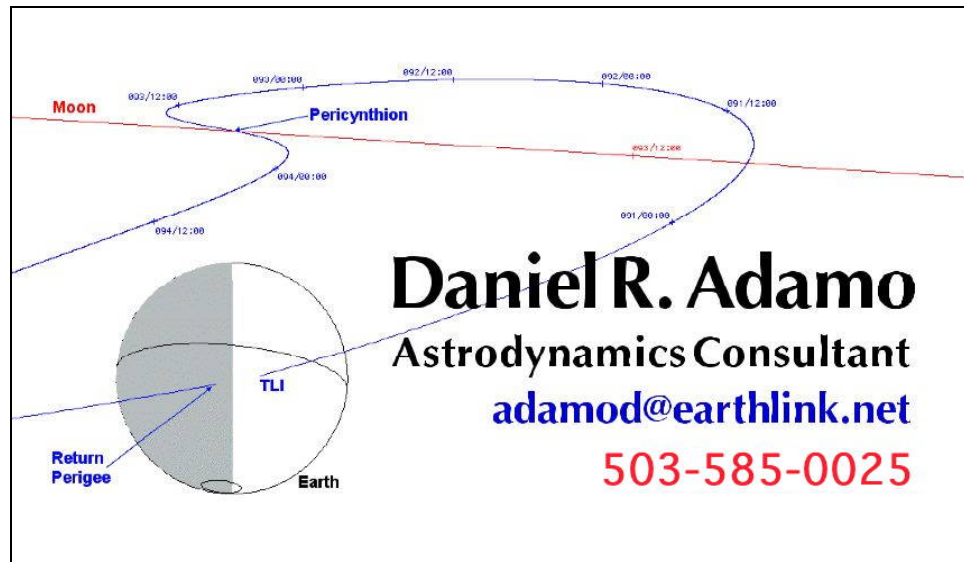


Trajectory Challenges Faced By Orbiting Infrastructure Supporting Multiple Earth Departures For Mars



The Space Show Classroom
19 November 2013

Multiple Mars Departures From Earth-Orbiting Infrastructure

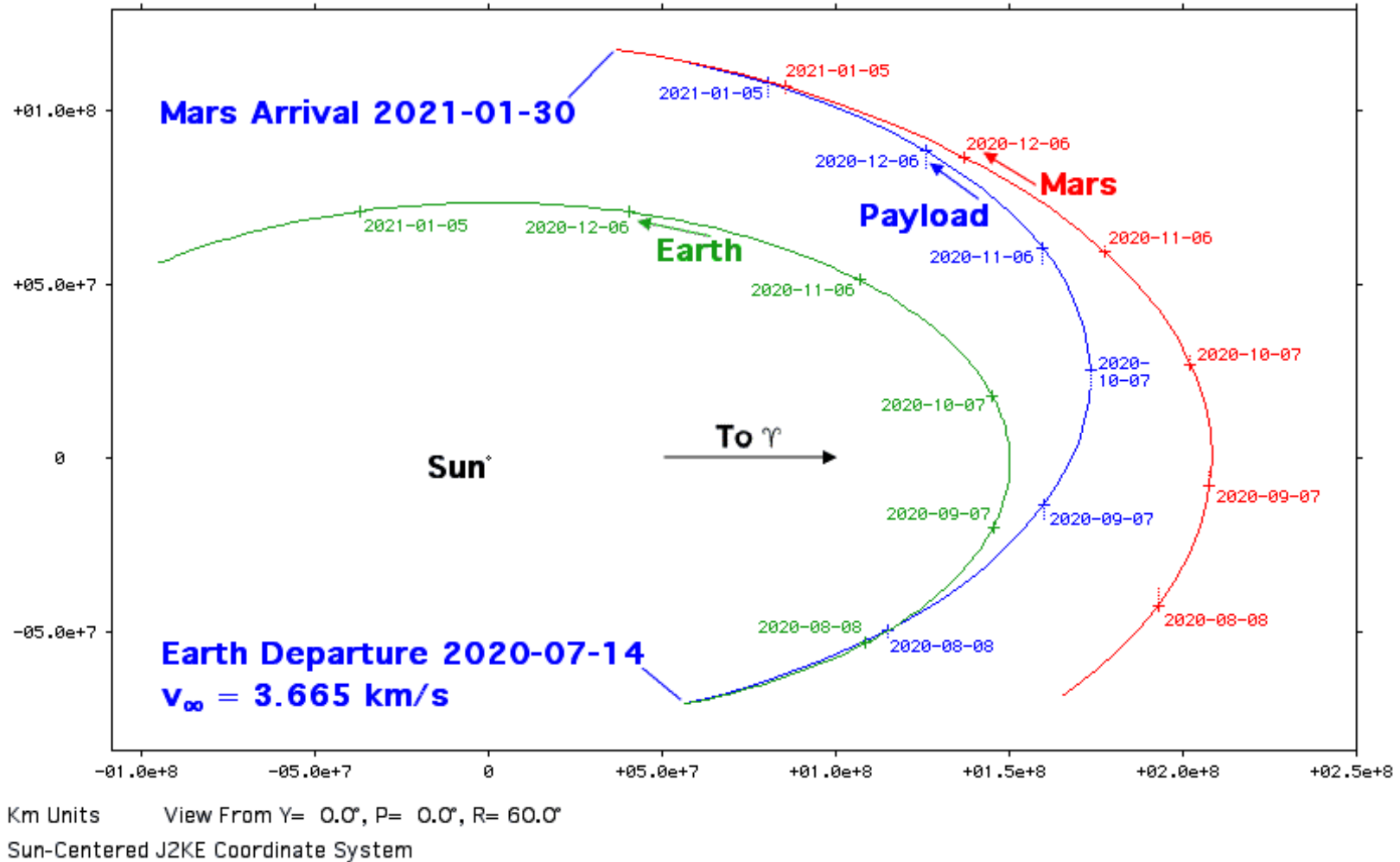
Agenda

- Assume infrastructure in Earth orbit supporting massive payload assembly and servicing
 - The payload performs a single-impulse, high-thrust, in-plane trans-Mars injection (TMI) departure for Mars
 - Assess trajectory challenges to infrastructure supporting departures in 2020 and 2022
- Initially assume payload assembly, servicing, and departure from a height $H = +400$ km circular prograde low Earth orbit (LEO)
- Review TMI geometric constraints and apply them to the 2020 and 2022 departures
- Coast the 2020 departure LEO to 2022 with Sun/Moon/ J_2 perturbations (ignore aero drag to simulate orbit lifetime maintenance) and compare to the 2022 departure LEO
- Introduce the celestial sphere plot (CSP) as a means to assess TMI geometry
- Suggest strategies by which an Earth orbit supporting 2020 TMI can be evolved into an Earth orbit supporting 2022 TMI if the infrastructure can maneuver between TMIs
 - Drop the $H = 400$ km constraint
 - Drop the circular LEO constraint
- Cite pros and cons for infrastructure orbit evolution strategies

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TMI Geometric Constraints

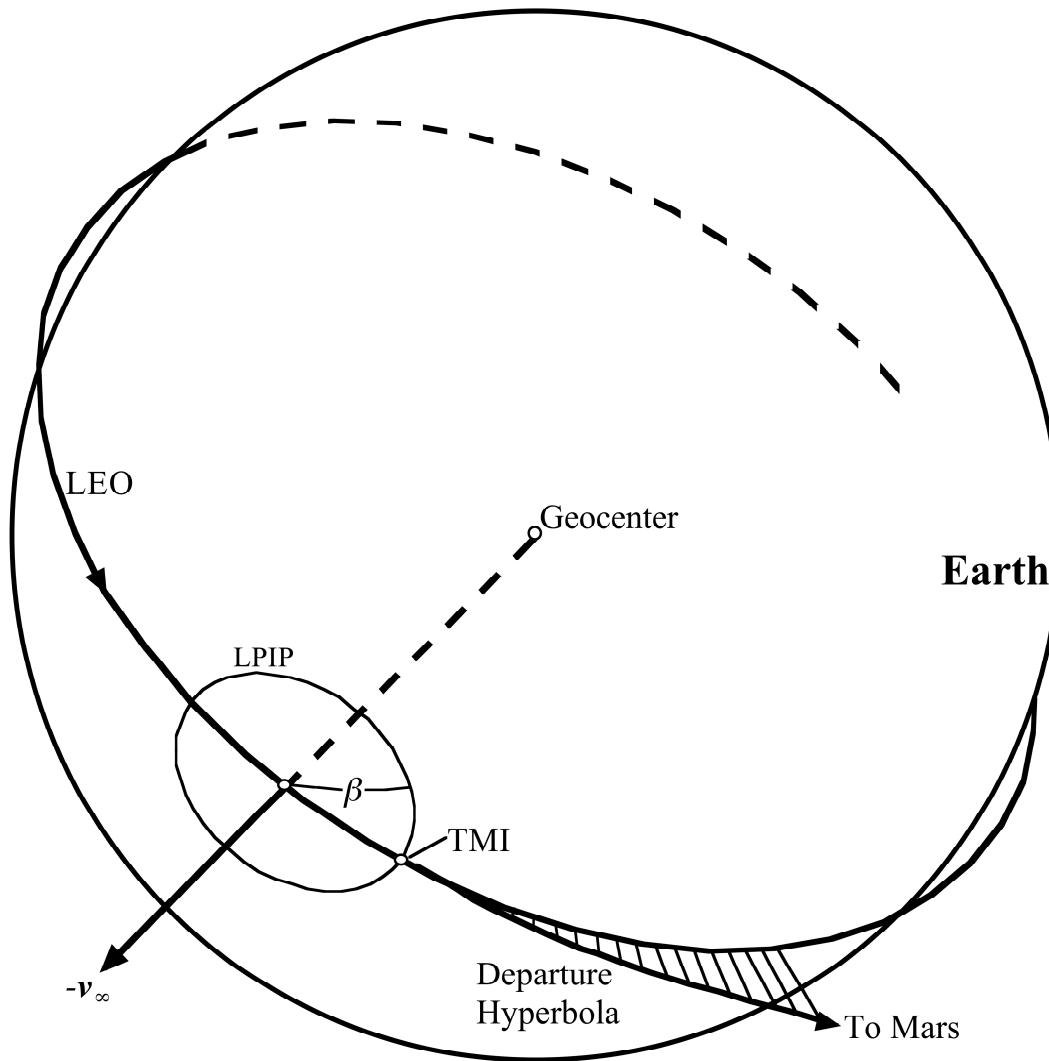
- Asymptotic Earth departure velocity v_∞ is heliocentric velocity in the Earth-to-Mars transfer ellipse at Earth departure, minus Earth heliocentric velocity at Earth departure



