Session 10: Control of Aircraft, Missiles,
Launch Vehicles, and Spacecraft

HST Inertia Tensor Optimization for Two-Gyro Science

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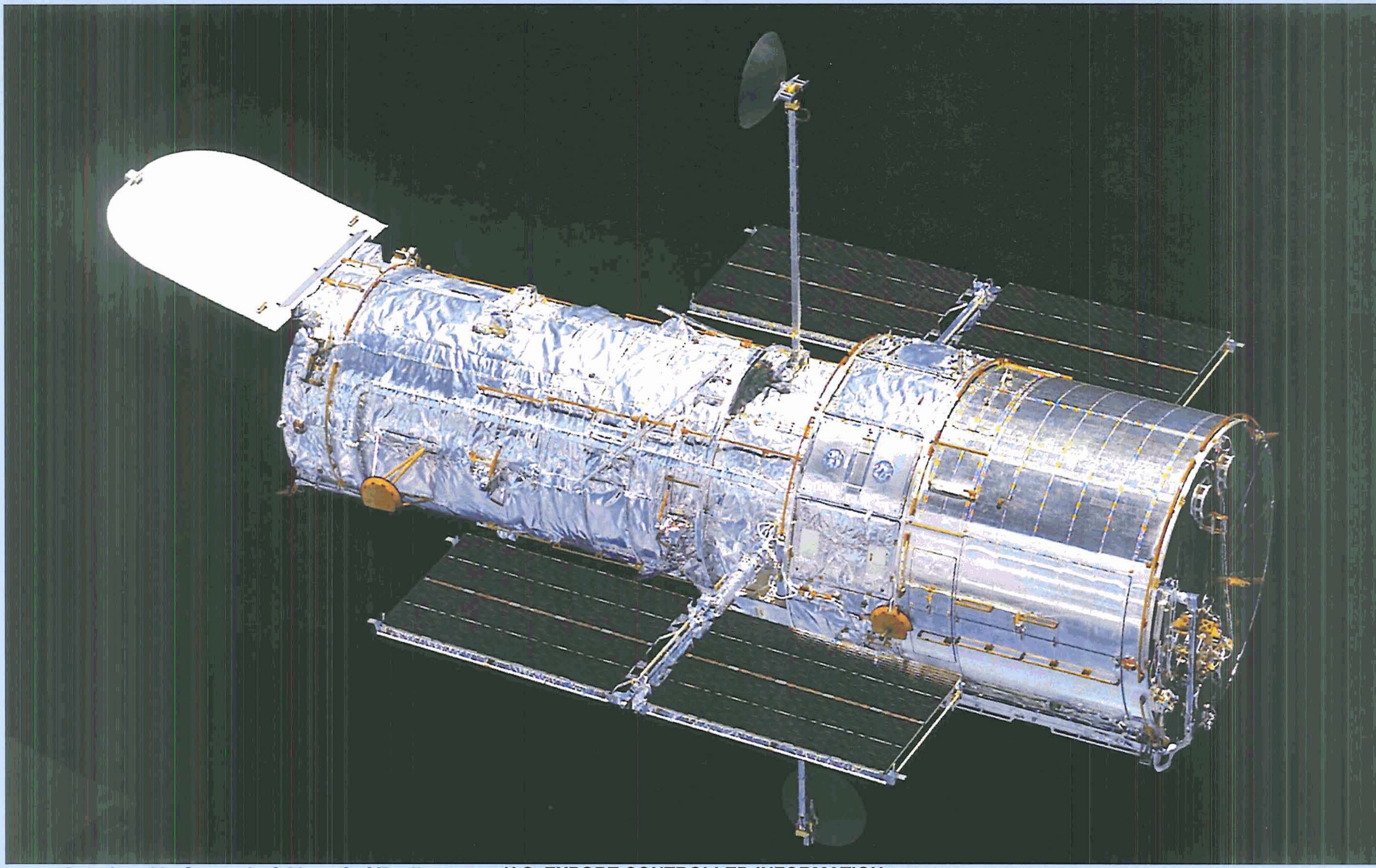
HST Overview

- Size: 13.2 m long, 4.2 m dia, 11819 kg
- Orbit: nearly circular, 570 km altitude, 28.5° inclination
- Predominant external disturbances: gravity gradient and aerodynamic torques

