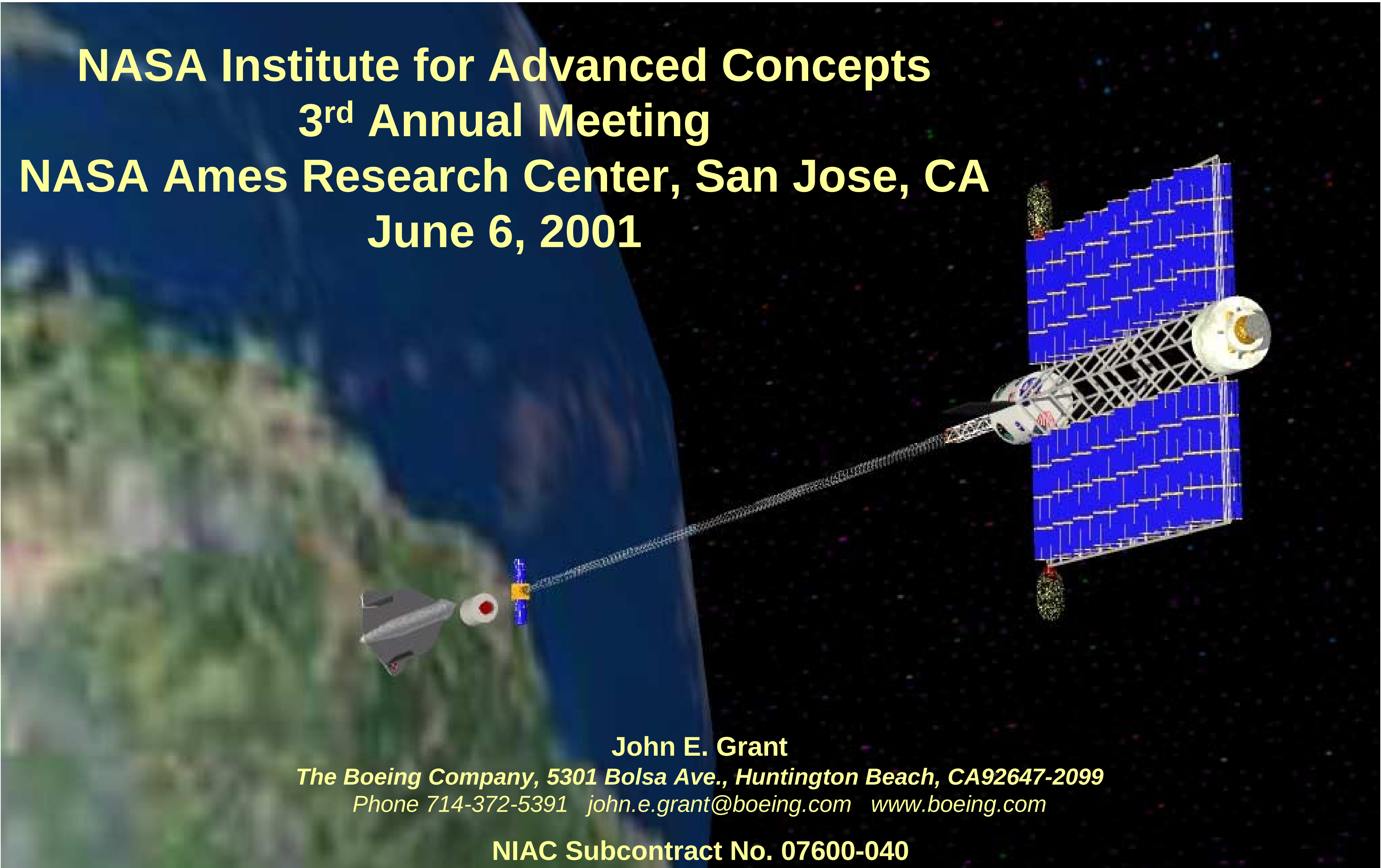
Hypersonic Airplane Space Tether Orbital Launch -- HASTOL



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HASTOL Phase II Study Team

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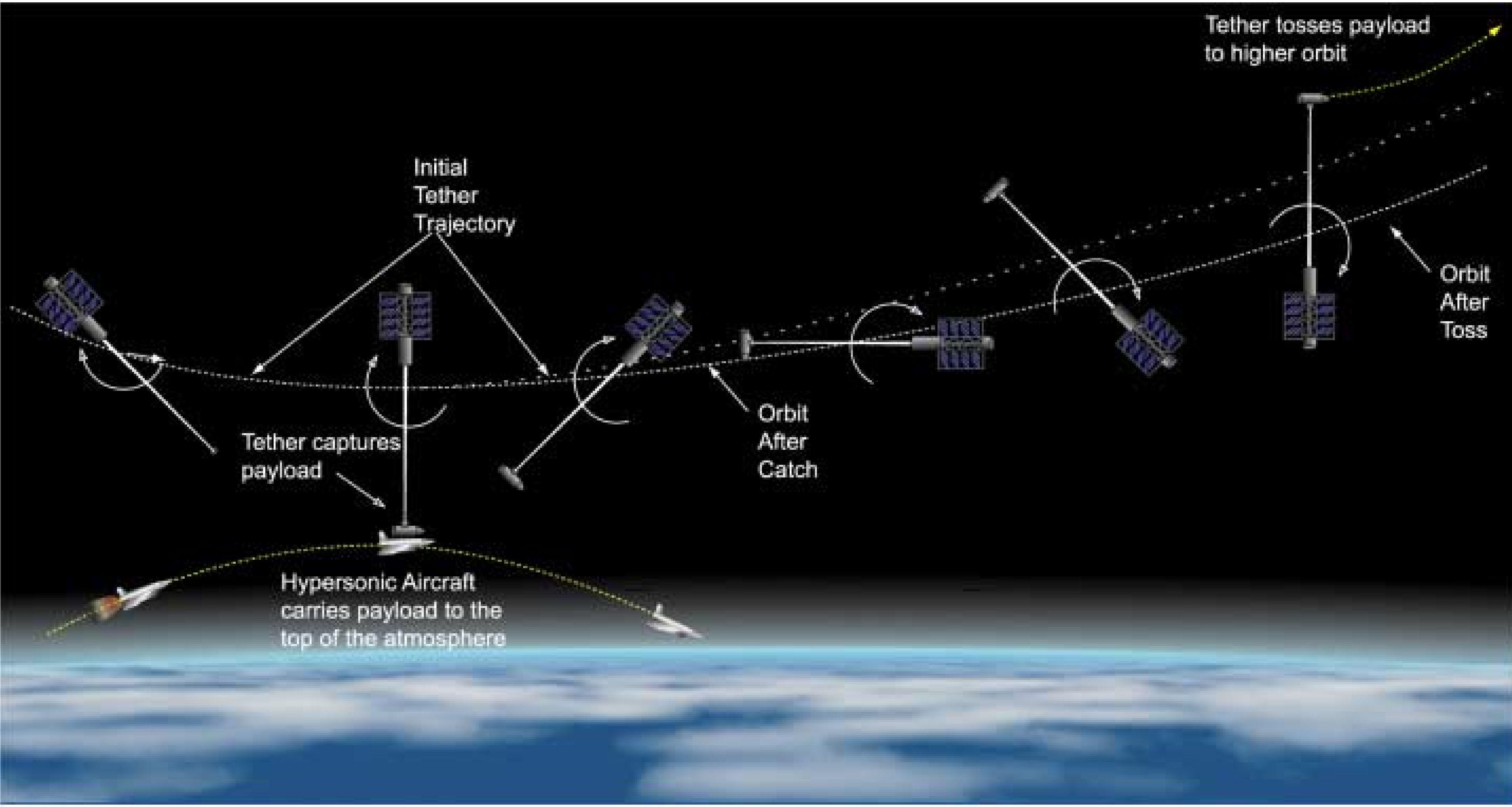
HASTOL Contract funded by NASA Institute for Advanced Concepts
Dr. Robert Cassanova, Atlanta, Georgia