Multiple Mars Departures From Earth-Orbiting Infrastructure

TMI Geometric Constraints (continued)

- Before and after TMI, \mathbf{v}_∞ must lie in the plane of payload motion



The locus of possible injection points (LPIP) is a geocentric small circle centered on $-\mathbf{v}_\infty$ whose angular radius β is related to H at TMI and to $|\mathbf{v}_\infty|$

True anomaly in the Earth departure hyperbola increases from zero at TMI to $180^\circ - \beta$ as the payload enters interplanetary space

Multiple Mars Departures From Earth-Orbiting Infrastructure

TMI Geometric Constraints (concluded)

- The geocentric angle \mathbf{v}_∞ makes with Earth's equator is declination δ_∞
 - For \mathbf{v}_∞ to lie in a prograde orbit plane, that plane must have inclination $i \geq |\delta_\infty|$
 - Assume launches to orbiting infrastructure occur at $\delta = +28.5^\circ$, imposing the condition $i \geq 29.0^\circ$ in addition to $i > |\delta_\infty|$
 - With $i > |\delta_\infty|$, \mathbf{v}_∞ can lie in only two prograde orbit planes: one has TMI on a southbound heading, and one has TMI on a northbound heading
 - Assume TMI is on a northbound heading, equivalent to "Pacific" trans-lunar injection (TLI) during the Apollo Program

Multiple Mars Departures From Earth-Orbiting Infrastructure

Departure Date 14 July 2020 | $v_{\infty 20}$ | = 3.665 km/s $\Rightarrow \beta_{20} = 35.504^\circ$

- Box denotes notional Earth departure window 10 days in duration

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Mars Arrive	Earth Depart Date																		
2	Date	4/25/20	5/5/20	5/15/20	5/25/20	6/4/20	6/14/20	6/24/20	7/4/20	7/14/20	7/24/20	8/3/20	8/13/20	8/23/20	9/2/20	9/12/20	9/22/20	10/2/20	10/12/20	10/22/20
3	5/5/20	208.536																		
4	5/15/20	99.212	195.961																	
5	5/25/20	63.285	93.045	183.769																
6	6/4/20	45.590	59.241	87.063	171.956															
7	6/14/20	35.105	42.610	55.313	81.260	160.588														
8	6/24/20	28.177	32.771	39.708	51.490	75.693	149.591													
9	7/4/20	23.260	26.281	30.491	36.870	47.830	70.290	138.967												
10	7/14/20	19.599	21.685	24.422	28.245	34.153	44.263	65.065	128.772											
11	7/24/20	16.781	18.267	20.133	22.578	26.095	31.494	40.804	60.070	118.941										
12	8/3/20	14.562	15.640	16.949	18.579	20.808	23.979	28.904	37.509	55.245	109.538									
13	8/13/20	12.791	13.574	14.506	15.618	17.087	19.058	21.907	26.444	34.323	50.661	100.679								
14	8/23/20	11.363	11.926	12.588	13.351	14.337	15.602	17.334	19.945	24.065	31.317	46.411	92.415							
15	9/2/20	10.208	10.598	11.060	11.574	12.237	13.056	14.131	15.707	18.048	21.839	28.588	42.525	85.016						
16	9/12/20	9.276	9.524	9.830	10.160	10.595	11.118	11.780	12.750	14.137	16.293	19.872	26.166	39.224	78.810					
17	9/22/20	8.529	8.655	8.836	9.025	9.292	9.608	9.998	10.589	11.421	12.704	14.794	18.198	24.264	36.728	74.165				
18	10/2/20	7.945	7.954	8.030	8.108	8.249	8.414	8.616	8.961	9.450	10.231	11.534	13.595	17.035	23.070	35.254	71.663			
19	10/12/20	7.520	7.393	7.380	7.368	7.410	7.463	7.531	7.709	7.979	8.458	9.318	10.681	12.916	16.549	22.736	35.138	71.722		
20	10/22/20	7.320	6.954	6.856	6.770	6.734	6.701	6.672	6.734	6.862	7.154	7.758	8.740	10.364	12.900	16.840	23.481	36.480	74.581	
21	11/1/20	8.305	6.624	6.438	6.290	6.191	6.092	5.990	5.971	6.004	6.183	6.639	7.411	8.710	10.690	13.591	18.035	25.261	39.276	80.280
22	11/11/20	61.926	6.424	6.107	5.907	5.758	5.606	5.449	5.373	5.345	5.456	5.830	6.490	7.615	9.291	11.648	15.044	20.005	27.988	43.436
23	11/21/20	62.101	7.214	5.846	5.606	5.416	5.222	5.024	4.907	4.839	4.913	5.246	5.850	6.880	8.382	10.425	13.244	17.086	22.641	31.557
24	12/1/20	62.059	62.011	5.640	5.377	5.154	4.924	4.693	4.547	4.453	4.509	4.826	5.405	6.383	7.777	9.623	12.089	15.292	19.616	25.852
25	12/11/20	61.980	61.995	42.488	5.243	4.967	4.702	4.442	4.273	4.163	4.212	4.525	5.095	6.043	7.365	9.075	11.306	14.104	17.709	22.565
26	12/21/20	61.869	61.949	61.932	5.672	4.880	4.555	4.263	4.072	3.950	3.997	4.312	4.878	5.806	7.074	8.685	10.747	13.268	16.409	20.451
27	12/31/20	61.727	61.871	61.930	60.705	5.077	4.501	4.153	3.935	3.800	3.844	4.161	4.725	5.636	6.860	8.393	10.327	12.646	15.466	18.978
28	1/10/21	61.555	61.763	61.888	61.852	7.979	4.633	4.125	3.859	3.704	3.741	4.055	4.614	5.508	6.694	8.162	9.995	12.158	14.742	17.887
29	1/20/21	61.352	61.624	61.814	61.881	60.801	5.456	4.229	3.852	3.658	3.679	3.984	4.533	5.408	6.559	7.971	9.718	11.758	14.161	17.035
30	1/30/21	61.121	61.456	61.708	61.848	61.760	12.527	4.652	3.940	3.665	3.652	3.939	4.473	5.325	6.443	7.804	9.479	11.416	13.674	16.341
31	2/9/21	60.863	61.259	61.573	61.779	61.819	60.713	6.246	4.207	3.741	3.664	3.918	4.428	5.255	6.338	7.653	9.263	11.113	13.251	15.753
32	2/19/21	60.577	61.034	61.408	61.677	61.797	61.721	17.393	4.913	3.925	3.721	3.920	4.396	5.192	6.241	7.511	9.063	10.837	12.874	15.241
33	3/1/21	60.266	60.782	61.216	61.546	61.733	61.812	60.518	7.149	4.323	3.845	3.951	4.378	5.136	6.148	7.376	8.875	10.581	12.530	14.782
34	3/11/21	59.930	60.504	60.996	61.386	61.636	61.801	61.693	20.520	5.237	4.083	4.020	4.375	5.087	6.060	7.245	8.694	10.338	12.209	14.362
35	3/21/21	59.569	60.201	60.749	61.198	61.508	61.742	61.822	60.172	7.839	4.547	4.152	4.395	5.047	5.976	7.118	8.519	10.106	11.907	13.973
36	3/31/21	59.186	59.873	60.477	60.983	61.351	61.648	61.823	61.647	21.219	5.544	4.394	4.448	5.018	5.896	6.994	8.348	9.882	11.619	13.607
37	4/10/21	58.780	59.521	60.180	60.743	61.168	61.523	61.770	61.820	59.647	8.188	4.853	4.557	5.007	5.823	6.873	8.181	9.665	11.342	13.259
38	4/20/21	58.353	59.147	59.859	60.477	60.957	61.369	61.680	61.835	61.641	19.989	5.812	4.766	5.024	5.759	6.757	8.017	9.453	11.074	12.926
39	4/30/21	57.905	58.750	59.514	60.186	60.721	61.189	61.559	61.788	61.872	58.677	8.238	5.168	5.088	5.710	6.646	7.857	9.245	10.813	12.605
40	5/10/21	57.436	58.332	59.147	59.871	60.460	60.981	61.408	61.702	61.902	61.627	17.798	6.008	5.235	5.684	6.543	7.702	9.043	10.560	12.295
41	5/20/21	56.948	57.892	58.757	59.532	60.174	60.748	61.231	61.583	61.861	61.936	56.751	8.064	5.543	5.694	6.452	7.551	8.844	10.312	11.993
42	5/30/21	56.442	57.432	58.345	59.171	59.864	60.490	61.026	61.434	61.777	61.984	61.569	15.357	6.204	5.770	6.378	7.408	8.650	10.070	11.699
43	6/9/21	55.916	56.952	57.912	58.787	59.530	60.207	60.796	61.258	61.659	61.949	61.987	52.732	7.811	5.970	6.333	7.273	8.462	9.832	11.412
44	6/19/21	55.373	56.453	57.458	58.381	59.173	59.900	60.541	61.056	61.512	61.868	62.055	61.510	13.089	6.437	6.336	7.152	8.279	9.600	11.131
45	6/29/21	54.812	55.935	56.983	57.953	58.793	59.569	60.261	60.827	61.336	61.751	62.026	62.089	44.513	7.595	6.429	7.051	8.103	9.372	10.856
46	7/9/21	54.234	55.397	56.488	57.503	58.391	59.214	59.956	60.573	61.134	61.604	61.945	62.179	61.366	11.237	6.711	6.984	7.937	9.150	10.586
47	7/19/21	53.640	54.842	55.974	57.033	57.966	58.836	59.627	60.294	60.905	61.429	61.829	62.153	62.196	32.797	7.469	6.978	7.786	8.934	10.321
48	7/29/21	53.028	54.268	55.439	56.541	57.519	58.435	59.274	59.989	60.650	61.226	61.681	62.073	62.312	61.052	9.843	7.096	7.656	8.725	10.060
49	8/8/21	52.401	53.677	54.886	56.029	57.050	58.011	58.896	59.660	60.370	60.996	61.503	61.954	62.289	62.293	22.666	7.518	7.565	8.525	9.805
50	8/18/21	51.757	53.068	54.313	55.496	56.560	57.564	58.495	59.306	60.064	60.740	61.298	61.803	62.207	62.435	60.460	8.931	7.551	8.340	9.555

