Precision Attitude Control for the BETTII Balloon-Borne Interferometer

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Abstract

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) is an 8-meter baseline far-infrared interferometer to fly on a high altitude balloon. Operating at wavelengths of 30-90 microns, BETTII will obtain spatial and spectral information on science targets at angular resolutions down to less than half an arcsecond, a capability unmatched by other far-infrared facilities. This requires attitude control of the gondola at the several arcsecond level, and phase correction of the gondola attitude at a level of less than a tenth of an arcsecond, great challenges for a lightweight balloon-borne system. We have designed a precision attitude determination system to provide gondola attitude knowledge at a level of 2 milliarcseconds at rates up to 100 Hz, with accurate absolute attitude determination at the half arcsecond level at rates of up to 10 Hz. A multi-stage control system involving rigid body motion and tip-tilt-piston correction provides precision pointing stability to the level required for the far-infrared instrument to perform its spatial/spectral interferometry in an open-loop control. We present key aspects of the design of the attitude determination and control and its development status.

Keywords: Precision Pointing, Balloon-borne telescope, Infrared interferometry, Attitude determination, Attitude control

1. INTRODUCTION

The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII; Figure 1) is an eight-meter baseline Michelson interferometer to fly on a high-altitude balloon. The long baseline will provide unprecedented angular resolution (~0.5″) in the 30-90μm band. This band is inaccessible from the ground; the high atmospheric transmission at balloon altitudes, in combination with BETTII's unique double-Fourier instrument will allow spectral resolution of up to $R \equiv \lambda/\Delta\lambda \sim 200$. The integration of these capabilities allows BETTII to provide spatially resolved spectroscopy, a new tool for exploring astronomical regimes that remain hidden from our view. Simultaneously, BETTII will raise key technologies and techniques for spaceborne interferometry beyond TRL 6.

Previously, we have reported upon the scientific objectives of the BETTII mission[1]; in short, the prime science goal of the first BETTII flight will be to study clustered star formation, with secondary scientific objectives of obtaining spatially resolved spectroscopy of the cores of Active Galactic Nuclei. In a companion to this paper, we present the design work that is currently complete for BETTII[2]. BETTII was selected for funding in fall 2010, and the official project start was January 3, 2011. The design focuses on mechanical aspects of BETTII and its optical design. Additionally, the fringe tracker subsystem of BETTII is presented in another companion paper[3].

BETTII is a two-element Michelson interferometer that collects light on an 8-meter baseline with a pair of siderostats that steer the beams to confocal telescopes. In one arm, the collimated beam then passes through a warm delay line to correct phase differences arising from, among other things, pointing errors; in the other arm, the opposite beam passes through a K-mirror to rotate the beam such that all field angles overlap. The two beams enter a cryostat where cold optics use near infrared light used for fringe tracking while using far-infrared light for science purposes.

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Ground-based and Airborne Telescopes IV, edited by Larry M. Stepp, Roberto Gilmozzi, Helen J. Hall,
Proc. of SPIE Vol. 8444, 84442P · © 2012 SPIE · CCC code: 0277-786/12/$18 · doi: 10.1117/12.927224

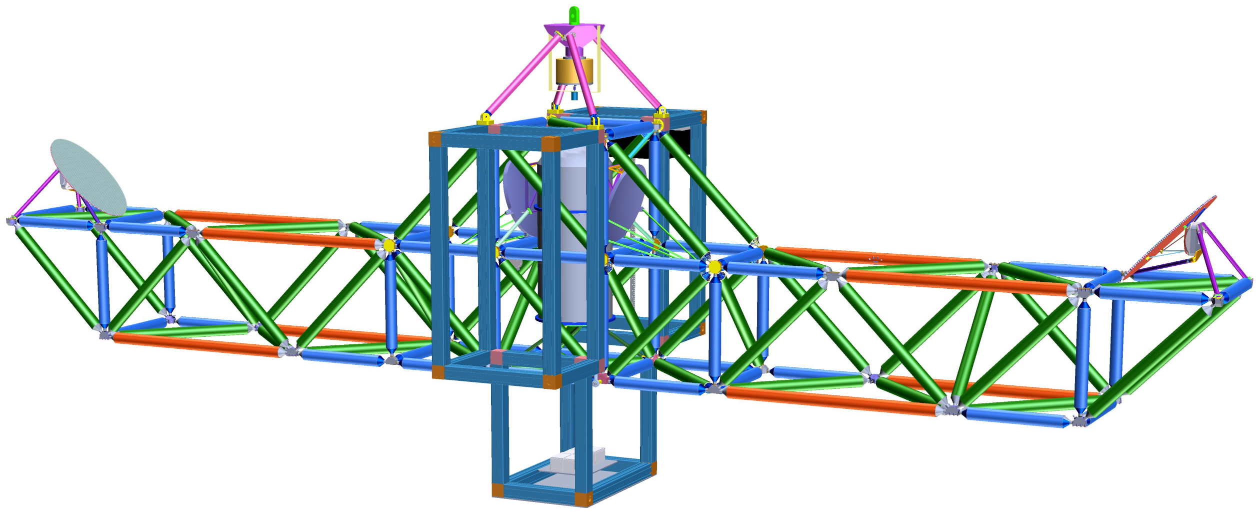

Figure 1: By using a metering truss made of carbon fiber tubes and compact steel endpieces, we create a structure that is strong, stiff, and which behaves well under temperature change. Individual mounts for siderostats, the cryostat, etc. use a combination of titanium and Invar tubing to provide stiffness and to match CTE effects. Surrounding the center of the metering truss is a load structure made of 80/20 aluminum, designed to hold non-optical components of the BETTII system

