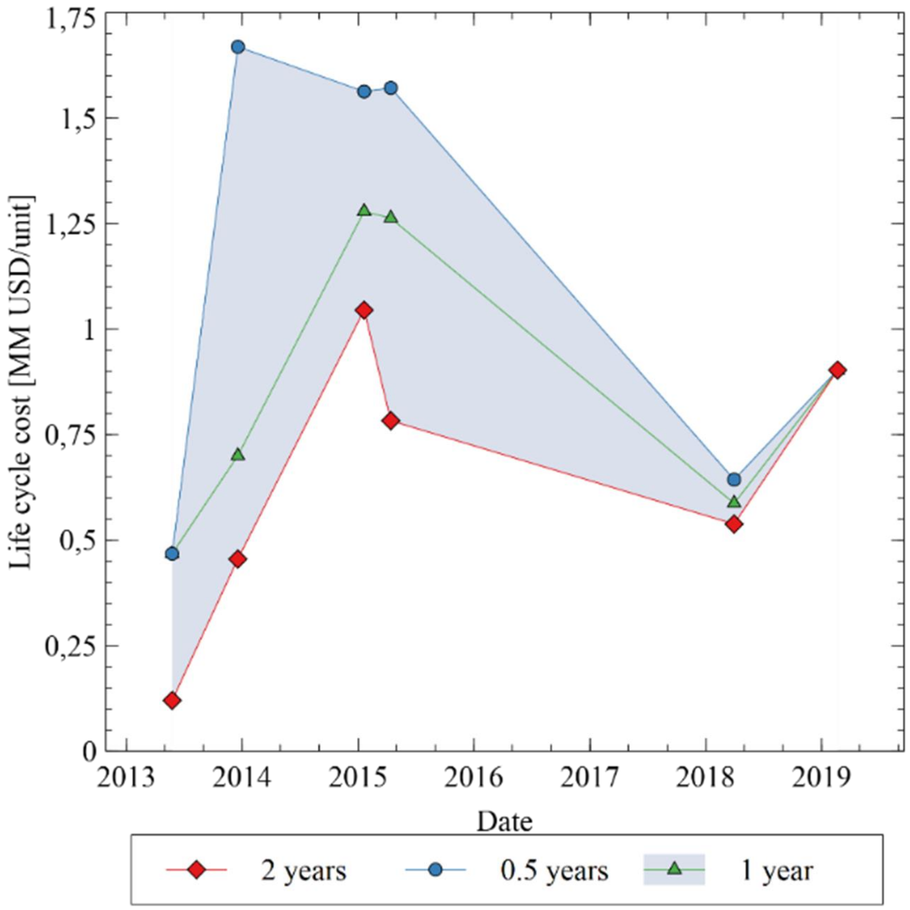


Fig 3-10 LCC for Planet CubeSats

3.1.4.2 Life-Cycle Cost estimation / SPIRE

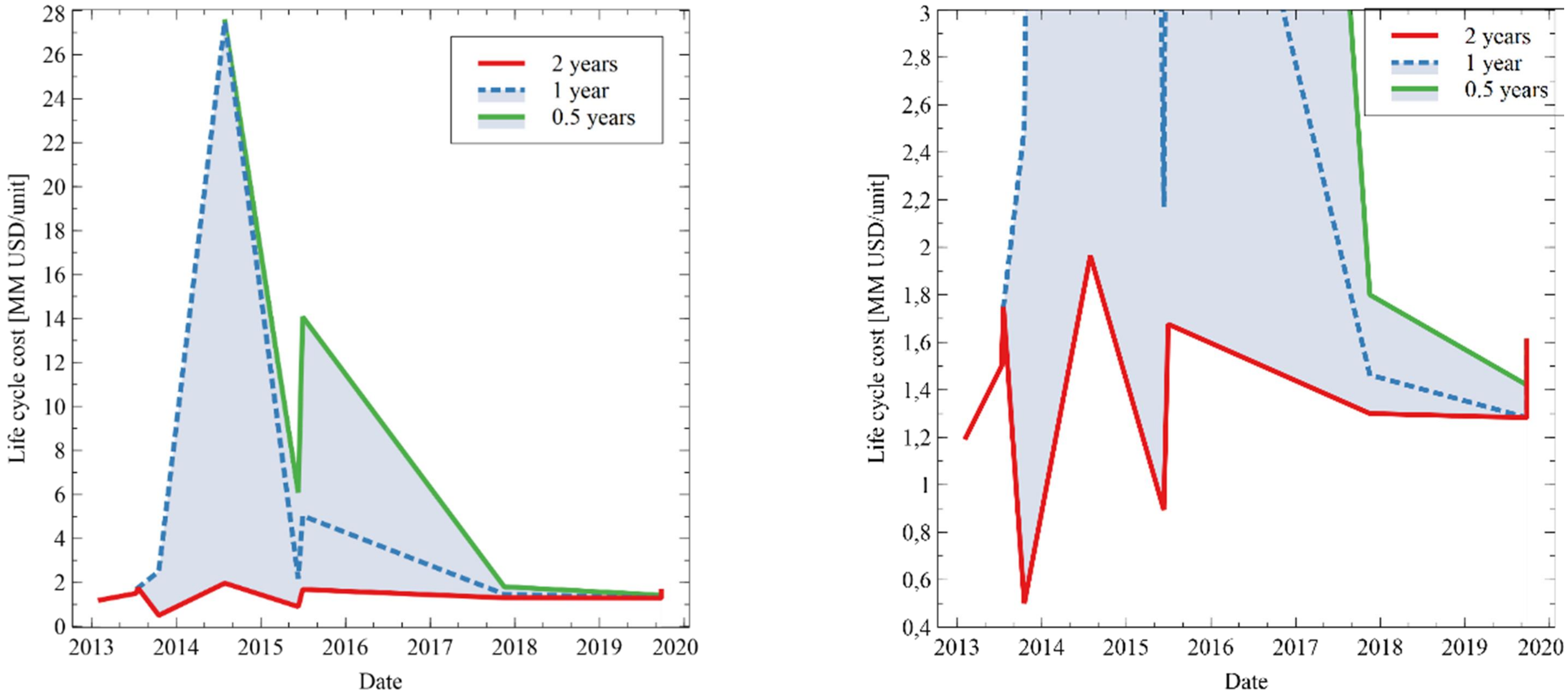
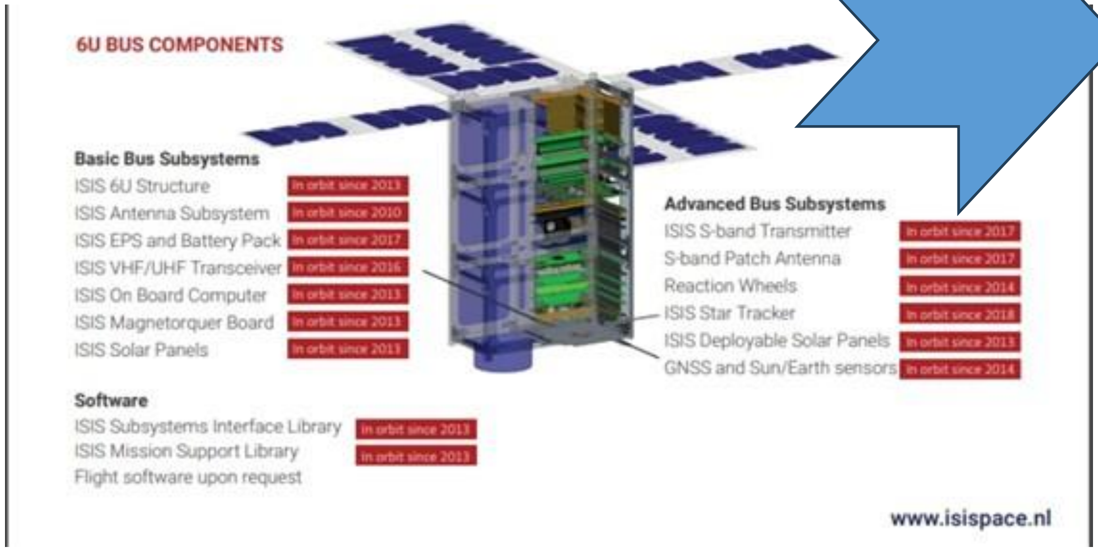
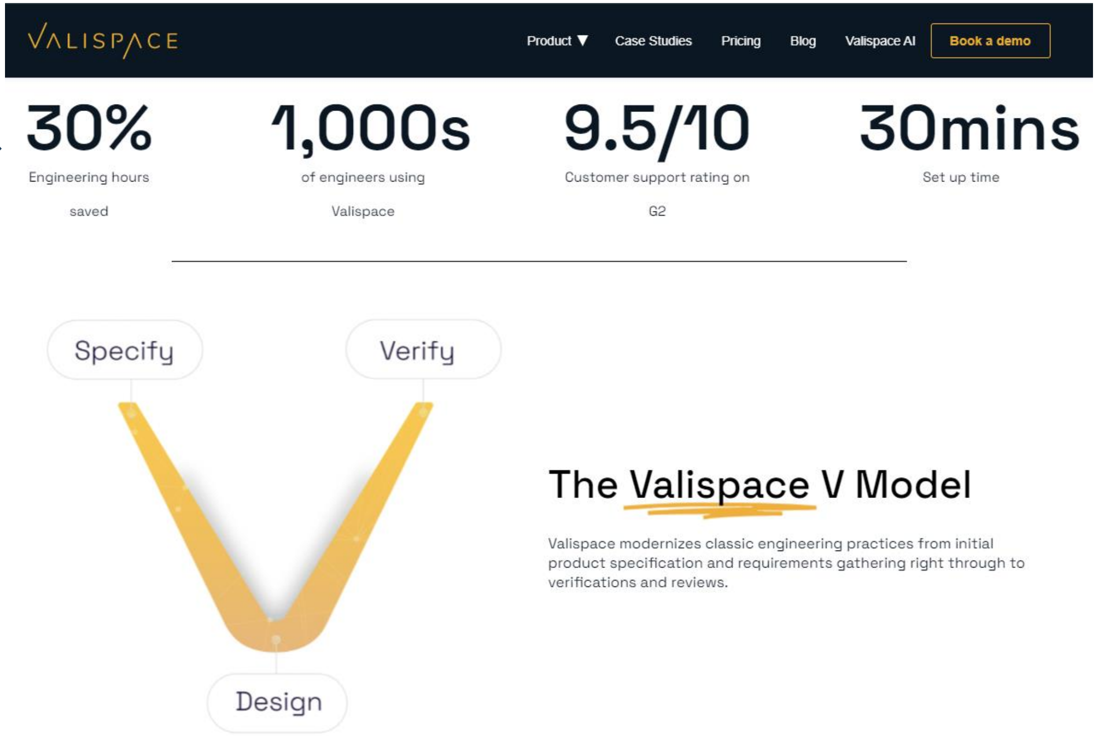


