The Mars Exploration Rover (MER) Transverse Impulse Rocket System (TIRS)

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Basic Entry Descent and Landing Architecture

- **The Mars Exploration Rover (MER) spacecraft used an Entry Design and Landing (EDL) system based on the successful airbag landing system of Mars Pathfinder (MPF) in 1997**
- **The basic EDL MPF architecture consists of the following phases that bring the spacecraft from an initial velocity of 6 km/sec to zero in about six minutes**
  - Entry: Protected by a heatshiled, aerodynamic drag brings the spacecraft velocity from 6 km/sec to about 400 m/sec
  - Parachute Descent: A supersonic parachute reduces the velocity to about 75 m/sec
  - RAD Firing: Three solid rockets in the backshell bring the lander vertical velocity to zero at an altitude of 12 meters at which point the bridle is cut. The time of RAD firing and bridle cut is determined by an algorithm using a Radar Altimeter. Typical times between RAD firing and bridle cut is about 4 seconds
  - Landing: The lander free falls 12 meters and impacts the ground with a vertical velocity of 10 m/sec. During impact and lander is protected by a set of four airbags that completely surrounds the lander, until it comes to a stop.

Entry, Descent & Landing Timeline

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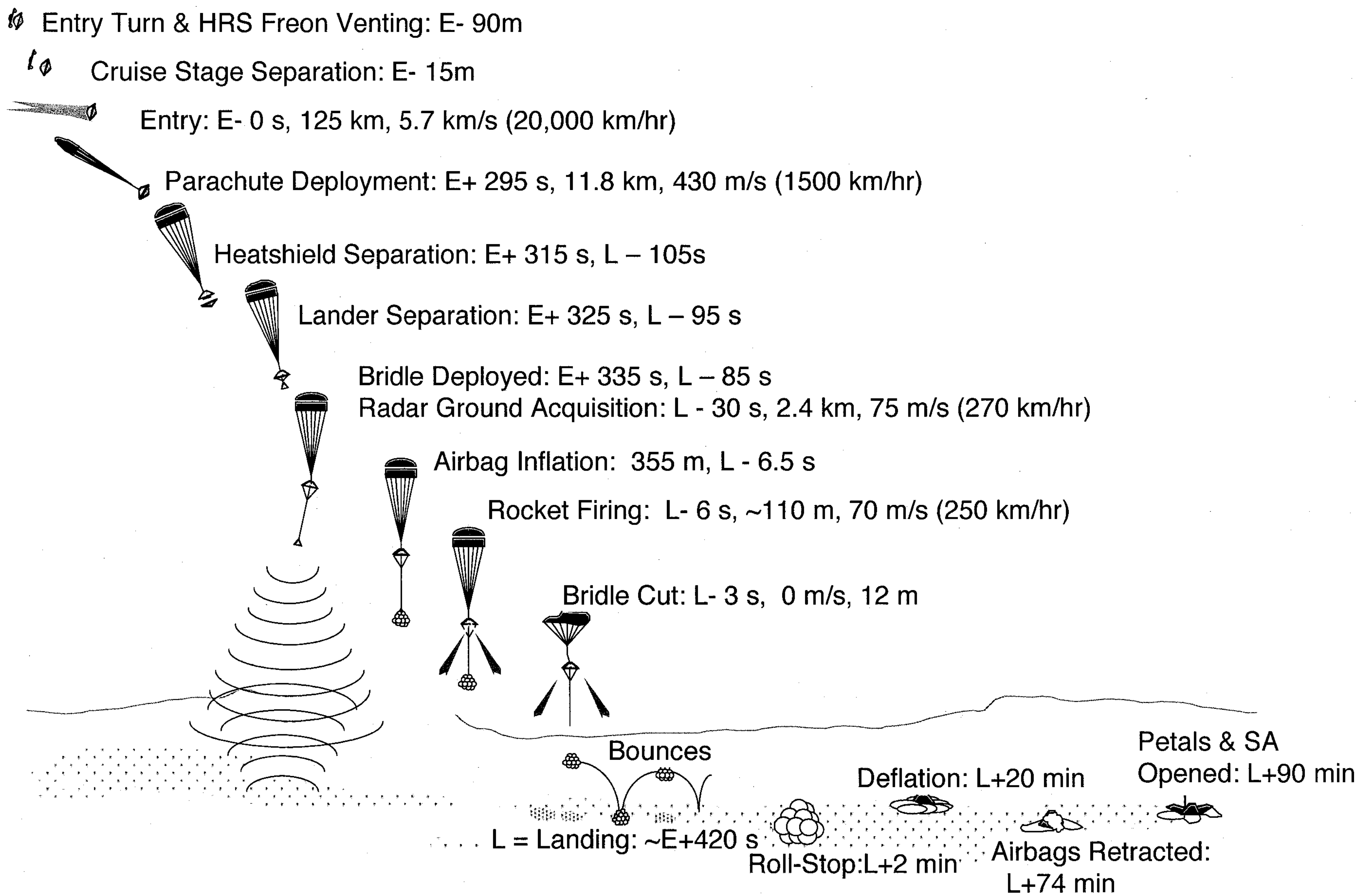

The Vulnerability of the MPF EDL Architecture

- **The airbag system can protect the lander as long as the impact velocity is less than ~12 m/sec in the vertical direction and less than ~24 m/sec in the horizontal direction**
  - Excessive vertical velocity produces stroke-out failures
  - Excessive horizontal velocity produces abrasion damage

- **Martian winds can result in the lander impacting the surface with an excessive horizontal velocity due to the following two effects**
  - *Steady State Winds* impart an horizontal velocity to the lander prior to RAD firing
  - *Wind Shear* excites the oscillation of the dynamics of the chute-backshell-lander system, which can result in the RAD rockets to fire in a direction off-the vertical, thus inducing an horizontal velocity

Sources of Horizontal Velocity

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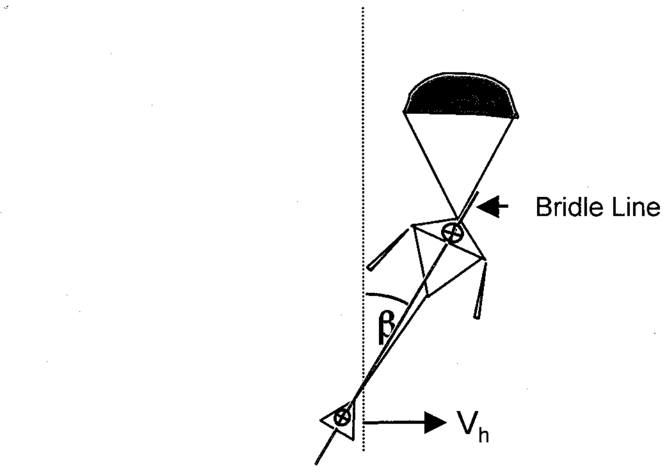
- **Definitions:**
  - *Initial Horizontal Velocity*
    - Steady State winds
    - Parachute instability (I.e. trim angle) induced
  - *RAD Induced Horizontal Velocity*
    - Wind Shear
    - Parachute instability
    - Uncontrolled
      - RAD rockets thrust mismatch induced
      - RAD rockets misalignment induced
      - Backshell c.o.m. offset induced
      - Bridal confluence point offset induced



Initial Horizontal Velocity   RAD Induced Horizontal Velocity

$$V_h(t_{bc}) = \underbrace{V_h(t_{RAD})}_{\text{Initial Horizontal Velocity}} + \underbrace{\int F_{RAD}/m * \sin(\beta)\, dt}_{\text{RAD Induced Horizontal Velocity}}$$

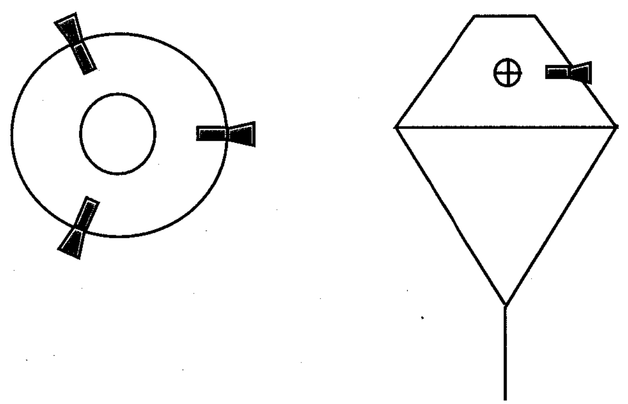
- **Example:**
  - a 20 degrees Bridle Angle angle results in an horizontal velocity of 29 m/s

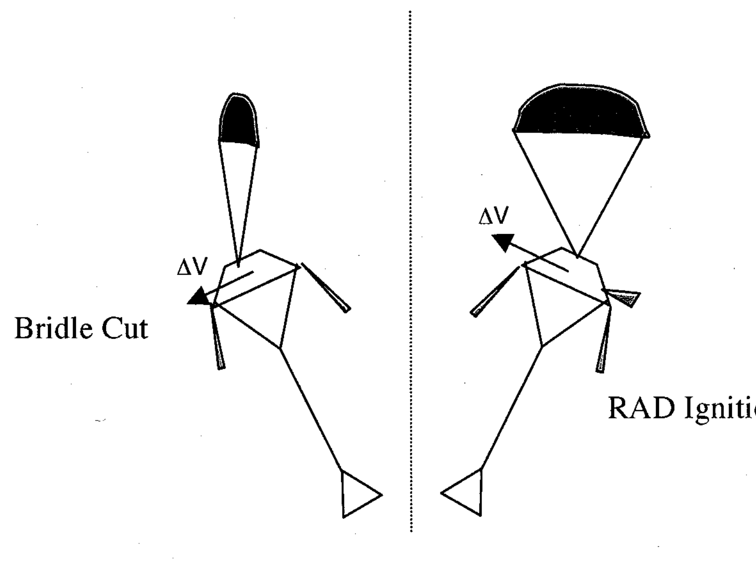
The MER Solution

- **While the vulnerability of EDL to martian winds was tolerated by the MPF project, MER had to find a solution due to the following reasons**
  - Increased landed mass
  - Some of the MER more scientifically desirable landing sites have large Steady State and Wind Shear winds (higher than the wind models used in MPF)
  - A different project risk posture
- **First the MER project decided to tackle the RAD induced horizontal velocity problem**
  - Knowledge
    - Add a 6-axis Inertial Measurement Unit (IMU) to the backshell to estimate the system multibody dynamics (e.g. β in the previous page)
  - Control
    - The project explored several ways of controlling the bridle angle during RAD firing
      - Differential RAD Firing: Ignite the RAD rockets at different times in order to generate a backshell transverse acceleration
      - Transverse Impulse Rocket System (TIRS): Add three small solid rockets aimed transversely at the backshell c.o.m.
- **Later on the project deemed that the risk due to Steady State winds was to high and added DIMES (Descent Image Motion Estimation System) to measure the horizontal velocity of the lander at the instant of RAD ignition**

TIRS Control

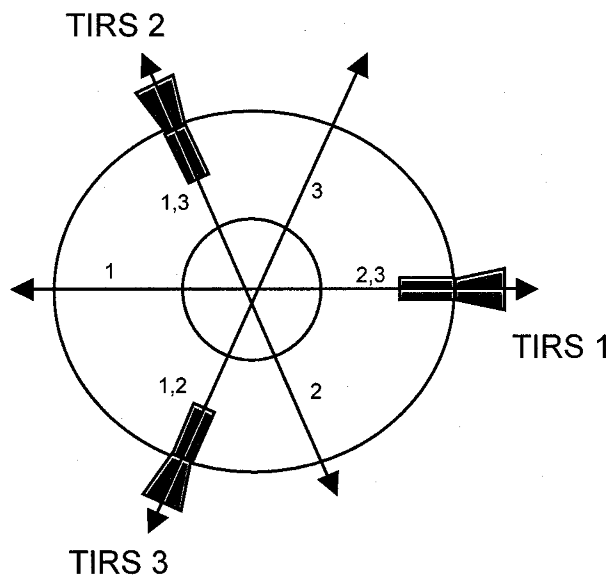
- **Add three small rockets aimed at the backshell c.o.m. to impart impulsively a transverse delta-V to the backshell in order to reduce the average off-nadir angle during RAD firing.**
  - Transverse Impulse Rocket System (TIRS)
  - Backshell deltaV = 5 m/sec
    - 40 degrees bridle angle correction in 3.3 sec of RAD firing
  - TIRS burn duration < 0.5 seconds



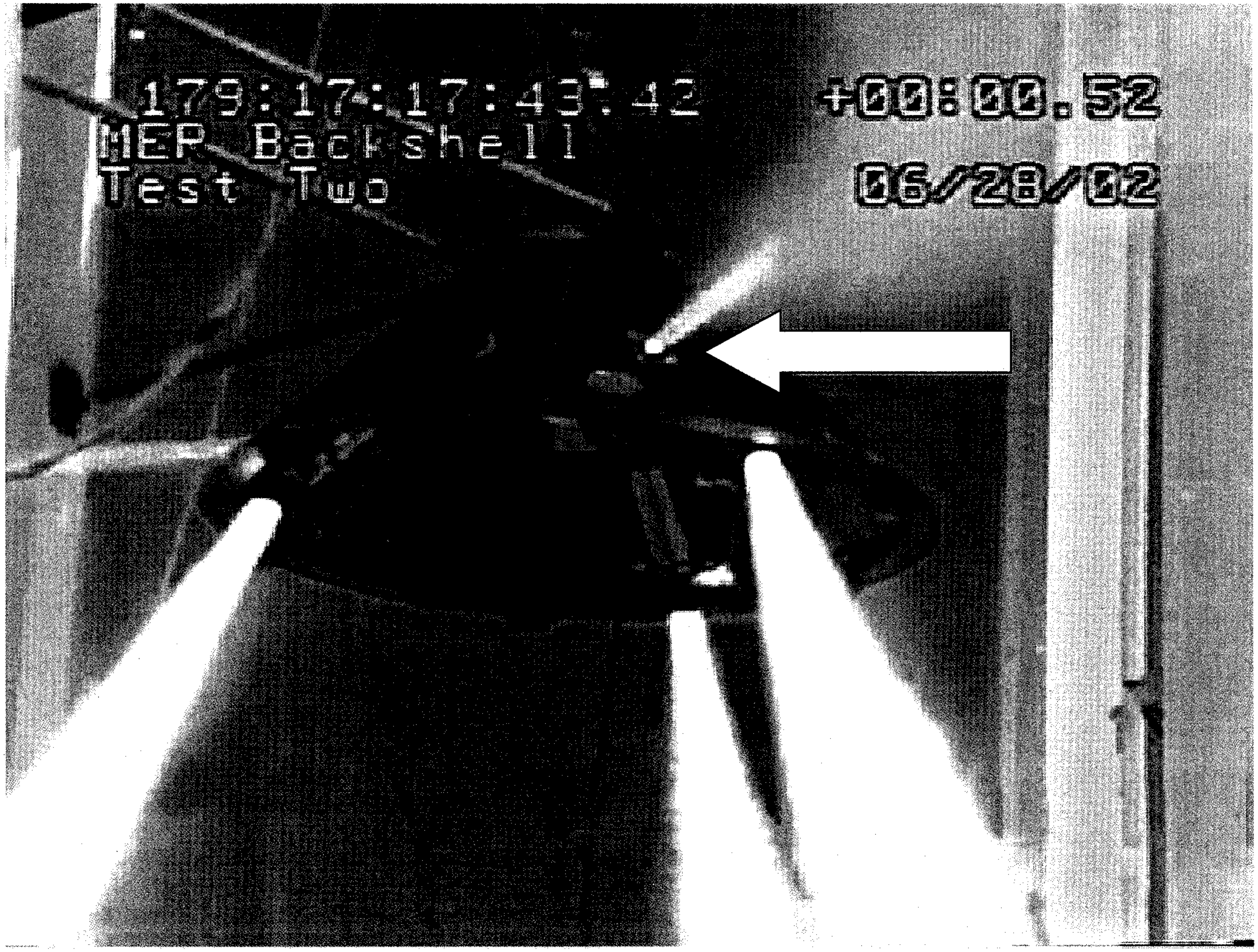


Single TIRS Control Strategy

- Fix the magnitude and direction of the horizontal velocity correction by firing at RAD ignition either a single or two TIRS rockets simultaneously
- Six TIRS rockets combinations result in a 60 degree direction quantization. The control law must pick the direction that is the closest to the predicted RAD induced horizontal velocity.
- Select the impulse of the TIRS rockets corresponding to the <u>optimum</u> horizontal velocity correction magnitude quantum



