Precision pointing for balloon payloads: some initial analysis

Nov.11, 2009

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Outline

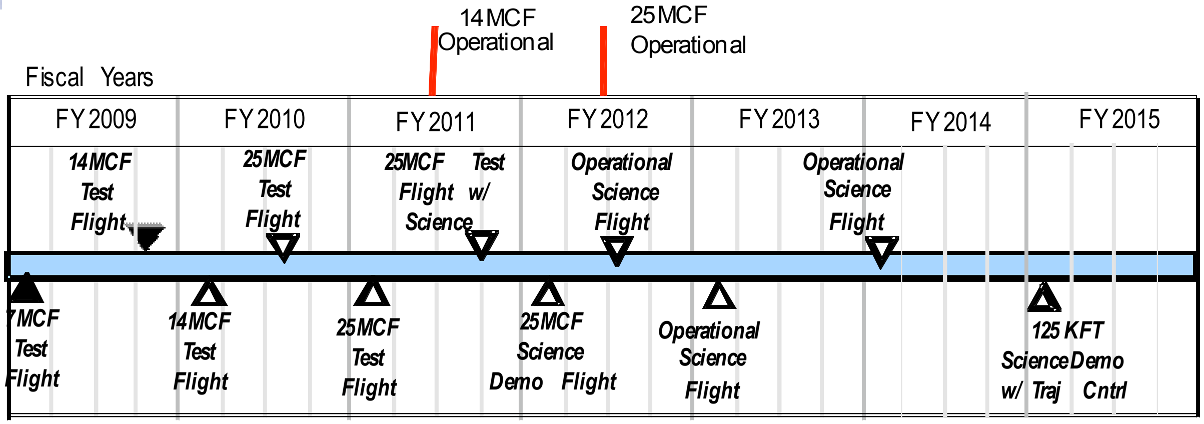
- Balloon workshop
  - Current state of the art
- Status to date
  - Summarize requirements envelope
  - Gather balloon/gondola flight dynamics/disturbances
  - Block diagram
  - Create simulation model
  - Simulation model and results
  - Identify hardware solutions for lab exp and flight
- Guide Sensing Solutions
- Next Steps

Goals of Balloon Fine Pointing Study

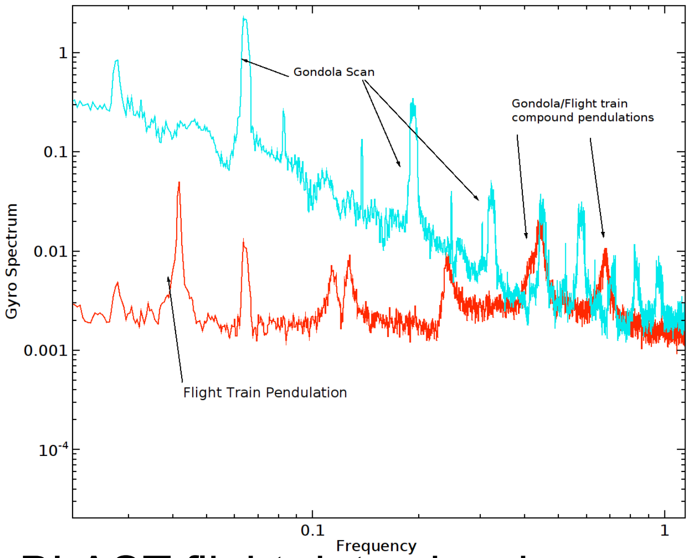
- Precision, sub-arcsecond pointing stability defined as an enabling requirement across multiple proposals
- Given JPL expertise in s/c pointing control, can we design and build an equivalent control system for balloons (affordably)?
- First, addressed requirements, design, and simulation
- Further steps may include a table-top test setup and simulations specific to new proposals

Low Cost Access to Near Space LCANS 09

- http://www.boulder.swri.edu/LCANS09/Home.html
- http://www.boulder.swri.edu/LCANS09/Talks/



Upcoming SuperPressure launch Schedule (Dave Pierce, Wallops)

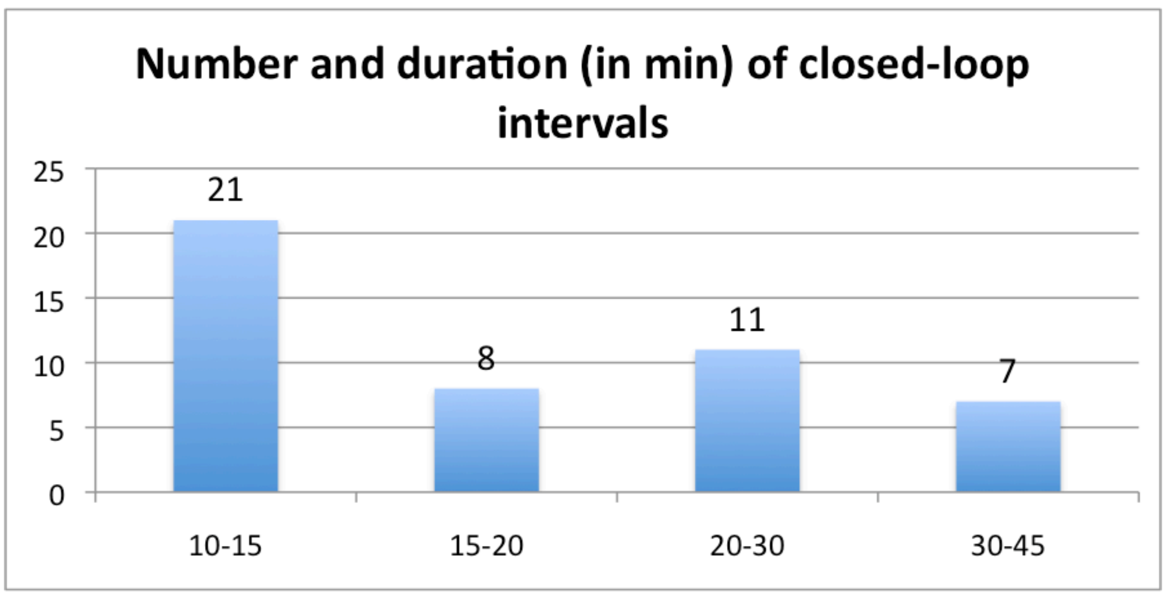


BLAST flight data showing pendulation

Report forthcoming on Conf. Recommendations

Balloon Pointing: State of the Art

- Sunrise mission (2009 flight) has demonstrated fine line of sight pointing control
  - 2 mas 1 sigma pointing measurement accuracy (1000 Hz sampling, 90 Hz bandwidth)
  - **50 mas** angular resolution science camera
  - Gondola coarse control to 50 asec
  - Integration times between 200ms and 30s
  - Open questions: design details of Wavefront Control System? 100 Hz noise coming from flywheel??



