Electrodynamic Thrust Performance

for

Space Solar Satellite Applications

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Introduction

The use of spinning tethers to transfer payloads from low earth orbit (LEO) to geosynchronous earth orbit (GEO) has previously been considered for payload masses up to 4000 kg (4 MT).[1] The construction of the solar power station requires a transfer of 22,568 MT per year from LEO to GEO. This is envisioned to be carried out in payload units of 20 MT or 40 MT, which implies a frequency of 1188 or 594 flights per year, respectively. We could say from the outset that the use of spinning tethers for such large payloads at such high launch frequencies does not appear promising. This is inherent in the principles of spinning tether transfer, which we will briefly sketch below. Somewhat different scenarios are possible, but the basic physics remains the same. We consider only a single stage from LEO to GTO tether system, since the complexity involved in phasing the launches, dockings, and spinups for a two-stage system for so many payloads rules out a two-stage system, in our opinion.

The payload must first be launched to LEO, where it docks with the tether launch platform and is connected to the tether. The tether (tens of kilometers long) is then deployed with the payload upward. In order to give the payload the velocity necessary to launch it into a geosynchronous transfer orbit (GTO), i.e., to impart the required Δv, the tethered system must be spun up about the center of mass of the tether-platform-payload system. The two end masses (platform and payload) are driven to rotate about the center of mass of the tethered system. Both the final rotational velocity and the phasing of the tether spin have to be controlled so that payload is in the vertically up position at the perigee of the LEO and with the velocity required to achieve the GTO when it is released at that point. Upon release, the payload then goes into GTO, where it again requires an acceleration to reach GEO (circularization of the orbit). The platform goes into a lower orbit, from which it must be raised in order to be at the proper LEO for docking with another payload. For this scheme to make sense at all, the platform must be envisioned as having a solar powered electrical thrust system to regain LEO and to spin up the tethered system. Similarly, solar powered electrical propulsion would be used to circularize the orbit to GEO.

The platform-tether system must have sufficient mass not to re-enter the Earth's atmosphere after separation from the payload, and consequent recoil. This required mass is substantially greater than the payload mass. Such a large mass, in turn, implies a time of several to many weeks to regain the initial LEO through the use of an electrical thruster system, even one operating at high power (which implies a large solar panel system). Weeks more would be required to spin up the tethered system after rendezvous with a newly launched payload. Thus, for launch rates of more than one per day (possibly over three per day), a large number (several hundred) of tether launch platforms would be required. This study gives some quantitative estimates of the required number of orbiting systems and of their masses under different assumptions of initial orbit, payload mass, and tether length. After achieving GTO, the payloads would require further boosting by electric thrusters to reach GEO. This would also require days or weeks, which again implies a large number of electric boosters on the order of a hundred. We will also give some quantitative examples of GTO to GEO, as well as a simple comparison of the spinning tether scheme to an all-electric-thruster scheme to go from LEO to GEO. As one would expect, the long transfer times for the all-electric tug (possibly electrodynamic tether-based) approach also imply hundreds of electric tugs.

Quantitative Results

For the purposes of illustration, we choose an initial LEO (e.g., 400 km altitude at perigee and 1906 km altitude at apogee) and a definite length from the center of mass of the total system to the payload (e.g., 50 km). With the spinning launch scenario sketched above, these parameters then determine the GTO and the Δv required to achieve it. The Δv in turn determines the minimum tether mass required based on the tether's ability to withstand the stress of the rotation. Calculations have previously been presented[1,2] using a tapered tether (fatter where stress is greater) to minimize the tether mass, and we will follow the same procedure. We approach the choice of material in two ways. In the first, we utilize present day kevlar with a safety factor of 1.75 (equivalent to spectra with a safety factor of 2.0). In the other approach, we attempt to take into account, somewhat, future improvements in the strength to mass ratio of the tether material by using kevlar with a safety factor of only 1.0.

Left undetermined are the total length of the tether and the mass of the terminating platform at the other end of the tether from the payload. Fixing either one determines the other. We assume no mass at the payload end except for the payload itself, though some mass would be associated with the thruster required at that end during the spin up process. For the purposes of our study, it has a secondary effect. As we release the payload from LEO perigee, we cannot have the platform too far away from the overall center of mass if we wish to have it avoid re-entry after release. This requirement leads to a large platform/payload mass ratio.

Table 1 shows tether dimensions and masses and platform masses under thirteen different assumptions of payload mass, initial GEO, and tether length and strength safety factor. The following tables correspond to these same cases. In addition to the large masses of the platform-tether system, another concern would be the large tether diameters.

