GLOBAL CONSTELLATION OF STRATOSPHERIC SCIENTIFIC PLATFORMS

Presentation to the NASA Institute of Advanced Concepts (NIAC)

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Global Stratospheric Constellation

TOPICS

• CONCEPT OVERVIEW
• EARTH SCIENCE OVERVIEW
• CONSTELLATION MANAGEMENT
• TRAJECTORY CONTROL
• BALLOON
• GONDOLA
• INTERNATIONAL CONSIDERATIONS
• PHASE 2 PLAN
• SUMMARY
CONCEPT OVERVIEW
Global Stratospheric Constellation

BENEFITS OF STRATOSPHERIC CONSTELLATIONS TO NASA

• Provide low-cost, continuous, simultaneous, global Earth observations options

• Provides in situ and remote sensing from very low Earth “orbit”
Global Stratospheric Constellation

CONCEPT DESCRIPTION

• Tens to Hundreds of Small, Long-life Stratospheric Balloons or StratoSats
• Uniform Global Constellation Maintained by Trajectory Control Systems (TCS)
• Flight Altitudes of 30-35 km Achievable With Advanced, Lightweight, Superpressure Balloon Technology
• Gondola and TCS Mass of 235 kg at 35 km Altitude
• Goal of ~50% Science Instrument Payload of Gondola
Global Stratospheric Constellation

CONCEPT SCHEMATIC

Global Constellation

StratoSat Flight System

~40-50 m dia. Super-pressure Balloon
30-35 km Flight Altitude

Gondola
Rel. Wind 0.3-10 m/s

Dropsonde

10-15 km

StratoSail™
Trajectory Control System (TCS)

Possible Science Sensors
~50-100 kg

Rel. Wind 5-50 m/s
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RATIONALE FOR STRATOSATS

- High Cost of Space Operations (Spacecraft and Launchers) Relative to Balloon Platforms
- Advanced Balloons Are Capable and Desirable High Altitude Science Platforms
- In Situ Measurement Costs Are Reducing With the Advance of Technology (Electronics Miniaturization, Sensor Advances)
- There is an Emerging and Widely Accessible Global Communications Infrastructure
- Balloons Fly Close to the Earth and Are Slow, Both Positive Characteristics for Making Remote Sensing Measurements
- A Constellation of Balloon Platforms May Be More Cost Effective Than Satellites for Some Measurements
KEYS TO THE CONCEPT

Affordable, Long-duration Stratospheric Balloon and Payload Systems

Lightweight, Low Power Balloon Trajectory Control Technology

Global Communications Infrastructure
EARTH SCIENCE OVERVIEW
ESE STRATEGIC PLAN GOALS

Expand scientific knowledge of the Earth system . . . from the vantage points of space, aircraft, and in situ platforms

- Understand the causes and consequences of land-cover/land-use change
- Predict seasonal-to-interannual climate variations
- Identify natural hazards, processes, and mitigation strategies
- Detect long-term climate change, causes, and impacts
- Understand the causes of variation in atmospheric ozone concentration and distribution
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PROMISING EARTH

SCIENCE THEMES

– Climate Change Studies
  • Water Vapor and Global Circulation in the Tropics*
  • Radiative Studies in the Tropics:
  • Global Radiation Balance*

– Ozone Studies
  • Mid-latitude Ozone Loss
  • Arctic Ozone Loss*
  • Global Distribution of Ozone*

– Weather Forecasting
  • Hurricane Forecasting and Tracking
  • Forecasting Weather from Ocean Basins & Remote Areas

– Global Circulation and Age of Air
– Global Ocean Productivity
– Hazard Detection and Monitoring
– Communications for Low Cost, Remote Surface Science