Multiple Mars Departures From Earth-Orbiting Infrastructure

Departure Date 14 July 2020 $\delta_{\infty 20} = +26.822^\circ \Rightarrow i_{20} = 29.0^\circ$

- **Box** denotes notional Earth departure window 10 days in duration

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Mars Arrive																			
2	Date	4/25/20	5/5/20	5/15/20	5/25/20	6/4/20	6/14/20	6/24/20	7/4/20	7/14/20	7/24/20	8/3/20	8/13/20	8/23/20	9/2/20	9/12/20	9/22/20	10/2/20	10/12/20	10/22/20
3	5/5/20	-15.001																		
4	5/15/20	-12.896	-12.845																	
5	5/25/20	-10.828	-10.611	-10.579																
6	6/4/20	-8.920	-8.440	-8.257	-8.259															
7	6/14/20	-7.258	-6.453	-6.023	-5.902	-5.936														
8	6/24/20	-5.886	-4.732	-3.993	-3.655	-3.593	-3.653													
9	7/4/20	-4.813	-3.314	-2.242	-1.628	-1.383	-1.370	-1.474												
10	7/14/20	-4.030	-2.203	-0.803	0.110	0.595	0.762	0.692	0.555											
11	7/24/20	-3.520	-1.385	0.324	1.532	2.278	2.654	2.692	2.556	2.390										
12	8/3/20	-3.265	-0.834	1.162	2.645	3.646	4.252	4.449	4.378	4.180	3.966									
13	8/13/20	-3.251	-0.523	1.743	3.475	4.711	5.543	5.918	5.956	5.783	5.489	5.252								
14	8/23/20	-3.470	-0.424	2.102	4.062	5.506	6.544	7.092	7.257	7.146	6.816	6.466	6.202							
15	9/2/20	-3.926	-0.512	2.279	4.449	6.075	7.292	7.995	8.281	8.247	7.907	7.474	7.063	6.768						
16	9/12/20	-4.640	-0.764	2.312	4.683	6.469	7.837	8.666	9.054	8.091	8.749	8.249	7.706	7.227	6.948					
17	9/22/20	-5.675	-1.163	2.243	4.815	6.742	8.235	9.161	9.621	9.709	9.353	8.783	8.112	7.453	7.000	6.741				
18	10/2/20	-7.187	-1.697	2.117	4.900	6.953	8.546	9.538	10.039	10.147	9.751	9.093	8.285	7.444	6.825	6.414	6.217			
19	10/12/20	-9.606	-2.377	1.989	5.003	7.169	8.836	9.863	10.371	10.463	9.990	9.214	8.247	7.218	6.448	5.914	5.634	5.566		
20	10/22/20	-14.412	-3.266	1.922	5.200	7.465	9.178	10.208	10.684	10.722	10.129	9.195	8.044	6.826	5.929	5.312	5.000	4.953	4.996	
21	11/1/20	-30.257	-4.589	2.013	5.596	7.930	9.654	10.649	11.054	10.994	10.234	9.101	7.744	6.343	5.353	4.701	4.409	4.433	4.567	4.738
22	11/11/20	15.384	-7.354	2.439	6.347	8.684	10.358	11.270	11.557	11.353	10.378	9.006	7.426	5.859	4.814	4.171	3.941	4.068	4.322	4.646
23	11/21/20	18.871	-24.781	3.667	7.736	9.896	11.410	12.165	12.275	11.875	10.634	8.987	7.176	5.465	4.395	3.790	3.643	3.888	4.273	4.754
24	12/1/20	19.129	17.209	7.962	10.409	11.848	12.969	13.446	13.295	12.635	11.076	9.118	7.069	5.229	4.149	3.591	3.531	3.891	4.402	5.032
25	12/11/20	18.984	17.328	61.609	16.381	15.092	15.280	15.252	14.712	13.708	11.768	9.461	7.162	5.193	4.099	3.582	3.596	4.056	4.679	5.443
26	12/21/20	18.706	16.992	15.907	36.282	20.938	18.763	17.777	16.636	15.168	12.770	10.063	7.490	5.376	4.247	3.749	3.817	4.357	5.073	5.950
27	12/31/20	18.366	16.566	14.938	22.327	33.326	24.239	21.320	19.207	17.096	14.134	10.959	8.071	5.777	4.581	4.075	4.171	4.767	5.557	6.526
28	1/10/21	17.990	16.107	14.245	13.455	65.768	33.532	26.389	22.627	19.587	15.913	12.177	8.914	6.392	5.087	4.539	4.635	5.265	6.106	7.147
29	1/20/21	17.590	15.630	13.623	11.971	17.784	50.918	33.906	27.198	22.768	18.166	13.745	10.024	7.212	5.750	5.125	5.191	5.831	6.704	7.798
30	1/30/21	17.174	15.144	13.031	11.044	10.448	77.985	45.571	33.410	26.822	20.973	15.695	11.411	8.233	6.560	5.818	5.827	6.453	7.339	8.466
31	2/9/21	16.746	14.651	12.454	10.282	8.647	14.259	63.693	42.043	32.017	24.444	18.074	13.092	9.456	7.510	6.611	6.531	7.121	8.001	9.145
32	2/19/21	16.307	14.153	11.886	9.592	7.551	7.178	72.403	54.162	38.749	28.737	20.952	15.093	10.889	8.600	7.498	7.297	7.828	8.684	9.828
33	3/1/21	15.861	13.652	11.325	8.943	6.686	5.132	11.221	69.593	47.550	34.080	24.428	17.459	12.549	9.834	8.477	8.123	8.571	9.384	10.513
34	3/11/21	15.408	13.148	10.769	8.317	5.926	3.904	3.820	65.925	58.827	40.781	28.645	20.253	14.463	11.221	9.551	9.006	9.346	10.099	11.198
35	3/21/21	14.949	12.641	10.215	7.709	5.225	2.960	1.538	8.766	70.581	49.188	33.806	23.569	16.671	12.778	10.727	9.949	10.155	10.829	11.883
36	3/31/21	14.484	12.132	9.664	7.112	4.561	2.150	0.194	0.553	62.141	59.335	40.177	27.540	19.234	14.532	12.014	10.955	10.998	11.573	12.568
37	4/10/21	14.015	11.621	9.116	6.524	3.922	1.416	-0.812	-1.994	7.170	68.699	48.044	32.353	22.236	16.519	13.430	12.031	11.877	12.333	13.254
38	4/20/21	13.542	11.109	8.569	5.943	3.301	0.728	-1.657	-3.450	-2.486	60.775	57.392	38.260	25.802	18.792	14.995	13.187	12.798	13.110	13.942
39	4/30/21	13.064	10.595	8.023	5.368	2.693	0.073	-2.412	-4.509	-5.358	6.956	66.062	45.550	30.105	21.424	16.742	14.436	13.765	13.909	14.634
40	5/10/21	12.583	10.079	7.478	4.798	2.096	-0.558	-3.109	-5.380	-6.930	-5.170	61.029	54.311	35.396	24.524	18.714	15.797	14.788	14.732	15.332
41	5/20/21	12.099	9.562	6.934	4.231	1.508	-1.172	-3.767	-6.143	-8.037	-8.468	9.016	63.065	41.999	28.251	20.974	17.294	15.877	15.585	16.038
42	5/30/21	11.611	9.043	6.391	3.668	0.927	-1.772	-4.397	-6.839	-8.922	-10.173	-7.327	61.883	50.193	32.840	23.612	18.962	17.046	16.474	16.756
43	6/9/21	11.119	8.522	5.848	3.107	0.352	-2.361	-5.005	-7.488	-9.683	-11.324	-11.206	14.843	59.331	38.634	26.763	20.851	18.315	17.407	17.490
44	6/19/21	10.625	8.000	5.305	2.549	-0.218	-2.940	-5.596	-8.105	-10.366	-12.216	-13.066	-8.804	62.540	46.073	30.636	23.033	19.709	18.394	18.245
45	6/29/21	10.127	7.477	4.762	1.993	-0.783	-3.511	-6.173	-8.696	-10.996	-12.964	-14.259	-13.492	26.008	55.258	35.560	25.617	21.266	19.450	19.025
46	7/9/21	9.626	6.951	4.219	1.438	-1.345	-4.076	-6.739	-9.268	-11.588	-13.623	-15.148	-15.531	-9.394	62.374	42.042	28.776	23.041	20.594	19.838
47	7/19/21	9.121	6.424	3.676	0.885	-1.903	-4.634	-7.296	-9.823	-12.151	-14.221	-15.872	-16.760	-15.258	40.185	50.687	32.794	25.117	21.851	20.693
48	7/29/21	8.613	5.894	3.132	0.332	-2.459	-5.188	-7.844	-10.365	-12.690	-14.776	-16.495	-17.634	-17.505	60.399	38.164	27.627	23.262	21.603	
49	8/8/21	8.102	5.363	2.587	-0.220	-3.012	-5.737	-8.384	-10.895	-13.211	-15.298	-17.049	-18.320	-18.761	-16.436	52.160	45.718	30.798	24.885	22.585
50	8/18/21	7.587	4.829	2.041	-0.771	-3.563	-6.281	-8.918	-11.414	-13.716	-15.793	-17.554	-18.892	-19.606	-18.913	-6.642	56.247	35.041	26.815	23.664

