A Reusable Solar-Electric Orbit Transfer Service

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C. Colin Helms, chelms@airst.org

Don V. Black Ph.D, dvblack@airst.org

American Institute for Research in Science and Technology LLC

www.airst.org

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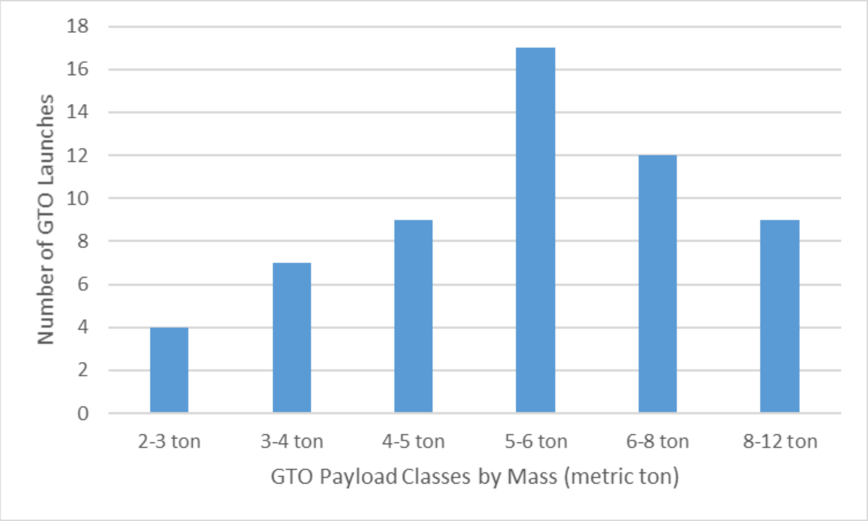
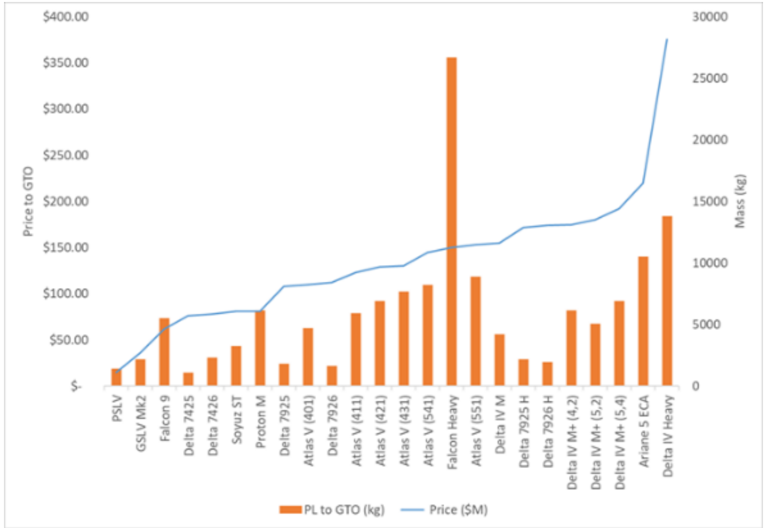
What is this Paper About?

- A large reusable Solar-Electric Powered upper-stage using "off-the-shelf" technology
- Edelbaum-Alfano combined inclination change and orbit raising
- In-orbit propellant resupply
- Concept of Operations and Economic Viability for such a service
- A vision for service for larger payloads and more distant orbits

Rank	Top Level Objective	Constraints
Primary	P.1. Transfer 4 – 12-ton payload mass to low inclination geo-synchronous orbit.	C.1. Operating Profit > $600M per year
Secondary	S.1. Provide service to customers from disadvantaged launch latitudes.	C.2. Circular LEO rendezvous orbit
	S.2. Provide the service in the mid 2020's.	C.3. Use components with TRL-5 or above

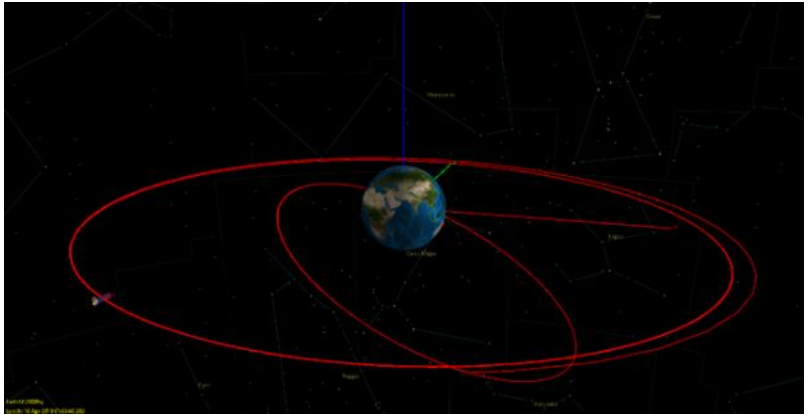
Where is the action in the Geosynchronous Market?





