GLOBAL CONSTELLATIONS OF STRATOSPHERIC SATELLITES

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by
Kerry T. Nock
Global Aerospace Corporation

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Global Constellations of Stratospheric Satellites

PHASE II STUDY

CONTRIBUTORS

Global Aerospace Corporation (GAC)
Dr. Kim M. Aaron
Dale R. Burger
Dr. Matthew Heun
Brenda Wistor-Linfield
Kerry T. Nock, Principal Investigator and NIAC Fellow
Dr. Alexey A. Pankine, Project Scientist
R. Stephen Schlaifer

Princeton University
Dr. Naomi Leonard
Dr. Edward Belbruno

Consultant
Dr. Elliot Weinstock, Harvard University
TOPICS

CONSTELLATION CONCEPT
STRATOSAT SYSTEMS
EARTH SCIENCE AND OBSERVATIONS
DEMONSTRATION MISSIONS
SUMMARY
CONSTELLATIONS OF STRATOSPHERIC SATELLITES
Global Constellations of Stratospheric Satellites

CONCEPT

• Tens to hundreds of small, long-life (3-10 years) stratospheric balloons or StratoSats
• Uniform global and regional constellations maintained by trajectory control systems (TCS)
• Flight altitudes of 35 km achievable with advanced, lightweight, superpressure balloon technology

BENEFITS

• Provide low-cost, continuous, simultaneous, global and regional earth observations
• Provides in situ and remote sensing from very low earth “orbit”
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CONCEPT SCHEMATIC

Global Constellation

StratoSat Flight System

Balloon

Gondola 35 km Altitude

Dropsonde

Science Pod

StratoSail®

TCS

20 km Altitude
BENEFITS OF GLOBAL BALLOON PLATFORMS

- Good diurnal coverage of entire globe
- Low altitude observations that can improve resolution and/or signal-to-noise ratios of measurements
- Provide frequent to continuous measurements
- Provide horizontal gradients in addition to vertical profiles
- Extended duration and low-cost potentially provide a cost-effective method for earth science and/or satellite calibration and validation
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REMOTE SENSING

StratoSat vs Satellite Remote Sensing Factors

- Surface image: $R - 20$-times closer
- Surface emission: $R^2 - 400$-times better
- Lidar at 15 km: $R^2 - 1200$-times better
- Radar at surface: $R^4 - 160,000$-times better
- Integration time at surface: $\sim 8$-times more

Angular Nadir Rate = 11 mrad/s

Angular Nadir Rate = 1.4 mrad/s
STRATOSAT™ BALLOON DESIGN

- Euler Elastica Pumpkin Design
- Volume ~ 70,000 m³
- Advanced Composite Film, 15 g/m²
- 140 Gores ~1.3 m Wide
- Zylon® Load Tendons
- Balloon Mass ~ 250 kg

NASA ULDB Scale Model Tests
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INTEGRATED SOLAR ARRAY & BALLOON ENVELOPE

Example Power
- 48 m dia
- 100 Gores/Seams
- 30 cm Wide Solar Array
- 10 % Efficiency
- ~45 kW
THE NEED FOR GLOBAL CONSTELLATION MANAGEMENT

FREE FLIGHT

SIMPLE CONTROL

ASSUMPTIONS

• 100 StratoSats @ 35 km
• 82 day Simulation
• 5 m/s Control
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CONSTELLATION MANAGEMENT

- Constellation management is the process of maintaining a desired spatial distribution of balloons in constellation
- Constellation management DOF
  - Environment information used
  - Fidelity of balloon model
  - Coordinate system
  - Constellation control method
    - Nearest neighbor (molecular)
    - Biological analogs (flocks, pods, schools, herds)
    - Weak Stability Boundary (WSB) theory
- Constellation management objectives
  - Uniform global and regional distributions
  - Targeted overflight
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BALLOON TRAJECTORY CONTROL

First Generation System Trajectory Control System (TCS)

- Wing hanging vertically on long tether in higher density air below balloon system
- Rudder controls angle of attack
- Relative wind at StratoSail® TCS generates lift force, which alters balloon trajectory
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TCS FEATURES

- 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

Radio-Controlled Dynamically-scaled Model (1:4) Tested in Natural Winds Suspended From Tethered Blimp, April 2001
TCS Wing Assembly (TWA)

- Tether
- Instruments/Counterweight
- Boom
- Wing
- Rudder
- Control Pod
SCALE MODEL TEST
Advanced StratoSail®
TCS Design Features

