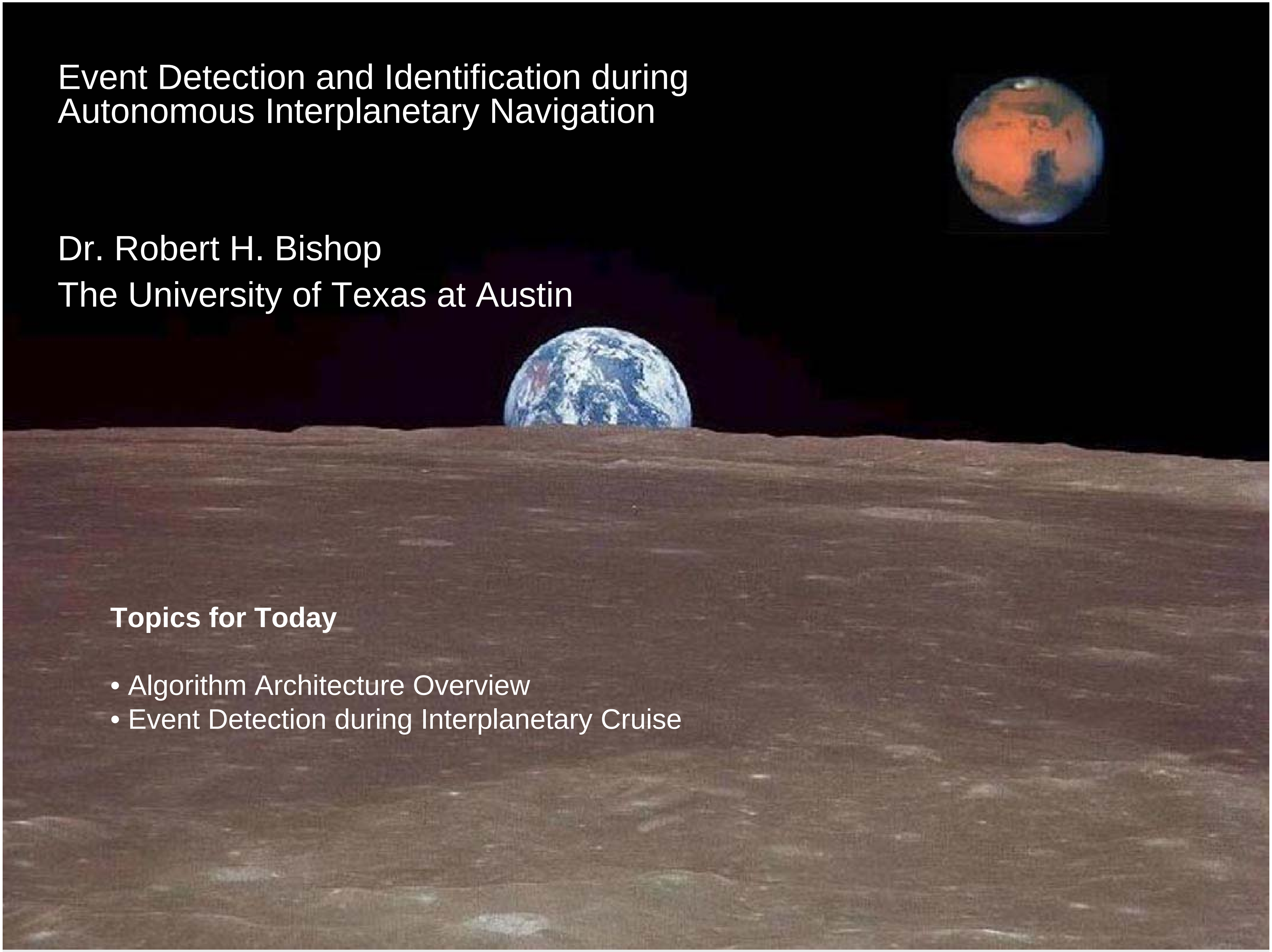

Event Detection and Identification during Autonomous Interplanetary Navigation

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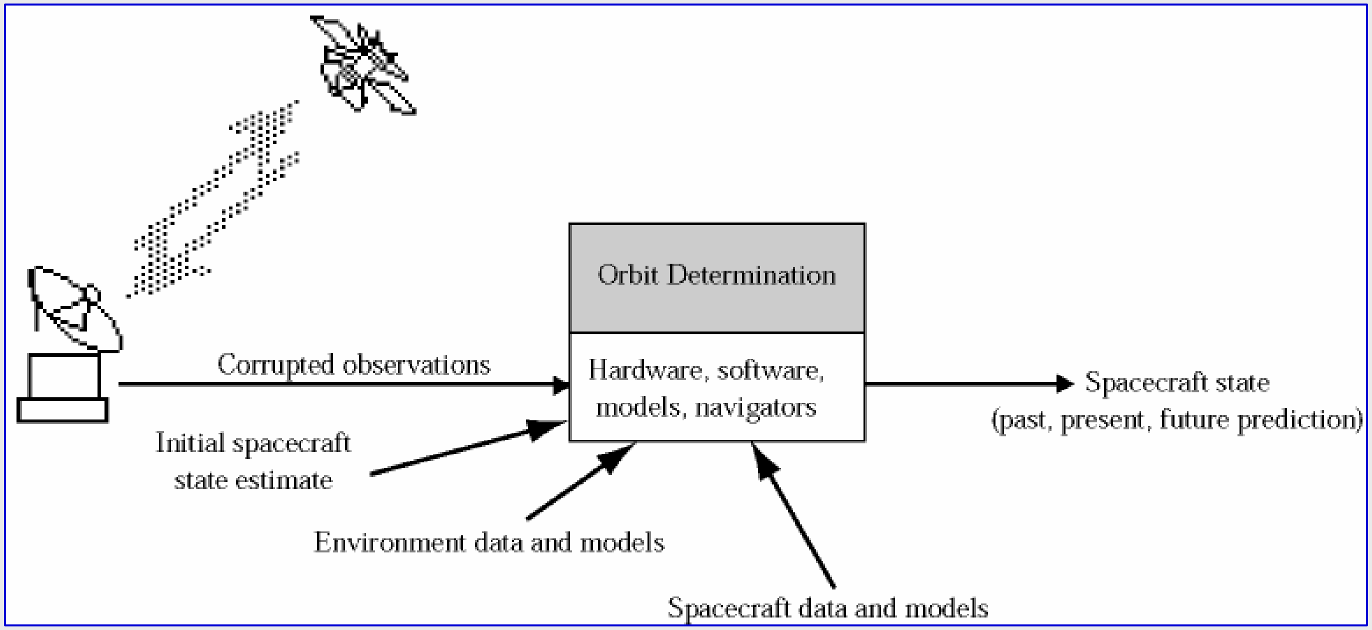
Topics for Today

