Two-Gyro Science Mode and Gyro Usage Options

Presented to:

The Space Telescope Users Committee

Keith Kalinowski
Deputy Manager, HST Operations Project
NASA/GSFC Code 441
November 17, 2004

Outline

- TGS Implementation Status
- Operations and TGS Mode
- FSW Overview
- Orbital Scenario
- Gyro Availability Forecast
- Options for utilization of TGS Mode

TGS Mode Description and Limitations

Description:

- Two-Gyro Science (TGS) Mode provides spacecraft attitude control and slew capability using only two gyros
- Its purpose is to extend the scientific life of the HST

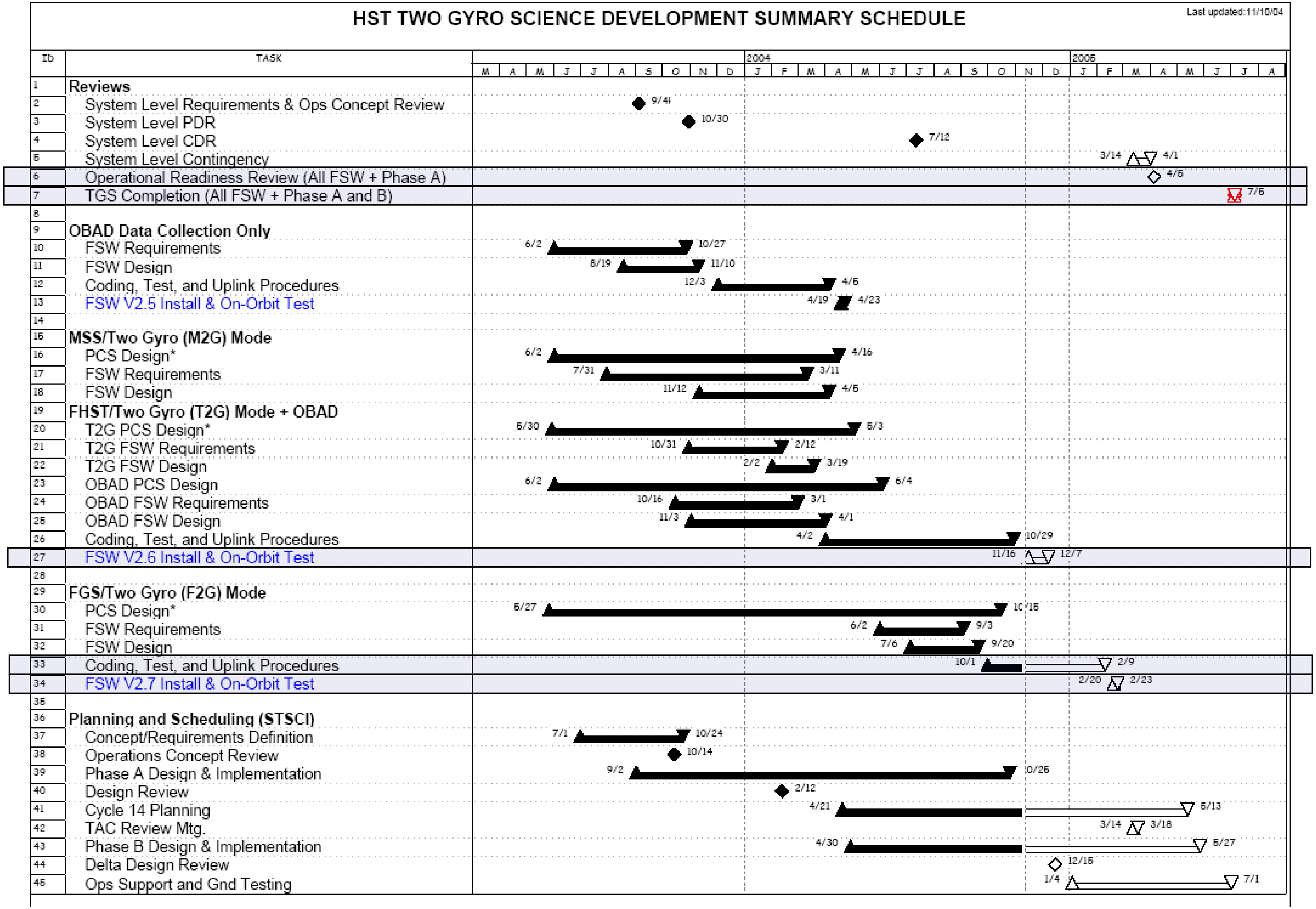
Principle Limitations:

- TGS Mode operations will achieve less efficiency and have less flexibility compared to operations using 3 gyros
- All science observations will be more constrained from a scheduling perspective
- Some classes of observations may not be possible

TGS Implementation

- **Development planning defined 3 FSW builds, installations, and on-orbit tests**
  - OBAD Data Collection [April 04] (HST486 FSW version 2.5)
  - M2G, OBAD, T2G [Nov/Dec 04] (FSW version 2.6)
  - Full OBAD with maneuvers, T2G [Feb 05] (FSW version 2.7)
- **Test 1 of 3 tests of TGS Build 2 executed successfully (Nov 16)**
  - Successive tests are more stringent measures of M2G and T2G performance
- **The third FSW build is on schedule**
- **We expect to achieve TGS Mode Initial Operating Capability in early April 2005**

TGS Schedule Milestones



HST TWO GYRO SCIENCE DEVELOPMENT SUMMARY SCHEDULE

Last updated:11/10/04

ID	TASK	
1	**Reviews**	
2	System Level Requirements & Ops Concept Review	9/4
3	System Level PDR	10/30
4	System Level CDR	7/12
5	System Level Contingency	3/14 4/1
6	Operational Readiness Review (All FSW + Phase A)	4/6
7	TGS Completion (All FSW + Phase A and B)	7/6
8		
9	**OBAD Data Collection Only**	
10	FSW Requirements	6/2 10/27
11	FSW Design	8/19 11/10
12	Coding, Test, and Uplink Procedures	12/3 4/6
13	FSW V2.5 Install & On-Orbit Test	4/19 4/23
14		
15	**MSS/Two Gyro (M2G) Mode**	
16	PCS Design*	6/2 4/16
17	FSW Requirements	7/31 3/11
18	FSW Design	11/12 4/6
19	**FHST/Two Gyro (T2G) Mode + OBAD**	
20	T2G PCS Design*	5/30 5/3
21	T2G FSW Requirements	10/31 2/12
22	T2G FSW Design	2/2 3/19
23	OBAD PCS Design	6/2 6/4
24	OBAD FSW Requirements	10/16 3/1
25	OBAD FSW Design	11/3 4/1
26	Coding, Test, and Uplink Procedures	4/2 10/29
27	FSW V2.6 Install & On-Orbit Test	11/16 12/7
28		
29	**FGS/Two Gyro (F2G) Mode**	
30	PCS Design*	5/27 10/15
31	FSW Requirements	6/2 9/3
32	FSW Design	7/6 9/20
33	Coding, Test, and Uplink Procedures	10/1 2/9
34	FSW V2.7 Install & On-Orbit Test	2/20 2/23
35		
36	**Planning and Scheduling (STSCI)**	
37	Concept/Requirements Definition	7/1 10/24
38	Operations Concept Review	10/14
39	Phase A Design & Implementation	9/2 0/26
40	Design Review	2/12
41	Cycle 14 Planning	4/21 6/13
42	TAC Review Mtg.	3/14 3/18
43	Phase B Design & Implementation	4/30 5/27
44	Delta Design Review	12/16
45	Ops Support and Gnd Testing	1/4 7/1

Current vs. TGS Operations

- **Operations Today**
  - Uses 3 gyros to provide rate control at all times
    - Attitude errors rarely exceed ~200 arcseconds after very large vehicle slews
      - Errors are typically 10-20 arcsec
  - Onboard attitude updates using Fixed Head Star Tracker (FHST) data bring pointing errors within the Fine Guidance Sensor (FGS) search radius (usually ~50 arcsec)
  - FGS data are used with gyro data to hold S/C position during science gathering
  - Guide star re-acquisitions for multiple-orbit pointings are simple and quick
- **Two-Gyro Operations**
  - Must use another sensor (e.g. MSS, FHST, FGS) to replace missing gyro rate data about one axis
    - Results in 3 distinct modes based upon the sensor being used
    - MSS and FHST are significantly noisier and have less resolution than the gyros
    - Every non-CVZ orbit requires use of all TGS sub-modes and a full guide star acquisition