Multiple Mars Departures From Earth-Orbiting Infrastructure

Departure Date 9 September 2022 | $v_{\infty 22}$ | = 4.309 km/s $\Rightarrow \beta_{22} = 40.535^\circ$

- Box denotes notional Earth departure window 10 days in duration

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	
1	Mars Arrive Date										Earth Depart Date										
2	7/11/22	216.412																			
3	7/21/22	104.852	207.160																		
4	7/31/22	68.022	100.130	197.788																	
5	8/10/22	49.753	64.795	95.312	188.234																
6	8/20/22	38.836	47.277	61.481	90.368	178.538															
7	8/30/22	31.559	36.819	44.718	58.057	85.355	168.631														
8	9/9/22	26.354	29.857	34.722	42.053	54.584	80.215	158.530													
9	9/19/22	22.447	24.883	28.077	32.520	39.350	51.014	74.980	148.351												
10	9/29/22	19.415	21.153	23.336	26.193	30.285	36.564	47.381	69.751	138.121											
11	10/9/22	17.006	18.261	19.787	21.688	24.279	27.977	33.730	43.786	64.536	128.043										
12	10/19/22	15.059	15.964	17.037	18.321	20.012	22.300	25.630	30.953	40.235	59.500	118.424									
13	10/29/22	13.466	14.108	14.856	15.717	16.831	18.278	20.289	23.354	28.242	36.886	54.866	109.572								
14	11/8/22	12.152	12.591	13.096	13.656	14.378	15.290	16.520	18.362	21.163	25.757	33.948	50.831	102.078							
15	11/18/22	11.065	11.340	11.658	11.995	12.442	12.995	13.733	14.858	16.540	19.225	23.709	31.590	47.810	96.614						
16	11/28/22	10.168	10.307	10.475	10.642	10.887	11.192	11.606	12.288	13.324	15.001	17.761	22.261	30.170	46.184	93.835					
17	12/8/22	9.441	9.454	9.499	9.532	9.626	9.753	9.948	10.346	10.994	12.107	13.977	16.927	21.735	29.947	47.179	94.415				
18	12/18/22	8.892	8.762	8.696	8.619	8.596	8.592	8.636	8.852	9.264	10.055	11.445	13.614	17.008	22.288	31.038	48.944	98.547			
19	12/28/22	8.601	8.225	8.042	7.870	7.754	7.653	7.592	7.691	7.963	8.576	9.709	11.465	14.143	18.062	23.914	33.490	52.572	106.053		
20	1/7/23	9.018	7.873	7.529	7.262	7.067	6.891	6.759	6.785	6.981	7.505	8.508	10.045	12.333	15.530	19.989	26.556	37.052	57.810	116.514	
21	1/17/23	13.999	7.841	7.164	6.782	6.513	6.278	6.096	6.082	6.242	6.734	7.679	9.100	11.161	13.934	17.618	22.685	29.937	41.507	64.363	
22	1/27/23	57.922	8.739	6.998	6.429	6.078	5.790	5.573	5.539	5.693	6.185	7.112	8.469	10.388	12.889	16.091	20.294	25.889	33.887	46.660	
23	2/6/23	61.803	14.904	7.204	6.222	5.754	5.411	5.167	5.127	5.291	5.800	6.727	8.049	9.869	12.180	15.057	18.705	23.326	29.475	38.270	
24	2/16/23	62.044	56.696	8.461	6.222	5.545	5.130	4.861	4.820	5.001	5.536	6.470	7.766	9.512	11.680	14.321	17.586	21.574	26.627	33.352	
25	2/26/23	62.059	61.652	14.832	6.618	5.475	4.945	4.640	4.599	4.798	5.356	6.297	7.572	9.257	11.312	13.772	16.756	20.303	24.641	30.134	
26	3/8/23	62.005	61.986	54.369	8.062	5.608	4.860	4.496	4.447	4.660	5.237	6.182	7.435	9.067	11.028	13.343	16.109	19.332	23.171	27.863	
27	3/18/23	61.912	62.028	61.520	13.907	6.123	4.900	4.427	4.353	4.571	5.160	6.102	7.334	8.917	10.797	12.991	15.584	18.557	22.029	26.163	
28	3/28/23	61.786	61.988	61.982	49.890	7.582	5.124	4.437	4.309	4.520	5.110	6.045	7.253	8.790	10.598	12.690	15.140	17.914	21.104	24.830	
29	4/7/23	61.631	61.902	62.052	61.346	12.535	5.685	4.548	4.315	4.498	5.080	6.001	7.183	8.677	10.420	12.423	14.751	17.361	20.328	23.741	
30	4/17/23	61.450	61.783	62.024	61.995	42.218	7.035	4.809	4.374	4.502	5.062	5.964	7.118	8.570	10.255	12.177	14.400	16.872	19.656	22.823	
31	4/27/23	61.241	61.634	61.945	62.101	61.051	11.015	5.343	4.503	4.531	5.054	5.930	7.055	8.466	10.095	11.945	14.075	16.428	19.059	22.025	
32	5/7/23	61.007	61.456	61.830	62.084	61.995	32.407	6.497	4.743	4.591	5.055	5.898	6.990	8.361	9.938	11.723	13.769	16.018	18.517	21.316	
33	5/17/23	60.748	61.252	61.684	62.012	62.140	60.598	9.550	5.187	4.695	5.066	5.866	6.922	8.253	9.782	11.505	13.475	15.631	18.015	20.672	
34	5/27/23	60.463	61.022	61.509	61.901	62.135	62.042	23.510	6.088	4.874	5.092	5.834	6.852	8.142	9.624	11.290	13.191	15.263	17.545	20.078	
35	6/6/23	60.154	60.765	61.307	61.757	62.067	62.233	59.692	8.313	5.193	5.143	5.805	6.778	8.028	9.464	11.076	12.912	14.908	17.098	19.522	
36	6/16/23	59.820	60.483	61.078	61.585	61.957	62.237	62.098	17.106	5.829	5.238	5.781	6.701	7.909	9.301	10.862	12.638	14.563	16.670	18.995	
37	6/26/23	59.461	60.175	60.822	61.383	61.815	62.171	62.345	57.629	7.352	5.421	5.769	6.623	7.786	9.135	10.647	12.366	14.226	16.255	18.492	
38	7/6/23	59.077	59.842	60.539	61.154	61.642	62.061	62.356	62.138	12.801	5.804	5.780	6.545	7.660	8.966	10.430	12.096	13.894	15.852	18.007	
39	7/16/23	58.669	59.483	60.231	60.898	61.440	61.916	62.289	62.446	52.372	6.740	5.840	6.470	7.530	8.793	10.212	11.826	13.566	15.457	17.536	
40	7/26/23	58.236	59.099	59.896	60.615	61.209	61.741	62.177	62.458	62.231	9.968	6.012	6.405	7.398	8.616	9.991	11.556	13.241	15.070	17.078	
41	8/5/23	57.779	58.689	59.535	60.304	60.950	61.535	62.030	62.387	62.598	39.764	6.492	6.363	7.265	8.436	9.767	11.285	12.918	14.687	16.629	
42	8/15/23	57.297	58.254	59.147	59.966	60.664	61.301	61.851	62.270	62.604	62.351	8.221	6.374	7.133	8.253	9.540	11.013	12.596	14.309	16.189	
43	8/25/23	56.790	57.792	58.732	59.601	60.349	61.037	61.641	62.117	62.525	62.761	24.294	6.531	7.008	8.067	9.311	10.740	12.275	13.934	15.754	
44	9/4/23	56.258	57.305	58.291	59.208	60.006	60.745	61.401	61.932	62.399	62.752	62.503	7.276	6.900	7.878	9.078	10.464	11.954	13.561	15.324	
45	9/14/23	55.702	56.792	57.823	58.788	59.635	60.423	61.131	61.715	62.238	62.660	62.904	14.465	6.844	7.686	8.841	10.186	11.632	13.189	14.899	
46	9/24/23	55.120	56.253	57.327	58.339	59.235	60.072	60.832	61.468	62.044	62.525	62.867	62.783	6.990	7.495	8.600	9.905	11.308	12.819	14.476	
47	10/4/23	54.513	55.687	56.805	57.862	58.805	59.692	60.502	61.189	61.818	62.354	62.759	63.076	9.360	7.309	8.354	9.621	10.984	12.448	14.056	
48	10/14/23	53.881	55.095	56.254	57.357	58.347	59.281	60.142	60.880	61.560	62.150	62.611	63.005	63.134	7.148	8.103	9.333	10.657	12.077	13.637	
49	10/24/23	53.224	54.476	55.676	56.822	57.859	58.840	59.750	60.540	61.271	61.913	62.428	62.878	63.220	7.252	7.844	9.041	10.328	11.706	13.219	