In designing BETTII, one of the most stringent requirements is that pointing jitter must be tightly controlled. Small variations in the rigid body pointing of the gondola leads to phase noise contributions in the measured interferogram; this can be measured and compensated at low frequencies, so that such phase noise can be eliminated. Above some frequency, though non-rigid-body oscillations can cause "blurring" of the individual fringes, leading to a reduction in the apparent fringe visibility and a reduction in the overall data quality. Hence, the BETTII structure is strong, lightweight, and has a high natural frequency of ≈25 Hz. In the balloon environment, fortunately, there are no external forces that excite high frequency oscillations; all lower frequencies will be measured and corrected. The most significant perturbation are the pendulation modes of the gondola itself, which occur at frequencies < 1 Hz. However, since the amplitudes of these oscillations can be relatively large (~10 arcminutes[4]), we also require a number of different mechanisms to compensate for these effects, as well as mechanisms to allow us to obtain the interferometric fringes in the time domain (i.e. a delay line).

In this paper, we describe the attitude determination hardware, discuss mechanisms to enable attitude control or beam control to stabilize overall pointing and relative phase in the interferometer, and show the strategy for closed loop control of this complex system in various observing modes. We pay particular attention to the design of a star tracker as a portion of the attitude determination hardware, as it makes use of new technology to yield precision absolute attitude determination from balloon altitudes in both day and night observing conditions.

2. ATTITUDE DETERMINATION COMPONENTS

The most critical subsystem for determining the attitude of the gondola body is a pair of gyros used to measure rotation around the elevation and cross-elevation axis. As will be shown later, it is required for all observing modes. The gyros must respond quickly enough to determine the rotation induced by the pendulation modes of the balloon-gondola system, as the effective path length difference introduced by this rotation is fed forward to control the phase of the two beams with a delay line mechanism. Because of the long baseline and short wavelengths involved, a typical pendulation velocity of 10″/sec will produce phase delays corresponding to ~200 fringes/sec. This motivates 100 Hz update rates and requires subarcsecond precision and accuracy. Over sufficiently long timescales, drift in the gyros will be corrected by a co-mounted star tracker than provides both absolute and stable pointing determination. To provide a wide margin of safety on the performance of the gyros, we specify a desired accuracy of <1″ accuracy over 10ms-100s. Of the many gyro options available, we have selected fiber optic gyros as being the most promising candidates due to their excellent performance and solid-state design. We plan on using a slightly modified version of a previously-flown commercially-available single-axis gyro produced by Optolink[5], the SRS-2000. Its stated performance of <0.0005 °/√hr angular random walk and <0.005 °/hr bias drift are exceptionally good, resulting in a net angular uncertainty of around 0.6″ (1σ) over 100 s. Our modified version contains synchronization electronics such that the exact time of readout can be stabilized to an external reference, thereby eliminating pointing errors due to drifting phase between the sensor and controller.

As mentioned above, a star tracker is used to provide absolute pointing knowledge in three axes and to measure precise, rapid pointing drifts in two axes while holding on a target. Our modeling suggests that an absolute accuracy of <0.5″ (1σ) in elevation and cross-elevation can be achieved in only a few seconds, while differential motion can be tracked at the ~0.3″ (1σ) level at 10 Hz; uncertainties in roll angle are roughly a factor of 30 larger. Further details of the design are presented below.

The third, and most sophisticated, major portion of our attitude determination system is a fringe/angle tracker; this is the subject of a companion paper[3]. Briefly, its purpose is to enable angular/phase motions of each interferometer beam with the goal of overlapping the beams from both arms and to measure the phase between the beams with a goal of moving the optical delay line to keep the phase stable. It achieves this using a single infrared megapixel detector array, and H1RG from Teledyne[6]. Four small (~hundred pixel on a side) patches of the array are illuminated. Two of these are near-infrared single beam images corresponding to J-band intensity of each arm of the interferometer. The position of the brightest star in each patch (which should be the same source) is determined and mirrors can then be adjusted to achieve beam overlap, after which the location of the centroid of the star in each patch is held constant. The other two patches are used to monitor the phase in the interfered beams using a broadband H+K near-infrared filter. One patch is the constructive, white light image that is brightest when the optical path length difference is zero. The other patch is the destructive, null image that should be suppressed in this state. This patch is dispersed by a low-resolution prism, so that the wavelength-dependence inherent in the phase shift induced by a path length difference will be measurable.

Other components are used to provide additional information useful for attitude determination in certain cases. A high accuracy tilt-compensated magnetic compass (Honeywell HMR3500[7]) provides <0.5° three-axis attitude for the gondola referenced to true north. A GPS unit determines the position relative to the Earth. Inclinometers will be used to detect a tilt in the gondola such that a (seldom used) mechanism can level the interferometer arms to operate as closely as possible as an alt-az telescope.

To maintain the pointing system stability over long timescales, BETTII's attitude determination hardware (and most other data generating devices) will be operated in a minimally varying fashion. For instance, the science detectors and angle/fringe tracker detector are read constantly throughout the duration of operation. Slower data streams – including the above compass, GPS, and inclinometers, but also with thermometers, accelerometers and magnetometers for other diagnostic purposes – are read and archived continuously. Even the gyros, at their higher data rate, will be stored in their entirety – requiring perhaps 20MB of storage. The only data streams that provide overwhelmingly large volumes are the angle/fringe tracker (generating around 1.4GB per hour) and the star tracker (400GB per hour). For those devices, data decimation will be employed to permit the saving of representative data; otherwise, only the attitude determination results will be stored.