FSW Overview

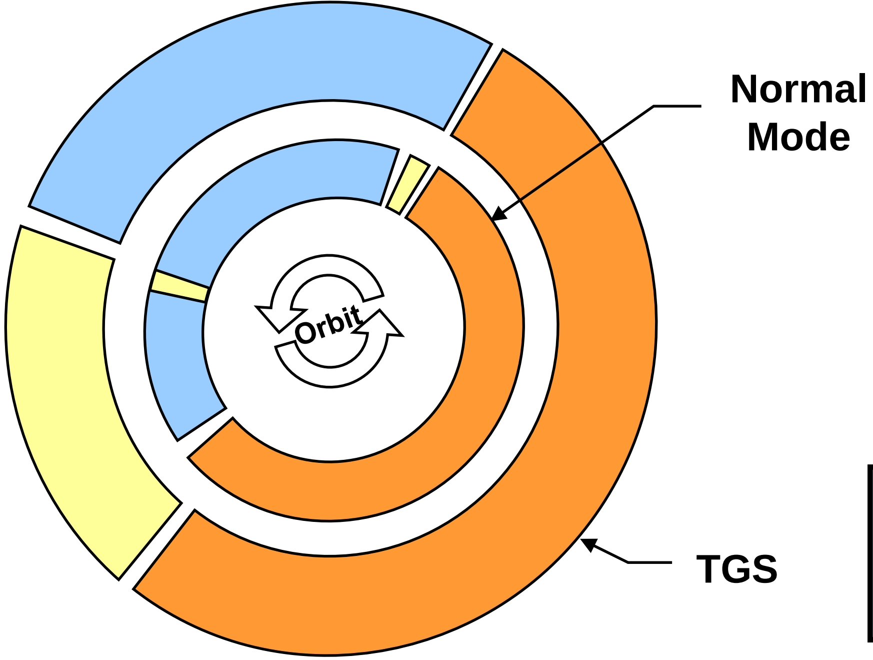
- **TGS retains HST’s basic PCS system PID (Proportional, Integral, Derivative) controller design; but augmented to “replace” the missing gyro**
- **Adds On-Board Attitude Determination (OBAD) to calculate attitude error using FHST map data and software algorithm**
  - Autonomously determines attitude errors up to 10 degrees
  - Generates updated command quaternion for correcting attitude error

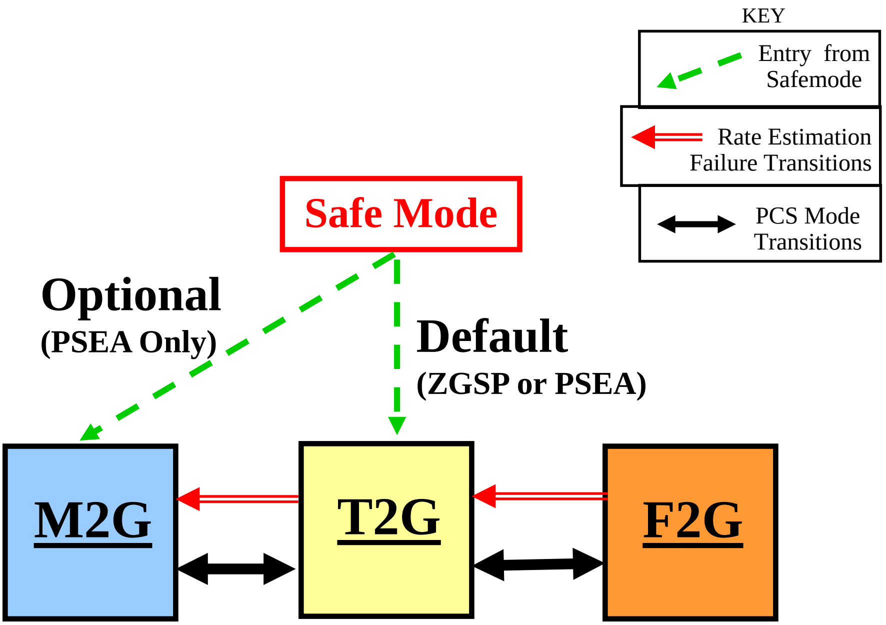
Three TGS Sub-Modes

- **M2G: MSS + 2 Gyros**
  - Compares MSS output to on-board Magnetic Field Model to control attitude and rates with maximum errors less than 6-8 degrees
  - All large vehicle maneuvers conducted in M2G
- **T2G: FHST + 2 Gyros**
  - Requires one tracker to be visible (un-occulted) to use FHST data and gyros to control rates
  - On Board Attitude Determination (OBAD) using FHST map data from 2 FHST units will bring attitude error within FGS search radius
- **F2G: FGS + 2 Gyros.**
  - Use of Coarse Track control to provide further rate damping and jitter reduction in order to achieve successful Fine Lock Walk-down
  - Requires FGS visibility to use FGS data and gyros to control rates and attitude to allow for science

Each Orbit will typically require a transition from M2G (degrees of error) to T2G (arcsec of error) to F2G (milliarcsec of error)