- Launch Date: April 24, 1990 (STS-31)
- On-Orbit Servicing Performed
  - SM1 STS-61 Dec-1993 (gyros, SA-1, WF-PC2, COSTAR)
  - SM2 STS-82 Feb-1997 (FGS-1R, RWA, SA-2, STIS, NICMOS)
  - SM3A STS-103 Dec-1999 (gyros, FGS-2R, 486FC, SSR, VIK)
  - SM3B STS-109 Mar-2002 (RWA, SA-3, ACS, PCU, NCC)

- SM4 STS-125, planned for September 2008 (gyros, FGS-3R, batteries, WFC-3, COS, repair of STIS & ACS, SCM)

HST at SM3B Deploy



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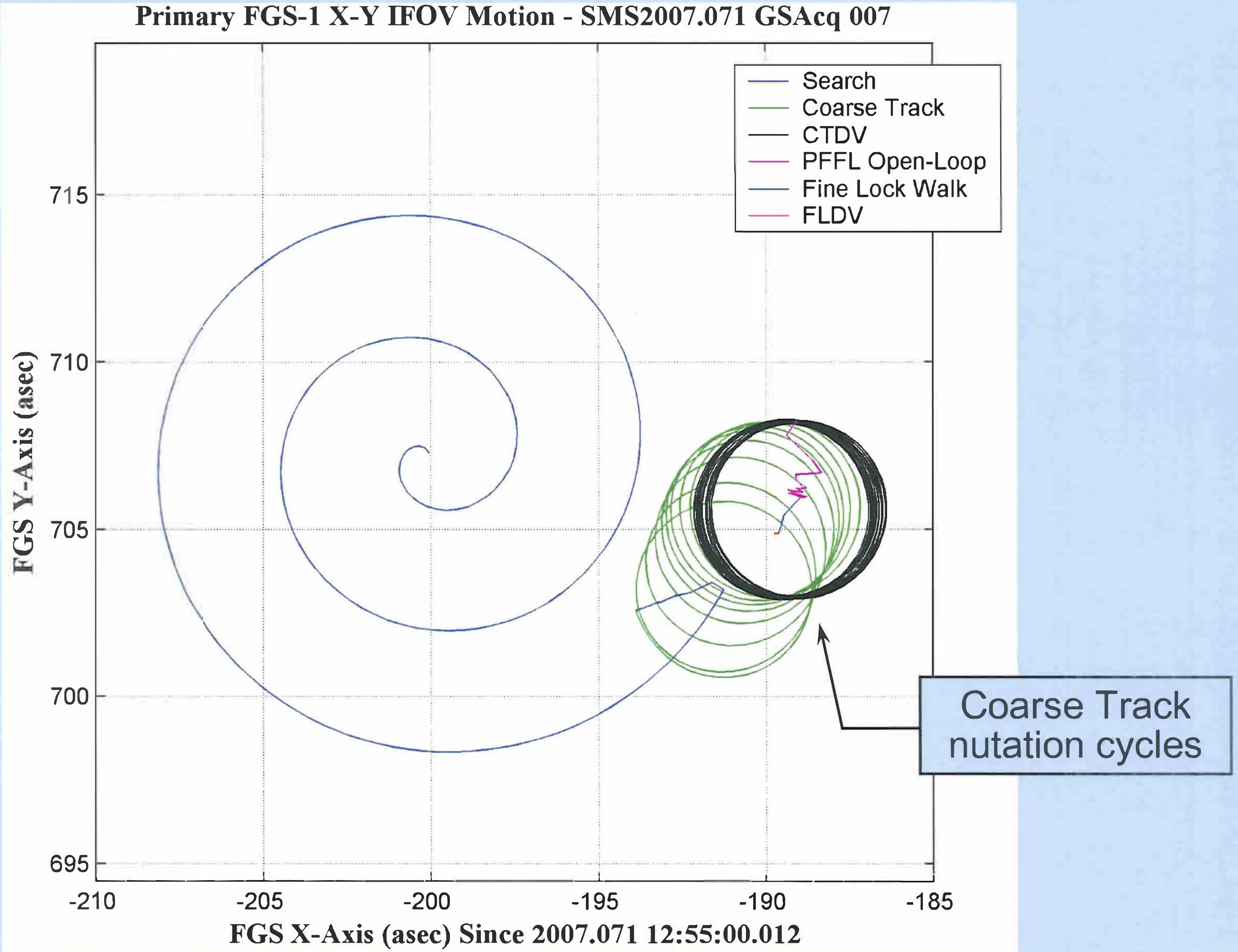
Pointing Control Hardware Peculiarities

