MULTI-OBJECTIVE DESIGN SPACE EXPLORATION FOR LUNAR GNSS

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INTRO

- The success of future lunar missions depends on the quality of the supporting positioning, navigation, and timing infrastructure.
- Target absolute and relative position accuracy needed for rendezvous, docking and precise landing is 0.4m [1]
- Current Global Navigation Satellite System (GNSS) signals suffer from poor geometric dilution of precision (GDOP) at lunar distance.
- No coverage of the lunar far side
- Deep space network operating close to capacity
- This study [2] explores the design space of a GNSS constellation in lunar orbit and discusses the existing design trade-offs.

METHODS

- Design decisions: Keplerian and Walker-delta pattern parameters. Hybrid constellations allowed
- Objectives: GDOP (98% PCTL)@ lunar surface(min), GDOP availability (GDOP < 6.0) [%](max), space segment cost(min), station-keeping ΔV(min), and robustness to single-satellite failure(max)
- High-fidelity satellite orbit propagation (NASA's GMAT software)
- Station-keeping ΔV magnitudes computed analytically based on mean Keplerian orbit parameter errors [3] and executed every 7 days (27 days for comparison)
- Space segment cost based on USCM8 CER. Key assumptions for satellite dry mass estimate:
  - Link budget for min. received power level (lunar surface) = -150dBW@ L1
  - Chemical propulsion with hydrazine monopropellant
- Multi-Objective Evolutionary Algorithm framework (BorgMOEA [4])
- "No station-keeping maneuver" scenario considered
- Variance-based sensitivity analysis and association rule mining

TABLE 1 Architecture design decisions

	Design decisions (constellation 1)	Value range		Design decisions (constellation 2)	Value range
1	Semi-major axis (SMA)	[3474, 17370] km	8	Semi-major axis (SMA_2)	[3474,17370] km
2	Number of satellites (T)	**{8, 9, …, 30}**	9	Number of satellites (T_2)	**{0, 1, …, 10}**
3	Number of planes (P)	{1, …, T}	10	Number of planes (P_2)	{1, …, T_2}
4	Phasing (F)	{0, …, P-1}	11	Phasing (F_2)	{0, …, P_2-1}
5	Eccentricity (e)	[0 – 0.7]	12	Eccentricity (e_2)	[0 – 0.7]
6	Inclination (i)	[0 – 180] deg	13	Inclination (i_2)	[0 – 180] deg
7	Argument of periapsis (ω)	{90, 270} deg	14	Argument of periapsis (ω_2)	{90, 270} deg