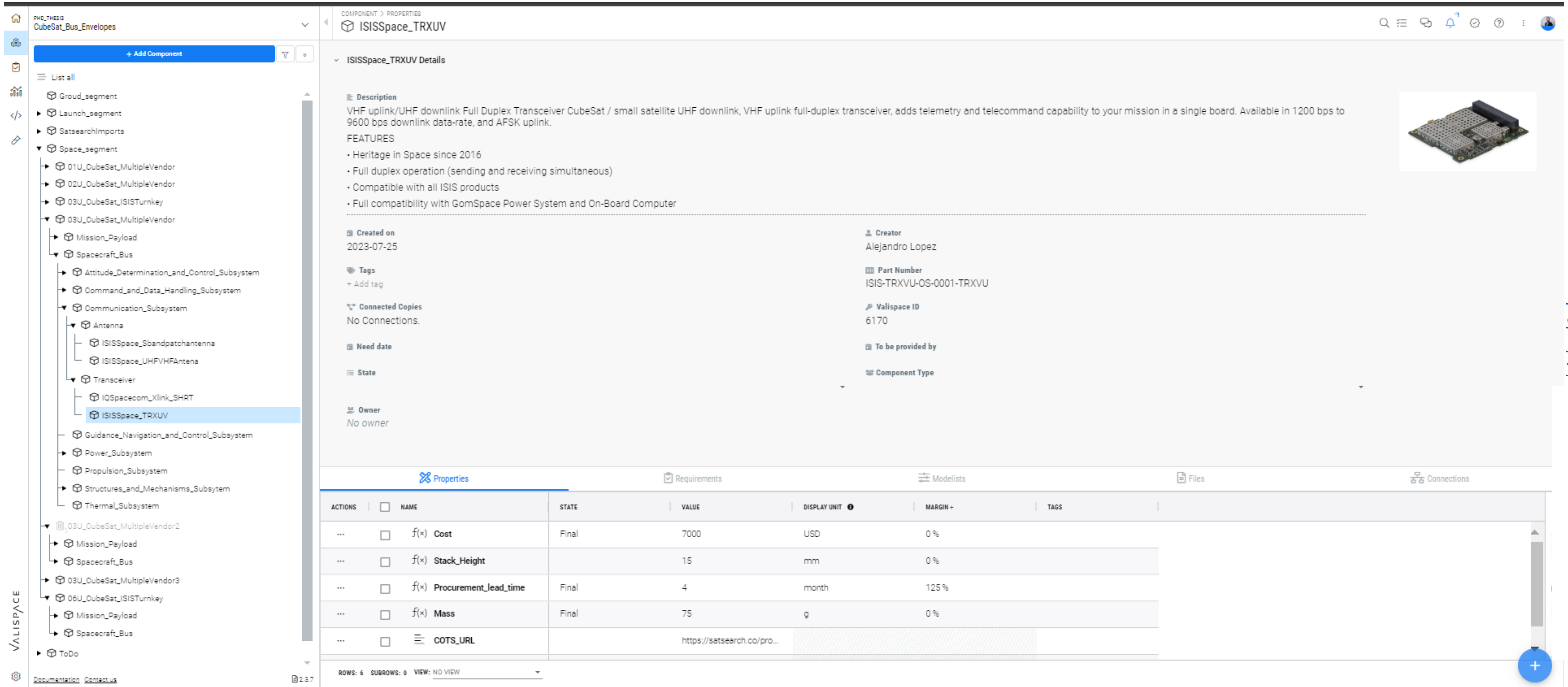
Fig 3-11 LCC estimations for Spire CubeSats

Valispace: from data sheet to model





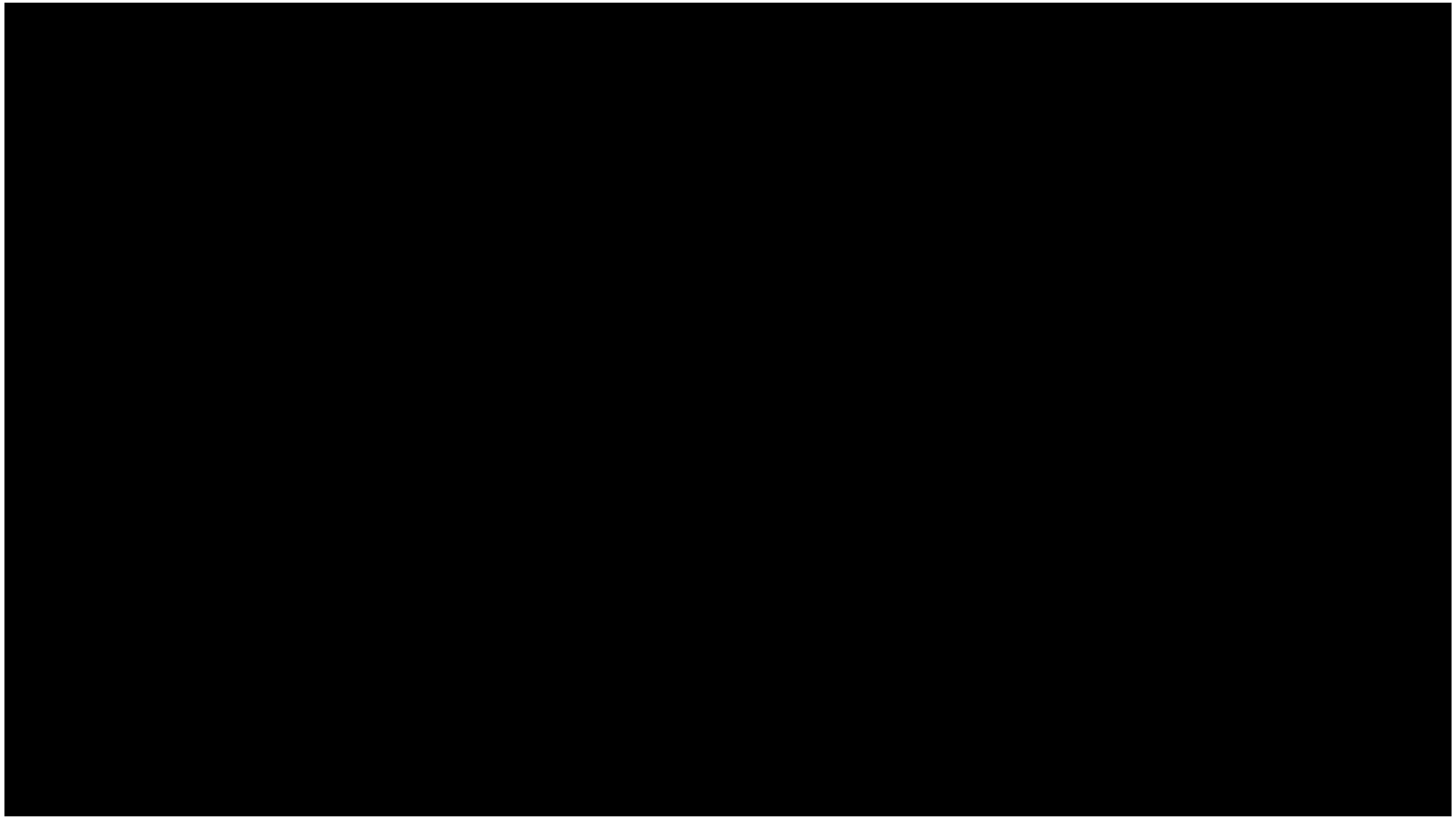
3.2 CubeSat SE envelopes from COTS (in Valispace) - INPUT



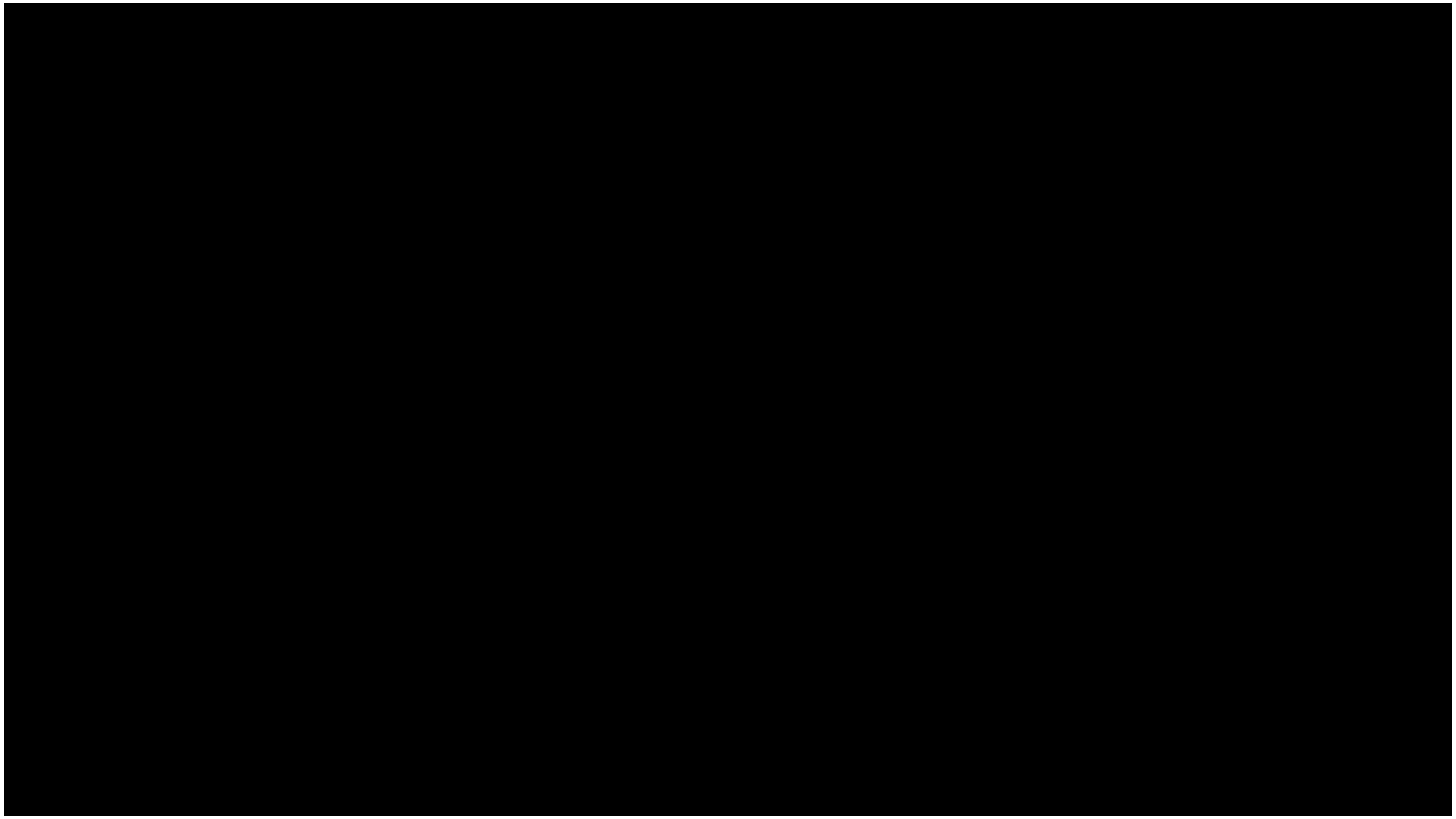
https://udec-chile.valispace.com/project/116/components/6170/properties

Valispace component input

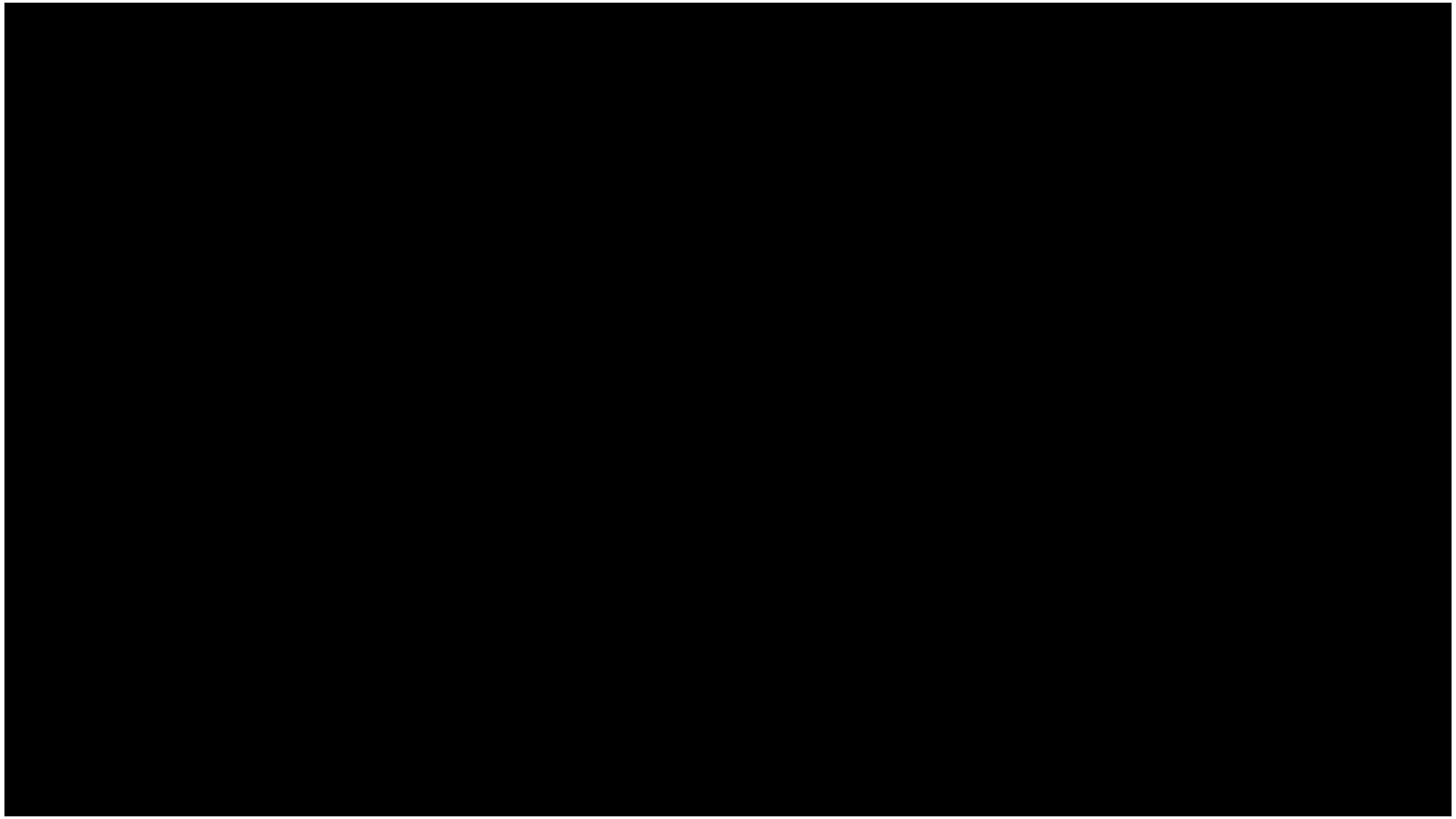
Valispace PBS and input at component (video)