- Rate Gyros (mechanical float)
  - Fail due to Flex Lead degradation and Rotor Restrictions
  - Replaced all 6 gyros during SM3A (Dec 1999)
  - Gyro-5 failed April 2001, and Gyro-3 failed April 2003
- Fine Guidance Sensor (FGS) Star Selector Servo (SSS) Bearings
  - SSSs rotate optical elements to position the IFOV anywhere within the FGS FOV
  - 6.5 inch ID 88-ball duplex pair bearings per SSS, 2-SSS per FGS
  - Failure due to brushless DC motor stall caused by lubricant degradation and contamination during bearing manufacture
  - Bearing degradation exacerbated by Coarse Track operation (±0.4° shaft dithering) where IFOV nutates around guide star

FGS Guide Star Acquisition



Two-Gyro Science (TGS) Control System

- Pointing Control System (PCS) Group directed to design TGS control system in June 2003
  - Columbia disintegrated in February, second gyro failed in April, and HST SM4 appeared unlikely (O'Keefe)
  - Expectation of "degraded" science performance (30 mas rms)
  - PCS delivered TGS to FSW in 16-months (2-months early)
- TGS on-orbit test in February 2005 demonstrated:
  - LOS jitter (4 mas rms), at or better than 3-gyro performance
  - Within HST LOS jitter requirement of 7 mas (60-second rms)
- TGS Concept
  - Replace missing gyro-rate measurement using other sensors of successively greater accuracy
  - Magnetometers (M2G) → Star Trackers (T2G) → Fine Guidance Sensors (F2G)
- TGS became the nominal control system for HST in August 2005, and TGS has been in use for over 2-years.

TGS Modes and Capabilities

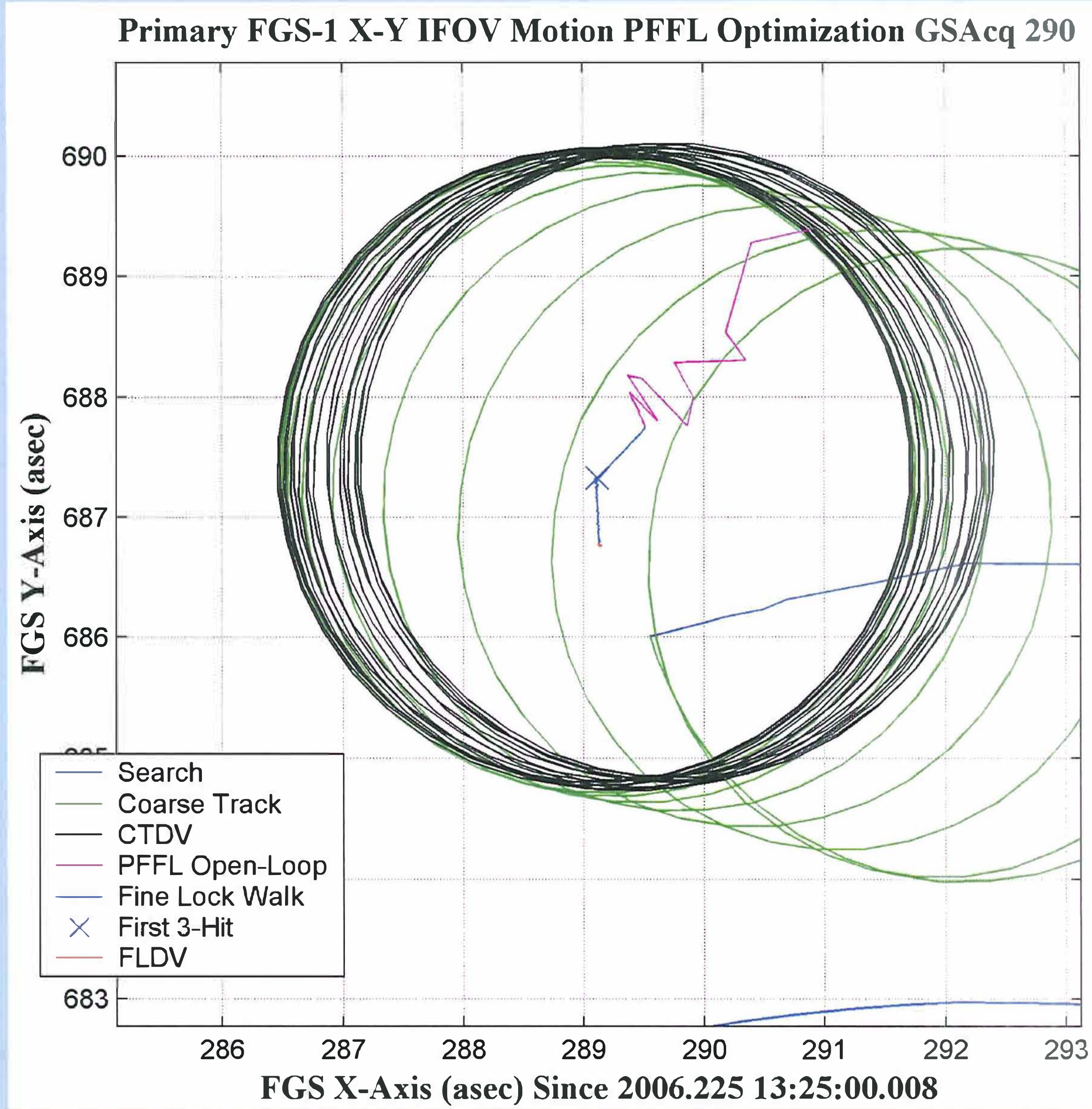
Mode	Function	Maneuver Size	Gyro-Less Axis Sensor	Actuator	Jitter (60-sec rms)	Attitude Error (max)	Rate Error (max)	Bandwidth (Hz)	Duration
M2G	Attitude Hold	> 10 deg	magnetometer	RWA	-	2 - 10 deg	100 asec/sec	0.001 Hz	remainder of orbit
T2G	Attitude Hold, damp M2G rates	< 10 deg	star tracker	RWA	7 asec	30 asec	5 asec/sec	0.02 Hz	10 min
F2G-CT	Attitude Hold, damp T2G rates	-	fine guidance sensor	RWA	30 mas	1 asec	100 mas/sec	0.1 Hz	75 sec
Fine Lock Walkdown									5 - 10 sec
F2G-FL	Attitude Hold, damp F2G-CT rates, science imaging	< 100 asec	fine guidance sensor	RWA	4 mas	< 10 mas	40 mas/sec	1.0 Hz	40 min