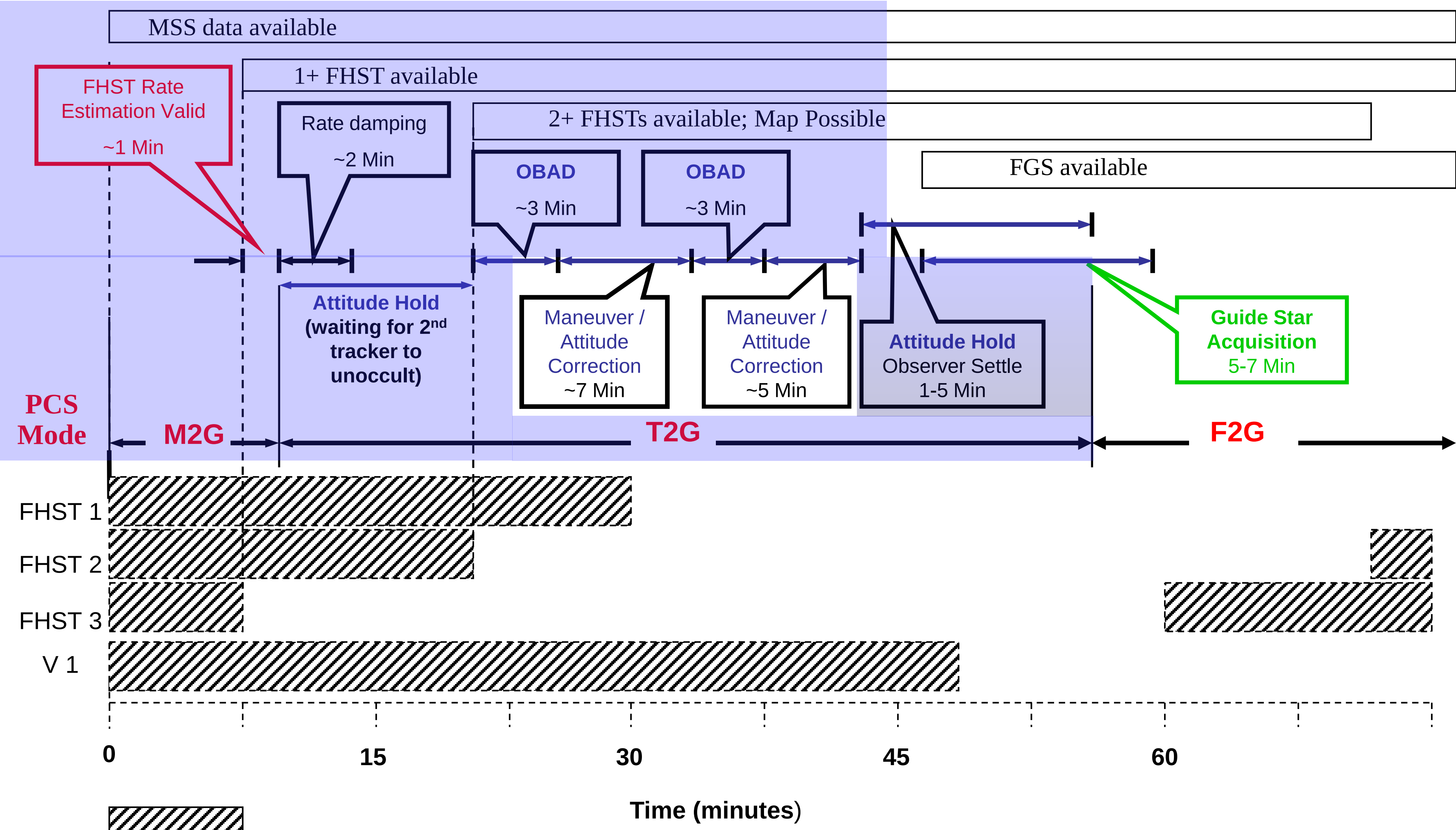
Two Gyro Science Modes Overview





	Normal Mode	Two-Gyro Science Mode (TGS)
🟦	Slew, and/or maintain Inertial Hold on 3 Gyros	M2G Mode: Slew, and/or maintain Inertial Hold on 2 gyros and MSS. Rate Estimation based on 2 gyros + MSS & on-board Mag Field Model
🟨	Attitude Update using FHSTs (usu. 2 pre-slew; usu. 1 post-slew)	T2G Mode: 2 On-Board Attitude Determinations requiring continuous FHST coverage with period of dual, simultaneous coverage. Rate Estimation based on 2 gyros + FHST
🟧	Guide star acquisition followed by science targeting	F2G Mode: Guide star acquisition (requires FHST coverage) followed by science targeting. Rate Estimation based on 2 gyros + FGS data (in FL or CT)

TGS Mode – Typical Timeline



MSS data available

1+ FHST available

2+ FHSTs available; Map Possible

FGS available

FHST Rate Estimation Valid ~1 Min

Rate damping ~2 Min

OBAD ~3 Min

OBAD ~3 Min

Attitude Hold (waiting for 2nd tracker to unoccult)

Maneuver / Attitude Correction ~7 Min

Maneuver / Attitude Correction ~5 Min

Attitude Hold Observer Settle 1-5 Min

Guide Star Acquisition 5-7 Min

PCS Mode

M2G

T2G

F2G

FHST 1

FHST 2

FHST 3

V 1

0

15

30

45

60

Time (minutes)

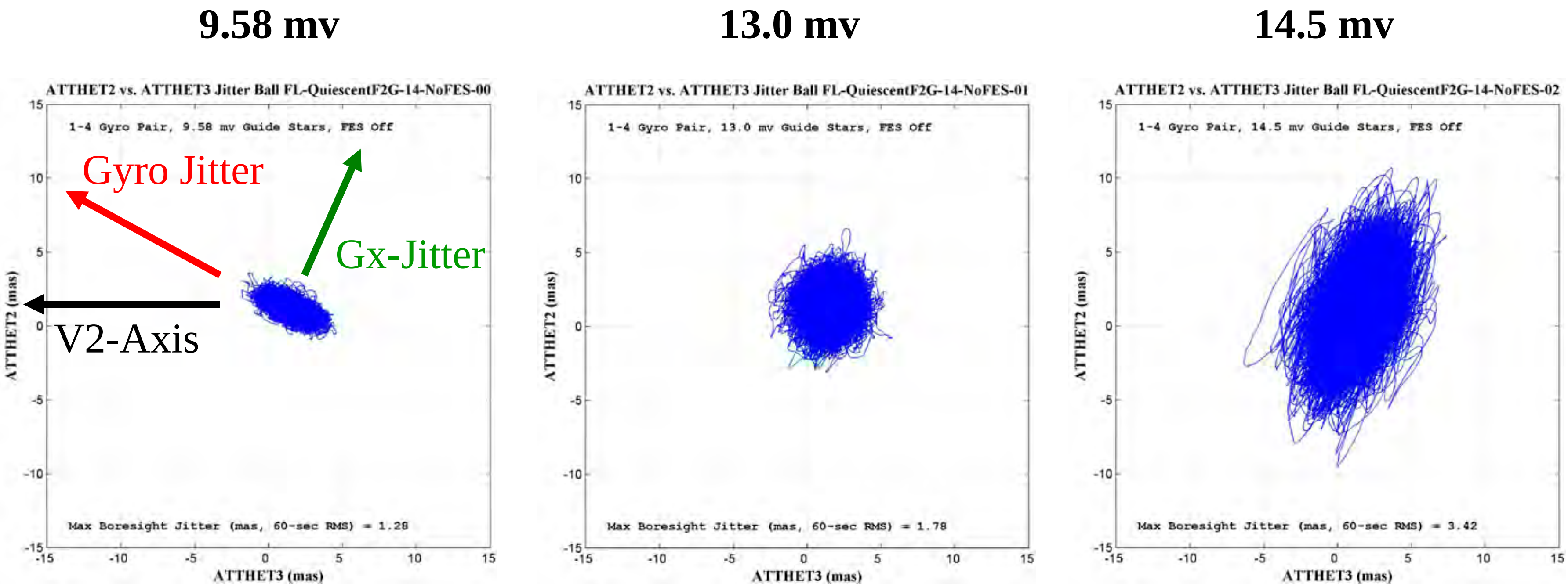
▨ FOV Occulted

Completed TGS Mode Capabilities

HST orbital period approximately 96 minutes

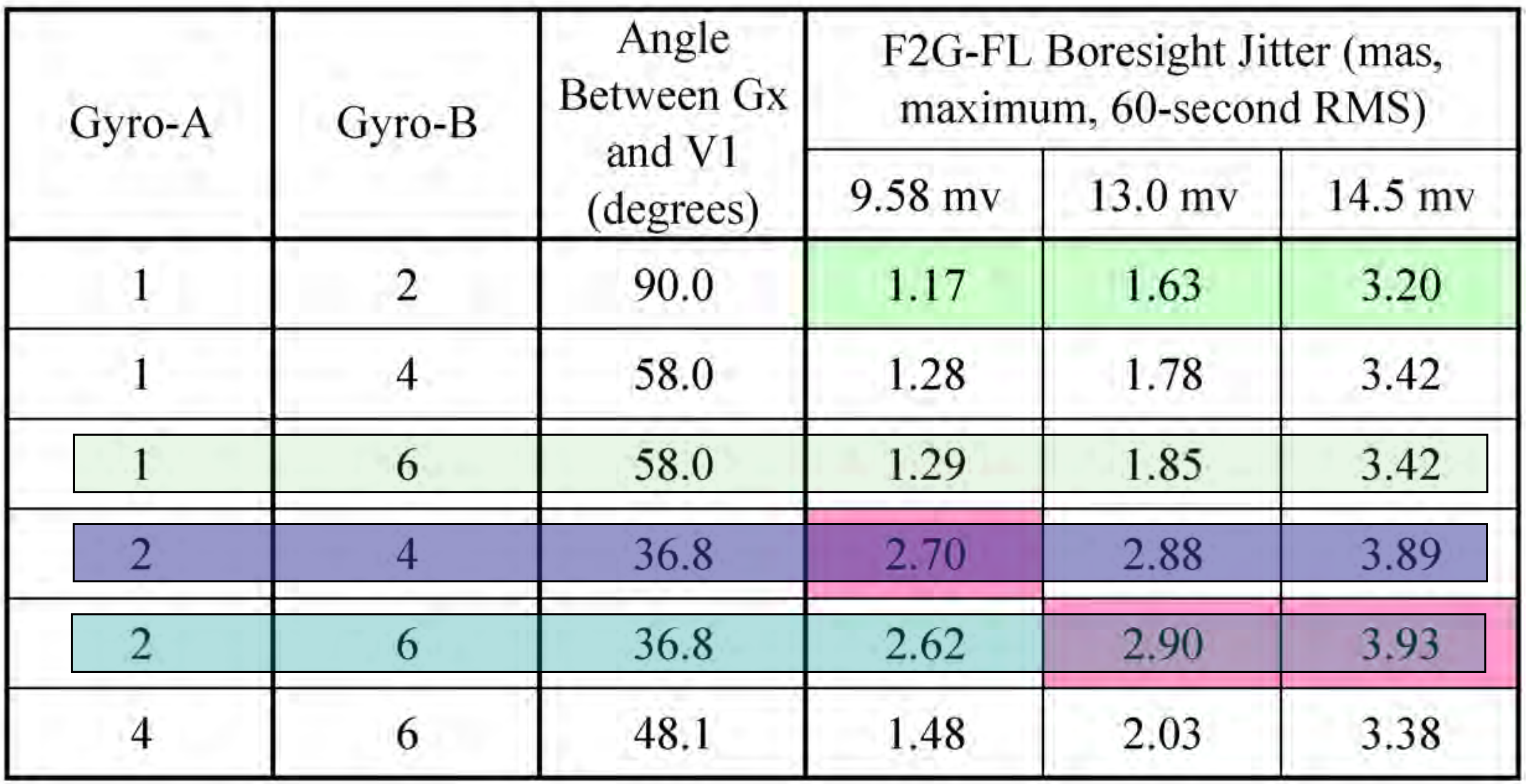
F2G-FL Quiescent Jitter Prediction G1,4

Jitter will manifest itself as an ellipse with magnitude, eccentricity, and orientation dependent upon gyro combination and guide star brightness