Satsearch to Valispace export (Video)



Valispace Reports and analysis (video)



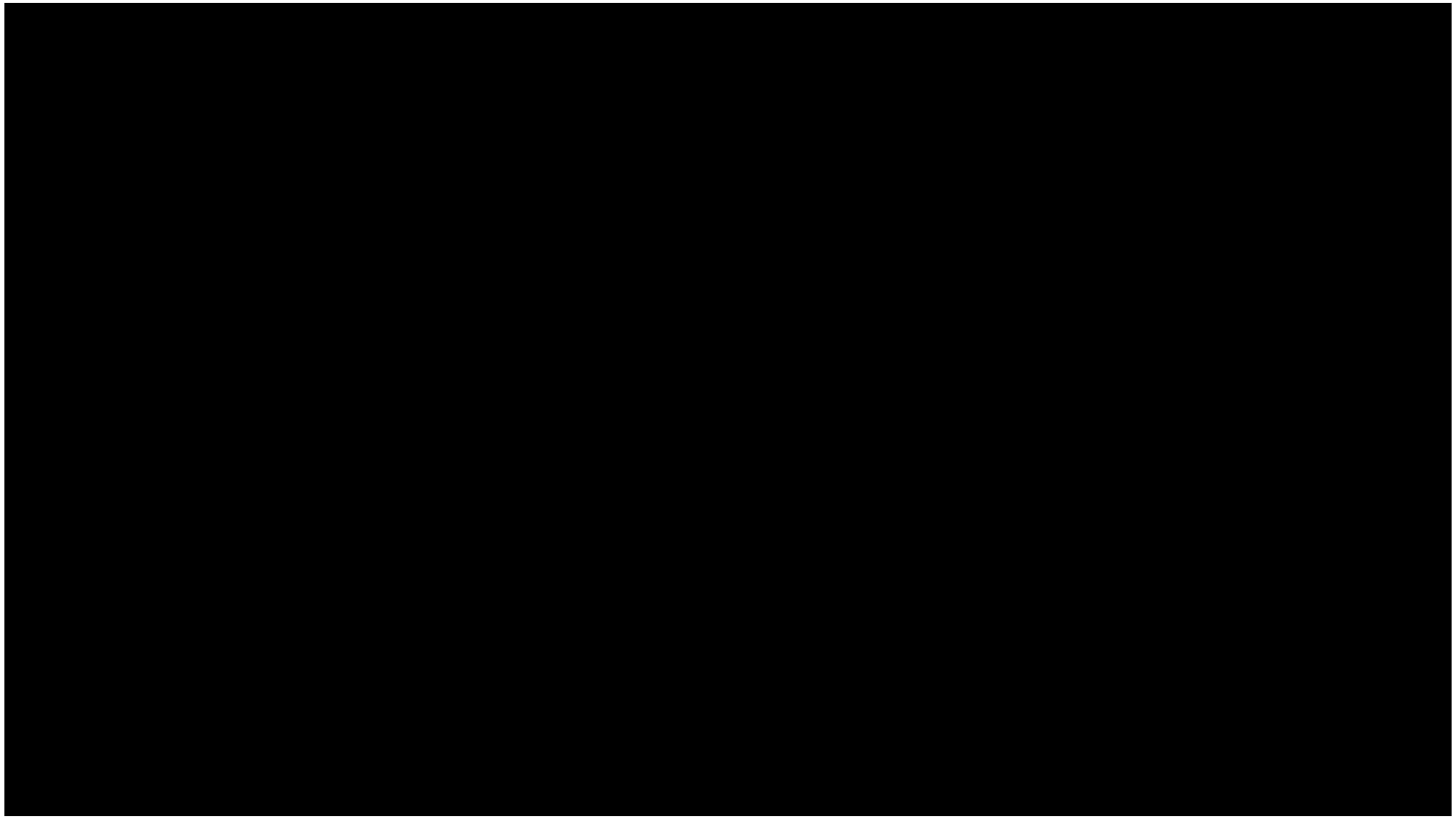
https://udec-chile.valispace.com/project/116/analyses/89

SE Envelopes Table

https://udec-chile.valispace.com/project/116/analyses/70

2U SE envelopes report

Valispace Requirements with AI (video)



https://udec-chile.valispace.com/project/154/specifications/requirements

Valispace FIreSat Reqs

3.3 CubeSat and Small Sat developers interviews

- 5 interviews between 2020 and 2024 in parallel to the development (provided relevant insight into the rational behind their desitions)
- Details are in the report

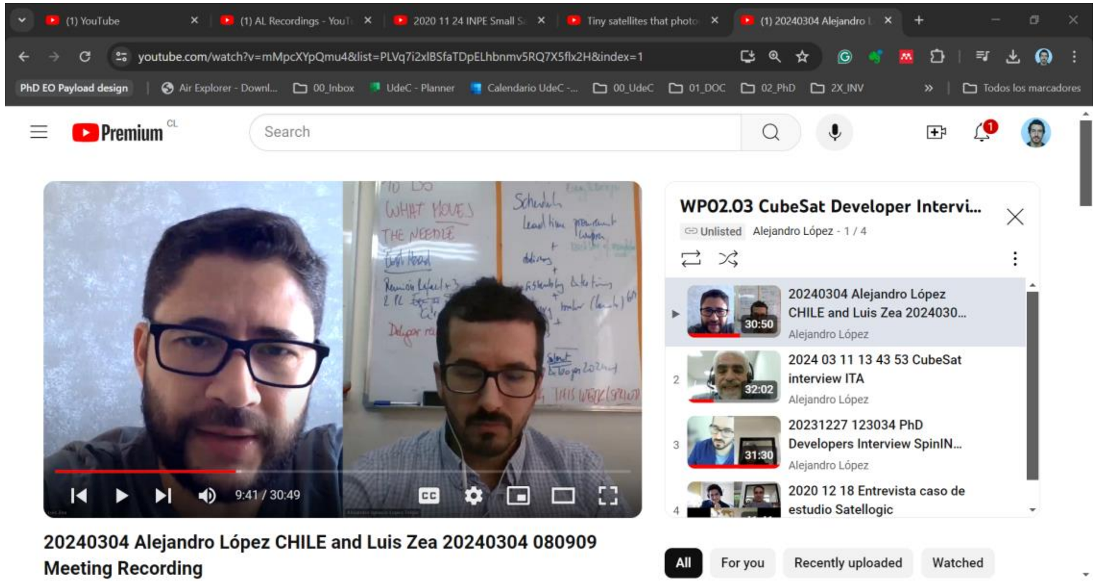


Table 3-17 Summary of interviewed organization approach to satellite development.

Developer	Satellogic	SPEL	BST	SPiN	UVG	ITA
Organization / Business	Private / Geospatial service provider	University / R&D, capacity building, science	Private / Supplier of small satellite systems and technologies	Private / Interface adapter	University / STEM outreach, capacity building, R&D	University / R&D, capacity building
Spacecraft	Small satellite 43 kg	3 U CubeSat	Small satellite 50 kg	1 U CubeSat	1 U CubeSat	6U CubeSat
Estimated S/C Cost*	1 million USD	< 1 million USD	N/A	N/A	N/A	3 to 5 million USD
Time to orbit*	< 1 year	~4 years	< 1 year (claim less than two months assemble and tested)	10 months	~7 years (2014-2020)	~ 3 years
Testing approach	Testing in house at different integration stages (shaker and thermal vacuum) and at launch site	In-house capabilities, testing in external to fulfil launch reqs for POD	In-house, extensive automation of testing execution to reduce manpower costs	N/A	Pass no pass qualification and acceptance testing following Agency specifications for flying into ISS	Reduced testing (ex. Thermal cycling but not Thermal Vacuum)
Redundancy	Yes, at component level		Moving to no single point failure architecture for institutional customers (implies bigger spacecraft)	N/A	Reliability was approached through testing of components	
Principles	Vertical integration, in-house assembly; industrialized production for fast delivery.	Buy everything below 5000 USD (~2 man months)	Vertical integration, automated testing. COTS form automotive industry	In-house manufacturing capability? depends on business plan	Secure initial funding	Focus in prototyping, incremental complexity
Score	Cost-effective (++) and fast (++)	Cost effective (++), mid speed (+)	Cost (N/A) - Fast delivery (++) through mass production facilities/factory	Cost effective (+) and fast delivery (++)	No salaries (cheap), yet too slow (7years) Cost effective (++), slow (--)	Cost-effective (++) and mid speed (+)

*Source: the author based on interviews and educated guesses**

3.4 Botom's-up cost estimation

- Based on declared Manpower (IAA 2017) plus PhD modified leansat survey mission cost was estimated

$$C_{total} = C_{manpower} + C_{sat} + C_{launch}$$

$$= (C_{dev}+C_{op}) + (C_{bus}+C_{PL}) + C_{Launch}$$

Table 3-19 Extract of answer to PhD survey by CubeSat developers

Developer type	**University**	**University**	**University**	**Government body[68]**	**University**	**Commercial**
Country	**Brazil**	**Chile**	**Costa Rica**	**Brazil**	**Guatemala**	**Europe**
Configuration, Orbit (Launch year)	6U (2022)	3U SSO (2022)	1U ISS/KIBO (2017)	2U (2024[69])	1U ISS/KIBO (2017)	1U SSO (2020)
Mission type main focus	Educational	Science	Educational	Science	Technology demonstration	Technology demonstration
1.- Total Cost:	3MUSD ≤ A < 5MUSD		A < 3MUSD		A < 3MUSD	A < 3MUSD
1'.- Total Cost		A' < 1MUSD		2MUSD ≤ A' < 5MUSD		
2.- Satellite delivery time:	B ≥ 3 years	2 ≤ B < 3 years	B ≥ 3 years	2 ≤ B < 3 years	B ≥ 3 years	B < 6 months
3.- Simple satellite:	H ≤ 2	5 ≤ H	H ≤ 2	3 ≤ H < 5	H ≤ 2	H ≤ 2

Man power cost (estimates)

Figure 3-30 Manpower development costs estimations per launch year (all data).

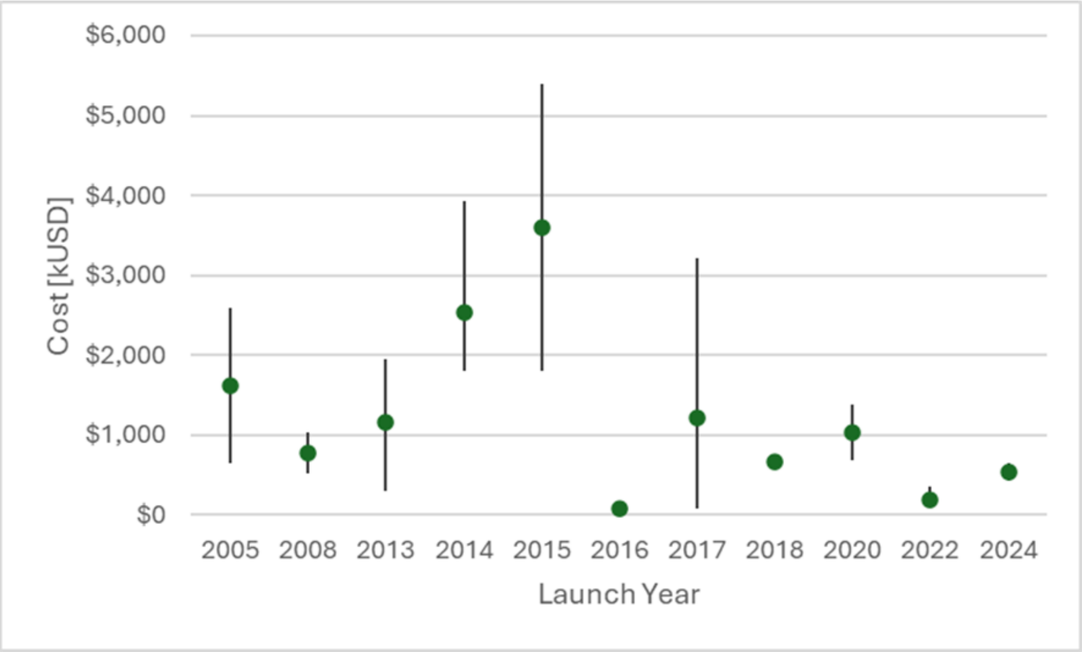


Figure 3 31 Manpower operation costs estimations per launch year (all data).