- Algorithm Architecture Overview
- Event Detection during Interplanetary Cruise

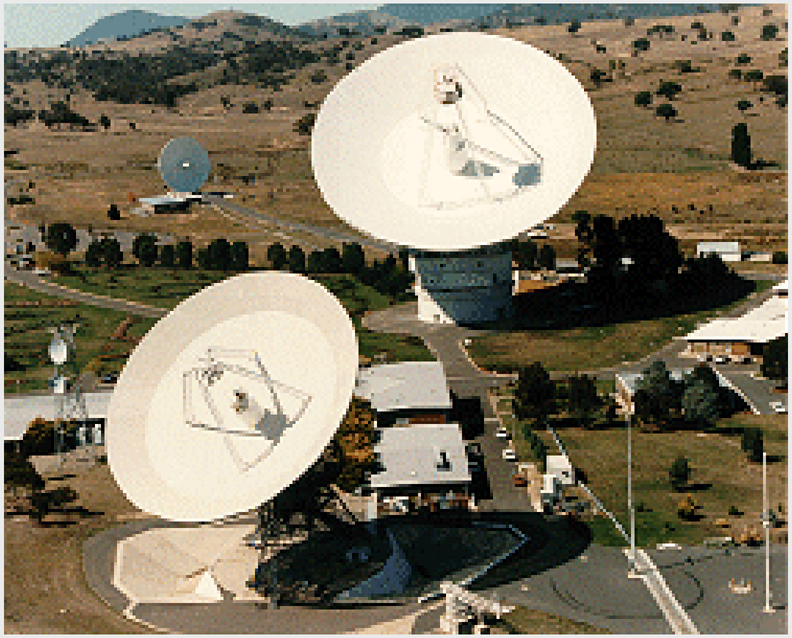
WHAT IS ORBIT DETERMINATION?

- **Orbit Determination (OD):** The process of describing the past, present, or predicted position of a satellite in terms of the orbital parameters.



THE DEEP SPACE NETWORK

- Interplanetary tracking is accomplished by 34 and 70m dishes
- DSN dish time is expensive and in high demand
- The primary data type is Doppler with a large number of supporting range measurements



WHY ADAPTIVE ORBIT DETERMINATION?

- There is no systematic approach for selecting the operational orbit determination filter parameters.
  - Costly filter tuning in terms of manpower and time
- There is a need for greater state estimation accuracies with less data (of potentially lower quality).
  - Low-cost, high-performance
- There is a need to detect environmental and spacecraft changes on-orbit and to take appropriate action.
  - Smart systems to aid the navigators
- Desire to increase robustness and reliability.
  - Mission safety and success

WHY ADAPT FOR INTERPLANETARY CRUISE?

- Spacecraft environment modeling challenge
  - Environment typically mismodeled early in mission
  - Dynamics can change unexpectedly during cruise
- Recent interplanetary examples
  - Mars Pathfinder (MPF) Solar Radiation Pressure (SRP) model was modified 4 times during mission
  - Mars Climate Orbiter and Mars Polar Lander experienced small force errors throughout trajectory
  - Mars Global Surveyor momentum de-saturation burns introduce small force errors in ongoing mission

RESEARCH OBJECTIVES

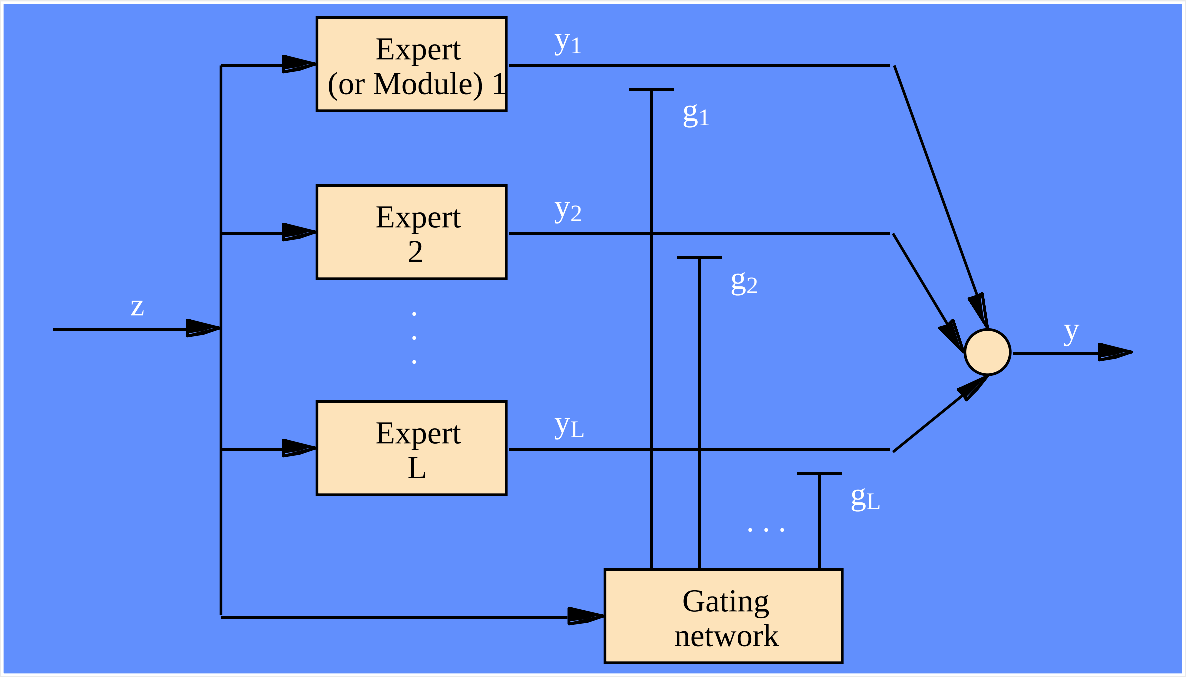
- Traditional orbit determination techniques use batch least-squares estimation.
  - Optimize over long data arcs and are not easily adapted to real-time operation.
- Environment changes are resolved by navigators in an *ad hoc* process relying heavily on
  - Navigator Experience
  - Trial and Error Adaptation
- Successful adaptive orbit determination algorithm:
  - Identify the nature of changes in the spacecraft environment that cause it to deviate from the operational filter model.
  - Tune the filter and model parameters corresponding to these changes to resume optimal tracking.
- The adaptive algorithm must perform these tasks with a general structure based upon numerical analysis of the available data.

ADAPTIVE ORBIT DETERMINATION ELEMENTS

- The Hierarchical Mixture-of-Experts (HME)
  - Modular framework modified from neural network theory of regulating expert systems
- The Extended Kalman Filter (EKF)
  - "Expert" used in HME in place of neural network expert systems that provides orbit determination capability
- The Gating Network (GN)
  - Single-layer neural network that assigns weights to filters in the HME based upon pre-fit residual and innovation covariance values.

ALGORITHM ARCHITECTURE

- Each module is an expert network— a Kalman filter.
- z is the input vector—radiometric range and doppler
- y_i is the ith module output—state estimate and error covariance.
- g_i is the activation of the ith output neuron of the gating network.
- Known as a hierarchical mixture-of-experts (HME) architecture.