HASTOL Concept of Operation



HASTOL Phase I Results Showed Concept Feasibility

- Top -Level Requirements Developed; Top-Level Trades Conducted to Define Basic Design Approaches
- Selected Hypersonic Aircraft Concept (DF-9)
- Validated Overlap of Tether Tip and Hypersonic Aircraft Velocity and Geometry Envelopes for Capture
  - Defined Aircraft Apogee Altitude/Velocity Envelope
  - Tether Tip Can Withstand Thermal Loads as it Dips into the Atmosphere
- Tether Boost Facility Concept Defined
- Rotovator Tether Concept Selected
- Simplified Grapple Concept Identified

HASTOL Phase II Study Approach

Phase I Results
• Rotovator concept
• Technology Readiness Level 2 systems (hypersonic airplane, tether control station, tether, grapple assembly, payload accommodation assembly)
• Trade study results: discovery that rendezvous point can be achieved by existing airplane (X-43) without overheating tether tip
• Selected concepts
- DF-9 hypersonic vehicle
- Rendezvous point at Mach 10, 100-km altitude
- Hoytether™ with Spectra2000™ material and PBO tip material

■ Hypersonic Airplane Space Tether Orbital Launch (HASTOL) Study Program, Phase II

Task 1 Mission Opportunities Definition
• Develop contact plan
• Conduct kick-off with potential customers and NIAC
• Meet with customers to assess potential missions and near-term applications
• Identify opportunities to integrate into NASA programs

Candidate list of mission needs

Task 2 System Requirements Definition
• Derive preliminary system requirements for each of the HASTOL systems
• Determine payload characteristics, traffic rate, guidance and control, g-force limitations, initial and life cycle costs, and system interface requirements
• Identify, define, allocate, and trade major system requirements

Task 3 Conceptual Design
• Integrate into system architecture
• Conduct trade studies
• Develop ROM cost estimate

Task 4 System Analysis
• Conduct modeling and simulations
• Conduct preliminary technical assessment
- Identify high-risk areas
- Develop mitigation plans

Task 5 Technology Development Planning
• Identify technology needs
• Develop technology development roadmap
- Flight test plan
- Laboratory tests

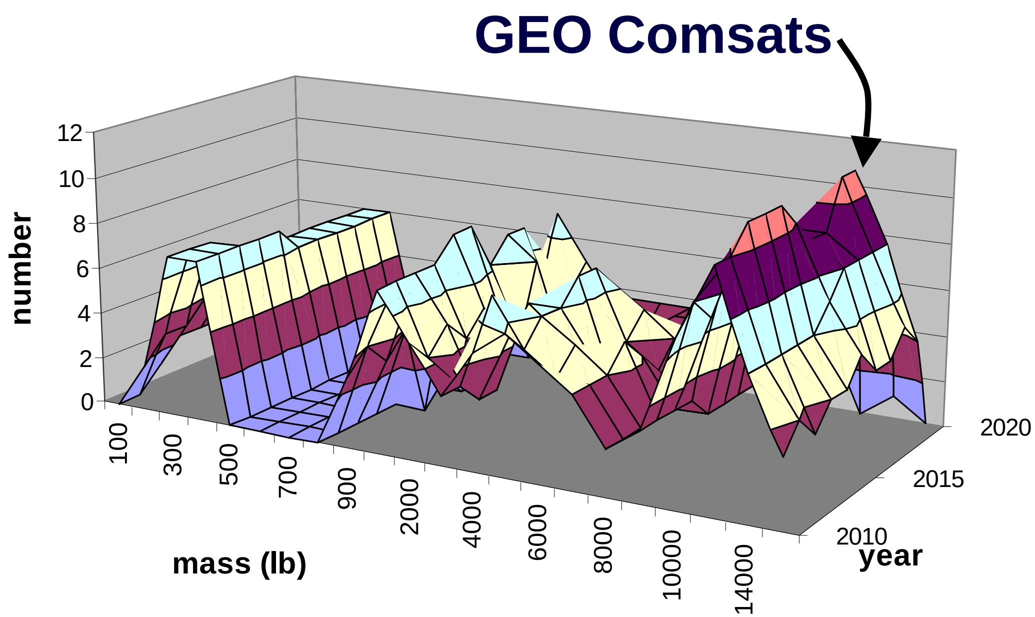
Phase II Deliverables
- Final Phase II program review
- Phase II final report
  - System requirements
  - Complete system design concept to TRL 3
  - Areas of development work needed
  - Technology roadmap
  - Cost models
  - Analyze key technical issues
    - ✔ GN&C
    - ✔ Payload transfer operations
    - ✔ Tether design and dynamics
    - ✔ Material selection
    - ✔ Simulation results
- Phase III customer funding commitment

Markets Drive Requirements

- Current & Emerging Markets
  - GEO Comsats
  - US Civil Satellites
  - US Military Satellites
  - Small-Vehicle Tourism
  - Mission Requirements at IOC
- Future Markets
  - Human Exploration & Development of Space
  - Solar Power Satellites
  - Large-Vehicle Tourism
  - Mission Requirements for Extended Operation Capability

Total Existing Markets

- Dominated by GEO Comsats => size HASTOL for that market
  - GEO destination matches HASTOL well
  - Aggressive pricing required
- Other markets offer targets of opportunity, not core business
  - Extra revenue
  - Protection from non-US competition allows higher prices

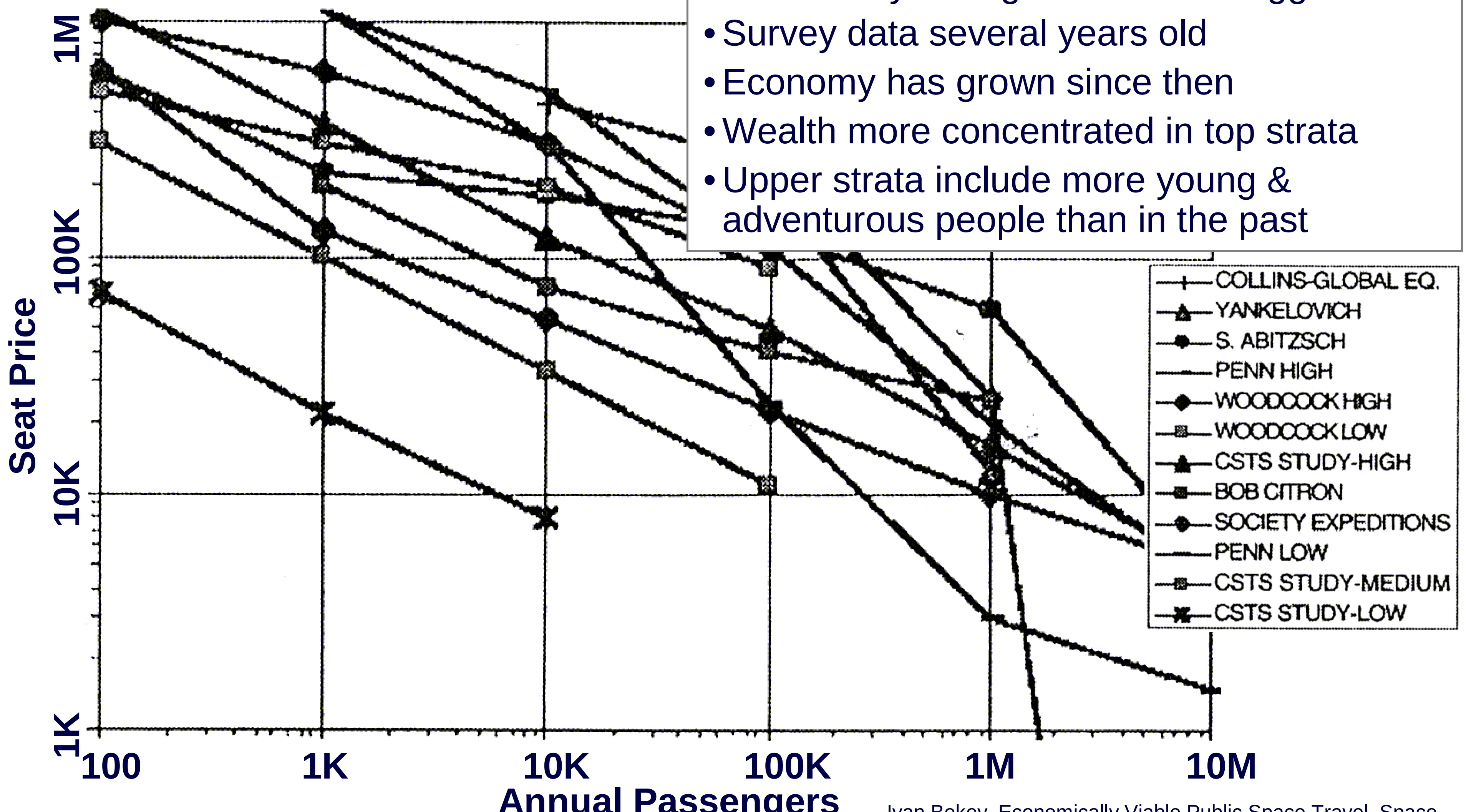


- Total 2010 Market
  - ~33 Launches / yr
  - $1.5 B / yr revenue
  - 50% revenue capture?