Transverse Impulse Rocket System

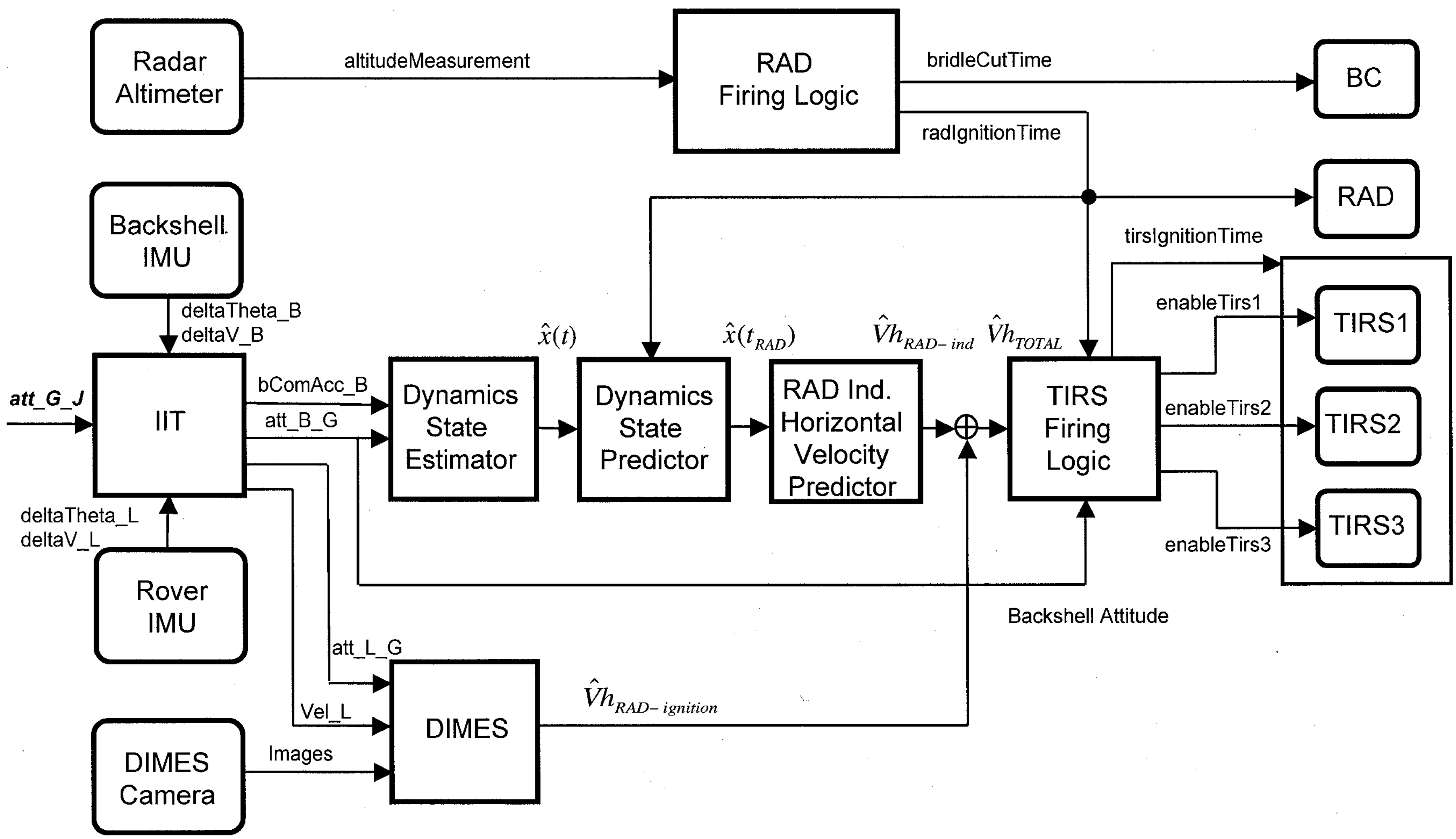


Dual TIRS Control Strategy

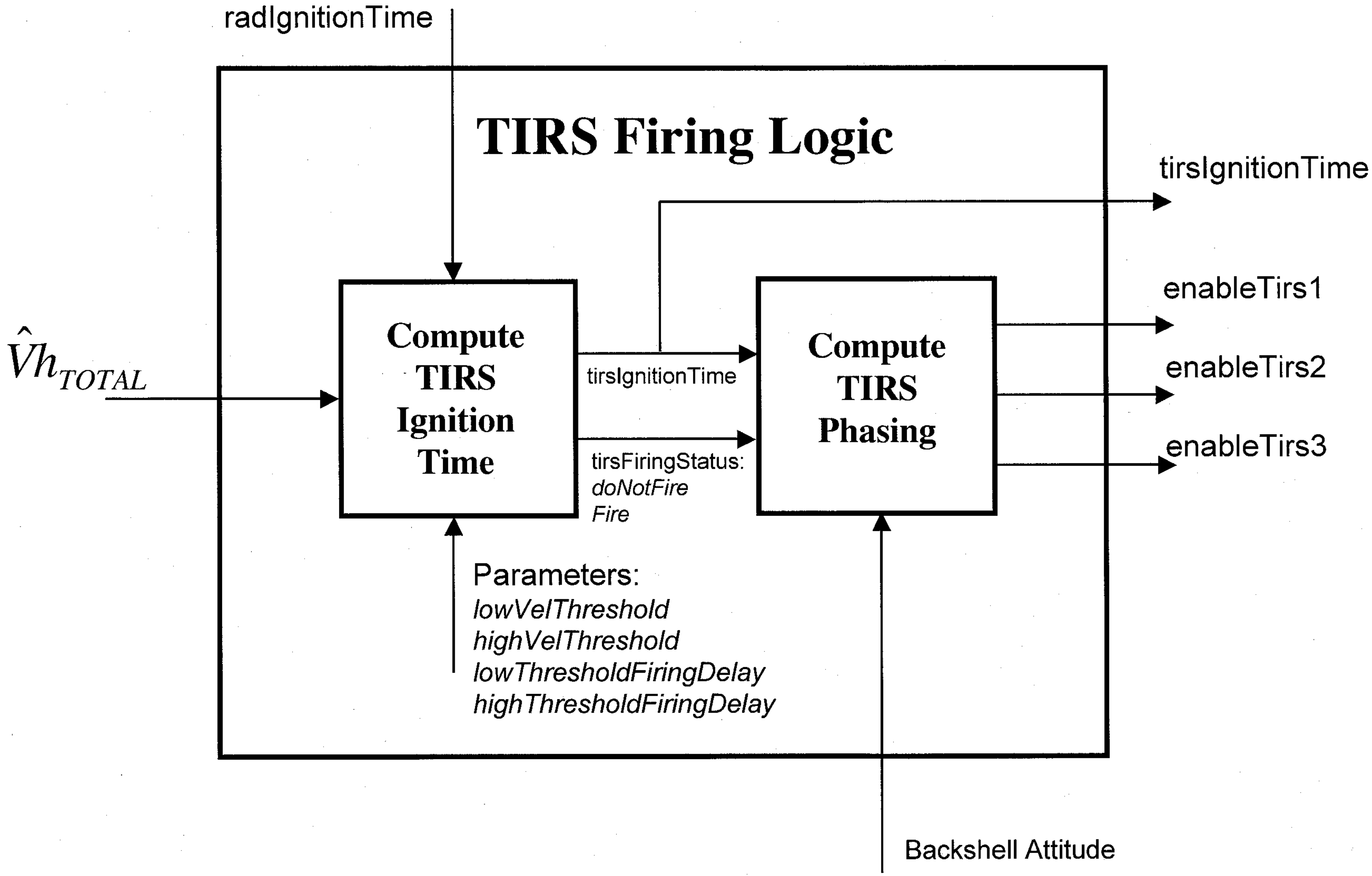
- **Later on it was determined that in order to increase the system performance more than one size of horizontal velocity correction was needed**

- **By delaying the ignition of the TIRS rockets with respect to the RAD ignition, there is less average transverse motion of the backshell during RAD firing, thus resulting in a smaller horizontal velocity correction**
  - Fire TIRS 0.2 seconds after RAD firing => velocity correction is 27 m/sec
  - Fire TIRS 1.1 seconds after RAD firing => velocity correction is 15 m/sec

Dual TIRS Architecture



Dual TIRS Architecture (Cont.)



Dual TIRS Architecture (Cont.)

- **Compute TIRS Ignition Time Logic**

  If totalHorizontalVelMag < ***lowVelThreshold***

  tirsFiringStatus = *doNotFire*

  tirsIgnitionTime = 0

  elseif totalHorizontalVelMag < ***highVelThreshold***

  tirsFiringStatus = *Fire*

  tirsIgnitionTime = radIgnitionTime + *lowThresholdFiringDelay*

  else

  tirsFiringStatus = *Fire*

  tirsIgnitionTime = radIgnitionTime + *highThresholdFiringDelay*

Dual TIRS Architecture (Cont.)

- **Compute TIRS Phasing Logic**

If tirsFiringStatus == *doNotFire*

enableTirs1 = enableTirs2 = enableTirs2 = FALSE

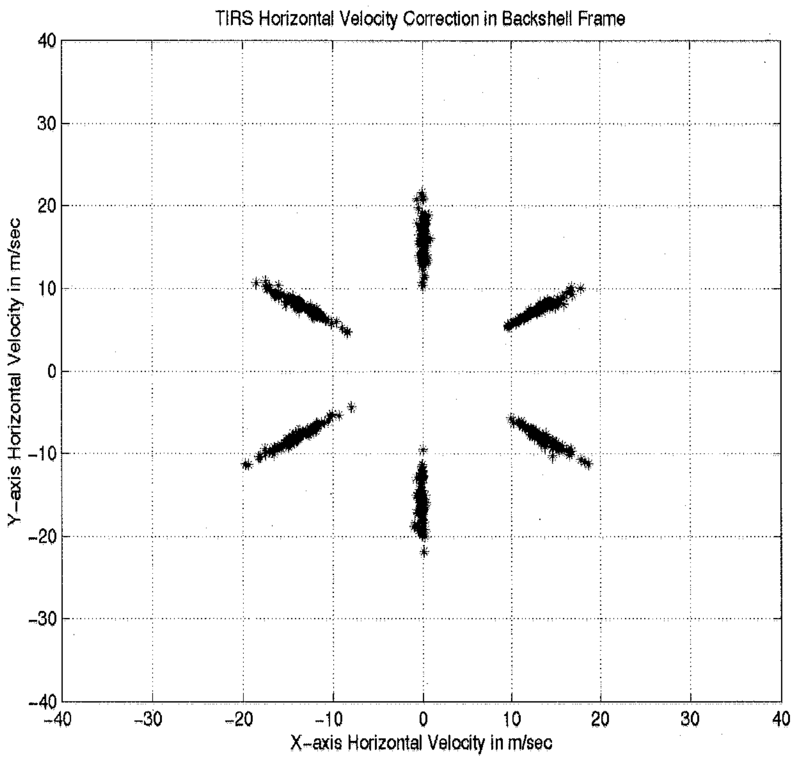
else

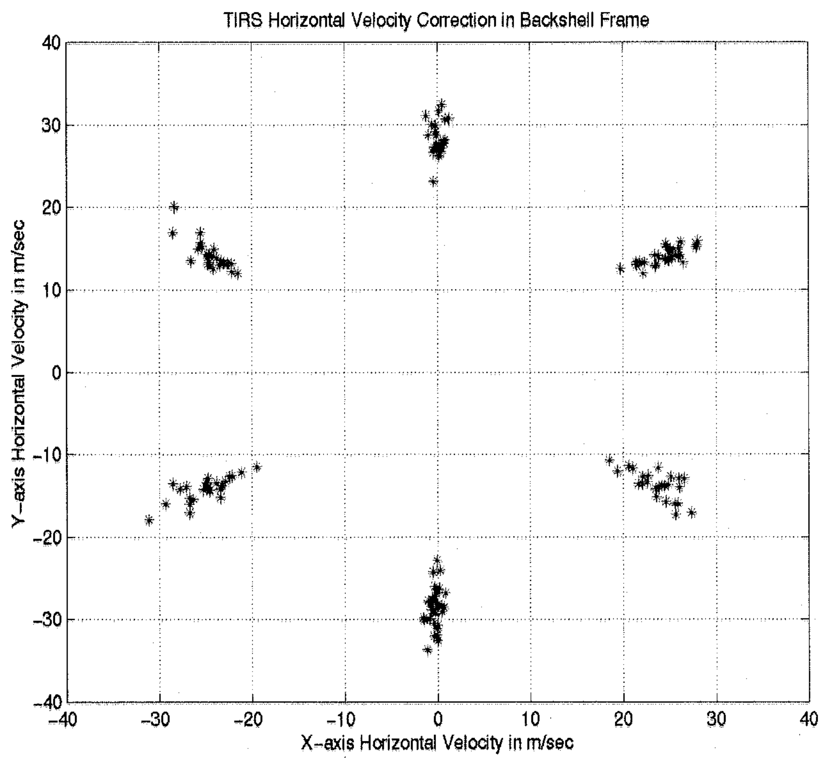
compute Backshell attitude at t = tirsIgnitionTime + 0.3 sec

transform total horizontal velocity into the Backshell frame

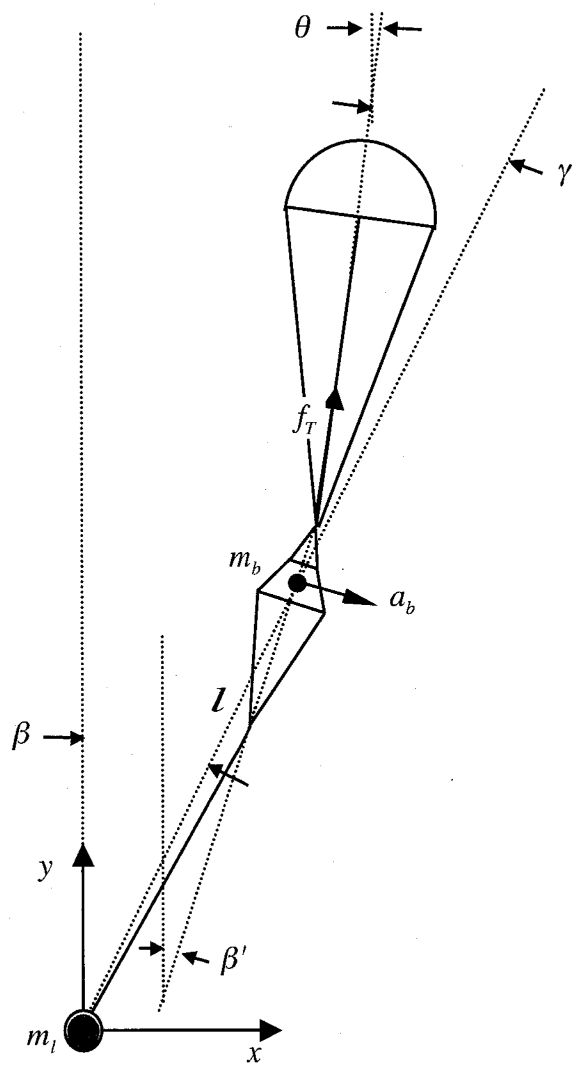
determine TIRS combination that is closest to null horizontal velocity

Dual TIRS Velocity Correction





Geometry



β = bridle-vertical angle
β' = backshell-vertical angle (IMU)
θ = chute-vertical angle
γ = chute-bridle angle
l = backshell-lander distance
m_b = mass of backshell
m_l = mass of lander
m_p = mass of chute
a_b = transverse backshell acceleration (IMU)

RAD Induced Horizontal Velocity Prediction

- **The Predictor implementation assumes a linear relationship between the system dynamic state at the instant of RAD firing and the resulting induced horizontal velocity**

$$V_{h_i}(t_{cut}) = \frac{\partial V_{h_i}(t_{cut})}{\partial \underline{x}_i(t_{RAD})} \bullet \underline{x}_i(t_{RAD})$$

where

$$i = east, north$$

$$\underline{x} = [\beta \quad \dot{\beta} \quad \theta]$$

- **The gradient is computed numerically by least-squares fitting the data generated by a Montecarlo simulation**