THE EXTENDED KALMAN FILTER

- $\mathbf{r}_k$ is the innovation (pre-fit residual)

$$\mathbf{r}_k = \mathbf{Y}_k - \mathbf{h}\left(\hat{\mathbf{x}}_k^{(-)}, \boldsymbol{\alpha}, t_k\right)$$

- $\mathbf{W}_k$ is the innovation covariance

$$\mathbf{W}_k = \mathbf{H}_k \mathbf{P}_k^{(-)} \mathbf{H}_k^T + \mathbf{R}_k$$

- A properly configured Kalman filter will generate a white $\mathbf{r}_k$ sequence with covariance $\mathbf{W}_k$ at each t_k

GATING NETWORKS

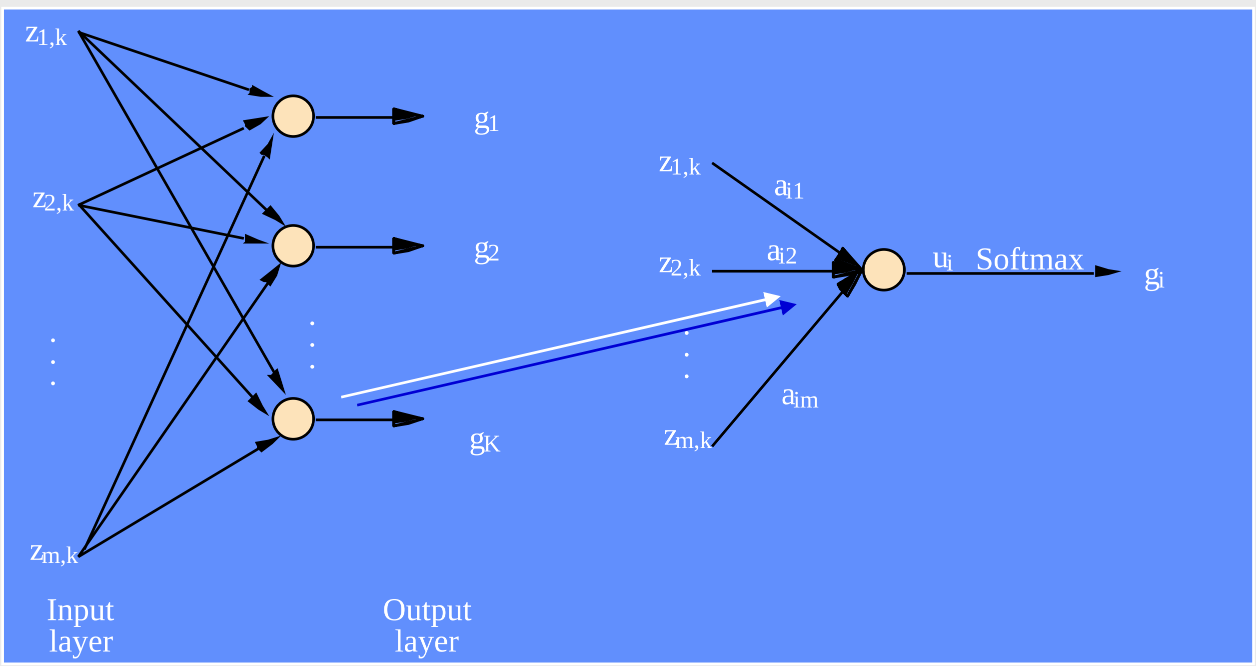
- The GN calculates gating weights, g_i, by mapping synaptic weights via the *softmax* operation
- The i^{th} filter is associated with a GN neuron with synaptic weight $a_{i,k}$
- The g's may be interpreted as *apriori* probabilities
- Why Softmax?
  - Differentiable function
  - Generalization of a "winner-takes-all" operation

$$u_i = \mathbf{z}_k^T \mathbf{a}_i$$

$$g_i = \frac{e^{u_i}}{\sum_{i=1}^{L} e^{u_i}}$$

$$0 \leq g_i \leq 1, \quad \forall\ i=1, 2, \ldots L$$

$$\sum_{i=1}^{L} g_i = 1$$



SYNAPTIC WEIGHT UPDATE FORMULA

- Conditional density function
- Distribution of the bank
- Learning is achieved by maximizing log-likelihood l with respect to $\boldsymbol{g(a)}$
- Instantaneous *a posteriori* probability injects filter performance into learning
- Synaptic weights update

$$f(\mathbf{z}_k|\alpha_i) = \frac{1}{\sqrt{2\Pi|\mathbf{W}_k|}} e^{-\frac{1}{2}\mathbf{r}_k^T \mathbf{W}_k^{-1}\mathbf{r}_k}$$

$$f(\mathbf{z}_k) = \sum_{i=1}^{L} f(\mathbf{z}_k|\alpha_i)g_i$$

$$l = \ln f\left(\mathbf{z}_k\right) = \ln \sum_{j=1}^{L} g_{j,k} f\left(\mathbf{z}_k \middle| \alpha_j\right)$$

$$h_i = \frac{f(\mathbf{z}_k|\alpha_i)g_i}{\sum_{i=1}^{L} f(\mathbf{z}_k|\alpha_i)g_i}$$

