Airships 101: Rediscovering the Potential of Lighter-Than-Air (LTA)

John Melton
NASA Ames Research Center
John.Melton@nasa.gov  (650) 604-1461

Ron Hochstetler
SAIC
hochstetlerr@saic.com  (703)516-3162
Agenda

• Intro to NASA Ames Aeronautics
• Airship classifications
• LTA Theory
• LTA Revival – Why Now?
• R&D Challenges
• LTA “Game-Changers”
Aeronautics at Ames Research Center

- Video available at:
Airships were focus of much early NACA work (Munk, Zahm)
ARC home of the Macon (1933-35) and various USN blimp squadrons until 1947
Approximately 50 research papers from the mid-1970s to mid-1980s were spawned by the energy crisis of 1973-1974
1970s research identified three potential LTA roles:
- Heavy-lift airship
- Short-haul commercial transport
- Long-endurance naval patrol
1979 AIAA LTA conference in Palo Alto
1980s studies confirmed potential role for LTA in lifting heavy and oversized cargo
1980s research focused on quad-rotor + LTA concepts for heavy lift
Minor involvement with Piasecki quad-rotor and Cyclocrane
1994 operations research with Westinghouse used Vertical Motion Simulator
USS Macon on Mooring Mast near Hangar 1 Moffett Field 1935
70+ Years of Innovation

- Tektites
- Apollo Re-Entry Shape
- Blunt body Concept (H. Allen)
- Transonic Flow
- Apollo Heat Shield Tests
- Flight Research
- Conical camber
- Swept-Back/wing
- Arcjet Research
- Lifting body
- Apollo Guidance System
- Air Transportation System
- Hypervelocity Free Flight
- Flight Simulation
- Computational Fluid Dynamics
- Life Sciences Research
- 80x120 Wind Tunnel
- Galileo
- Viking
- Pioneer
- Pioneer Venus
- Tiltrotor
- ER-2
- Lunar Prospector
- Nanotechnology
- Astrobiology
- Kuiper Observatory
- NASA Research Park
- World’s fastest operational supercomputer
- X-36

Ames Spacecraft and Aeronautics Expertise

- Inflatable (Fabric) and Lightweight Structures
  - Advanced FEA tools: LS-DYNA, Abaqus, NASTRAN
- Piloted Simulation requiring Vertical Motion Sims
  - Helicopters, Moon landers
  - Controls development for VTOL aircraft
- Aerodynamics Design, Analysis, and Test
  - CFD tools: OVERFLOW, STAR-CCM+
  - Large wind tunnels, Supercomputers

LTA vehicles face many of the same engineering challenges that confront current NASA Ames aircraft AND spacecraft programs
LTA Taxonomy and Theory
Aircraft Taxonomy

Aircraft

Heavier-Than-Air (HTA)
- Fixed Wing (Airplanes)
  - Hybrid (V-22)
  - Powered Lift (JSF)
- Rotary Wing (Helicopters / Autogyros)

Lighter-Than-Air (LTA)
- Unpowered
  - Untethered (Balloons)
  - Tethered (Aerostats)
- Powered and Steerable (Airships = Dirigibles)
  - Conventional (Fully buoyant)
    - Rigid
    - Semi-rigid
    - Non-rigid
  - Hybrid (Semi-buoyant)
    - Rigid
    - Semi-rigid
    - Non-rigid
### Airship Examples

**Powered and Steerable**

*Airships = Dirigibles*

- **Conventional** *(Fully buoyant)*
  - Rigid
  - Semi-rigid
  - Non-rigid

- **Hybrid** *(Semi-buoyant)*
  - Rigid
  - Semi-rigid
  - Non-rigid

---

**Design space for LTA is at least as large as HTA, but has only been “randomly sampled” with flight vehicles spaced over decades**

**LTA engineering is MUCH broader than the Hindenburg (LZ-129) and Goodyear Blimp**

---

**AMS Skyship 600 Airship**

**Graf Zeppelin LZ-127**

**Russian Lenticular Airship**

**21st Century Airships**

**Spherical Airship**

**Boeing SkyHook**

**Lockheed ADP P-791**

**Piasecki PA-97 Helistat**
Conventional airships control heaviness by changing aerostatic (buoyant) lift and ballast.

Hybrid airships combine aerostatic (buoyant) lift with aerodynamic lift (wing-borne) and direct (propulsive) lift.
LTA Theory

- Lifting force from displacement (Archimedes, 287-212 BC)
  - Useable Lift = \( \text{Vol} \times (\rho_{\text{He}} - \rho_{\text{air}}) \times g - W_{\text{dead}} \)

- Hydrogen (H\(_2\)): 70 lbf per 1000 ft\(^3\) (1.14 kg/m\(^3\))
- Helium (He): 65 lbf per 1000 ft\(^3\) (1.06 kg/m\(^3\) or 93% of H\(_2\))

- Dead weight historically > 50% of displacement lift
  - Hindenburg (H\(_2\)): 54%, 260K lbs Dead, 220K lbs Useable

- Fuel, ballast, crew, consumables further reduce useable lift available for cargo

- Lift, Drag, Weight, and Thrust still apply – but apparent mass, buoyancy control, and ballast complicate design
LTA Revival and Missions
Reviving the LTA Dream – Why Now?