- **TGS design required 75 seconds of Coarse Track**
  - **Primary FGS remains in CT while Secondary FGS acquires, performs walkdown, and locks onto guide star**
  - **SSS motor torque trending began to show an upward trend in bearing degradation**

TGS Mods to Preserve Hardware Lifetime

- Modifications to TGS were proposed in November 2005
  - Reduce FGS Coarse Track time from 75 seconds to 29 seconds
  - Use a single FGS in the guide star acquisition process
  - Requires an open-loop drift interval prior to F2G-FL
    - Interval between the end of CT nutations and the completion of the Fine Lock Walkdown
    - For guide stars fainter than 13.5 mv, interval is 5-10 seconds
    - Gyro-less axis only (Gx-axis, currently the V2-axis w/G1-2 pair)
  - Analyzed probability of guide star acquisition success
    - Predicted 100% success for guide stars 9.0 mv – 13.5 mv
    - Predicted 90% success for stars fainter than 13.5 mv
    - Estimate aero and gravity gradient torque compensation errors
- TGS algorithm changes were uplinked in April 2006
  - Bright Star Acq Success: 99.94% (3 failures / 5003 acqs)
  - Faint Star Success (to date): 95.90% (46 failures / 1123 acqs)

TGS Gx-Axis Open-Loop Time Interval



Open-Loop Time Interval (flight):

Begins at Open-Loop start when primary IFOV leaves CT nutation circle and ends when 3-Hit Success occurs (in X-axis for FGS-1R or Y-axis for FGS-2R)

Approximately 5-10 seconds for 13.5 mv and fainter stars, and 3-5 seconds for bright guide stars

Chasing-Down Disturbances ≥0.002 Nm

- Project directive
  - Investigate ways to reduce number of failed acquisitions
  - No dedicated spacecraft time available for on-orbit testing
- "Peel the onion" to find uncompensated disturbance torques causing drift during open-loop interval
  - Uncompensated gravity gradient torques (0.015 Nm)
    - Flight Software Inertia Tensor contains errors (why errors?)
    - Already compensate for inertia variation with SA angle
  - HGA gimbal articulation disturbance torque (0.012 Nm)
    - Antennas tracking TDRSS – gimbal rates <0.3 deg/min
  - Uncompensated aerodynamic torque (0.001 Nm mean + random component due to density variation)
  - Solar pressure torque (0.002 Nm)