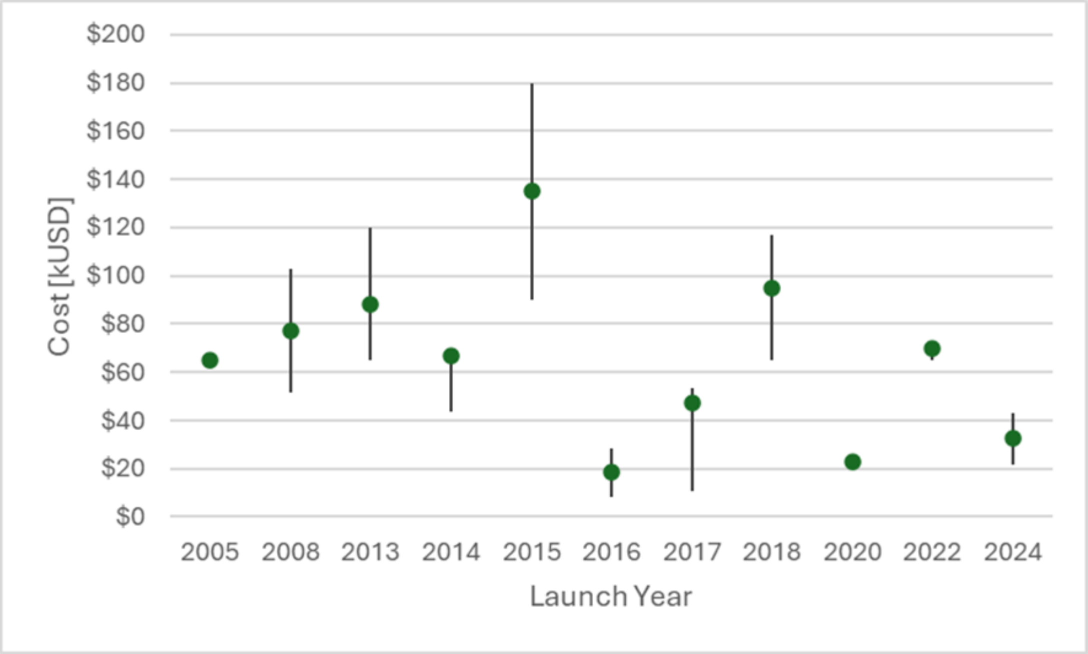


Figure 3-32 Human resources development costs divided by number of units per launch year (all data).

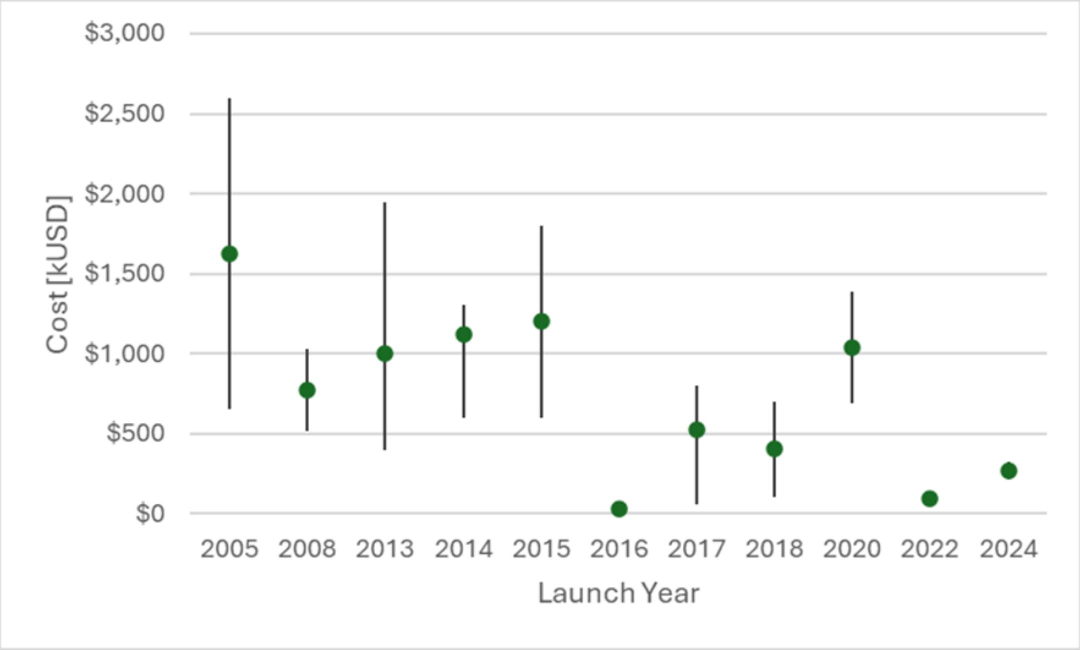
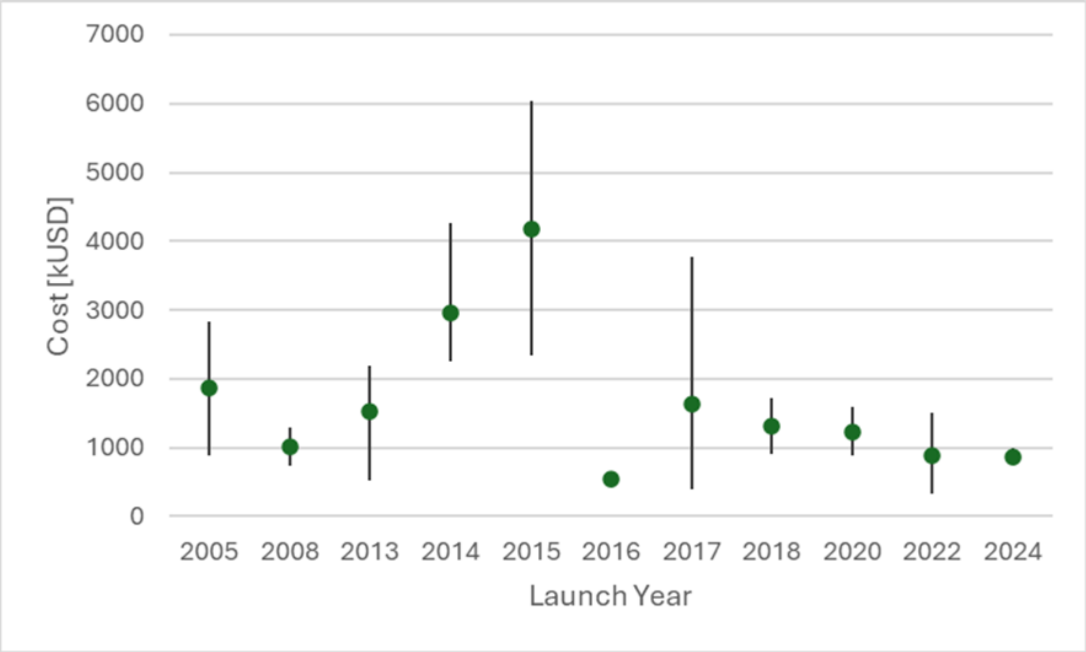


Figure 3 33 Total costs estimations per launch year (all data).



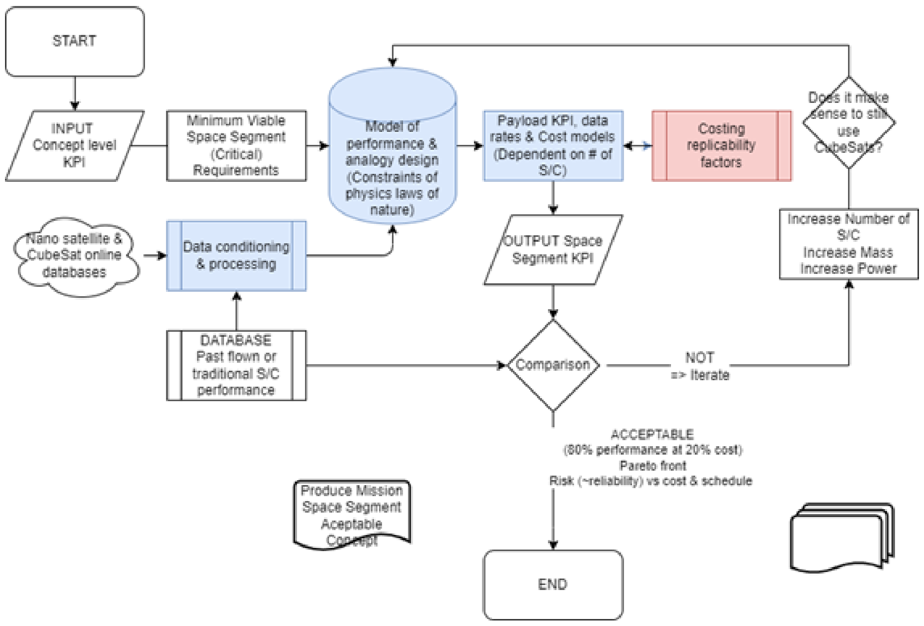
3.4.3.2 SPEL CubeSats detailed cost estimation

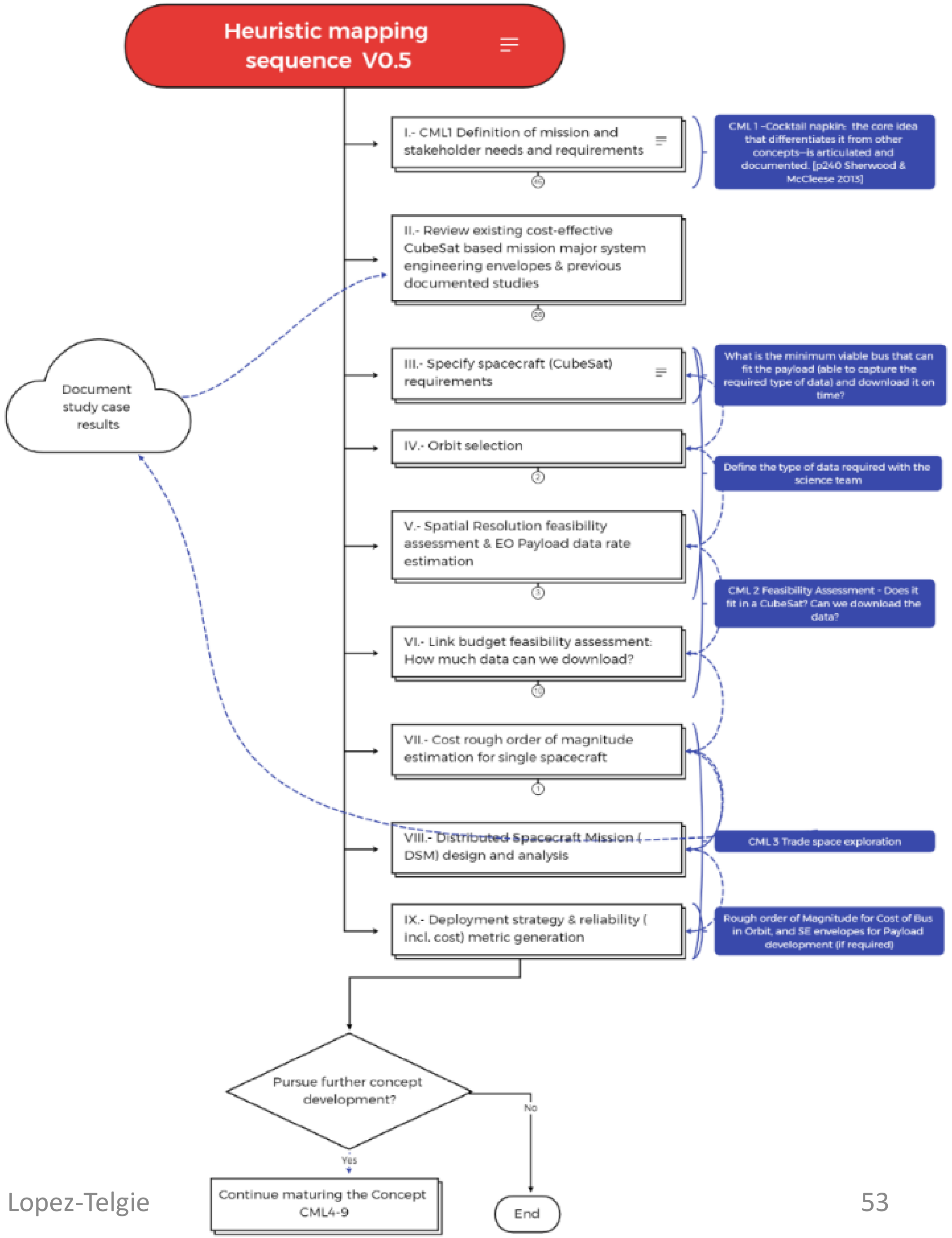
	Survey Suchai-II		Cluster
	Min	Max	Interview
Development team [people]	10	20	4 FTE
Development time [years]	2	3	3
HR dev cost [manyrs]	20	60	12
Salary [USD/yr]	30k		
HR dev cost [kUSD]	600	1800	360
Hardware cost for 3U (100kUSD/unit)	300	300	300
Launch [kUSD]	150	150	(2/3)*150
Operations	≤ 2 people		
Ops time [yrs]	2	3	
Ops HR costs [kUSD]	60	90	Not paid
Total [kUSD]	**1110**	**2340**	**760**