Case	initial alt at perigee (km)	initial alt at apogee (km)	payload mass (MT)	safety factor	CM to payload (km)	ΔV (km/sec)	tether mass (MT)	tether length (km)	tether diam (cm)	platform mass (MT)	tether + platform mass (MT)
1	400	1,906	20	1	50	1.98	35	60	2.77	170	205
2	400	1,906	20	1	50	1.98	35	70	2.57	76	112
3	400	1,906	40	1	50	1.98	70	70	3.63	153	223
4	400	1,906	20	1	80	1.96	34	100	2.11	131	165
5	400	1,906	40	1	80	1.96	68	100	2.98	262	330
6	400	1,906	20	1.75	50	1.98	85	60	4.31	270	355
7	400	1,906	20	1.75	50	1.98	85	70	3.99	114	199
8	400	1,906	40	1.75	50	1.98	170	70	5.64	227	397
9	400	1,906	20	1.75	80	1.96	81	100	3.26	202	283
10	400	1,906	40	1.75	80	1.96	162	100	4.62	403	566
11	350	1,845	20	1	50	1.99	36	60	2.80	172	207
12	450	1,967	20	1	50	1.97	35	60	2.75	169	204
13	300	1,784	20	1	50	2.01	36	60	2.82	173	209

Table 1. System masses and dimensions (all orbits have eccentricity = 0.1).

Once a tether length (or platform mass) has been chosen, the energy required to spin up the system to achieve the required payload Δv is easily calculated, as is the post-release orbit of the platform-tether system. The number of orbiting tether systems required to meet the frequent launch requirements for the solar station application is then determined by the efficiency of the electrical thrusters, the power available to them, and the fraction of the time they can operate to perform the required orbit adjustment and spin-up. We represent this as an effective average power. The time to regain the orbit and spin up the system is just the total energy required divided by the effective average power. To improve things slightly, we make use of one other energy source. When the payload is released, the platform-tether system continues to rotate about its center of mass. We assume that we have a way of capturing some of this energy (50% in these calculations) for future use, so that it is not all lost when we despin the system. This does not greatly affect our results, as the energy to regain the original LEO after release of the payload is several times larger than the energy to spin up the system.

For a fixed effective average power of the thruster, the minimum number of platforms is then the number of launches per day times the time in days to "reload" a platform (the time from one payload release to another for a given platform). Several hundred platforms are required. Results for several assumptions are summarized in the tables below. Once the process was under way there would be around 50 systems spinning up at any given time at the initial LEO with another 250 regaining altitude.

Table 2 shows the orbits into which the platform-tether system falls after release and the energy required to regain the rendezvous GEO, as well as the energy needed to spin up the system after docking. An effective average energy of 50 kW is used to calculate the number of days to regain the docking orbit and then spin up the system for launch to GTO. The number of platforms is roughly 300 for all cases, but much more massive platforms would be required for the 40 MT payloads, as seen in Table 1.

Case	post release CM to platform (km)	Rotational energy about CM (MJ)	post release platform alt at perigee (km)	post release platform alt at apogee (km)	Energy to regain launch orbit (MJ)	$^*E_o/E_w$	Orbital + rotational energy needed (MJ)	Residual rotational energy (MJ)	Energy needed using 50% of rotational residual (MJ)	Days to regain @ 50 kW avg.	Platforms required
1	5.13	71,961	395	1,076	319,342	4.4	391,303	24,619	378,993	87.7	286
2	11.03	80,734	389	456	317,083	3.9	397,817	31,133	382,250	88.5	288
3	11.03	161,468	389	456	634,166	3.9	795,633	62,265	764,500	177.0	288
4	10.29	71,512	390	895	317,237	4.4	388,749	21,966	377,766	87.4	285
5	10.29	143,025	390	895	634,474	4.4	777,498	43,931	755,533	174.9	285
6	7.18	107,095	393	1,407	326,879	3.1	433,973	67,289	400,329	92.7	302
7	14.96	117,169	385	1,038	327,170	2.8	444,340	77,656	405,512	93.9	306
8	14.96	234,338	385	1,038	654,341	2.8	888,679	155,311	811,024	187.7	306
9	14.34	104,482	386	1,287	328,617	3.1	433,099	66,316	399,941	92.6	301
10	14.34	208,964	386	1,287	657,235	3.1	866,198	132,631	799,883	185.2	301
11	5.18	73,294	345	1,026	322,626	4.4	395,920	25,467	383,186	88.7	289
12	5.09	70,663	445	1,126	316,111	4.5	386,774	23,801	374,873	86.8	283
13	5.22	74,664	295	976	325,963	4.4	400,628	26,348	387,453	89.7	292

Table 2. Energy and time required to regain docking orbit and spin up payload; platforms required to maintain launch rate of 22,568 MT per year. $^*E_o$ = energy to regain orbit; E_w = energy to wind up system.

Table 3 shows how long is required for a payload to move from LEO to GEO, starting from the time it docks with the tethered system. This includes the days required to wind up the system plus the time to go from GTO to GEO (See Table 4).