Interval [min]	Total [min]	Number
1	262	349
2	120	80
5	334	89
10	600	80
15	236	21
20	120	8
30	248	11
45	236	7
	2156	min

From A.Lecinski, Sunrise, LCANS09

Sub-arcsecond pointing is feasible

- BLAST has data during quiescent period showing ~few arcsecond gondola stability
- Stratosphere achieved a 50 mas stability in 1968
  - 0.05” on 7.5 mag stars, stable for 1 min to 1 hour at 80,000 ft
  - Passive design, not active FSM control. ~3600 kg payload
- Sub-arcsecond pointing with telescopes on balloons has been done (and recently) with multiple-stage solutions and is feasible
- But… still some challenges…

Balloons Payloads: Requirements Envelope for Study

Defined our challenge as a two-stage control system:

- Assume a few asec gondola+telescope unit outer stage (such as Wallops Arcsecond Pointing System design, updated BLAST design)
- internal instrument Fast Steering Mirror to provide ~x20 improvement

This study focuses on internal FSM primarily.

Envelope Requ.	Outer Stage Performance (asec on sky, max)	Pointing Requirement (asec on sky, 1sigma)	Integration time over which need to stabilize jitter	FSM requ. for "throw angle"
General case	10	0.05	hours	~1 mrad

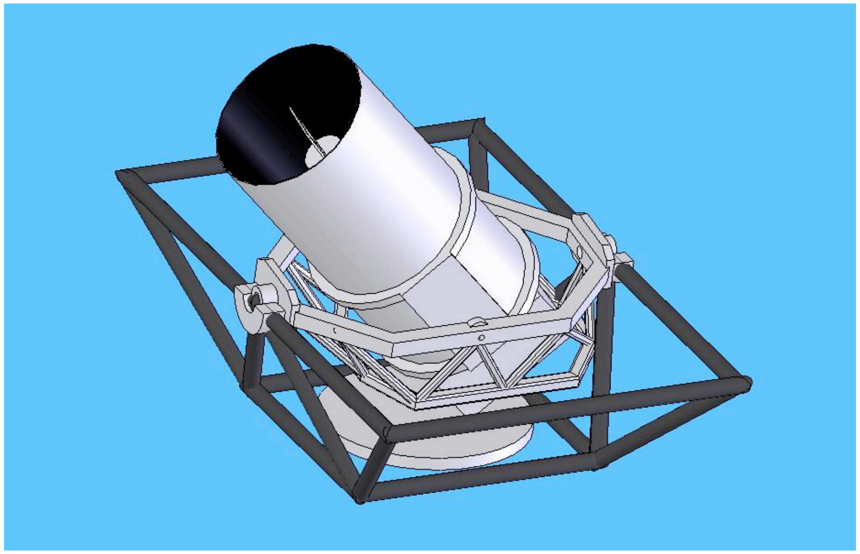
Brainstorming! How much (and which) different payloads would ease (or tighten) these nominal envelope requirements?

Gondola dynamics & disturbances

- Gathered info/data from BLAST, Boomerang, Sunrise, Wallops arcsecond pointing system gondola simulator, Traub & Chen, CNES
- Difficult to get appropriate data sets at resolution that showed true dynamics, not sensor noise, at broad frequency range

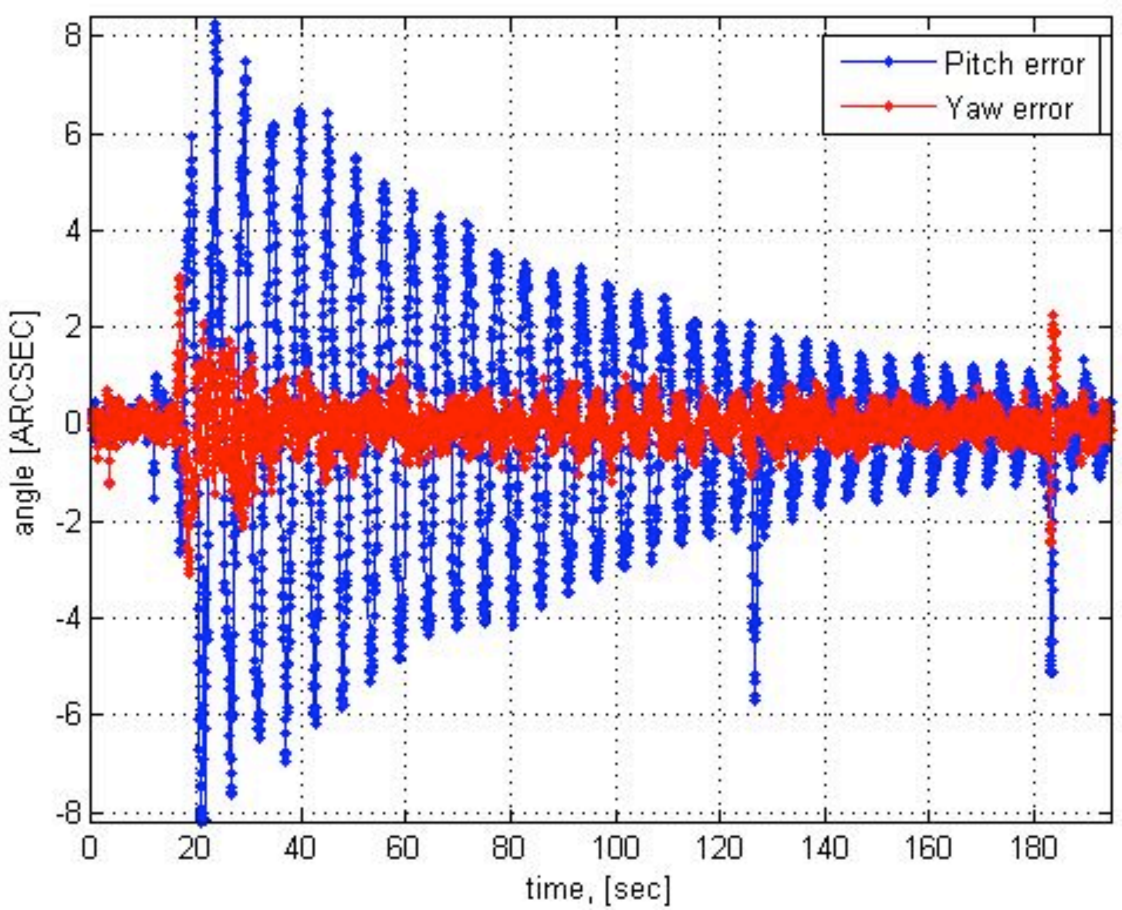
Identified primary disturbances at low frequencies:
- 0-10 Hz

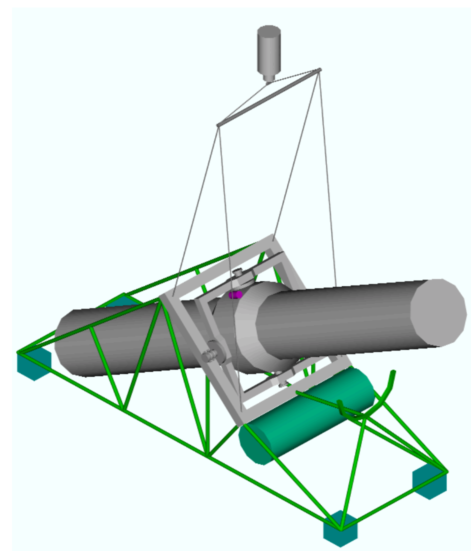
Sunrise had spurious 100 Hz noise that affected them occasionally.