* Discussed further in later charts
CLIMATE CHANGE: GLOBAL RADIATION BALANCE

Stratosphere

Cloud LIDAR

Detector System

Laser System

Rotatable

Pyronometer

Data Acquisition

Detector & Filter

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CLIMATE CHANGE: DYNAMICAL PROCESSES IN TROPICS

- Tropopause
- Subsidence
- Troposphere
- Stratosphere

in situ TDL Water, Ozone & CO₂ Absorption Measurement Cell

Air Flow

Source Beam
Detector

Ozone & Water Vapor LIDAR

Laser System

Microwave Temperature Profiler

Cal Target
Scanning Mirror
LO
Mixer
Detector

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- At 30 km a StratoSat Platform is >30 times closer to the Earth’s Surface than Sun-synchronous LEO Satellites.
- The Ground Speed of a 30 km StratoSat is a factor of >140 times slower than LEO Satellites (angular rates over nadir are >2 times less).
- A Constellation of Stratospheric Balloons can observe the Entire Earth at the Same Time.
CONSTELLATION MANAGEMENT
GLOBAL CONSTELLATION WITHOUT TRAJECTORY CONTROL

ASSUMPTIONS
- 100 StratoSats @ 35 km
- Simulation Start: 1992-11-10
- UK Met Office Assimilation
- 4 hrs per frame
- 4 month duration

STATISTICS

Start Date: 1992-11-10T00:00:00
35 km constant altitude flights
100 balloons, UKMO Environment
Global Stratospheric Constellation

CONSTELLATION

GEOMETRY MAINTENANCE

• Balloons Drift in the Typical and Pervasive Zonal Stratospheric Flow Pattern
• Trajectory Control System Applies a Small, Continuous Force to Nudge the Balloon in Desired Direction
• Balloons Are in Constant Communications With a Central Operations Facility
• Stratospheric Wind Assimilations and Forecasts Are Combined With Balloon Models to Predict Balloon Trajectories
• Balloon TCS Are Periodically Commanded to Adjust Trajectory Control Steering to Maintain Overall Constellation Geometry
ILLUSTRATION OF CONTROL EFFECTIVENESS

5 m/s Toward Equator

5 m/s Toward Poles
MAINTENANCE STRATEGIES

• Environment Information Used
  – Successive Correction Data (Interpolated Measurements)
  – Assimilations (Atmospheric Model Tuned by Actual Measurements)
  – Forecasts (Can Be Used for “Look-ahead” Decision-making)

• Level of TCS Model Fidelity
  1. Omni-directional Delta-v of Fixed Amount Applied at StratoSat
  2. Delta-v Proportional to True Relative Wind at TCS
  3. Actual TCS Aerodynamic Model and Sophisticated TCS Control Algorithms

• Network Control Algorithms
  – Randomization: Move StratoSats North or South Randomly
  – “Molecular” Control: Each Balloon Responds Only To Its Neighbor
  – Macro Control: Entire Network Is Managed, Balloons Are Moved Between Zones

• Cyclone Scale Coordinates for Control Algorithms
GLOBAL CONSTELLATION WITH SIMPLE, INTELLIGENT CONTROL

ASSUMPTIONS
- 100 StratoSats @ 35 km
- Simulation Start: 1992-11-10
- UK Met Office Assimilation
- 4 hrs per frame
- 4 month duration
- 5 m/s control when separation is < 2000 km
- Same initial conditions

STATISTICS
TRAJECTORY CONTROL
Global Stratospheric Constellation

FEATURES OF STRATOSAIL™ TCS

- Passively Exploits Natural Wind Conditions
- Operates Day and Night
- Offers a Wide Range of Control Directions Regardless of Wind Conditions
- Can Be Made of Lightweight Materials, Mass <100 kg
- Does Not Require Consumables
- Requires Very Little Electrical Power
- Relative Wind at Gondola Sweeps Away Contaminants
Global Stratospheric Constellation

ADVANCED TRAJECTORY CONTROL SYSTEM

Advanced Design Features

- Lift force can be greater than weight
- Will stay down in dense air
- Less roll response in gusts
- Employs high lift cambered airfoil
- Greater operational flexibility
BALLOON
Global Stratospheric Constellation