3.5 Summary

- Data gathering tool was developed and reseach published with CubeSat clasification and LCC estimates for 2000-2020
- Valispace models implemented with 5 CubeSat buses, providing SE envelopes and starting point design and analyisis
- Interviews provided insight in the rationale behing design desitions of developers
- Lessons learned are used for the herusit mapping aproach

4.A heuristic approach for mapping alternative space missions

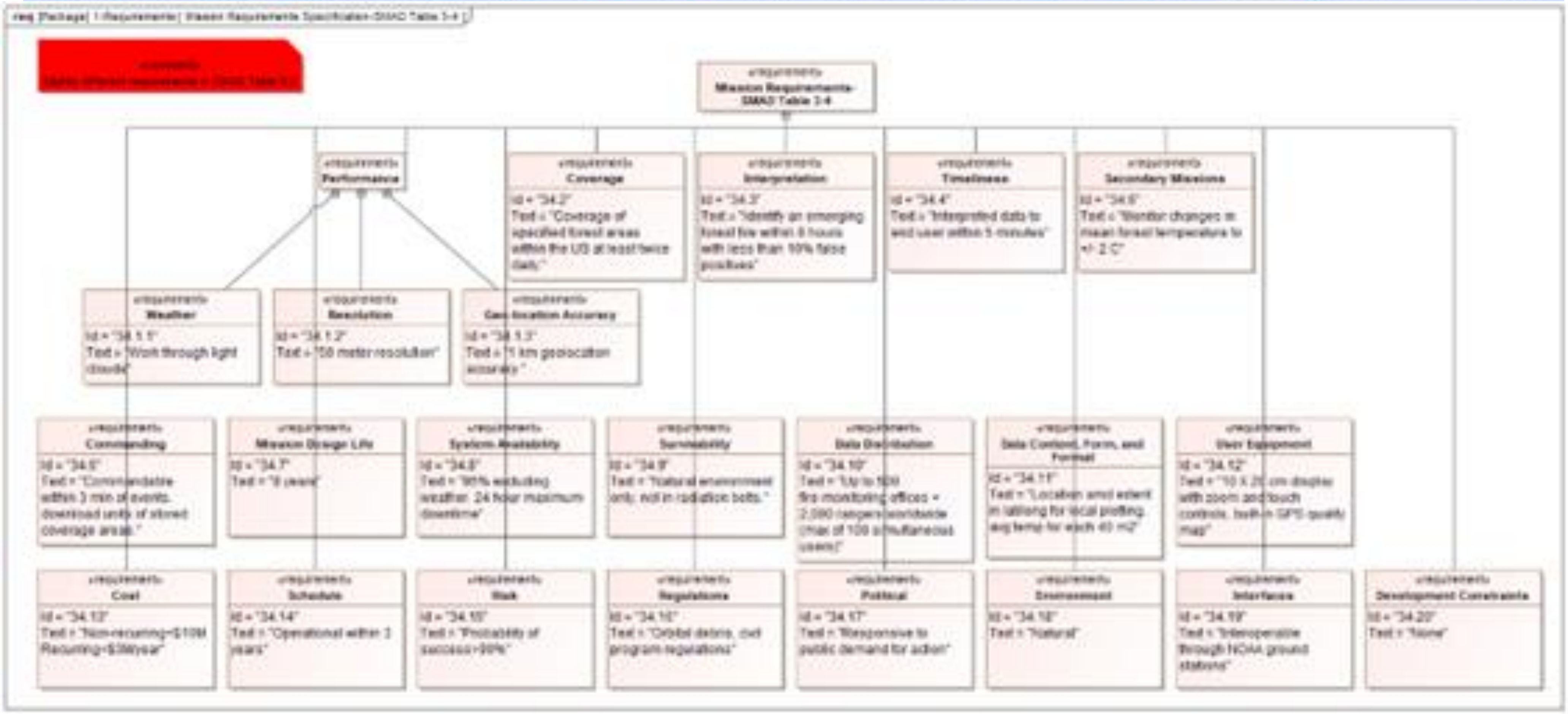




5 Test case: CubeSat-based DSM architecture for fire detection in Brazil

Highlihgts

Step I Definition of mission and stakeholder needs and reqs.



Step I Definition of mission and stakeholder needs and reqs.

Table 5-1 Selection of relevant initial requirements

Id	Name	Text	
31.1	Performance		Functional
34.1.2	Resolution	50 meter resolution	Functional
34.2	Coverage	Coverage of specified forest areas within the Brazil at least twice daily	Functional
34.7	Mission Design Life	8 years	Operational
34.13	Cost	Non-recurring < 10 M Recurring < 3 M/year	Constrains
34.14	Schedule	Operational within 3 years	Constrains
34.15	Risk	Probability of success 90%	Constrain

Step II Review existing cost-effective CubeSat based mission SE envelopes & previous studies

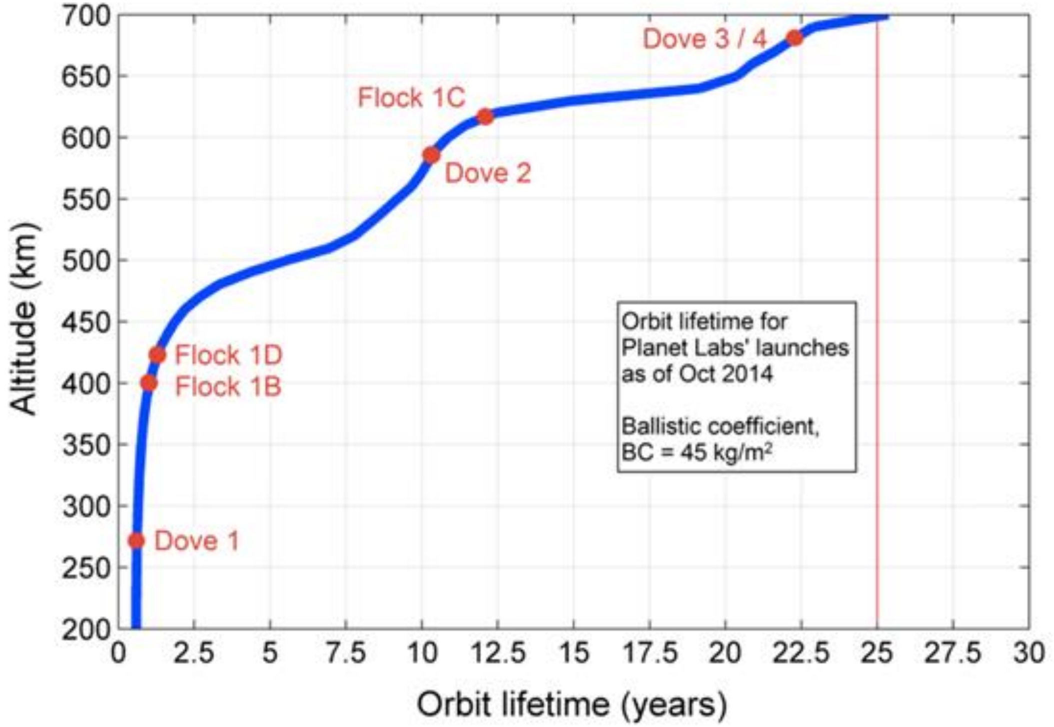
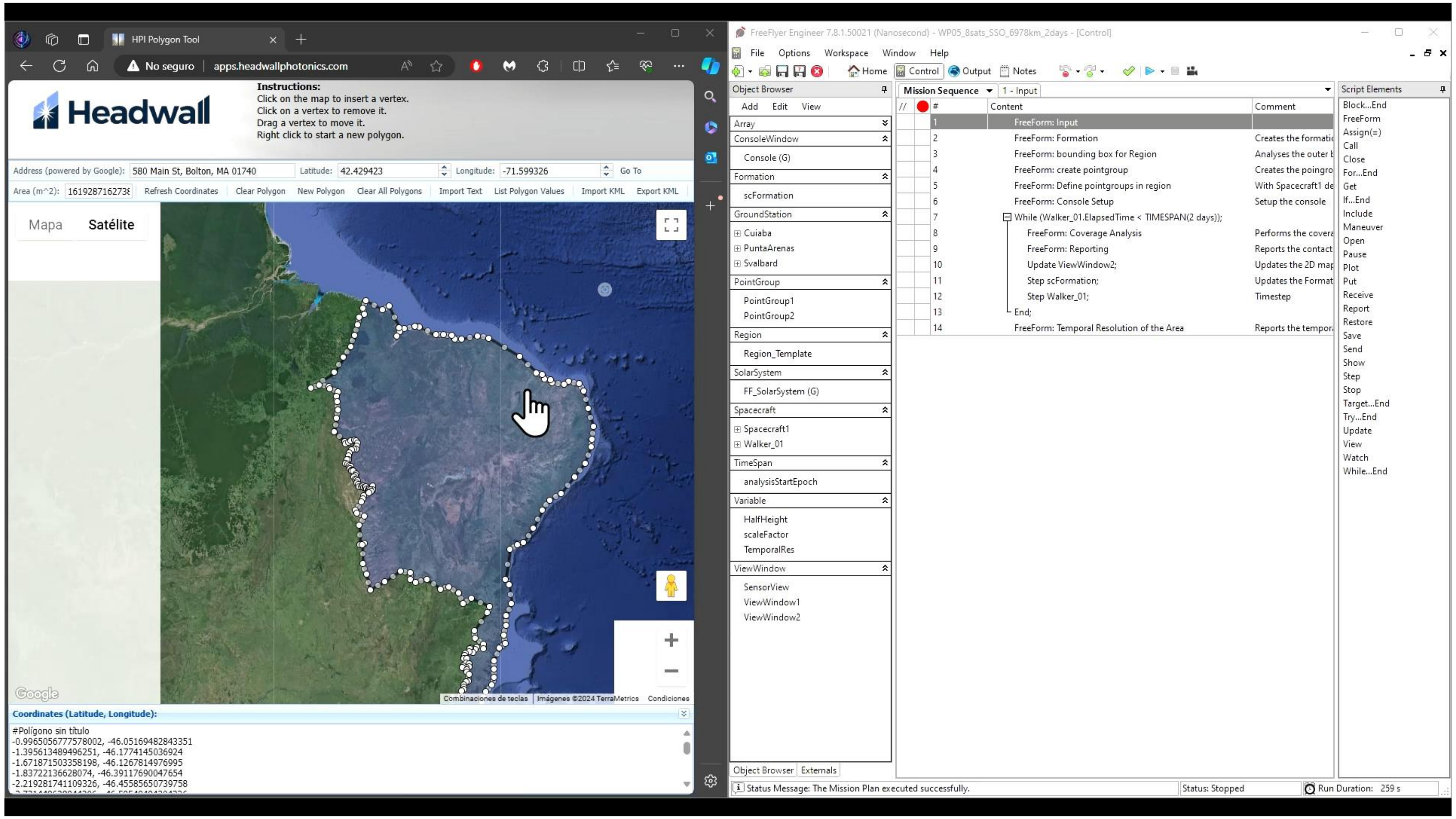