Example gondola enclosure w/telescope
Courtesy Steve Benton, U.Toronto

Wallops Gondola Pointing Emulation: simulated gondola residual pointing errors

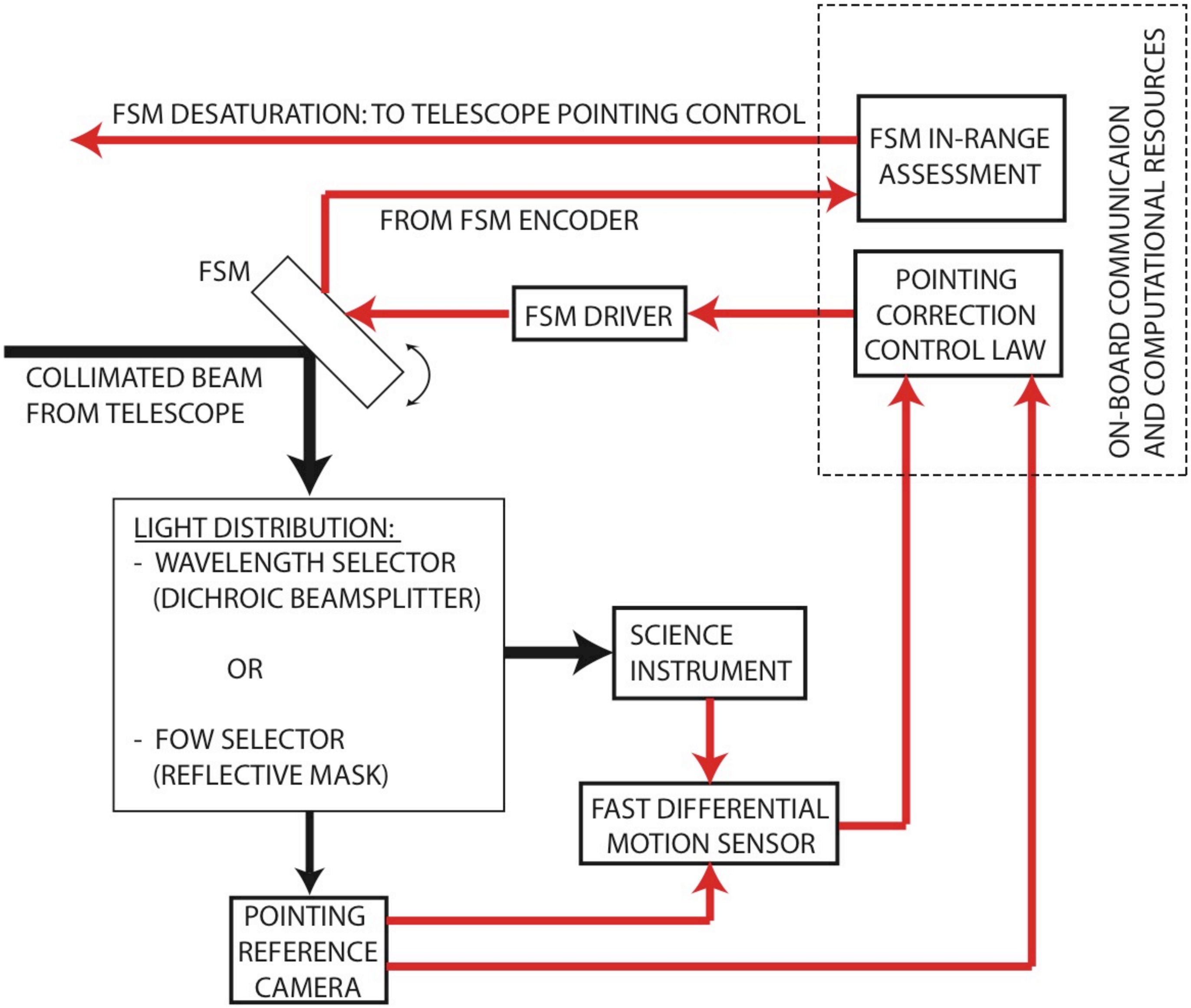




Test gondola and telescope mounted in hangar, disturbed, then damped using WAPS

Balloon Astronomy Experiment: Fine Pointing Control System

V2, June 24, 2009

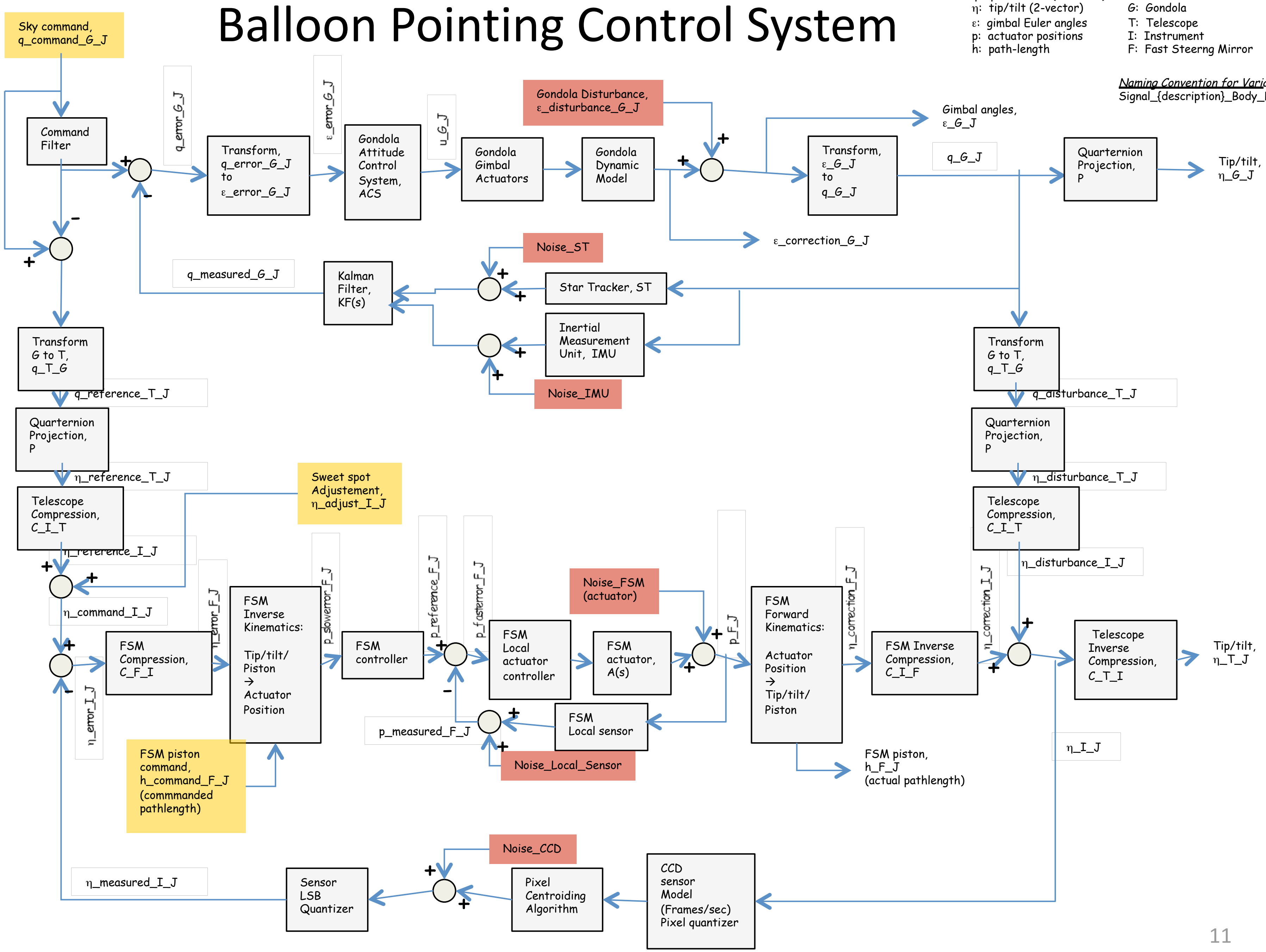


Balloon Pointing Control System

Signal Types:
q: quarternion (4-vector)
η: tip/tilt (2-vector)
ε: gimbal Euler angles
p: actuator positions
h: path-length

Body Names, Reference Frames:
J: J2000 inertial
G: Gondola
T: Telescope
I: Instrument
F: Fast Steerng Mirror

Naming Convention for Variables:
Signal_{description}_Body_Frame



Fine Pointing Simulator

The Instrument Fine Pointing Control System has been modeled in a MATLAB Simulink Environment.

- Telescope and FSM line-of-sight pointing error transformations
- Disturbance models for Gondola pointing errors (pendulation model or feed-through for Wallops disturbance data)
- Design goal: 50Hz control bandwidth. Sensing goal ~500Hz
- FSM model:
  - 3 actuator Kinematics model
  - FSM local loop transfer function representation with hysterisis.
  - Physik Instrumente (316-S10).
- Fine Guidance Sensor model:
  - **Currently modeled as an ideal sensor**
- Fine Pointing Controller:
  - PII controller with 50 Hz bandwidth.

PhysikInstrumente S-316 (actuator candidate)

S-310.10, S-316.10 piezo systems for scanning, optics alignment and mirror shifter alignment

Technical Data

Model	S-310.10	S-314.10	S-311.10	S-315.10	S-316.10	Units	Tolerance
Active axes	Z	Z	Z, Θ_X, Θ_Y	Z, Θ_X, Θ_Y	Z, Θ_X, Θ_Y		
Motion and positioning							
Integrated sensor	–	–	–	–	SGS		
Open-loop travel, 0 to +100 V	6 / –	12 / –	6 / –	12 / –	12 / 12	µm	min. (+20%/-0%)