- Most current GTO payloads are in the 4 – 12 ton class
- Capability > 4-ton/Price < $100m: Falcon 9, Proton M, Atlas 411, Falcon Heavy
- Falcon Heavy is a game-changer
- No reusable upper stages

How Well do Launch Providers Service the GEO market?

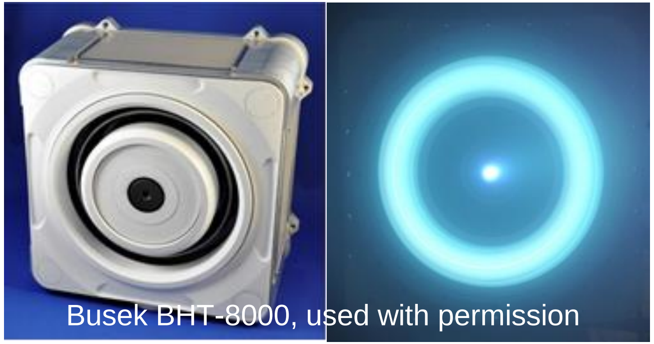


- ISRO GSAT-6A, 2140-kg [7][10]
- Launched 29 March 2018
- Starting orbit 149-km by 36,508-km
- 20.5-degree inclination change
- Delta-V 2403-m/s, 1280-kg propellant

- Standard Geosynchronous Transfer Orbit (GTO) is highly elliptical and inclined
- Client payload must supply propellant for inclination change
- This propellant penalty costs $313M/year (current $) in revenue for the case of GSAT-6A

Which Thruster Technology?

Voltage	Power	Thrust (N)	Isp	Efficiency
400	4537	0.260	2077	0.58
400	6295	0.359	2165	0.61
400	8061	0.449	2217	0.61


Busek BHT-8000, used with permission

$$\frac{T}{P} = \frac{2\eta}{(9.81 * I_{sp})}$$

η = Power efficiency of the propulsion system
I_{sp} = specific impulse
P = Propulsion input power
T = Thrust

- Hall-Effect Thrusters (HETs)
  - Selected for Life > 50,000-hours
  - Selected for Thrust 0.45-N, Isp = 2217-s
  - Selected for Technical Readiness
- Comparisons
  - Kerslake and Gefert 1999 [13]:
    - 8x100-kW Hall-Effect thrusters
    - 80-ton cargo to high lunar orbit
    - Selected for thrust
  - Sarver-Verhey and Kerslake 2012 [14]:
    - 8x50-kW gridded ion thrusters
    - 36-tons to EML1
    - Life > 10,000-hours
    - Selected for high Isp and efficiency

Which Vehicle Configuration?

$$I_{sp}\frac{1}{\eta}\frac{\partial \eta}{\partial I_{sp}} < 1$$

Where:

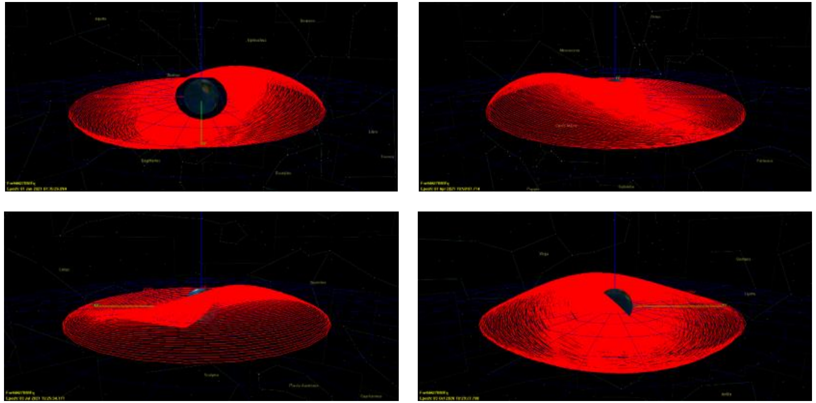
η = Power efficiency of the propulsion system

