Vela

A Data-Driven Proposal for Joint Collaboration in Space Exploration

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Motivation and Rationale

- Large space exploration missions will benefit from programmatic redundancy such as:

    1. Redundant technological capabilities in the event of a malfunction.
    2. Redundant funding capabilities to ensure continuity of mission financial support.
    3. Redundant programmatic capabilities for efficient resource allocation.

Mission scenario proposed to achieve the technical, financial, and programmatic redundancy necessary for a manned Mars mission.

Multinational Approach

- This work proposes a cooperation scenario between five space agencies: China, the European Union, Japan, the Russian Federation, and the United States, based on

   1. All five space agencies manufactured and launched heavy-lift launch vehicles capable of performing deep space missions.

   2. All five space agencies successfully developed and launched space station habitats capable of supporting human life in space.

   3. All five space agencies launched robotic missions to Mars.

Launch Capabilities

- Current and proposed super-heavy lift launch vehicles
- Capability to send crew and habitat modules to deep space

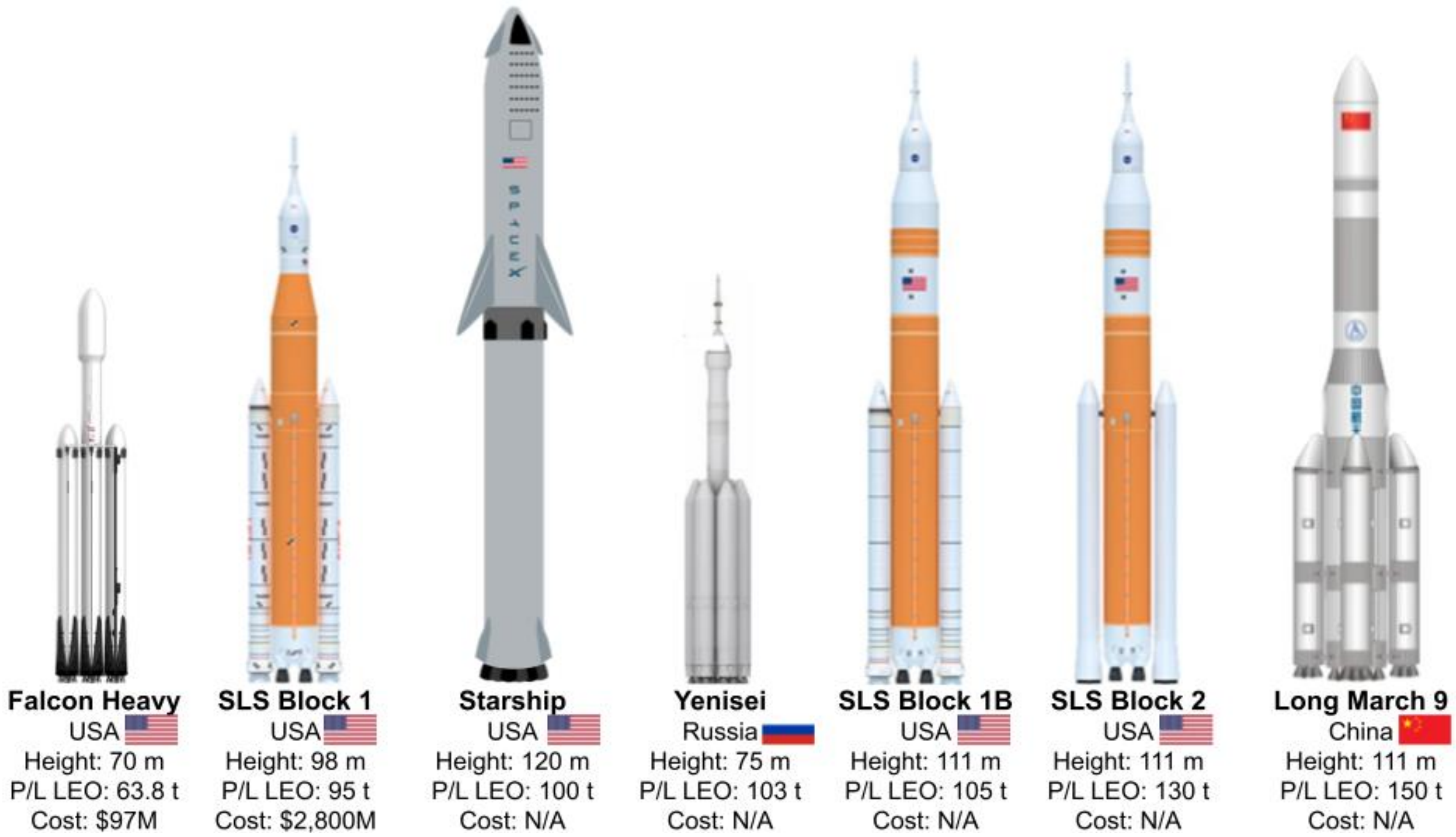

Figure 1: Super-Heavy Launch Lift Vehicles (Existing and Proposed)

Human Spaceflight Capabilities

- Summary of modules developed by the five agencies under consideration
- All agencies have heritage knowledge creating long-duration space habitat modules

Table 1: Human Habitat Development for LEO

Year	Government	Station	Habitat Module	Mass (kg)
2022	China	Tiangong	Wentian	23,200
2021	China	Tiangong	Tianhe	22,600
2021	Russia	ISS	Nauka	20,357
2009	Japan	ISS	Kibo	15,900
2008	EU	ISS	Columbus	10,300
2007	USA	ISS	Harmony	14,300
2001	USA	ISS	Destiny	14,515
2000	Russia	ISS	Zvezda	20,320
1998	USA	ISS	Unity	11,612
1998	Russia	ISS	Zarya	19,323

