Galileo Systems - Graf Galileo family of high altitude airships

Peter Lobner, 12 January 2024

1. Introduction

In the early 2000s, Galileo Systems, located in Denver, CO, with Dr. Gary E. Snyder serving as President, developed conceptual designs for the Graf Galileo family of low-cost, high altitude airship (HAA) sensor platforms. These semi-rigid airships shared a common design featuring a pressure-stabilized, elliptical, finless hull with large diameter propellers at the nose and tail. These low drag design concepts were solar powered, with commercial off-the-shelf (COTS) power storage technology, which offered a low cost, low risk solution for fielding an operational HAA in the near-term.

General configuration of a Graf Galileo high altitude airship.
Source: Galileo Systems (2004)

2. The Graff Galileo family of HAAs

In January 2004, Galileo Systems presented the results of a Phase 1 conceptual design study and described two subscale platforms and two full-scale operational platforms as part of a comprehensive, staged development program.

- **Graf Galileo Day Flier**: This subscale platform would serve as an applied engineering research tool to validate the low drag finless architecture with active control, thin film solar panel performance, autonomous daytime station keeping, and performance of COTS systems and materials.
- **Graf Galileo Day / Night Station Keeper (DNSK)**: This was a scaled-up development platform to test all technologies, COTS systems and materials required for an operational platform, including propellers, thin film solar panels, batteries, motors, fuel cells and day/night station keeping.
- **Graff Galileo One**: This was an operational platform built with COTS technologies to carry internally a small radar system payload on 24/7 extended missions. Multiple airships would rotate on station to provide long-term coverage.
- **Graff Galileo Two**: This was a larger operational platform built with COTS technologies to carry internally a large radar system payload on 24/7 extended missions, possibly with fuel cells in place of Li-Ion batteries.

These airships share to following design features.

Semi-rigid, air pressure-stabilized hull with active pressure control

A pressure-stabilized, multi-layer fabric hull with internal catenary curtains supports an axial, rigid, inflated “airboom” that runs down the center of the hull from the tip of the nose to the tip of tail. The airboom is a rigid pneumatic structure (an air beam) to which the large-diameter propellers at the nose and tail, and their electric motors, are mounted.

The airboom performs the following functions:

- Transfers propulsion / steering system static and live loads from the propellers into the hull via the catenary curtains.
- Allows lower internal pressure than a conventional non-rigid, pressure stabilized hull, reducing hull stress & fabric stretch
- Allows reduction or elimination of nose battens

The hull is pressurized with air, with an active pressure control system to maintains the desired internal pressure, vehicle rigidity and low drag shape at all altitudes. The lifting gas is contained in many sealed lifting gas cells arranged axially within the hull.

The air-filled, pressure stabilized hull functions as a single ballonet volume, with its positive internal air pressure actively controlled within fixed limits as the lifting gas cells expand and contract during ascent and descent. No makeup gas or ballast is used.

The payload and energy storage system are carried internally, eliminating the need for a gondola, and thereby reducing drag and radar cross-section.

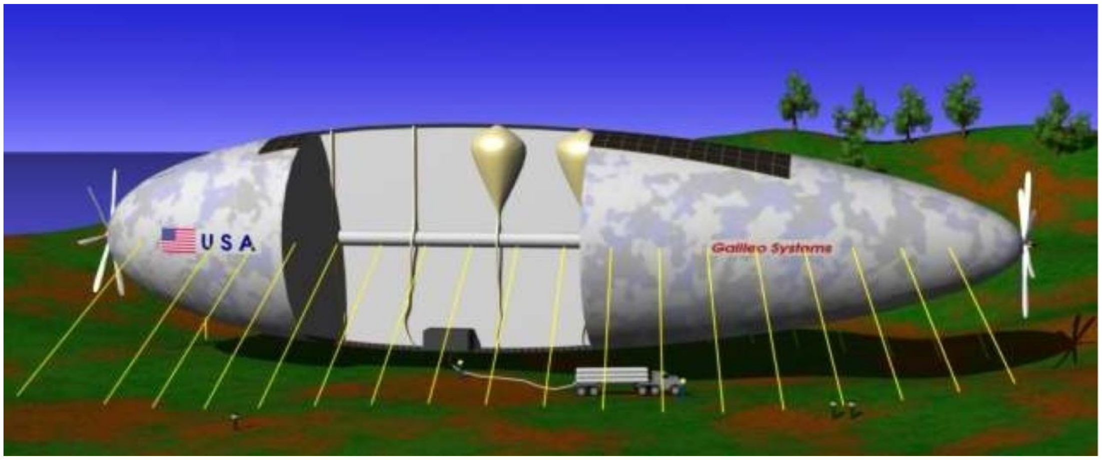
Hydrogen lifting gas

The airships are designed to use hydrogen as the lifting gas. Helium could be used as the lifting gas, but with a size / weight penalty due to reduced buoyancy relative to hydrogen. Helium also has a higher permeability than hydrogen and would require periodic makeup gas.