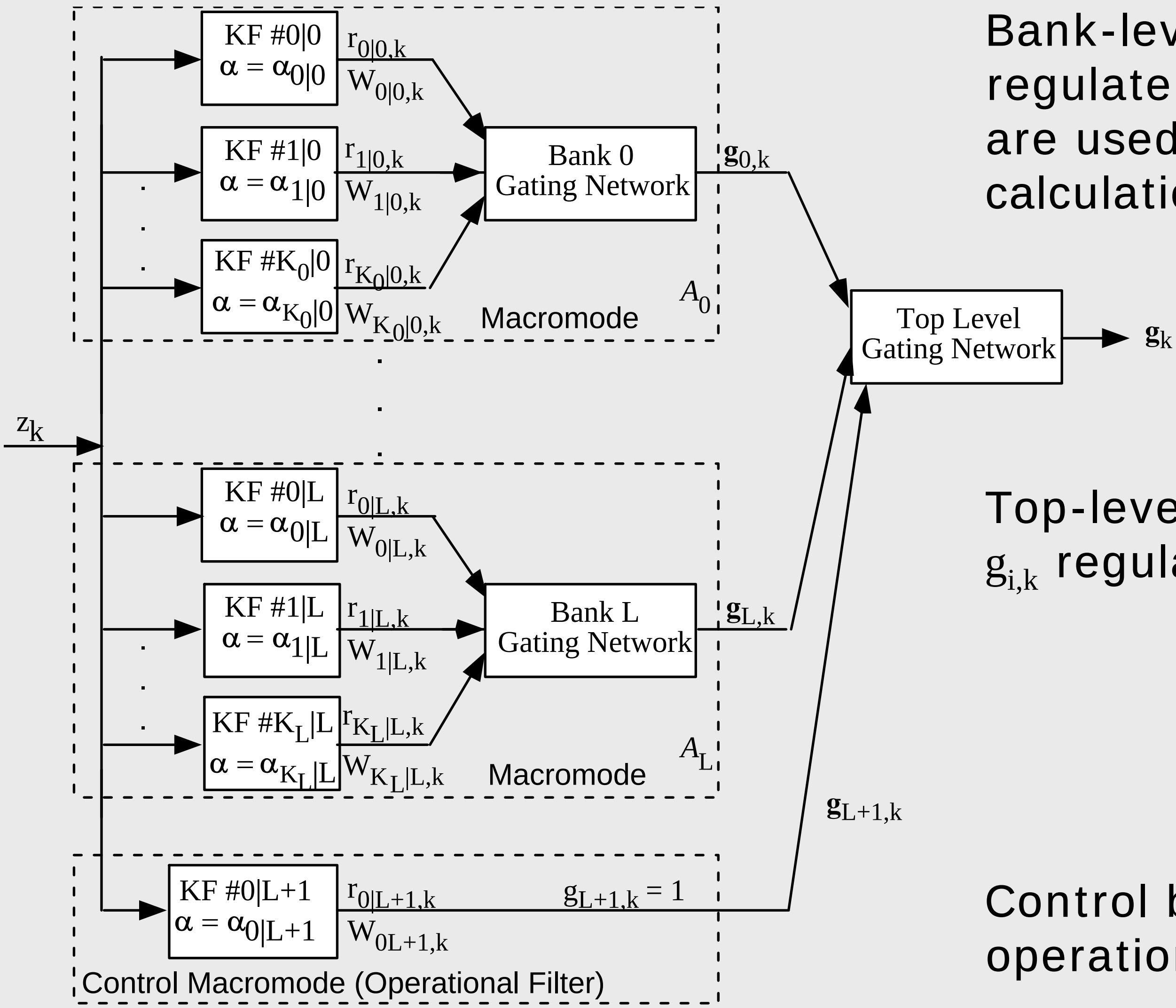
$$a_i \rightarrow a_i + \eta(h_i - g_i)\mathbf{z}_k$$

Learning rate

MULTIPLE LEVELS OF MODULARITY

- Filters are collected into banks to represent macromode environment changes
- Within each bank, individual filter realizations represent fine, micromode, environment changes
- "Best" filter in HME has the highest bank-level $g_{ji,k}$ in the bank with the highest top-level $g_{i,k}$
- Optimal filter configuration can be "masked" when containing bank does not receive highest top-level g
- Method desired for identifying nominal environment without bank "masking": Operational Control bank
  - The operational filter parameters and model reflect the mission nominal environment
  - The top-level GN identifies the nominal environment by selecting the control bank

MULTIPLE-LEVEL HME ARCHITECTURE



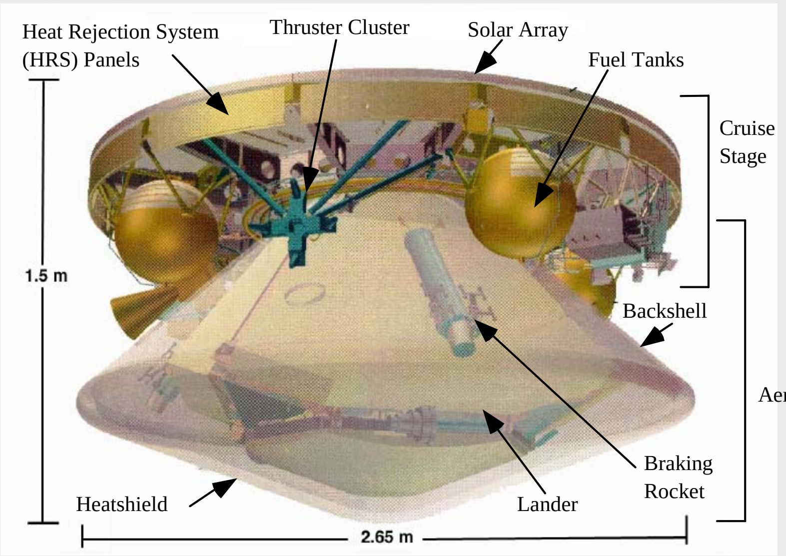
Bank-level weights $g_{ji,k}$ regulate micromodes and are used in top-level calculation.

Top-level weights $g_{i,k}$ regulate macromodes

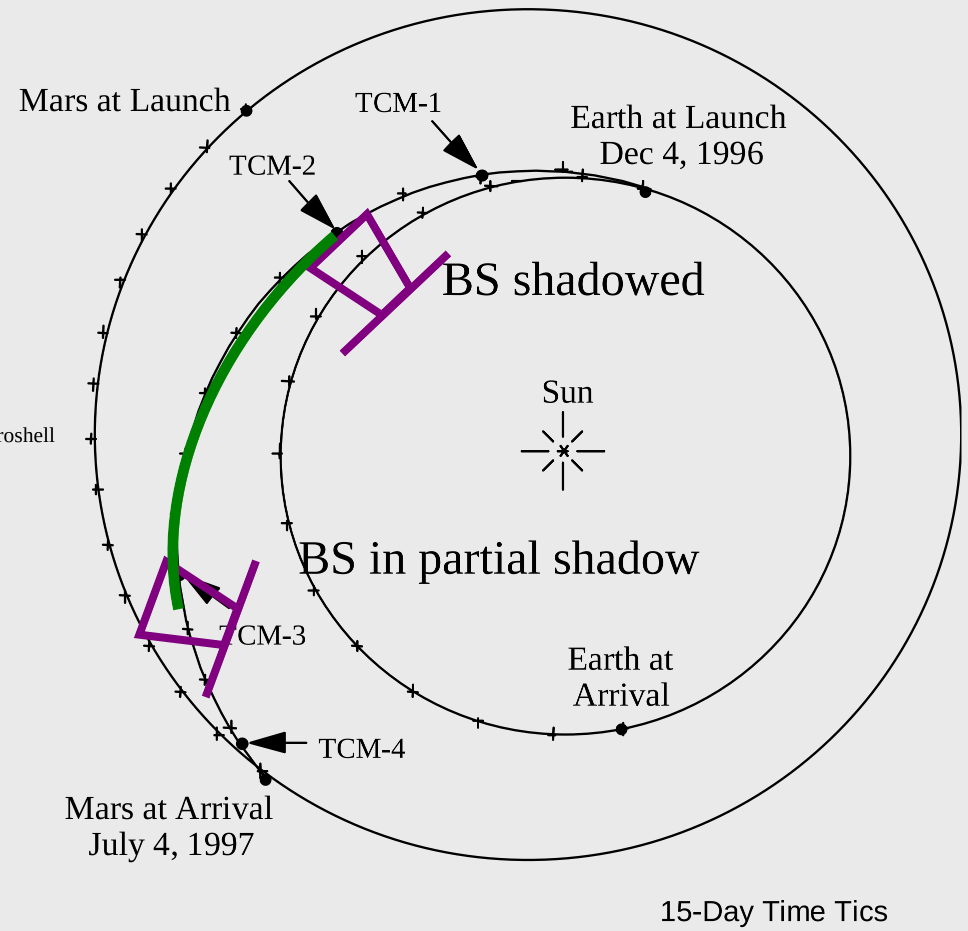
Control bank only contains operational filter