Case	Energy to wind up needed using 50% of rotational residual (MJ)	Energy to wind up using 50% of rotational residual (kW-days)	Days to wind up	Days to reach GEO from LEO
1	5.97E+04	6.90E+02	13.8	33.5
2	6.52E+04	7.54E+02	15.1	34.8
3	1.30E+05	1.51E+03	30.2	65.7
4	6.05E+04	7.01E+02	14.0	33.7
5	1.21E+05	1.40E+03	28.0	63.5
6	7.35E+04	8.50E+02	17.0	36.7
7	7.83E+04	9.07E+02	18.1	37.9
8	1.57E+05	1.81E+03	36.3	71.8
9	7.13E+04	8.26E+02	16.5	36.2
10	1.43E+05	1.65E+03	33.0	68.5
11	6.06E+04	7.01E+02	14.0	33.8
12	5.88E+04	6.80E+02	13.6	33.3
13	6.15E+04	7.12E+02	14.2	34.1

Table 3. Energy and time required to wind up payload in GEO and total time to reach GEO starting from time of tether docking.

Table 4 shows the time to go from GTO to GEO, using a 5 MT tug with 50 kW effective average power to generate thrust and the time for the tugs to return to GTO. The corresponding number of tugs required to meet the requirements of launch rate are shown in the last column.

Case	Mass of tug (MT)	Effective avg. power of tug (kW)	Energy to reach GEO (MJ), using electric tug	Energy to reach GEO (kW-days)	Days to reach GEO from GTO using tug	Energy to return to GTO (MJ), using tug	Energy to return to GTO (kW days)	Days to return to GTO using tug	Upper tugs required
1	5	50	85,262	987	19.7	17,052	197	3.9	77
2	5	50	85,262	987	19.7	17,052	197	3.9	77
3	5	50	153,472	1,776	35.5	17,052	197	3.9	129
4	5	50	85,138	985	19.7	17,028	197	3.9	77
5	5	50	153,248	1,774	35.5	17,028	197	3.9	129
6	5	50	85,262	987	19.7	17,052	197	3.9	77
7	5	50	85,262	987	19.7	17,052	197	3.9	77
8	5	50	153,472	1,776	35.5	17,052	197	3.9	129
9	5	50	85,138	985	19.7	17,028	197	3.9	77
10	5	50	153,248	1,774	35.5	17,028	197	3.9	129
11	5	50	85,470	989	19.8	17,094	198	4.0	78
12	5	50	85,055	984	19.7	17,011	197	3.9	77
13	5	50	85,678	992	19.8	17,136	198	4.0	78

Table 4. Energy and electric tugs required for GTO to GEO transfer of payload.

For comparison, using the same effective average power approach, we can also compute how long it takes to move the payload from LEO to GEO, assuming it connects with an electrical powered tug in LEO. The results are shown in Table 5.

Case	Energy to reach GEO from LEO (MJ)	Energy to reach GEO (kW-days)	Days to reach GEO from LEO using same tug as GTO to GEO	Energy to return to LEO (MJ)	Energy to return to LEO (kW-days)	Days to return to LEO	Tugs required
1	543,617	6,292	126	108,723	1,258	25	491
2	543,617	6,292	126	108,723	1,258	25	491
3	978,511	11,325	227	108,723	1,258	25	409
4	543,617	6,292	126	108,723	1,258	25	491
5	978,511	11,325	227	108,723	1,258	25	409
6	543,617	6,292	126	108,723	1,258	25	491
7	543,617	6,292	126	108,723	1,258	25	491
8	978,511	11,325	227	108,723	1,258	25	409
9	543,617	6,292	126	108,723	1,258	25	491
10	978,511	11,325	227	108,723	1,258	25	409
11	548,535	6,349	127	109,707	1,270	25	496
12	538,771	6,236	125	107,754	1,247	25	487
13	553,527	6,407	128	110,705	1,281	26	500

Table 5. Energy and electric tugs required for direct LEO to GEO transfer of payload.

Conclusions

The results presented here can only be taken as general indicators. The large payload masses and high launch frequency required for the solar power station construction imply a large number (hundreds) of orbital transfer vehicles, whether some are of the spinning tether type or all are electrical-powered thrust systems. In either case the orbital transfers require tens of days, but the spinning tether system (combined with electrical tug for GTO to GEO) would bring payloads to GEO roughly four times faster, assuming equal electrical energy expenditures. The number of total vehicles required is also smaller for the spinning tether systems. However, the complexity of the spinning tether is greater, and we have not dealt in detail with questions such as phasing the spin up correctly. We cannot put forth the spinning tether systems as practical alternatives at this point because of the large masses and tether diameters required. Orbital congestion would seem to be a problem for either alternative, but judging the general feasibility of the concept is beyond the scope of this study.

References

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