RAD Induced Horizontal Velocity Predictor

JPL

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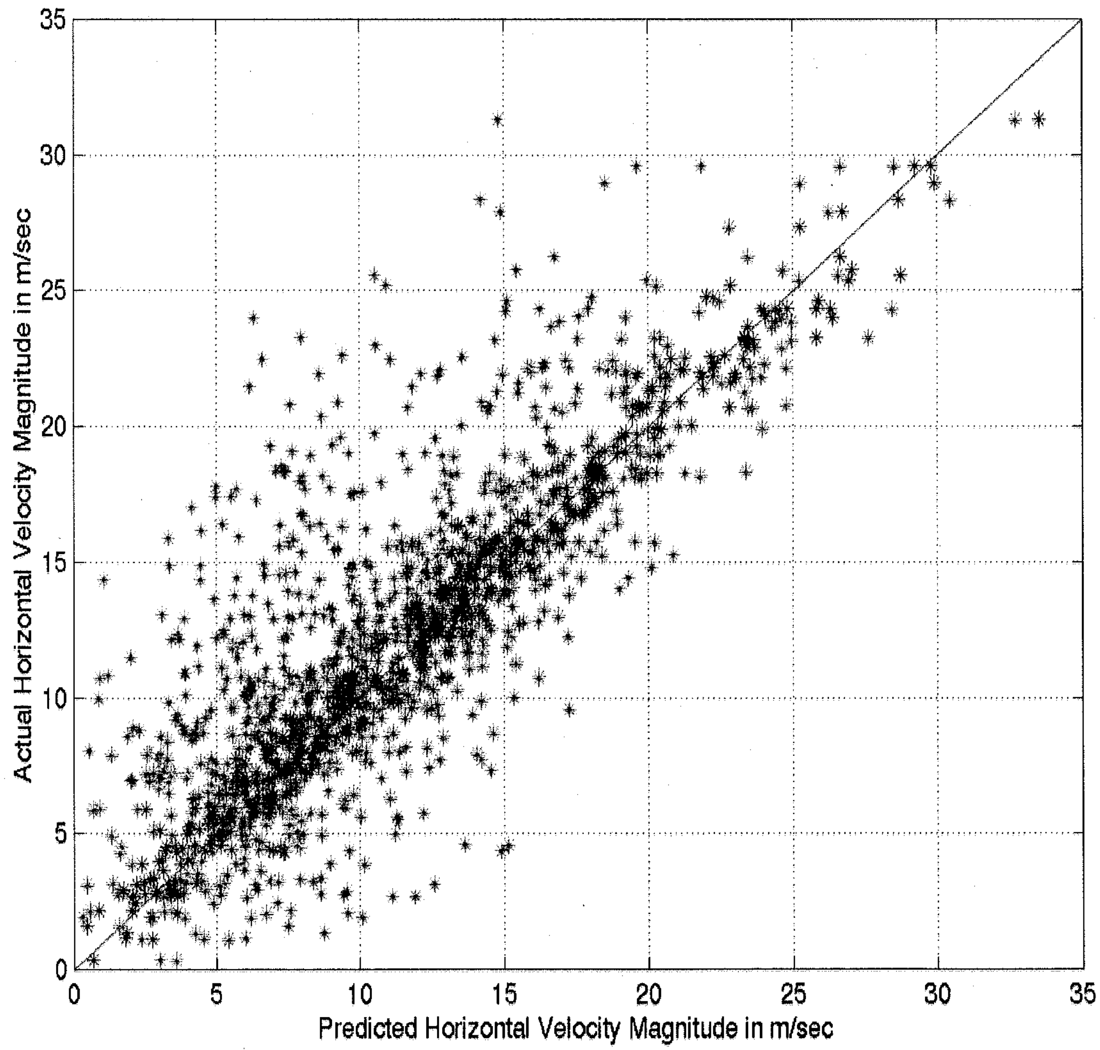


Green: β

Red: $\beta, \dot{\beta}$

Blue: $\beta, \dot{\beta}, \theta$

Dynamics State Estimator

- Given attitude and acceleration measurements from the Backshell IMU it estimates the dynamic state of the multi-body system at the current time
- Linearized dynamics equations

$$\ddot{\beta} = \frac{-f_T}{l\, m_b}(\beta - \theta),$$

$$\textit{where} \quad f_T = g_{mars}(m_b + m_l),$$

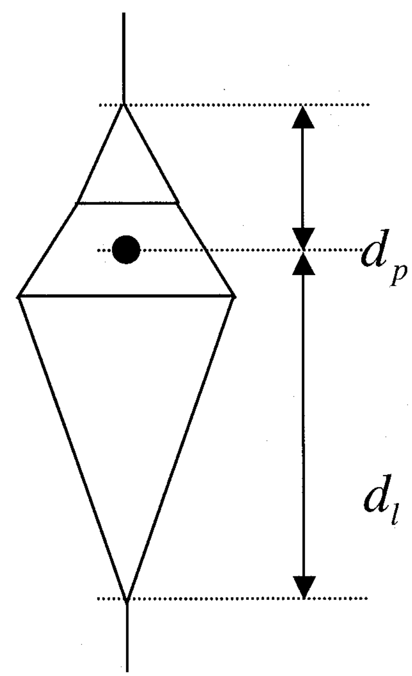
$$\dot{\theta} = n_w,$$

$$\textit{where} \quad n_w = \textit{zero mean white noise}$$

- Angle measurement equation

$$\beta' = C\,\theta + (1 - C)\,\beta,$$

$$\textit{where} \quad C = \frac{d_p}{\frac{m_l}{m_l + m_b} d_l + d_p}$$



Dynamics State Estimator (Cont.)

- **Acceleration measurement equation**

$$a_b = \frac{-f_T}{m_b}(\beta - \theta)$$

- **State Space Equations**

$$\dot{x} = A\,x + b\,n_w$$

$$y = M\,x + \upsilon$$

$$\textit{where} \quad x = \begin{bmatrix} \beta \\ \dot{\beta} \\ \theta \end{bmatrix}, \quad y = \begin{bmatrix} \beta' \\ a_b \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{-f_T}{l\,m_b} & 0 & \frac{f_T}{l\,m_b} \\ 0 & 0 & 0 \end{bmatrix}, \quad b = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$M = \begin{bmatrix} (1-C) & 0 & C \\ \frac{-f_T}{m_b} & 0 & \frac{f_T}{m_b} \end{bmatrix}$$

Dynamics State Estimator (Cont.)

- **Use Steady-State Kalman filter formulation**
  - Fixed gain K and matrices Φ and M computed on the ground
  - No on-board covariance propagation

$$x_k = [\beta_k \quad \dot{\beta}_k \quad \theta_k \quad \dot{\beta}_{k-1}], \quad y_k = \begin{bmatrix} \beta'_k \\ a_{h_k} \end{bmatrix}$$

$$\hat{x}_k^- = \Phi \cdot \hat{x}_{k-1}^+$$

$$\hat{x}_k^+ = \hat{x}_k^- + K \cdot (y_k - M \cdot \hat{x}_k^-)$$

where

$$\Phi = \begin{bmatrix} (1 - 0.5 \cdot Acc \cdot \Delta T^2) & \Delta T & (0.5 \cdot Acc \cdot \Delta T^2) & 0 \\ (-Acc \cdot \Delta T) & 1 & (Acc \cdot \Delta T) & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$Acc = \frac{g_{mars}(m_b + m_l)}{l \, m_b}$$

$$M = \begin{bmatrix} (1 - c) & 0 & c & 0 \\ g_{mars} & \frac{l}{\Delta T} & 0 & -\frac{l}{\Delta T} \end{bmatrix}$$

Dynamics State Estimator (Cont.)

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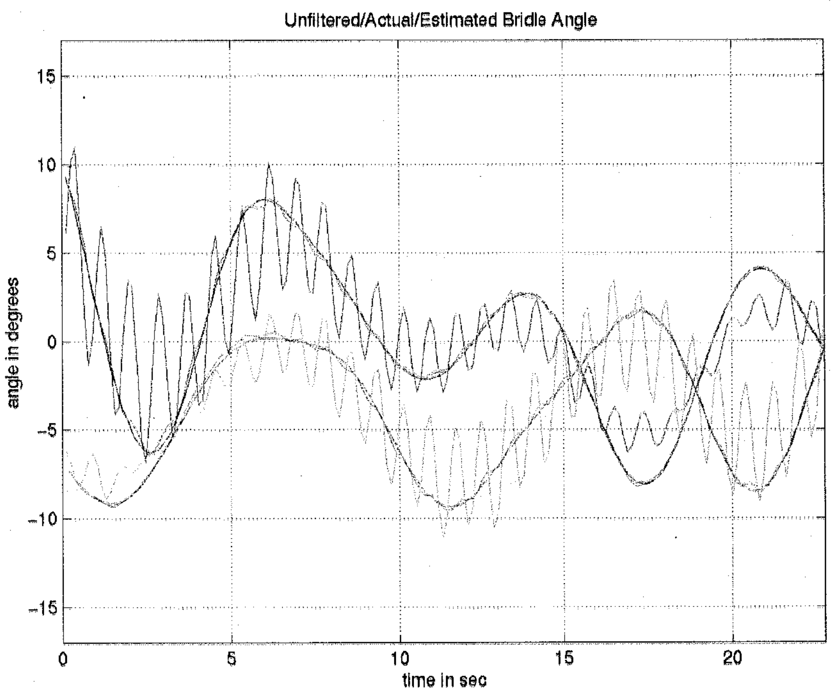

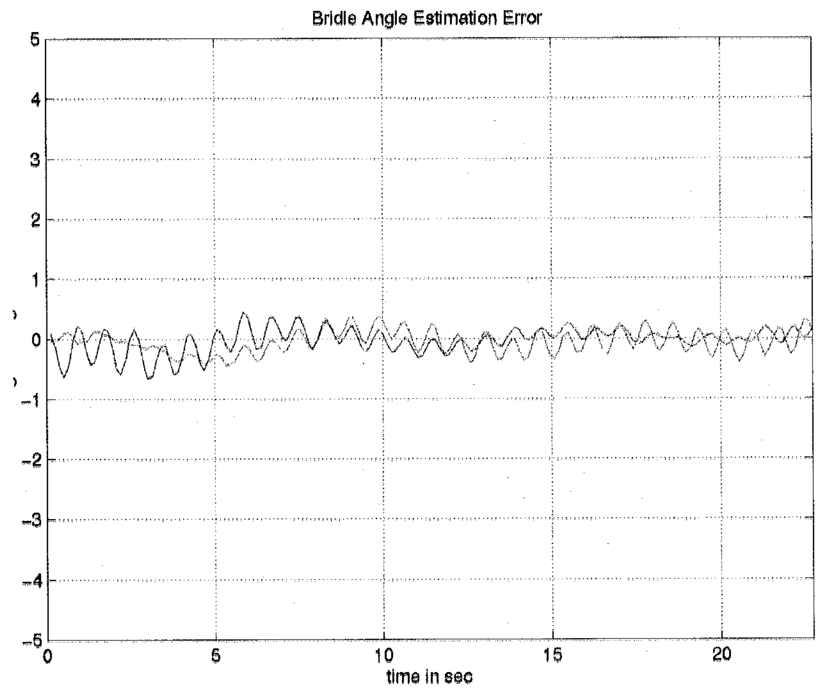

Dynamics State Estimator (Cont.)

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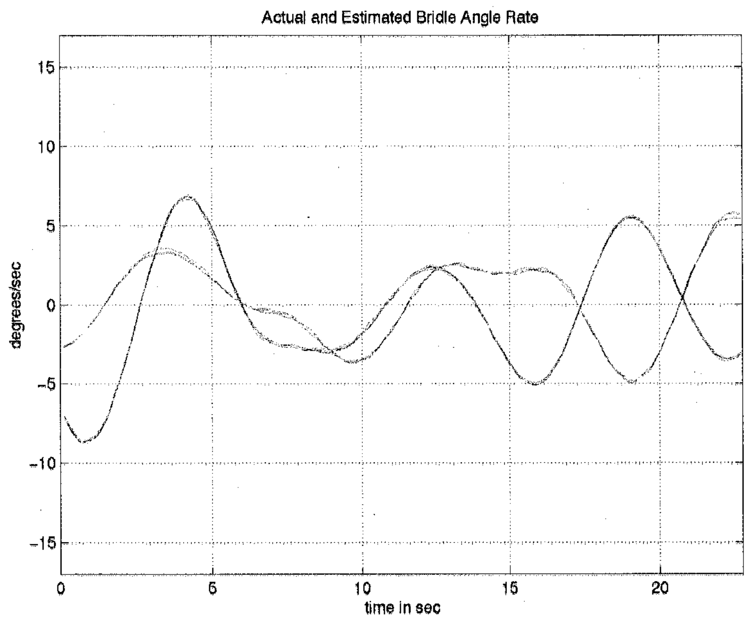

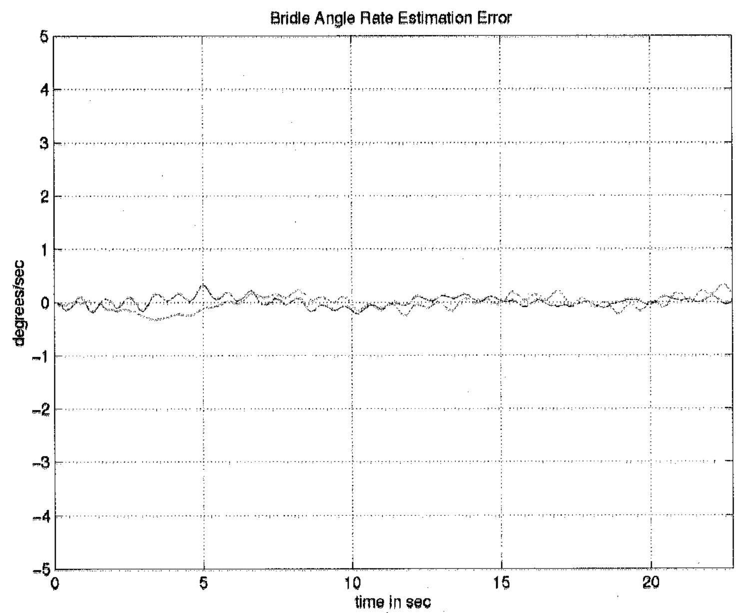

Dynamics State Estimator (Cont.)

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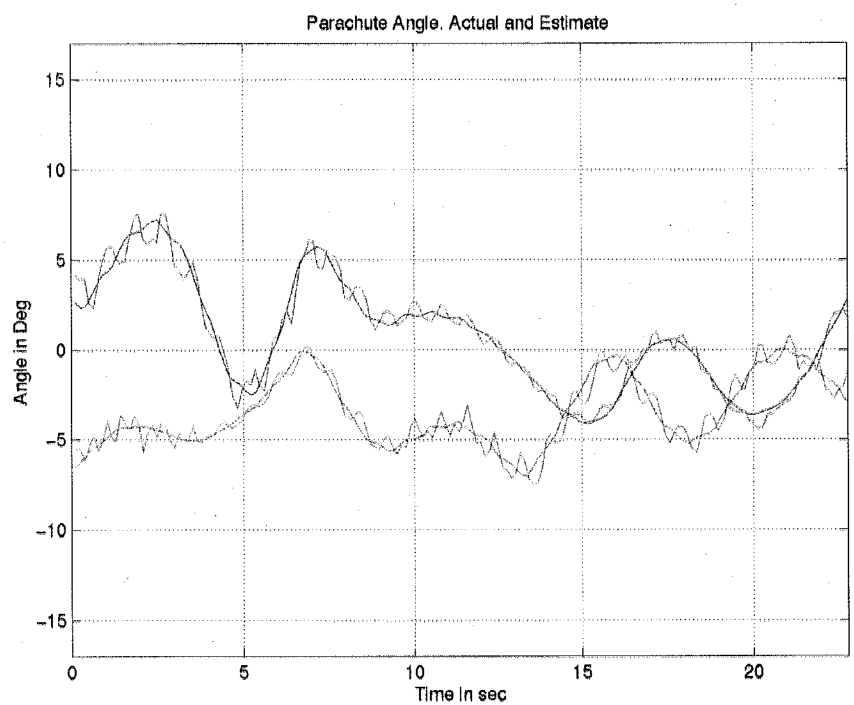

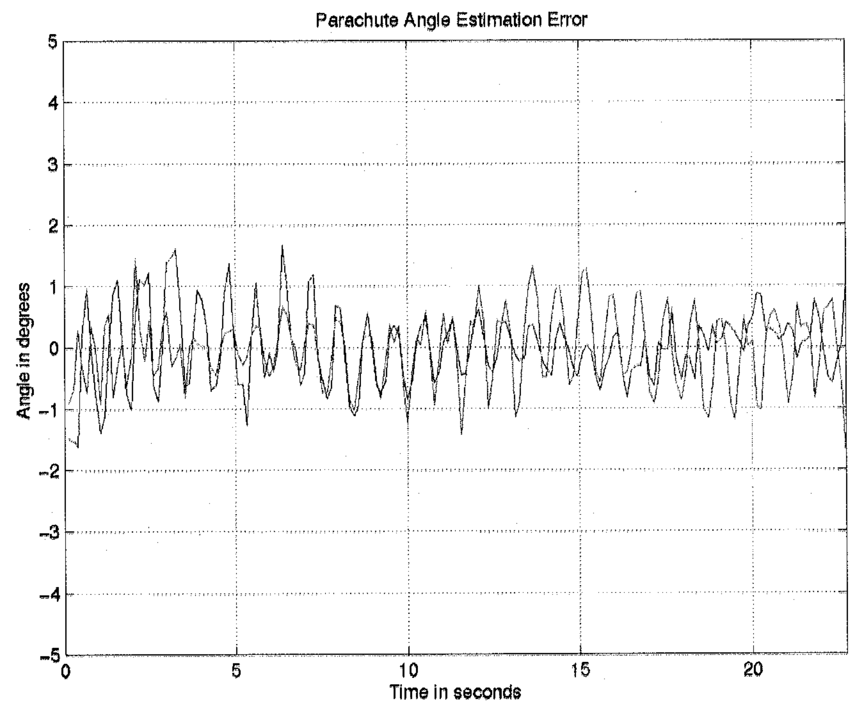

Dynamics State Estimator (Cont.)

