Redundancy Management For Navigation Functions on X-33

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Why Redundancy Management At Fusion Workshop ?

- Redundancy Management Is Fault Detection, Isolation and Reconfiguration
- Meets Functional Requirement Using Outputs From Similar and Dissimilar Sensors
- Especially Relevant For Unpiloted Applications

Redundancy Management For Navigation Functions on X-33

- Representative Mission Trajectory
- Navigation Function Related Architecture
- Air Data System
- INS/GPS System
- Air Data RM
- INS/GPS RM
- Algorithm Tuning
- Summary

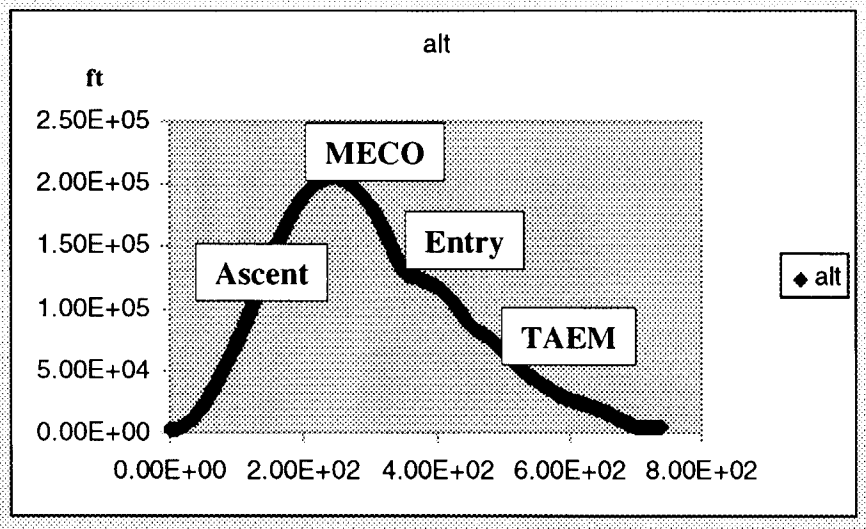
X-33

X-33 Objectives

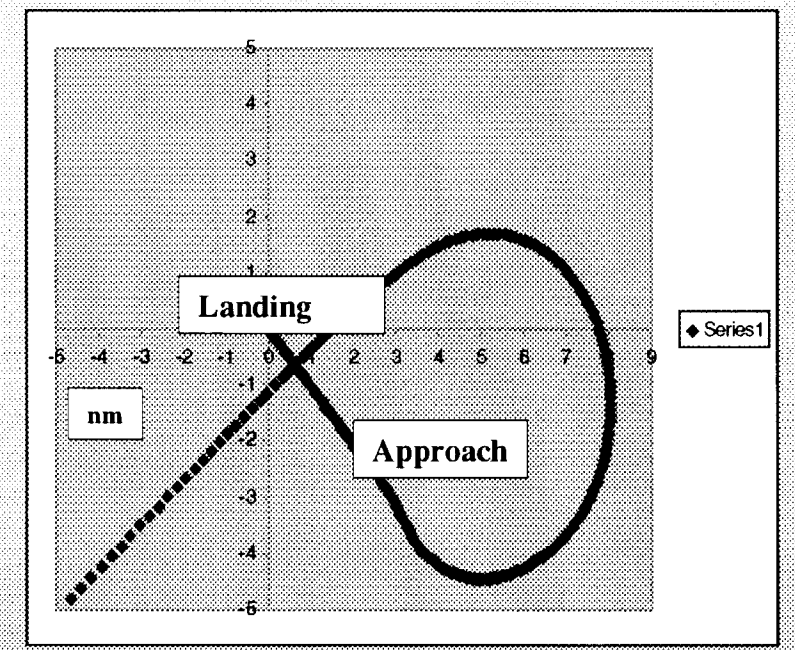
SSTO

- **Demonstrate Critical Technologies For Single Stage to Orbit Reusable Launch Vehicle**
  - **Propulsion**
  - **Thermal Dissipation**
  - **Autonomous Landing**
  - **Others**

Representative Mission Trajectory



Altitude vs Time



Terminal Area Ground Track vs Time

Mission Phases-
-Ascent
-Transition (After Main Engine Cut Off)
-Entry
-Terminal Area Energy Management
-Approach
-Landing