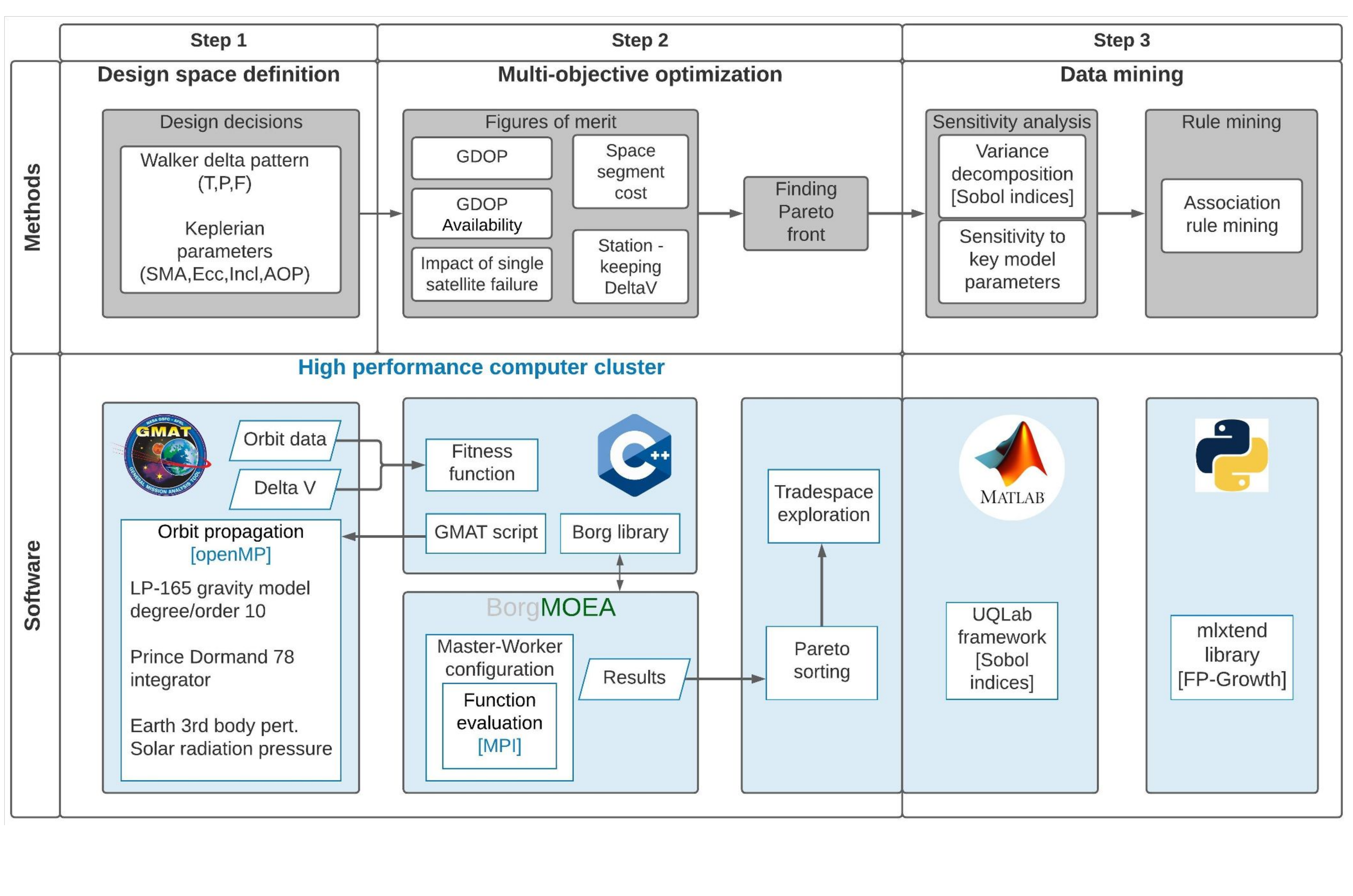

FIGURE 1 Research methods and software setup

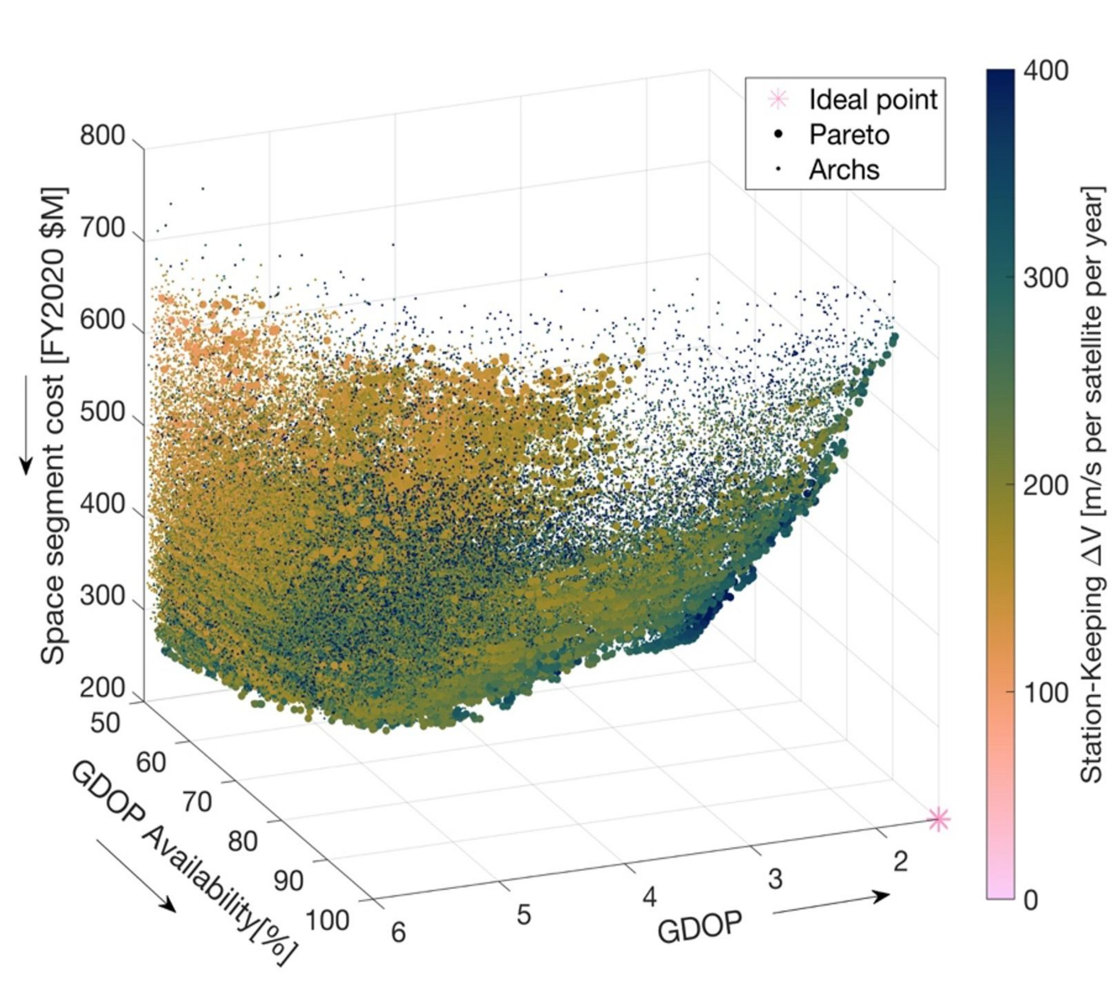

FIGURE 2 Solutions in 4-objective space for archs. with GDOP Availability ≥ 50%. Robustness metric values are not shown. Every dot represents a distinct architecture. Pareto-front archs. are shown in larger dots. The ideal point is shown as a pink asterisk in the front, lower right corner.