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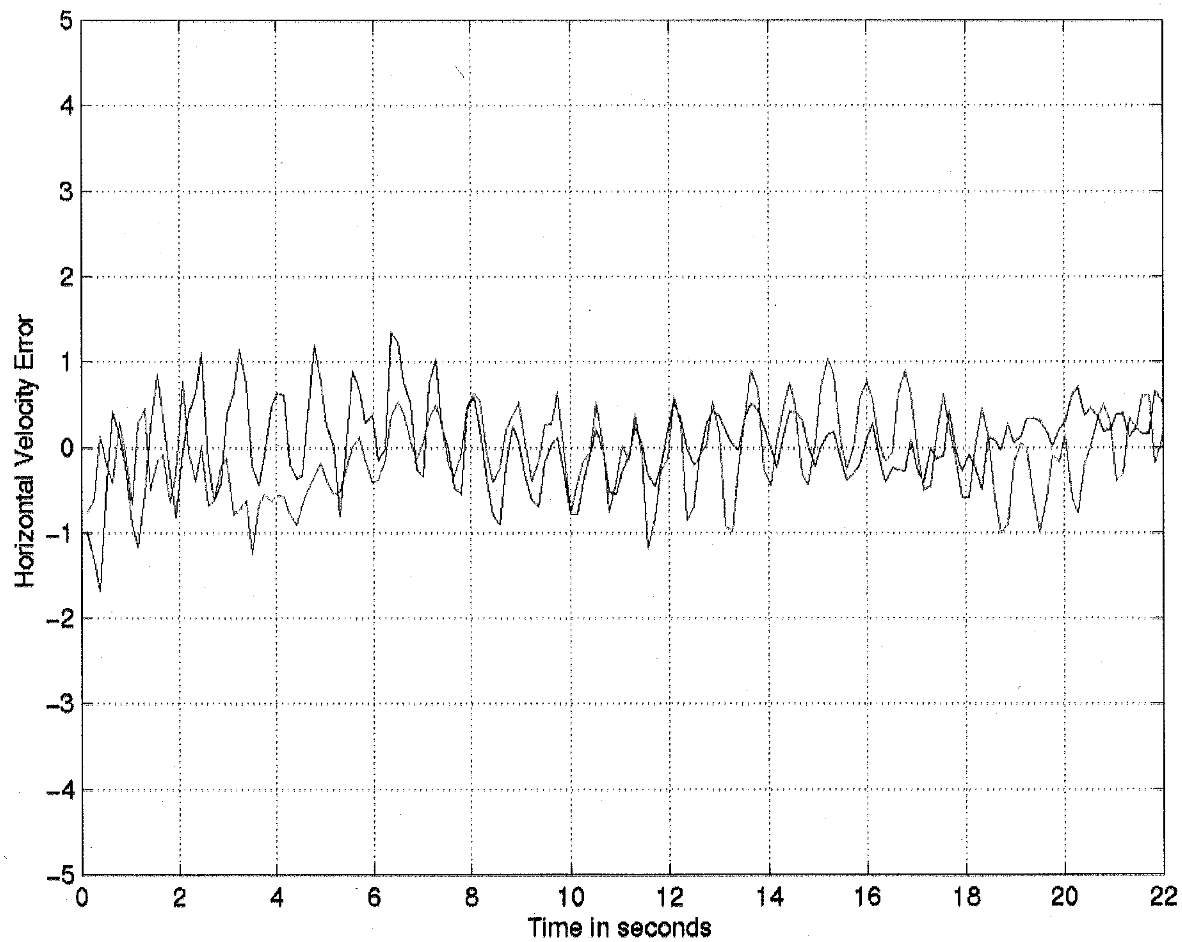

Statistcal Trade Study Tool

Summary of TIRS Dependencies

- **Multi-Body Dynamics**
  - Excited by Parachute catching the winds
- **Rotation of Backshell**
  - Initially spinning at 2Hz
  - Torques on the Backshell produced by EDL Events:
    - Lander Deployment on DRL
    - Bridle "Snatch Force" Loading
    - RAD Firing Backshell Deformation
- **All of these modeled in Monte Carlo simulations**
- **Individual contributions were shown to be either Uniform or Gaussian**
  - Within the TIRS design space
  - Confirmed by both Test and Simulation
- **Problem: Hi-Fi Monte Carlo sims take 20+ minutes to run**
- **Solution: Statistical simplification of Terminal Descent**
  - Seeded by Monte Carlo Simulation result statistics

Statistical Tool Implementation

- **Used High-Fidelity Monte Carlo Simulation Results**
  - Generated statistical distributions of errors in flight system
- **Created MATLAB command-line tool to combine individual statistical components**
  - Each component had distribution type, standard deviation, and expected value
- **Results for given configuration compared favorably to high-fidelity simulations**
  - Results agreed within 3% between MATLAB and high-fidelity ADAMS and POST simulations
- **Stat Tool operated in backshell frame velocity space**
  - Rotational effects were part of distributions in V-space gathered from high-fidelity simulations which modeled backshell dynamics and applied torques

Tool Block Diagram

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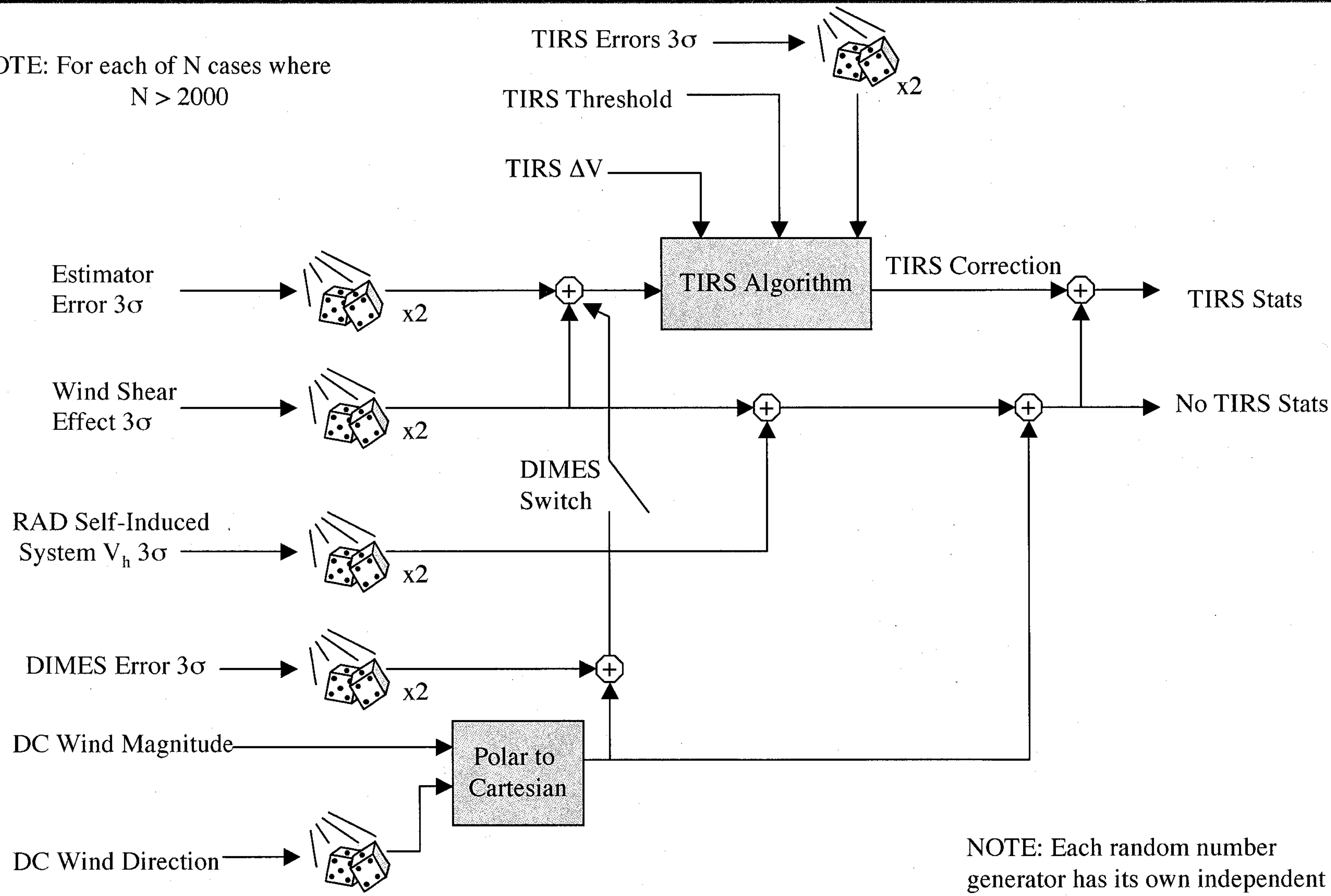
NOTE: For each of N cases where N > 2000



NOTE: Each random number generator has its own independent seed.

Studies performed with TIRS Statistical Tool

- **Isolation and Analysis of "problem" cases in velocity space**
  - False Positives and False Negatives
- **Soft goods trade studies:**
  - Effect of Changing Disk-Gap-Band (DGB) Parachute Band Height
    - Stability of Multi-Body system effected, less stable w/ shorter band
  - Effect of changes in Airbag Performance Map
    - Airbag Testing produced velocity-space success/fail map used in a separate simulation tool to evaluate ***each impact*** of airbag bounces in simulation
    - Stat Tool seeded the impact/bounce tool studies with initial conditions
    - Airbag bounce tool also produced success/fail map for Statistical Tool given bridle cut state
- **Investigation of hypothetical enhancements - both of which became real**
  - "Variable" TIRS design
    - Ability to change TIRS delta-V
    - Eventually implemented Post-Launch as Dual-TIRS
  - Steady-State Wind Sensor
    - Can sense non-multi-body lateral velocity (not sensed by IMU)
    - Study resulted in addition of Descent Image Motion Estimation System
- **TIRS triggering threshold and applied delta-V tuning**
  - Explored for "final four" candidate landing sites
  - Resulted in development of 4D visualization of landing P(success)

Data Visualization

Overall System Effect

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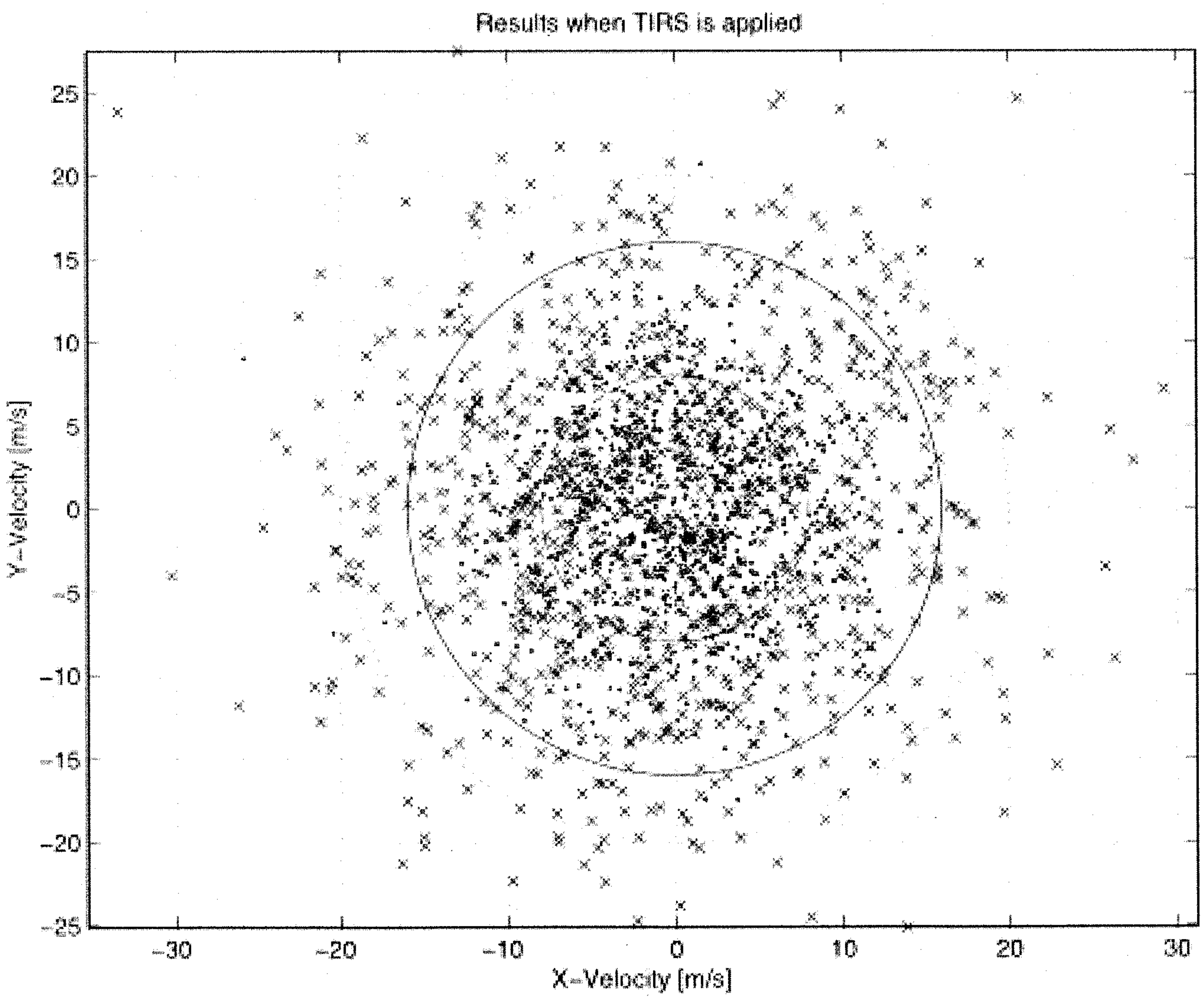
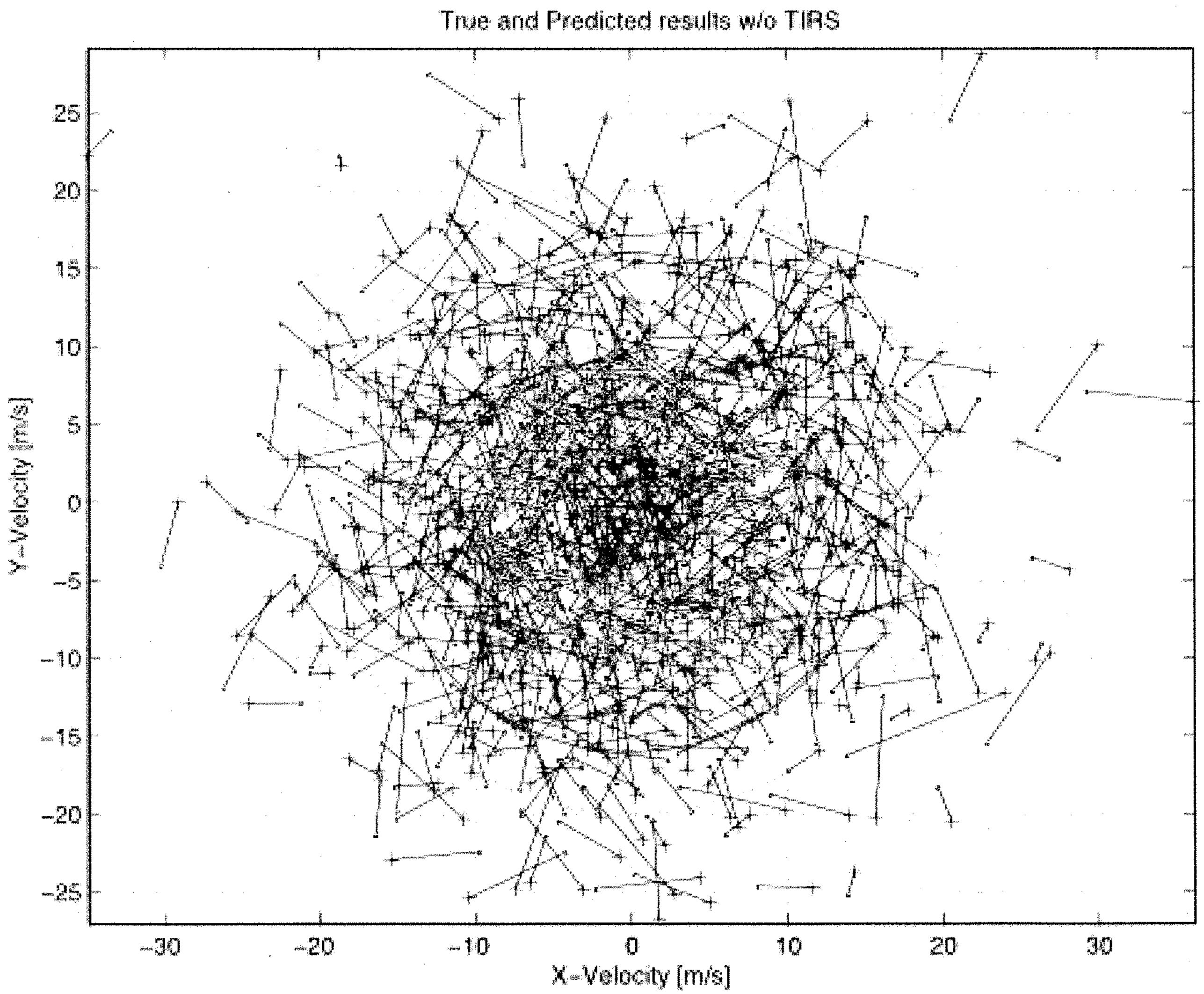