BALLOON DESIGN OPTIONS

Spherical Envelope
• Spherical Structural Design
• High Envelope Stress
• High Strength, Lightweight Laminate Made of Gas Barrier Films and Imbedded High Strength Scrims
• Multi-gore, Load / Seam Tapes

Pumpkin Envelope
• Euler Elastica Design
• Medium Envelope Stress
• Lightweight, Medium Strength Films
• Lobbed Gores With Very High Strength PBO Load-bearing Tendons Along Seams
Baseline Balloon Design

- Euler Elastica Pumpkin Design
- 68,765 m³, 59/35 m Eq/Pole Dia., Equivalent to 51 m dia. Sphere
- Advanced Composite Film, 15 μm thick, 15 g/m² Areal Density
- 140 gores each 1.34 m Max Width
- Polybenzoxazole (PBO) Load Tendons At Gore Seams
- Balloon Mass of 236 kg
SOLAR ARRAY / BALLOON INTEGRATION

Example Power
- 48 m dia Spherical Design
- 100 Gores/Seams
- 3 cm Wide Solar Array
- 10 % Efficiency
- 4.7 kW
GONDOLA
StratoSat Gondola

- Example Climate Change Science Payload
- 2x1x0.5 m warm electronic box (WEB) with louvers for daytime cooling
- Electronics attached to single vertical plate
- LIDAR telescopes externally attached to WEB
- TCS wing assembly (TWA) stowed below gondola at launch before winch-down
- Science pods on tether
INTERNATIONAL OVERFLIGHT CONSIDERATIONS
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INTERNATIONAL OVERFLIGHT

• Current Scientific Balloon Program
  – Overflight Often Allowed Especially If No Imaging and If Scientists of Concerned Countries Are Involved
  – Not All Countries Allow Overflight and This List Changes Depending on World Political Conditions

• Treaty on Open Skies - Signed By 25 Nations in 1992
  – Establishes a Regime of Unarmed Military Observation Flights Over the Entire Territory of Its Signatory Nations
  – First Step of Confidence Building Security Measures (CBSM)

• Future Political Climate
  – Global Networks Can Build on World Meteorological Cooperation
  – World Pollution Is a Global Problem Which Will Demand Global Monitoring Capability
  – First Steps Need to Be Important Global Science That Does Not Require Surface Imaging
PHASE II PLAN
Global Stratospheric Constellation

PHASE II PLAN

• Constellation Management
  – Control of Distributed Systems in Chaotic Environments Research
  – Develop Advanced Constellation Geometry Control Algorithms
  – Integrate Balloon Model, Environment and Advanced TCS Models and Control Algorithms in Constellation Simulations and Analysis

• Advanced Trajectory Control
  – Develop Control Models and Design Concepts

• Advanced Balloon Design
  – Materials Research
  – Structural and Thermal Design
  – Envelope Design and Fabrication Technology

• Science Applications Development
  – Proof-of-Concept Flight Definition - A Logical Next Step
  – Broaden Search for New Earth Science Concepts
SUMMARY
SUMMARY

• The StratoSat Is a New Class of *in situ* Platform Providing:
  – Low-cost, Continuous, Simultaneous, Global Observations Options
  – *In Situ* and Remote Sensing From Very Low Earth “Orbit”

• Global Stratospheric Constellations Will Expand Scientific Knowledge of the Earth System

• Broader Involvement of the Earth Science Community Is Encouraged and Sought in the Definition of Constellation Mission and Instrument Concepts

• A Proof-of Concept Science Mission Is One Essential First Step on the Path Toward Global Stratospheric Constellations
APPENDIX
## Global Stratospheric Constellation