Surveys Show Space Adventure Travel Is Large And Elastic Market

Market likely stronger than data suggest

- Survey data several years old
- Economy has grown since then
- Wealth more concentrated in top strata
- Upper strata include more young & adventurous people than in the past

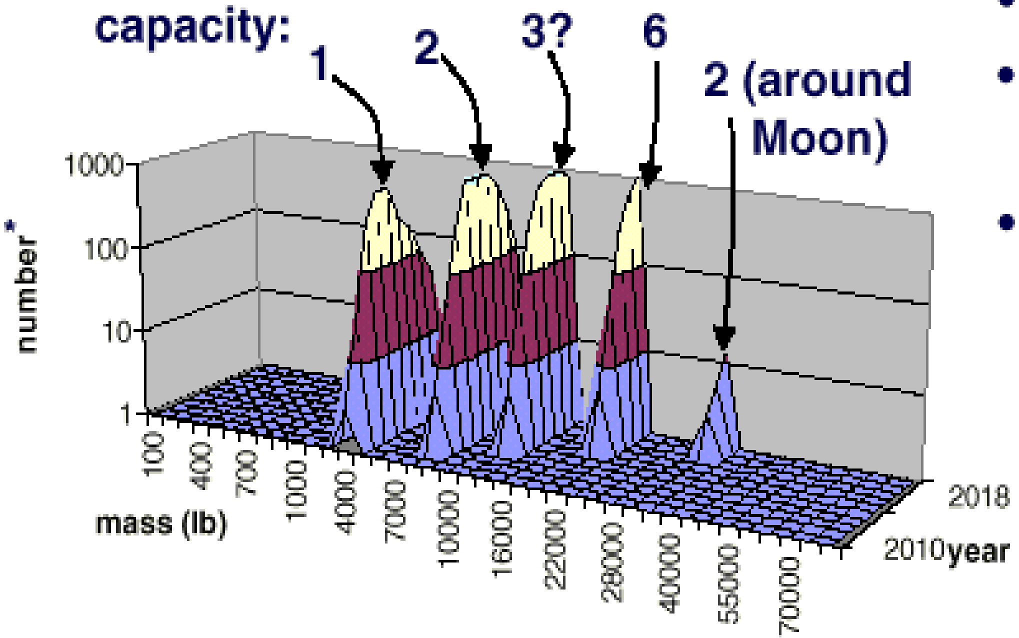


Ivan Bekey, Economically Viable Public Space Travel, Space Energy and Transportation, vol 4, No 1,2, 1999.

Tourism Market Projection

- Schedule passenger flights around high-revenue cargo flights
- Limit one flight per 2 orbits => max ~2000 flights per year
- Vehicle size increase every two years
- Tether size increase begins 5 years after IOC

Increments of passenger capacity:



- Market ignites at IOC
- 1st year: 3 seats sold
- 5th year: > 1300 seats sold
  - $130 M / yr revenue
- 10th year:
  - 9800 seats @ $60K/seat
  - 24 translunar seats @ $3M/seat
  - $1.05 B / yr revenue

Comsat and Passenger Flights Drive IOC Mission Requirements

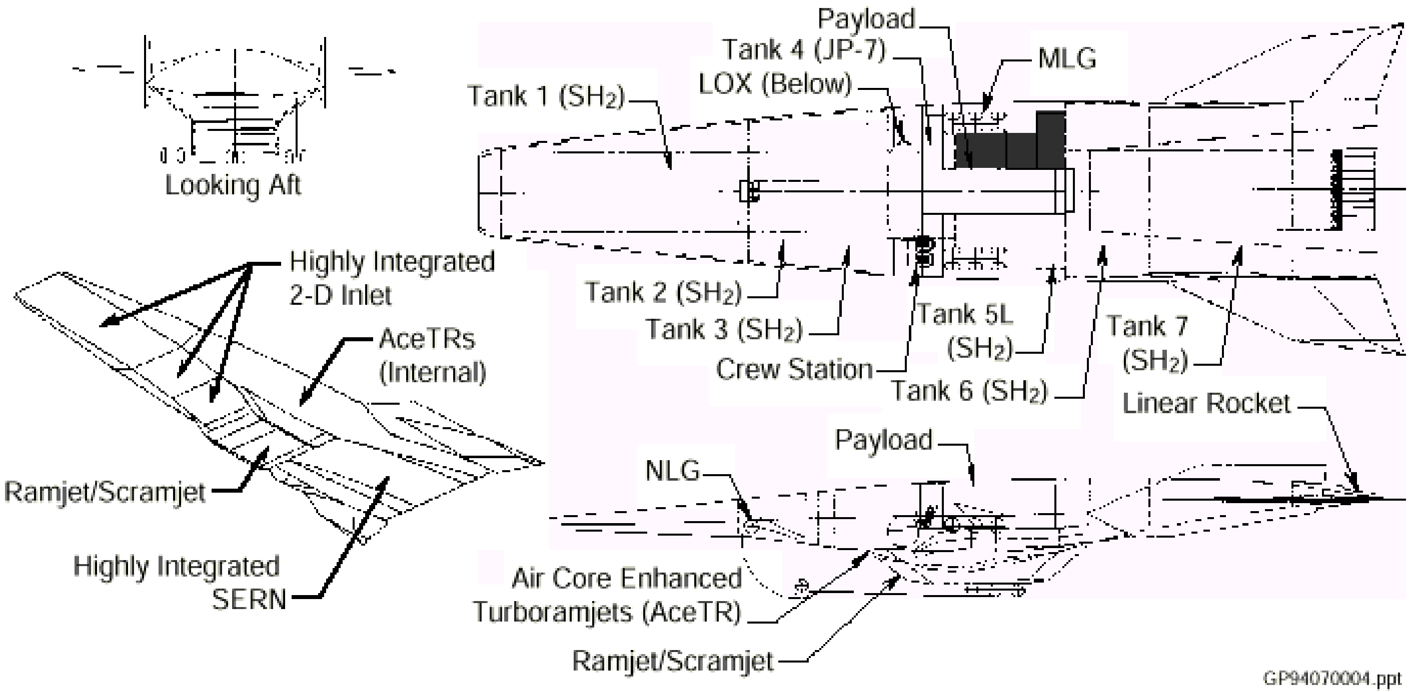
- Payload mass: 5500 kg
- Release orbits: GTO + assured safe re-entry orbit
- Release orbit insertion error to GTO: < Ariane 5 and Delta 4 error
- Passenger orbit insertion error: not to exceed safe entry limits
- Epoch: 2015 to 2025
- Mission reliability: 98% for comsats, 99% for passengers
- Mission safety:
  - 99% chance that comsat payloads will be undamaged
  - 99.99% chance that passengers will survive
- Orbital debris produced: zero
- Collision avoidance: “shall not endanger any tracked operational spacecraft”

Extended Operational Capability Mission Requirements

HEDS and SPS Drive Requirements

- Payload mass: 36,000 kg
- Release orbits: GTO + transfer orbit to Earth-Moon L1
- Release orbit insertion error: < Saturn V error
- Rate: 1000 SPS flights / yr, 15 HEDS flights / yr
- Epoch: 2020 to 2030
- Mission reliability: 98% for HEDS & SPS
- Mission safety: 99% chance that HEDS & SPS payloads will be undamaged
- Orbital debris produced: zero (incl. lunar downmass)

HASTOL Phase I Hypersonic Aircraft Concept: Boeing-NASA/LaRC DF-9 Dual-Fuel Aerospaceplane



Takeoff Wt:	**270 MT (590,000 lb)**
Payload:	**14 MT (30,000 lb)**
Length:	**64 m (209 ft)**
Apogee:	**100 km**