Visualizing Estimate/Actual pairs



Isolating "False Positive" Cases

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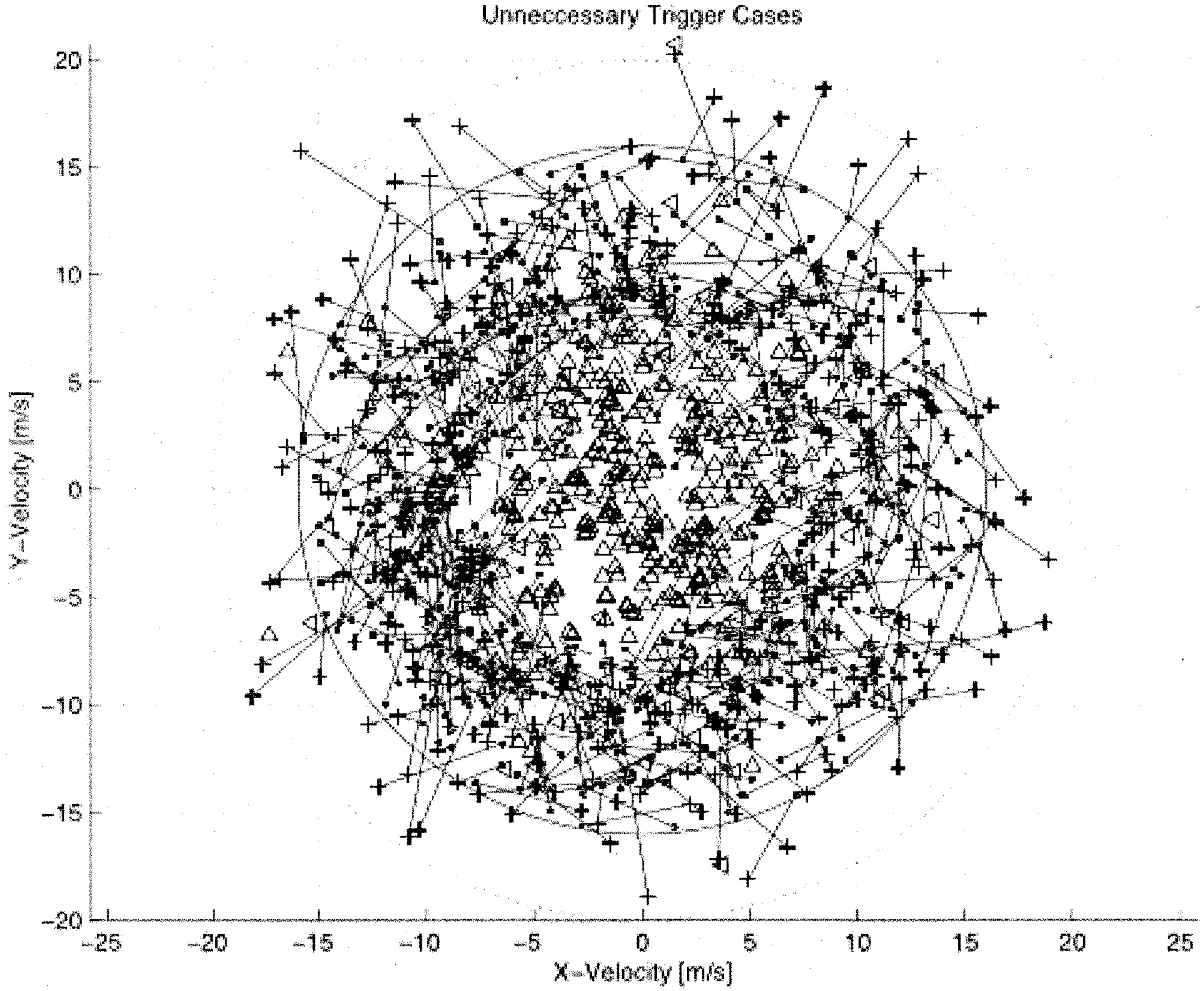

Isolating "False Negative" Cases

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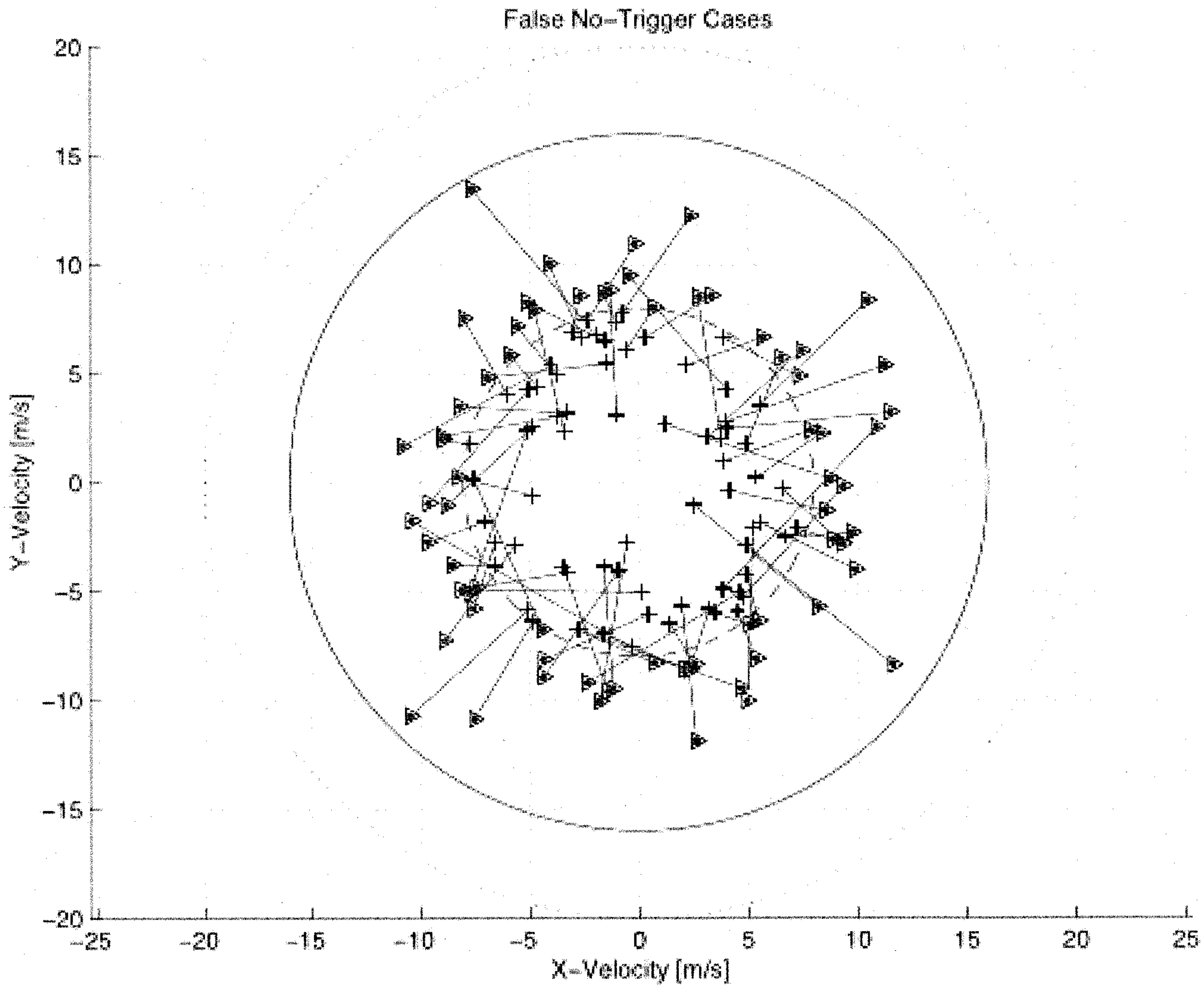

Effect of Systemic TIRS Delta-V Change

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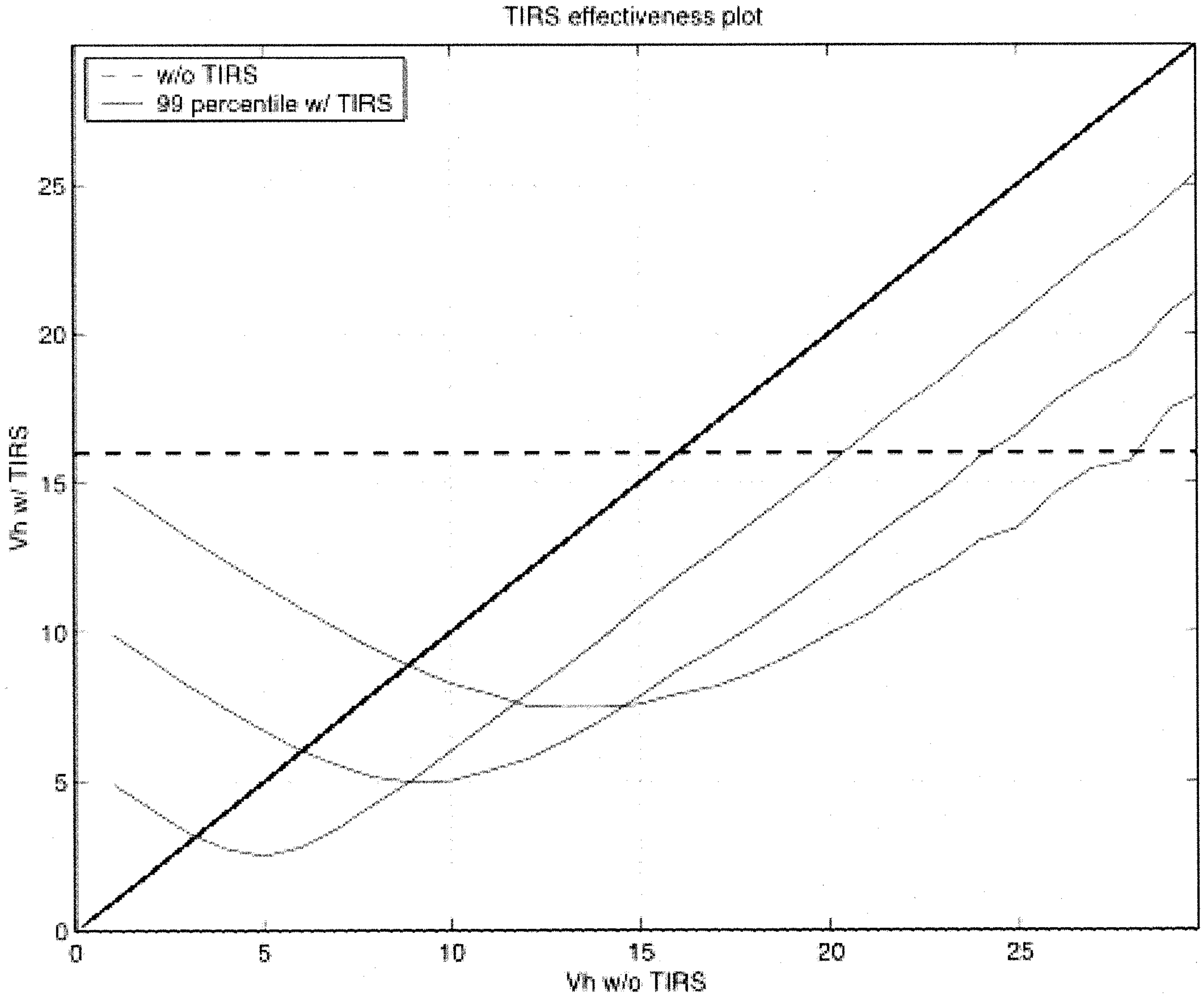

Effect of Constant-Velocity Sensor

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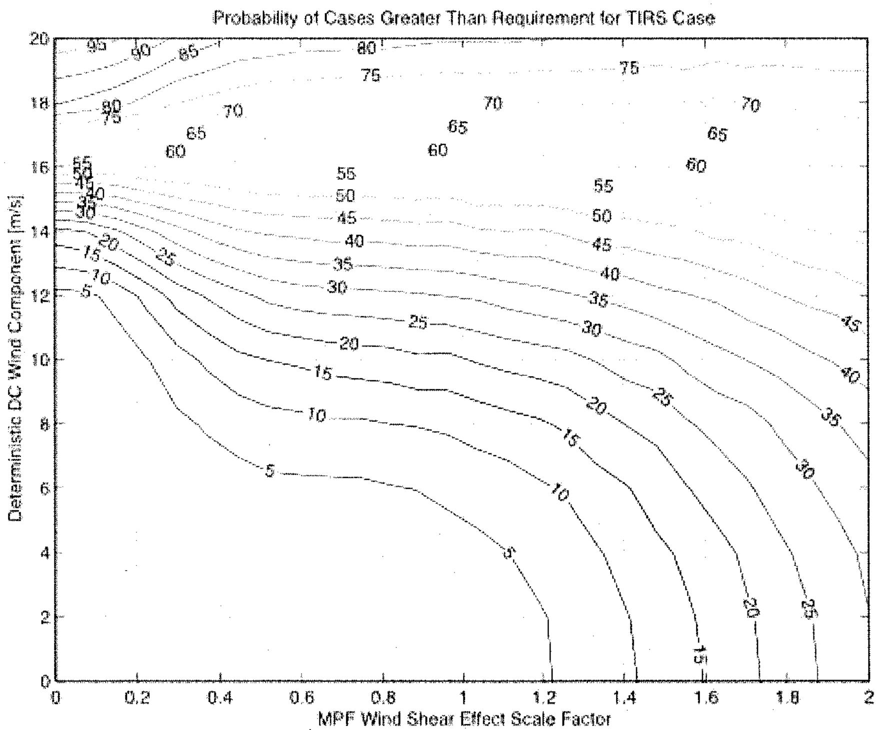