FIRST SUCCESSFUL TEST

MPF SOLAR RADIATION PRESSURE MODELING



MARS PATHFINDER (MPF)



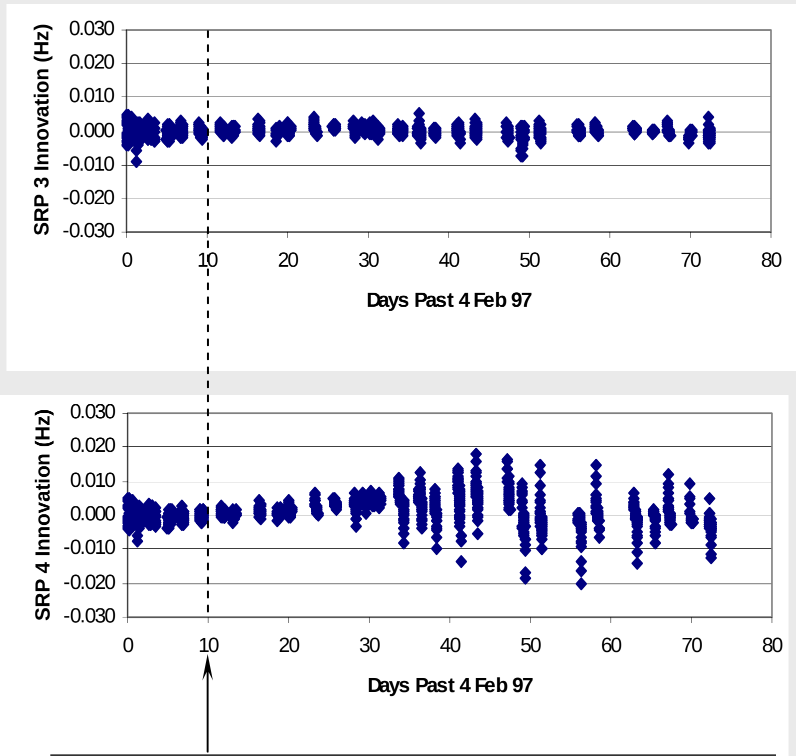
SRP MODEL SELECTION

- The process of tuning the operational filter during the Mars Pathfinder mission was very time-consuming for the navigation team.
- One of the main difficulties was choosing solar flux parameters.
- We considered this situation using the mixture-of-experts architecture.
- Data span of interest between TCM2 and TCM3
  - Starts 4 Feb 97 & 91 days long
  - 2 Way Doppler observables from 3 DSN sites

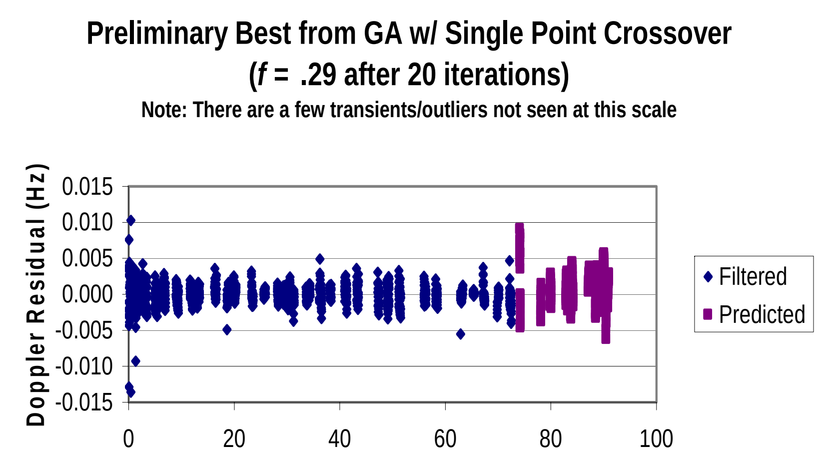
MPF navigation team best SRP model		
Spacecraft Part	**Component Type**	**Active**
Solar array	Flat plate	Entire cruise
Launch vehicle Adapter	Flat plate	Entire cruise
Heat rejection system	Cylinder	Entire cruise
Backshell 1	Cylinder	Before 4/16/97
Backshell 2	Flat plate	After 4/16/97

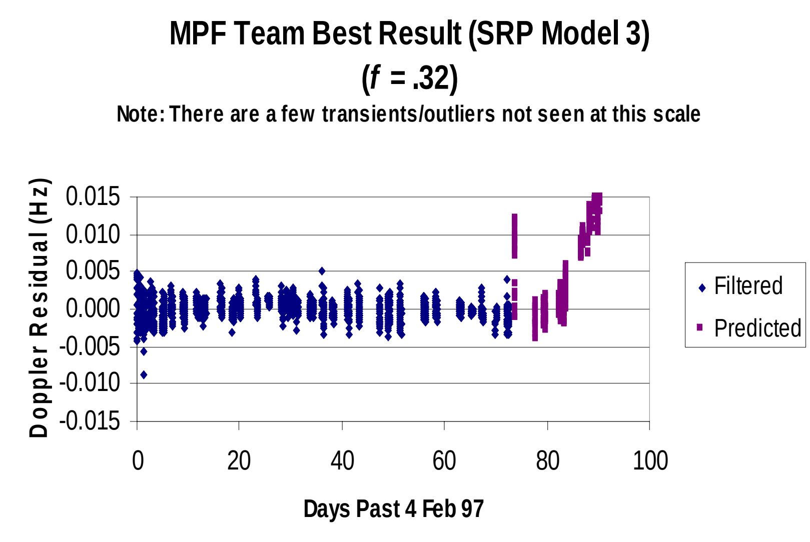
TCM=Trajectory Correction Maneuver

NUMERICAL RESULTS



The GN determines that the SRP3 model is better than SRP4 with only 10 days of Doppler residual data.