Speed at Apogee: 3.6 km/sec (approx. Mach 12)
4.1 km/sec (inertial)

Turboramjets up to Mach 4.5
Ram-, Scramjets above Mach 4.5
Linear Rocket for Pop-Up Maneuver

Variation with Rendezvous Velocity

- **Determined System Design for Hypersonic Airplane Apogee Velocities of Mach 10-19**

HASTOL Tether Facility Parameter Variations with Initial Payload Parameter Variations - 600 km - TCS 10X

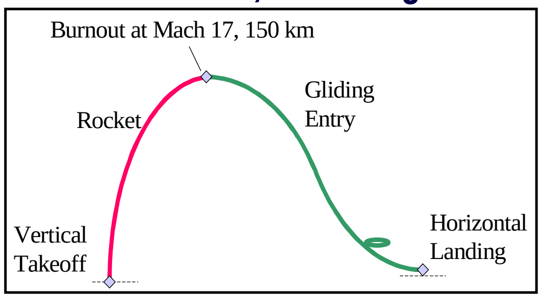
Fixed Parameters

Tether length	600km
TCS Mass	150 Mg (10X payload mass)
Payload Mass	15 Mg
Tether Safety Factor	3.0 along entire length

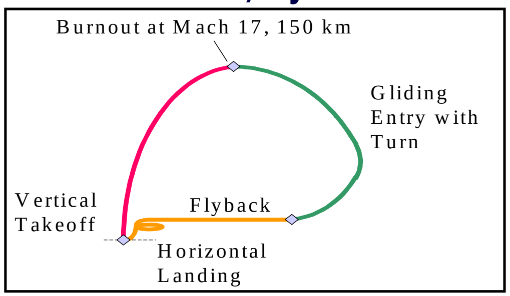
Run	Rendezvous					Facility			Mass Ratio			Tip Altitude		GTO
	Velocity		Altitude		Accel	CM Peri	CM Apo	Tip Vel	TCS	Tether	Total	Perigee	Apogee	Apogee
	(Mach)	(m/s)	(km)	(n.mi.)	(gees)	(km)	(km)	(m/s)	(ratio)	(ratio)	(ratio)	(km)	(km)	(X Geo)
3111	19.0	5791	**113**	**61**	0.88	549	1314	1977	10	16	26	80	186	1.00
3007	18.0	5486	110	60	1.18	540	1012	2229	10	28	38	88	80	1.44
3010	17.0	5182	110	60	1.55	522	835	2502	10	51	61	97	80	2.76
3015	16.0	4877	110	60	1.96	512	701	2780	10	94	104	102	80	13.51
3032	15.0	4572	110	80	2.40	509	612	3064	10	175	185	106	80	-8.66
3031	14.0	4267	110	60	2.86	511	559	3353	10	331	341	108	80	-2.49
3030	13.0	3962	110	60	3.33	517	531	3645	10	638	648	109	80	-1.68
3027	12.0	3658	110	60	3.82	524	524	3941	10	1253	1263	109	85	-1.31
3029	11.0	3353	110	60	4.33	533	533	4241	10	2515	2525	110	97	-1.09
3028	10.0	3048	110	60	4.87	542	542	4541	10	5108	5118	110	103	-0.95

Broad Range of Mission Profiles and Propulsion Systems Considered

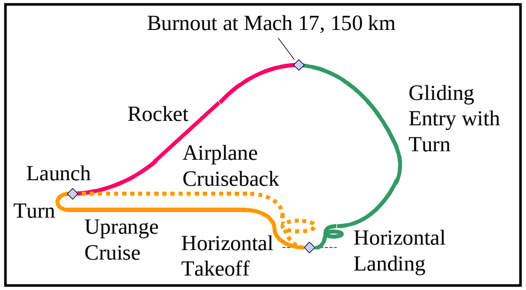
Vertical Launch, Downrange Land



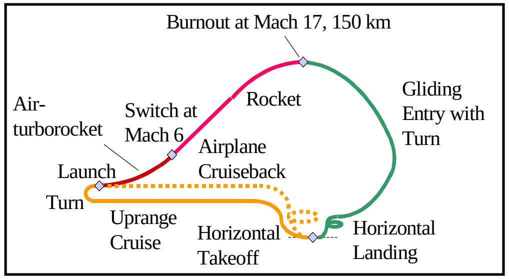
Vertical Launch, Flyback Rocket



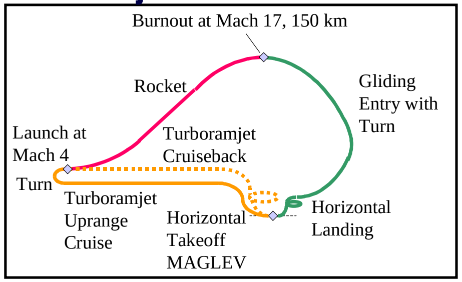
Air Launched Rocket



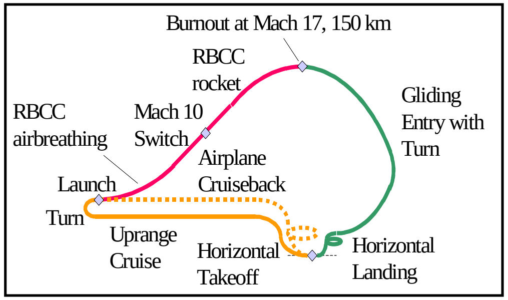
Air-Turborocket



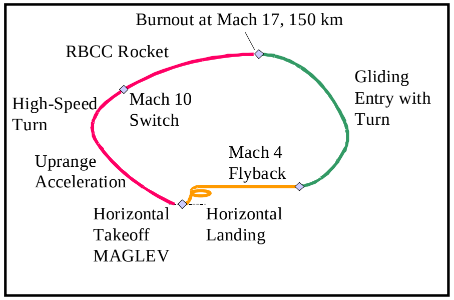
Turboramjet Booster and Rocket



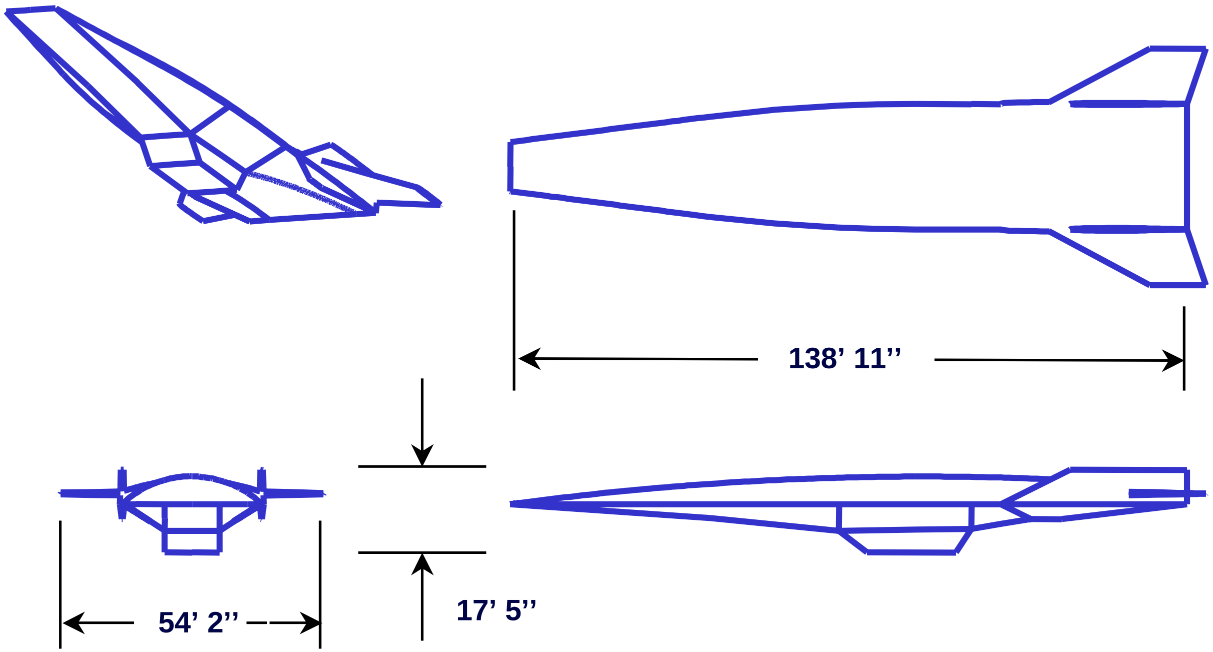
Air Launched RBCC

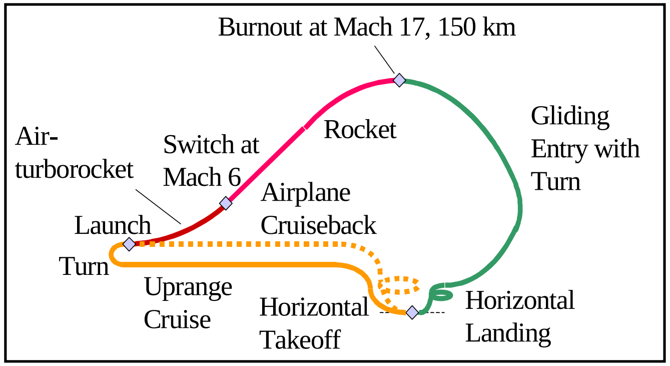


Single Stage Airbreather (RBCC)