Multiple Mars Departures From Earth-Orbiting Infrastructure

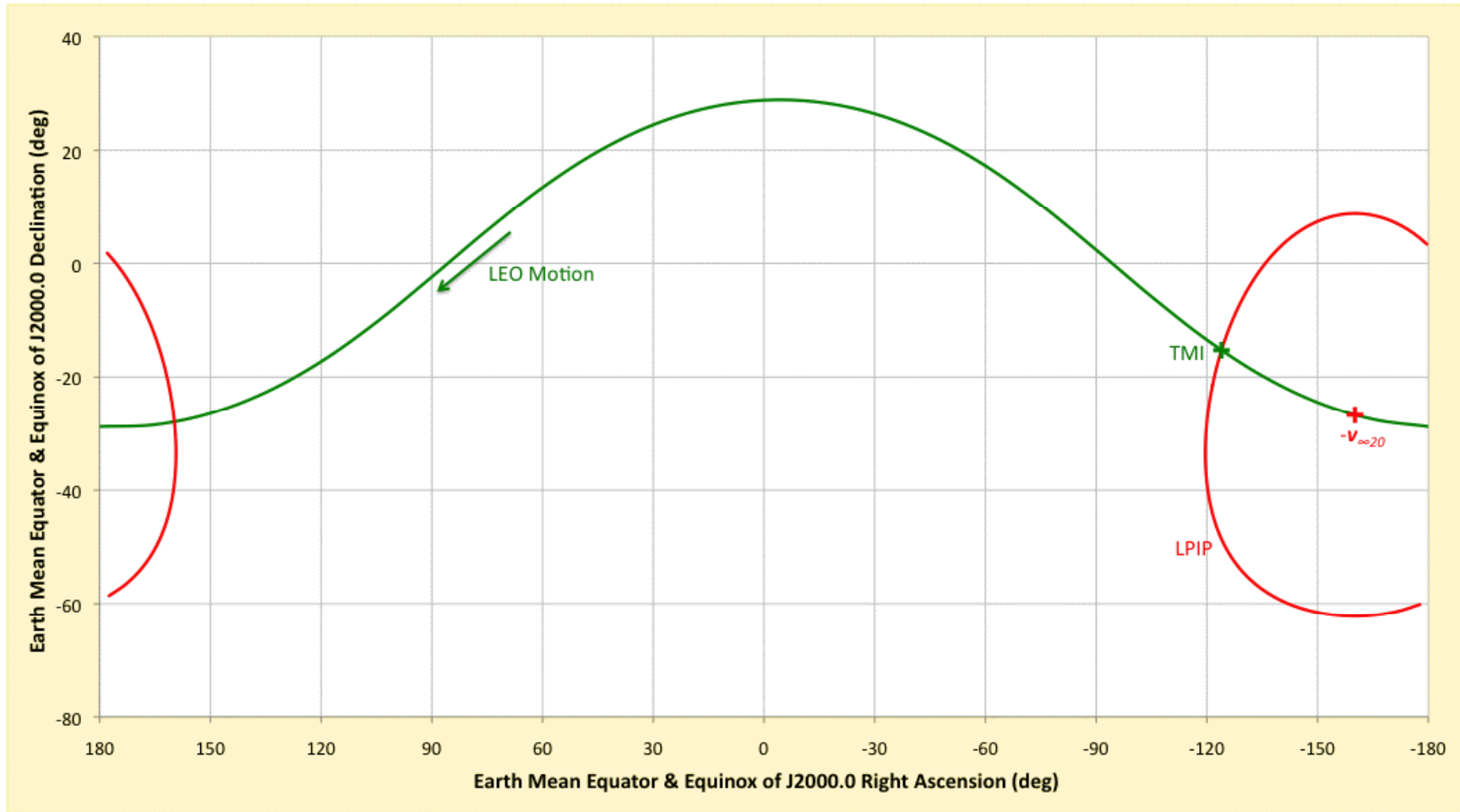
Departure Date 9 September 2022 $\delta_{\infty 22} = +44.496^\circ \Rightarrow i_{22} = 45.0^\circ$