I_{sp} = specific impulse

Configuration	Payload Mass (kg)	Power (kW)	Total Thrust (N)	Alpha (kg/kW)	Initial Mass (kg)	Final Mass (kg)
32 HET, 8061W	8000	262.92	14.268	22	25138	16854
	12,000	262.92		22	30609	20854
64 HET, 6295W	16,000	388.94	22.976	27	48178	32256
	24,000	388.94		27	59119	40256
64 HET, 8061W	24,000	520.84	28.736	30	67350	45018
	36,000	520.84		30	83762	57018

- Optimize vehicle for payload and power supply mass
  - Melbourne & Sauer [12]
- Change in efficiency with Isp should be as small as possible
  - Implies regulated beam voltage
- 32x8-kW Hall-Effect
  - 4-to-12-ton PL
- 64x6295W Hall-Effect
  - 16-24-ton PL
- 64x8-kW Hall-Effect
  - 24-36-ton PL

How is Mission Analysis Performed?



[20] Edelbaum Control Law
With Wiesel and Alfano Multi-Revolution Optimization

$$\vartheta(\nu) = \tan^{-1} \frac{\cos \upsilon}{\sqrt{1/u(R) - 1}}$$

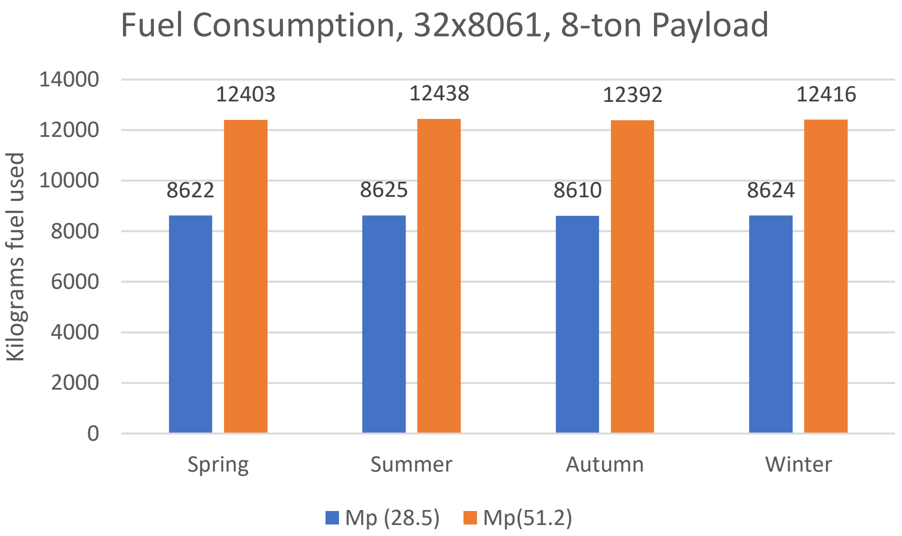
$\vartheta(\nu)$, the yaw angle for an orbit ratio
υ, Argument of Latitude (AOP+TA)
R, current orbit ratio
$u(R)$, Alfano trajectory scale factor

- The Edelbaum-Alfano control law reliably arrives at GEO with low inclination in 700 – 1100 revolutions
- Four Cases for 2 inclinations, 28.5 and 51.2-deg, for each configuration
- Eclipse considered, but decided to just let Edelbaum-Alfano run
- Fuel and Time-of-Flight plotted
- Reserve fuel determined and included in fuel budget (no margin)

8-ton Payload to GEO

Inclination: / Season:	51.2° Xfer Mp (kg)	51.2° Rsv Mp (kg)	51.2° Rtn Mp (kg)	28.5° Xfer Mp (kg)	28.5° Rsv Mp (kg)	28.5° Rtn Mp (kg)
Spring	8780	3623	3635	5814	2808	2748
Summer	8782	3656	3624	6988	2772	2769
Autumn	8744	3648	3606	7021	2749	2742
Winter	8780	3637	3600	6988	2768	2767