3. STAR TRACKER

Our star tracker concept is based a PCO.Edge scientific camera[8]. The detector is a Fairchild CMOS 5.5 megapixel array with a 6.5 micron pitch[9]. The typical quantum efficiency at red bands is 40%, with typical read noise 1.1 electrons. The readout rate is fast enough to permit 100 fps continuous acquisition, but speed and sensitivity requirements allow us to operate it at a 10 Hz rate. Data are acquired by a computer interfacing with the camera via a CameraLink acquisition card. A Nikon Nikkor *f*/2.8 lens[10] with 300 mm focal length provides high magnification (688″/mm), an adequate field of view (≈10° diameter), and large collecting area (90 cm^2). This older lens (c. 1980) features a very low dispersion glass to mitigate chromatic aberration and a manual focus lock; it does not feature built-in autofocus and image motion compensation mechanisms, which could become liabilities when uncontrolled in a balloon environment.

The star tracker has a designed plate scale of 4.47″/pixel and a field of view of 3.18°x2.68°. A baffle of 21 cm diameter and 60 cm long provides a Sun avoidance angle of about ±16 degrees, which allows the star camera to be operated easily during daytime with suitable precautions. A long wavelength (R-I band) filter improves the contrast between typical stars and the bluer atmospheric background. The star tracker should be able to determine our elevation and cross-elevation to within 0.35″, and our roll angle to within 22″, at a frequency of 1 Hz. We plan on using exposure times of 100 ms in nominal operation. An early ground-based demonstration with a lower-performing camera validates these results in both angular resolution and overall design, but at poorer sensitivity (Figures 2 and 3).

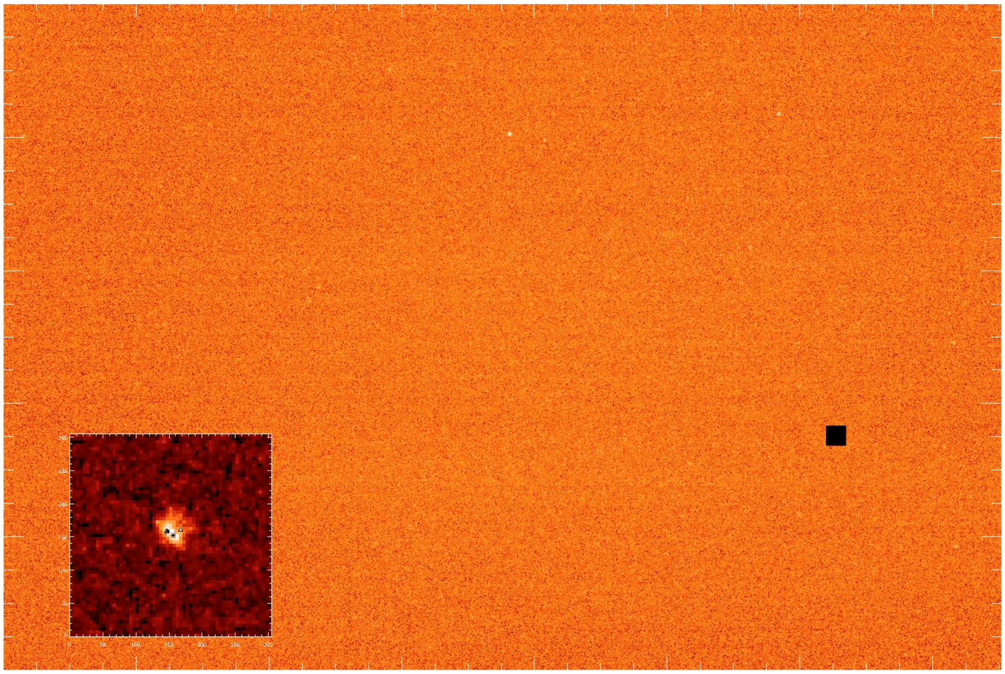

Figure 2: The BETTII Star Tracker prototype is able to provide precise determination of single star positions; in this case, HD41079 (mag ~6.7; near the top center and the magnified inset) is measured with a 1σ uncertainty of 0.318″ in a 100 ms integration. The very bright star Betelgeuse has been blanked in this image as it saturates. HD40491 can be seen in the upper right of the image, and measured with similar precision; these two can provide three-axis attitude determination with subarcsecond precision at 10Hz update rates. This star density is generally found across the sky.