The hydrogen lifting gas is contained in sealed, low permeability, co-extruded Vectran / PPS (Polyphenylene Sulfide) membrane gas cells inside the pressure stabilized hull. Galileo Systems reported that their Vectran / PPS material demonstrated the following attributes:

- $1/4000^{th}$ the hydrogen permeability of polyethylene
- 412 ksi tensile strength
- Low creep
- Possible to apply metal cladding, such as aluminized Mylar

The sealed lifting gas cells are only about 7% filled at the elevation of the launch site, with space inside the hull for a 14:1 expansion of the lifting gas cells as the airship ascends to its operating altitude of about 18,288 m (60,000 ft).



Cutaway of a Graf Galileo HAA secured on the ground, showing typical hydrogen lifting gas cells (gold) partially filled for liftoff, with space inside the hull for 14:1 volume change at high altitude. Source: Galileo Systems (2004)

Cutaway of a Graf Galileo HAA at its pressure altitude, showing fully expanded lifting gas cells. Source: Galileo Systems (2004)

Propulsion and active maneuvering / stability control

There are two large diameter propellers, one thrust-vectoring propeller (pitch and yaw) at the nose for maneuvering and stability control and one fixed tail-mounted propeller for main propulsion. Galileo Systems claims that, with this propeller arrangement, their airships are inherently stable in roll and pitch, but slightly unstable in yaw.

With active maneuvering and stability control with the bow propeller, the slight yaw instability is managed and airship does not need conventional aerodynamic stabilizing fins or controls surfaces.

This has several benefits:

- Significant reduction in overall vehicle weight and surface area, and consequently, a reduction in drag and radar cross-section.
- Propulsion power requirements are reduced, enabling the use of less powerful motors and less energy storage for propulsion.

Galileo Systems claims that the stern location of the main propulsion propeller reduces drag at the aft end through better boundary layer control.

Each propeller is driven by a high-efficiency, lightweight DC brushless motor with a long service life. The large span propellers are optimized for high propulsive efficiency in the stratosphere. These lightweight propellers were constructed with a hollow graphite/epoxy center spar, thermal cut foam core and a graphite/epoxy overwrap.

Overall drag reduction

Through a combination of measures, including finless hull, no gondola, internal payload, and improved boundary layer control with the stern-mounted propeller, Galileo Systems claimed more than 40% drag reduction for their HAA designs, relative to a conventional airship design. This results in a substantially smaller airship than a conventional airship with comparable mission capabilities.

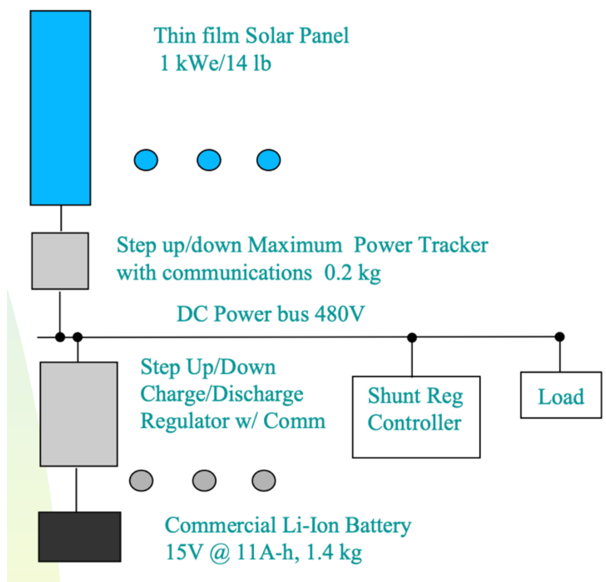
- Graf Galileo Day/Night Station Keeper
  - Finless: 97.5 m long, 28.3K m^3 volume, 2,495 kg GVW [320 feet, 1M ft^3, 5,500 lb]
  - Conventional: 167.6 m long,142K m^3 volume, 12,700 kg GVW [550 feet, 5M ft^3, 28,000 lb]
- Graf Galileo Two
  - Finless: 253 m long, 498K m^3 volume, 42,184 kg GVW [830 feet, 17.6M ft^3, 93,000 lb]
  - Conventional: 296 m long, 793K m^3 volume, 68,039 kg GVW [970 feet, 28M ft^3, 150,000 lb]