- Find all disturbance sources ≥0.002 Nm and prepare to perform a torque balance analysis to find true inertia tensor

Inertia Tensor Optimization Concept

- Estimate HST Inertia Tensor by performing a torque balance (using flight telemetry) during open-loop interval
- Euler's equations for the Gx-axis (V2-axis) simplify greatly under two-gyro control during the open-loop interval
  - Remaining terms (greater than 0.0001 Nm) are a function of <u>all six</u> terms of the true Inertia Tensor
  - Account for gravity gradient, aerodynamic, HGA articulation, and solar torques and <u>assume</u> remaining torque error is due to Inertia Tensor error

$$\dot{\omega}_2 = \frac{1}{I_{22}}\left\{T_2^G - T_2^{Gfsw} + T_2^A - T_2^{Afsw} + T_2^H + T_2^S\right\}$$

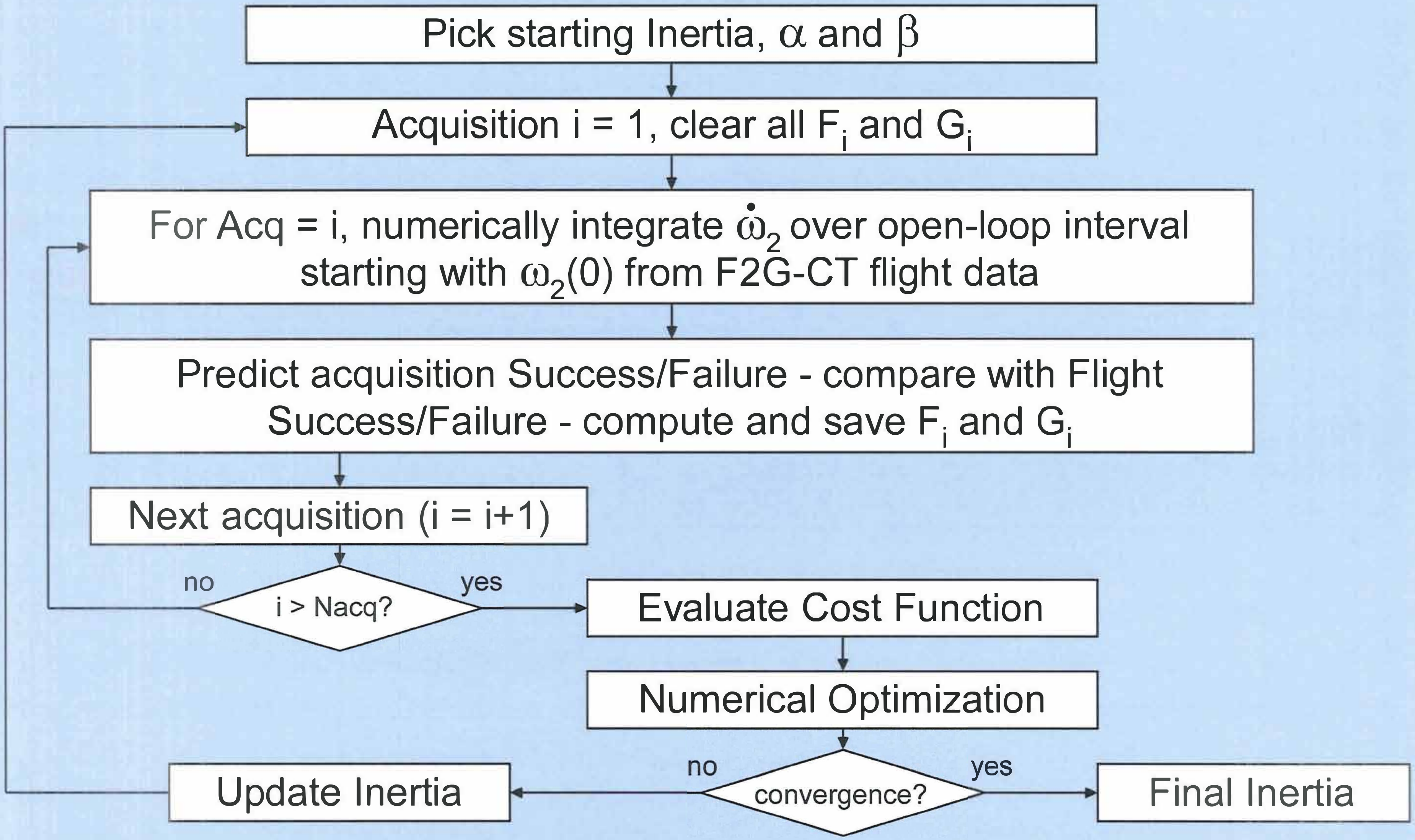
$$T_2^G = \frac{3\mu}{\left\|\vec{R}\right\|^5}\left[\left(I_{11} - I_{33}\right)R_1R_3 + I_{13}\left(R_3^2 - R_1^2\right) + I_{12}R_2R_3 - I_{23}R_1R_2\right]$$

