STOP Modeling in Support of GHAPS Balloon Based Telescope

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In Support of Gondola for High Altitude Planetary Science (GHAPS)

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Introduction

GHAPS is a Mission to Launch a Reusable, 1-M Balloon Based Telescope to Address the Needs of Planetary Science

Design Cycles Led by GRC / MSFC Taught Us:
1. Unique Challenges for Balloon Based Optical Telescopes are:
   – Combination of: Wide Thermal Range, Gravity, Lightweight
2. Design / Analysis Indicate that Design Solutions Can Be Found
   – Small Portion of the Overall WFE
3. Stability / Environment Demands Focus Changes on Float
   – Creates Requirements for WFS / WFC
4. Tools for Integrated Analysis
   – Elusive and “Home Grown”
Planetary Science that is Well Suited for Balloon Missions

SCIENCE INSPIRATION
Balloon-based telescopes offer “means of studying planetary bodies at wavelengths inaccessible from the ground” – 2013 Planetary Science Decadal Report

NASA is currently in the demonstration phase of super-pressure balloons – offering diurnal cycle missions up to 100 days.

Reusable balloon platforms with 100 day missions provide planetary science observations at cadences prohibitive for other assets.

Path Finding Missions Included: BOPPS and BRRISON

Workshop Science Target Outputs: Venus, giant planets, icy satellites, and small bodies (e.g. KBO)

Suggested Observations: Atmospheric composition / dynamics, surface composition, orbital mechanics of small bodies

J. Dankovich (et al.) “Planetary Balloon-Based Science Platform Evaluation and Program Implementation” NASA/TM-2016-218870
Observatories Features

High Spatial Resolution: 0.1 arcsec to 0.2 arcsec
Broadband: UV – IR (300 nm to 5 um)
Small Observing Field of View: 60 arcsec to 100 arcsec

Aperture: 1-m (for Resolution)
WFE: Diffraction Limited at 650 nm
Temperature: “Cold” for Spectroscopy
Prescription: Cassegrain / R-C for Small FoV
Instruments: Spectrometer & Imaging
Gravity, Thermal, Mass

UNIQUE DESIGN CHALLENGES
• Begin with Mass Allocation and Areal Density
• Areal Density = 100 kg/sq-m
  – Mass = 78 kg
  – Area = 0.78 sq-m
• Why So Heavy?
  – Gravity and Thermal

STO Flew with 0.8 m Primary @ 50 kg
Areal Density: 100 kg/sq-m*

* P. Bernasconi, “Balloon-borne telescope for high resolution solar imaging and polarimetry” 2000
How Do Gravity and Thermal Drive a Solution?

- Gravity
  - Elevation Angle Causes Deflection / Surface Errors
  - Requires Extensive Support System Like Ground Based Telescope
    - Whiffle Tree + Tangent Bars

Keck Mirror Support

TMT Mirror Support
Thermal Environment

• **Telescope Sensitivity** *(OTA WFE Budget = 26.6 nm RMS)*

<table>
<thead>
<tr>
<th></th>
<th>Focus</th>
<th>Decenter</th>
<th>Tilt</th>
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<tr>
<td>Sensitivity</td>
<td>5 um / 26.6 nm</td>
<td>&gt; 100 um / 26.6 nm</td>
<td>&gt; 200 ur / 26.6 nm</td>
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• **Environment on Float:** +30°C to -60°C
  – Athermalize to 5 um / 2.5 m over 90°C

\[
\frac{\Delta L}{L} = \epsilon = \alpha \cdot \Delta T \rightarrow \alpha = \frac{\epsilon}{\Delta T} = 0.022 \text{ ppm/C}
\]

1. Very Low Expansion Material
2. Great Athermal Design
3. Low Gradients
4. Good CTE Uniformity

Telescope Needs Focus Control?
Total Mass Budget

Standard Balloon

- **Mission Duration**
  - 1.5 days to 30 days
- **Lift Capacity**
  - +2900 kg
- **Day / Night Locations**
  - Antarctica = Day @ 10 – 30 d
  - Domestic = Day / Night @ 1.5 d

Super Pressure Balloon

- **Mission Duration**
  - 100 days
- **Lift Capacity**
  - +2500 kg
- **Day / Night Locations**
  - New Zealand @ + 90 d

Balloon Type / Site has Impact on: Wavelength, Temperature, Duration
Thermal Stability Demands Changes to Focus on Float
Implying WFS / WFC

NEED FOR FOCUS / COMA
CONTROL
Refocus Still Needed After Complex Athermalization

- **Low Thermal Expansion Materials**
  - Constructed w/Zerodur + CFRC

- **Moderate Thermal Expansion in M1 Support**
  - Whiffle Tree Includes Invar and Titanium

- **High Thermal Expansion in COTS Hexapod**
  - M2 Actuation Includes Aluminum

- **Even With Athermal Design…BFL Changes**
  - $\Delta BFL / \Delta t = 1 \text{ um} / \text{hr}$ to $40 \text{ um} / \text{hr}$
Wavefront Sense / Control

Wavefront Sensing
- Modified COTS Shearing Interferometer (Phasics)
- SCMOS Sensor w/Std Optics

• Few Sample Points
  - 40 x 40
  - 20 x 20

• Repeatability of 5 nm RMS Possible with Magnitude 7 or Less
  - Driven by Putting Wavefront Over as Few Pixels as Possible

Actuated M2
- Baseline Solution
  - Heated 6 DoF (Hexapod)
- Alternate Solution
  - Tip / Tilt / Piston Mechanism
  - 3 DoF

HST: (x6) DoF
Spitzer: (x1) DoF
WFE Budget Not Dominated by Analysis

DESIGN / ANALYSIS
Key Components for STOP Analysis

**Thermal**
- **CTE Uniformity**: When M1 cools, CTE uniformity affects surface figure.
- **Thermal Distortion**: Non-Ideal support transfers stress to mirror at temperature.