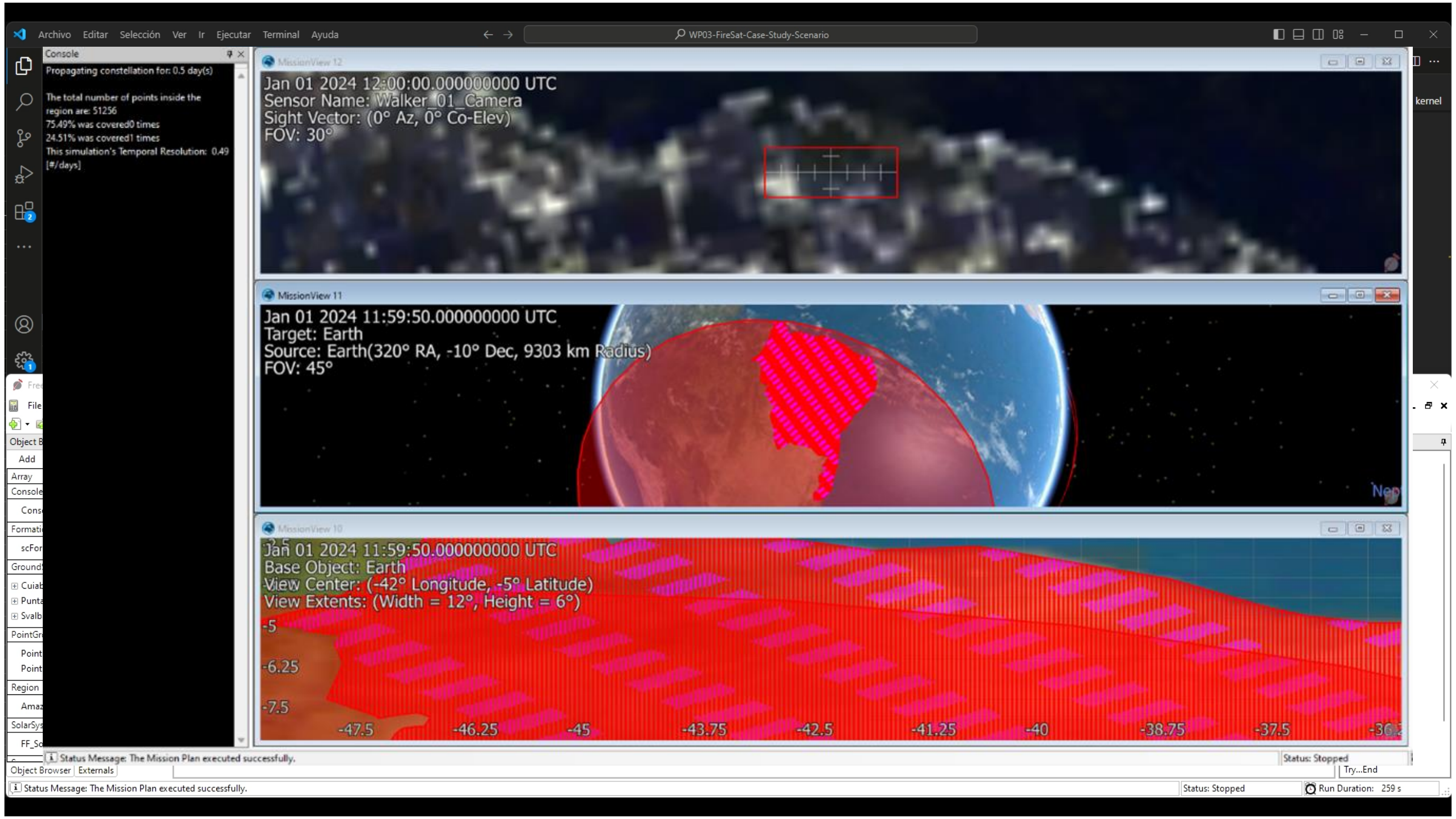
Figure 5 5 Orbital lifetime for Planet Satellites. Source. Slide 13 (SAFYAN, 2015)

	TUBIN	Spire Nanosat	Lume-1	FIREBIRD	CSIROSat-1
Operator or contractor	Technische Universität Berlin	OroraTech	l'Université de Vigo	DLR	CSIRO[1]
Satellite Mass (kg)	17	9	2.1	15	4
Size	-	6 U	2 U	two 1.5 U CubeSats	3 U
Launch date	2017	2021	2018	2012	Not launched, but expected in 2022
Payload	Infrared microbolometer	Thermal-infrared camera	Software-defined radio (SDR) and HUMPL	Imaging multi-spectral radiometers (vis/IR)	Detector of invisible infrared light
Source	[2]	[3]	[4]	[5]	[6]

Step VI: Link budget feasibility assessment – AoI setup (Video)



Step VI: Instrument calculations (Python) and setup Free Flyer (video)



Step VI: initial scenarios

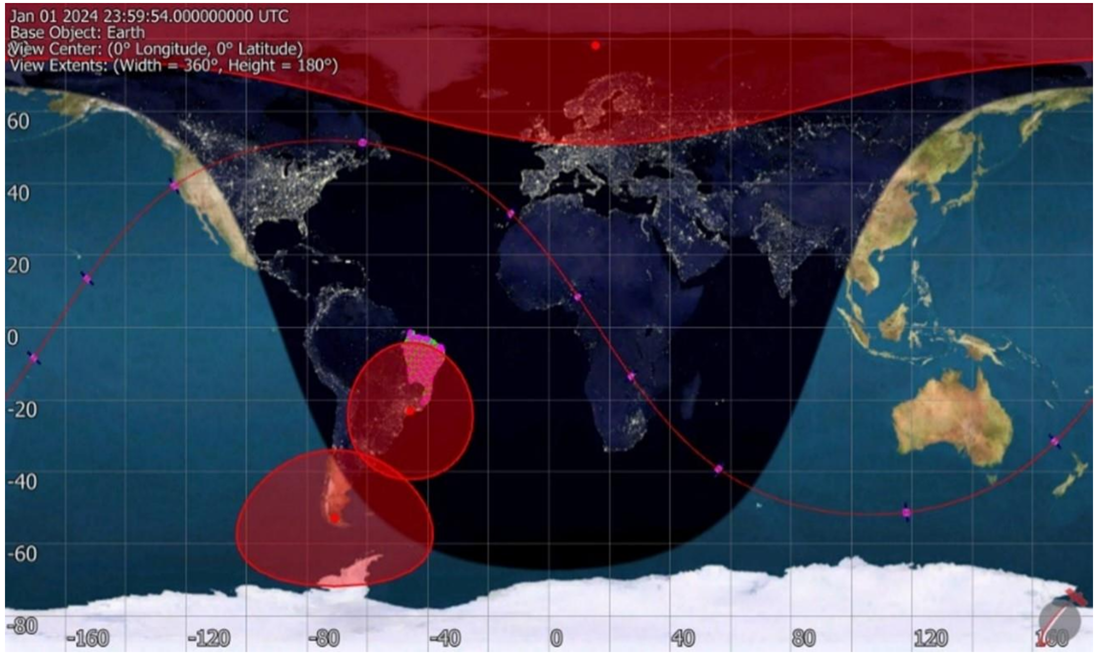
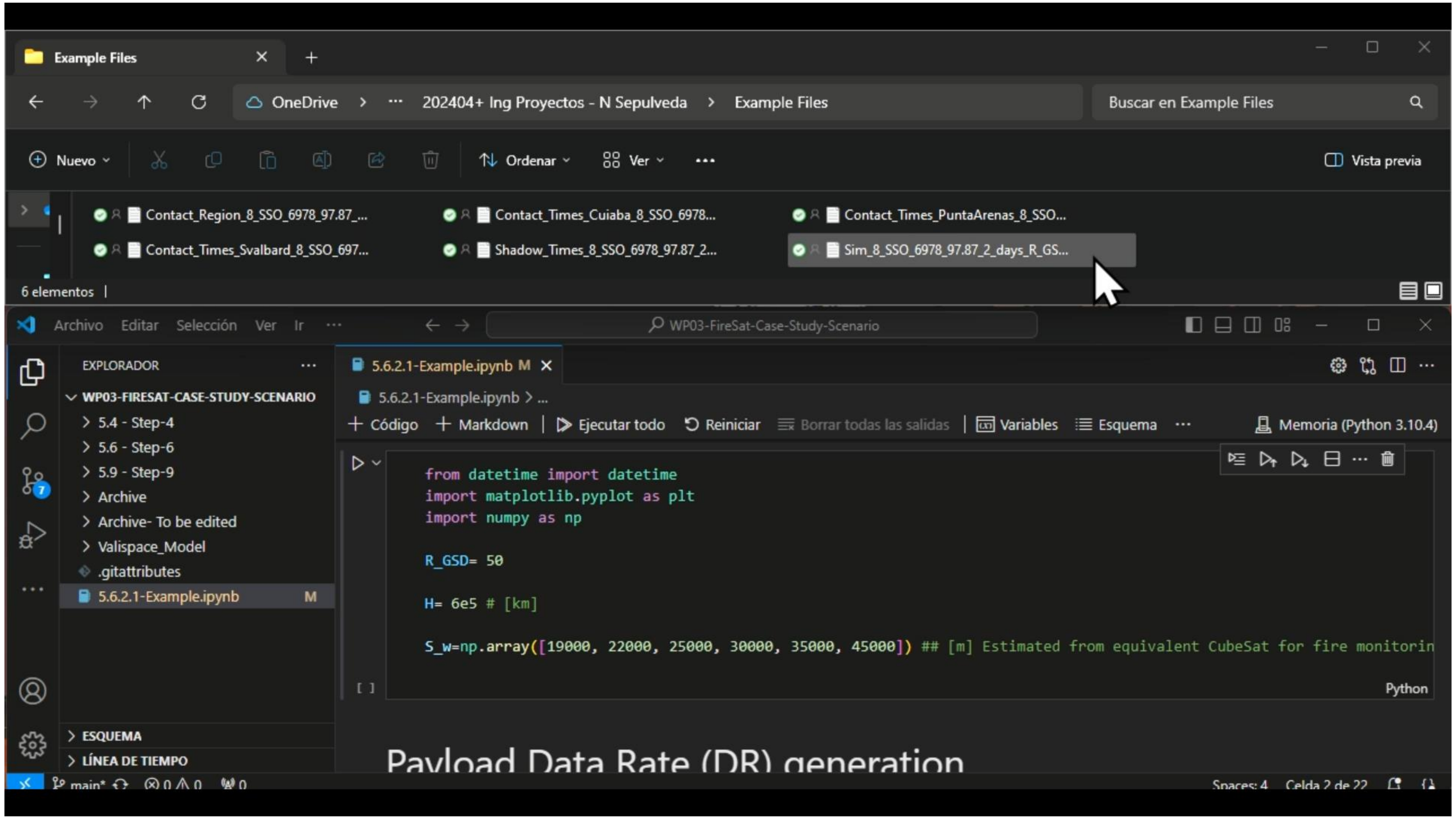


Table 5-9 Orbital scenarios description and main orbital parameters.

Scenario	Type of Orbit	# S/C	Altitude [km]	Inclination	Ground Sample Distance
1	SSO	10	450	97.21°	25 m
2	SSO	10	600	97.87°	25 m
3	ISS	10	275	51.64°	25 m
4	ISS	10	350	51.64°	25 m
5	ISS	10	460	51.64°	25 m
6	SSO	2	600	97.87°	50m
7	SSO	5	600	97.87°	50m
8	SSO	10	600	97.87°	50m

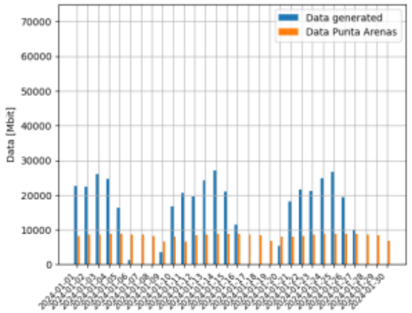
Source: author.

Step VI: Contact graph generation in Python (video)

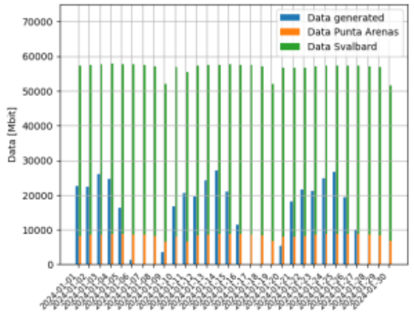


Scenario 8: SSO 600 km, GSD 50 m, 10 sats

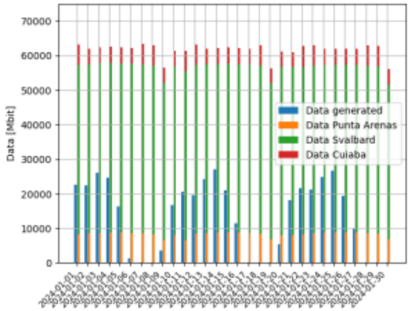
Figure 5-27 Data generated by satellite Walker_1 and downloaded at different ground stations and combinations of them for scenario 8.