Role of Navigation Functions

- **Air Data**

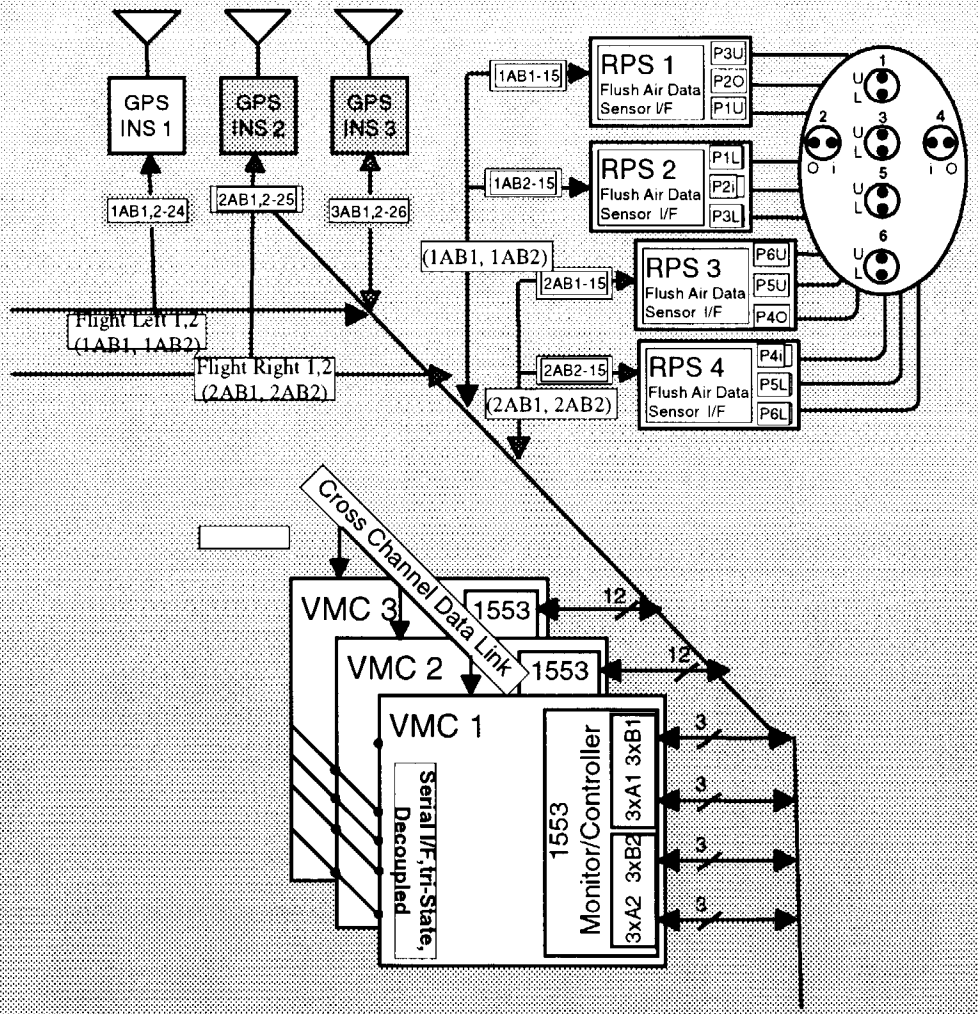
Ascent - Gain Table Lookup, Load Alleviation
Descent - Gain Table Lookup, Cross-channel Coupling

- **INS/GPS**

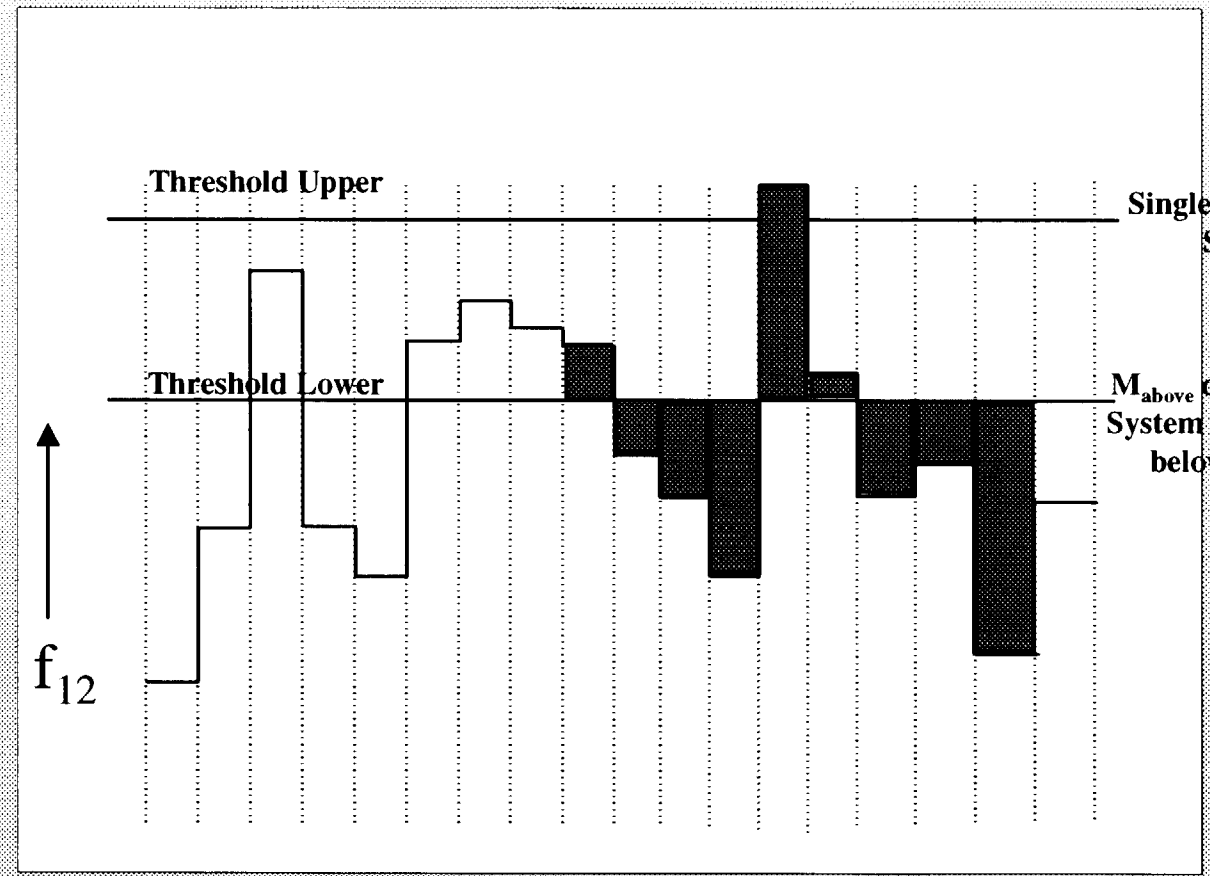
Ascent-Guidance (P,V,A) and Flight Control State Data (p,q,r, Attitude, Hdg) -
Descent and Landing-G&C State Data
Position wrt runway - differential GPS mode