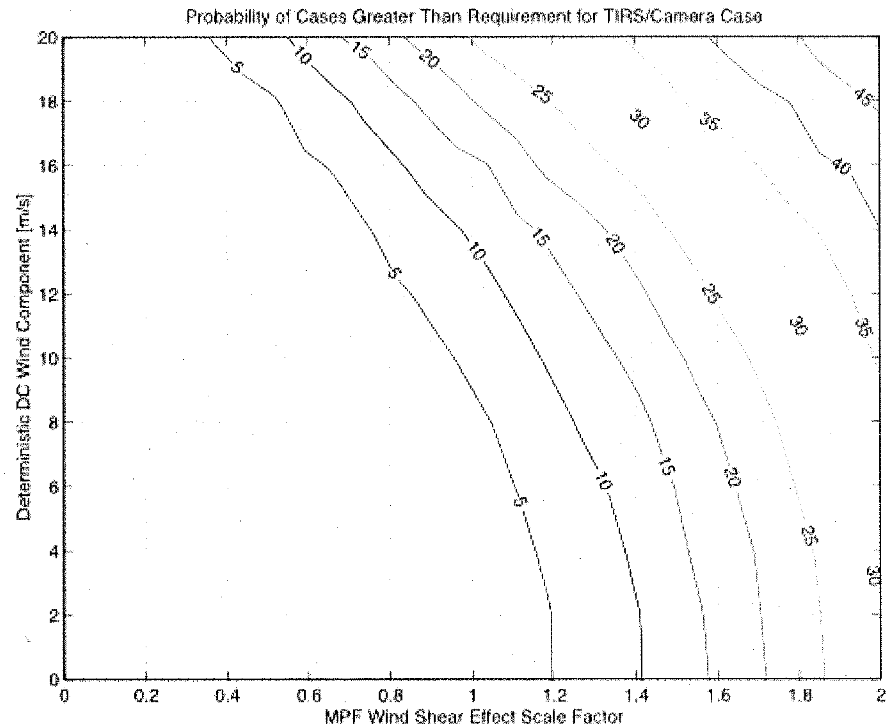

Landing Site Success Probability Surfaces

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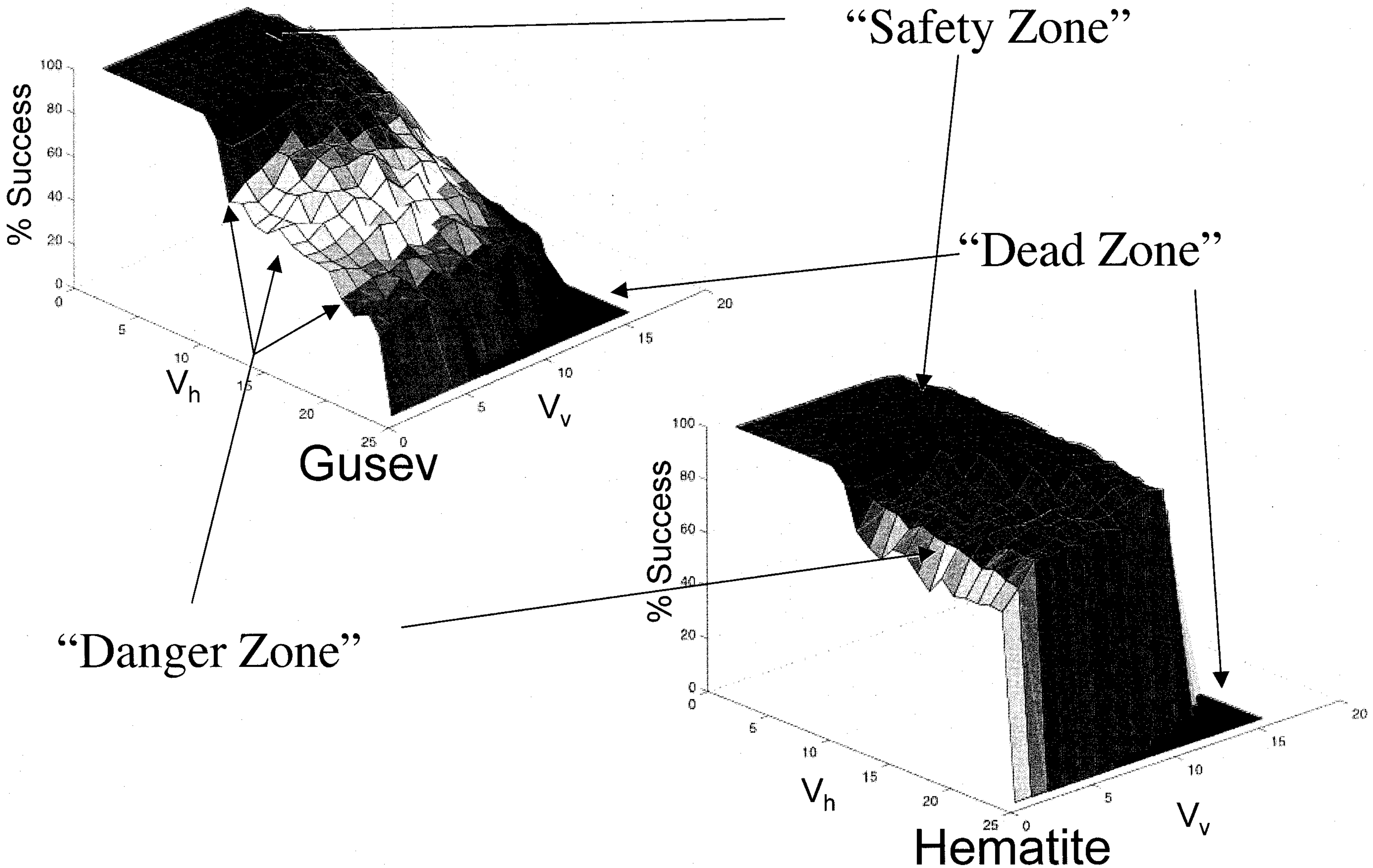

Parachute Band Reduction Effect (Gusev)

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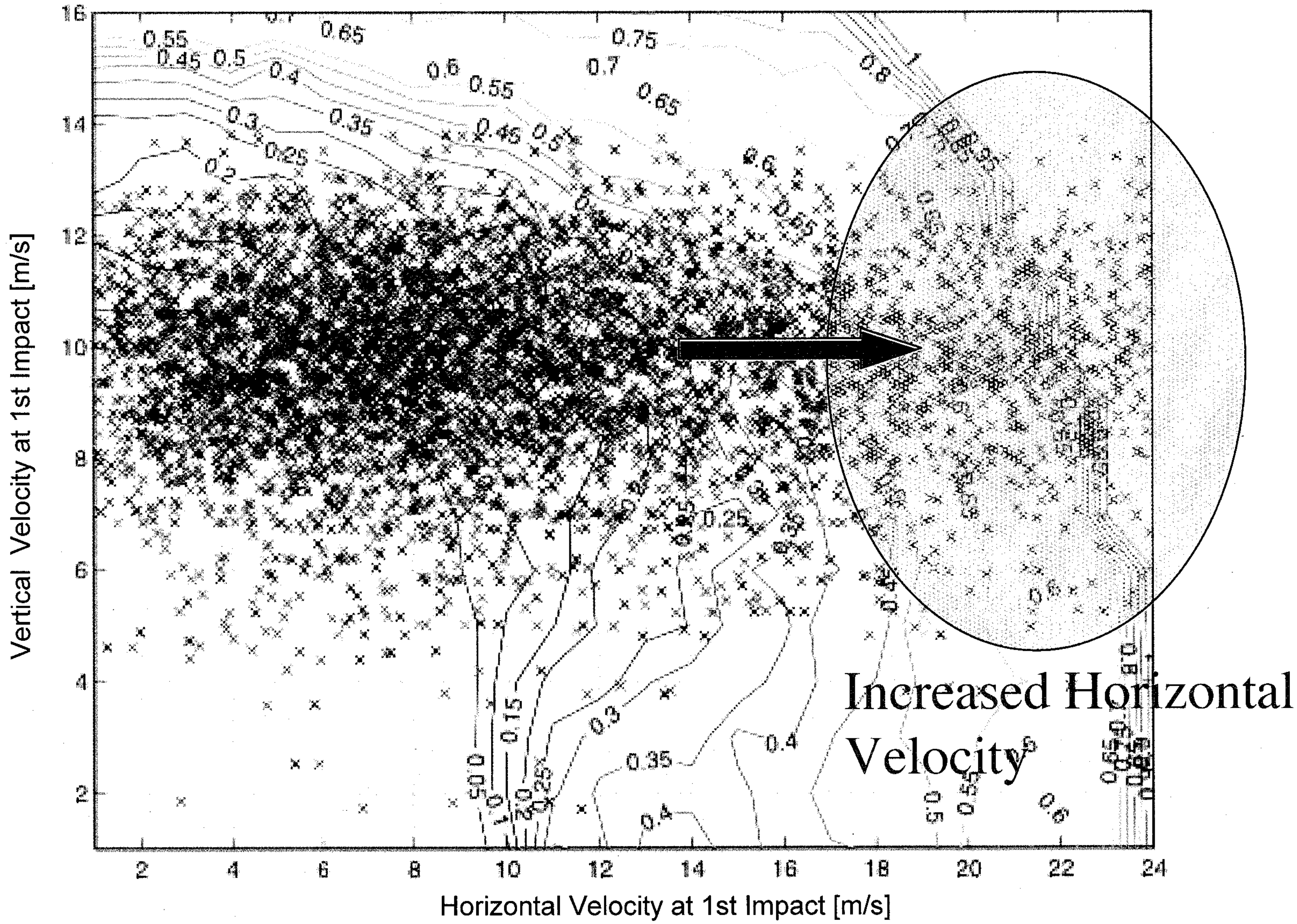

Added TIRS Impulse Effect (Gusev)

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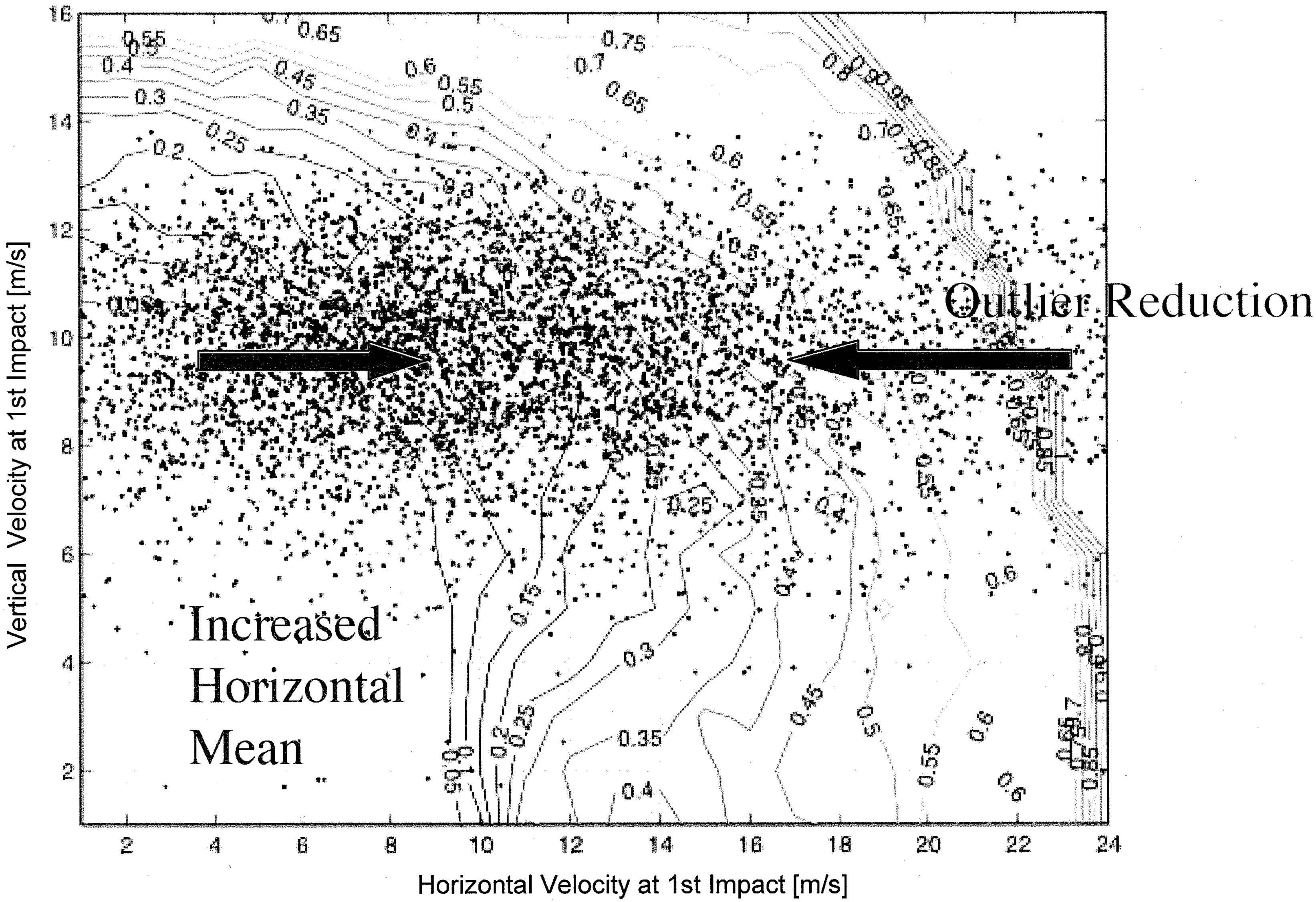

Variable TIRS & Tuned Vertical Channel

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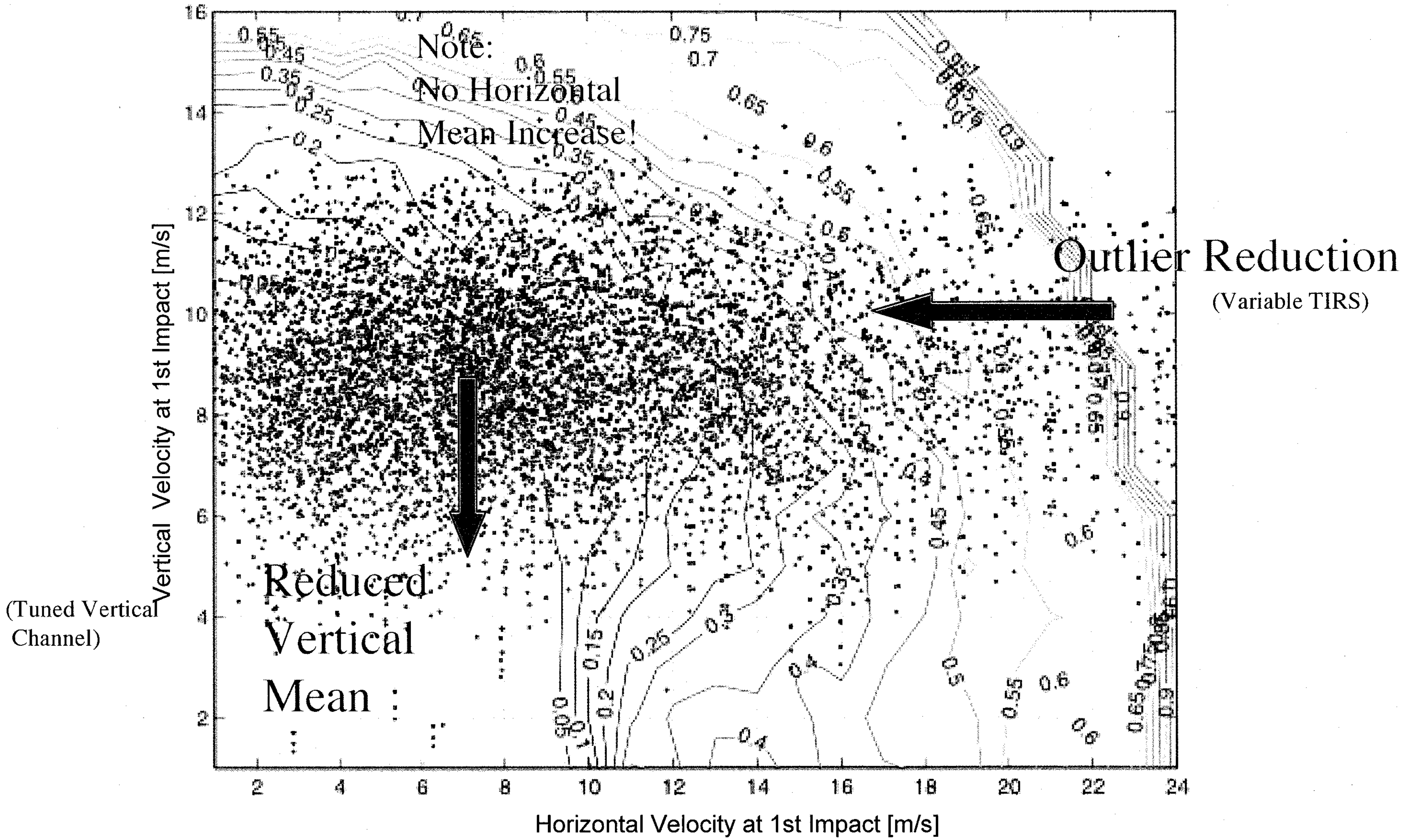

Variable TIRS becomes Dual TIRS

Description of Dual-Threshold TIRS

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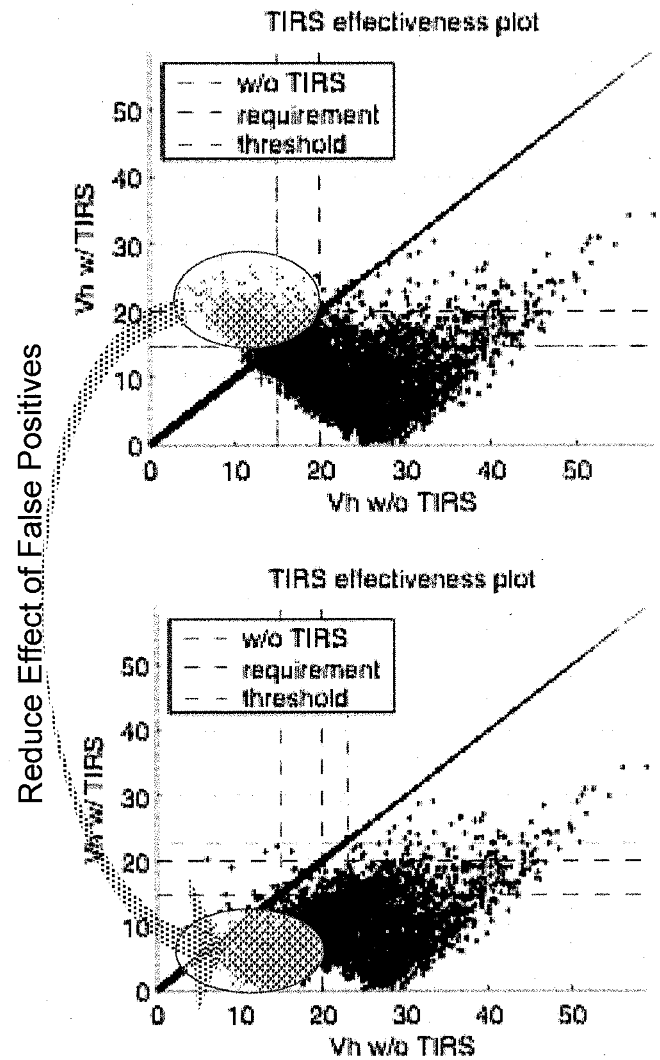
- **Concept to address review board concerns**
  - High ΔV
  - Comparatively low Threshold
  - Large Estimation Errors
- **Reduces effects of False Positives with a "Big Stick"**
  - Adds second threshold
  - Uses delayed TIRS firing to reduce ΔV
- **Does not address control authority limitations**
  - High wind failures not addressed
- **Requires IMU & IIT to function through RAD burn**
  - Enables proper TIRS selection
  - IMU/IIT Error tolerance not yet investigated



What is "Dual Threshold" TIRS?