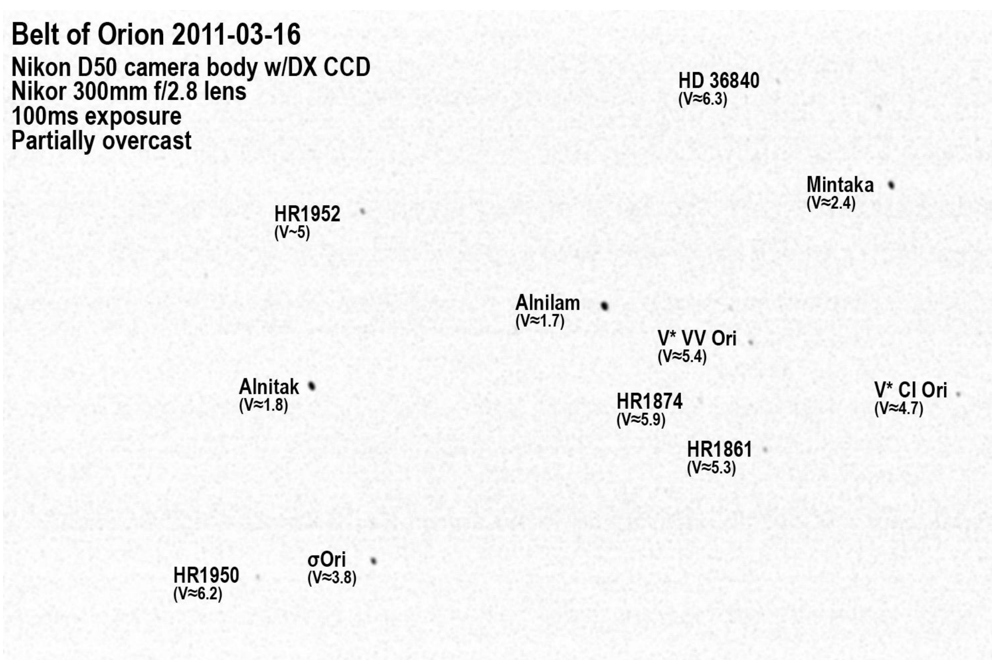

Figure 3: The BETTII Star Tracker prototype has adequate sensitivity to measure the positions of even relatively faint stars. Designed to reach sufficient signal-to-noise down to magnitude V=8 stars with the PCO.Edge camera, even a lower performance camera achieves V≈6 detections on the ground.

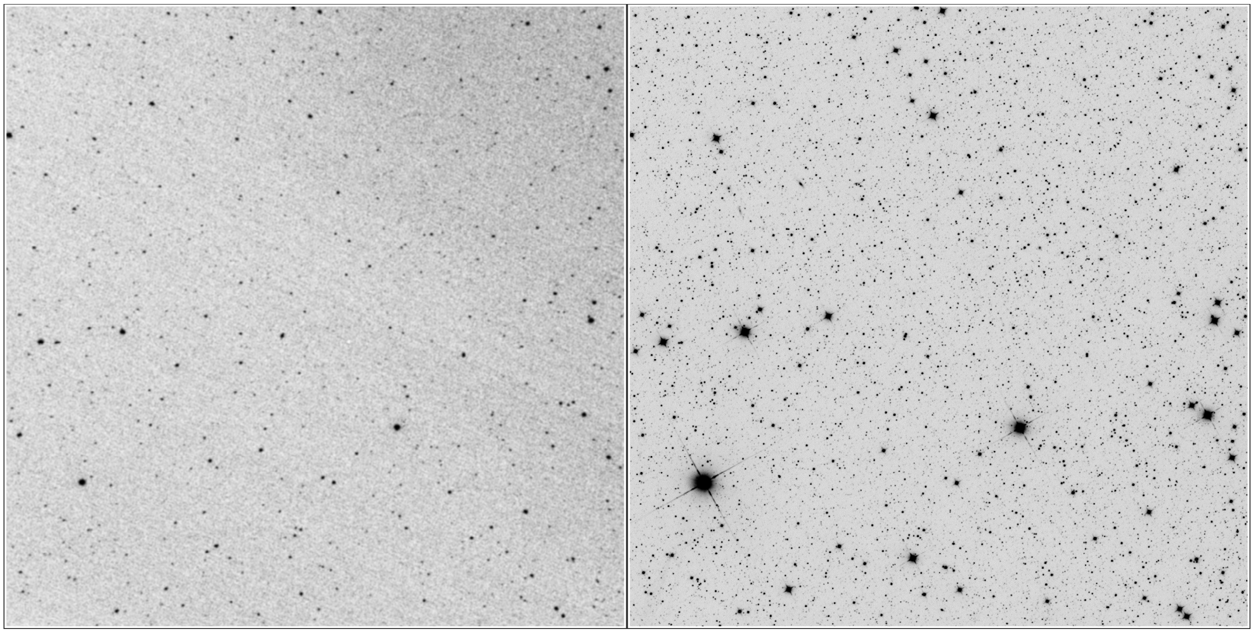

Figure 4: (Left) Image made from two coadded star tracker frames taken from the ground in dark conditions. Using Astrometry.net[11] to solve for the field, this image is centered at 20:27, +10:17 in the constellation of Delphinus. The average plate scale of 4.43″/pixel is almost exactly the design plate scale of 4.47″/pixel; the field of view of 3.15°×2.66° very closely matches the design field of 3.18°×2.68°. (Right) As can be seen in comparison to the WISE 3.4μm image (from SkyView[12]) of the same field, the star tracker with only 2 seconds of integration is able to find very faint stars; the bright star just south of the center is HR 7810, a V≈6.3 magnitude variable star. Stars as faint as 11^{th} magnitude are easily identified in the star tracker image. By comparison with this image we can determine that distortions of the star tracker field are very small (roughly 5″ across the field), and hence absolute pointing errors will be small.

The BETTII Star Tracker with its flight camera has been demonstrated successfully on the ground (Figure 4 and 5 Left), so will next be flown along with other pieces of prototype hardware as a hitch-hiker payload on another balloon experiment in Fall 2012. This experiment will validate the performance predictions and provide essential data to optimize the autonomous absolute pointing and precision varying attitude determination algorithms. The hitchhiker payload, baptized RUBBLE, is described briefly in Section 6.