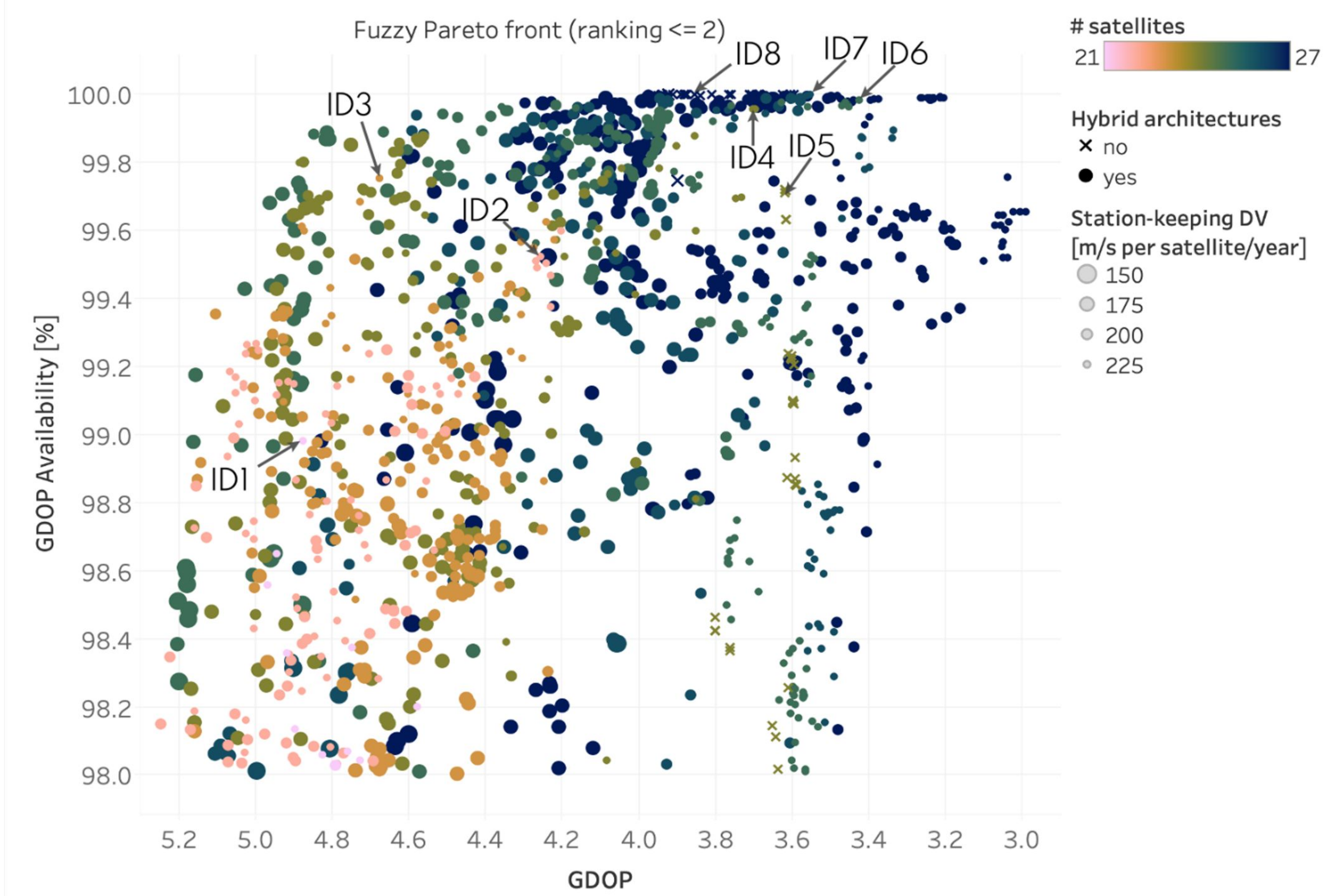

FIGURE 3 Solutions in the fuzzy Pareto front (ranking <=3) with GDOP availability ≥ 98%, station-keeping ΔV < 250 m/s/sat/year, and a total constellation size ≤ 27 satellites. Marker color corresponds to the total number of satellites. Marker type indicates whether the arch. is hybrid (circle) or pure Walker (cross). Marker size is proportional to station-keeping ΔV. Highlighted archs. in Table 2.