- Lift force can be greater than weight
- Will stay down in denser air
- Less roll response in gusts
- Employs high lift cambered airfoil
- Greater operational flexibility
- Possible Dynamic Power Generation
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CENTRALIZED STRATOSAT OPERATIONS

- Constellation Geometry & Environments
- Gondola calculates TCS commands
- Observed Strat. Winds & In-situ Data
- Standard Sat. & In-situ Observations
- Constellation Geometry & Atm. Param.
- Location & Environment
- TWA
- Improved Stratospheric Forecasts

Stratospheric Forecast Center

Constellation Operations Center
EXAMPLE
STRATOSAT GONDOLA

StratoSat Mass of 221 kg
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

• Global Circulation and Age of Air

• Global Ocean Productivity

• Weather and Adaptive Sampling
  – Hurricane forecasting and tracking
  – Tropospheric winds
  – Forecasting weather from ocean basins & remote areas

• Hazard Detection and Monitoring
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ADVANTAGES OF STRATOSATS TO ERB

• Radiative flux measured directly at 35 km
  – Commonly accepted TOA to which ERBE/ERBS products are extrapolated; no extrapolation required from 800 km down to 35 km
  – High spatial resolution measurements
  – No angular modeling needed
• Complete diurnal coverage (no diurnal model required, the leading source of uncertainty in daily and monthly regional flux averages)
• No sun angle bias (Sun synchronous orbits, except ERBE/ERBS and CERES/TRMM)
• Global synoptic coverage allows actual dynamics of ERB to be seen (including horizontal fluxes); never before possible
HURRICANE PREDICTION

• More accurate prediction of a hurricane track and its intensity can avoid economic disruption and save lives

• Current data sources
  – Satellites provide low resolution atmospheric data,
  – Buoys provide surface wind, pressure, air and ocean temperature, and
  – Crewed aircraft fly into the storm to supplement the wind, pressure and temperature data around the storm.

• While this data and better models have continued to improve hurricane forecasting, more high quality, high resolution in situ data is needed

• For example, more accurate wind data is needed
  – The winds in the vicinity of the hurricane are important for predicting the hurricane’s path
  – The winds inside the hurricane are important to estimating its eventual intensity
ECONOMIC BENEFITS TO IMPROVED PREDICTION

• In a 72 hour forecast the current average hurricane landfall error is 200 miles

• When a hurricane is predicted to hit a coast, up to 300 miles of a coastal zone is placed under a warning, which is 4-times the area actually seriously effected

• The estimated financial impact on US of a hurricane warning is between $1-50 M per mile of coast, depending on economic sectors along that stretch of coast

• If landfall prediction could be improved by 50% a potential savings of at least $150 M per hurricane landfall could be achieved
HURRICANE ALBERTO

Hurricane Alberto - 2000
32.7N 58.7W at 21:00 UTC
POSSIBLE HURRICANE TRACKING NETWORK

• Track a moving target (hurricane) with multiple balloons
• As one balloon moves beyond the horizon, new balloon enters the scene for observations
• Deploy one or more StratoSat “string-of-pearls” around the World near the latitude of hurricanes
• Example constellation management strategy
  – When > 90° longitude from hurricane, maintain hurricane's latitude
  – When < 90° longitude from hurricane, aim directly for the eye
• After Northern Hemisphere hurricane season the network could move to the Southern Hemisphere
• Hurricane Alberto
• 20 balloons
• 1-day look-ahead
• 4 hrs/frame
• 31 days
• Actual easterly winds at 35 km
• Advanced TCS (0.5-5 m/s)
• Lat control strategy
  – >90° track lat
  – <90° aim eye
DEMONSTRATION MISSIONS
EXAMPLE DEMONSTRATION MISSION OPTIONS

- Hurricane Intercept Mission
- Satellite Radiometry Calibration and Validation
- Wind Lidar Measurements
- Demonstration Earth Radiation Budget Experiment (DERBE)
- Or a Combination of Mission Objectives
HURRICANE INTERCEPT MISSION (HIM)

• Hurricane Alberto
• UKMO winds at 35 & 20 km
• Red
  – Aerodynamic TCS model
  – ~ 2 m/s control authority
  – Maintains lat.
• Blue
  – Uncontrolled
  – Floats with winds
• 4 hrs/frame
• 4.25 days