- **Radar Altimeter - Height Above Ground At Approach and Landing**

Navigation Function Architecture



Dual Thresholds Catch 'Catastrophic' and Persistent Soft Faults



Redundancy Management Output Data Focus

- Data Quality Management
  - INS/GPS
  - Air Data
- One Coherent Output from Each Subsystem
- Once INS/GPS Chosen, System Is Used Until Faulty

Distance Metrics For χ^2 Testing-AirData

$$DP2\_i = \Sigma_{j = \text{all valid ports}} [(pest_j - p_j)^2 / Q_c^2] / (Num\_Val\_Ports^* Sigma\_a\_airdata^2),$$

Test Pressure estimates at ports from averaged airdata values

- One metric for each set of ports - Each tested against a threshold (=function of (Num_Val_Ports)

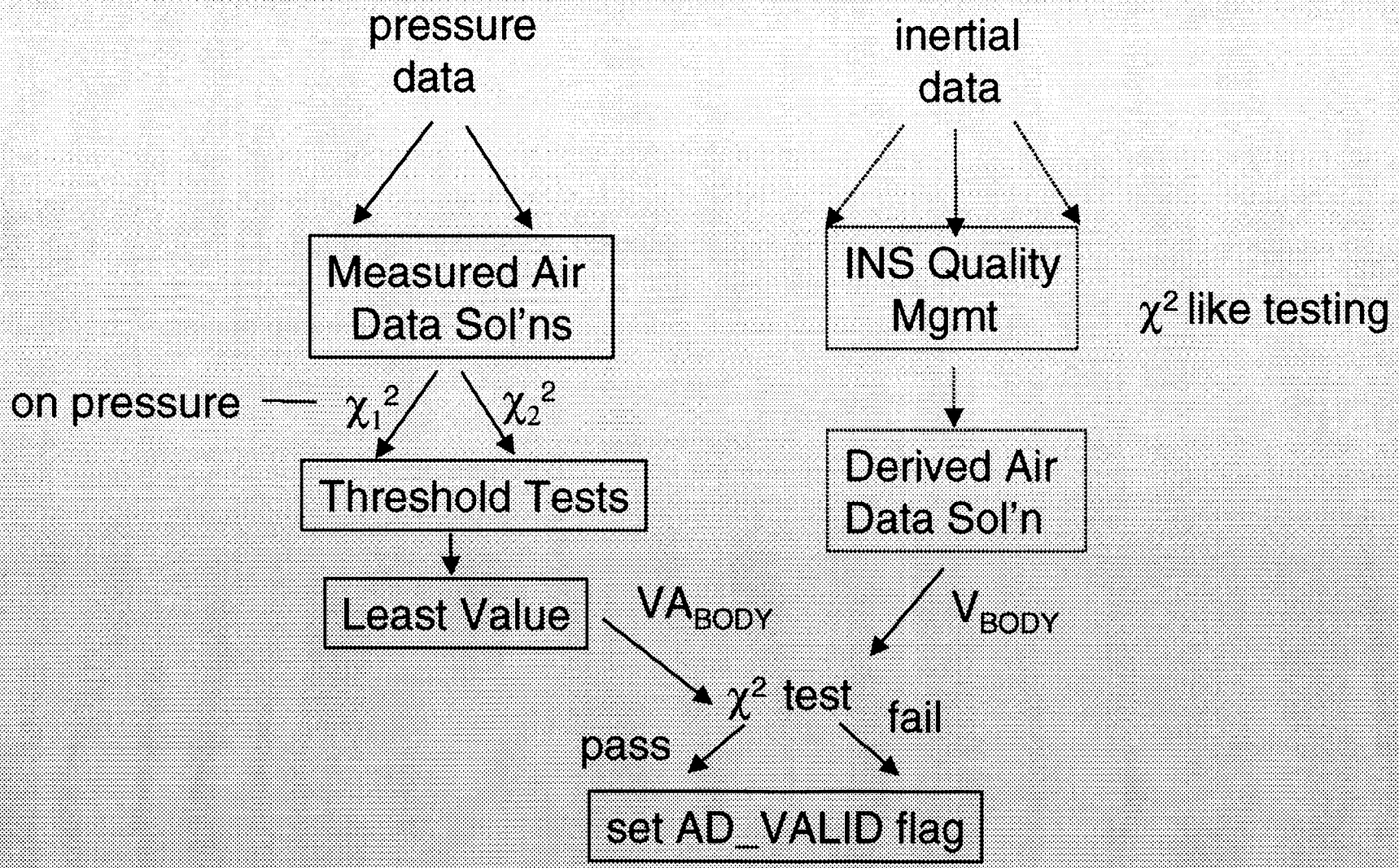
$$DV = [(VAX\_BODY - V_{BX})^2 / (\sigma_{vax}^2 + \sigma_{vwx}^2) + (VAY\_BODY - V_{BY})^2 / (\sigma_{vay}^2 + \sigma_{vwy}^2) + (VAZ\_BODY - V_{BZ})^2 / (\sigma_{vaz}^2 + \sigma_{vwz}^2)]$$