- Box denotes notional Earth departure window 10 days in duration

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Mars Arrive	Earth Depart Date																		
2	Date	7/1/22	7/11/22	7/21/22	7/31/22	8/10/22	8/20/22	8/30/22	9/9/22	9/19/22	9/29/22	10/9/22	10/19/22	10/29/22	11/8/22	11/18/22	11/28/22	12/8/22	12/18/22	12/28/22
3	7/11/22	11.145																		
4	7/21/22	13.291	13.393																	
5	7/31/22	15.093	15.337	15.411																
6	8/10/22	16.549	16.950	17.135	17.171															
7	8/20/22	17.701	18.242	18.547	18.660	18.670														
8	8/30/22	18.613	19.258	19.666	19.862	19.922	19.915													
9	9/9/22	19.352	20.065	20.543	20.805	20.919	20.943	20.915												
10	9/19/22	19.984	20.731	21.245	21.543	21.695	21.753	21.740	21.707											
11	9/29/22	20.569	21.319	21.838	22.143	22.309	22.386	22.391	22.366	22.333										
12	10/9/22	21.163	21.887	22.385	22.671	22.824	22.901	22.916	22.905	22.876	22.843									
13	10/19/22	21.824	22.488	22.940	23.185	23.306	23.363	23.372	23.371	23.356	23.326	23.301								
14	10/29/22	22.617	23.177	23.554	23.739	23.811	23.832	23.822	23.822	23.821	23.803	23.778	23.750							
15	11/8/22	23.627	24.013	24.277	24.378	24.387	24.361	24.324	24.318	24.326	24.320	24.296	24.250	24.208						
16	11/18/22	24.973	25.071	25.163	25.150	25.077	24.996	24.926	24.908	24.920	24.917	24.881	24.800	24.704	24.638					
17	11/28/22	26.845	26.449	26.275	26.101	25.922	25.776	25.668	25.633	25.638	25.619	25.540	25.386	25.195	25.040	24.940				
18	12/8/22	29.576	28.292	27.693	27.285	26.963	26.733	26.580	26.518	26.499	26.428	26.253	25.964	25.621	25.335	25.194	25.023			
19	12/18/22	33.815	30.833	29.531	28.767	28.242	27.901	27.684	27.574	27.500	27.315	26.966	26.466	25.913	25.467	25.146	25.042	24.894		
20	12/28/22	41.024	34.472	31.952	30.634	29.810	29.307	28.996	28.798	28.611	28.225	27.605	26.820	26.021	25.417	24.998	24.767	24.758	24.661	
21	1/7/23	55.009	39.967	35.215	33.002	31.727	30.984	30.522	30.173	29.786	29.085	28.098	26.980	25.940	25.211	24.735	24.496	24.431	24.501	24.478
22	1/17/23	85.430	48.892	39.755	36.043	34.072	32.966	32.266	32.266	31.668	30.966	29.827	28.402	26.948	25.709	24.909	24.423	24.213	24.197	24.253
23	1/27/23	19.597	64.715	46.341	40.016	36.952	35.296	34.228	33.251	32.099	30.413	28.523	26.771	25.396	24.578	24.121	23.966	24.015	24.132	24.292
24	2/6/23	4.430	84.233	56.412	45.339	40.522	38.029	36.413	34.896	33.153	30.844	28.507	26.518	25.067	24.270	23.867	23.779	23.897	24.076	24.296
25	2/16/23	1.179	18.445	72.576	52.692	45.010	41.247	38.837	36.589	34.125	31.160	28.421	26.255	24.773	24.020	23.679	23.660	23.844	24.080	24.351
26	2/26/23	-0.530	1.325	79.790	63.206	50.764	45.070	41.535	38.344	35.046	31.420	28.331	26.033	24.546	23.842	23.562	23.606	23.847	24.130	24.441
27	3/8/23	-1.745	-2.342	19.642	78.625	58.320	49.679	44.572	40.199	35.968	31.689	28.287	25.885	24.398	23.740	23.512	23.608	23.896	24.214	24.552
28	3/18/23	-2.734	-4.192	-1.400	77.672	68.495	55.344	48.055	42.219	36.956	32.025	28.328	25.826	24.335	23.711	23.523	23.659	23.980	24.323	24.676
29	3/28/23	-3.598	-5.462	-5.632	24.269	82.479	62.469	52.142	44.496	38.079	32.475	28.475	25.865	24.354	23.747	23.585	23.748	24.091	24.447	24.804
30	4/7/23	-4.384	-6.471	-7.643	-3.557	77.375	71.620	57.063	47.149	39.412	33.078	28.746	26.001	24.449	23.841	23.691	23.867	24.220	24.579	24.930
31	4/17/23	-5.116	-7.335	-8.966	-8.602	32.867	83.221	63.135	50.337	41.036	33.870	29.149	26.235	24.615	23.986	23.832	24.009	24.363	24.715	25.051
32	4/27/23	-5.809	-8.109	-9.984	-10.810	-4.866	77.986	70.727	54.267	43.046	34.889	29.696	26.565	24.846	24.175	24.002	24.169	24.512	24.850	25.163
33	5/7/23	-6.472	-8.822	-10.836	-12.187	-11.125	43.610	79.540	59.220	45.568	36.181	30.399	26.991	25.138	24.403	24.196	24.341	24.666	24.981	25.265
34	5/17/23	-7.111	-9.491	-11.586	-13.205	-13.577	-4.984	78.593	65.520	48.776	37.808	31.278	27.517	25.489	24.666	24.410	24.522	24.819	25.105	25.355
35	5/27/23	-7.729	-10.126	-12.268	-14.035	-15.009	-13.116	53.640	73.158	52.927	39.865	32.360	28.147	25.897	24.960	24.639	24.708	24.970	25.222	25.431
36	6/6/23	-8.331	-10.734	-12.900	-14.748	-16.020	-15.869	-3.254	77.639	58.382	42.495	33.690	28.894	26.362	25.282	24.881	24.896	25.117	25.328	25.494
37	6/16/23	-8.919	-11.319	-13.494	-15.385	-16.813	-17.353	-14.507	62.027	65.521	45.925	35.335	29.775	26.888	25.632	25.132	25.084	25.257	25.424	25.542
38	6/26/23	-9.493	-11.886	-14.058	-15.967	-17.478	-18.342	-17.631	1.600	73.333	50.534	37.405	30.820	27.482	26.009	25.392	25.270	25.388	25.506	25.574
39	7/6/23	-10.057	-12.436	-14.598	-16.507	-18.056	-19.085	-19.156	-15.238	68.735	56.929	40.085	32.073	28.151	26.412	25.657	25.451	25.508	25.574	25.590
40	7/16/23	-10.610	-12.972	-15.116	-17.014	-18.574	-19.683	-20.105	-18.799	12.243	65.764	43.701	33.611	28.914	26.844	25.925	25.624	25.615	25.626	25.588
41	7/26/23	-11.154	-13.495	-15.616	-17.493	-19.046	-20.188	-20.778	-20.343	-15.341	72.229	48.872	35.560	29.794	27.307	26.195	25.786	25.705	25.659	25.567
42	8/5/23	-11.689	-14.006	-16.100	-17.949	-19.482	-20.627	-21.293	-21.226	-19.373	31.596	56.816	38.155	30.833	27.804	26.462	25.934	25.777	25.672	25.524
43	8/15/23	-12.216	-14.506	-16.568	-18.385	-19.887	-21.016	-21.708	-21.806	-20.887	-14.892	68.811	41.872	32.100	28.344	26.723	26.061	25.825	25.660	25.458
44	8/25/23	-12.736	-14.996	-17.023	-18.801	-20.267	-21.366	-22.053	-22.220	-21.667	-19.364	52.809	47.819	33.729	28.938	26.973	26.162	25.843	25.620	25.366
45	9/4/23	-13.248	-15.476	-17.465	-19.201	-20.623	-21.683	-22.345	-22.529	-22.130	-20.770	-14.121	58.971	35.993	29.605	27.202	26.227	25.825	25.547	25.243
46	9/14/23	-13.753	-15.947	-17.895	-19.585	-20.959	-21.972	-22.595	-22.765	-22.423	-21.404	-18.813	68.707	39.576	30.381	27.397	26.241	25.760	25.432	25.085
47	9/24/23	-14.252	-16.408	-18.313	-19.954	-21.275	-22.235	-22.810	-22.947	-22.611	-21.723	-19.998	-13.428	46.747	31.344	27.534	26.181	25.631	25.265	24.885
48	10/4/23	-14.744	-16.861	-18.720	-20.308	-21.574	-22.476	-22.994	-23.086	-22.727	-21.878	-20.435	-17.782	68.782	32.689	27.564	26.012	25.418	25.034	24.633
49	10/14/23	-15.229	-17.304	-19.115	-20.649	-21.854	-22.695	-23.152	-23.188	-22.789	-21.933	-20.585	-18.606	-13.221	35.113	27.389	25.670	25.085	24.717	24.318
50	10/24/23	-15.707	-17.739	-19.498	-20.975	-22.118	-22.894	-23.285	-23.259	-22.808	-21.920	-20.589	-18.798	-16.276	44.174	26.745	25.035	24.575	24.284	23.922

Multiple Mars Departures From Earth-Orbiting Infrastructure

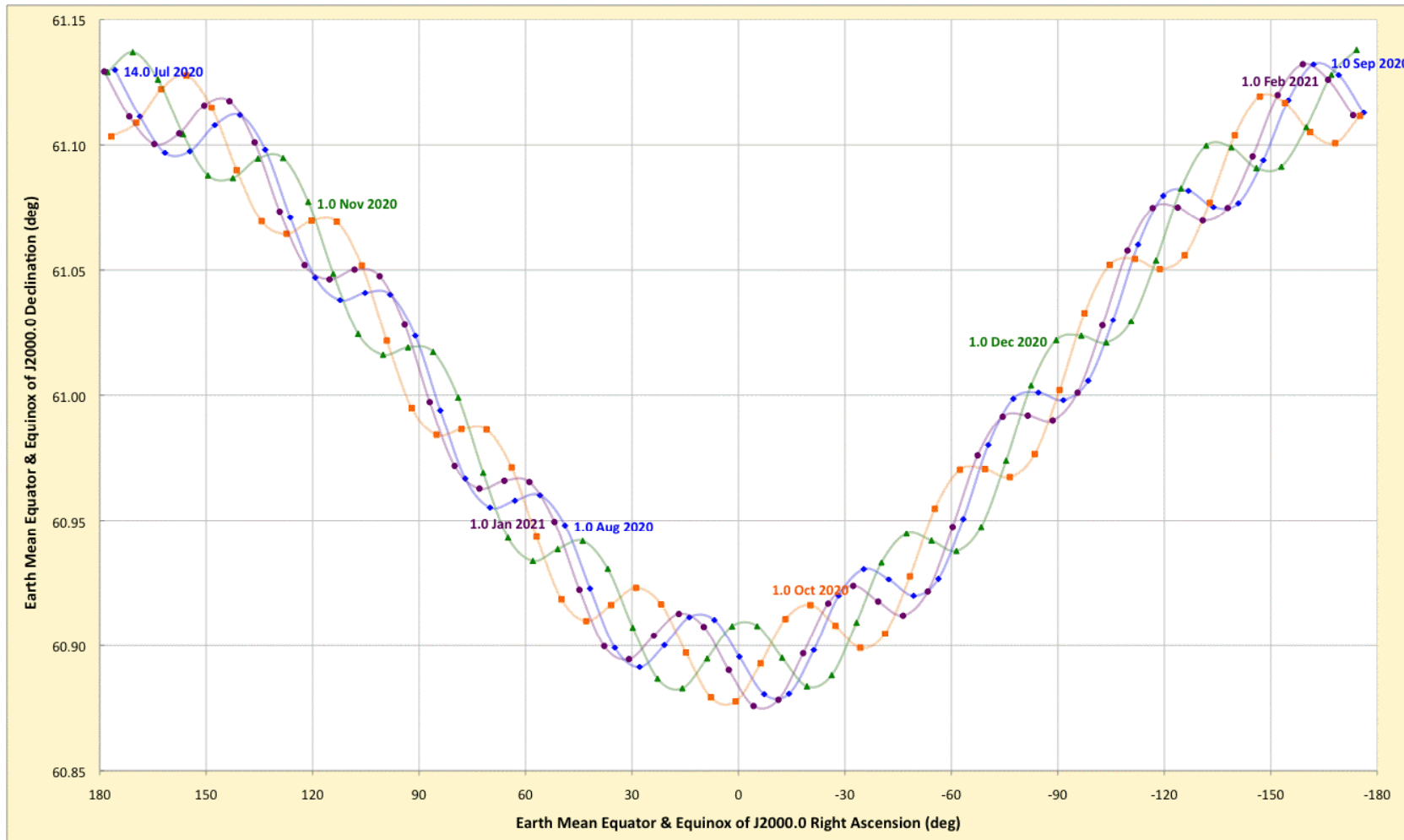
Departure Date 14 July 2020 TMI Geometry Summarized On A CSP