HASTOL Phase II Hypersonic Aircraft Concept: Air Launched Turbo-Rocket





Takeoff Wt:	**177 MT (390,883 lb)**
Payload:	**7 MT (15,000 lb)**
Payload bay:	**3 m dia x 9.1 m (10 ft x 30 ft)**
Apogee:	**150 km**

Speed at Apogee: 5.2 km/sec (approx. Mach 17)
5.7 km/sec (inertial)

Air-turborocket to Mach 6

Linear Rocket above Mach 6

HASTOL Tether Facility Design

Mass Ratios:

- Control Station 10x payload
- Tether 58.8x
- Grapple 0.12
- TOTAL: ~ 69 x payload

Tether Length: 630 km

Orbit:

- 582x805 km ->569x499

Maximum Total ΔV ~ 5 km/s

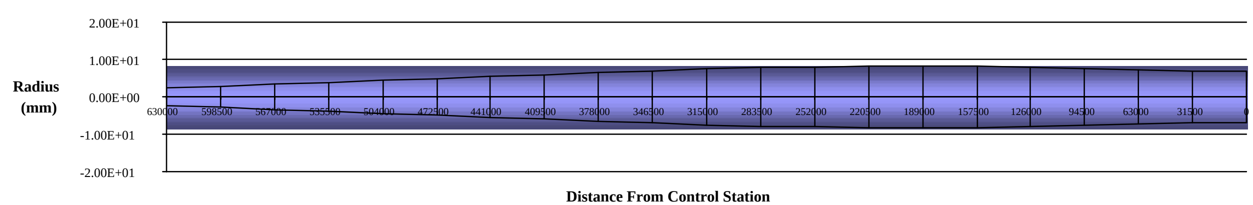
Capability to toss payload to 107,542 km

Tosses to GTO by releasing off-vertical

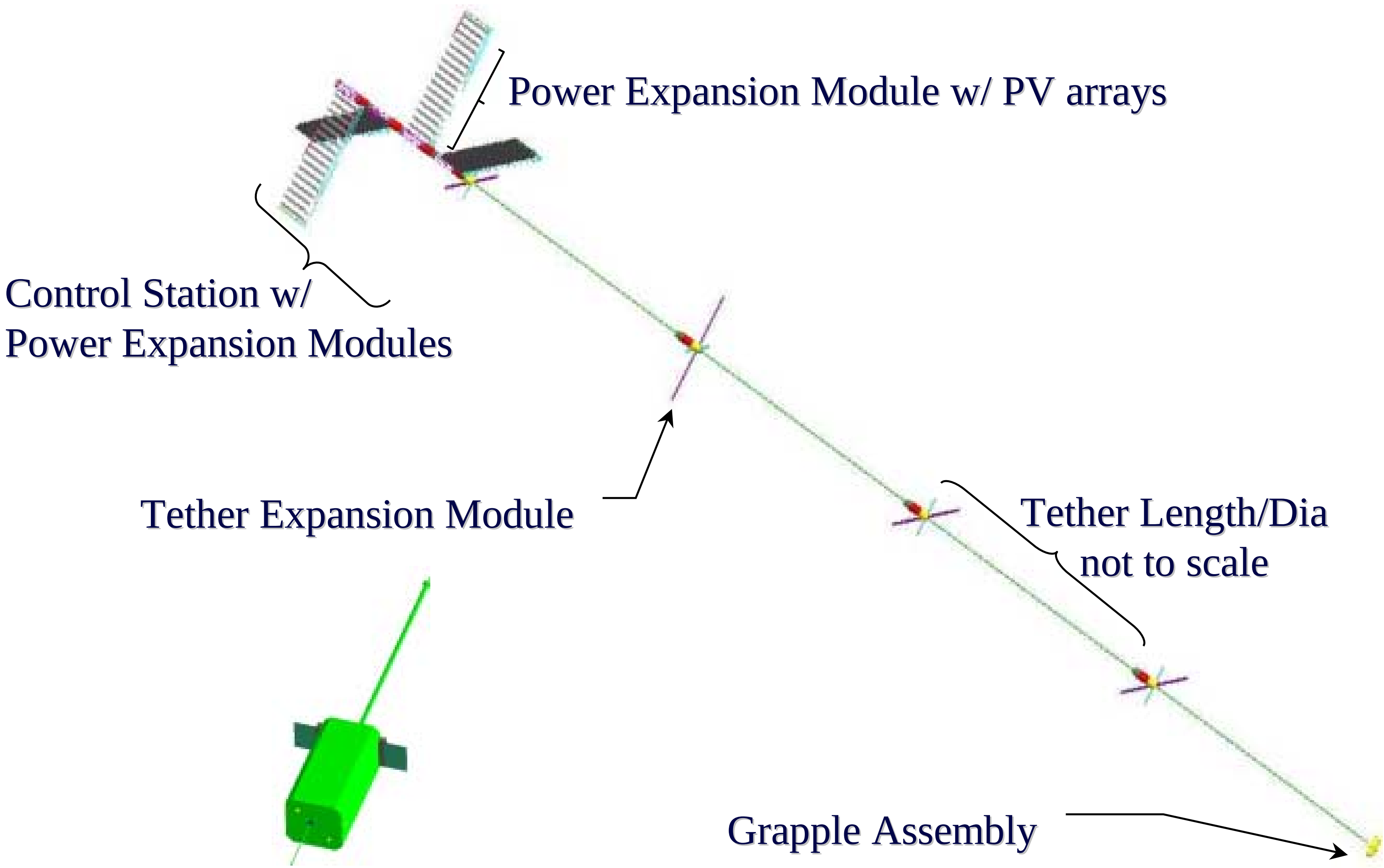
System Masses		
Tether mass	323,311	kg
CS Active Mass	51,510	kg
CS Ballast Mass	3490	kg
Grapple mass	650	kg
Total Facility Mass	**378,961**	kg
Total Launch Mass	**375,471**	kg
Payload Mass	**5,500**	kg

Tether Characteristics		
Tether Length	636,300	m
Tether mass ratio	58.78	
Tether tip velocity at catch	2,517	m/s
Tether tip velocity at toss	2,481	m/s
Tether angular rate	0.00583	rad/s
Gravity at Control Station	0.73	g
Gravity at payload	1.48	g
Rendezvous acceleration	1.50	g

		Pre-Catch		Joined System	Post-Toss	
Positions & Velocities		**Payload**	**Tether**	**Post-catch**	**Tether**	**Payload**
resonance ratio		41	20		1	26.0
perigee altitude	km	-4603	582	576	569	1001
apogee altitude	km	150	805	650	499	107542
perigee radius	km	1775	6960	6954	6948	7379
apogee radius	km	6528	7183	7028	6877	113921
perigee velocity	m/s	18789	7627	7591	7555	10073
apogee velocity	m/s	5110	7390	7511	7632	652
CM dist. From Station	m		204469	210647	204469	
CM dist. To Grapple	m		431831	425653	431831	
²V to Reboost	m/s				72	
²V to Correct Apogee	m/s					-484
²V to Correct Precess.	m/s					416
²V To Circularize	m/s					1218
Basic Orbital Parameters						
semi-major axis	km	4152	7072	6991	6912	60650
eccentricity		0.6	0.016	0.005	-0.005	0.878
inclination	rad	0	0	0	0	0
semi-latus rectum	km	2792	7070	6991	6912	13861
sp. mech. energy	m2/s2	-4.80E+07	-2.82E+07	-2.85E+07	-2.88E+07	-3.29E+06
vis-viva energy	m2/s2	-9.60E+07	-5.64E+07	-5.70E+07	-5.77E+07	-6.57E+06
period	sec	2662	5918	5817	5720	148647
period	min	44.4	98.6	97.0	95.3	2477.5
station rotation period	sec		1077.8	1077.8	1077.8	
rotation ratio			5.5	5.4	5.3	