*Open-loop tilt angle @ 0 to 100 V	–	–	600	1200	1200	µrad	min. (+20%/-0%)
Closed-loop travel	–	–	–	–	12	µm	
*Closed-loop tilt angle	–	–	–	–	1200	mrad	
Open-loop resolution	0.1	0.2	0.1	0.2	0.2	nm	typ.
Open-loop tip/tilt angle resolution			0.02	0.05	0.05	µrad	typ.
Closed-loop resolution	–	–	–	–	0.4	nm	typ.
Closed-loop tip/tilt resolution	–	–	–	–	0.1	µrad	typ.
Linearity	–	–	–	–	0.2	%	typ.
Mechanical properties							
Stiffness	20	10	20	10	10	N/µm	±20%
Unloaded resonant frequency (Z)	9.5	5.5	9.5	5.5	5.5	kHz	±20%
Resonant frequency (with 15 x 4 mm glass mirror)	6.5	4.4	6.5	4.1	4.1	kHz	±20%
Resonant frequency (with 20 x 4 mm glass mirror)	6.1	4.2	6.1	3.4	3.4	kHz	±20%
Distance of pivot point to platform surface	–	–	5	5	5	mm	±1 mm
Platform moment of inertia	–	–	150	150	150	g • mm²	±20%
Drive properties							
Ceramic type	PICMA® P-882	PICMA® P-882	PICMA® P-882	PICMA® P-882	PICMA® P-882		
Electrical capacitance	0.39	0.93	0.39	0.93	0.93	µF	±20%
Dynamic operating current coefficient	8	10	8	10	10	µA / (Hz • mrad)	±20%
Miscellaneous							
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Stainless steel		
Mass	0.045	0.055	0.045	0.055	0.055	kg	±5%
Cable length	2	2	2	2	2	m	±10 mm
Sensor connection	–	–	–	–	LEMO		
Voltage connection	LEMO	LEMO	LEMO	LEMO	LEMO		

Resolution of PI piezo tip/tilt platforms is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier (p. 2-146).

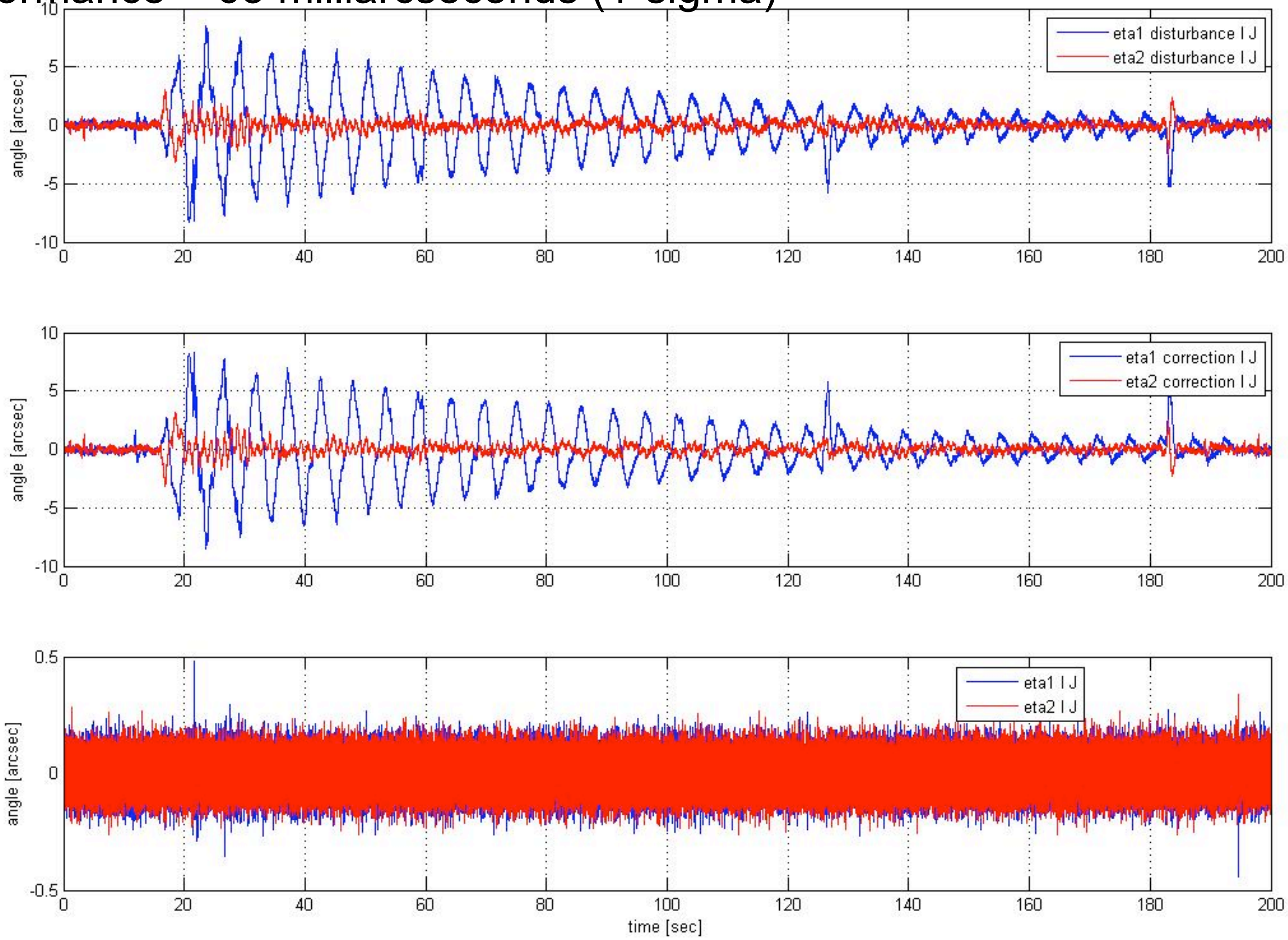
*Mechanical tilt, optical beam deflection is twice as large. For maximum tilt range, all three piezo actuators must be biased at 50 V. Due to the parallel-kinematics design linear travel and tilt angle are interdependent. The values quoted here refer to pure linear / pure angular motion (equations p. 2-84).