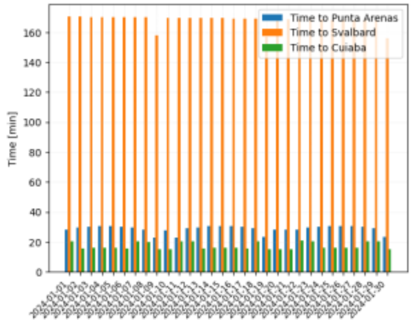
e) Data downloaded at Punta Arenas



f) Data downloaded at Punta Arenas and Svalvard

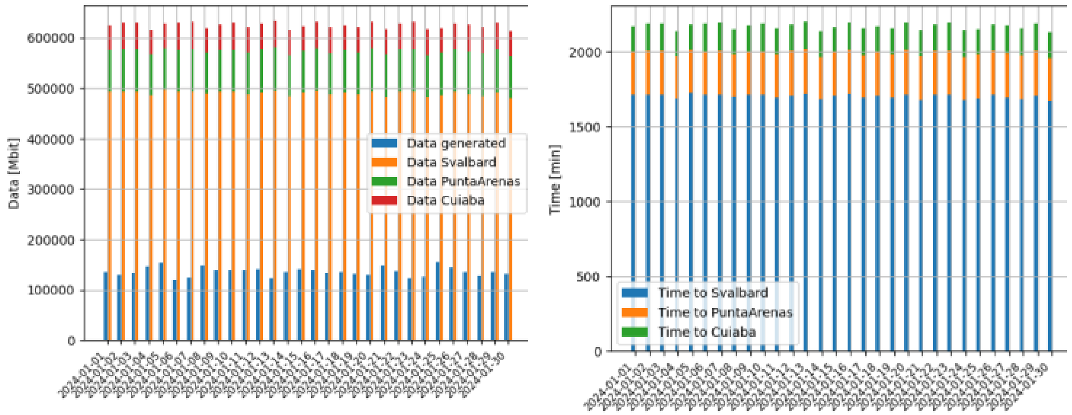


g) Data downloaded at all 3 ground stations



h) Contact times per station [min] per day

Figure 5-28 Scenario 8 total data generated and download per day (left), and total contact time with ground stations (right).



Source: the author

Coverage & reducing the number of sats

Table 5-11 Summary of coverage for the different scenarios (includes 6 to 8) over 30 days.

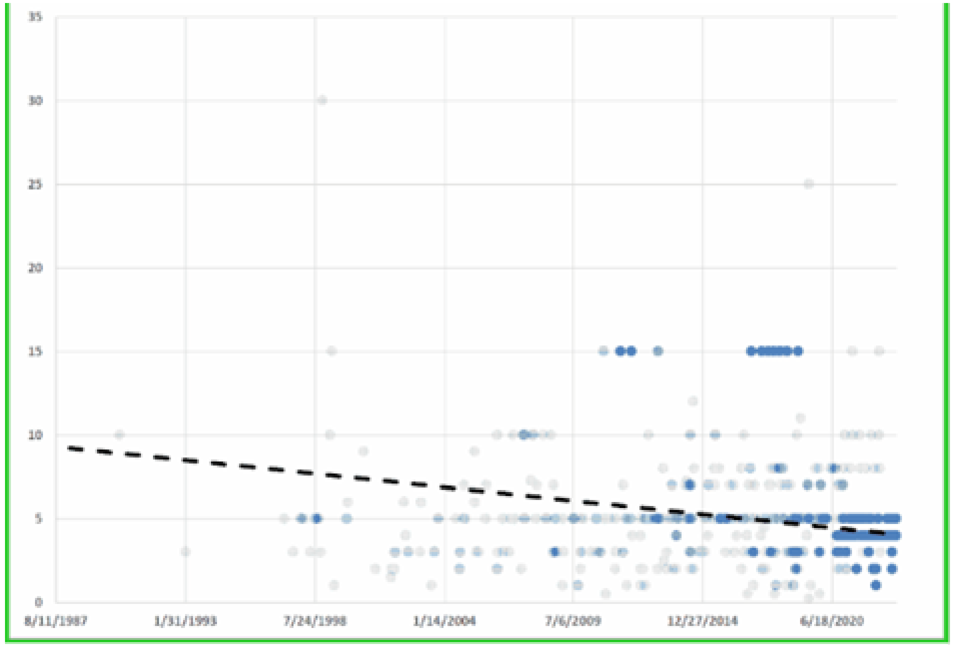
Scenario #	# of sats	Orbit	Semimajor axis a [km]	Coverage (passes/day)	R_{GSD} [m]
1	10	SSO	6828	1.31	25
2	10	SSO	6978	1.28	25
3	10	ISS	6653	1.05	25
4	10	ISS	6728	1.32	25
5	10	ISS	6838	1.57	25
6	2	SSO	6978	0.51	50
7	5	SSO	6978	1.24	50
8	10	SSO	6978	2.55	50

Table 5-12 Summary of coverage for the different scenarios (includes 6 to 8) over 30 days.

Scenario #	# of sats	Orbit	Semimajor axis a [km]	Coverage (passes/day)	R_{GSD} [m]
9	6	SSO	6978	1.53	50
10	7	SSO	6978	1.75	50
11	**8**	**SSO**	**6978**	**2.04**	**50**
12	9	SOO	6978	2.33	50

Note highlighted the scenario 11 in which the coverage matches the required 2 passes per day. Source: the author based on the scenario simulations.

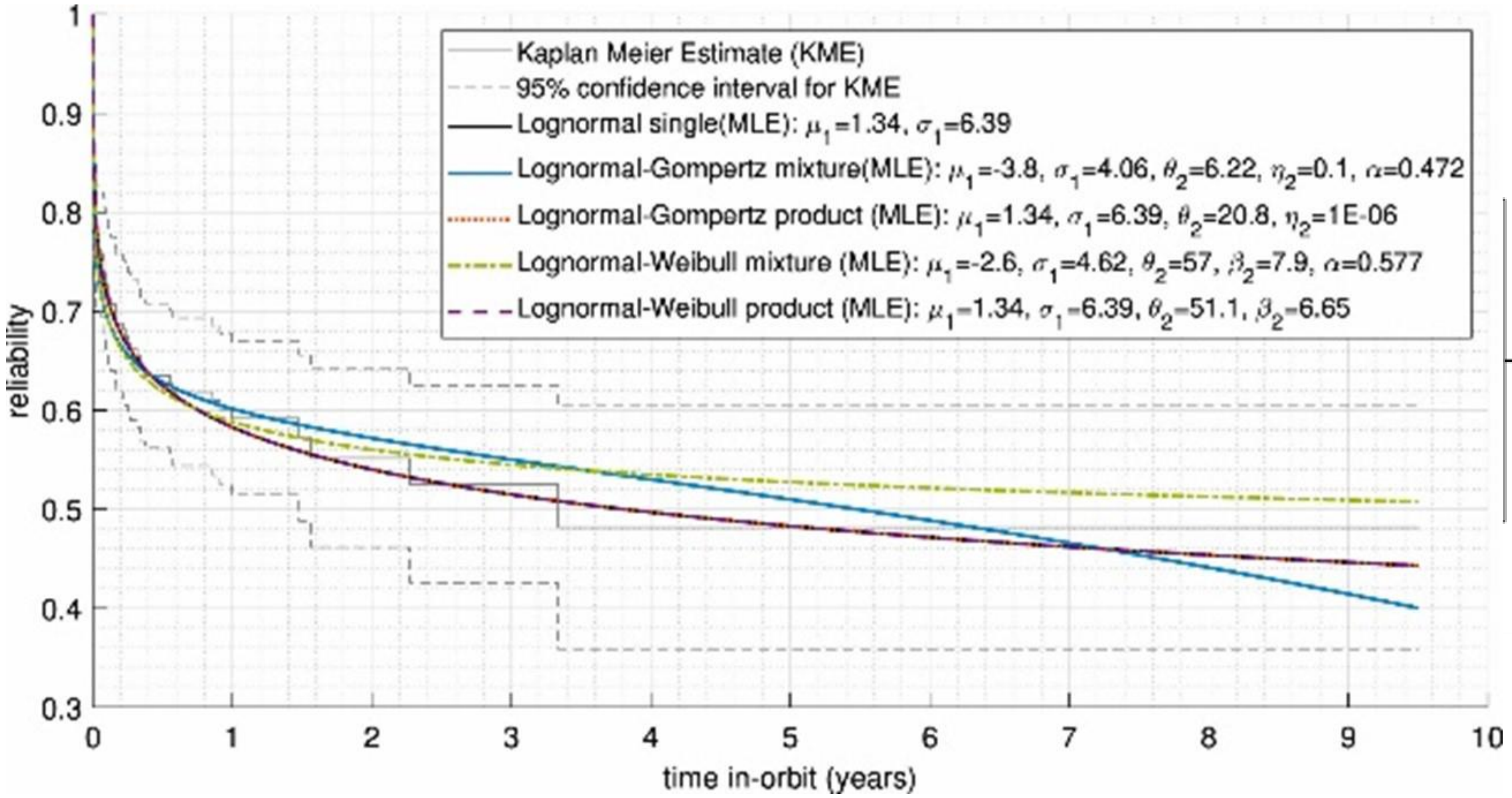
Step VIII: DSM design and analysis



- Lifetime of CubeSats set as maximum 3 years

5.9 Step IX.- Deployment strategy & reliability (incl. cost) metric generation.

(BOUWMEESTER; MENICUCCI; GILL, 2022b)



<u>OUTPUTS</u>

- DSM deployment strategy (iterative result to achieve required reliability of mission)

-- DSM deployment cost for different deployment strategies (scenarios)

- -DSM reliability over time (curves, and punctual at 6, 12, 18, and 24 months after deployment)

Phased deployment and parallel reliability

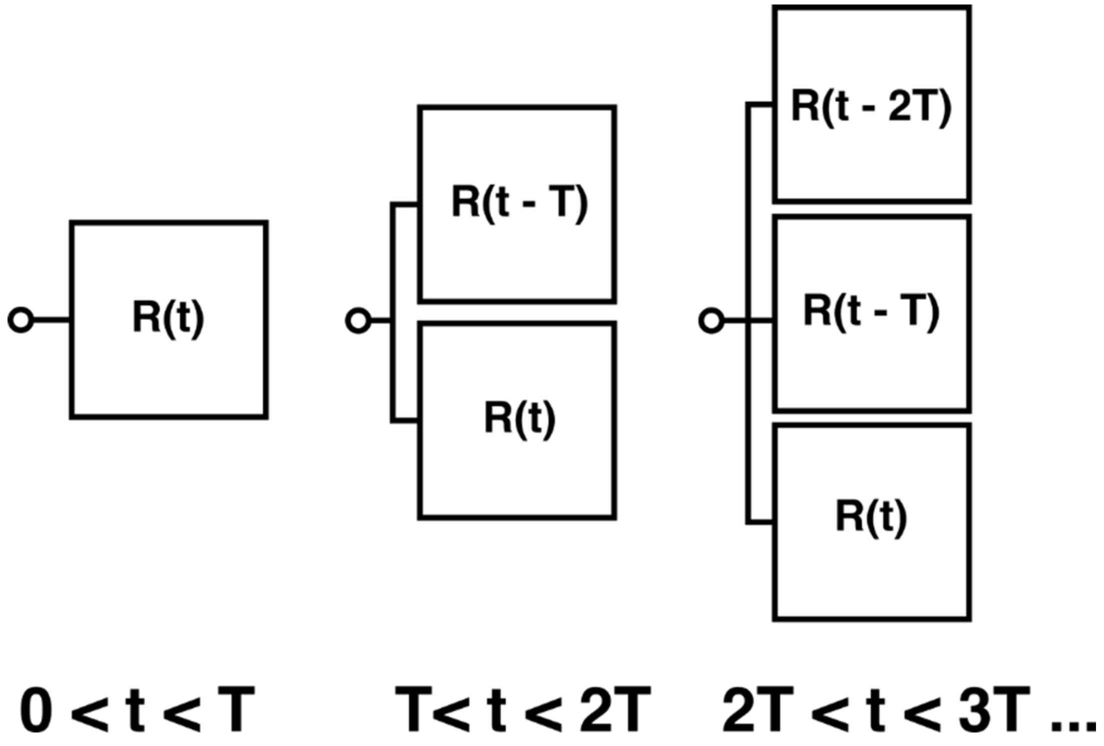


Table 5-16 Scenario description[89]