Boost Facility Concept

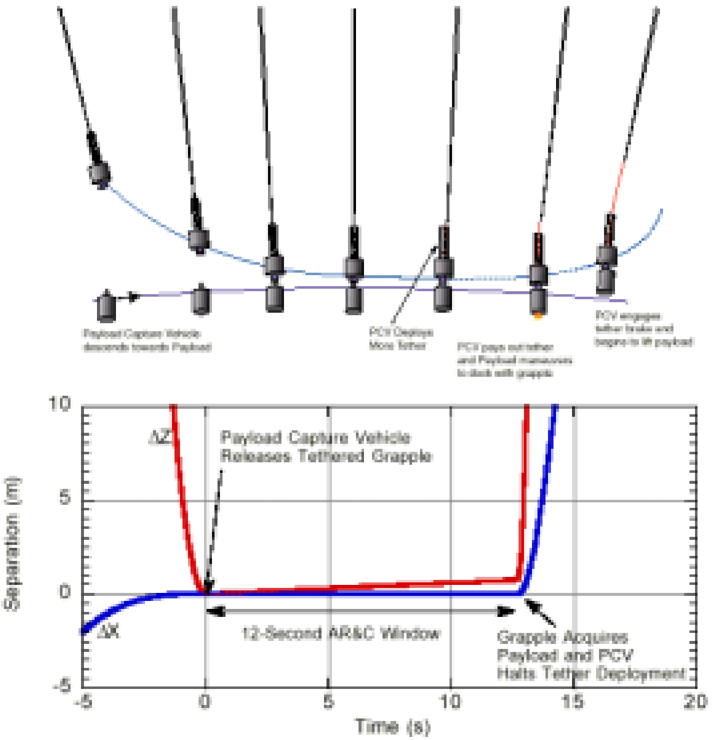


Operational HASTOL Control Station Initial Subsystem Mass Allocations

Control Station mass≈ 55,000 kg

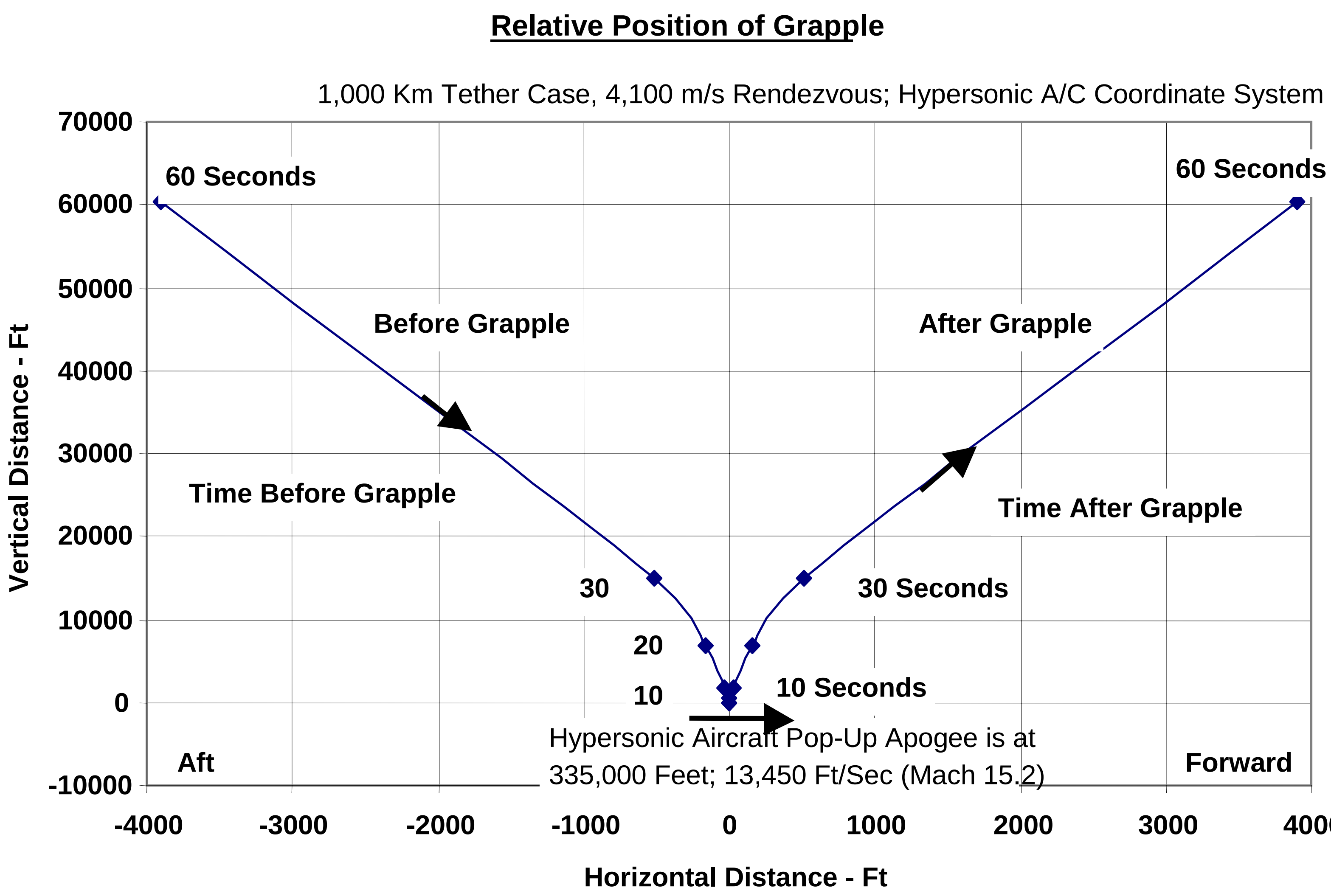
Subsystems	**Mass, kg.**
Thermal Control	**1,970**
Cabling/Harnesses	**1,380**
Structure	**4,730**
Electrical Power (EPS) & Tether Power	**9,060**
Command & Data Handling (C&DH) and Communication	**200**
Attitude Determination & Control (ADCS) and Guidance & Navigation (GN&C)	**590**
Tether Deployment and Control (TDCS)	**1,380**
Docking	**390**
Ballast	**35,300**