- **Elliptical "Jitter Balls" in F2G-FL**
  - Bright guide stars: jitter ellipse semi-major axis is due to gyro noise
  - Faint guide stars: jitter ellipse semi-major axis is usually in Gx-axis direction (FGS noise)
- **Jitter performance with 3 gyros is typically 5-6 milliarcsec, rms**

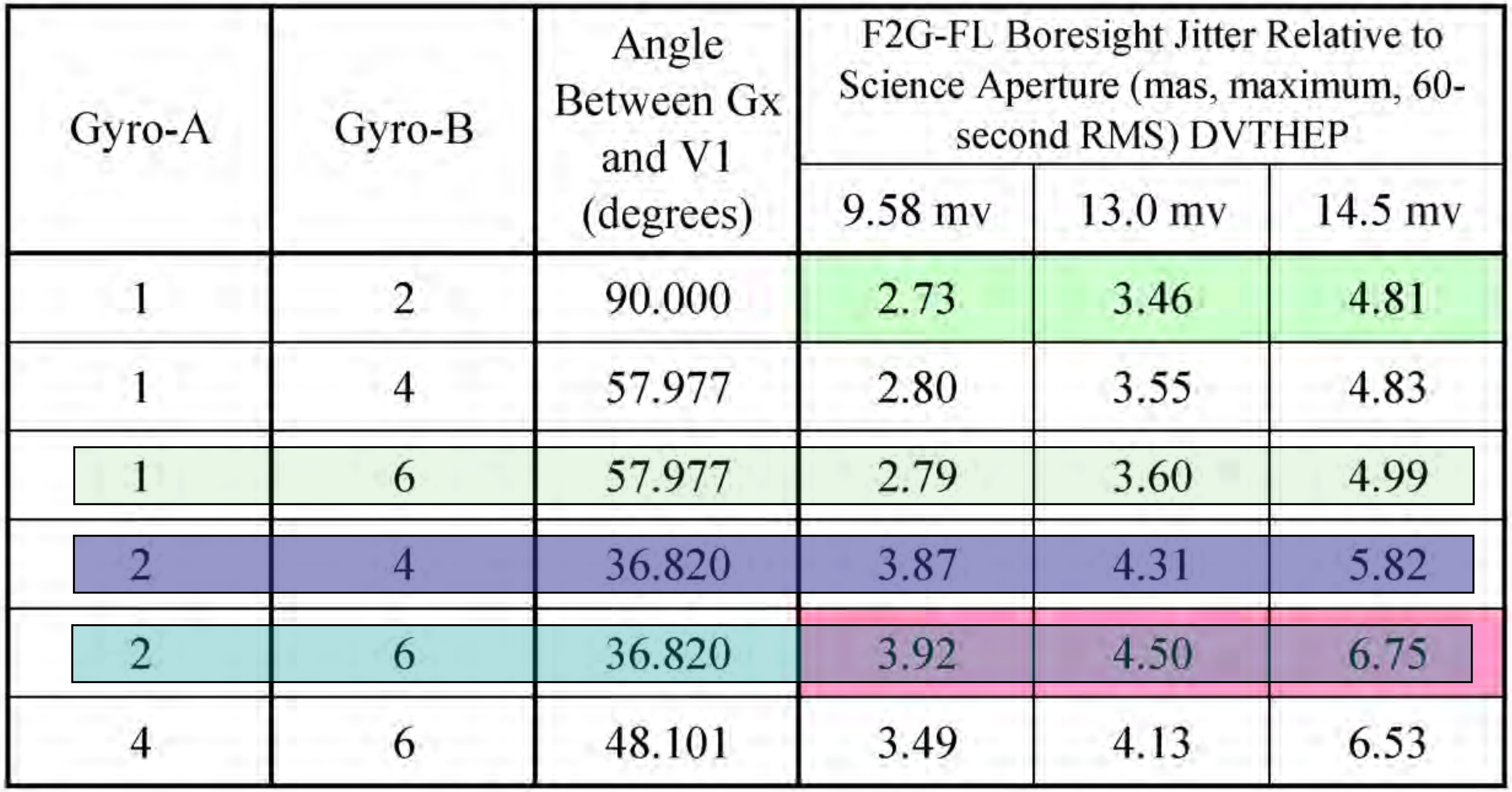
F2G-FL Quiescent Jitter Prediction



Gyro-A	Gyro-B	Angle Between Gx and V1 (degrees)	F2G-FL Boresight Jitter (mas, maximum, 60-second RMS)		
			9.58 mv	13.0 mv	14.5 mv
1	2	90.0	1.17	1.63	3.20
1	4	58.0	1.28	1.78	3.42
1	6	58.0	1.29	1.85	3.42
2	4	36.8	2.70	2.88	3.89
2	6	36.8	2.62	2.90	3.93
4	6	48.1	1.48	2.03	3.38

- **HST F2G-FL worst-case boresight jitter is 3.93 mas (60-second RMS)**
  - Unfavorable gyro pair
  - Faint guide stars
  - Maximum 60-second RMS jitter observed during 3000 second simulation (1/2 orbit)

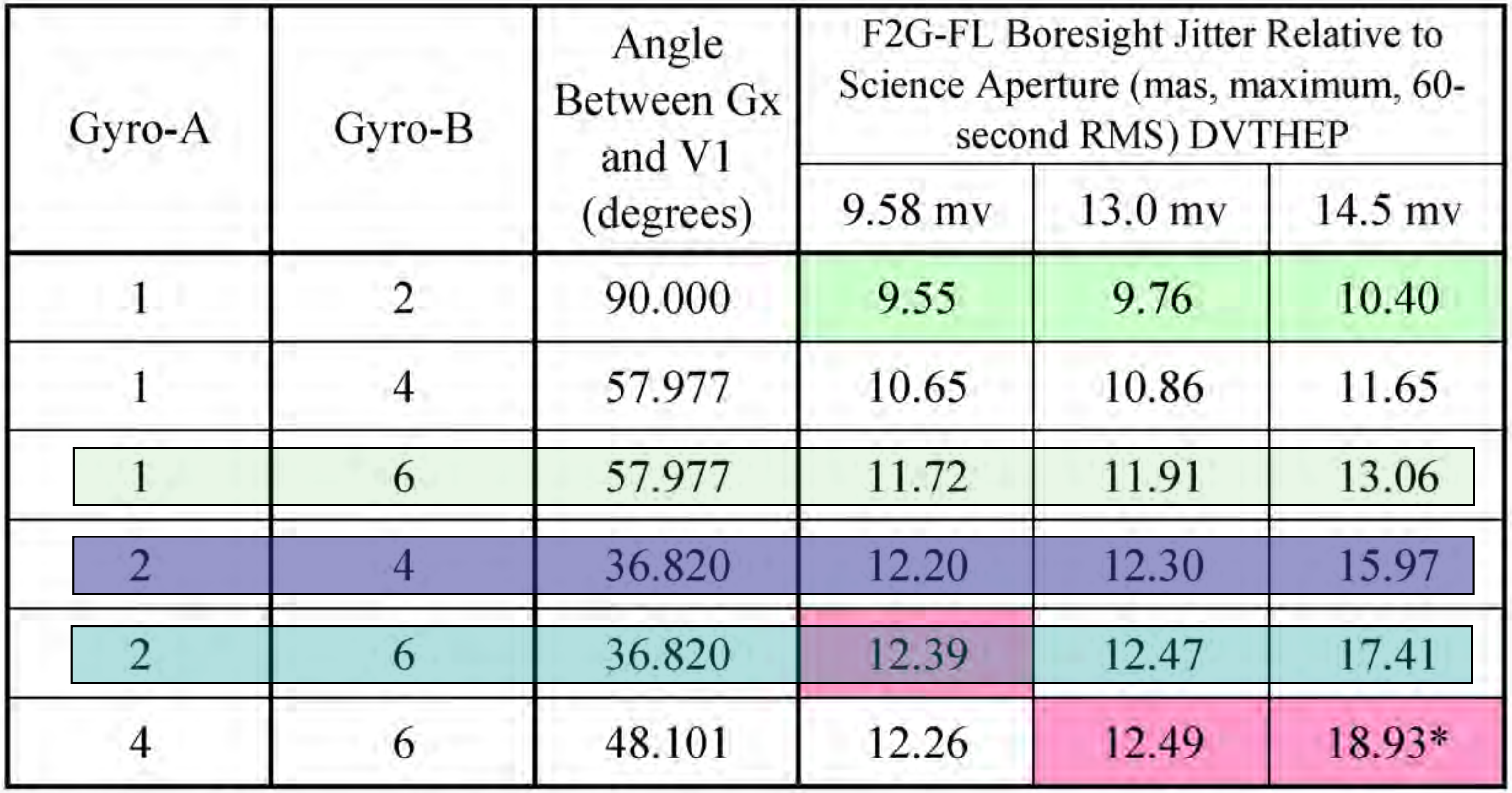
F2G-FL Jitter with HGA Ephemeris Track Disturbances Only