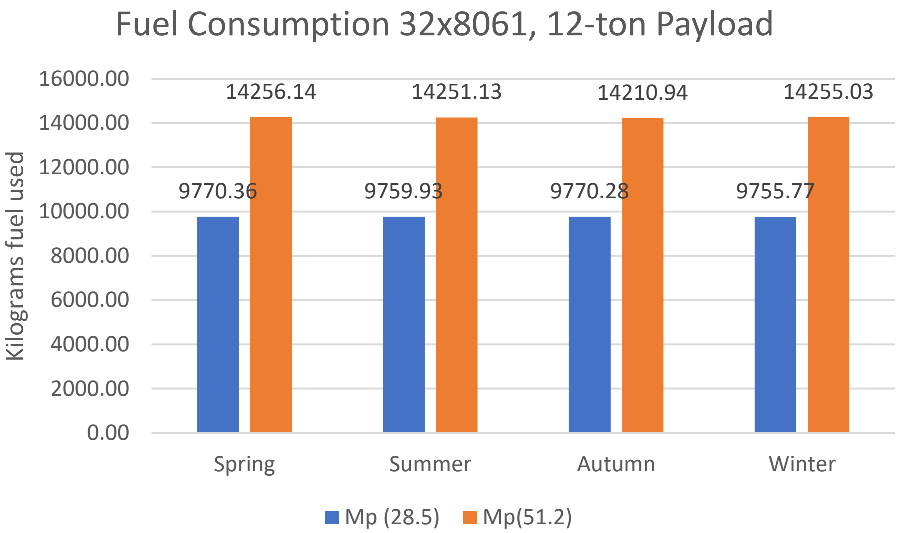
Inclination:	28.5° Duration (days)	Return Duration (days)	51.2° Duration (days)	Return Duration (days)
Season:	28.5 out	28.5 rtn	51.2 out	51.2 rtn
Spring	114.67	58.01	168.32	72.11
Summer	137.80	54.79	167.90	71.27
Autumn	136.03	57.99	168.25	71.31
Winter	137.61	54.69	167.83	70.77



12-ton Payload to GEO

Inclination:	**51.2°**	**51.2°**	**51.2°**	**28.5°**	**28.5°**	**28.5°**
Season:	**Xfer Mp (kg)**	**Rsv Mp (kg)**	**Rtn Mp (kg)**	**Xfer Mp (kg)**	**Rsv Mp (kg)**	**Rtn Mp (kg)**
Spring	10525	3731	3635	7025	2745	2748
Summer	10567	3684	3624	6988	2772	2769
Autumn	10546	3665	3606	7021	2749	2742
Winter	10562	3693	3600	6988	2768	2767

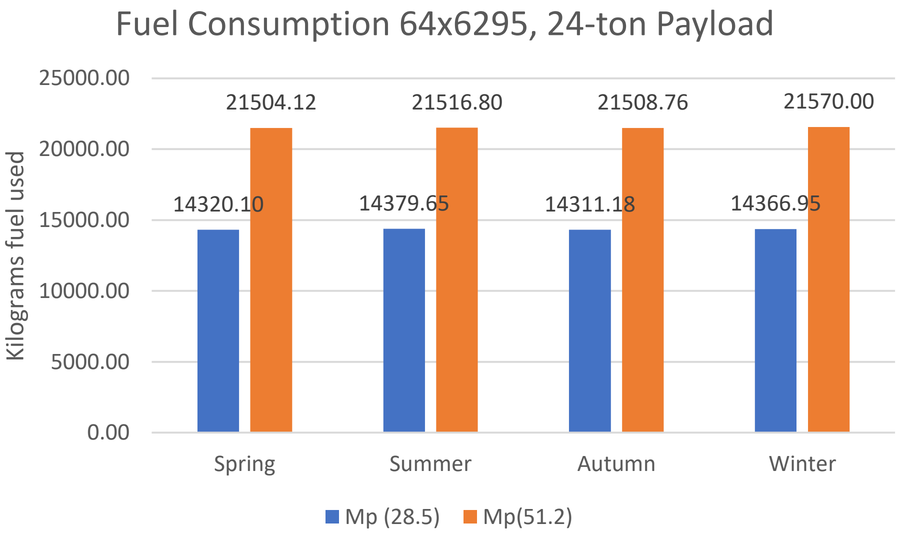
Inclination:	**28.5 Duration (days)**	**Return Duration (days)**	**51.2 Duration (days)**	**Return Duration (days)**
Season:				
Spring	136.04	58.01	203.97	72.11
Summer	137.80	54.79	200.76	71.27
Autumn	136.03	57.99	203.60	71.31
Winter	137.61	54.69	200.52	70.77