Scenario #	Initial S/C Batch at t_0	Subsystem Redundancy (EPS only)	Phased Deployment Strategy	Relaunch Rate [months]	Relaunch Amount [S/C]	Programmed Retirement[90]
1	8	False	False	N/A	0	False
2	8	False	True	36	8	True
3	2	False	True	6	2	True
4	4	False	True	12	4	True
5	8	False	False	N/A	N/A	True
6	8	False	True	30	4	True
7	8	False	True	24	4	True
8	8	False	True	20	4	True

Source: the author

Step X deployment cost

Scenario
1[1]
2
3
4
5[2]
6
7
8

Deployment Scenario	Total # of CubeSats	# of Generations	Sats per generations	Deployment cost (lowest) [kUSD]	Spacecraft cost incl. dev. HR [MUSD]		Total [MUSD]	
					Min	Max	Min	Max
2	24	3	8	900	19.2	36.0	21.1	36.9
6	20	1+3 = 4	8 (at t_0), 4 every 30 months	1200	16.0	24.0	17.2	25.2

[1] All deployments are above two 3 U CubeSats, and thus the rideshare provides and advantage is launch cost with respect to POD launches (since the estimate has the cost of two 3U PODs equal to 50 kg at Space-X which can fit up to 8 triple-unit CubeSats).
[2] Without operations (i.e. ground segment)
[3] Min at 800.000 USD/3U CubeSat
[4] Max at 1.500.000 USD/3U CubeSat (NAG; LEMOIGNE; DE WECK, 2014b)

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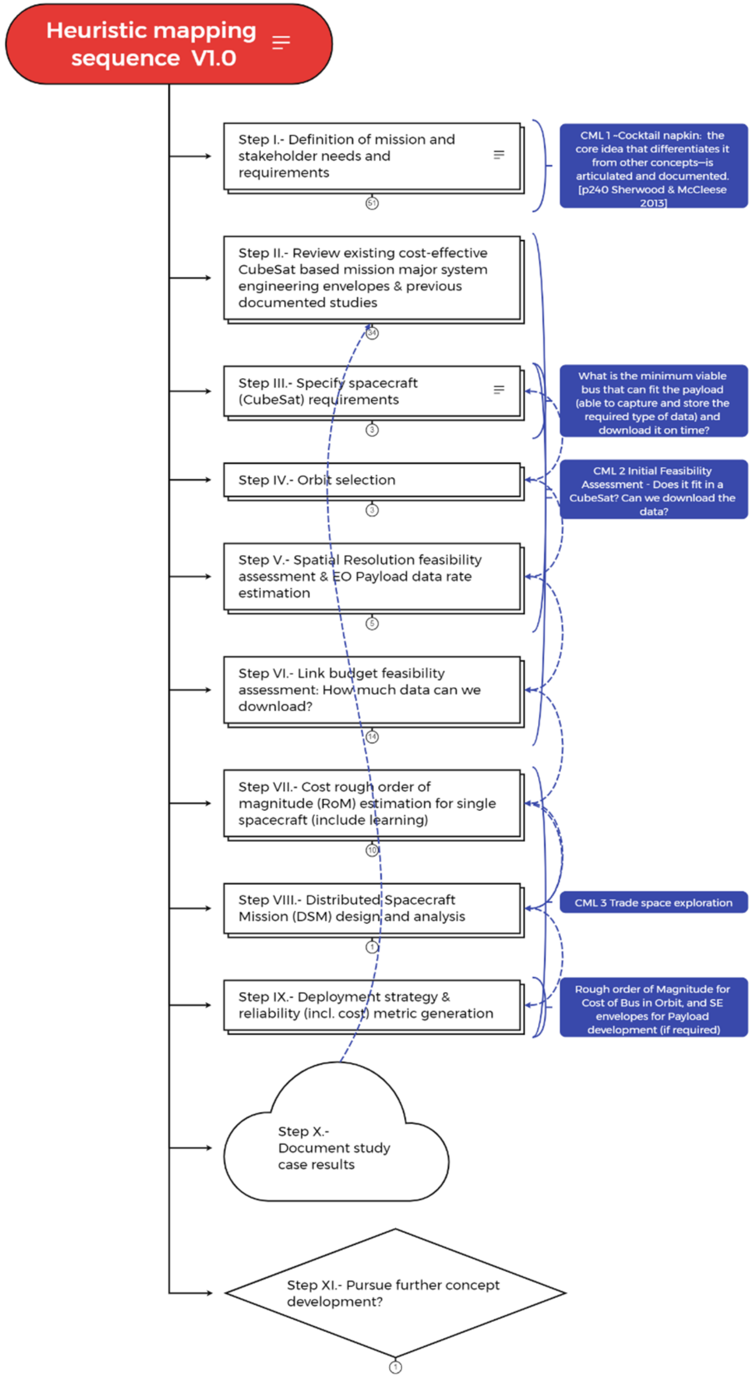
6 Revisiting and improving the mapping heuristic approach



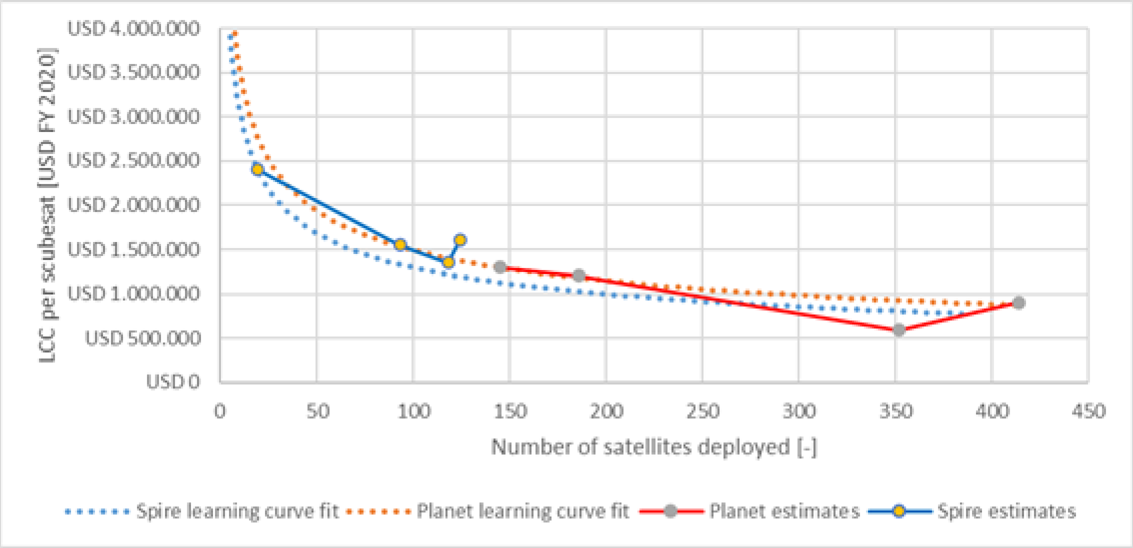
Step VI – include power modes

Table 6-2 Example of power consumption for a 3U satellite with a camera payload in LEO under different operational modes.

3U CubeSat multiple vendor										
							Operation Modes F_{mode}			
Subsystem [CSRM]	**Equipment**	Manufacturer	Component	Max Power P_{max} [W]	Power Factor F_p [-]	**Av. Power P_{av} [W]**	Default	Capture	Ground Station Pass	Eclipse
Power	Power conversion, distribution, and control	ISIS Space	ICEPS2	0,89	1,00	0,89	100%	100%	100%	100%
CDH	On Board Computer	ISIS Space	ISIS On Board Computer	0,40	0,35	0,14	100%	100%	100%	100%
Communications	Antenna	ISIS Space	S band Antenna	2,50	1,00	2,50	0%	0%	100%	0%
	Transceptor	IQ Spacecom	Transmitter	15,00	0,30	4,50	0%	0%	100%	0%
		IQ Spacecom	Receiver	4,00	0,40	1,60	100%	100%	100%	100%
GN&C	Integrated ADCS	CubeSpace	CubeADCS 3-Axis Small	6,00	0,60	3,60	0%	100%	100%	0%
Payload	Camera	-	Camera	18,40	0,40	7,36	0%	100%	0%	0%
				Total specified consumed power			2,63	13,59	13,23	2,63

Source: the author

Step VII – Include learning effects over LCC



7 Conclusions

7.1 Regarding the objectives of this work

1. Identify three small satellites design practices and philosophies for achieving cost-effective space missions, specifically CubeSat ones.

2. Develop a test case of a CubeSat-based distributed spacecraft mission (DSM) architecture for FireSat II.

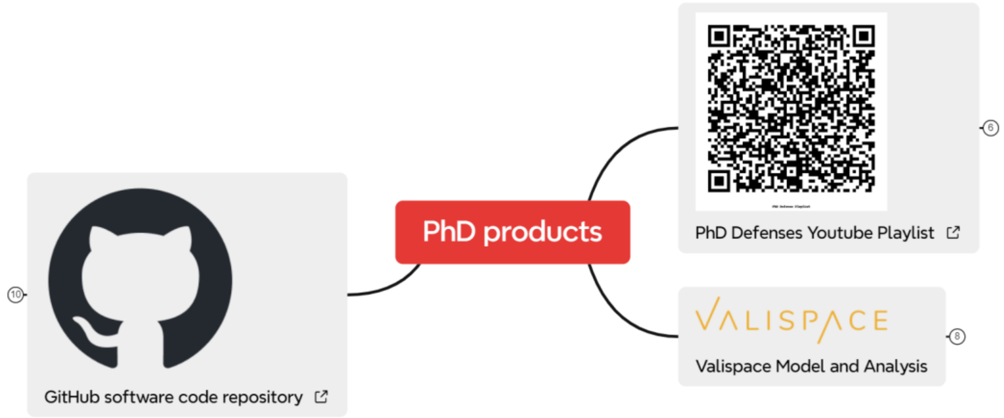
3. Integrate parametric sizing models (rough order of magnitude) for Earth Observation (optical) payloads in relevant orbits for CubeSat missions.

7.1 Regarding the objectives of this work

- Regarding the main objective of this **PhD to develop a heuristic for the conceptual design of a CubeSat-based distributed spacecraft mission which could eventually replace traditional low Earth orbit monolithic satellites**

Products of this work

- Heuristic mapping approach
- Publications
- Valispace models
  - 5 CubeSats buses and
  - SE envelopes reporting
- Github repository
  - Free flyer scrips
  - Datasheets for Valispace busess
  - Data processing algorithem
  - Payload sizing



List of publications

- **Lopez-Telgie, A.,** Quappe-Gutierrez, M., & dos Santos, W. A. (2024). An Automated Data-Gathering Tool for Earth Observation CubeSats Classification. IEEE Latin America Transactions, 22(6), 451–459. https://latamt.ieeer9.org/index.php/transactions/article/view/8620 (Journal Citation Report JCR =1.3)
- **Lopez-Telgie, A.,** & dos Santos, W. A. (2020). IAA-BR-20-1p-01 Methodology for conceptual design phase assessment of traditional vs small satellite mission space segment concepts Part 1: input and outputs. IV IAA Latin American CubeSat Workshop.
- **Lopez-Telgie, A.,** & dos Santos, W. A. (2020). Low Earth Orbit Earth Observation CubeSat Classification in its second decade. XI Workshop Em Engenharia e Tecnologia Espaciais.
- **Lopez-Telgie, A.,** & dos Santos, W. A. (2019). Advancements in satellite data collection and relay concepts using small satellites. X Workshop Em Engenharia e Tecnologia Espaciais.

7.2 Limitations

- **Vendors hardly provide any price and or detailed specifications** on their websites. The effort to keep up to date was also found in the literature and discussed in the respective section. As significant effort and time are required, the rough order of magnitude models, coupled with the systems engineering envelopes, provide a starting point for the feasibility assessment of CubeSat cluster concepts.

- **All implemented models are subject to improvements and updates**. The fundamental trade-off between fidelity and complexity remains valid in models, as more realistic models require significant effort and data. In contrast, the ones implemented allow initial sizing and assessment.

7.3Future lines of work

- Extend the CubeSat models into a SysML implementation following the release of the CubeSat System Reference Model (if licenses for tools are available).
- Update the web scrapping algorithm, as changes in the SatCat query structure occurred during the development of the thesis and rendered the algorithm outdated.
- CubeSat reliability models and real access to failure data from DSM with tens of satellites deployed over time will significantly support the sizing efforts and increase their fidelity.
- Include learning effects in cost models for DSMs.
- Integration of the different tools developed, to reduce the cycle time.