Recommended controller / amplifier
Single-channel (1 per axis): E-610 servo-controller / amplifier (p. 2-110), E-625 servo-controller, bench-top (p. 2-114)

Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152) (optional), E-517 interface module (p. 2-156) (optional)

Line-Of-Sight (LOS) Performance

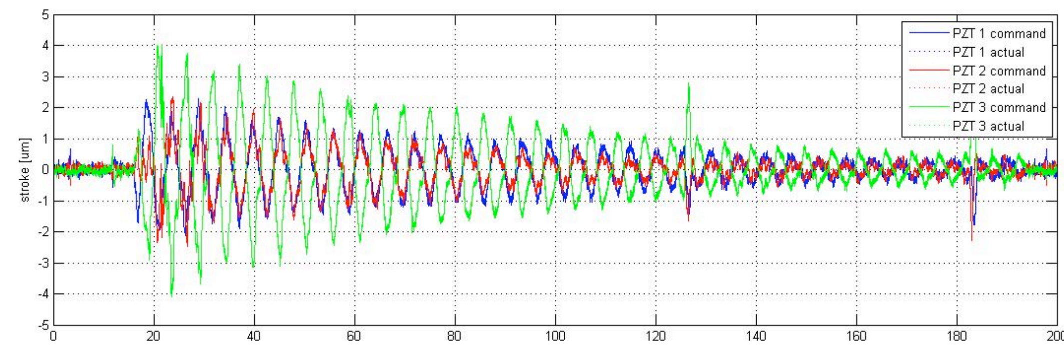
- LOS performance = 63 milliarcseconds (1-sigma)

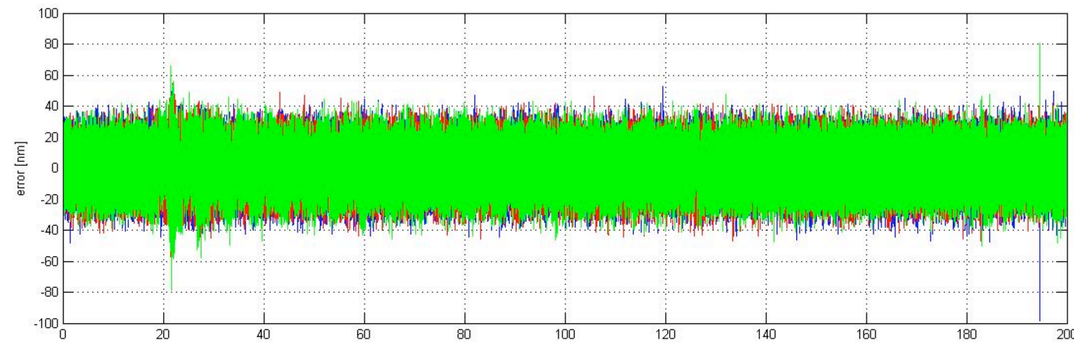


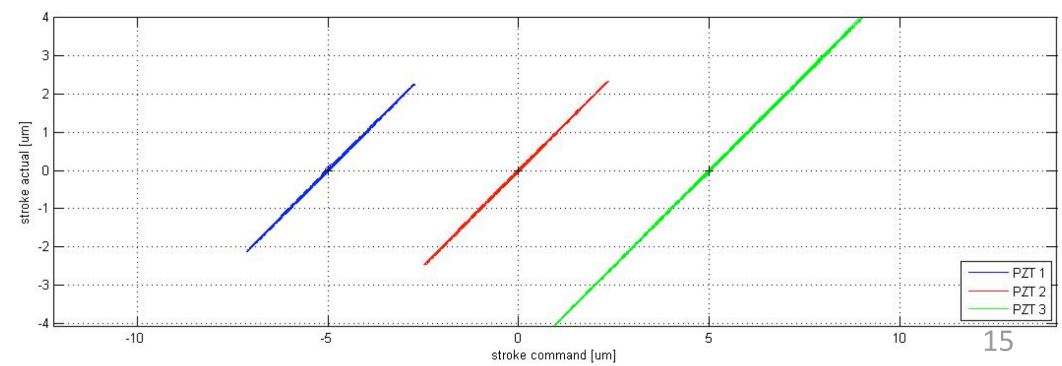
Jitter is surpressed down to reasonable levels without optimized controller (and including 50 mas noise component)

Line-Of-Sight Actuator

- Target Actuator = PI-316
- Maximum Stroke =12um
- Used Stroke = 8um
- Closed-Loop Linearity = 0.2%. (Deadband = 16nm)
- 0.1urad closed-loop resolution = 0.02 arcsec (1-sigma) = FSM Actuator noise.
- 0.05 arcsec white noise added to Wallops tip/tilt disturbance data (data sampled at 20Hz.)