4. MECHANISMS FOR CONTROL

With the same sentiment as above, mechanisms will be operated continuously when possible. This stabilizes their thermal behavior, and additionally mitigates disturbances from switching device states. One such mechanism is the cold delay line, which modulates the optical path in the far-IR portion of the interferometer. The entire time, this cold delay

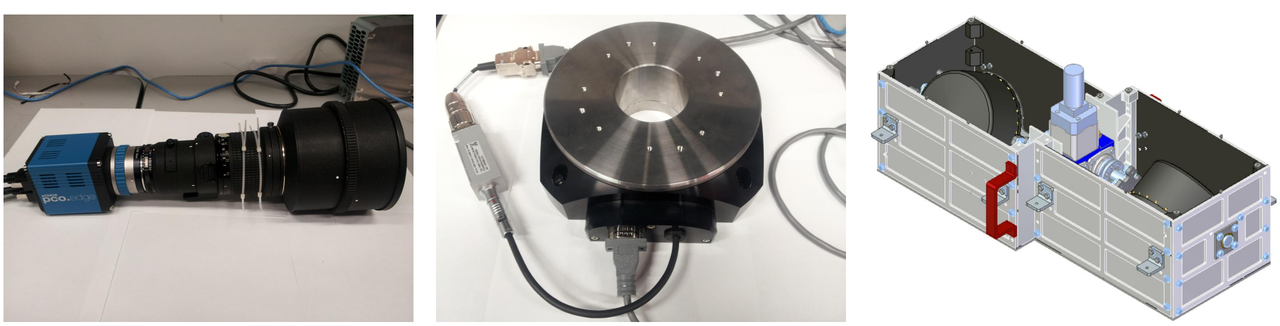

Figure 5: (Left) The BETTII Star Tracker assembly consists of a large aperture, high magnification lens coupled to high performance camera. (Middle) A Griffin rotator will provide elevation control at subarcsecond resolution. (Right) A compensated control moment gyro has been designed to provide rapid, low jitter, high torque azimuth control.

line moves back and forth, generating interferograms in the science detectors. Knowledge of the relative phase at each point in time during operation can be used for offline processing of the interferograms, correcting the errors in phase (esp. path length) that arise from being imperfectly equalized by the warm delay line.

The BETTII gondola is rotated in azimuth using a Compensated Control Moment Gyro (CCMG). Control moment gyros are often used to provide high torque with prompt response as they are tilted perpendicular to their rotation axes. In this instance, a pair of identical control moment gyros are used, each spun at a high and constant rate. If they begin in an antiparallel orientation, their angular momenta cancel and the system does not rotate. As they tilt towards each other, a net angular momentum is imparted to the gondola to rotate it; tilting the other direction imparts angular momentum in the opposite sense. Because of the balancing of the individual wheels in each control moment gyro, the large torque and stored angular momentum required for the large gondola can be imparted with very low vibration. The two wheels in the CCMG are heritage designs from prior space missions, so are a mature technology.

The siderostat mirrors, star tracker, and fiber optic gyros are all moved in elevation in the same fashion. Three identical rotation stages (Griffin RTS-DD-200mm[13]) are used for this purpose; one carrying the star tracker and gyros (the 'star platform') to sense attitude in elevation, cross-elevation, and roll; the other two are slaved to the first to ensure identical pointing of the two siderostats. These direct-drive rotators are able to execute rapid motions, while the built-in glass encoder disks provide subarcsecond rotation angle knowledge. The stages are also compatible with the wide temperature range and low air pressure encountered in balloon experiments. The wobble of the stage is at the 10″ level, well within the control range of later optics.

A rapid tip/tilt mirror of modest size is present near a pupil stop in each beam to correct the beam position to overlap for interferometry. These mirrors are controlled using the angle tracker position centroiding. A warm delay line mechanism adds or subtracts path length from one arm of the interferometer to stabilize the phase delay measured by the fringe tracker. A K-mirror mechanism in the other arm is rotated in the opposite direction to the siderostat to remove the differential sky rotation present in the BETTII alt-az telescope configuration.

BETTII has several different observing modes, but in each mode there is a closed loop proportional-integral-derivative loop that ingests all relevant attitude determination information and produces the appropriate control signal for each relevant control hardware component. A logical table showing which sensors/controllers are relevant for the four primary BETTII modes is shown in Table 1. There are multiple parameters for each nonempty cell in the table, many of which will vary in value depending in which mode is active. For example, the elevation-sensing gyro provides attitude determination that is fed to the star platform to hold the position steady. In 'Lost-In-Space' (LIS) mode, stability against jitter or drifts while computations are being run incentivizes a frequency response tailored to a slow (and thus low drift) parameter set. In contrast, when in 'Slew' mode, agility may matter more than stability and so terms such as the derivative may take precedence over others.

5. CLOSED LOOP CONTROL FOR OBSERVING MODES

In this section we describe the five operating modes for BETTII: Lost-In-Space (LIS), Slew, Acquire on Calibrator, Acquire on Science Target, and Observe. For each of these modes, there is a set of PID loops that connect the mechanisms to the sensors, as illustrated in Table 1. We use several abbreviations: CDL = cold delay line; WDL = warm delay line; LIS = lost in space; ST = star tracker; FT = fringe tracker; AS = angle sensor (using portions of an H1RG to determine positional offsets between arms); SFP = slew flight plan.

Several processes happen all the time:

- CDL strokes back and forth (unless stopped for calibration) to modulate interferogram on science detectors
- Science detectors are read
- Temperatures, magnetometer (compass), GPS, etc. are read
- ST producing solutions (discarded during fast slews)
- Gyros are read in two axes.