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Mars Exploration Capabilities

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Table 2: Exploration Missions to Mars

Year	Vehicle	Government	Mission (P/L Type†)	P/L Mass (kg)	Cost ($M)§
2020	H-IIA	Japan	Emirates Mars Mission (O)	1,350	$90.00
2020	Long March 5	China	Tianwen-1 (L + O)	5,000	$150.00‡
2020	Atlas V	USA	Mars 2020 (L)	3,649	$243.00
2020	Atlas V	USA	InSight (L)	721	$163.40
2016	Proton-M / Briz-M	Russia*	ExoMars (L + O)	4,332	N/A
2011	Atlas V 541	USA	Mars Science Laboratory (L)	3,839	N/A
2007	Delta II 7925	USA	Phoenix (L)	670	$86.20
2005	Atlas V 401	USA	Mars Reconnaissance Orbiter (O)	2,180	$90.00
2003	Soyuz-FG / Fregat	Russia*	Mars Express (L + O)	1,189	N/A
2003	Delta II 7925	USA	Mars Exploration Rover Mission - Spirit (L + O)	1,063	N/A
2003	Delta II 7925H	USA	Mars Exploration Rover Mission - Opportunity (L + O)	1,063	N/A
2001	Delta II 7925-9.5	USA	2001 Mars Odyssey (O)	758	$53.90
1999	Delta II 7425-9.5	USA	Mars Polar Lander (L)	290	$90.70
1998	M-V	Japan	Nozomi (O)	258	$70.00
1998	Delta II 7425-9.5	USA	Mars Climate Orbiter (O)	638	$90.70

Note: Country, Payload Mass, and Cost are provided for launch. *Payload: EU †L: Lander, O: Orbiter ‡Estimated §N/A: Not Available

Diverse experience launching missions to Mars and sustained infrastructure of mars orbiters

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Space Agency Funding Analysis

- Aim to understand funding situation of each agency and trends that guide the space budgets
  - Collected a budgetary dataset for each agency
  - Carried out an econometric analysis of the space budgets

Space Agency Funding Analysis

Budget Dataset

Econometric Analysis Procedure

Budget Modeling

Budget Dataset

- Time series budgetary data collected for each agency.
- Space budget, GDP per capita, researchers per million, military spending, education spending, science R&D spending collected from 1998 through 2020.
  - Some 2021 and 2022 values not yet available.

