Hypersonic Airplane Space Tether Orbital Launch (HASTOL) Study

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Presentation Outline

• Team Acknowledgments
• HASTOL Concept of Operation
• Phase I Results
  – Hypersonic Airplane
  – Tether Boost Facility
  – Tether
  – Payload Capture
• Phase II Plan
• Follow-On Efforts
HASTOL Phase II Study Team

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Tethers Unlimited, Inc.
Rob Hoyt, Seattle, WA
Bob Forward, Seattle, WA
The HASTOL System Concept of Operation Features a Reusable Launch Architecture

- Hypersonic Airplane Carries Payload up to 100 km, Mach 12
- Rendezvous with Tip of Rotating Tether in Orbit
- Tether Lifts and Tosses Payload into Orbit or Escape
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 Baseline 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**
Aircraft “Pop-Up” Mission Profile Analysis Shows Required Speed and Altitude are Attained

Launch Ascent

High Speed Climb Mach 4.5 - 10

Ballistic Trajectory to Tether Rendezvous

Mach 0.8 - 4.5

Initial Climb

Subsonic Cruise

Decel

Post Flight Operations

Descend

Alternate Upper Stage to Tether Rendezvous

Tanker Rendezvous

Inflight Refueling

Pattern, Landing, Post Flight Operations

VeLOCITY

ft/s

km

m/s

Achivable Points

Unachivable Points

Dynamic Pressure (p)

Time Since Apogee (s)

Normal Load Factor (g)

Time Since Apogee (s)
Ongoing Hypersonic Aircraft Development Programs Will Benefit HASTOL Concept Maturity

- **DF-9** - Horizontal takeoff, horizontal land concept
  - Developed by Boeing for NASA LaRC
  - Derivative of DF-7 hypersonic cruise airplane concept
- **Hyper-X (X-43)** - Scramjet flight test vehicle from Pegasus booster
  - Microcraft prime contractor; Boeing subcontractor
  - First flight test vehicle delivered; flight to Mach 7 in Sept 2000
  - Second flight test vehicle to be delivered to NASA in August 2000
  - Third flight test vehicle in design/fab; will fly to Mach 10 in Oct 2001
- **X-34** - Rocket boosted hypersonic flight demo
  - Being developed by Orbital Sciences
  - Captive flight tests completed
  - Phase 1 flights to Mach 3.8; Phase 2 flights to Mach 8
- **X-33** lifting body, aerospike engine
  - Being developed by Lockheed-Martin
  - Flight vehicle being assembled; testing to Mach 10+ envisioned
- **X-37 (Future-X)** Hypersonic research test bed vehicle
  - Boeing/NASA MSFC Cooperative Effort
  - First flight planned for 2003 (Shuttle payload); re-entry to powerless horizontal landing
HEFT Tether Boost Facility is Adaptable to the HASTOL Mission

- High-Strength Electrodynamic Force Tether Facility
  Use Momentum-Exchange to Rapidly Boost Payloads
- Use Electrodynamic Reboost to Restore Tether Facility Orbit
- Creates Capability to Repeatedly Boost Payloads out of LEO Without Transfer Propellant

Facility center of mass in slightly elliptical orbit:
- 700 km apogee
- 610 km perigee
- 90 km from tether station
- 7.6 km/sec perigee velocity

Tether:
- Length: 600 km
- Tip velocity: 3.5 km/sec
- When facility center of mass is at perigee, tether tip is at 100 km altitude

Station Mass: 1,650 MT
Tether Mass: 1,360 MT
Grapple Mass: 650 MT
HEFT Tether Boost Facility is Adaptable to the HASTOL Mission

1,000- to 2,000-tonne Tether Control Station

600-km Spectra 2000 Tether

Solar Panel Array

20-m diameter

1000- to 2000-tonne Tether Control Station

Primary Lines

Secondary Lines (Initially Unstressed)

Effects of Damage Localized

Cut Primary Line

First Level of Secondary Lines Transfers Load Around Damaged Section

Tens of Meters

Second Level of Secondary Lines Redistributes Load Back on Undamaged Portion of Primary Line

Hoytether Design

Primary Lines

Tether Deployment and Retrieval Mechanism

Grapple Tether

Grapple Assembly

Housing for Tether Reel, Avionics, RCS Fuel, Batteries, and Battery Recharging Circuits

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Grapple
The Hoytether™ Design will survive meteorite strike cuts or material failure of primary lines

Effects of Damage Localized

First Level of Secondary Lines Redistributes Load to Adjacent Nodes

Second Level of Secondary Lines Redistributes Load Back to Undamaged Portion of Primary Line

Primary Lines

Secondary Lines (initially unstressed)

0.2 to 10's of meters

0.1-1 meter

a. b. c.
Rotovator™ Tether and Hypersonic Airplane Rendezvous occurs at 100 km, 4.1 km/sec
Phase I Results Show Feasibility of Payload Capture

- Tether-Payload Rendezvous Capability is a Key Enabling Technology
- TUI Has Developed Methods for Extending Rendezvous Window
  - Works in Simulation
  - Validation Experiments Needed
Simplified Grapple Approach Selected for Phase I

1. Grapple/End mass comes down on Payload
2. Grapple stops on Payload, levers on payload are in “in-close” position
3. Attach Levers then move radially outward toward ring; sliding on rails. Once contact with ring is made, they latch to the ring securing the payload to the grapple.