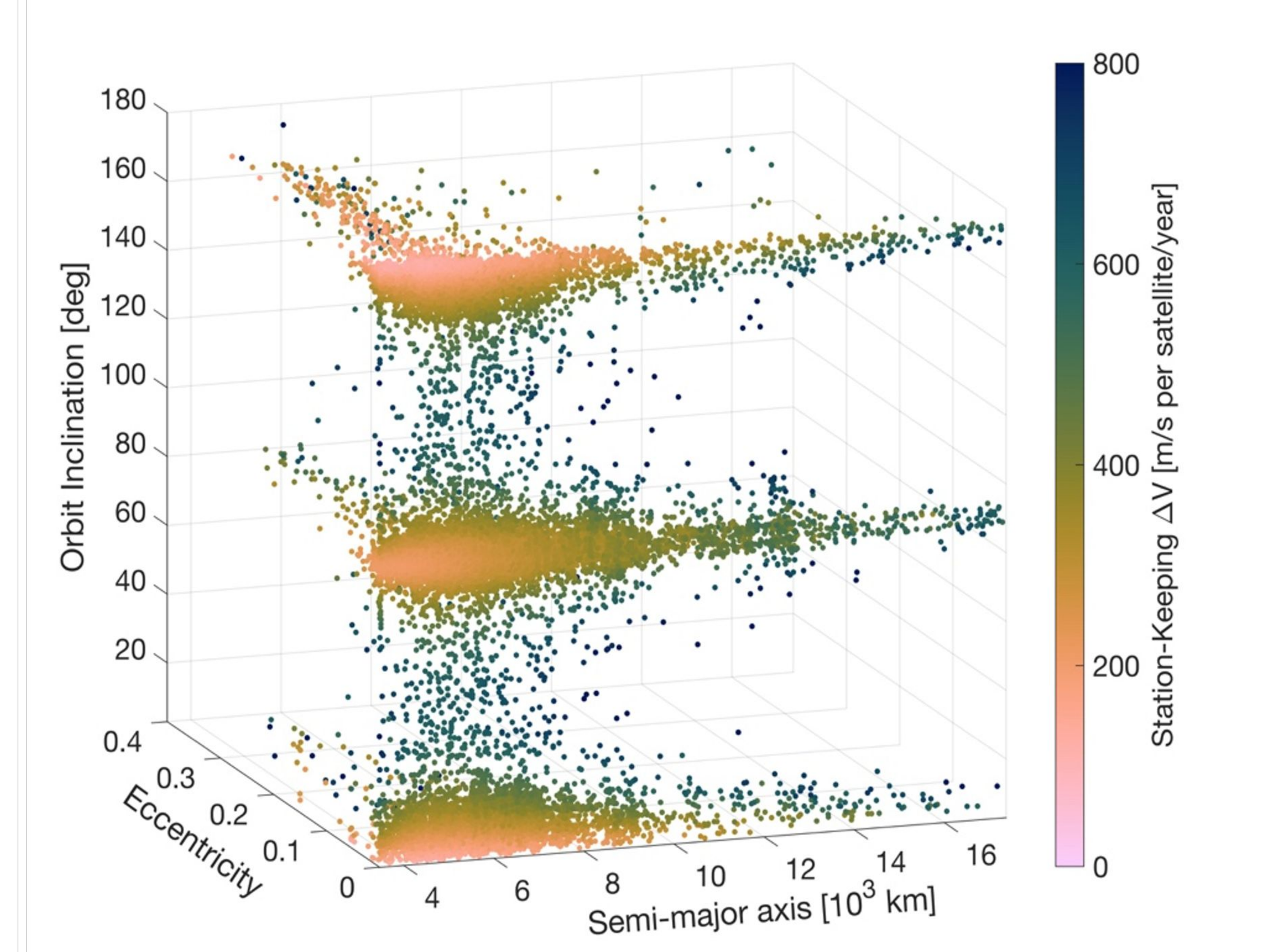

FIGURE 4 Pure Walker solutions in design subspace (color-coded by station-keeping ΔV). Every dot represents a distinct architecture.

Results (~ 250,000 architecture evaluations)

Lunar GNSS Pareto-optimal designs with **GPS-like geometry diversity** (GDOP 98% <6), have a minimum of **24** satellites equally distributed among 3 planes in **near-circular polar** orbit at **~2 R_c altitude**

- The station-keeping (SK) maneuver scheme can maintain GDOP for a period of at least 5 years
- Pareto optimal solutions in the "No station-keeping maneuver" scenario show a ~25% degradation in overall GDOP performance and do not result in significant mass or cost savings when compared to the case with SK maneuvers

Association rule mining :

- Most SK-ΔV efficient orbits are retrograde near-equatorial (170 < incl < 180 [deg])
- Most Robust designs to satellite failure have inclinations of **~58** deg (typical of Earth GNSS)

Sensitivity analysis:

- Choice of Eccentricity and inclination drive SK- ΔV budget

Discussion

- Increasing maneuver frequency to once a month results in GDOP degradation (see Figures 5–6) but there is 3-fold reduction in SK-ΔV budget, allowing for an extension of satellite lifetime.
- Hybrid designs are a mix of polar and equatorial orbits and do not show any significant advantage over pure Walker design in part due to poorer GDOP at the poles.
- Proposed Walker constellations show great performance (GDOP 98% < 3) at scientifically important sites (South Pole Atkins basin) even in case of worst-case single satellite failure

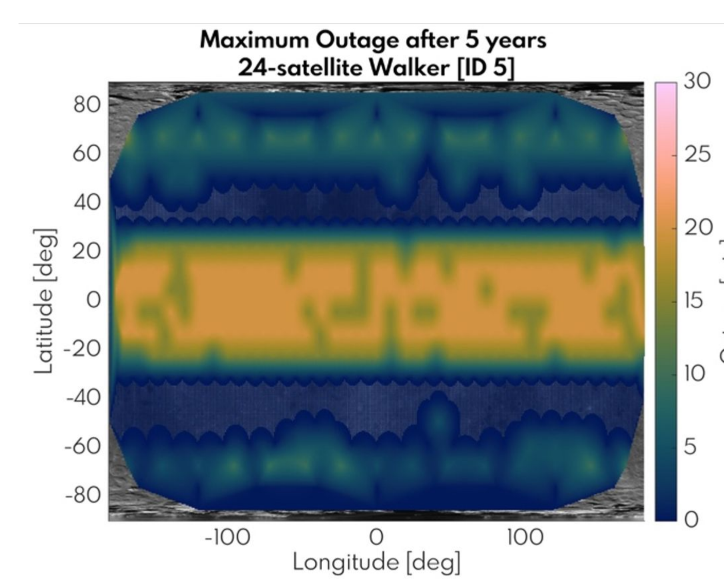

FIGURE 5 Maximum GDOP outage (GDOP > 6.0) plot over the lunar surface obtained over a 1-month period after propagating orbits for 5 years for arch. ID 5