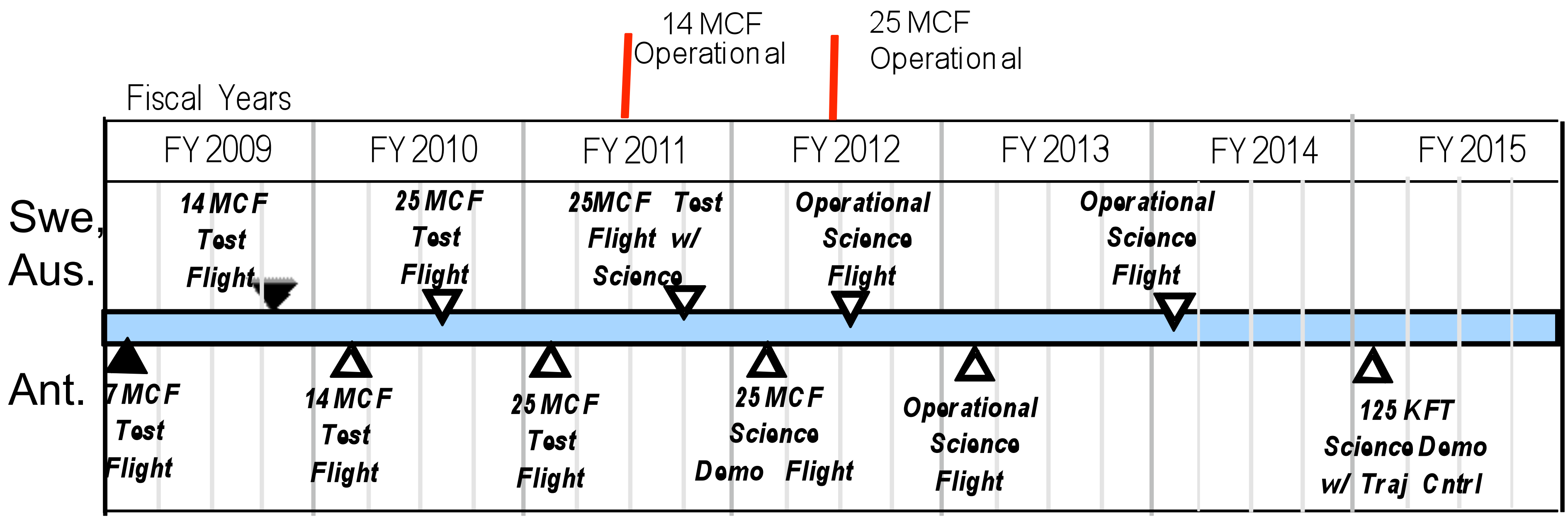
Fine Guidance Sensing

- Each instrument has its own Fine Guidance Sensor approach to achieve their desired pointing knowledge. This pointing knowledge is needed to sense the disturbances to feedback for pointing corrections.
- **Typical Exoplanets Architectures**
  - Use reflected light blocked from coronograph mask and redirect to pointing sensors
  - Use dichroic to split light not used for transits to redirect to pointing sensors
- Will need to readout sensors at high rate (~500 Hz) What are ideal sensors to use? (e2V CCDs for example?)
- Depending on pick-off architecture, guide sensors may not be in science focal plane
  - Misalignments of optical train between science FPA and guide sensors may introduce error (thermal gradients -- ie Wes' concern)
  - May require an additional high sampling rate sensor to measure the high frequency disturbances (e.g. gyro that can sample at 500Hz).
  - May need metrology system to measure alignment changes between sensor/ science FPAs
  - Long integration times (depending on science requ) may need a system that allows field rotation (as well as sensing jitter in roll and correcting for it)

Additional Payload Considerations

ULDB Development Schedule

(from David Pierce, Balloon Program Office)



Super Pressure Balloon Capability

Volume	2 MCF	7 MCF	14 MCF	25 MCF
Altitude	100 KFT	110 KFT	110 KFT	116 KFT
Science Payload	50 Lbs	500 Lbs	1000 Lbs	2200 Lbs*

Payload power is responsibility of payload team, not balloon facility.

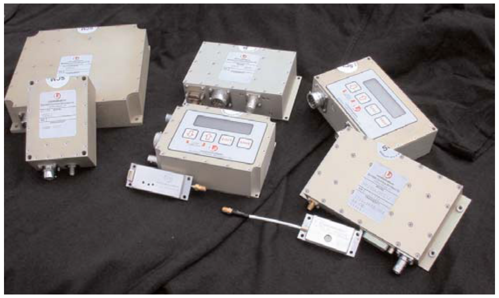
Super Pressure Balloon Development Steps

(from David Pierce, Balloon Program Office)

Balloon Volume	Balloon Diameter (ft)	Number of Gores	Float Altitude (ft)	Suspended Load (lbs)	Science Mass (lbs)	Launch Location
~2 MCF	178.71	200	100,000	650	50	Antarctica
~7.1 MCF	270.96	200	110,000	1,420	500-700	Antarctica
~14.8 MCF	347.21	230	110,000	4,000	1000	Antarctica
~25.6 MCF	417.48	280	118,420	4,200	1,000	Australia
			122,423	4,200	1,000	Antarctica
			116,272	5,640	2,000	Australia
			119,897	5,640	2,000	Antarctica

Long and Ultra-long Duration Balloon supporting technology needs (1): High Bandwidth Telemetry (from David Pierce, Balloon Program Office)

- Current LDB/ULDB limit: ~100 Kbps high-gain TDRSS
  - Provides about 1 Gbyte per day throughput – **not enough** for complete data transfer for most missions!
  - ULDB missions flying over ocean face risk of data & payload loss

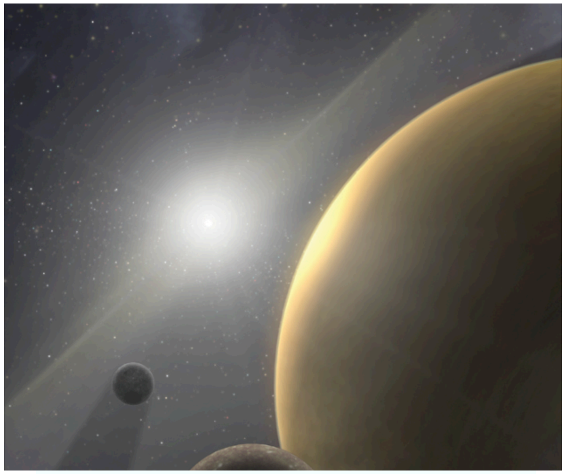


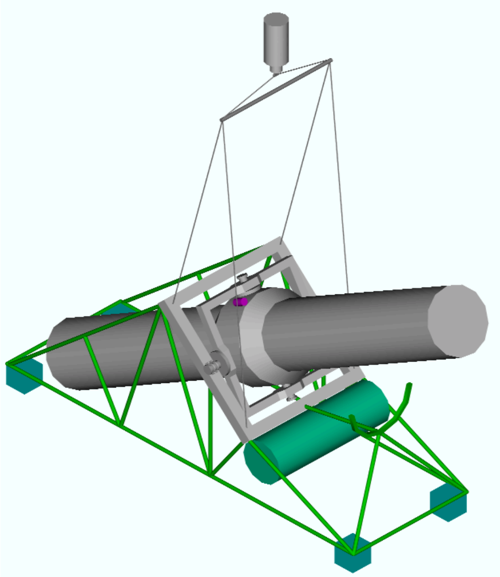
- Commercial aerospace line-of-site data links
  - S,C,X-band with capabilities of 20-320 Mbps
  - Would require access to ground stations with receivers
  - Up to 140 Gbyte per hour of line-of-sight contact