• Commercial – the “E’s”
  – Environment, Emissions, Energy, and Economics
  – New market opportunities
  – New aerospace exports
  – Endurance for scientific and commercial missions

• National Security
  – DoD transport and surveillance needs
  – Homeland security
  – Humanitarian airlift

There are numerous LTA missions besides tourism and advertising!
Environment, Emissions, and Energy

- Low noise
- Pavement “optional” – concrete not required
- Reduces port, freeway and railway congestion
- Reduces cargo aircraft at airports, reducing ramp/taxi delays and emissions
- Utilization of secondary airports and shallow ports
- Operations at lower altitudes reduce air traffic conflicts
- Large size and low speeds promote autonomous operations

*Airships have minimal infrastructure requirements and their low-altitude operations are inherently green*
Environment, Emissions, and Energy

• Safe, convenient, airborne platform for the development and demonstration of green propulsion technologies: biodiesel, electric, solar technologies

• Emissions restrictions:
  • will continue to tighten
  • provide barriers to trade
  • may supercede fuel costs
  • are aviation’s biggest environmental challenge

• Low altitude operations eliminate high-altitude aviation emission concerns

Unlike 1973-74, emissions will become increasingly important regardless of short-term oil price trends. Airships can stimulate the development of low-power green aviation prototype propulsion systems
Dramatically reduced power requirements

\[ \text{Power} = D \cdot V = \frac{1}{2} \rho_{\text{air}} S C_D V^3 = \text{Fuel Flow/SFC} \]

Uncertain future of oil prices and supply

Energy independence is a national goal

Speed will likely become MUCH more expensive due to rising energy costs and emissions

Strong arguments for LTA in 70s and 80s...


Modern airships can be a component of GREEN aviation
C-130, C-17, B747-400 and Hindenbug

<table>
<thead>
<tr>
<th></th>
<th>C-130</th>
<th>C-17</th>
<th>B747-400F</th>
<th>Hindenbug</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel + ballast (tons)</td>
<td>32</td>
<td>119</td>
<td>200</td>
<td>53+16</td>
</tr>
<tr>
<td>Cargo (tons)</td>
<td>22</td>
<td>85</td>
<td>124</td>
<td>43</td>
</tr>
<tr>
<td>Useful Lift (tons)</td>
<td>54</td>
<td>204</td>
<td>324</td>
<td>112</td>
</tr>
<tr>
<td>Range (miles)</td>
<td>2360</td>
<td>2785</td>
<td>5120</td>
<td>6840</td>
</tr>
<tr>
<td>Fuel/cargo-kmile</td>
<td>0.62</td>
<td>0.50</td>
<td>0.31</td>
<td>0.18</td>
</tr>
<tr>
<td>Power (hp)</td>
<td>4x4300</td>
<td>4x22000</td>
<td>4x1200</td>
<td></td>
</tr>
<tr>
<td>Speed (mph)</td>
<td>460</td>
<td>518</td>
<td>560</td>
<td>90</td>
</tr>
</tbody>
</table>

*Data is VERY approximate and from multiple sources*

- LTA can be VERY competitive on fuel use
- If Hindenbug ballast is considered cargo, F/c-km = 0.13
- Productivity comparisons *must* include speed differential
Advanced cargo airships will be the only aircraft capable of approaching trucks in freight fuel efficiency.
Economics

• LTAs open trade and supply routes to regions lacking surface transportation infrastructures
  – Logging
  – Mining
  – Oil exploration
  – Arctic/Africa/Asia and others
• Satellite surrogate, WiFi/Broadband relays
• Short haul passenger transport/feeder
• New class of aerospace vehicles for export (aka, jobs!)