Phase I Results Show Feasibility of Payload Capture

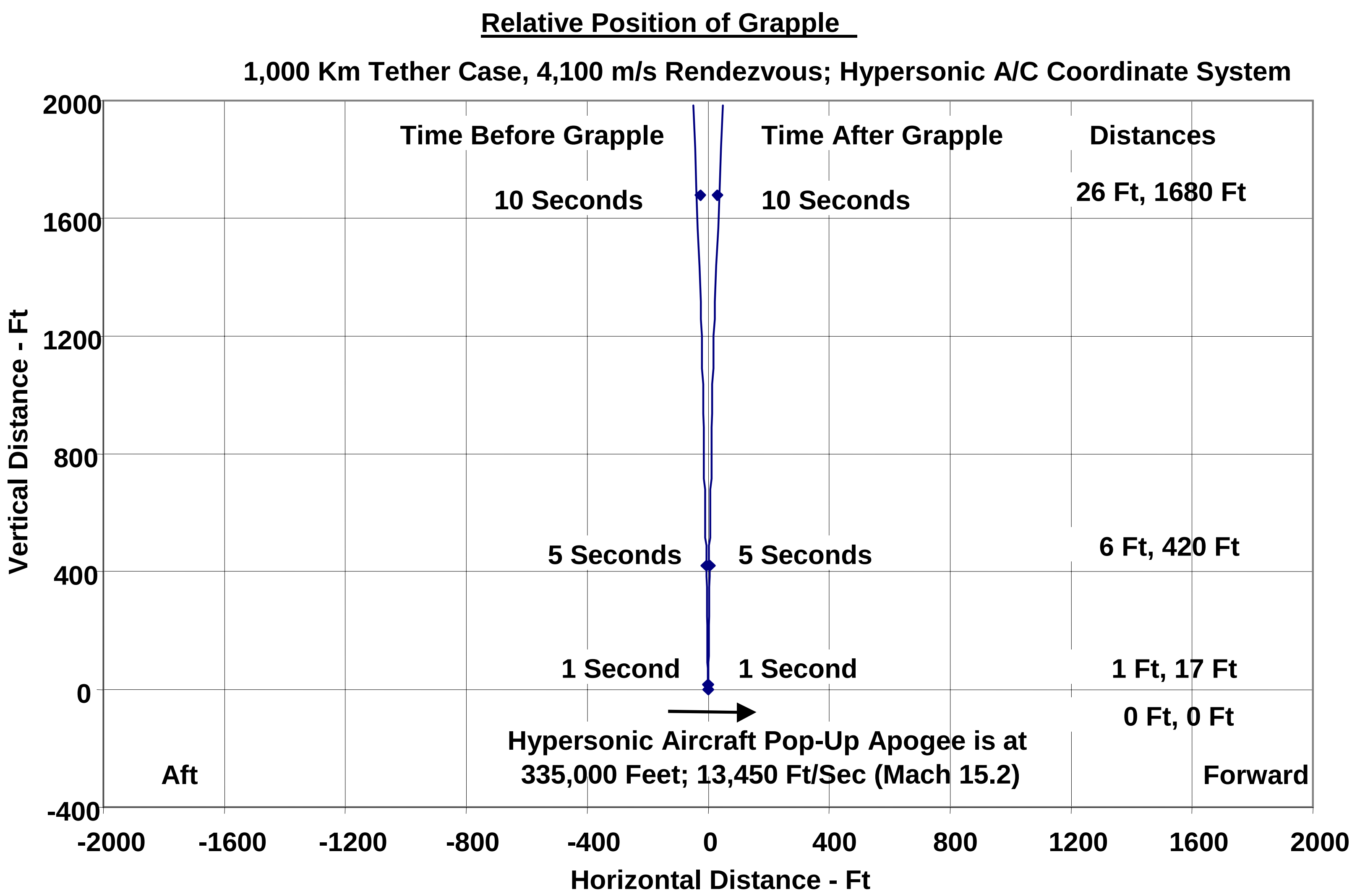


- **Tether-Payload Rendezvous Capability is a Key Enabling Technology**
- **TUI Developed Methods for Extending Rendezvous Window**
  - **Works in Simulation**
  - **Validation Experiments Needed**

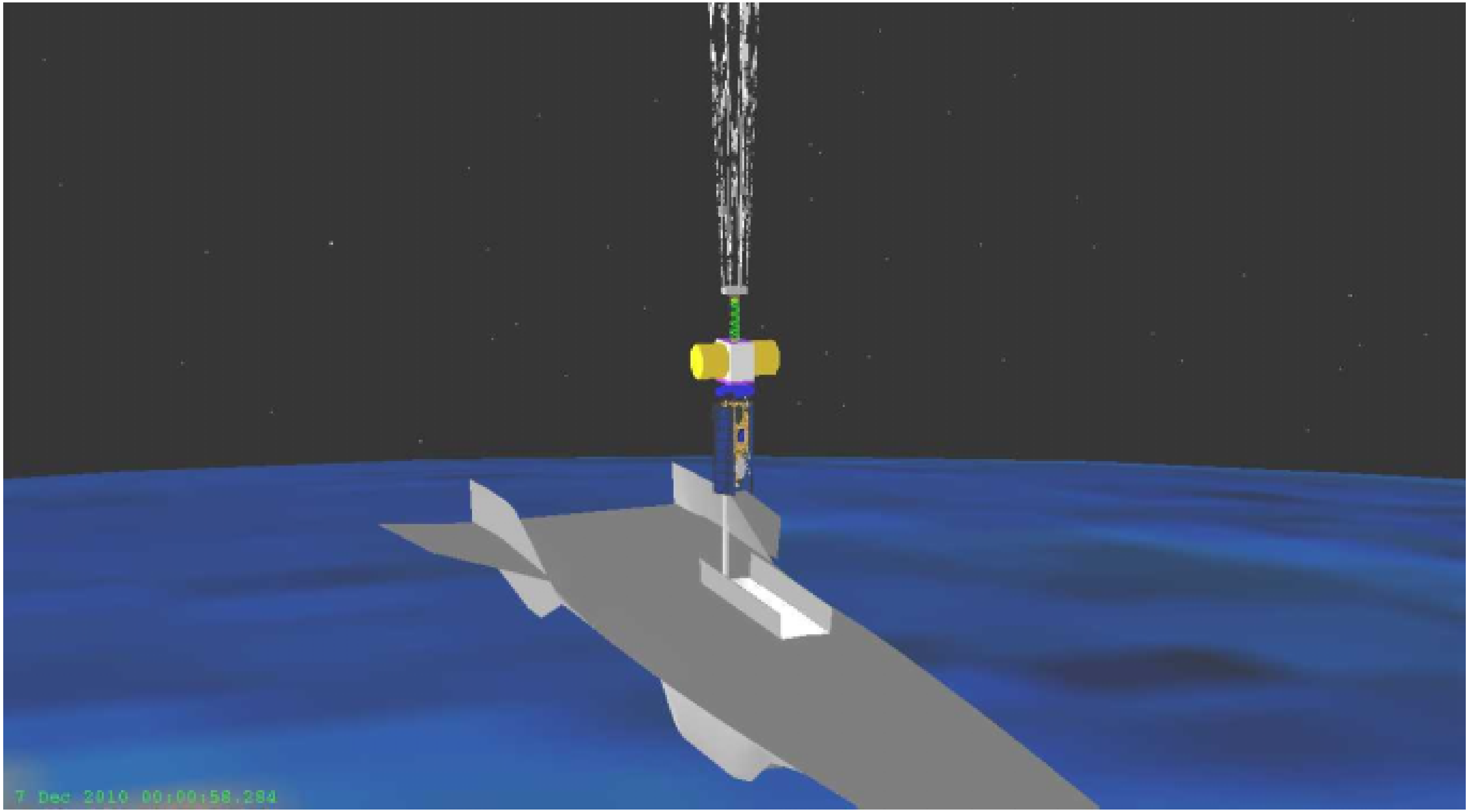
Relative Position of Grapple and Payload