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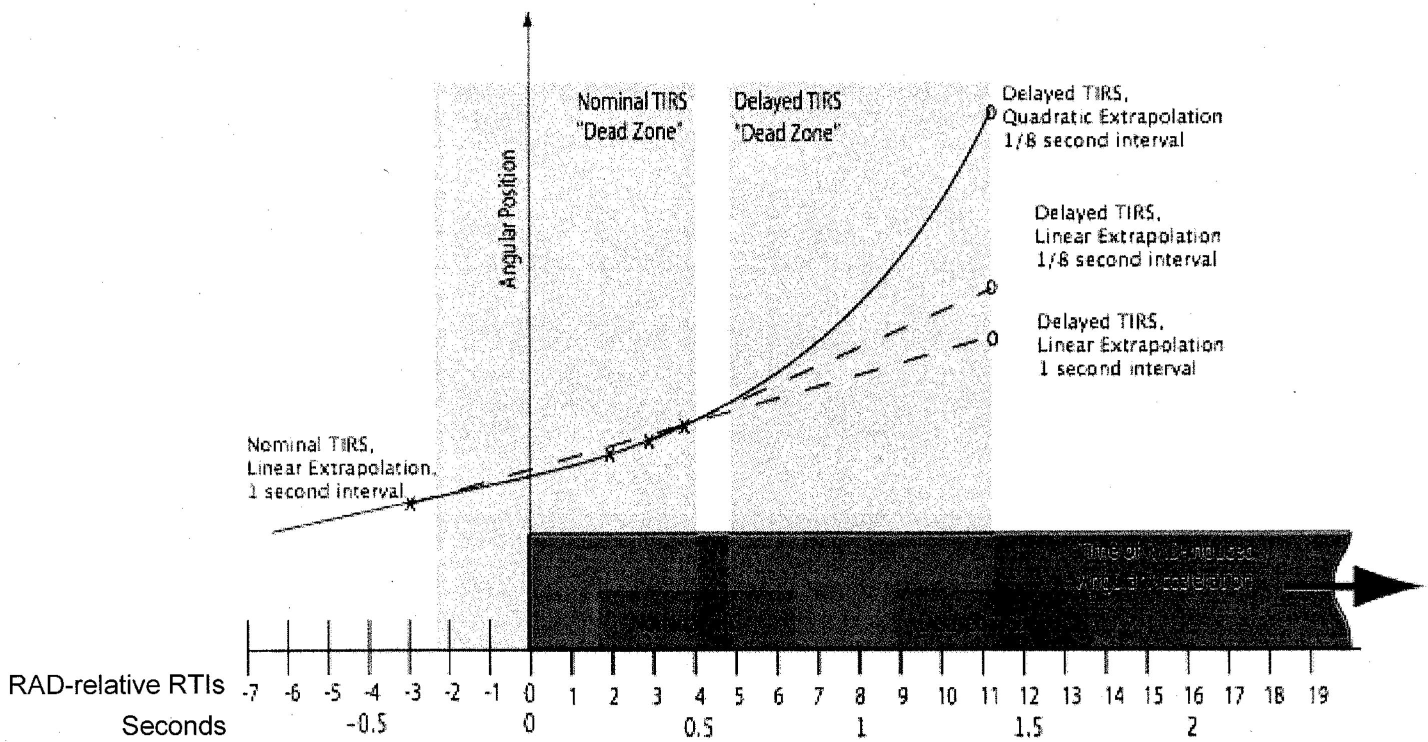
- **Two-state, descretized TIRS**
  - Greatly reduces self-induced system degradation of false positive cases
- **Conceived, tested, pitched, and implemented *POST-LAUNCH***
  - Software change was implemented using hooks already placed in the FSW
- **Uses what little flexibility we have in timing the firing of the TIRS**
  - Simple 2nd-order angular acceleration predictor to extends window
- **By firing later, we get LESS pitch over during RAD firing (reduced delta-V)**
  - dual-trigger system with two activation thresholds and corresponding lateral delta-Vs



Baseline TIRS

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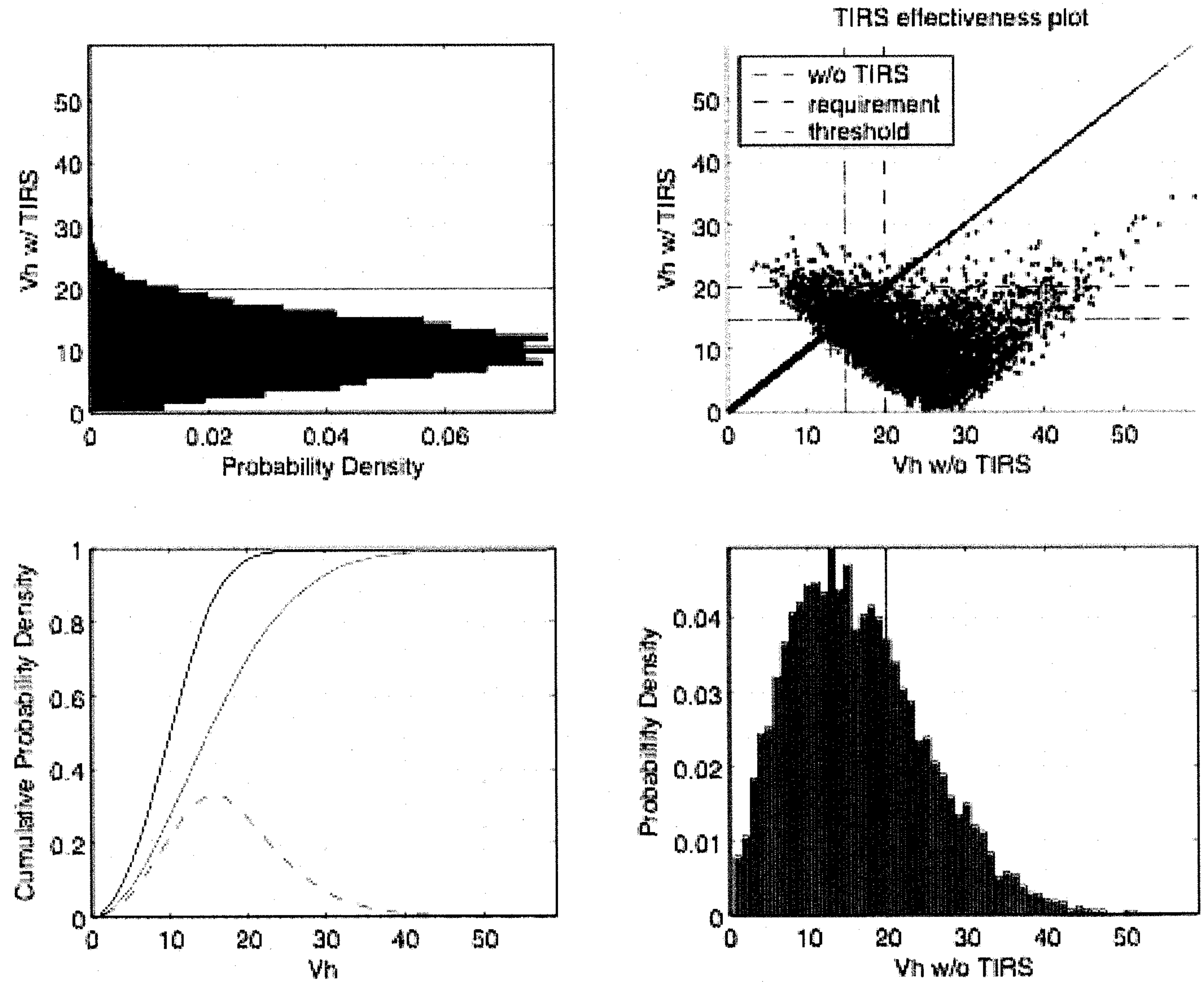

Dual-Threshold TIRS

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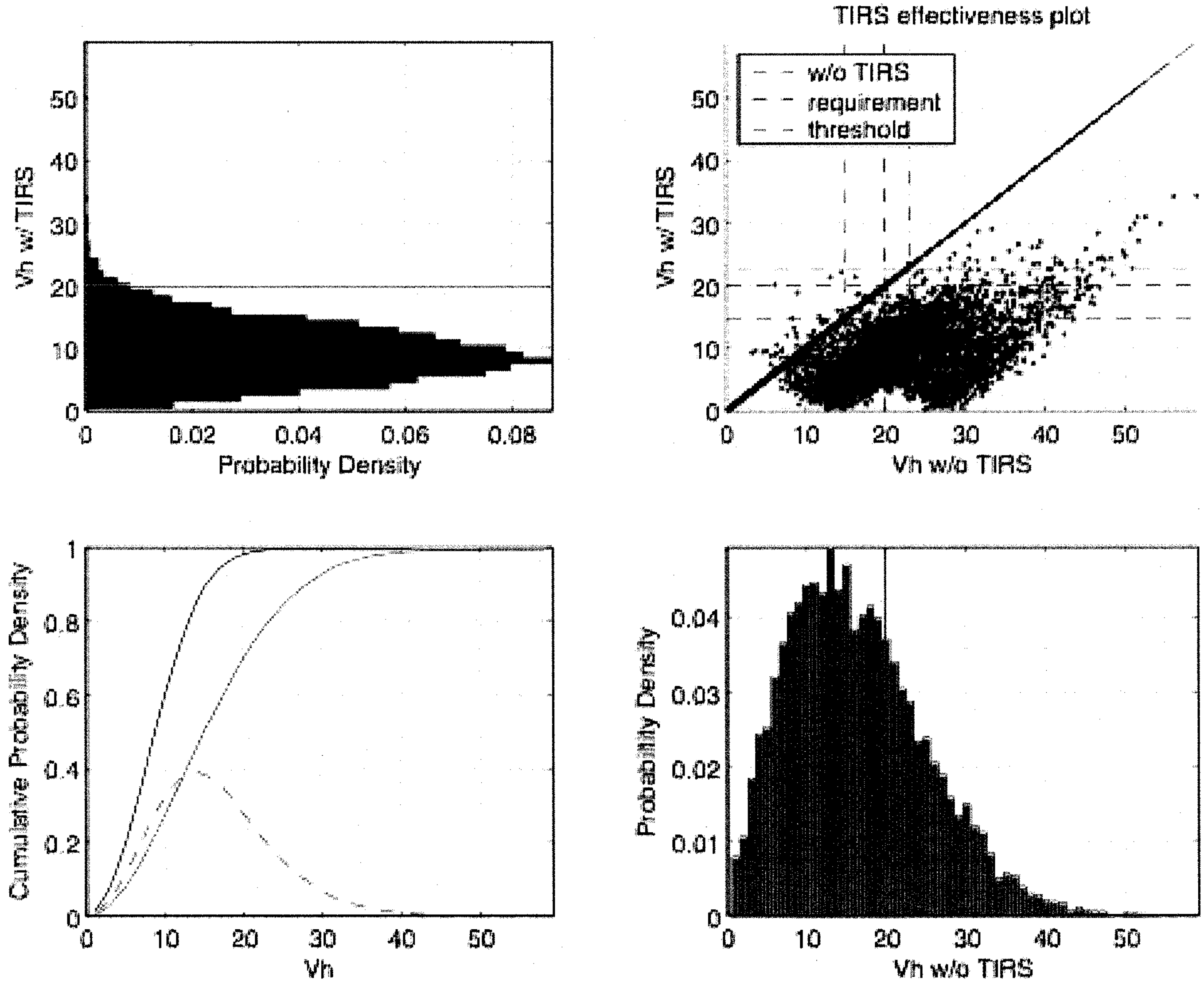

CDF Comparison

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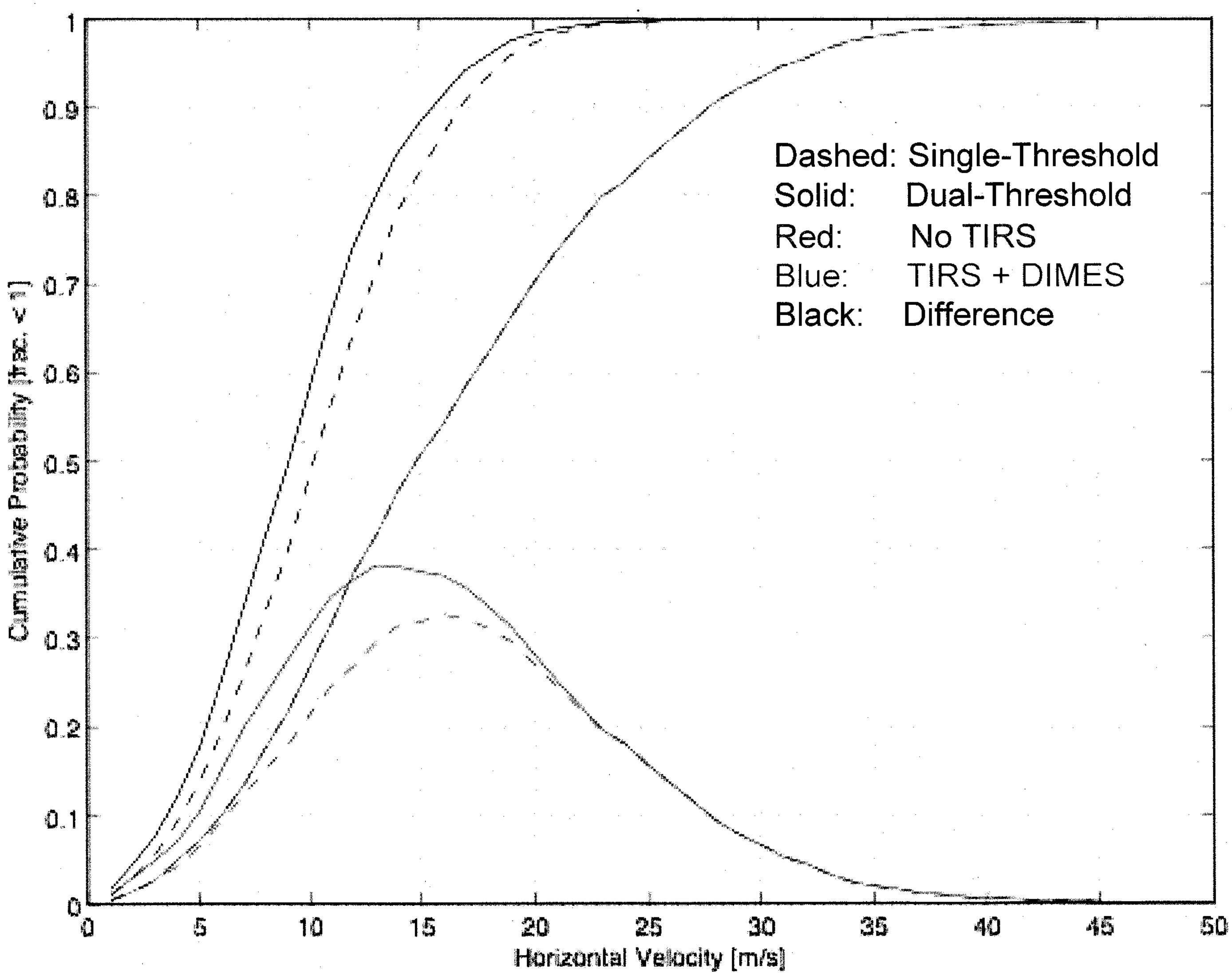