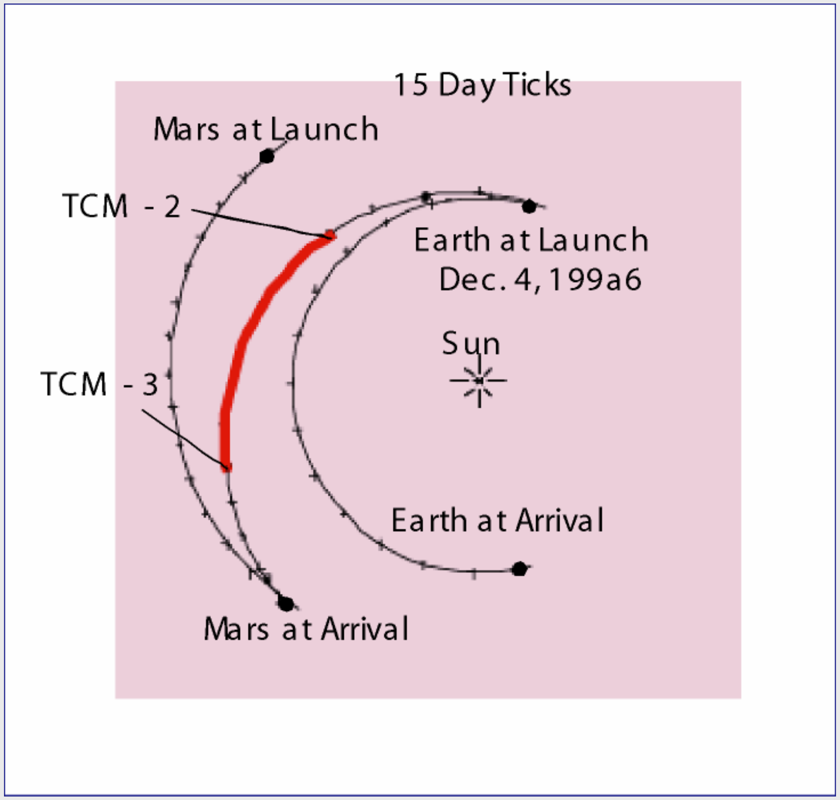


GENERAL HME CONFIGURATION: 5 BANKS

- Bank 0: Impulsive Velocity Macromode
  - Filter and model parameters
- Bank 1: SRP Environment Macromode
  - Filter and model parameters
- Bank 2: Doppler Noise Macromode
  - Filter parameters
- Bank 3: Range Noise Macromode
  - Filter parameters
- Bank 4: Experimental Control (Nominal Operation)

PROCESSING DSN DATA FROM MPF MISSION

- MPF Cruise from TCM-2 to TCM-3
  - Feb. 4 to Apr. 18, 1997
  - 1612 Doppler and 3144 range observations
- Unmodeled Impulsive Maneuver Identification
  - March 25 maneuver omitted from filter models
- SRP Environment Change Identification
  - MPF model 4 assumed operational model



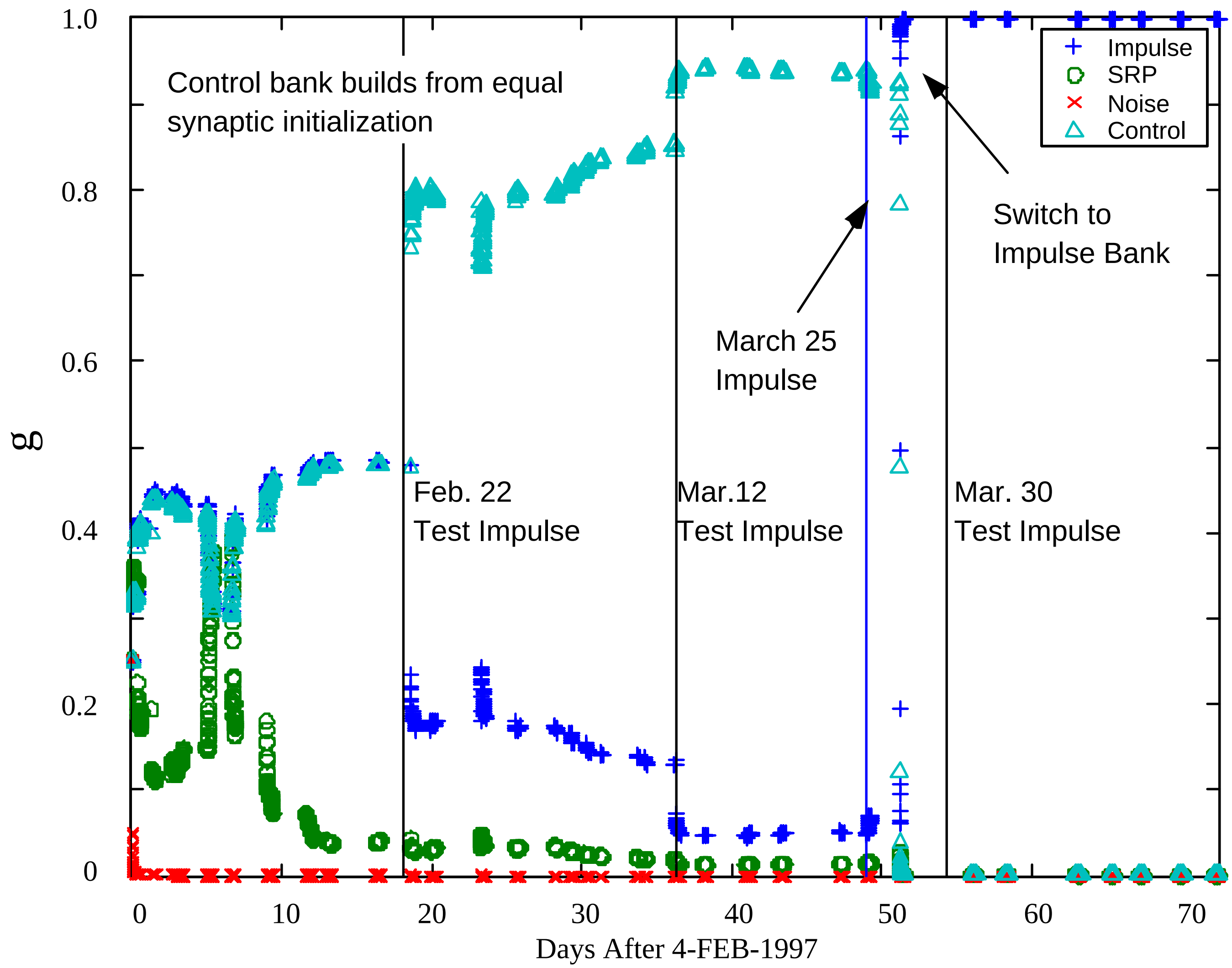
IMPULSIVE MANEUVER IDENTIFICATION

- The following small correction (0.7 mm/sec) was performed on March 25, 1997
    - ΔV = [0.4449 0.07304 0.5301] mm/sec
- The modeled Doppler noise = 0.2 mm/sec
- This maneuver has been omitted from all filter dynamic models to simulate an unmodeled impulsive event in the real mission data.
- Successful experiment will result in Control receiving highest top-level weight until March 25 when a switch to the Impulse macromode occurs.