Test Air Data with Inertial System

Air Data Derived Body Velocities

INS Derived Body Velocities

System Air Data Quality Flow



X-33 Distance Metrics For χ^2 Testing -INS/GPS

INS Fault Detection- Body Rates/Accels

$$F_{ij} = [(P_i - P_j)^2 + (Q_i - Q_j)^2 + (R_i - R_j)^2]/SIG\_OC^2$$
$$+ [(ACC\_X_i - ACC\_X_j)^2 + (ACC\_Y_i - ACC\_Y_j)^2 + (ACC\_Z_i - ACC\_Z_j)^2]/SIG\_AC^2$$

$$G_{ij} = [(LATNAV_i - LATNAV_j)^2 + (LONGNAV_i - LONGNAV_j)^2]/SIG\_LC^2 + (ALTNAV_i - ALTNAV_j)^2/SIG\_HC^2$$
$$+ [(VELNAV\_X_i - VELNAV\_X_j)^2 + (VELNAV\_Y_i - VELNAV\_Y_j)^2]/SIG\_VHC^2 + (VELNAV\_Z_i - VELNAV\_Z_j)^2/SIG\_VVC^2$$

GPS Fault Detection/Isolation - Positions/Velocities

$AX_{ij} = |ACC\_X_i - ACC\_X_j|$, $AY_{ij} = |ACC\_Y_i - ACC\_Y_j|$, $AZ_{ij} = |ACC\_Z_i - ACC\_Z_j|$,

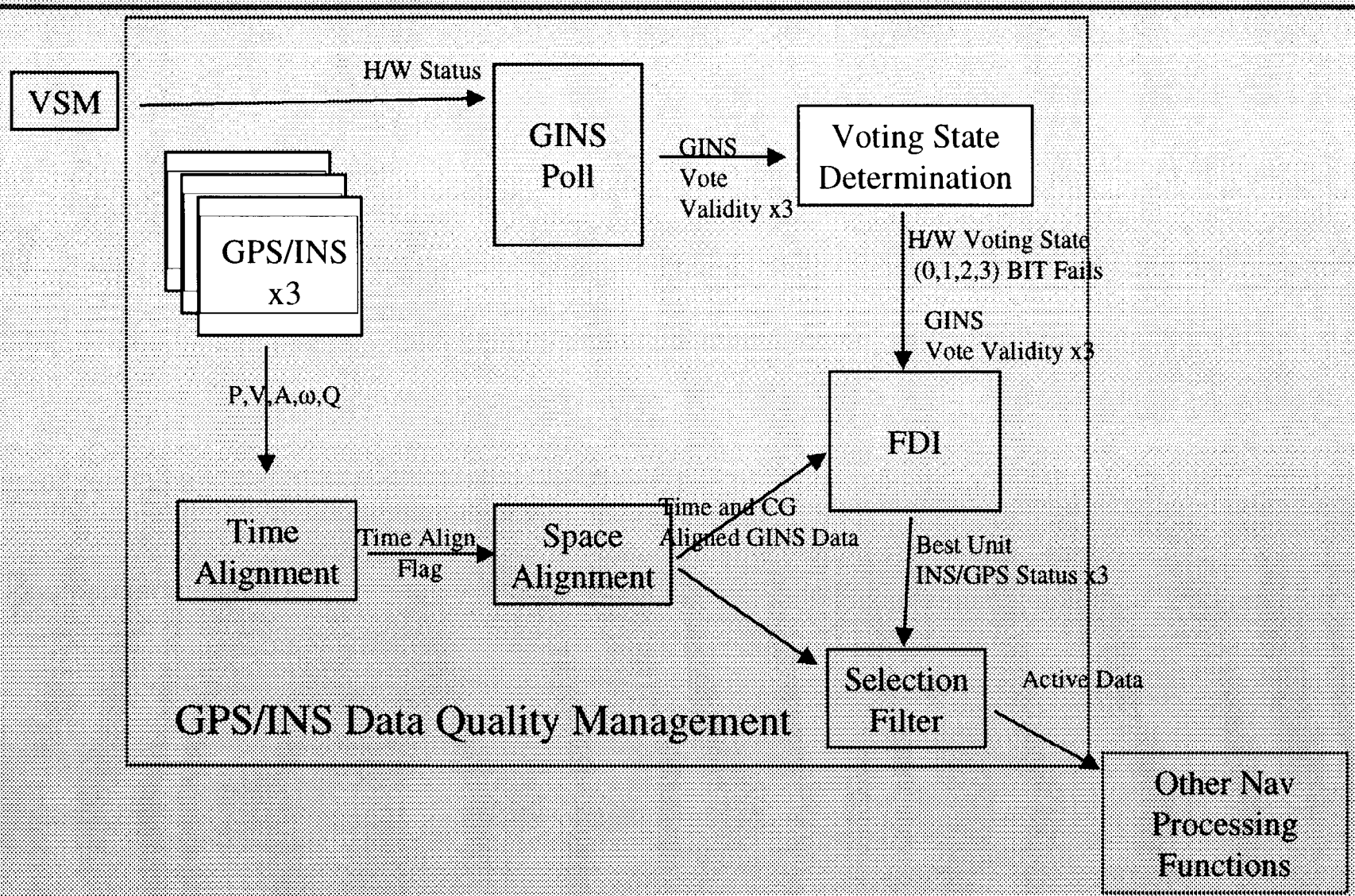
$BRX_{ij} = |P_i - P_j|$, $BRY_{ij} = |Q_i - Q_j|$, $BRZ_{ij} = |R_i - R_j|$,