Electric power system

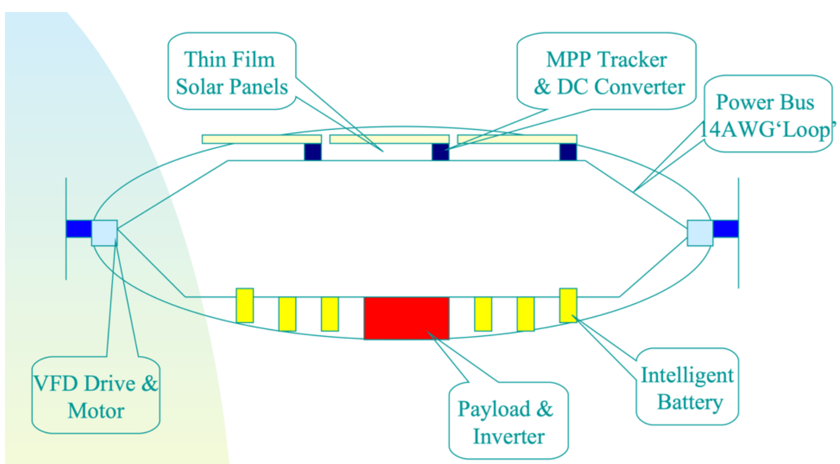
The solar-powered airship has an electrical system that uses COTS equipment:

- Thin-film solar panels @ 1 kWe / 6.6 kg (14 lb)
- 480 V DC power bus
- 15 V commercial Li-Ion battery @ 11 A-h / 1.4 kg (3.1 lb), possibly replaced by fuel cell on Gragg Galileo Two

The basic system configuration is shown in the following figures.



Typical electrical power generation and storage system



Location of electrical components in the airship.
Source, both graphics: Galileo Systems (2004)

General characteristics of Graf Galileo HAA

Parameter	Graf Galileo Day Flier	Graf Galileo Day/Night StationKeeper (DNSK)	Graf Galileo One	Graf Galileo Two
Hull type	Semi-rigid (central, inflated "airboom"), air pressure-stabilized, multi-layer fabric hull with catenary curtain			
Length	27.4 m (90 ft)	97.5 m (320 ft)	195 m (640 ft)	253 m (830 ft)
Diameter, hull			47.6 m (156 ft) (est.)	61 m (200 ft) (est.)
Aspect ratio			4.1:1 (est.)	
Diameter, prop	4.3 m (14 ft)	14.6 m (48 ft)	29.3 m (96 ft)	36.6 m (120 ft)
Volume, hull	637 m^3 (22,500 ft^3)	28,318 m^3 (1,000,000 ft^3)	229,366 m^3 (8,100,000 ft^3)	498,377 m^3 (17,600,000 ft^3)
Lifting gas	Hydrogen (helium could be used with revised lifting gas cells, but with penalties in lift performance and/or vehicle size)			
Lifting gas cell material	Co-extruded Vectran / PPS (Polyphenylene Sulfide) membranes. Adding aluminized mylar layer is possible.			
% initial lifting gas inflation			About 7%, with 14:1 lifting gas expansion at max. altitude	
Altitude, max			About 18,288 m (60,000 ft)	
Gross vehicle weight (GVW)	50 kg (110 lb)	2,495 kg (5,500 lb)	17,690 kg (39,000 lb)	42,184 kg (93,000 lb)
Textile hull weight		340 kg (750 lb)		
Payload	None	None	Small radar	Large radar
Payload weight	0	0	1,814 kg (4,000 lb)	5,443 kg (12,000 lb)
Solar array	Lightweight, thin film solar panels @ 1 kWe / 6.6 kg (14 lb)			
Solar array area	17.6 m^2 (190 ft^2)	660 m^2 (7,100 ft^2)	4,088 m^2 (44,000 ft^2)	10,219 m^2 (110,000 ft^2)
Solar power generation	0.68 kW (0.9 hp)	25 kW (33.5 hp)	160 kW (215 hp)	390 kW (523 hp)
Solar array weight	4.5 kg (9.5 lb)	165 kg (350 lb)	1,056 kg (2,240 lb)	2,574 kg (5,460 lb)
Propulsion	Bow-mounted, thrust vectoring tractor propeller provides maneuvering & stability control; stern-mounted fixed propeller provides main propulsion; both driven by high-efficiency, lightweight brushless DC motors.			
Motor power	0.66 kW	8.5 kW	34 kW	55 kW
Payload power	0	0	20 kW	75 kW
Energy storage type	Moderate energy density Li-Ion batteries @ 11 A-h / 1.4 kg (3.1 lb)			Li-Ion battery or fuel cell
Energy storage sys capacity	0.3 kW-hr	15 kW-hr	970 kW-hr	2,400 kW-hr
Energy storage sys weight	3.2 kg (7 lb)	1,315 kg (2,900 lb)	8, 165 kg (18,000 lb)	19,958 kg (44,000 lb)