Table 1: A single logical table illustrates which sensors (columns) and controllers (rows) are used in the four primary BETTII modes (L=Lost in space; S=Slew; A= Acquire; O=Observe). If a box has a letter, it means that there is a PID loop for it. In certain situations, one given mechanism is fed two sensor inputs. Calibration and testing, as well as adjustments during flights, provide measurements of the gain of each sensor with respect to each other, as well as the total gain fed to the mechanism.

	Star Tracker	El Gyro	Cross-El Gyro	H1RG Right	H1RG Left	H1RG FT	Right Tip-Tilt	Left Tip-Tilt	CCMG Encoder	CDL Cap Sensor	PID Zero
CDL										LSAO	
WDL			O			O					LSA
L Tip		A			OA						LS
L Tilt			A		OA						LS
R Tip		A		OA							LS
R Tilt			A	OA							LS
L Siderostat	A	LS						O			
R Siderostat	A	LS					O				
Star Platform	A	LS					O	O			
K Mirror	A	LS					O	O			
CCMG	A		LSA				O	O			
Momentum Dump			S						LSAO		

5.1 Lost-In-Space Mode

This mode is the startup mode from any of several initiation/recovery points. For instance, after launch and on power-on, the BETTII system begins in Lost-In-Space mode. Error conditions in other modes (for instance, at the end of Slew mode if the target hasn't been found) will return BETTII to Lost-In-Space mode. In this mode, the system begins by determining approximately where it is while minimizing motion until precise attitude determination is reached.

1. Tip tilts, siderostats, etc., left in last position
2. Check system status and readiness
3. PID gains changed to LIS values from PID Matrix
4. GPS and compass provide estimate (1°) of [RA,Dec] position to ST for star catalog winnowing
5. ST generates and publishes precise [RA,Dec] solution
6. GOTO Slew

5.2 Slew Mode

Slew mode is used to produce large angle motions of the gondola. Most optical mechanisms are turned off, and the gyros are the predominant source of attitude determination. A diagram of the connections between sensors and control components is shown in Figure 6.

1. Retrieves [RA,Dec] of target (precessed to current epoch or via ephemeris); convert to [Az,El]
2. Generate a corresponding "slew flight plan" including waypoint [Az,El]s & incorporating accel/deceleration
3. PID gains changed to Slew values from PID Matrix
4. Acquire Star Tracker absolute pointing solution (again using GPS & compass to speed solution time)
    a. If current position differs from target, GOTO 4.
    b. If no solution, then GOTO Lost-In-Space
5. GOTO Acquire on Science Target

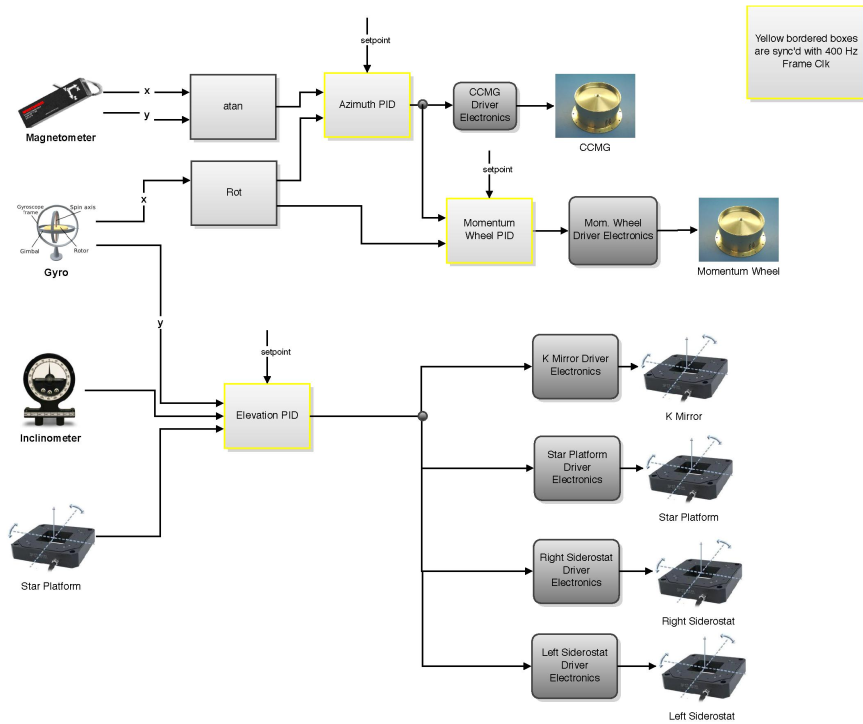

Figure 6: BETTII's Slew Mode can be represented graphically in terms of the sensing and control components.

5.3 Acquire On Calibrator Mode

For observing calibrators, we presume that the source is very bright and approximately point-like. The Star Tracker will have assured that it (although not necessarily the science instrument) is pointed toward the source, so that the bright source is incident somewhere in the field of view of the Angle Sensor focal plane segments.