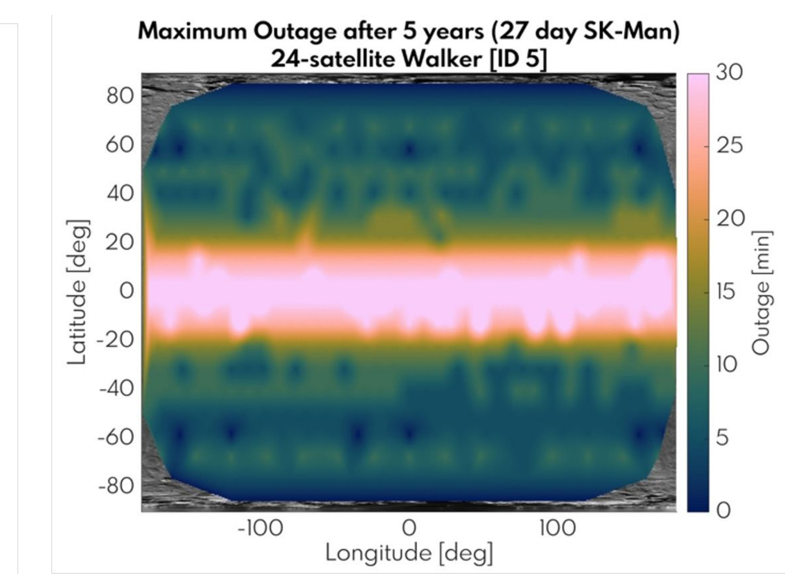

FIGURE 6 Maximum GDOP outage (GDOP > 6.0) plot for architectures ID 5 with station-keeping maneuvers every 27 days.

TABLE 2 Archs. ID 1-13 are examples in the fuzzy Pareto front (ranking ≤3) that achieve GDOP Availability ≥ 98% and station-keeping ΔV≤250m/s/sat/year. For reference, arch.ID 14 is the 30-satellite arch. with best GDOP performance. Arch. ID 15 has the best GDOP performance overall

ID	SMA [km]	T	P	F	e	i [deg]	ω [deg]	SMA_2 [km]	T_2	P_2	F_2	e_2	i_2 [deg]	ω_2 [deg]	GDOP [98th PCTL]	GDOP Availability [%]	Space segment cost [FY20 $M]	Station-keeping ΔV[m/s]	Impact of SSF [%]
1	6691	13	13	9	4.9E-03	90.51	90	7198	8	2	1	4.9E-03	179.73	270	4.88	98.98	406.8	242.11	3.00
2	6630	14	14	10	4.2E-03	90.53	90	6534	8	2	1	4.5E-03	179.74	270	4.26	99.52	419.2	229.38	2.56
3	5664	15	5	3	4.0E-03	87.42	90	7412	8	4	3	1.6E-02	173.91	90	4.68	99.75	438.1	246.45	1.43
4	5513	16	16	10	4.4E-03	86.84	90	7177	8	8	0	2.0E-02	179.66	270	3.70	99.96	448.4	225.13	1.13
5	5730	24	3	0	5.7E-03	89.32	90	—	—	—	—	—	—	—	3.62	99.72	452.5	248.45	0.93
6	5734	17	17	2	4.0E-03	95.19	90	7994	8	8	6	2.0E-03	178.34	270	3.43	99.98	470.3	246.27	0.21
7	5919	18	9	4	4.4E-03	90.06	90	7198	8	2	1	8.4E-03	179.75	270	3.55	100	481.9	231.83	0.50
8	5195	27	3	2	3.5E-04	88.26	270	—	—	—	—	—	—	—	3.85	100	493.4	231.34	0.39
9	6001	19	19	2	1.2E-03	95.14	90	5003	9	9	6	1.9E-03	178.34	270	3.36	100	508.9	225.25	0.07
10	5754	19	19	2	5.4E-04	94.67	270	8410	10	1	0	1.5E-02	177.98	270	3.06	100	532.8	240.20	0.03
11	5867	27	3	0	1.6E-03	89.03	270	8543	3	1	0	1.9E-02	178.42	90	3.11	100	548.4	248.85	0.04
12	7262	24	3	2	4.7E-03	88.84	270	5357	9	1	0	6.1E-03	177.78	270	2.35	100	597.0	246.69	0
13	6320	30	3	2	2.1E-03	88.45	90	7665	9	9	3	1.3E-02	0.16	270	2.08	100	688.6	245.50	0
14	6999	30	3	2	1.6E-03	91.66	90	—	—	—	—	—	—	—	2.72	100	562.7	288.43	0
15	8592	30	3	1	4.0E-03	88.29	270	7049	10	1	0	8.9E-03	178.69	270	1.85	100	730.9	296.88	0

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