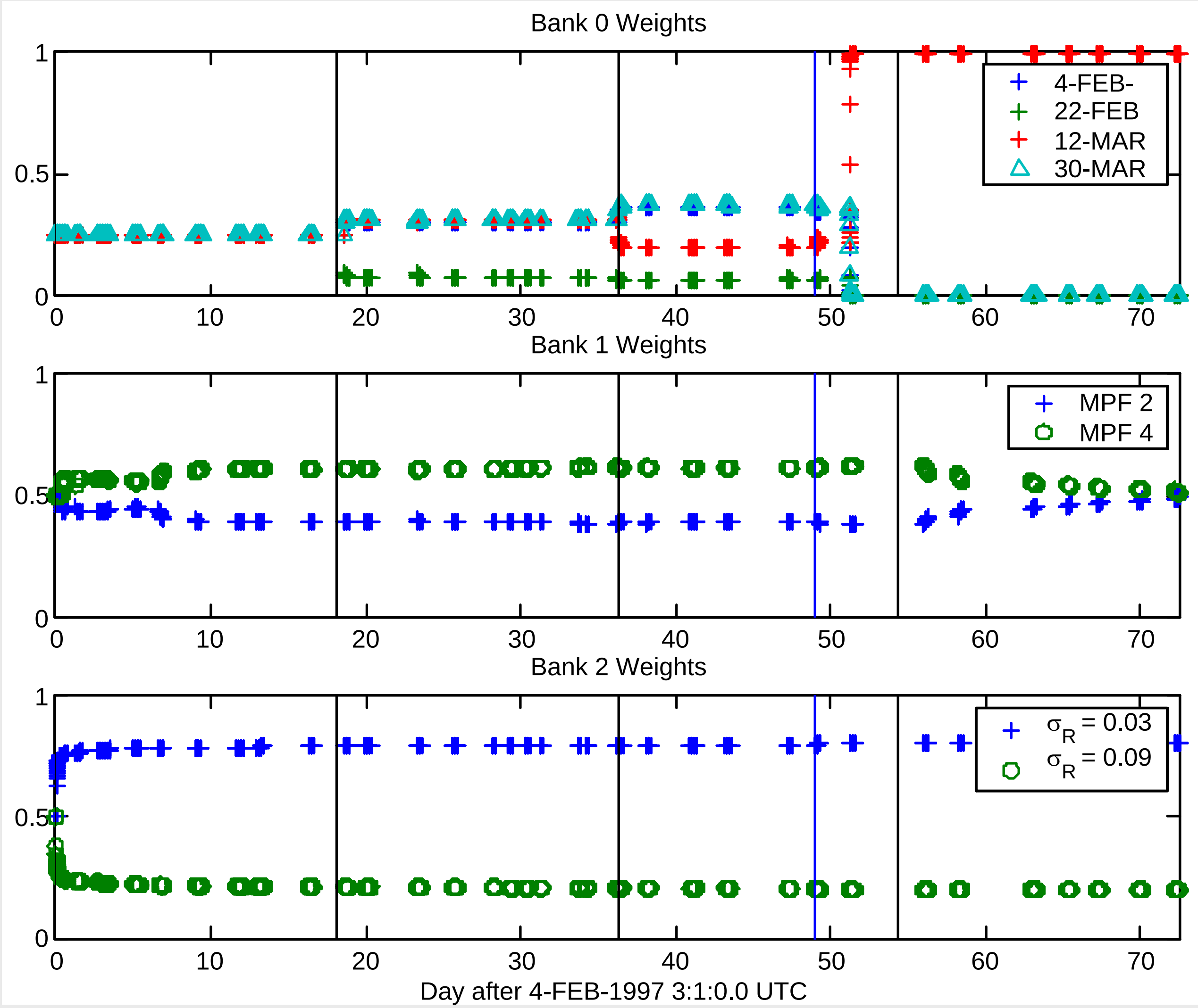
IMPULSE HME CONFIGURATION

	Bank #	Filter #	Impulse	SRP	R
Impulse	0	(0,0)	Feb. 4	*	*
	0	(1,0)	Feb. 22	*	*
	0	(2,0)	Mar. 12	*	*
	0	(3,0)	Mar. 30	*	*
SRP	1	(0,1)	---	MPF 2	*
	1	(1,1)	---	MPF 4	*
Noise	2	(0,2)	---	*	X3
	2	(1,2)	---	*	X9
Control	3	(0,3)	---	*	*

IMPULSE IDENTIFICATION TOP-LEVEL



IMPULSE IDENTIFICATION BANK-LEVEL



IMPULSIVE MANEUVER IDENTIFICATION SUMMARY

- Rapid identification of unmodeled impulse on March 25 -- on the order of two hours data
- Signature of residuals within measurement noise during initial period of top-level switch
- Appropriate filter given highest weight within impulse bank
- Identification of other small maneuvers also successful

CHANGES IN SRP ENVIRONMENT

- Changes in SRP environment represent continuous and low-level changes in spacecraft dynamics

- Although not necessarily critical, it is important to identify SRP as a source of OD error.

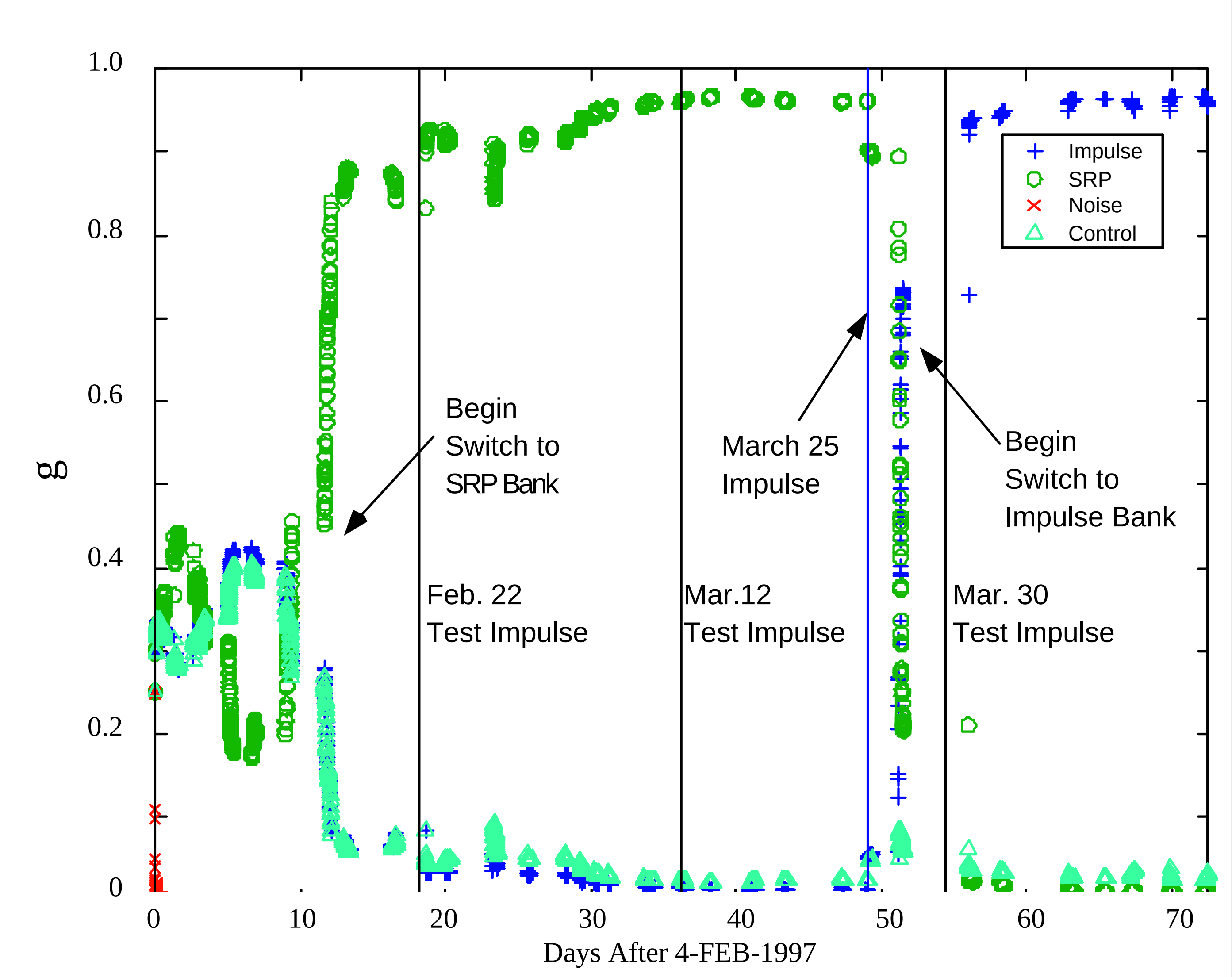
- MPF model 4 is assumed to be operational model and the GA optimized model is included in the SRP identification macromode.