Airships can promote new markets for US exports and service environmentally sensitive and remote regions
Transport Airship Markets

• Short distance movement of cargo, equipment, and supplies
  – Direct delivery of materials, equipment, prefab structures, etc...for roadway, rail, port, bridge, and building construction projects
    • Reduces ground footprint and disruption to areas surrounding construction sites compared to conventional approach
    • Permits “just-in-time” movement of materials and supplies; reduces on-site storage, shortens project schedules, and reduces project costs
  – Moving cargo where deep water port facilities aren't available

• Long distance freight transport
  – Transport between multi-modal shipping centers (trucking terminals, etc.)
  – Transport within transportation poor developing countries
  – Transport into and out of remote or otherwise inaccessible regions
DoD Mobility Needs

- Insert materials into critical points that can’t easily be reached
- Provide additional deployment lift for current force
- Service Operational Concepts + Network-Centric Operations (NCO)
  - Reduce number of moves required in the Area of Operations
- Move new things in new ways (support to Seabasing concepts)
- US forces need advantage of adaptive power projection
  - Bypass choke points
  - Deliver intact capabilities at multiple entry points
  - Maintain uninterrupted deployment momentum
  - Move select air cargo forward from last secure area
  - Minimize surface convoys
    - Avoid IEDs and ambushes
2005 CAA Transport Airship Study

- Heavy lift airships are feasible with current technologies up to around 90 tons.
- Follow on development to larger sizes require timed S&T investments
  - 5 years and 8 years for two distinct development phases
- 12 years development to achieve conventional airship with 360 tons lift.
- 18 years development to achieve hybrid airship with 450 tons lift.
- Commercial market demand is strongest for project freight
  - Ranges for commercial demand are 25 to 250, and 400 to 800 miles.
  - Ranges for military demand are 400 to 800 miles, and (1,000 to 3,000 miles).
- Recommended airships be commercially developed, for lease to DoD.
Major Project Freight Applications

Oil and Gas Pipeline Construction

• In-land logistics (from main entry port) is 25% of construction costs
• 90% of cost is just moving heavy equipment, materials, and consumables up and down the project right of way
• For typical 52” pipeline, this is $100-150 million per 1000 km of pipeline
• $100 to 120 billion in pipeline projects scheduled over next 10 – 15 yr

Logistics Support to Canada

• University of Manitoba study shows interest in airships for shipping fuel
• Forecast for transport airships in Canada alone could range between 185 to 635 airships, of 50 metric tons lift
Vertical Lift for Precision Positioning

- Installing pre-fab windmills and geothermal generation equipment in optimized locations
- Electrical grid installations
  - Towers, transmission lines, switches, transformers, etc.
- High speed rail components

- Supports regional movement of equipment which otherwise must be moved by conventional means
  - Airship transport reduces handling steps, point-to-point distances, overall transport time, and overall expense
- Vertical lift airships can deliver and install temporary capital equipment to meet cyclical industrial production demands
  - Production equipment and facilities can be leased on as needed basis
  - Reduces investment commitment and financial risks
  - Encourages industrial expansion, and economic growth

MAGLEV Pylons and Rail Segments

Generator Moving Through a Village

Crane Hoisting Propeller onto Windmill
Outsized Freight and Load Exchange Handling

- Internal winch in gondola can accommodate high point loads
  - Supports sling loads and palletized freight
- Wide landing gear stance can handle outsized payloads
  - Extended fixed landing gear provides ground clearance for large outsized items
- Internal payload bays can be equipped for roll-on-roll-off load handling

- Initial operations can utilize ballast exchange
  - Pre-loaded ballast bags can be winched or loaded into gondola structure
    - Lightweight composite boxes allow more payload weight
    - Roll on, roll off boxes can facilitate quick movement of wheeled loads
  - Facilitates quick payload/ballast load exchange in austere areas
  - Ballast environmental issues minimized in short distance operations within region
- NASA Ames R&D needed to facilitate development of optimal buoyancy control system
Operational Concepts and Missions

• Approximately 82% of Alaskan communities are not served by roads
• The Canadian North has only 48 certified airports and 73 aerodromes
• How can a cargo airship operation best serve this community?
  – Cargo only, or combination cargo and passengers (combie)
  – Out and back flights from a central hub (with “deadhead” returns)
  – Three way (triangle) flights between sites
  – Two ships flying in opposite directions between several sites
• What mix of cargos will be most efficient, useful, and profitable?
  – Diesel fuel, jet fuel, gasoline, kerosene
  – Dry cargo in containers
  – Outsized freight in sling loads
  – Passengers
Why aren’t there more Cargo Airships?

• Many cargo airships have been proposed but have failed to succeed or have yet to come to fruition for various reasons
  – Inadequate program funding and resources
  – Poor management practices
  – Shortage of designers and engineers with unique airship skills
  – Insufficient customer input on airship design and operation
  – Unmanageable gap between airship capabilities and customer expectations
  – Excessively short or unachievable development schedules
  – Investor or customer impatience with airship development time and costs
  – Reluctance by investors and customers toward staged development approach
  – Schedule delay or increased costs due to unanticipated technical obstacles
  – Investors and customers impatience with airship technology R&D efforts to reduce future program risks
  – Unfamiliarity by aviation authorities with factors governing airship design, operation, and promulgation of appropriate regulations
What is the Right Size for a Cargo Airship?