Source: Galileo Systems (2004)

3. Manufacturing and assembly process

With a flexible, multi-layer fabric hull and an inflatable airboom forming the semi-rigid structure, the Graff Galileo family of airships can be manufactured in facilities significantly smaller than the airship itself. The airship is not inflated until after hull manufacturing has been completed, the hull has been moved out of the manufacturing facility to an separate outdoor staging area for final assembly, check out and launch. Galileo Systems outlined the following process for assembling a Graf Galileo HAA outdoors:

Step 1: Unroll the multi-layer fabric hull with integrated catenary curtain & central, inflatable airboom

Step 2: Install batteries in the keel

Step 3: Inflate the central airboom, mechanically install motors

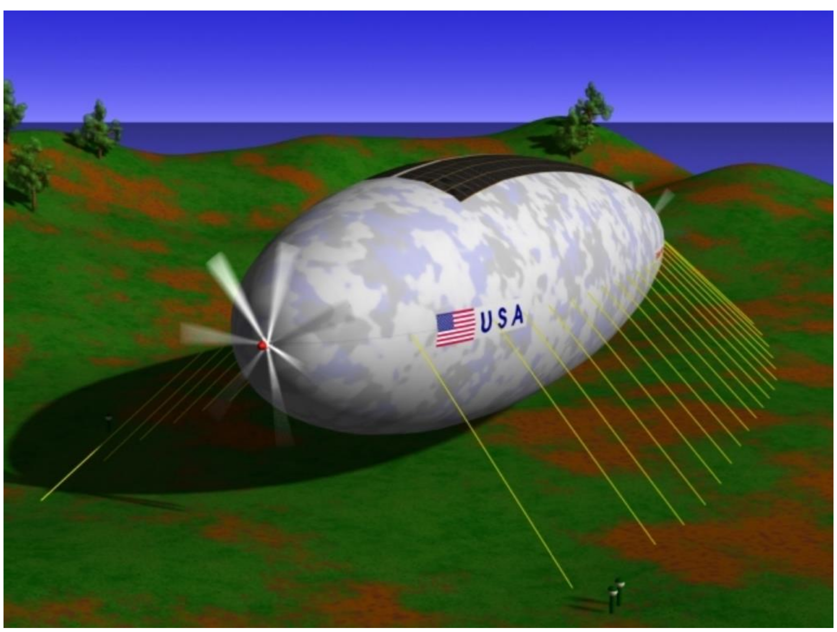
Step 4: Install & check out the payload

Step 5: Install the lifting gas cells inside the hull

Step 6: Mechanically & electrically integrate thin-film solar panels

Step 7: Stake down the hull & inflate it with air

Step 8: Attach propeller blades & check out propulsion system



A Graf Galileo HAA secured on the ground and testing the propulsion system. Source: Galileo Systems (2004)

Step 9: Load lifting gas into the lifting gas cells

Step 10: Untether ship, liftoff & fly to assigned station

This manufacturing and assembly process results in significant cost savings in comparison to traditional airship construction in a hangar.