Gyro-A	Gyro-B	Angle Between Gx and V1 (degrees)	F2G-FL Boresight Jitter Relative to Science Aperture (mas, maximum, 60-second RMS) DVTHEP		
			9.58 mv	13.0 mv	14.5 mv
1	2	90.000	2.73	3.46	4.81
1	4	57.977	2.80	3.55	4.83
1	6	57.977	2.79	3.60	4.99
2	4	36.820	3.87	4.31	5.82
2	6	36.820	3.92	4.50	6.75
4	6	48.101	3.49	4.13	6.53

- **HGA Ephemeris Track disturbances are nearly always present and thus elevate HST jitter above quiescent gyro/FGS noise levels**

F2G-FL Jitter with Integrated Disturbances



Gyro-A	Gyro-B	Angle Between Gx and V1 (degrees)	F2G-FL Boresight Jitter Relative to Science Aperture (mas, maximum, 60-second RMS) DVTHEP		
			9.58 mv	13.0 mv	14.5 mv
1	2	90.000	9.55	9.76	10.40
1	4	57.977	10.65	10.86	11.65
1	6	57.977	11.72	11.91	13.06
2	4	36.820	12.20	12.30	15.97
2	6	36.820	12.39	12.47	17.41
4	6	48.101	12.26	12.49	18.93*

* LOL at 1200 seconds due to SA3 disturbance concurrent with HGA Spline

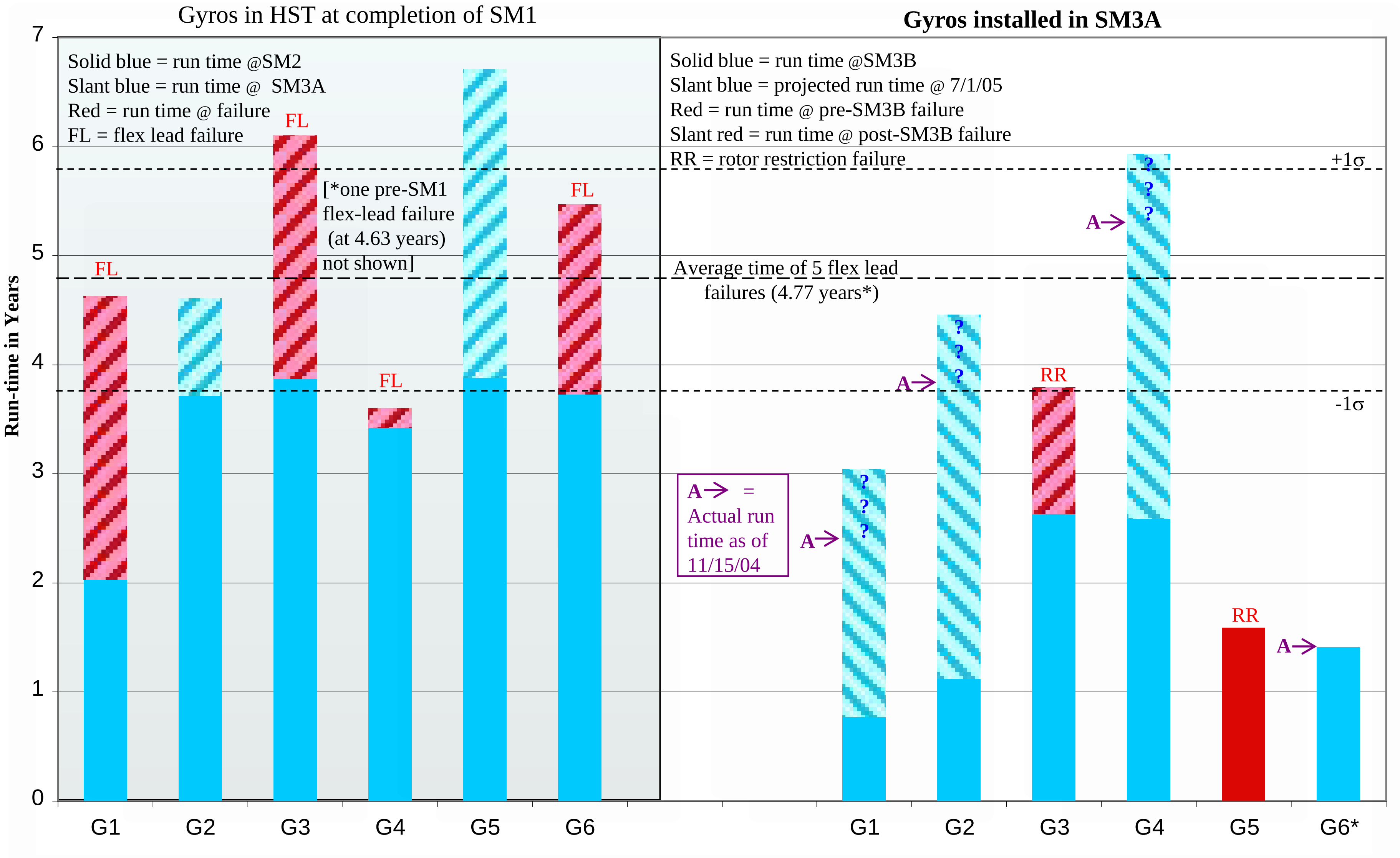
- **Integrated disturbance simulations include HGA Ephemeris Track (always active), HGA Spline, V2-Disturbances, and SA3 disturbances. Concurrent disturbances represent worst-worst situations rarely expected on-orbit.**

TGS Summary and Open Issues

- **TGS Mode is expected to yield very good jitter performance**
- **Scheduling efficiency, though reduced, should remain high**
- **Overall assessment of the mode’s productivity requires more knowledge of some issues that will only become understood with experience**
  - Guide star Loss-of-Lock (LOL) frequency
    - TGS has no LOL-recovery capability; observing time is lost
      - High fidelity simulations predict 1.1 LOLs/day
  - G6 bias instability, if problematic, may affect productivity
  - Degradation of subsystem performance, e.g., the FGS-2R CT-FL transition anomaly, may be harder to work around
  - The FGSs will accumulate Coarse-Track time and cycles faster