**Gravity**
- **Stiffness**: Elevation changes result in mirror surface figure changes.

**Drift**
- **Thermal Changes Between Refocus / Realign Operations**: Cause WFE.
M1 CTE Non-Uniformity

- Published Example for Zerodur CTE Distribution
  - Synthesize Distributions with Similar Spatial Frequencies
- Run Thermo-Elastic Models on M1
  - Determine Ensemble WFE from CTE Non-Uniformity
- \[ WFE = 0.25 \text{ nm WFE RMS / deg C} \]
M1 Thermal Gradients

- Thermal Gradients for Varied by Mission Locations / Flights
  - Ft Sumner (~1 day)
    - Environment Changes Faster than the Thermal Time Constant
  - New Zealand; Antarctica
    - Quasi-Equilibrium Achieved (~2 days) Prior to Observation

NZ = Astigmatism

FS = Spherical
M1 SFE Over Elevation

- Orientation Changes Loads
- Polished for 37 deg
  - Residual Errs at Other Elevations
- Focus / Coma Assumed Correctable

Surface Figure Error after Correct with M2 and Figuring at 37 deg

16 nm RMS
Mirror Figured at $\theta_{\text{elevation}} = 37$ Deg
S/W “Glue” and Management

STOP
Architecture to Answer Key Questions

Science Simulation
- Blackbody Radiation
  • Mirror Temperatures
- PSF
  • Image Acuity
- Long Term Stability
  • Long Exposures
  • Impact of Slewing to Refocus

System Model
- Pointing
- Jitter
- PSF
  • WFE
  • Deterministic
  • Stochastic

Scenarios
- Simplified Boundary Conditions
- Design Reference Mission

Tools
- Nastran
- Zemax
- Thermal Desktop
- Matlab / Python
- Visual Studio / C#
• Models
  – Nastran
    – Static Model (x3) / Elevation, Thermal
    – Dynamic Model (x2) / +100 modes
  – Thermal Desktop
    – (x2) Configurations
    – (x5) Scenarios
    – (x100) Transient Temperature Outputs for Nastran Model
  – Optical Model (x1)

Robust Process to Support Iteration

Deterministic and Stochastic Scenarios

Top Level Outputs Not Supported by S/W

A Lot of Point-Click

10’s – 100’s Files
Hierarchical Object Oriented S/W with API Interface

- Altair HyperWorks
- FEMAP
- Zemax
- Microsoft Excel
- Sigmadyne
- Microsoft Visual Studio
- MATLAB
Automation through OOP with API

Class Definition

- Properties
- Method A
- Method B
- Method C

Inheritance

Tools:
- Microsoft Excel
- MATLAB
- Visual Studio
- FEMAP
- Zemax
Classes to GHAPS / STOP

M1

Mirror Surface
- Deformation
- Rigid Body Motion
- Zernikes

Telescope
- Mirror Surfaces
- PSF
- Pointing

M2

Mirror Surface
- Deformation
- Rigid Body Motion
- Zernikes

Telescope Ensemble
Objects Interact with Data to Import and Analyze

- Deformation
- Rigid Body Motion
- Zernikes
Telescope Object Analyzes w/API to Get System Level Answers

- **M1 - Gravity**
- **M1 - Thermal**

**Telescope**
- Remove Coma / Focus Errs

**System Level Performance (PSF)**

**Zemax**

**API**

**WFE**

**PSF**

**BFL**

**LoS**
Design Reference Mission to Science Eval

- **For Structure**
  - PSF, Mirror Temperatures

- **For Science**
  - SNR for Spectroscopy, Integration Time, Detection Rate for KBO, Evaluation of Image Quality

(x3) Missions
(x9) Targets Each
What Did This Enable?

• **Verification**
  – Verification through API and Cross Correlation with Different S/W

• **Automatic Export of Data to Scientists**
  – FITS Files for WFE and PSF to Verify Science Instrument Sims

• **Rapid Assessment of New Scenarios**
  – (x3) Flights; (x100) Thermal Conditions; (x2) Thermal Configurations; (x7) Elevations

• **Evaluation for CONOPS**
  – WFS / WFC: Range of Travel; Need for Corrections; Drift on Float
  – Jitter / Pointing: FSM in Instrument; Fine Steering in Instrument

• **Science Instrument Interface**
  – Pointing of Telescope vs. Pointing of Science Instrument
  – Opto-Mechanical Interface to Bench; Requirements for Call

• **Monte Carlo Simulation**
  – Incorporate Stochastic Errors in M1 Fabrication (100’s of Cases)
  – Identify Sensitivities, Requirements
  – Feedback to Scientists on Consequences of Requirements
Final Notes

- **Planetary Science Still Has a Need for an Observatory**
  - Decadal Science Questions Remain Unanswered with Existing Assets
- **Balloon Based Telescope Platform**
  - Addresses Many Science Questions
- **Design Solutions Can Be Found**
  - Challenging Environment Addressed with GHAPS as One Solution
- **STOP Analysis Still a Complex Endeavor**
  - Requires Several Disciplines Working Together
  - Software Tools not Widely Available

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