Backup slides

Fine Pointing System (FPS): Wallops study
(from David Pierce, Balloon Program Office)

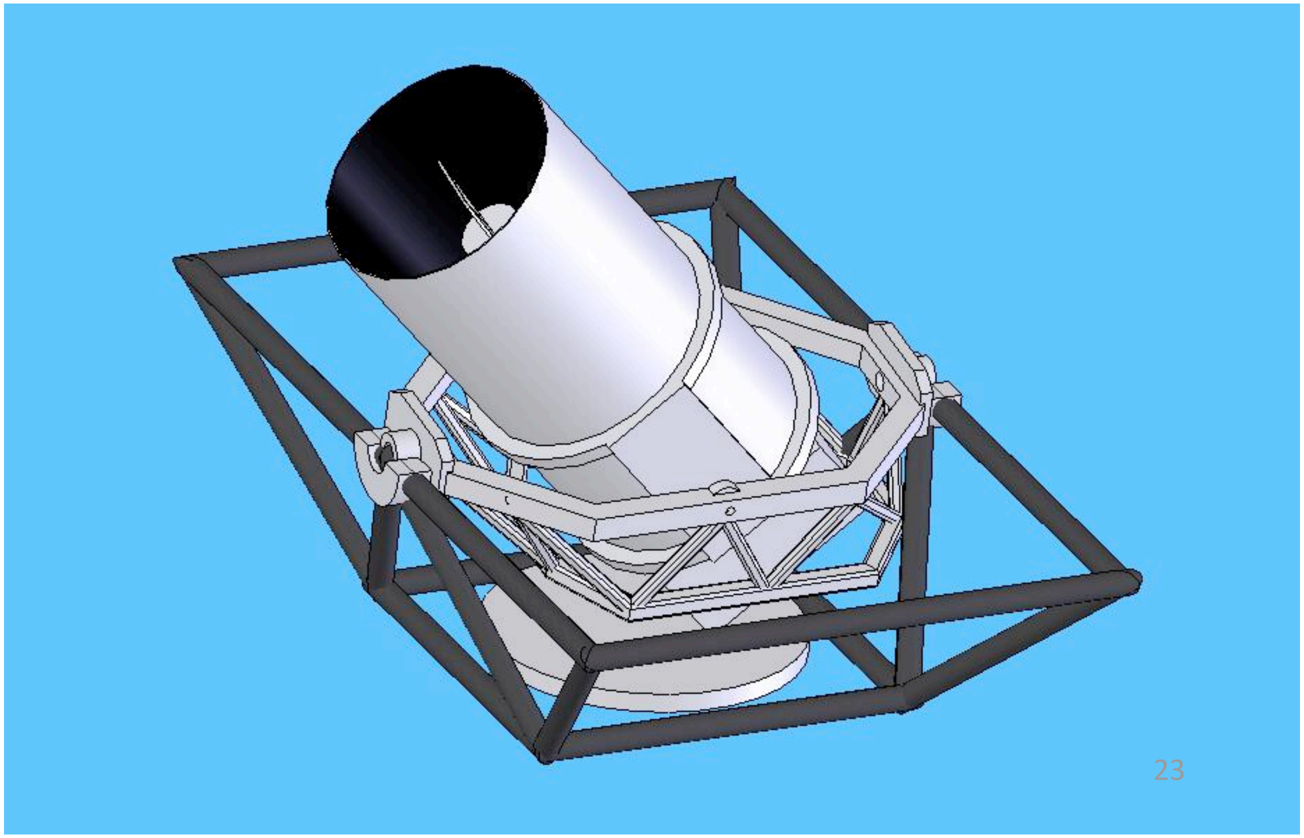
- Wallops feasibility study (1 m telescope):
  - demonstrated a prototype system in the lab using COTS components.
  - A multiple controller scheme (Coarse Pointing – Rotator)
  - A pitch & yaw gimbal system (orthogonally mounted to gondola) for fine pointing
- Low cost FPS with suitable stability achievable for a large balloon-borne instrument pointing at an inertial target.
- Strategy for the FPS:
  1. Increase Rotator accuracy to +/- 1 deg. or better.
  2. Target development of FPS to 1-2-3 arc seconds
  3. Provide a system such that experimenters can do <1 arcsec pointing at their instrument level.
- But there is a penalty: payload mass budget impact





Gondola-Telescope Outer Stage design

- The telescope inner frame is mounted to a middle frame/ring through an elevation mount.
- The inner ring is mounted to the outer frame through a roll mount. This decouples telescope motion from outer frame pitch and roll.
- Goal is for Outer Stage to deliver ~1-10 asec stability



Hi Frequency Gryo or accelerometer options

- Affordable, capable gyros *may* include:
  - TARA series from Kearfott; angle random walk ~ 0.0005 deg/sqrt(hour) = 0.03 asec/sqrt(second)
  - Dynapack 14, 3-axis stabilized from ATA; 2-1000 Hz bandwidth, <50 nanoradian rms noise equiv.angle
- More work needs done on selecting options
- Multiple (3+) accelerometers may also work, cheap relatively, require coordinating software development

Traub & Chen data on balloon pendulation modes

- Mode 1
  > Period: 2 s
  > Description of motion: rotation about the center-of-mass of the gondola/the gondola swings as the balloon and flight train rotate in the opposite direction.
  > Amplitude: 0.6' (0.01 deg)
  >
  > Mode 2
  > Period: ~10 s (6 s - 14 s)
  > Description of motion: bending of the train/the gondola and flight train swing in one direction as the balloon rotates in the opposite direction.
  > Amplitude: <0.6' (< 0.01 deg, this mode was only observed occasionally)
  >
  > Mode 3
  > Period: 22 s
  > Description of motion: pendulum motion of the 120-m length from the center of the balloon to the center of the gondola.
  > Amplitude: 120' (2 deg)
  > Damping time: ~ 30 minutes
  >
  > Mode 4
  > Period: 180 s - 435 s
  > Desciption: Buoyancy (Brunt-Vaisalla) oscillations (i.e. altitude oscillations of the balloon with period ~ 5 minutes, amplitude ~100m. This motion tends to occur when the balloon first reaches altitude and when ballast drops take place.)
  > Amplitude: 30' (0.5 deg).
  > Damping time: 2 - 5 periods. *Traub &Chen,American Astronomical Society, Vol. 41, p.438; Bulletin of the American Astronomical Society, Vol. 41, p.438*

Balloon Pendulation Disturbance Model

- 5 pendulation modes observed in roll rate gyro data of BLAST.
- This data is used to construct our first cut at a Tip/Tilt disturbance model. For each of the five modes, the frequency and relative magnitude data is determined from the plot below. The phase of each mode is a random number in [0,pi/2) radians. The “unscaled” disturbance signal is generated using the formulas highlighted below.
- For the simulation plots that follow, the “unscaled” signal is “scaled” so that its peak-2-peak value is approximately 20 arc-seconds.