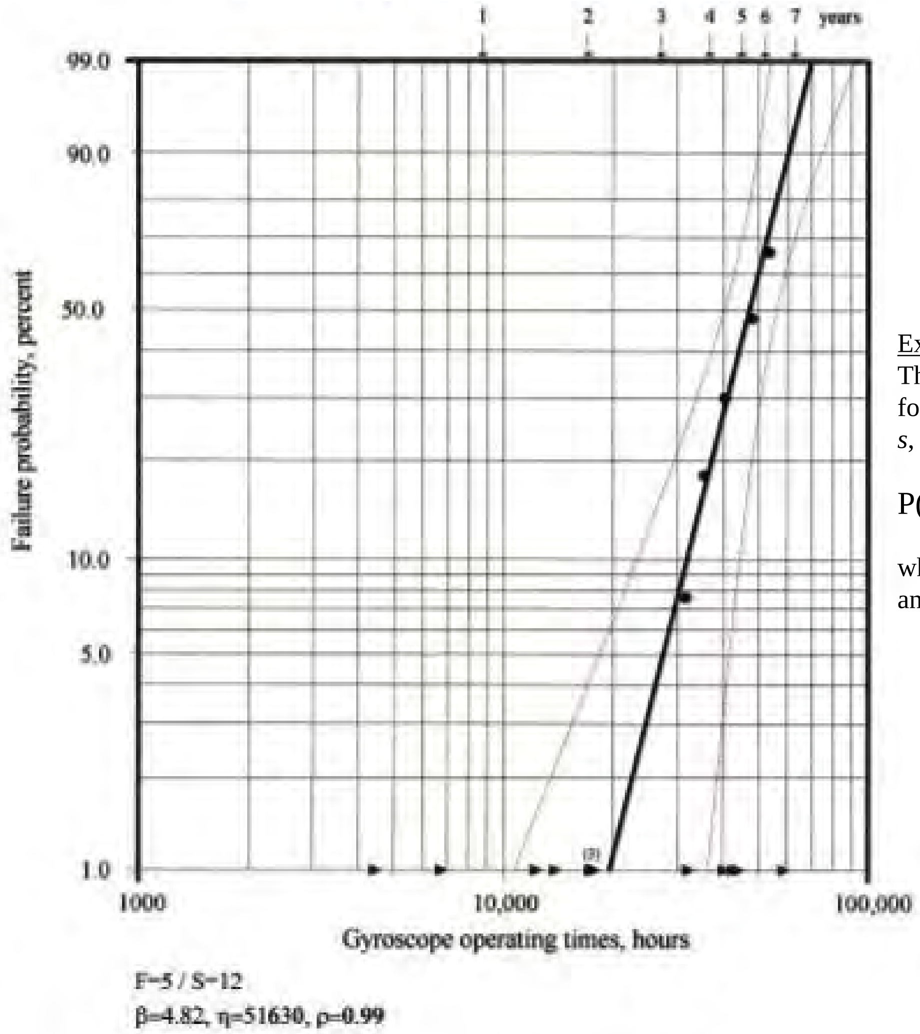
Why consider pro-active initiation of TGS Mode usage in mid-2005?

Run Times of HST Gyros at 7/1/05 without Additional Failures



HST Gyro Status

Determination of HST Reliability Model Parameters for Gyro Flex-Lead Wear-out



Weibull plot of HST gyroscope on-orbit performance.
"Flex" failures are solid circles; dashed lines are 95% confidence limits.
Censored data are triangles on "1.0" line.

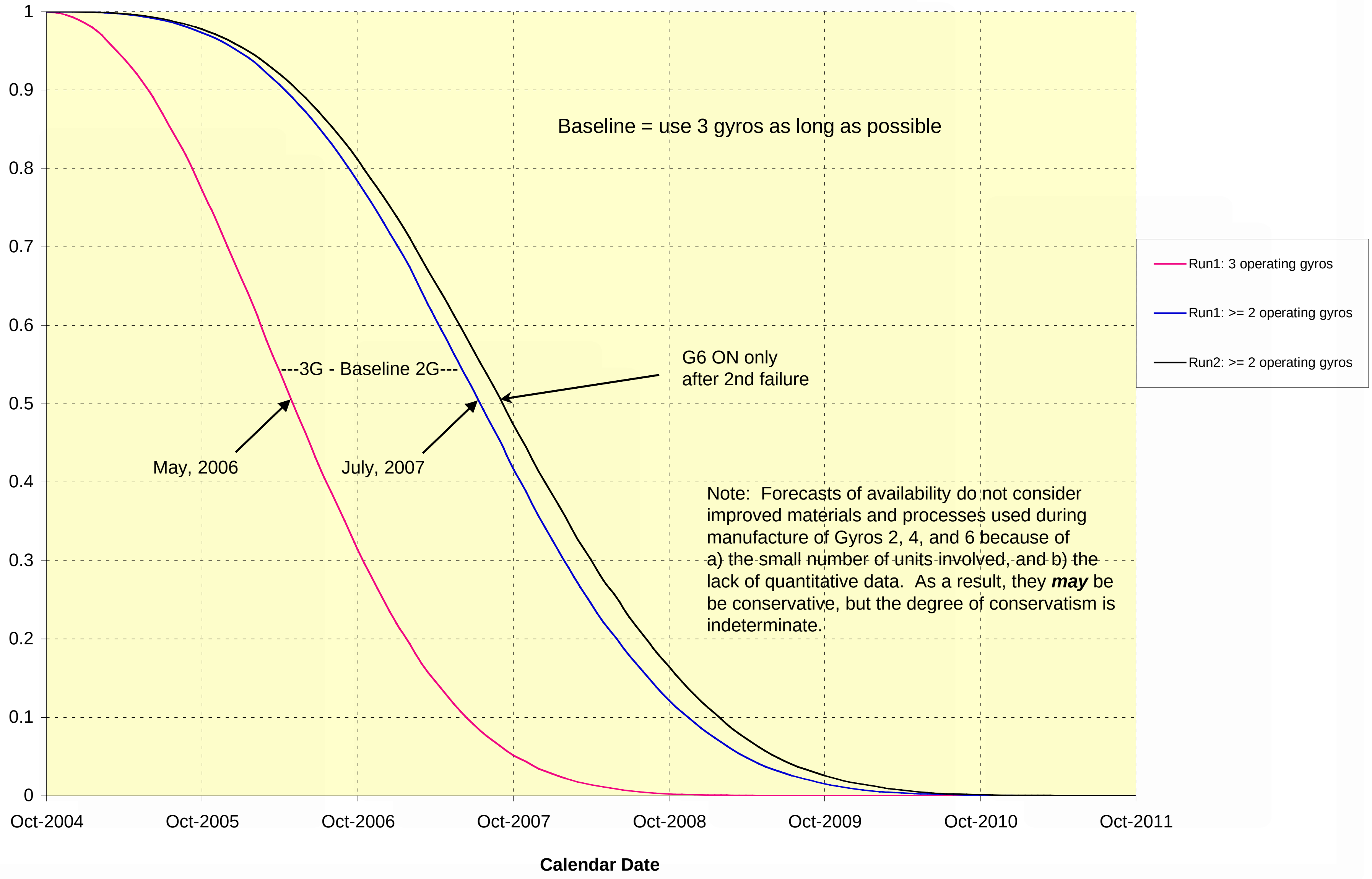
<u>Expression for the Reliability of an Individual Gyro</u>
The probability, P(t) that an individual gyro survives for an additional run-time *t* beyond the run-time "age", *s*, it already has at *t*=0 (both *t* and *s* are in years) is:

$$P(t) = P_{Weibull}\ \ P_{random} = e^{-[(t+s)/\eta]\beta}\ \ e^{-\lambda t}$$

where η = 5.894 years (51,630 hours), β = 4.82 and λ = 1/14 years^{-1}

HST Gyro System Availability from 10/1/04

(availability of 2 or more gyros vs. date)