- The March 25 maneuver is omitted from all models to examine ability to distinguish between discrete and continuous model changes.

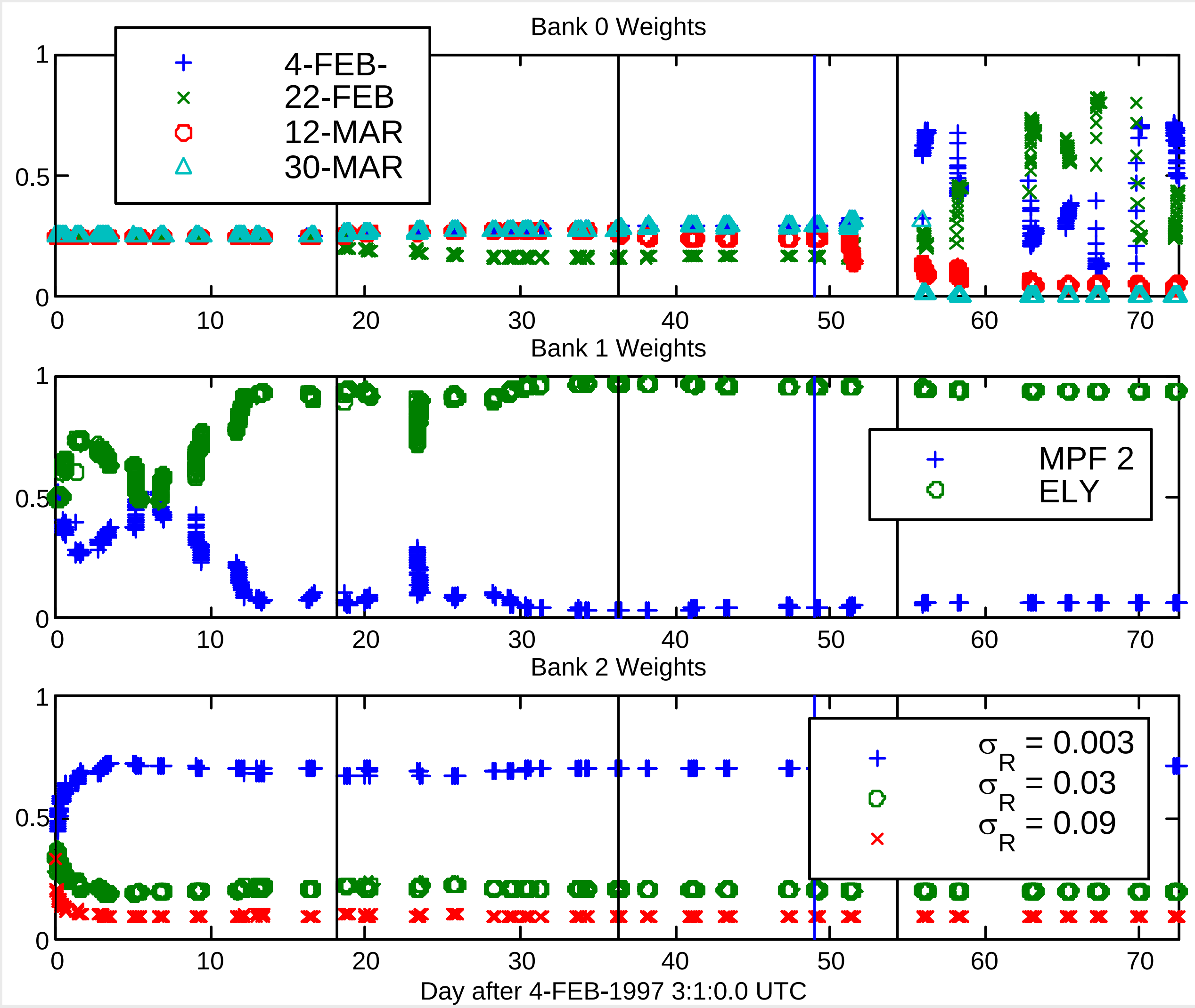
SRP HME CONFIGURATION

	Bank #	Filter #	Impulse	SRP	R
Impulse	0	(0,0)	Feb. 4	MPF 4	*
	0	(1,0)	Feb. 22	MPF 4	*
	0	(2,0)	Mar. 12	MPF 4	*
	0	(3,0)	Mar. 30	MPF 4	*
SRP	1	(0,1)	---	MPF 2	*
	1	(1,1)	---	*	*
Noise	2	(0,2)	---	MPF 4	X3
	2	(1,2)	---	MPF 4	X9
Control	3	(0,3)	---	MPF 4	*

SRP IDENTIFICATION TOP-LEVEL



SRP IDENTIFICATION BANK-LEVEL



SRP CHANGE IDENTIFICATION SUMMARY

- SRP macromode strongly indicated within first 10 days of data
- Difference in HME and operational residuals well below noise level until March 25
- HME switches to impulse bank within hours of March 25 impulse
  - March 12 test impulse filter indicated in bank 0
- Eventual switch back to SRP macromode

HME PERFORMANCE AS IDENTIFIER

- The top-level GN correctly identified the first macromode change in all cases.
  - False detections avoided at test impulse times.
  - Decisions based upon residual signatures near level of measurement noise.
  - Distinguished continual and discrete dynamic changes.

- Bank-level GN identified appropriate micromodes in most cases, but work remains in placement of test impulse times.

- CONCEPT PROVEN IN SIMULATION WITH ACTUAL DSN INTERPLANETARY CRUISE TRACKING DATA.

ACKNOWLEGEMENTS

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