1. Using gyroscopes, try to maintain gondola pointing centered on the calibration source (gyroscopes provide movement in inertial space directly)
2. Turn on full AS (4′×4′ FOV) and read (which takes roughly 0.7 s).
3. Identify calibration source (the brightest object).
4. Use the siderostat elevation and tilt actuators to position source on the desired AS pixel coordinates.
5. Record the angle offset between the current position of the ST compared to its prior position.
6. Progressively switch from guiding the gondola with the gyros to guiding the gondola with the AS and tip/tilts. Slowly decrease the size of the FOV to increase the readout rate of the AS (reaching roughly 15″×15″ at 100 Hz), and slowly increase the gain from the tip/tilts while decreasing the gains of the gyros.
7. Gondola azimuth and elevation are controlled slowly to keep tip/tilt mirrors within their range.
8. Feed tip/tilts + gyro combination to WDL. The WDL now compensates the bulk of the OPD motion.
9. Scan for fringes (uses at least one quadrant of the FT at 100 Hz).
10. When fringes are found, switch to fringe tracking mode – science data can now be considered good. If fringes cannot be found, request human intervention for data analysis and recovery.
11. Feed the difference between the identified location of the fringes and the center of the delay line range to the azimuth control, in order to stay in range.
12. GOTO Observe Mode.

5.4 Acquire on Science Target Mode

This mode is nearly identical to the previous one, except that now we cannot presume that the brightest source is our target, nor even that there is an especially bright source in the field. The ST field and AS field would be compared between steps 4 and 5 to ensure that the star being tracked by the AS is the one we expect (thereby guaranteeing pointing accuracy as well as pointing precision). Note that the guide star needs to be at the center of the AS field of view (on the chosen pixel mentioned before), because the center of the field of view is a natural optimum point in order to achieve proper Angle Tracking and Fringe Tracking. Our science target thus needs to be within 1′ of that guide star to be within the science detector field of view.

5.5 Observe Mode

Observing mode requires many more pieces of active hardware, but is logically simpler:

1. PID gains changed to Observing values from PID Matrix
2. Store diagnostic data to determine data validity & quality
3. Observe until predetermined criteria are met (for instance, a fixed amount of integration time)
4. Goto SLEW for next target

A diagram of the connections between sensors and control components is shown in Figure 7. During ground analysis, science data are selected and corrected based on diagnostic data to produce a set of high quality interferograms. A limited portion of the data will be sent down and processed in near-real time to permit rapid decisions on the function of BETTII and progress of the science program.

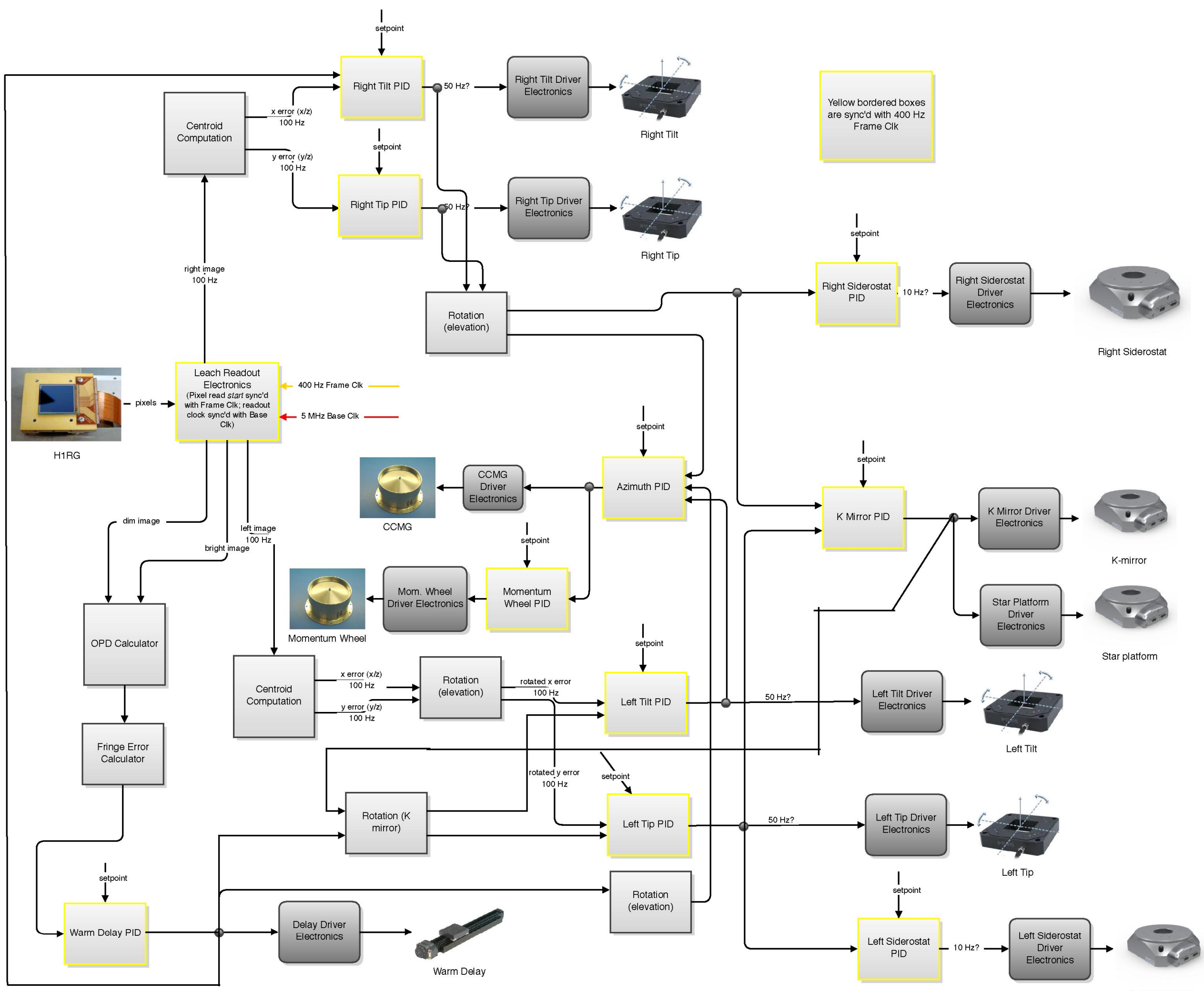

Figure 7. BETTII's Observe Mode can be represented graphically in terms of the sensing and control components.