Baseline = use 3 gyros as long as possible

G6 ON only
after 2nd failure

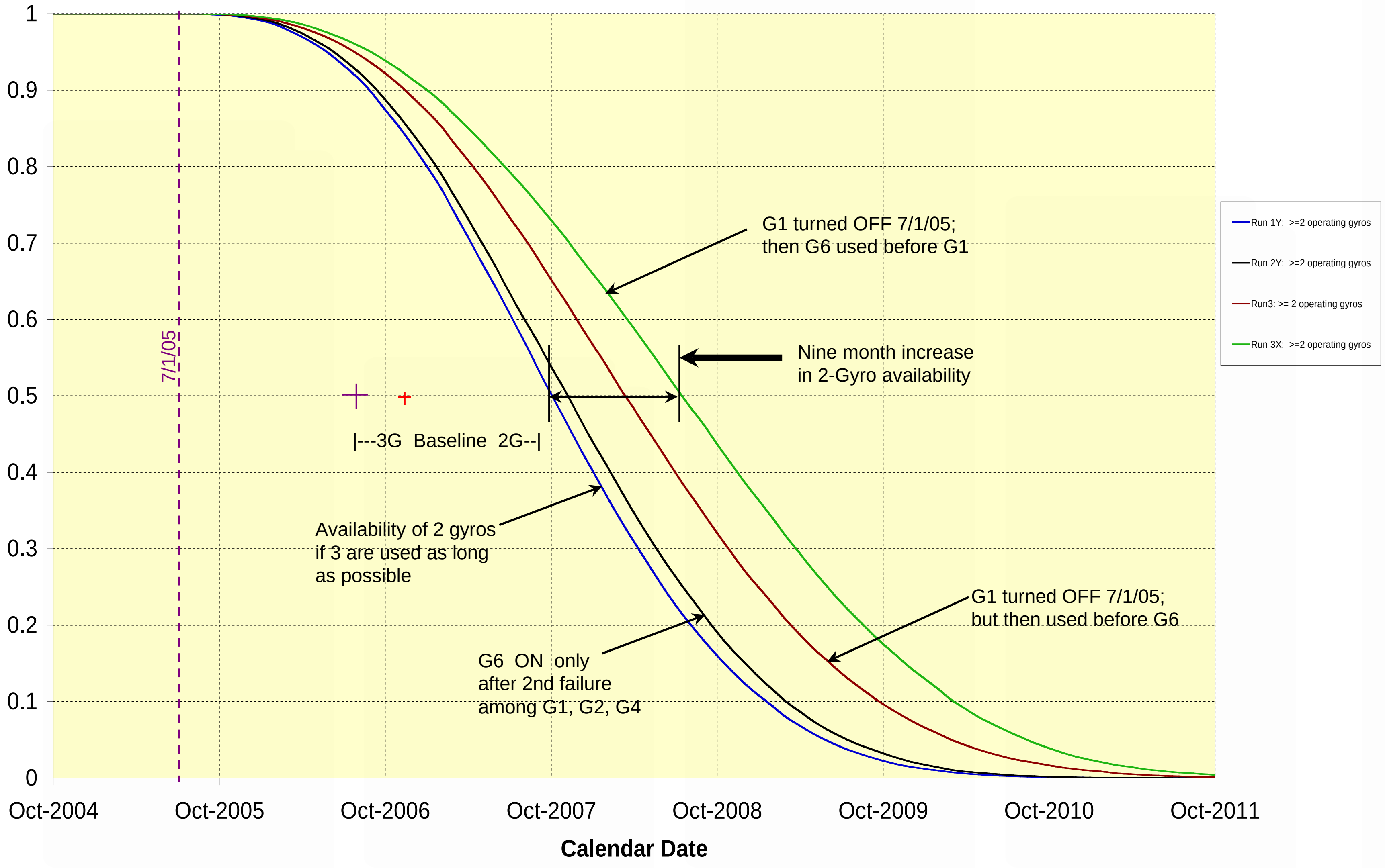
Note: Forecasts of availability do not consider improved materials and processes used during manufacture of Gyros 2, 4, and 6 because of a) the small number of units involved, and b) the lack of quantitative data. As a result, they ***may*** be conservative, but the degree of conservatism is indeterminate.

Alternative Cases and Assumptions

- Run 1Y
  - **Gyro status as of 7/1/05, assuming no failures between now and 6/30/05**
    - In use (Turned-On)
      - Gyro 1 has 3.041 years of total run time
      - Gyro 2 has 4.461 years of total run time
      - Gyro 4 has 5.930 years of total run time
    - In reserve (Turned-Off)
      - Gyro 6 has 1.41 years of total run time
    - Failed
      - Gyro 3 and 5 failed
  - **After 7/1/05, turn-on Gyro 6 when either Gyro 1, 2, or 4 fails**
- Run 2Y
  - **Gyro status: same as Run 1Y**
  - **Begin TGS Mode when Gyro 1, 2, or 4 fails; turn-on Gyro 6 only after a second gyro fails**
- Run 3
  - **On 7/1/05, turn off Gyro 1 and begin 2-gyro mode; turn Gyro 1 back on when a failure occurs; then turn on Gyro 6 after the next failure**
- Run 3X
  - **Same as Run 3, except turn on Gyro 6 when first failure occurs (before using Gyro 1 again)**

HST Gyro System Availability assuming no gyro failures through 6/30/05

(availability of 2 gyros vs. time)



G1 turned OFF 7/1/05;
then G6 used before G1

Nine month increase
in 2-Gyro availability

|---3G Baseline 2G--|

Availability of 2 gyros
if 3 are used as long
as possible

G1 turned OFF 7/1/05;
but then used before G6

G6 ON only
after 2nd failure
among G1, G2, G4

Risks of a Pro-active Gyro Turn-Off

- **Unless absolutely necessary it is unusual to deliberately power-cycle a critical component of an orbiting spacecraft**
  - There is no absolute certainty that G1 will come on again when needed and live an undiminished life
- **Gyro start-up is a relatively stressful event**
  - It uses a higher voltage for 27 seconds and, at start-up, it supplies 0.6 A of motor current through the gyro flex leads (vs. the normal running gyro motor current of ~0.12 A)
- **Electronic part failures might preclude start-up**
- **Debris in the gyro rotor journal bearing might restrict rotor motion**

Risk-Relevant Experience

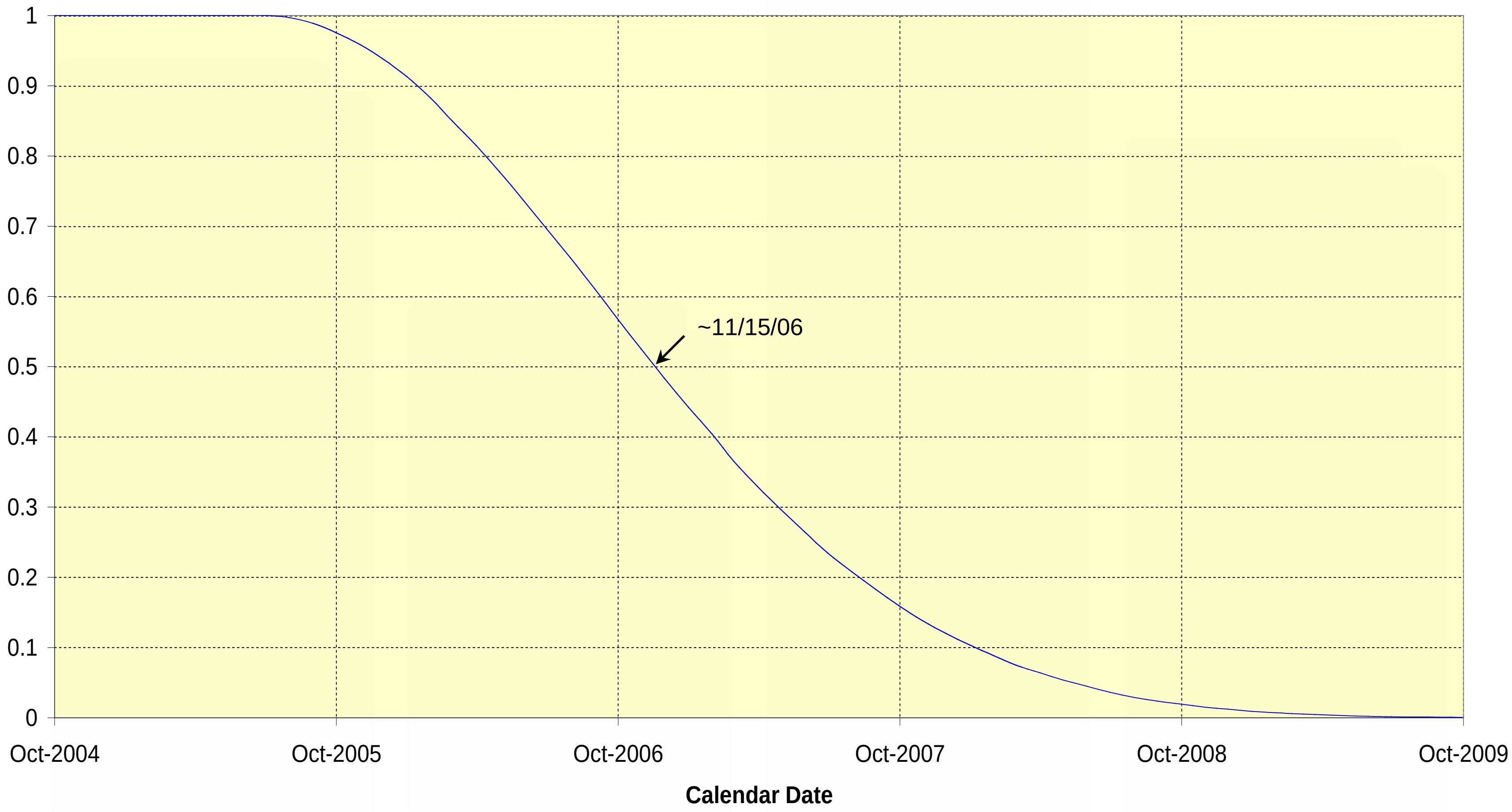
- **Since launch, HSTP has turned off and then successfully restarted orbiting gyros 18 times**
  - No gyro that was healthy when powered off has failed to restart
  - The run-time of Gyro 1 next summer (~27,000 hours) will be well-bracketed by the operating hours of gyros restarted on-orbit
    - The original G1 and G2 (both old build-process gyros) were restarted after they had much more run time on them than the present G1 will have accumulated (~31,000 and ~47,000 hours, respectively)
- **We have found that the presence of motor current in gyro flex leads is a major catalyst of flex-lead corrosion**
  - The corrosion of G1’s flex leads may not worsen greatly while it is un-powered
- **With one non-serious exception, no HST gyro lacking pre-turnoff evidence of a rotor-restrictive event has ever exhibited evidence of rotor restriction after it was restarted on-orbit**
  - All four of HST’s remaining gyros have run “cleanly” since turn-on
  - Each has been power-cycled at least once
  - None of them have exhibited any indication of debris within the gyro bearing