24-ton Payload to GEO

Inclination:	51.2° Xfer Mp (kg)	51.2° Rsv Mp (kg)	51.2° Rtn Mp (kg)	28.5° Xfer Mp (kg)	28.5° Rsv Mp (kg)	28.5° Rtn Mp (kg)
Season:						
Spring	21504	7416	7300	14320	5559	5552
Summer	21517	7446	7290	14380	5623	5594
Autumn	21509	7346	7294	14311	5563	5535
Winter	21570	7426	7290	14367	5626	5591

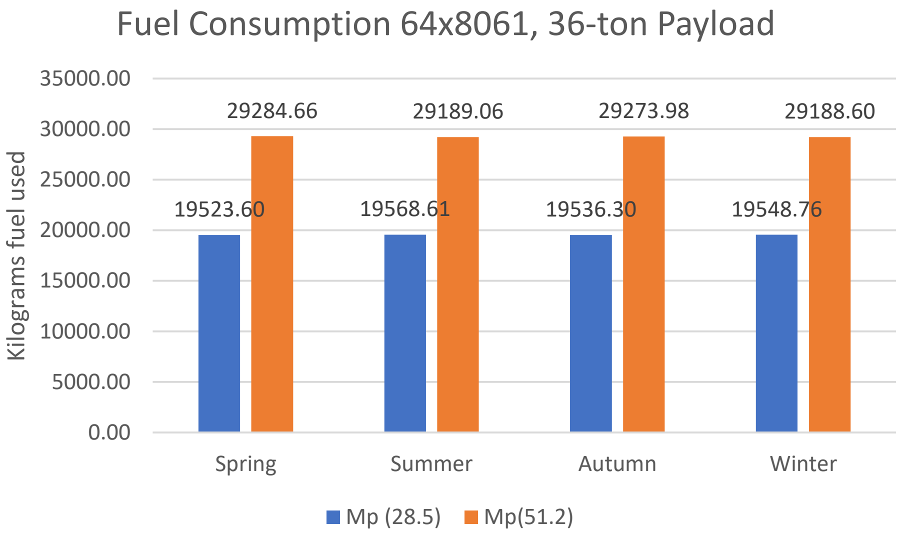
Inclination:	28.5° Duration (days)	Return Duration (days)	51.2° Duration (days)	Return Duration (days)
Season:				
Spring	172.59	70.74	253.22	89.21
Summer	173.43	66.44	250.97	86.18
Autumn	173.70	70.63	252.84	88.99
Winter	172.60	66.34	251.56	86.14



36-ton Payload to GEO

Inclination:	51.2°	51.2°	51.2°	28.5°	28.5°	28.5°
Season:	Xfer Mp (kg)	Rsv Mp (kg)	Rtn Mp (kg)	Xfer Mp (kg)	Rsv Mp (kg)	Rtn Mp (kg)
Spring	29285	9414	9355	19524	7137	7123
Summer	29189	9458	9409	19569	7243	7172
Autumn	29274	9384	9345	19536	7159	7108
Winter	29189	9496	9418	19549	7244	7174

Inclination:	28.5° Duration (days)	Return Duration (days)	51.2° Duration (days)	Return Duration (days)
Season:				
Spring	198.93	73.99	288.17	93.53
Summer	196.47	69.48	285.71	90.77
Autumn	199.46	73.92	287.92	93.29
Winter	195.51	69.43	286.11	90.82