Relative Position of Grapple and Payload



Visual 6-DOF Simulation Validates Rendezvous and Capture Scenario



R&C Scenario Timeline/Sequence of Events

Time (sec)	Event
0	Start R&C scenario
5	Initiate guidance predictions
15	Issue P/L bay door discrete
30	Issue P/L rotation mechanism commands
45	P/L rotation complete
58	Issue grapple assembly release discrete
60	Nominal capture point
65	End grapple assembly freefall
120	End R&C scenario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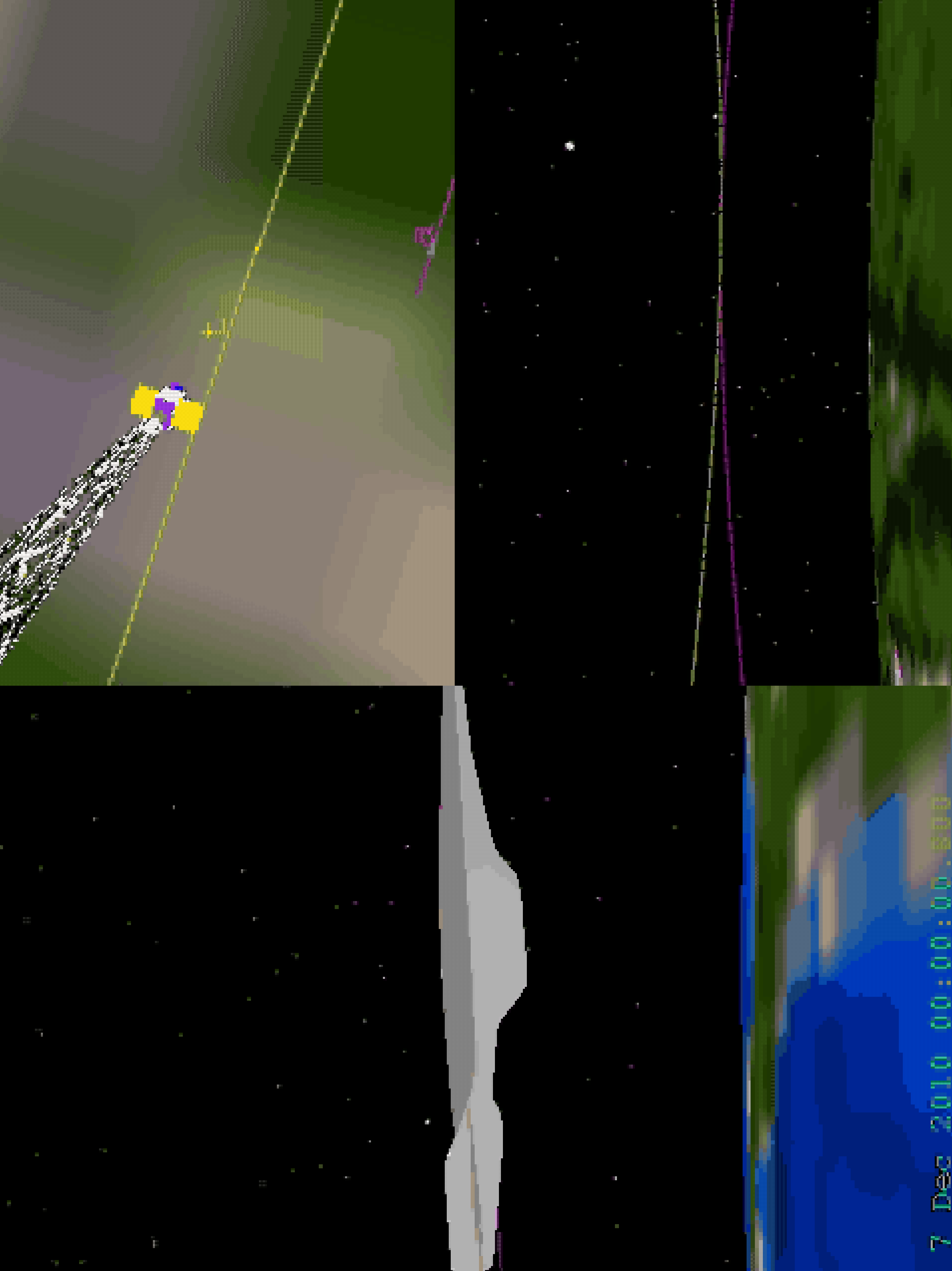
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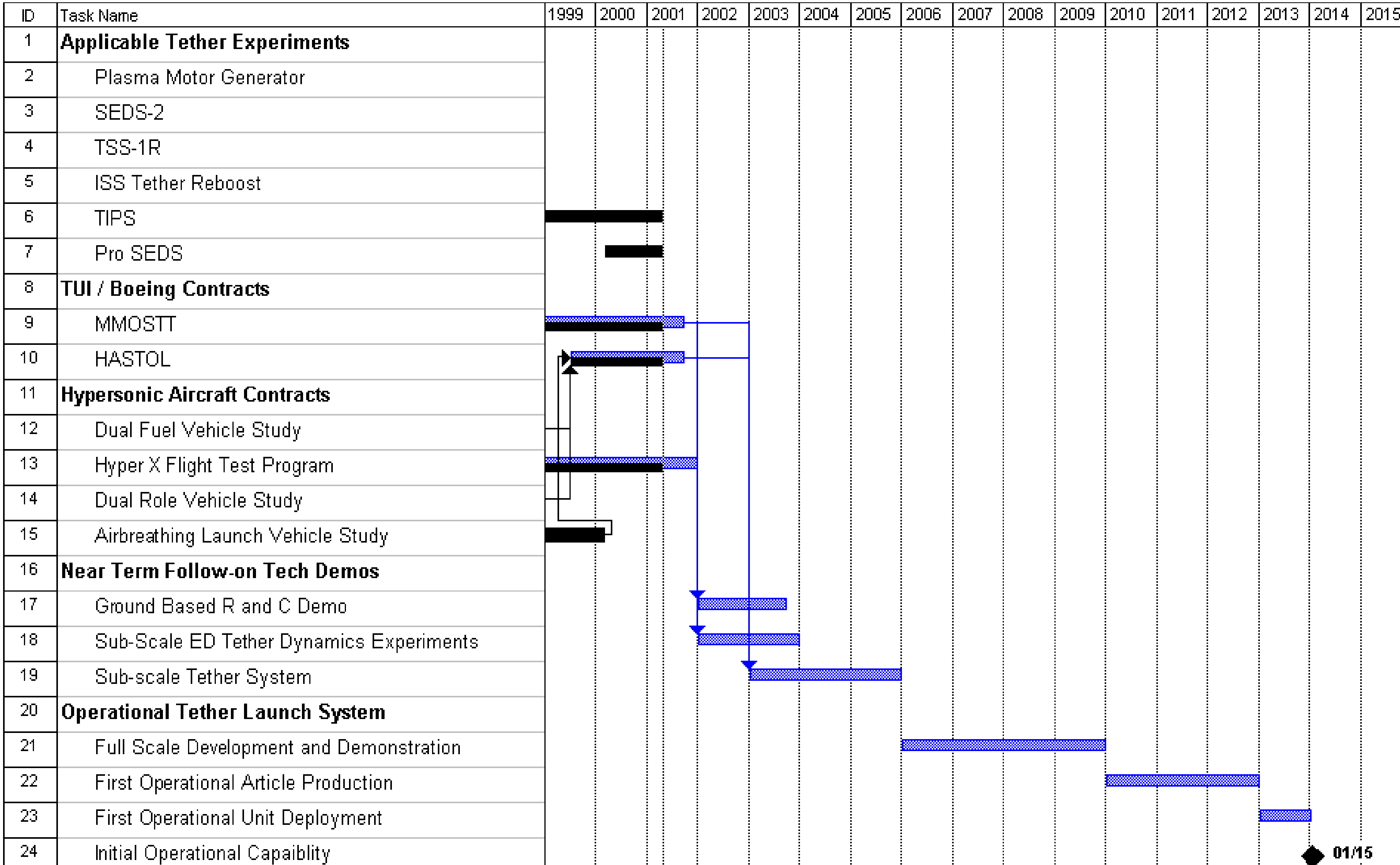
Possible Follow-on Projects and Tasks

- **Ground-Based Rendezvous and Capture Demo**
  - **Detailed rendezvous and capture simulation and analysis.**
  - **More detailed design of operational grapple**
  - **Detailed design of demo hardware**

- **Sub-Scale Electrodynamic Tether Dynamics Experiments**
  - **Secondary payload**
  - **4-5 km long ED tether; assess tether dynamics, survivability**

- **Sub-scale tether system to capture and toss payloads**
  - **Four phase program:**
    - **Design**
    - **Fabrication and ground testing**
    - **Flight experiment**
      - **1st, tether is in circular orbit just a little higher than payload and hanging. Then, tether and payload rendezvous and capture (low relative speed). Tether then uses thrust to start rotating and throw payload.**
      - **2nd, tether is in a higher elliptic orbit and rotating slowly. It rendezvous with payload (moderate relative speed), rotates, and tosses.**
      - **3rd, demo at maximum rotation.**
    - **Limited operation system for paying customers.**

Aggressive Development Plan Leads to a 2015 IOC



Remaining Phase II Tasks

- Complete Boost Facility Concept Definition
- Complete Operational System Deployment Concept
- Define Grapple Requirements Using Rendezvous and Capture Simulation
- Define Grapple Concept
- Complete Survivability and Collision Avoidance Analyses
- Complete Follow-on Program Plans
- Estimate System Cost

Tether Systems Have the Potential to Enable Low Cost Access to Space

- Concept feasibility study already completed.
- Key targets for technical risk reduction have been identified.
- Tether experiments have already flown in space.
- Near term experiments further reduce potential system risks.
- Phase II analyses reveal near term demonstrations and flight experiments required for full scale system development.
- Commercial development path will probably be required.

Modest near term government investment is encouraged to fund demos and experiments.