- Given an inertia estimate, integrate twice to predict Gx-axis attitude response during OL interval and compare to actual flight response
  - "Best" inertia will result in similar time-required-to-lock comparing predicted response with flight response (over many acquisitions)

Inertia Tensor Optimization Setup

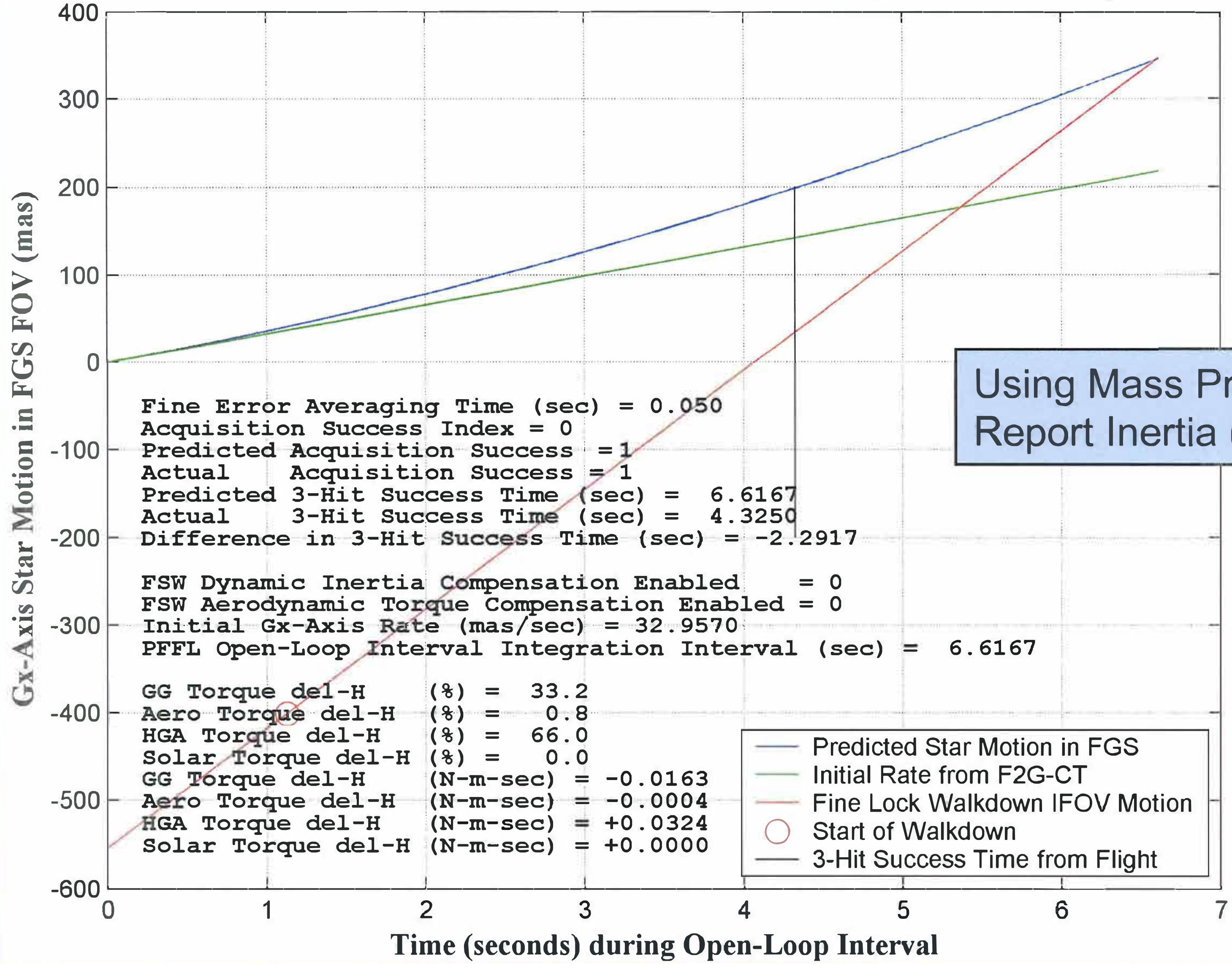
- Flight Data Set
  - Faint guide star acquisitions (>13.5 mv) over 1-year (~700 acqs)
  - Exclude acqs with RWA zero-speed crossings in/near OL interval
  - Large data set used to reduce affect of random aero density errors
- Cost Function $$C = \sum_{i=1}^{Nacq} \left(\alpha F_i + \beta G_i^2 \right)$$
  - Failure Index $$F_i = \begin{cases} 0 & \text{if predicted acq-i success/failure matches flight success/failure} \\ 1 & \text{if predicted acq-i success/failure does NOT match flight} \end{cases}$$
  - Time Difference Index $$G_i = \begin{cases} t_i^a - t_i^p & \text{acq-i actual minus predicted time-to-lock} \\ 0 & \text{if predicted and/or flight acq-i failed to lock} \end{cases}$$
- Optimization Algorithm
  - Nelder-Mead Simplex Direct Search (Matlab Optimization toolbox)
  - Works well for discontinuous cost functions not requiring analytic gradient functions