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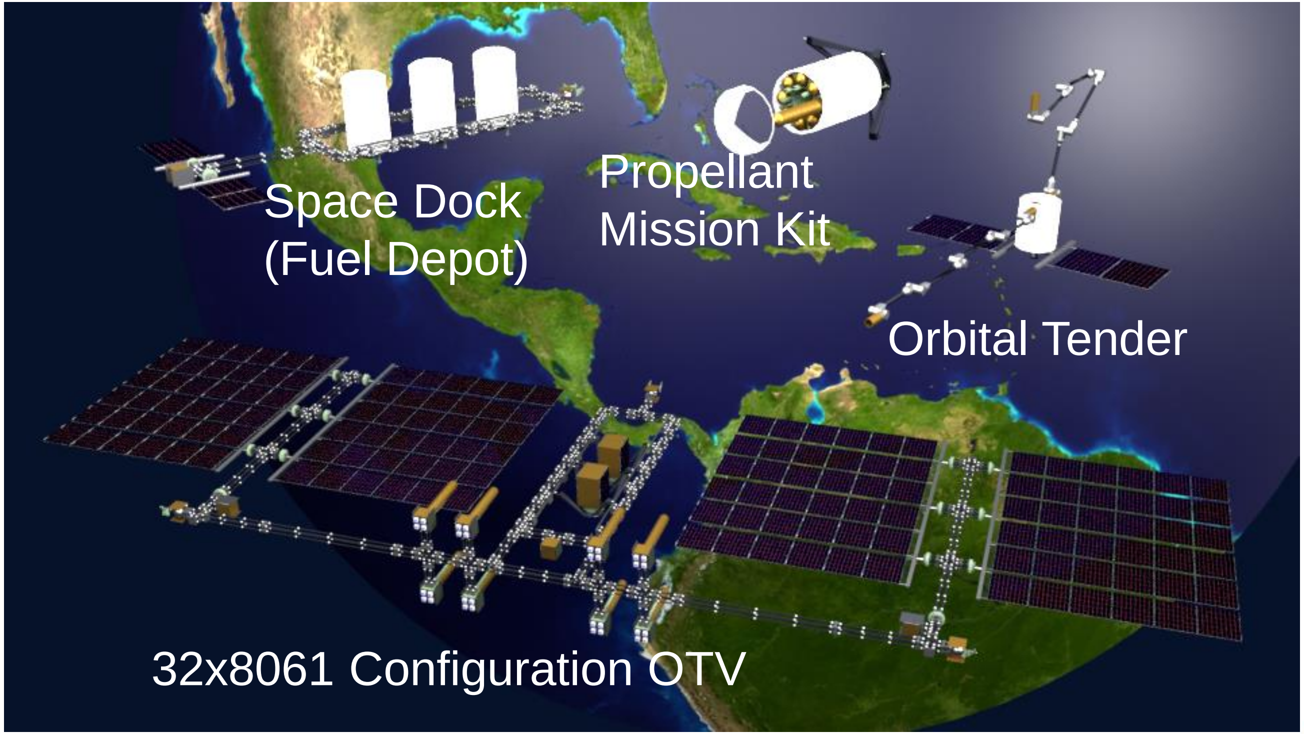
Elements in the Concept of Operations



Conclusions

Vehicle	Price ($M)	Mass to LEO (kg)	8-MT Missions (28.5)	Cost per Mission ($M)	8-MT Missions (51.2)	Cost per Mission ($M)
AtlasV (401)	$109	9800	1.1	95.95	0.8	-
GSLV Mk2	$54	5000	0.6	-	0.4	-
AtlasV (411)	$115	12000	1.4	82.66	1.0	119.21
AtlasV (421)	$123	13000	1.5	81.61	1.0	117.69
AtlasV (431)	$130	15000	1.7	74.75	1.2	107.8
AtlasV (541)	$145	17000	2.0	73.57	1.4	106.1
AtlasV (551)	$153	18856	2.2	69.98	1.5	100.93
Ariane 5 ES	$166	21000	2.4	68.18	1.7	98.33
Soyuz ST	$48	7100	0.8	-	0.6	-
Proton M	$95	23000	2.7	35.63	1.8	51.38
Falcon 9	$61	22800	2.6	23.08	1.8	33.28
Falcon Heavy	$98	63800	7.4	13.25	5.1	19.11

- Use Falcon Heavy: six 12-ton missions propellant supply per launch
- Revenues up to 136 times propellant launch costs

- System will likely meet its economic objectives operating from 28.5°
  - Priced at $150/client with multiple manifest
  - Target 4 missions per year with 2.5 clients per mission
  - System achieves an estimated operating profit of $794M/year on $1500M/year sales
    - Cost of sales includes propellant, plant, operations, services, engineering, and risk
    - Not including income tax, interest on debt
- Growth
  - Higher Mission Rate
  - Future Mission Types

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