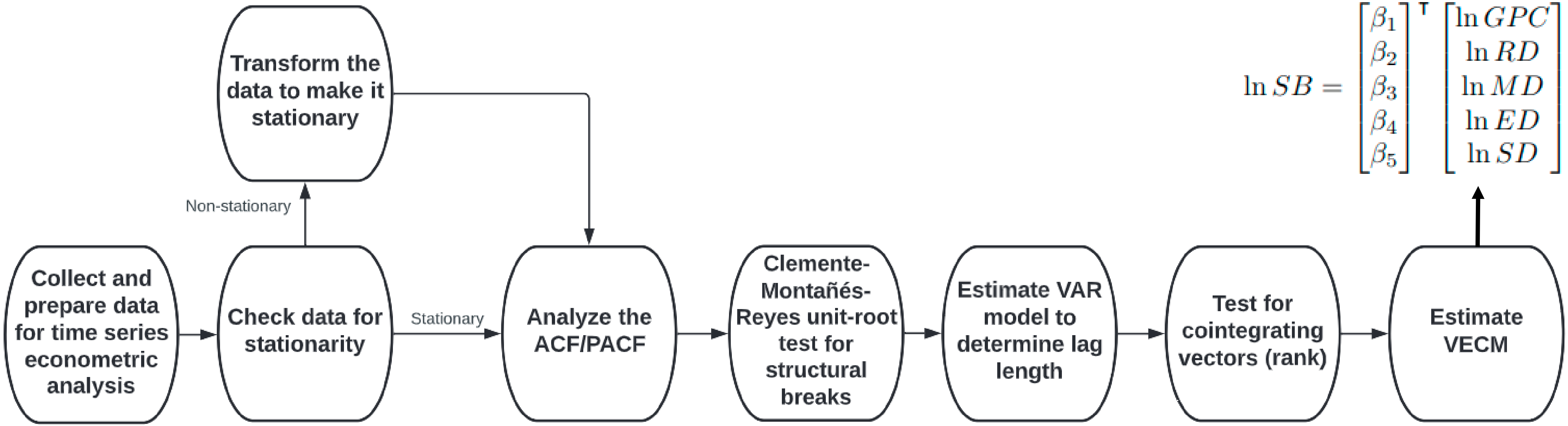
Table 3: Example Macroeconomic Data for China

Year	SB ($ B)	GPC ($/capita)	RD (per million)	MD (% GDP)	ED (% GDP)	SD (% GDP)
2020	8.900	10433.513	1584.865	1.750	3.570	2.401
2019	8.502	10143.838	1471.254	1.728	3.540	2.245
2018	8.103	9905.342	1307.121	1.740	3.542	2.141
2017	7.705	8816.987	1224.782	1.746	3.667	2.116
2016	7.306	8094.363	1196.688	1.771	3.794	2.100
2015	6.908	8016.431	1150.819	1.751	3.825	2.057
2014	6.509	7636.117	1089.196	1.729	3.727	2.022
2013	6.111	7020.338	1066.210	1.703	3.853	1.998
2012	5.625	6300.615	1014.312	1.693	4.077	1.912
2011	5.139	5614.352	957.565	1.666	3.522	1.780
2010	4.654	4550.453	884.593	1.739	3.750	1.714
2009	4.168	3832.236	846.560	1.886	3.750	1.665
2008	3.682	3468.305	1176.460	1.712	3.630	1.446
2007	3.196	2693.970	1057.494	1.740	2.700	1.374
2006	2.711	2099.229	914.337	1.855	2.440	1.369
2005	2.225	1753.418	840.636	1.853	2.390	1.308
2004	2.117	1508.668	700.070	1.928	2.306	1.215
2003	2.008	1288.643	655.444	1.983	2.223	1.120
2002	1.895	1148.508	619.974	2.050	2.139	1.058
2001	1.774	1053.108	571.710	1.976	2.055	0.940
2000	1.643	959.372	538.578	1.830	1.972	0.893
1999	1.503	873.287	414.431	1.871	1.888	0.750
1998	1.350	828.580	381.688	1.655	1.844	0.647

Note: The CNSA and Roscosmos space agency budget data are unofficial estimates. Official budget data are unavailable.
Note: Above dataset will generate pre-pandemic budgetary trends.

Econometric Analysis Procedure

- Goal: Determine relationship (or sensitivity) of space budget with other macroeconomic and political factors.
- Procedure: Use the Johansen Vector Error Correction Mechanism (VECM) approach to predict space agency budget as function of multiple variables.



$$\ln SB = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \\ \beta_5 \end{bmatrix}^{\intercal} \begin{bmatrix} \ln GPC \\ \ln RD \\ \ln MD \\ \ln ED \\ \ln SD \end{bmatrix} + C$$

Space Budget Modeling Example: EU

- In some instances, multiple co-integrating relationships were found in the data.
- In these cases, multiple model specifications used to fully capture the between-variable trends.