INS Fault Isolation- Body Rates/Accels

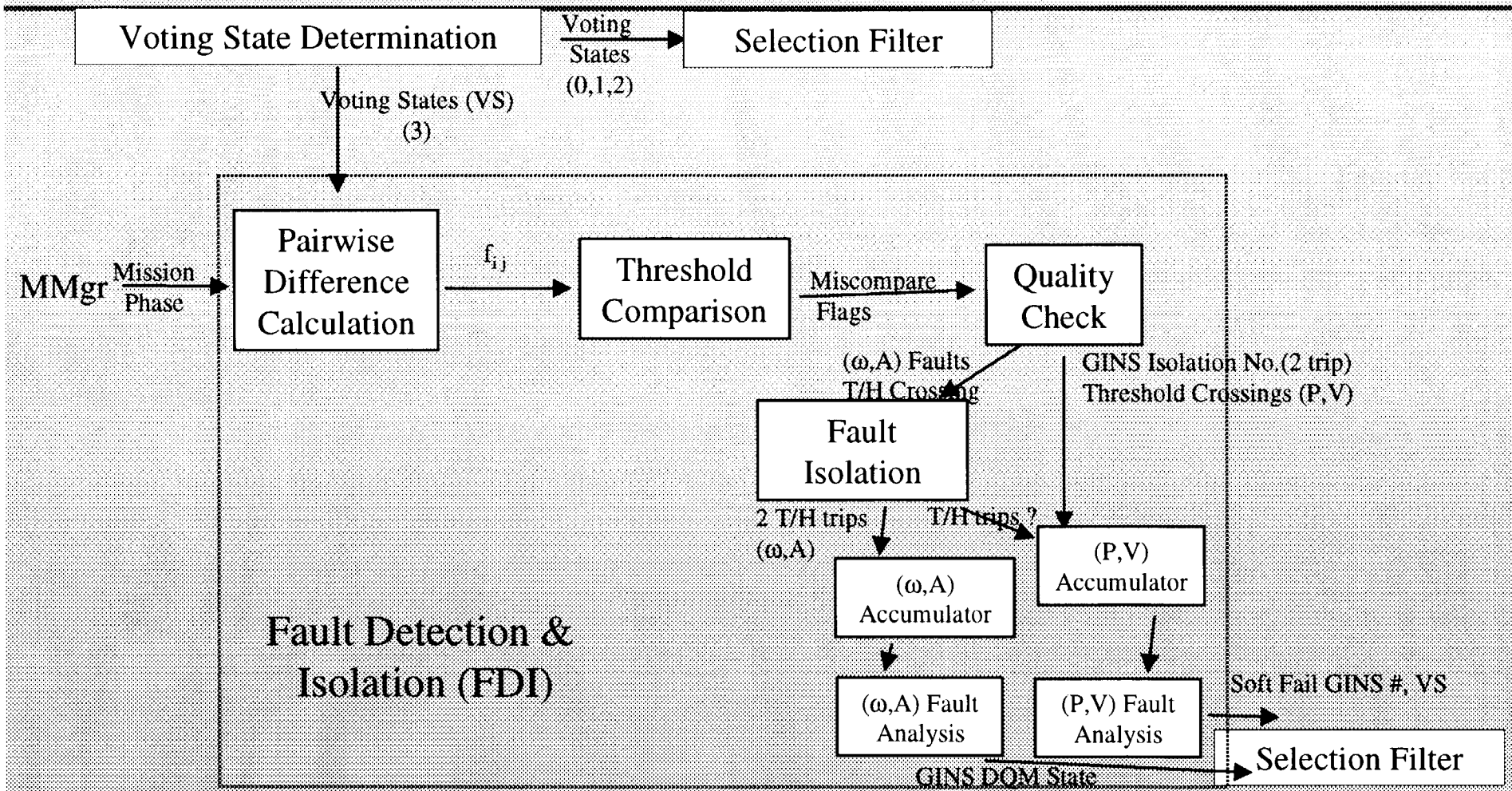
3 units => 3 pairwise differences (PD) => Threshold Comparisons => 2 PD with common unit => fault candidate