6. BETTII PROTOTYPE FLIGHT: RUBBLE

To demonstrate much of the BETTII attitude determination and housekeeping hardware designs, we are preparing a hitch-hiker payload to fly in Fall 2012, names RUBBLE: the Representative Unit BETTII/BOBCAT Limited Experiment (Figure 8). Its primary purpose is to test our star tracker in its operational environment, and will store many sky images in a variety of conditions for later detailed analysis on the ground. RUBBLE will also operate the elevation motion mechanism, demonstrate a representative sensor suite of GPS, inclinometer, compass, accelerometer, and thermometer components, and test a fluid-based approach to thermal management of electronics and computers operated in an ambient environment. It will be controlled through micro-controllers and the data will be saved on multiple SD cards for simplicity and fault tolerance. The flight computer will record the camera frames and control the rotating stage that will allow us to take frames at multiple elevations.

Since our hitchhiker payload does not have full attitude control, there is a chance that the star tracker camera could look directly at the Sun, which could be fatal for the CMOS sensor. A sunshade covers the lens aperture in its rest orientation, and power has to be turned on to drive it to view the open sky. A simple watchdog makes sure that the Sun is low enough in the sky before it enables the rotating stage. In case power is turned off unexpectedly, the lens is pulled towards its safe rest position through a spring, and a small latch locks it in place.

RUBBLE will allow us to test critical hardware for BETTII, such as the Griffin rotating stage. It will also capture images in real flight conditions with the lens-camera assembly. This will allow us to optimize the image processing strategy to prepare for the BETTII flight, where real-time autonomous processing is required; we can further validate how well the star tracker retrieves absolute celestial orientation.

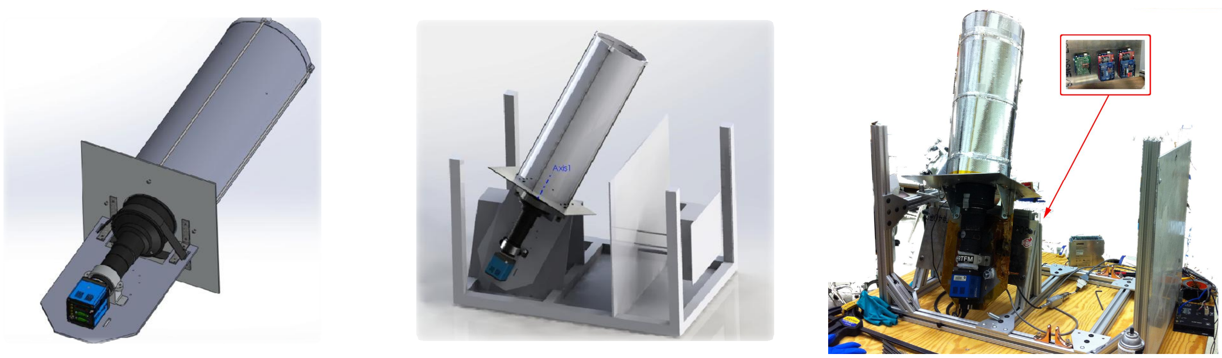

Figure 8: (Left) The BETTII Star Tracker design incorporates a 60cm-long but lightweight 3D-printed baffle to enable daytime operation over most of the sky. (Middle) A small hitchhiker package has been designed for this and other components. (Right) This payload is built and being readied for flight by September 2012.

7. CONCLUSIONS

BETTII has ambitious goals for its attitude determination and control, driven by stringent requirements on phase coherence of an astronomical source viewed through its two apertures. A comprehensive suite of sensors and actuators has been specified to meet this need, and the different operational modes of BETTII have defined subsets of the suite in use. Many of the components are commercially available, but some require development specific to BETTII's requirements. One of these is a star tracker, which has been demonstrated on the ground to provide accurate position determination with precision of $\approx 0.3''$ (1σ, per axis) at a 100 ms frame time. A near-future test flight will validate it in real balloon-borne conditions. The full BETTII payload is still in development, with plans for its first flight in Spring 2015. While BETTII is primarily motivated by potential for important scientific discovery, it will be a critical step towards demonstrating the feasibility of a future space-based far-infrared interferometer, particularly SPIRIT[14]. The precision attitude control approach detailed here will, once flown, provide a mature solution with heritage for such a future mission.

ACKNOWLEDGEMENTS

The authors would like to thank all of the members of the BETTII team for their contributions. Much of the work carried out on the BETTII project has been completed with the assistance of undergraduate student interns at Goddard Space Flight Center (http://asd.gsfc.nasa.gov/bettii/). Many thanks to all of these students, including: S. Gomillion, B. Hoffman, W. Tierney, C. Wagner, A. Cotto, R. Curley, T. Kale, T. Handleton, Y. Okafor, N. Mihalko, P. Nehme, L. Oliviera, A. Gore, H. Spooner, and J. Doiron. This work is being carried out under a grant issued through the NASA ROSES/APRA program. We acknowledge the use of NASA's SkyView facility (http://skyview.gsfc.nasa.gov) located at NASA Goddard Space Flight Center. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

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