Table 4: ESA Model Specifications

beta	Coefficient	Std. err.	z	P>|z|	[95% conf.	interval]
_ce1						
ln_SpaceBudgetBillions	1	.	.	.	.	.
ln_RD	.099548	.1507387	0.66	0.509	-.1958946	.3949905
ln_MD	.2119222	.1141919	1.86	0.063	-.0118898	.4357341
ln_ED	-.3106155	.0828155	-3.75	0.000	-.4729309	-.1483001
ln_SD	-2.847312	.1282051	-22.21	0.000	-3.09859	-2.596035
ln_GPC	-.1235765	.0303331	-4.07	0.000	-.1830283	-.0641247
_cons	1.274661	.	.	.	.	.

beta	Coefficient	Std. err.	z	P>|z|	[95% conf.	interval]
_ce1						
ln_SpaceBudgetBillions	1	.	.	.	.	.
ln_RD	.5795981	.1450514	4.00	0.000	.2953026	.8638935
ln_MD	.5920364	.0971646	6.09	0.000	.4015973	.7824755
ln_ED	-.5887153	.086826	-6.78	0.000	-.758891	-.4185395
ln_SD	-2.494983	.1346566	-18.53	0.000	-2.758905	-2.231061
_cons	-3.789117	.	.	.	.	.

Space Agency Budget Trends

- Table 5 highlights the trends of each agency's space budget with other economic indicators
- Space budgets highly correlated with political decisions and geopolitical events

Table 5: Variable Correlation with National Space Budgets

	CNSA	ESA	JAXA	Roscosmos	NASA
Researchers in R&D (per million)	+ ~	-	+	+	- ~
Military Spending (% GDP)	+	-	-	+	+
Education Spending (% GDP)	+	+	+	+	-
Science R&D Spending (% GDP)	+	+	+	-	+
GDP/Capita (2020 USD)	+	+	- *	+	+

∗Statistically insignificant correlation at 5% Confidence Interval
~Conflicting results from two different model specifications, value with larger Z-score used

Multinational funding approach required to ensure financial stability throughout planned mission.

Vela Mission Scenario

Station modules

Crew vehicle

Image: Lockheed Martin Space

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Vela Mission Modeling

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- Proposed 2021 budget allocations as % of total space budgets
- Vela budget and fixed costs
    - Fixed costs include modules and rockets

Agency	2021 Budget	Vela Budget	Fixed Costs	Modules	Launches
CNSA	$10.3B × 18%	$9.3B	$7.0B		
esa	$6.5B × 17%	$5.5B	$4.0B		
JAXA	$2.1B × 25%	×5 $2.6B	$1.6B		
РОСКОСМОС	$1.9B × 50%	$4.8B	$3.6B		
NASA	$23.3B ×10.5%	$12.2B	$9.0B		

*Vela Budget is 36% greater than estimated fixed costs, which controls for some level of operational costs over mission.

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Conclusions

- International cooperation provides technological, financial, and programmatic redundancy.
  - **This redundancy reduces risk and improves odds of mission success.**
- Cooperation enables ambitious space mission viability in the short-term.
  - Five-year financial plan proposed to fully fund a manned Mars mission with 36% additional funds available beyond direct costs for operational expenses.
- Cooperation enables mission sustainability in the long-term.
  - International partnerships and commitments increase likelihood of completing the mission.

Future Work

- Consider collaboration among a larger group of cooperating government space agencies in econometric analysis and mission planning.
- Perform a higher-fidelity mission plan for a human mission to Mars:
  - Incorporate scheduling constraints due to funding availability.
  - Incorporate operational, overhead, and diplomatic costs involved with a human Mars program.
  - Incorporate timeline constraints due to launch window availability.
  - Consider future reusability of super heavy-lift launch vehicles in mission cost estimation.
- Integrate econometric analysis and mission planning analysis by using the econometric models to forecast space agency funding levels.

Acknowledgments

Johannes Fedderke
Professor, School of International Affairs
The Pennsylvania State University

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