SIG_ are a function of Mission Phase

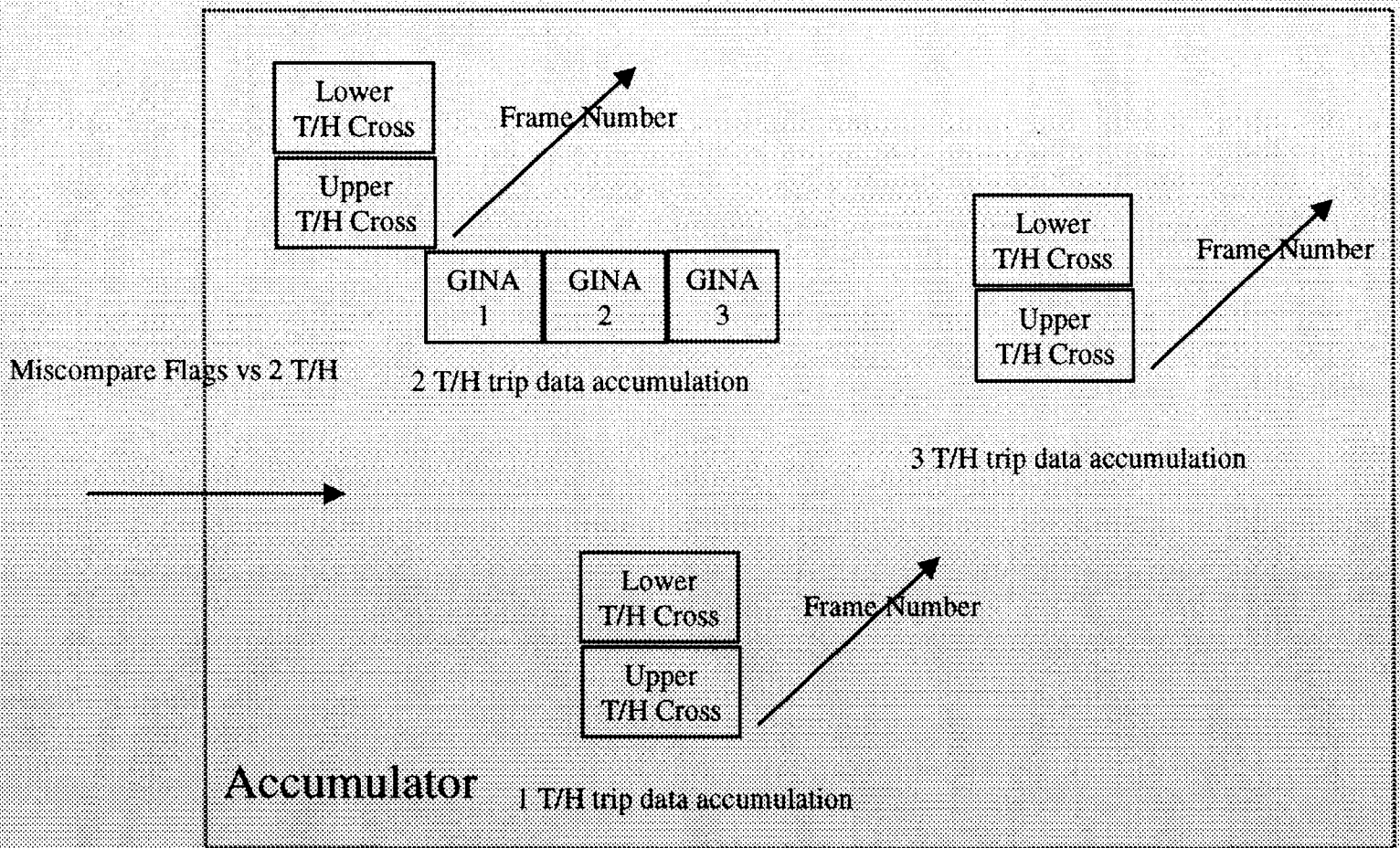
GPS/INS Data Quality Management



Fault Detection & Isolation (FDI)



Accumulator



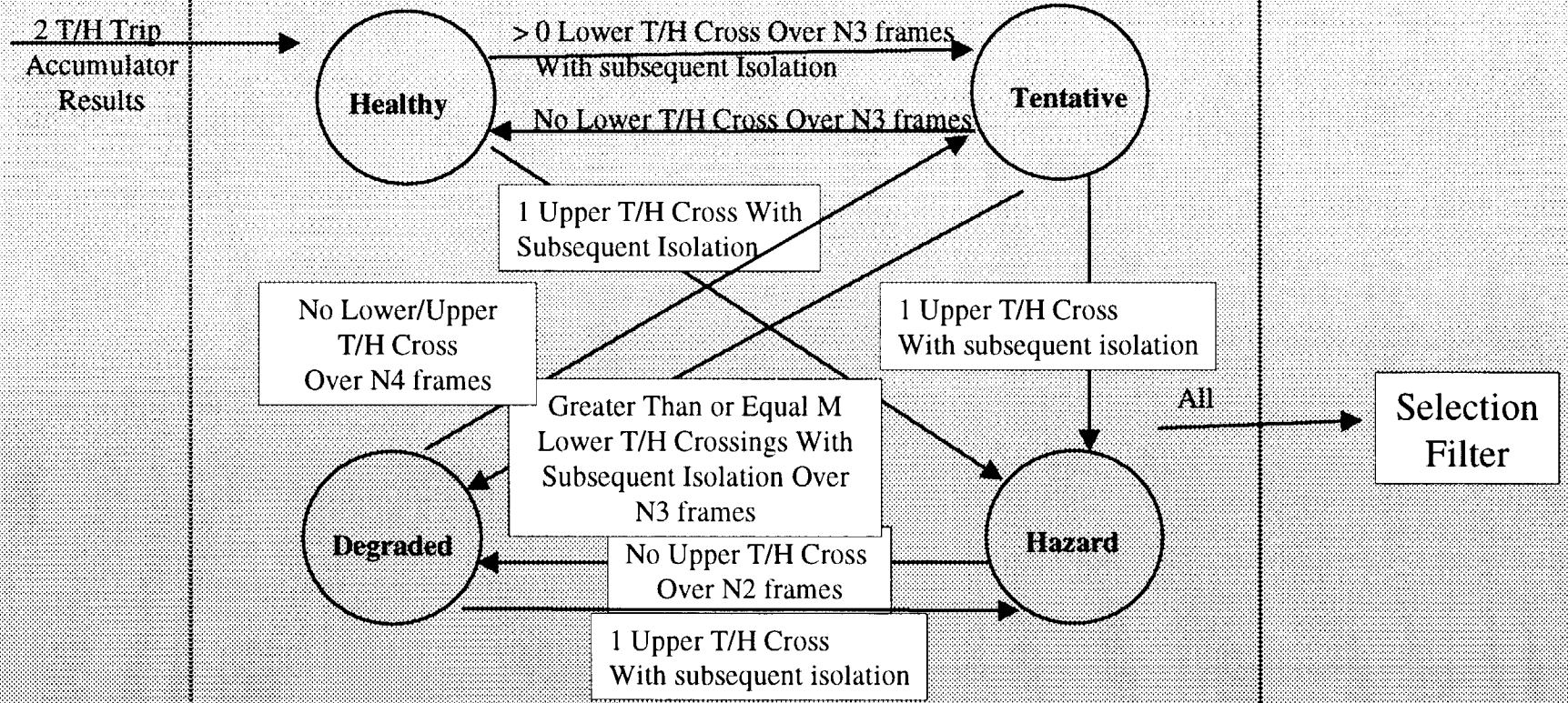
Some Failures May Not Be Caught By INS BIT