- High Temperature Tether With Embedded Conductor For Electrodynamics Tether Electric Power Generation
- Housing for Tether Reel, Avionics, RCS Fuel, Batteries, and Electrodynamics Tether Battery Recharging Circuits
- Mounting Structure for Reaction Control System
- RCS Nozzles Flush with Surface to Minimize Drag and Heating
- Tether Deployer and Retrieval Mechanism
Other Grapple Concepts Have Been Investigated; Baseline Approach Will Be Revisited in Phase II

1. Cable with tip grapnel flies by tether
2. Tether tip lifts upward, grapnel snags cable.

GRAPPLE TO PAYLOAD ATTACHMENT OPTION
Radially moving Levers move to ring and secure P/L.

1. Grapple / End mass comes down on Payload
2. Grapple stops on Payload, levers on payload are in “in-close” position
3. Attach Levers then move radially outward toward ring; sliding on rails. Once contact with ring is made, they latch to the ring securing the payload to the grapple.
HASTOL Phase II Study Tasks

- Mission Requirements and Mission Opportunity Definition
- System Requirements
- System Concept Definition
- System Analysis
- Technology Development Roadmap
  (near term demos)

- Contract Schedule/Key Milestones:
  - First 12 of 18 month program funded
  - Concept Definition and System Analyses will be nearly complete by end of 12th month
# HASTOL Phase II Study Schedule

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<th>Task Names</th>
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<td>2. System Requirements Definition (SOW 2.0)</td>
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TETH-1010
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\textsuperscript{TM} with Spectra2000\textsuperscript{TM} material and PBO tip material

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

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
- Phase III customer funding commitment
- Analyze key technical issues
  - GN&C
  - Payload transfer operations
  - Tether design and dynamics
  - Material selection
  - Simulation results
System Analysis Tasks Address Areas of Concern

- Detailed rendezvous and payload capture simulation will identify payload grapple requirements
- Abort modes will be investigated -- what if payload is not captured?
- Payload release orbits
- Cost modeling -- compare HASTOL to other launch system architectures
- Tether dynamics and associated interaction with grapple assembly
- Tether material survivability in space environment
- Electrodynamic thrust control for reboost and orbit transfer
- Collision avoidance of known orbiting assets

Technology Development Roadmap will identify near term demonstrations needed for low risk flight demonstration.
# Roadmap Identifies Stepwise Technology Demonstration and System Development, Production and Deployment

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Diagram: Operational System Production and Deployment Timeline

Prototype Demonstration Program

Operational System Production

Operational System Deployment

TETH-1023
Additional Near-Term Studies Can Assess Feasibility and Identify Key Flight Demos

- **Automated Rendezvous & Capture**
  - Time Window for Capture < 10 Seconds
  - High Accuracy Requirements
- **Electrodynamic Tether Operation**
  - High Power & Voltage Issues
  - Control of Tether Dynamics
- **Traffic Control/Collision Avoidance**
- **Economic Analysis/Business Plan**
  - Technology Risk Reduction
  - Incremental Commercial Development Path
  - Customer Acceptance
Near-Term Flight Experiments will Validate Feasibility for Prototype System Development

• **Spinning Tether Orbital Transfer System - STOTS**
  – Deploy Small Payload on a Tether
  – Demonstrate Spin-Up of Tether System Using Reeling
  – Demonstrate Controlled Toss of Payload
  – Build on SEDS Heritage
  – Piggyback on Delta II Launch

• **Tether Orbit Raising Qualification Experiment - TORQUE**
  – Deploy Hanging Tether Below Small Facility
  – Demonstrate Payload Rendezvous & Docking with Hanging Tether
  – Demonstrate Electrodynamic Spin-up of Tether
  – Demonstrate Controlled Toss of Payload
  – Demonstrate Electrodynamic Reboost of Facility
  – Perform Repeated Boosting of Commercial/Scientific Payloads
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.
- Planned near term experiments further reduce potential system risks.
- Phase II analyses will reveal near term demonstrations and flight experiments required for full scale system development.
- Modest near term government investment is encouraged to fund demos and experiments.