**STEPS TO GLOBAL STRATOSPHERIC CONSTELLATIONS**

<table>
<thead>
<tr>
<th>Constellation Types / Locale</th>
<th>Measurements Types</th>
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</thead>
<tbody>
<tr>
<td>- Regional</td>
<td>- In Situ &amp; Remote Sensing of Atmospheric Trace Gases</td>
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<tr>
<td>- South Polar</td>
<td>- Atmospheric Circulation</td>
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<tr>
<td>- Tropics</td>
<td>- Remote Sensing of Clouds</td>
</tr>
<tr>
<td>- North Polar</td>
<td>- Atmospheric State (T, P, U, Winds)</td>
</tr>
<tr>
<td>- Southern Hemisphere</td>
<td>- Radiation Flux</td>
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<tr>
<td>- Global</td>
<td>- Low Resolution Visible &amp; IR Surface and Ocean Monitoring</td>
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<tr>
<td>- Sparse Networks for Wide</td>
<td>- High Resolution Surface Imaging and Monitoring</td>
</tr>
<tr>
<td>representative Coverage</td>
<td></td>
</tr>
<tr>
<td>- Dense Networks for Global Surface</td>
<td></td>
</tr>
<tr>
<td>Accessibility</td>
<td></td>
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*A First Step Is a Proof-of-concept Science Experiment Using Soon to Be Available ULDB Technology*
Flight System Design Features

- Sample Payload for Climate Change Studies in Tropics
- 68,800 m³ Pumpkin balloon
- 5 kW capable integrated solar array
- Telecom capable of 6 Mb/s
- Advanced TCS
- Tethered science pods

Mass Summary

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass, kg</th>
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<tbody>
<tr>
<td>Balloon</td>
<td>236</td>
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<tr>
<td>Helium</td>
<td>87</td>
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<tr>
<td>Power</td>
<td>19</td>
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<tr>
<td>Telecom</td>
<td>5</td>
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<tr>
<td>Mechanical</td>
<td>30</td>
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<tr>
<td>Guidance &amp; Control</td>
<td>1</td>
</tr>
<tr>
<td>Robotic Controller</td>
<td>1</td>
</tr>
<tr>
<td>Trajectory Control</td>
<td>81</td>
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<tr>
<td>Science</td>
<td>56</td>
</tr>
<tr>
<td>Science Reserve</td>
<td>44</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>560</strong></td>
</tr>
</tbody>
</table>
HOW THE TCS WORKS

- Winds vary with altitude
  - Balloon at 30 km
  - Wing at 20 km
  - Relative wind velocity ~15 m/s
- Wing generates lift force
  - “Lift” force is horizontal
  - force is transmitted by tether to balloon
  - balloon drifts relative to local air mass
  - balloon drag ≈ wing lift
- Wing is in much denser air than balloon
  - 25km : 35km (5x); 20km : 35km (10x)
  - equivalent wing area increased relative to balloon
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HOW THE TCS WORKS, CONTINUED

LIFT vs ANGLE OF ATTACK

LIFT / DRAG FORCE POLAR
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HOW THE TCS WORKS, CONTINUED

\[ \begin{align*}
V_{\text{cross}} &= V_{\text{drift}} \cdot \cos \beta \\
V_{\text{true}} &= V_{\text{drift}} + V_{\text{rel}} \\
F_{\text{drift}} &\sim F_h \\
V_{\text{drift}} &= \left( \frac{2 \cdot F_{\text{drift}}}{\rho \cdot A_h \cdot C_D} \right)^{1/2} \\
\beta &= \phi - \tan^{-1}(D/L) \\
V_{\text{cross}} &= V_{\text{drift}} \cdot \cos \beta
\end{align*} \]
Global Stratospheric Constellation

ANGLES EXAGGERATED & FORCES NOT TO SCALE

**ASSUMPTIONS**
- BALLOON DRIFT ~ 2 m/s
- 0.6 million m³ BALLOON
- GONDOLA ~ 1500 kg
- TCS ~ 100 kg

**SYMBOLS**
- T -> TETHER
- G -> GONDOLA
- B -> BALLOON
- H -> HORIZONTAL
- V -> VERTICAL
- W -> WEIGHT
- F -> FORCE
- L -> LIFT

**ULDB TCS FORCE DIAGRAM**

LIFT OF ~ 70 N REQUIRES TCP WING
AREA OF ~ 16 m²
ASSUMING C_L of 1.0