• The technology and engineering expertise to design and develop large cargo airships is available today
• But what airship size and performance capabilities are required?
  – Choose too large and it’s too costly in time and money to develop
  – Choose too small and it’s economic utilization is too limited for markets
• What is the performance “sweet spot” for a successful cargo airship?

Cargo airship requirement considerations:
• Cargo airships need the right mix of mature technologies and advanced technologies
• Payloads need to meet the freight shipment sizes preferred by customers
• Utilization rates must be high to maintain operational profitability
  – The shorter the distances, or greater the speed, the greater the utilization
• Freight transport costs must be attractive compared to current alternatives
• Should accommodate current cargo shipping systems preferred by customers
• Have the capability of operating at well developed sites (airports) and austere sites
• Facilitate ease of operation and maintenance in remote areas
• **MUST MAKE MONEY FOR ALL PARTICIPANTS!**
Customer and User Inputs Needed

Alaska and Canada are the best initial markets for cargo airships

• Designers need user inputs to develop the right airship and operation
  – Cargo types, sizes, and weights
  – Priorities for freight type, delivery locations, and schedule
  – Critical cost points for freight and delivery locations
  – Specific cost factors that govern airship operations
    • Local cost and availability of airship fuel
    • Manpower costs for experienced aviation crews (flight and ground)
  – Local weather and site info on proposed airship cargo delivery areas
Research, Challenges, and Technology “Game-Changers”
LTA Research Opportunities

- Incorporation into future airspace
  - Utilization of secondary airports
  - Impacts of low-altitude operations
- Lightweight structures (design, analysis, fabrication)
- Materials (engineered fabrics, composites)
- Controls and Dynamics, especially near ground
- Ground operations
- Drag reduction, BLC, and synergistic propulsion
- Thrust vector control
- Showplace for green power sources (solar, biodiesel, hydrogen, fuel cells, etc.)
- Localized weather prediction
LTA Research Challenges

• Few modern examples, difficult to predict ultimate economic success
• Large lightweight structures are historically risky to build and fly
• Competition with HTA and surface transport industry
• Hindenburg imagery, public confusion of He and H₂
• Speed and Size do matter - must successfully match vehicles, cargo, and missions for economic success
• Weather and ground handling
• Conveying seriousness of emissions and environmental challenges
• Small number of LTA engineers
• LTA not included in aerospace engineering curriculum
• No existing national LTA “culture” (as compared to HTA)
• Existing LTA infrastructure (hangars) in disrepair...
Modern LTA can capitalize on advances in:

- Materials and instrumentation
- Digital/optical electronics and computers
- Structural design, analysis, and testing
- Aerodynamic design, analysis and testing
- Digital control
- Fabrication and advanced manufacturing
- Weather prediction and avoidance
- Propulsion system efficiencies
- Systems engineering processes
LTA “Game Changers”

• Eliminating Ballast: Buoyancy control via compression/cooling
  – Regulations governing brown/foreign water disposal
  – Heaviness avoids the cargo/ballast matching required during offloading
  – Availability of ballast materials in remote areas
• Ground handling: Control systems, thrusters, micro-climate
• Emissions: Solar cells, biodiesel, fuel cells, ocean sailing
• En route weather information and path optimization
• Autonomous capabilities
• Electrochromic paints
• Distributed, synergistic propulsion reduce $P_{\text{req}}$ by additional 30%
• Materials: Engineered fabrics, composite structures
• Advanced structures and engineered materials
• Lifting gases: H$_2$, H$_2$ encased in He, Hot Air, Steam
• Analysis and Design Tools: CFD, FEA, Controls
NASA Ames Airship Analysis

**Structures**
- Design and Analysis
- Testing and Instrumentation
- Materials

**Aerodynamics**
- Steady Loads Estimation
- Performance
- Gust and Fin loads

**Flight Simulation**
- Handling Qualities
- Controls Development
- Mooring
- Buoyancy Management
- Vectored thrust

**Mission Analysis**
- Airspace Operations
- Cargo Handling
- Risk Analysis
Conclusions

- LTA remains one of the last unexploited aviation frontiers

- LTA is the most environmentally responsible aviation transport technology

- LTA vehicles face numerous challenges, but today's technologies can provide the solutions

- LTA vehicles offer significant, game-changing capabilities for major economic and social advances