4. Epilogue

In 2004, Galileo Systems proposed a Phase 2 study to address open technical issues and demonstrate the feasibility of the Graf Galileo airship design

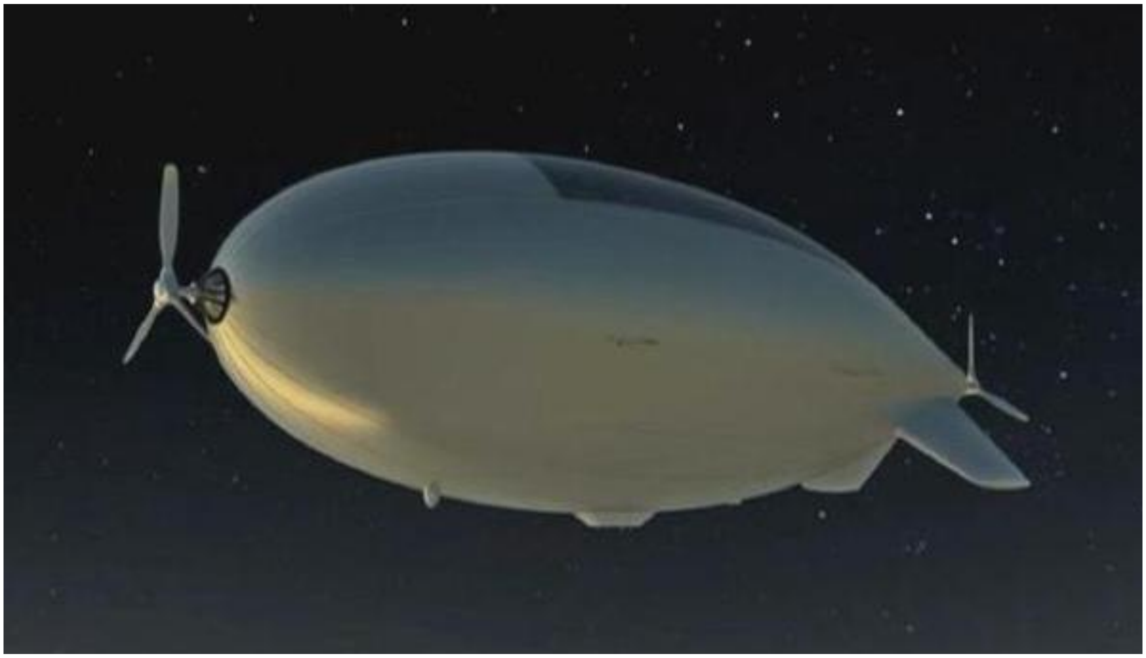
Technical issues requiring further investigation at the end of the Phase 1 conceptual design study included thermal control for specific payload characteristics, ozone effects on selected airship materials and systems, component service life and hull stretch.

Galileo Systems proposed flying two demonstrator airships:

- Conduct detailed design, fabrication and test flights of Graf Galileo Day Flier. First flight within 4 months of contract start.
- Allowing for any technology improvements, proceed to detailed design, fabrication and test flights of Graf Galileo DNSK.

Galileo Systems did not get the opportunity to build any of their proposed HAAs. The firm is no longer in business.

However, on 13 October 13, 2015, a Chinese airship with a very similar design made its first test flight from Xilinhot, Inner Mongolia, flying for 22 hours and reaching a peak altitude of 65,000 ft (19.8 km, 12.3 miles). The stratospheric airship *Yuanmeng (Dream)* was jointly developed by Beijing Aerospace Technology Company and Beijing University of Astronautics and Aeronautics (BeiHang). High strength materials for the airship were developed by Beijing University.



The general configuration of China's 2015 Yuanmeng (Dream) solar-powered stratospheric airship strongly resembles the Graf Galileo HAA designed more than a decade earlier by Galileo Systems. Source: CNTV, China

5. For more information:

- K.M. Caviezel, G.E. Snyder, R. Powers & Wil McCarthy, "Galileo Systems Interim Report - Low Cost High Altitude Sensor Platform," Galileo Systems presentation, 12 January 2004: http://redyns.com/Projects/HAA/HAA%20presentation.pdf
- "Graf Galileo High Altitude Airship," Flickr, posted by lazzo51, 3 December 2008: https://www.flickr.com/photos/lazzo13/3080037368

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- *Modern Airships - Part 1*: https://lynceans.org/all-posts/modern-airships-part-1/
- *Modern Airships - Part 2*: https://lynceans.org/all-posts/modern-airships-part-2/
    - China's Yuanmeng (Dream) stratospheric airship
- *Modern Airships - Part 3*: https://lynceans.org/all-posts/modern-airships-part-3/