• Potential Primary Objectives
  – Intercept and Possibly Follow Hurricane
  – Obtain High Resolution Meteorological Measurements
  – Demonstrate Hurricane Intercept Trajectory Control Capability

• Possible Science Experiments
  – Meteorological Dropsondes
  – High Resolution Wind Lidar
  – GPS Reflection Sea-state
  – Precipitation Radar
  – Low Resolution Imager
EXAMPLE DERBE MISSION PROFILE

- Radiative flux measurements of the Earth
- Float altitude of 35 km
- Generally “orbit” Earth at +15° latitude
- ~5 overflights of SGP CART at +35° latitude
- 100 day mission
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EXAMPLE DERBE
TRAJECTORY SIMULATION

Trajectory Objectives
- Achieve overflight of SGP CART site
- Avoid overflight of China and Libya
EXAMPLE DERBE SCIENCE PAYLOAD

- **Pyranometers**
  - Four instruments of different types
  - Hemispherical FOV
  - Short-wave (0.3-3 \( \mu \text{m} \))

- **Pyrgeometers**
  - Two instruments of different types
  - Hemispherical FOV
  - Long-wave (4-40 \( \mu \text{m} \))

- **Radiometers are modified Earth science instruments**
- **Instruments located on an optical benches**
- **Calibration system**
CALIBRATION SYSTEM

• **Pyranometers**
  – Periodically view Sun to provide known input source
  – **Issues**
    • Reflections off balloon will contaminate solar signal
    • Cosine response of instrument may necessitate corrections
    • 0.1° pointing knowledge with respect to the Sun required
  – Collimator tube to eliminate all other signal sources

• **Pyrgeometers**
  – Rotate to a “black body” to cover field of view of pyrgeometer
  – Black body temperature must be known to ± TBD (0.1) K
  – Emissivity of black body must be known to ± TBD (0.5) %
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EXAMPLE DERBE BALLOON SYSTEM CONCEPT

- Super-pressure ULDB (~60-80 m dia)
- Flight Train (ladder, parachute) ~100 m
- Gondola (<500 kg)
- TCS Tether (~1 mm dia) ~15 km
- Instrument Platform
- StratoSail® TCS (~50 kg)
EXAMPLE DERBE GONDOLA

Retractable instrument Chassis

FOV Limiters

Blackbody

Pyranometers

Pyrgeometers

Crush Pads
INTERNATIONAL PATHWAYS TO OVERFLIGHT
GLOBAL CONSTELLATIONS OF STRATOSPHERIC SATELLITES

INTERNATIONAL OVERFLIGHT OPTIONS

- Free flight in upper stratosphere
- Expand on the 1992 Treaty on Open Skies
- Exploit World Meteorological Organization (WMO) cooperation
- Seek new treaties
  - Committee on Space Research (COSPAR) study
  - World pollution issues
  - Growing interest in providing method for all countries of the world to participate in global observations
COSPAR RESOLUTION

- 33rd COSPAR Scientific Assembly in Warsaw, Poland in 2000
- Scientific Balloon Panel formulated a resolution to the COSPAR Executive Council
- Resolution requested a task group be formed to study and report to the bureau on the technical aspects of overflight of scientific balloons including:
  - altitudes,
  - balloon sizes and payload masses,
  - characteristics and features of payloads, and
  - safety requirements) and
  - possible international actions to enable the geographically-unrestrained and the peaceful free flight of such apparatus over all countries.
- This resolution was accepted as COSPAR Internal Decision No. 1/2000.
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PROPOSED OVERFLIGHT REQUIREMENTS

• Airworthiness certificates from appropriate organization, perhaps ICAO, indicating the craft meets equipment and safety requirements
• A means of identification
• Evidence of liability insurance
• Payloads must not compromise any State’s national security
• Launch and payload oversight
• Any nation free to operate stratospheric platforms if they meet all requirements
SUMMARY
SUMMARY

- **The StratoSat™ platform** is a stratospheric satellite that can provide:
  - Low-cost, continuous, simultaneous, global and regional observations options
  - In situ and remote sensing from very low earth “orbit”

- Global and regional stratospheric constellations will expand scientific knowledge of the Earth system

- A demonstration mission is essential first step toward regional and global measurements from 35 km

- Mission definition has progressed on two demonstration missions,
  - Demonstration Earth Radiation Budget Experiment (DERBE)
  - Hurricane Intercept Mission (HIM)