Conclusion

- **HSTP does not yet have a formal position in favor of, or against a planned Gyro 1 turnoff**
  - It has a technical memorandum from the gyro vendor, L3
    - The memo concludes that the non-restart risk is both compatible and in-line with the objective of preserving HST's fine-pointing capability as long as possible
  - It has requested an independent assessment of the risks from Goddard's Applied Engineering and Technology Directorate
- **If HSTP decides to recommend G1 turnoff, it must obtain the concurrence of the GSFC Director and NASA HQ**
  - Such a decision, and acceptance of the associated risk, does not appear inconsistent, a priori, with the Program's mandate to preserve HST's science operation as long as possible
    - It will be carefully considered
  - At this time, the HRSDM is neither fully-funded nor guaranteed to be successful
- **The STUC's thoughts about this decision will be welcomed**

Back-Up Charts

HST Gyro Availability for TGS with G1 un-recovered after 7/1/05



Gyro On-Orbit Restart and Performance Histories

	Original Deploy (April 1990)						SM1 Replacement (December 1993)						SM3A Replacement (December 1999)						Event History	Comments	Approximate On-Orbit Operating Hours at Event for Indicated Gyro
Gyro	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6			
RSU S/N	1005		1002		1003		1005 (n/c)		1007		1006		1003		1002		1008				
Gyro S/N	108	113	110	138	104	127	108 (n/c)	113 (n/c)	112	158	118	151	155	110-R	104-R	138-R	156	159			
Deploy																			Deploy		
			1990/115	1990/115	1990/115	1990/115													G3-6 Powered On		0
						1990/337													G6 Rate Signals Saturate	G6 remains on, but failed	5328
		1990/339																	G2 Powered On		0
				1991/17[illegible]															G4 Rate Signals Saturate	G4 remains on, but failed	10080
				1991/197															G4 Powered Off	Cycling Related to Hybrid Electronics Failure	10749
				1991/198															G4 Powered On	Cycling Related to Hybrid Electronics Failure	10749
				1991/198															G4 Powered Off	Cycling Related to Hybrid Electronics Failure	10758
				1991/199															G4 Powered On	Cycling Related to Hybrid Electronics Failure	10758
				1991/199															G4 Powered Off	Cycling Related to Hybrid Electronics Failure	10592
					1991/207														G5 Motor Current 123-173 mA	Rotor Restriction	10968
	1991/210																		G1 Powered On		0
				1991/213															G4 Powered On	Cycling Related to Hybrid Electronics Failure	10758
					1991/235														G5 Motor Current 173-187 mA	Rotor Restriction	11640
					1992/103														G5 Motor Current 187-192 mA	Rotor Restriction	17232
						1992/281													G6 Powered Off		21526
				1992/310															G4 Powered Off	Flex Lead Failure	21850
	1992/323																		G1 Power from ECU Lost (G1 OFF)		11469
SM1		1993/33x																	SM1		
	1993/339	1993/339							1993/339	1993/339	1993/339	1993/339							G1-6 Power Cycled	G1,G2 not replaced in SM1	0
											1994/341								G5 Motor Current 98-155 mA	Rotor Restriction	43
	1993/351																		G1 Powered Off		12151
		1993/351																	G2 Powered Off		26577
	1996/047																		G1 Powered On		12151
		1996/047																	G2 Powered On		26577
		1996/054																	G2 Powered Off		45558
	1996/054																		G1 Powered Off		31132
										1997/018									G4 Motor Current 130-153 mA	Rotor Restriction	27331
SM2																			SM2		
										1997/099									G4 Failure	Flex Lead	29297
	1997/108																		G1 Powered On		31132
	1997/158																		G1 Motor Current 133-153 mA	Rotor Restriction	32332
												1998/209							G6 Motor Current 120-210 mA	Caused by 1st Flex Lead Failure	40675
												1998/296							G6 Failure	2nd Flex Lead Failure	42779
		1998/307																	G2 Powered On		45558
									1999/025										G3 Motor Current 123-212 mA	Caused by 1st Flex Lead Failure	45019
									1999/110										G3 Failure	2nd Flex Lead Failure	47080
	1999/281																		G1 Motor Current 145-162 mA	Rotor Restriction	52788
	1999/317																		G1 Failure	Flex Lead	53674
SM3A																			SM3A		
													1999/356	1999/356	1999/356	1999/356	1999/356	1999/356	G1-6 Power Cycled	RSU 1-3 Installation	0
													2000/018						G1 Powered Off		643
														2000/018					G2 Powered Off		643
																		2000/195	G6 Bias Shift	G6 to Shadow Mode	4876
																		2001/022	G6 Powered Off	G6 Power Cycle Test	9506
																		2001/024	G6 Powered On	G6 Power Cycle Test	9506
																		2001/061	G6 Powered Off		10392
																	2001/113		G5 Motor Current 128-180 mA	Rotor Restriction	11668
																	2001/114		G5 Motor Current 180-210 mA	Rotor Restriction	11692
																	2001/118		G5 Motor Current 210-330 mA	Rotor Restriction - Stall, no restart tried until 2001/128	11788
														2001/118					G2 Powered On		643
																	2001/128		G5 Powered On at 140 mA		11788
																	2001/129		G5 Motor Current 140-330 mA	Rotor Restriction - Stall, not restarted	11804
															2001/177				G3 Motor Current 126-154 mA	Rotor Restriction	13204
															2001/230				G3 Motor Current 154-190 mA	Rotor Restriction	14476
															2001/310				G3 Motor Current 190-203 mA	Rotor Restriction	16396
SM3B														2002/065	2002/065	2002/065			SM3B	PCU Changeout	
													2002/065	2002/065	2002/065	2002/065		2002/065	G1-6 Power Cycled	G3 Restarts at 134 mA in SM3B	
																	2002/065		G5 Failure	Stall, failed to restart in SM3B	11918
																		2002/070	G6 Powered Off		10631
													2002/087						G1 Powered Off		1287
															2002/106				G3 Motor Current 134-207 mA	Rotor Restriction	20244
													2002/107						G1 Powered On		1287
													2002/119						G1 Powered Off		1581
															2002/158				G3 Transient Current Peak 330 mA	Rotor Restriction	21508
															2002/242				G3 Transient Current Peak 319 mA	Rotor Restriction	23524
															2002/295				G3 Transient Current Peak 319 mA	Rotor Restriction	24796
															2002/332				G3 Motor Current 207-330 mA	Rotor Restriction - Stall, restarted in 2 hours at 215 mA	25707
															2003/044				G3 Motor Current 214-206 mA	Note current decrease	27531
															2003/103				G3 Motor Current 206-330 mA	Rotor Restriction - Stall, restarted in 2 hours at 196 mA	28971
															2003/119				G3 Motor Current 196-201 mA	Rotor Restriction	29345
															2003/119				G3 Transient Current Peak 257 mA	Rotor Restriction	29345
															2003/119				G3 Motor Current 201-352 mA	Rotor Restriction - Stall	29345
															2003/119				G3 Failure	Stall, failed to restart	29345
													2003/119						G1 Powered On		1581

Key

Red	*Gyro Failure Event*		
Green	*Change in Power State*	ON	OFF

🟧 Initial Rotor Restriction event in this gyro appeared after initial on-orbit ON
🟦 Initial Rotor Restriction event in this gyro appeared after one or more on-orbit power cycles