Multiple Mars Departures From Earth-Orbiting Infrastructure

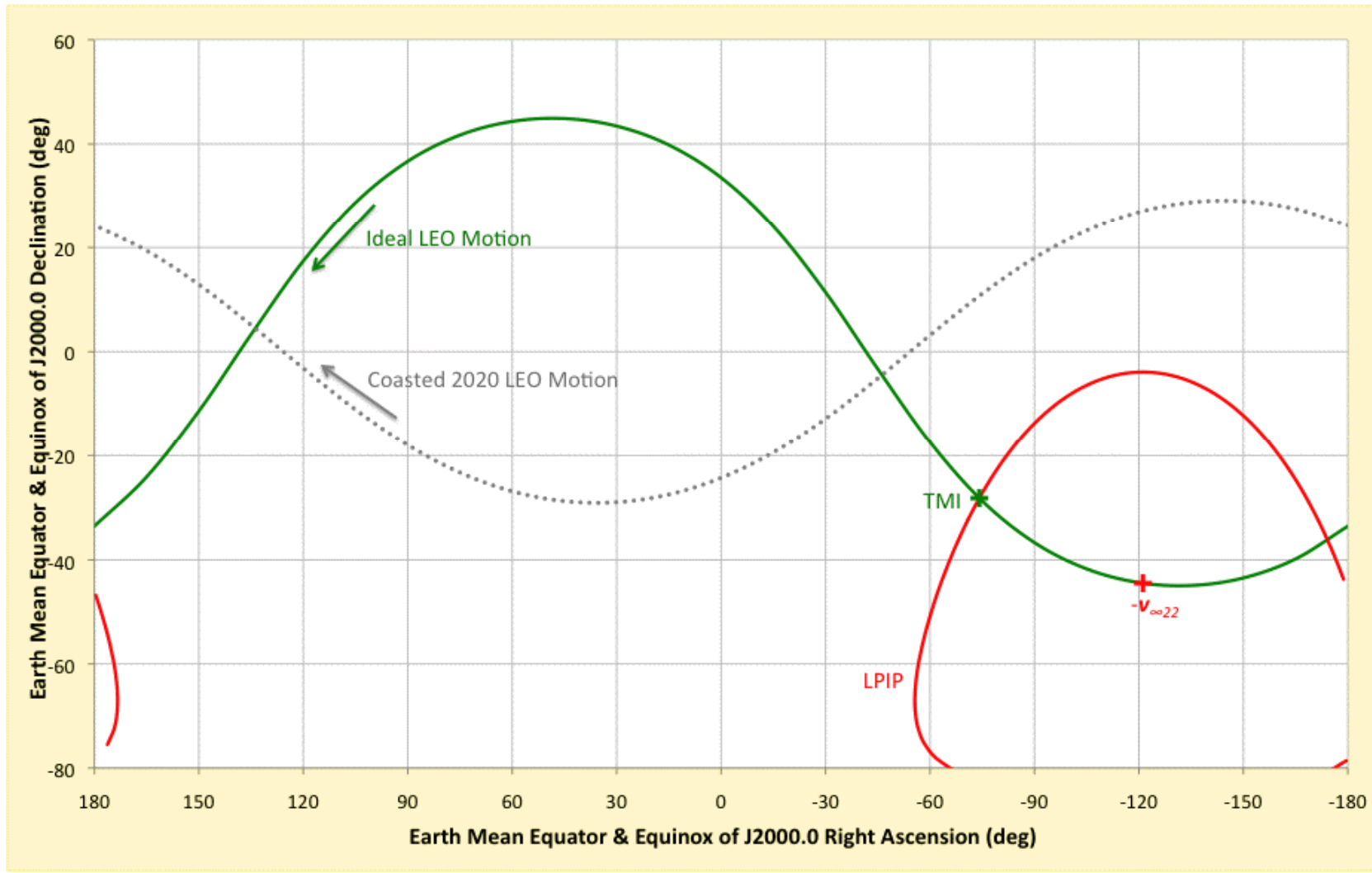
The 14 July 2020 Departure LEO's Coasted -Hbar Plotted On A CSP

- Six-day δ cycles arise from daily -Hbar sampling of $|\delta|$ -dependent J_2 effects
- Fifty-day δ cycles arise from wedge angle between true and J2000.0 Earth equators



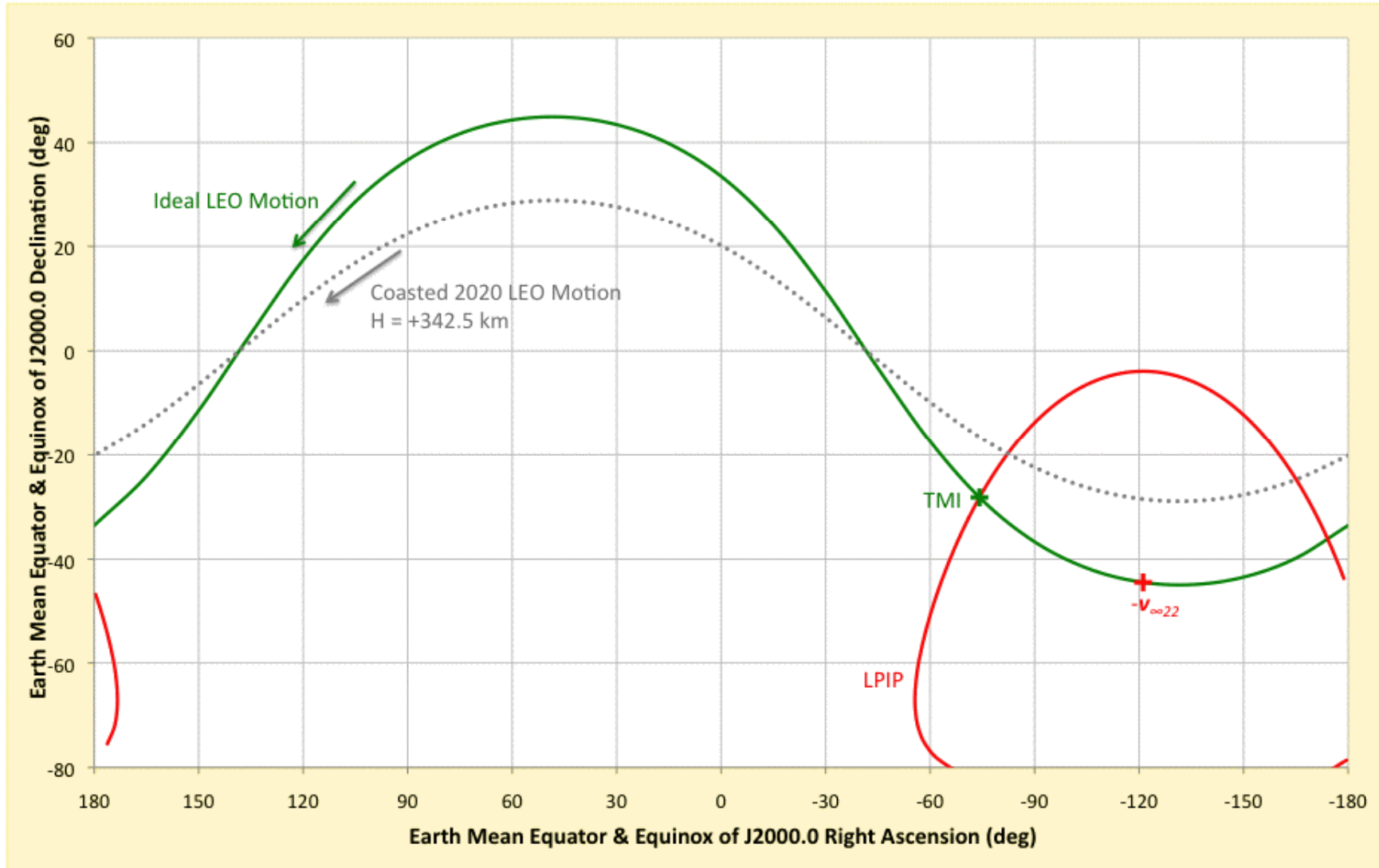
Multiple Mars Departures From Earth-Orbiting Infrastructure

The LEO Coasted From 14 July 2020 Has A 73.5° Wedge With The 9 September 2022 Departure LEO, Requiring $\Delta v_{PC} = 9.180$ km/s



Multiple Mars Departures From Earth-Orbiting Infrastructure

Lowering H From +400 km To +342.5 km Can Reduce Δv_{PC} to 2.114 km/s



Multiple Mars Departures From Earth-Orbiting Infrastructure

Deploying Reusable Infrastructure To Support Multiple Mars Departures From LEO Is Inadvisable