Optimization Process Description

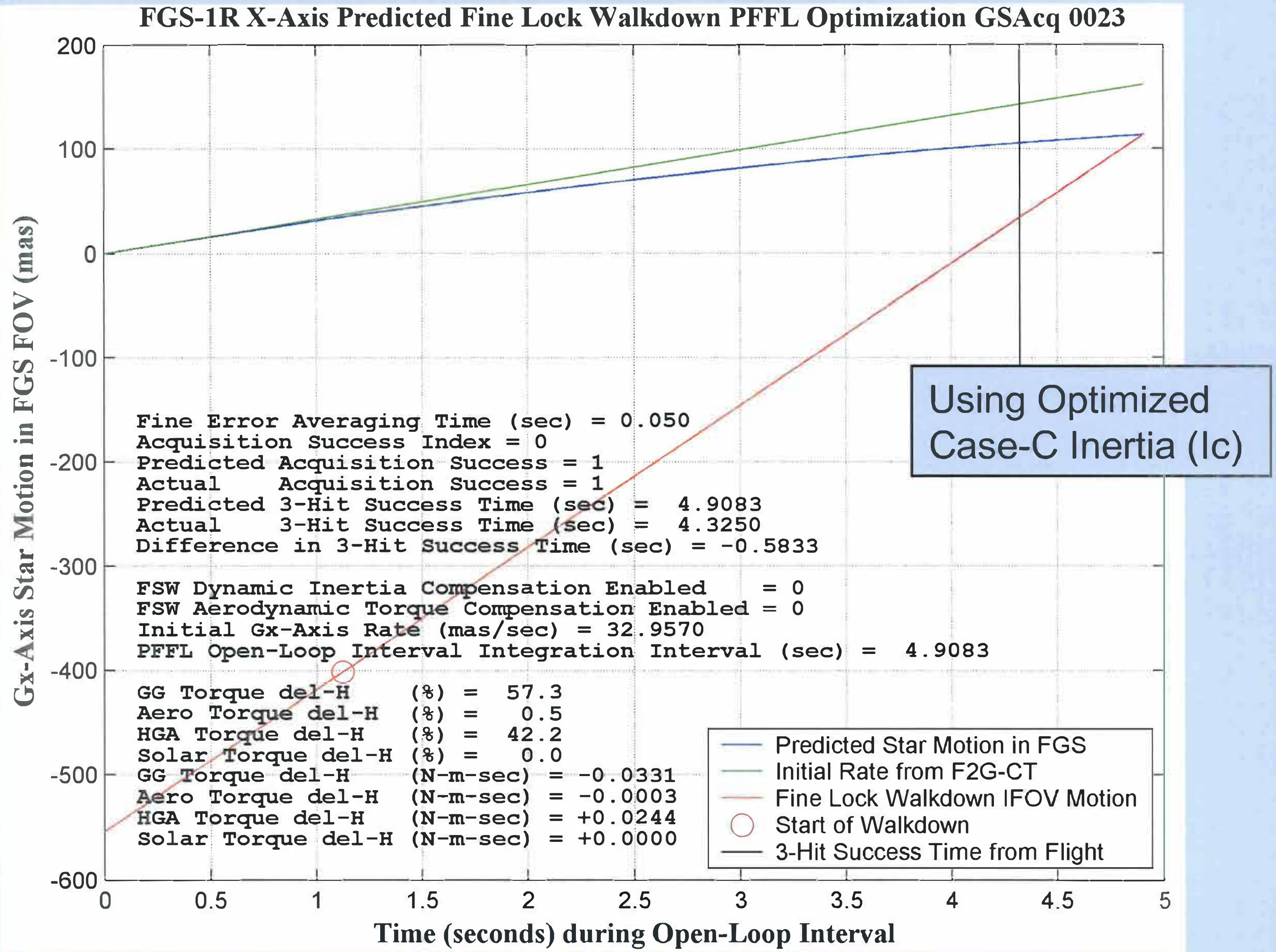


Predicted vs. Flight Acq FGS-1R Gx-Axis

FGS-1R X-Axis Predicted Fine Lock Walkdown PFFL Optimization GSAcq 0023



Predicted vs. Flight Acq FGS-1R Gx-Axis



Inertia Tensor Optimization Results

Inputs				Results								
Alpha	Beta	Initial Inertia	Process	$\sum_{i=1}^{Nacq} F_i$ Failure Index	$\sum_{i=1}^{Nacq} G_i^2$ Time Difference Index (sec^2)	Inertia Name	Inertia Tensor Elements (kg-m^2), HST Veh Frame at 90-degree SA angle					
							I11	I22	I33	I12	I13	I23
-	-	Ifsw	diagnostic	83	2039	Ifsw	36913	87775	93357	854	-1092	199
-	-	Impr	diagnostic	70	2003	Impr	37058	86955	93524	727	-2475	266
0	1	Impr	optimization	70	1835	Ia	37504	88586	89207	729	-2590	268
25	1	Ia	optimization	68	1830	Ib	39828	90917	91430	715	-2604	258
25	1	Ib	optimization	68	1829	Ic	39821	90958	91424	719	-2604	258

Notes: 1) Diagnostic runs are a 1-iteration evaluation of a particular inertia tensor without performing inertia optimization

2) Impr originates from HST Mass Properties Report LMMS/P564410 Rev K, 15 December 2006, the post-SM3B inertia. Ifsw is the current FSW inertia, documented in MOSES EM 1260 Change 01, 1 February 2006.

3) Cost Function $C = \sum_{i=1}^{Nacq} \left(\alpha F_i + \beta G_i^2 \right)$

Summary and Lessons Learned

- Method presented herein to determine the spacecraft Inertia Tensor from flight data during single-axis open-loop drift
  - Gravity gradient must be a predominant disturbance torque
  - Requires flight data from many events to reduce random errors

- HST Program has no plans to implement any changes at this time to reduce TGS guide star acquisition failures before SM4

- Sensor feedback is a great thing!
  - Without it, on-board disturbance compensation requires much greater fidelity to reduce attitude errors while drifting open-loop
  - Sensor-less drift is frustrating, so avoid it. Why did the acq fail?

Two-Gyro Science Lessons Learned

- Anticipate hardware failures in your spacecraft design
  - Your spacecraft may need to function with reduced sensors and/or actuators during its lifetime
  - Orient and size spacecraft actuators and sensors accordingly
- Work with your vendors, no matter how difficult it may be to do so
  - During HST development in the 1980's, the working relationship between Lockheed and Perkin Elmer (now Goodrich, the FGS vendor) was "difficult"
  - The original HST control law was designed around low-noise rate gyros, rather than the very capable FGS
    - Many dollars spent developing low-noise rate gyros
    - FGS was used only for attitude updates and low-rate gyro bias updates
  - In hindsight, HST could have meet all mission requirements using FGSs and less expensive gyros
- TGS works because HST can satisfy mission requirements using either gyros (6 onboard) or FGSs (3 onboard) for rate control