- No Change In Data - 1553 Buffers Not Updated
- Step Errors
- Data Word OverFlow (+ to - Full Scale)
- Slow Ramping
- Erratic Noisy
- Lo Frequency Sine Wave

Parameter	Step	Ramp	Sine Wave
Position (nm)	2.0	4.0 nm/hr	4. @ 84 min
Velocity (f/s)	9.0	0.01f/s/s	10. @ 84 min
Acceleration (f/s/s)	0.015	0.001(f/s/s)/s	N/A
Attitude (deg)	0.5	0.01(deg)/s	N/A
Att Rate (deg/s)	0.01	0.001(deg/s)/s	N/A
Ang Accel (deg/s/s)	0.001	0.0001(deg/s/s)/s	N/A

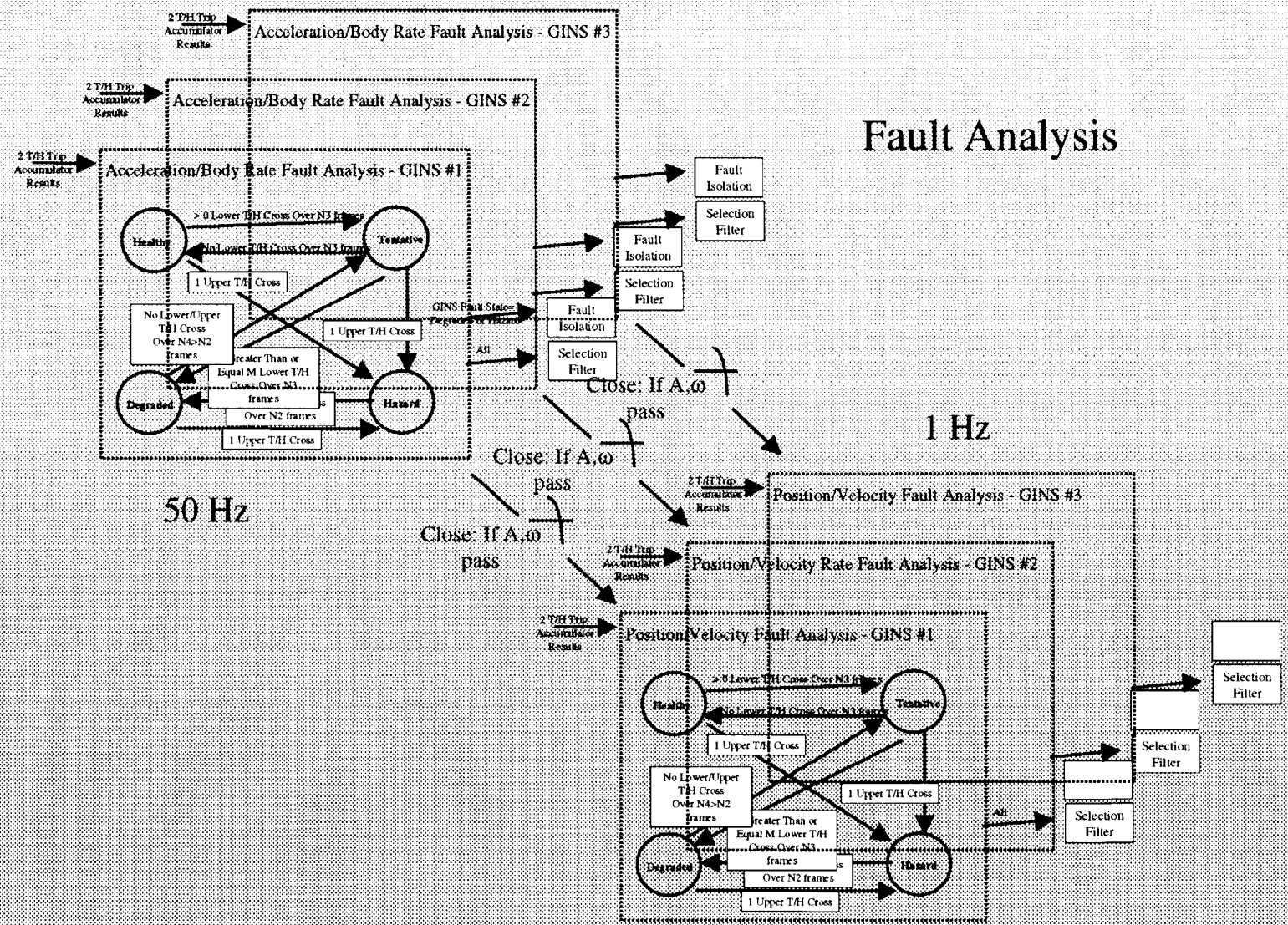
Fault Analysis State Diagram

Fault Analysis and Isolation State Diagram-(ω, A) Faults

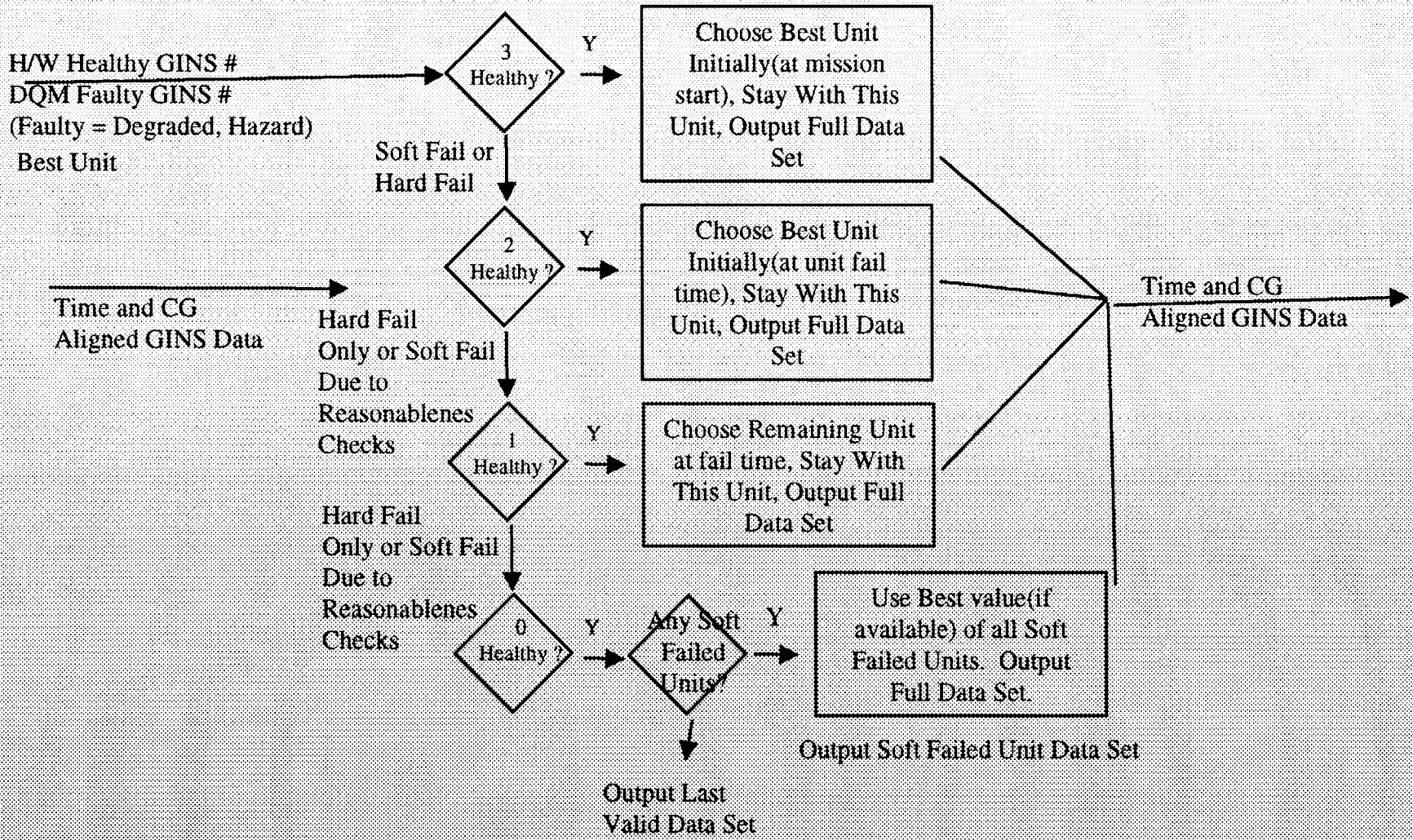


One Transition State Diagram Per Each GINS ω, A pair
One Transition State Diagram Per Each GINS P, V pair
(6 total)

Fault Analysis



Selection Filter - Single Unit-Output Full Set



Tuning Methodology

- Detailed Trajectory Simulation At Integrated Test Facility Used
- Errors Introduced Independently in:
  - Acceleration - 3 channels
  - Body Rates - 3 channels
  - Position - 3 channels
  - Velocity - 3 channels
- Error Magnitude and Duration Varied
  - Not Landing Successfully - Upper Threshold Related
  - Not meeting Performance Goals - Lower Threshold
- Varied Over Time in Mission Phase and Mission Trajectory Type

Summary

- Type of Fault Testing Relies on the Specific Functionality
- Additional Tests Could Be Done in Operational Launch Vehicle Between INS and GPS
- Detailed Characterization of Sensor Errors Is Paramount