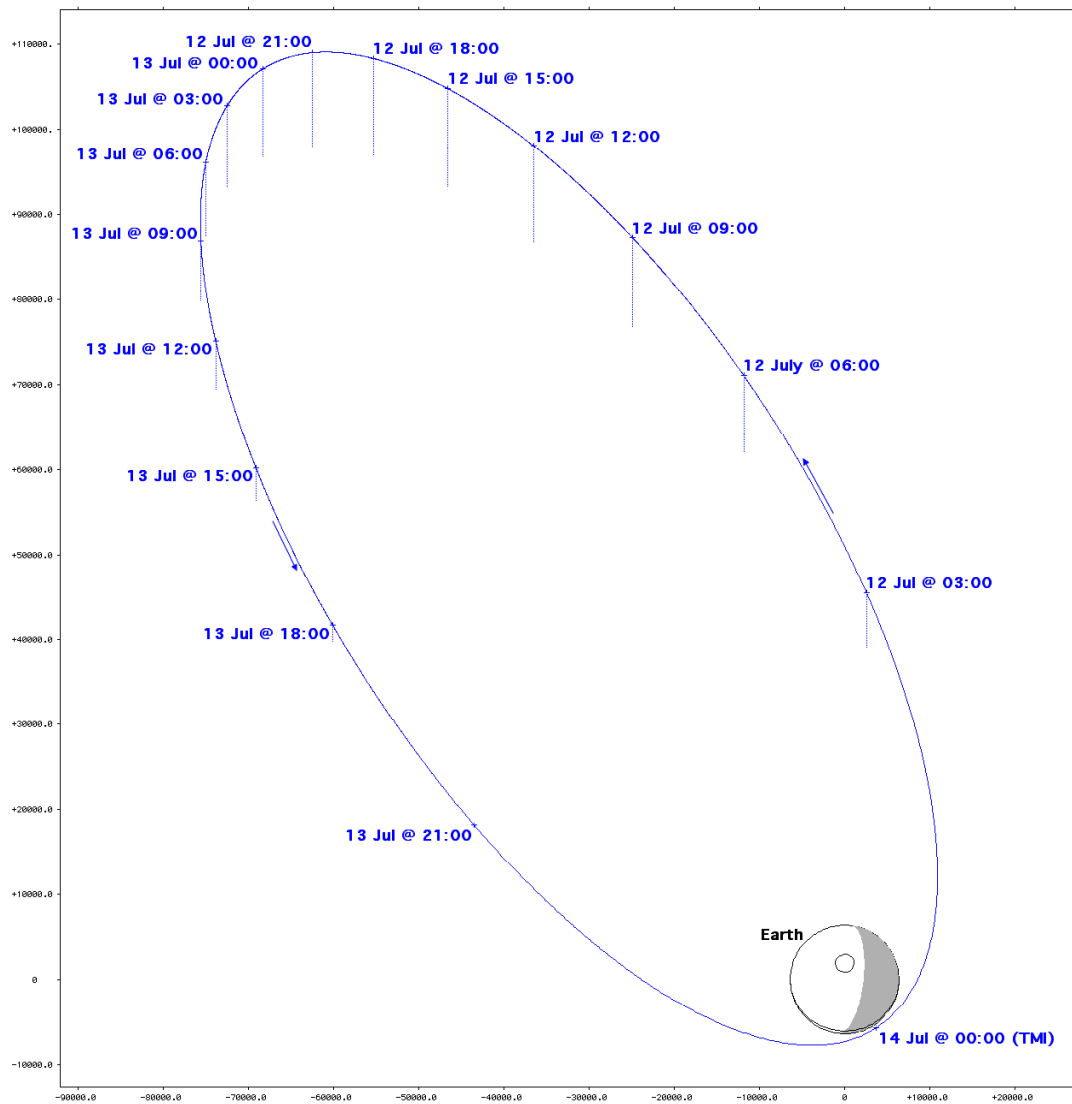
- Previous "lower H " strategy is likely incompatible with massive payload assembly/servicing (ISS only allowed down to H near +320 km early in assembly)
- Analogous "higher H " strategy exists, but it will encounter elevated radiation flux (ISS rarely exceeds $H = +430$ km at $i = 51.6^\circ$)
- Neither H strategy addresses tracking minimum i variations between departures

Consider Assembly/Servicing In An Elliptical Earth Parking Orbit (EEPO)

- TMI must be near EEPO perigee to take advantage of the "Oberth effect"
- If planar corrections can be placed near EEPO apogee, they are highly efficient
- An EEPO permits nearly all TMI energy Δv_{TMI} to be expended with each payload element delivery: could eliminate cryogenic propellant storage requirements for TMI
- An $H = +121,639 \times +400$ km EEPO has been assessed for 14 July 2020 departure
 - Offers 2-day phase repetition and standardized rendezvous planning/procedures
 - Higher perigee probably will be required to reduce long-term radiation exposure

Multiple Mars Departures From Earth-Orbiting Infrastructure

The EEPO Reduces 14 July 2020 Δv_{TMI} From 3.779 km/s To 0.893 km/s



Km Units View From Y= 0.0°, P= 0.0°, R= 18.0° Sun Illumination Earth-Centered EPM Coordinate System © 2020y 196d (7-14) 0: 0: 0 UTC

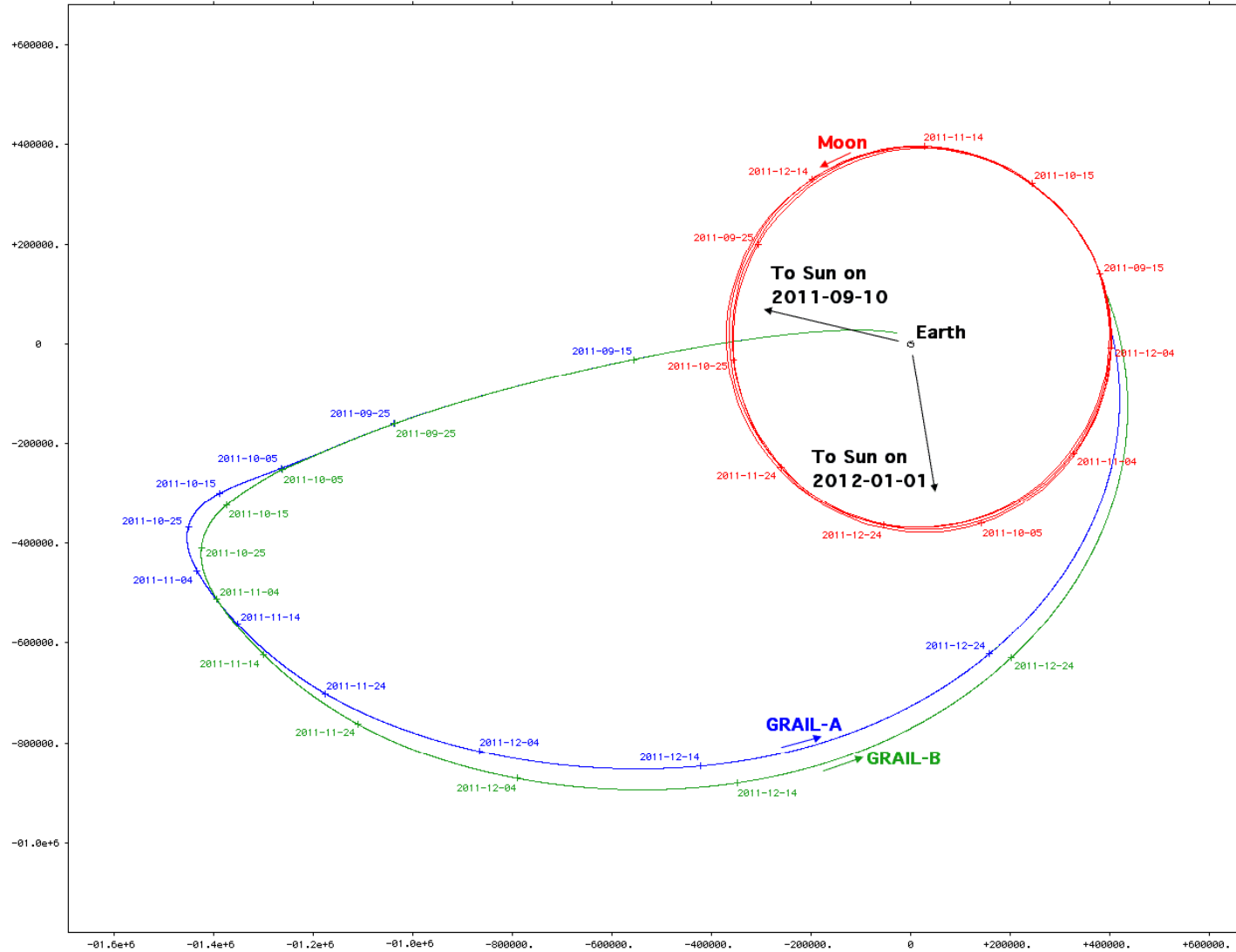
At TMI, EEPO perigee is typically located at ~8 PM local solar time

Loitering in the EEPO ~4 months post-TMI shifts perigee near local solar noon, and $\Delta v = \sim 0.28$ km/s would send infrastructure near the SEL2 libration point 1.5 million km outside Earth's heliocentric orbit

A distant retrograde orbit (DRO) about the Moon can then be accessed with $\Delta v = \sim 0.1$ km/s

Multiple Mars Departures From Earth-Orbiting Infrastructure

GRAIL: An Example Of Low- Δv Lunar Orbit Access Via SEL1 Flyby



Km Units View From Y= 0.0°, P= 0.0°, R= 0.0° Sun Illumination
Earth-Centered J2KE Coordinate System

Multiple Mars Departures From Earth-Orbiting Infrastructure

An EEPO Supporting 2020 Earth Departure For Mars Can Be Recycled To Support 2022 Departure With $\Delta v = \sim 1.2$ km/s In ~ 10 Months

PET (months)	Event
0	First Earth departure season TMI in 2020. Begin loitering in EEPO.
4	Depart EEPO for SEL2 flyby with 0.28 km/s TLI impulse.
8	Return to Moon and achieve 70,000 km radius DRO with 0.1 km/s impulse.
9	Perform 0.57 km/s TEI impulse and establish 2-day EEPO supporting second Earth departure season with 0.19 km/s impulse several days later.
10	Begin assembly/servicing operations for second Earth departure season TMI.
26	Second departure season TMI in 2022.

Multiple Mars Departures From Earth-Orbiting Infrastructure

Summary

- If TMI must be performed from LEO, reusable infrastructure supporting multiple payload departures for Mars is inadvisable
 - Large planar deviations may arise between successive departure LEOs
 - Managing these deviations in LEO may require more Δv than a re-launch
- An EEPO with ~2-day period is more compatible than LEO with infrastructure reuse
 - Further vehicle-specific study is necessary to develop radiation exposure constraints on the lowest permissible long-term EEPO perigee
 - Maximizing the Oberth effect will entail lowering EEPO perigee to ~400 km at the apogee prior to TMI. This impulse could serve as a TMI "readiness burn".