$$\theta_x(t) = \theta_{x,w}(t) + \sum_{k=1}^{n_x} A_{x,k} \sin\left(\omega_{x,k} t + \phi_{x,k}\right)$$

$$\theta_y(t) = \theta_{y,w}(t) + \sum_{k=1}^{n_y} A_{y,k} \sin\left(\omega_{y,k} t + \phi_{y,k}\right)$$

θ_x = Total Tip Angle Disturbance

θ_y = Total Tilt Angle Disturbance

$\theta_{x,w}$ = Tip Angle white noise disturbance

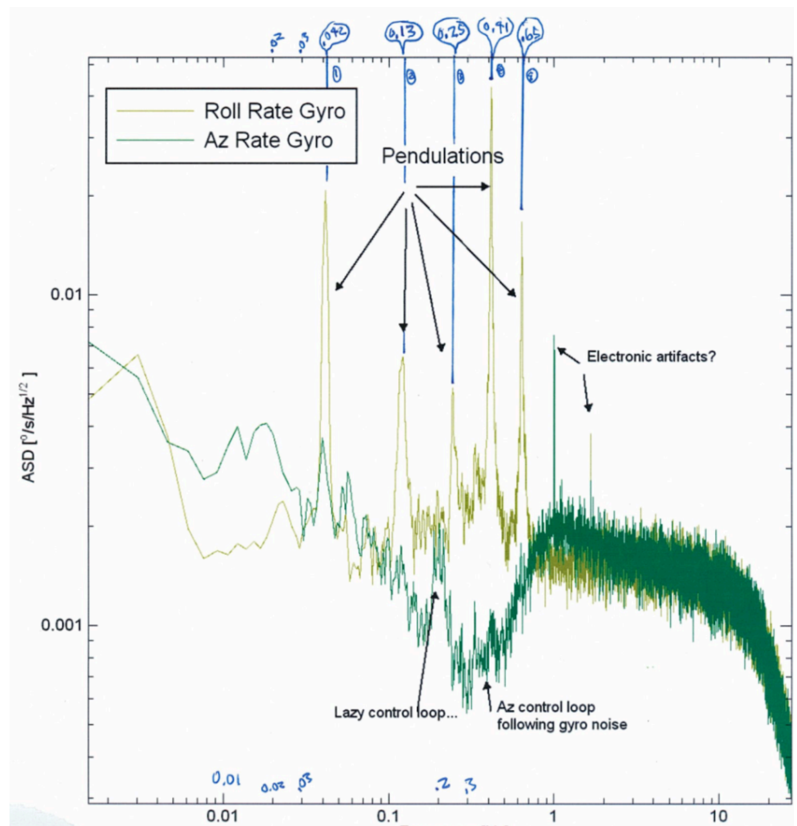
$\theta_{y,w}$ = Tilt Angle white noise disturbance

n_x = # of pendulum modes in tip data

n_y = # of pendulum modes in tilt data

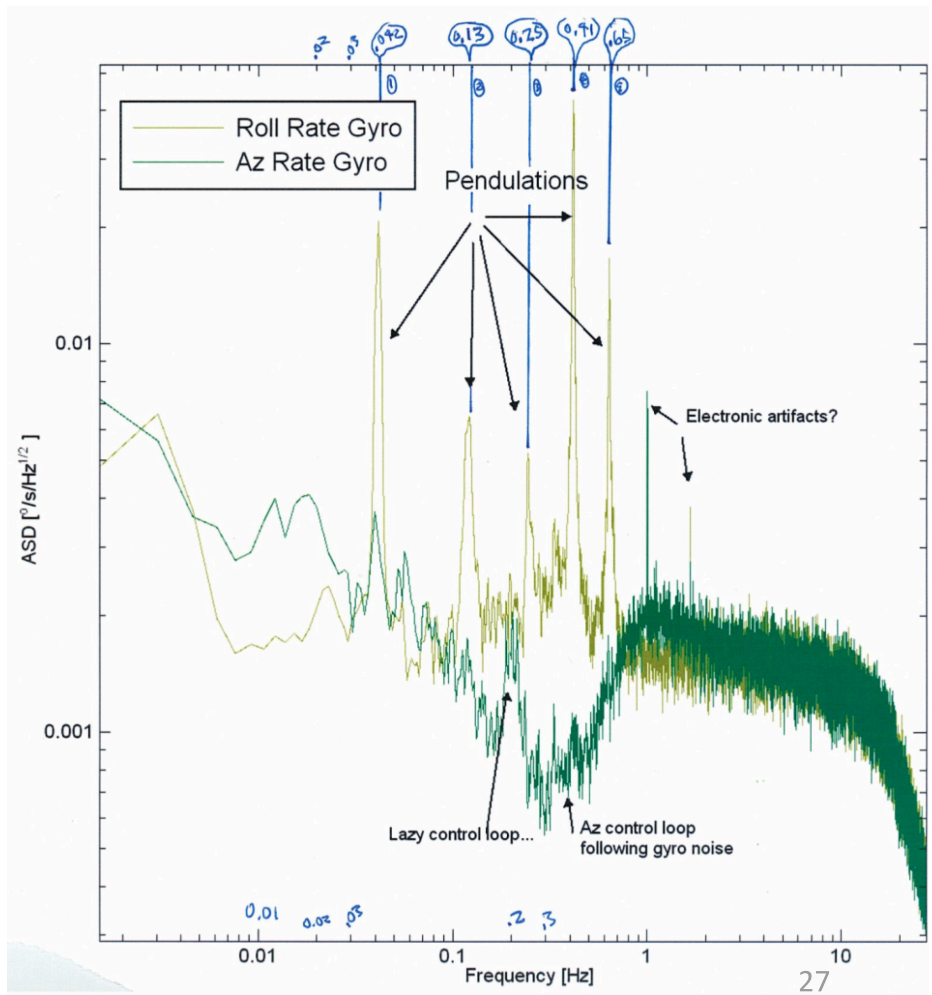
$(A_{y,k}, \omega_{y,k}, \phi_{y,k})$ = (mag,freq,phase) for mode #k in tip data

$(A_{y,k}, \omega_{y,k}, \phi_{y,k})$ = (mag,freq,phase) for mode #k in tilt data



Balloon Pendulation Disturbance Model

- Fitted BLAST Gyro data to disturbance model with 5 pendulation modes
- Rate frequency data (Hz):
  - Freq = {0.042,0.13,0.25,0.41,0.65}
- ||Rate|| (milli-deg/s)*(Hz)^(-1/2):
  - ASD = {21,6.5,5.3,43,16}
- Rates (mdeg/sec) i=mode#
  - Rate[i] = ASD[i]*(Freq[i])^(1/2)
  - Rate = {4.3,2.4,2.7,27.5,12.9}
- Magnitude (milli-deg)
  - Mag[i] = Rate[i]/(2pi*Freq[i])
  - Mag[i] = {16.3,2.9,1.7,10.7,3.2}



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