Flight Performance

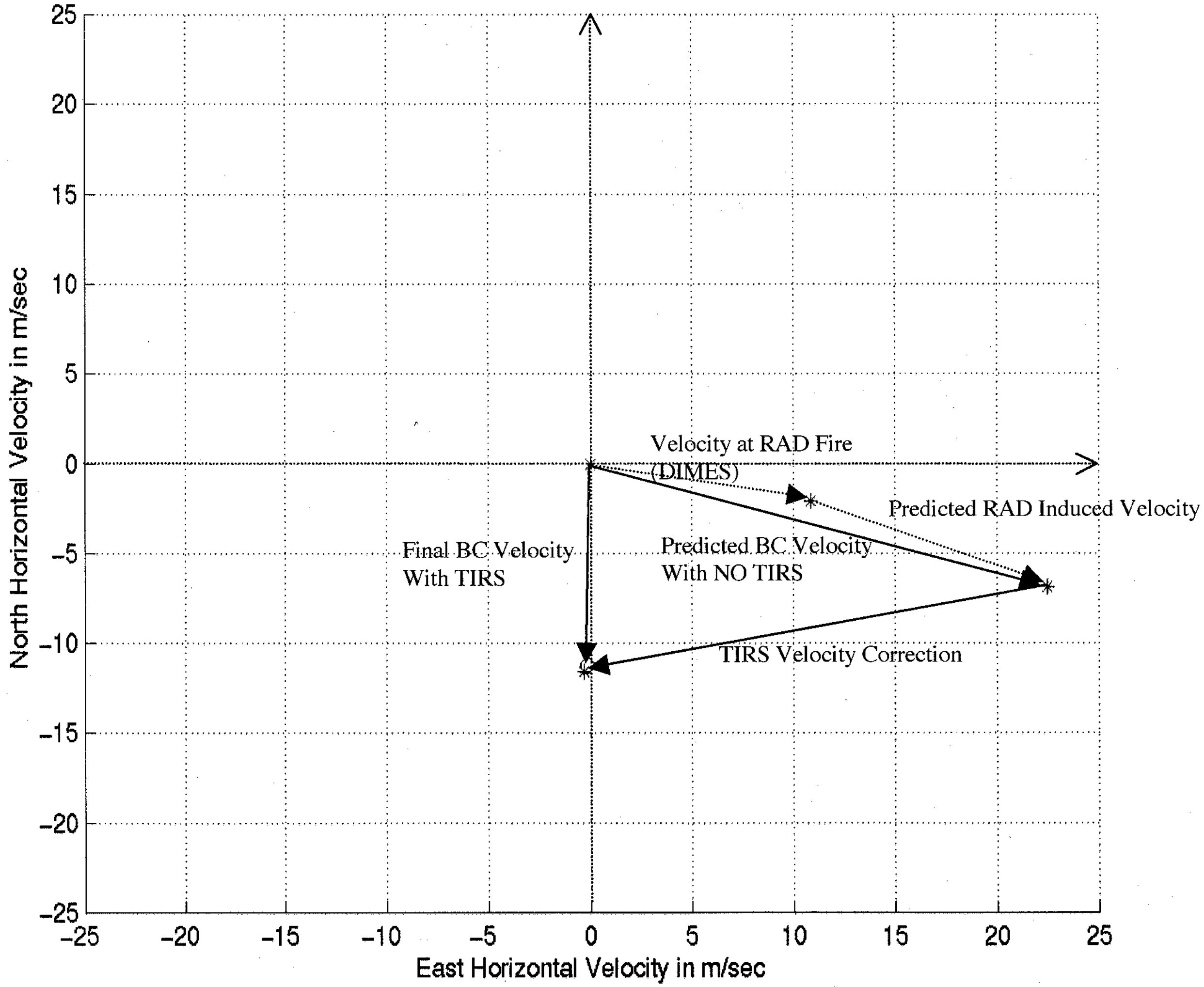
Spirit TIRS Flight Performance

- **BIG TIRS WAS FIRED**
  - ~23m/s correction

- **Predicted RAD Induced Hor. Velocity without TIRS:**
  - North = -5.67 m/s , East = 11.73 m/s
- **Hor. Velocity at RAD Ignition (DIMES):**
  - North = -1.18 m/s, East = 10.73 m/s
- **Total Predicted Hor. Velocity without TIRS:**
  - North = -6.85 m/s , East = 22.47 m/s
- **Reconstructed Hor. Velocity:**
  - North = -11.5 m/s, East = -0.1 m/s

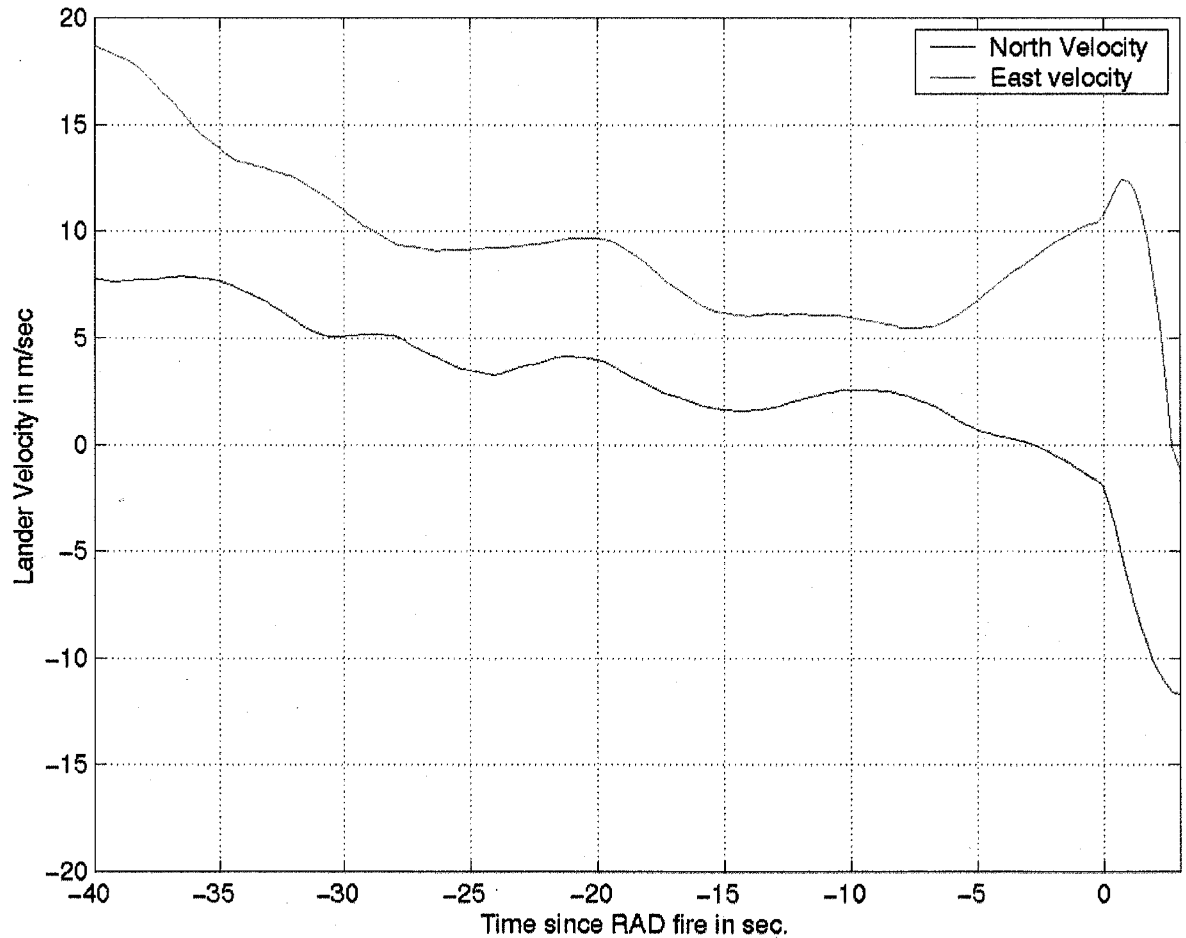
Spirit TIRS Velocity Diagram

Mars Exploration Rover



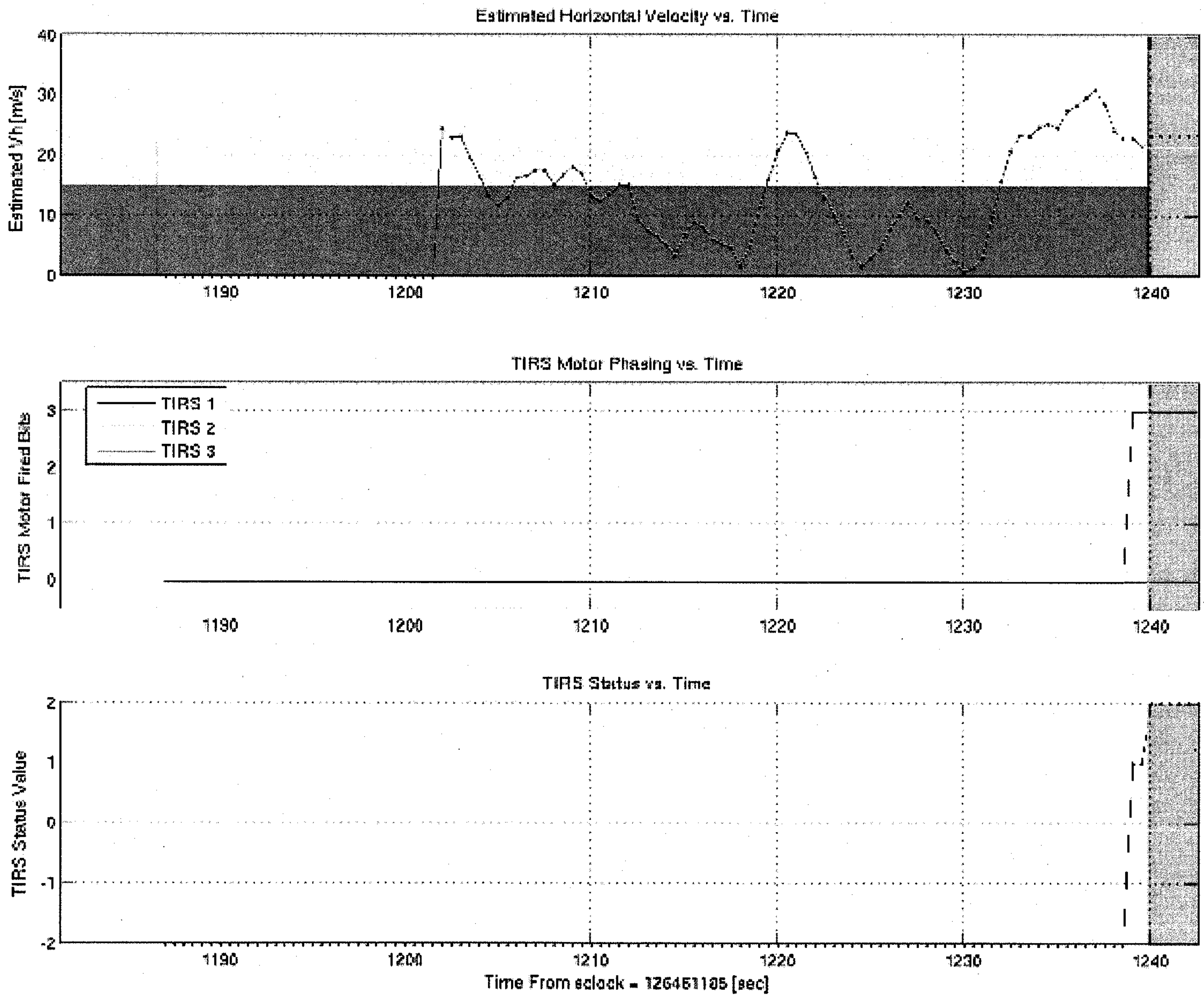
Spirit Reconstructed Horizontal Velocity

Mars Exploration Rover



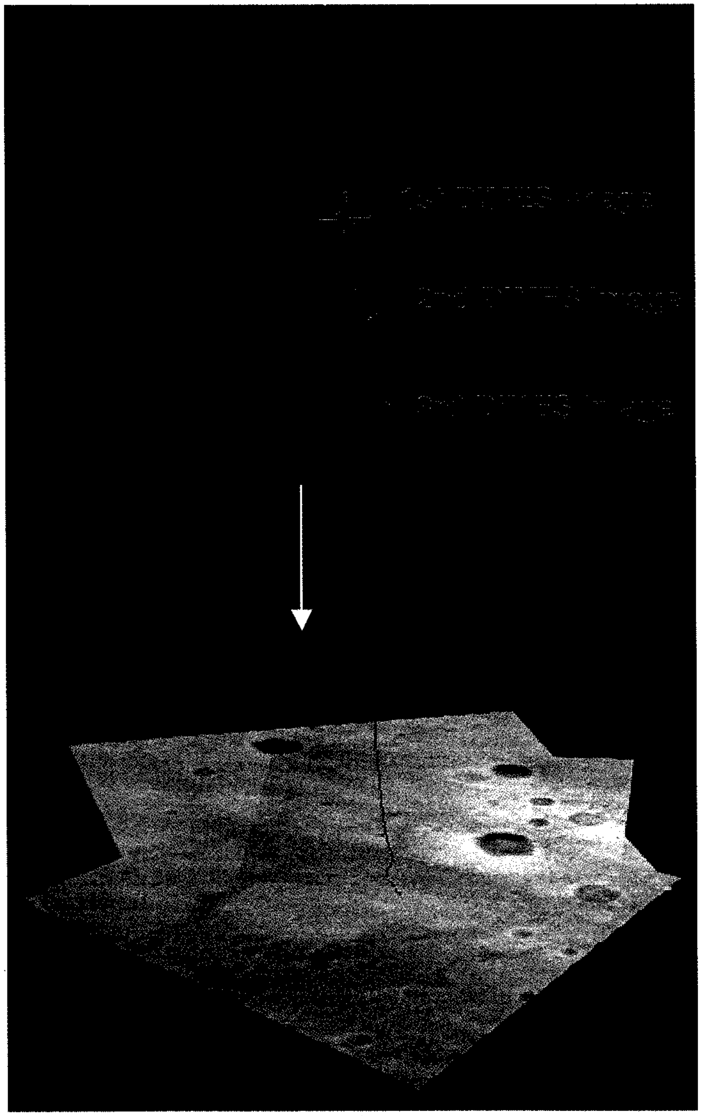
Spirit Predicted Total Horizontal Velocity Magnitude

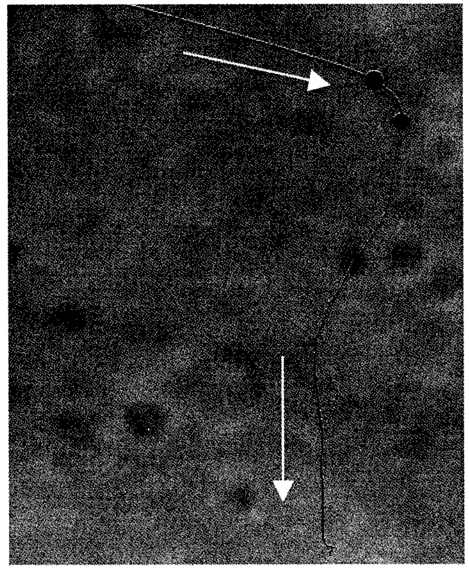
Mars Exploration Rover

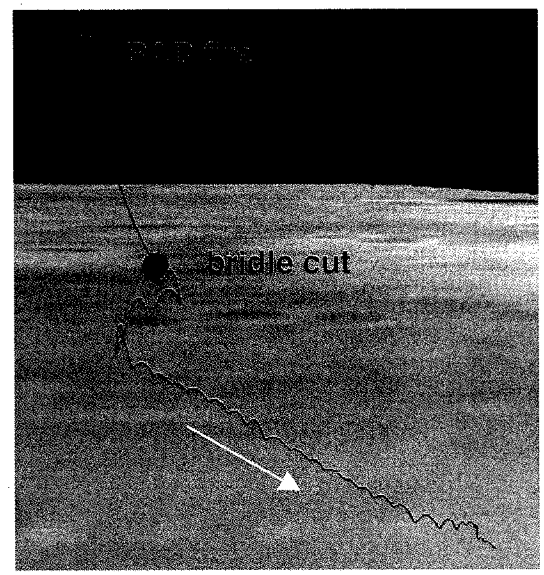


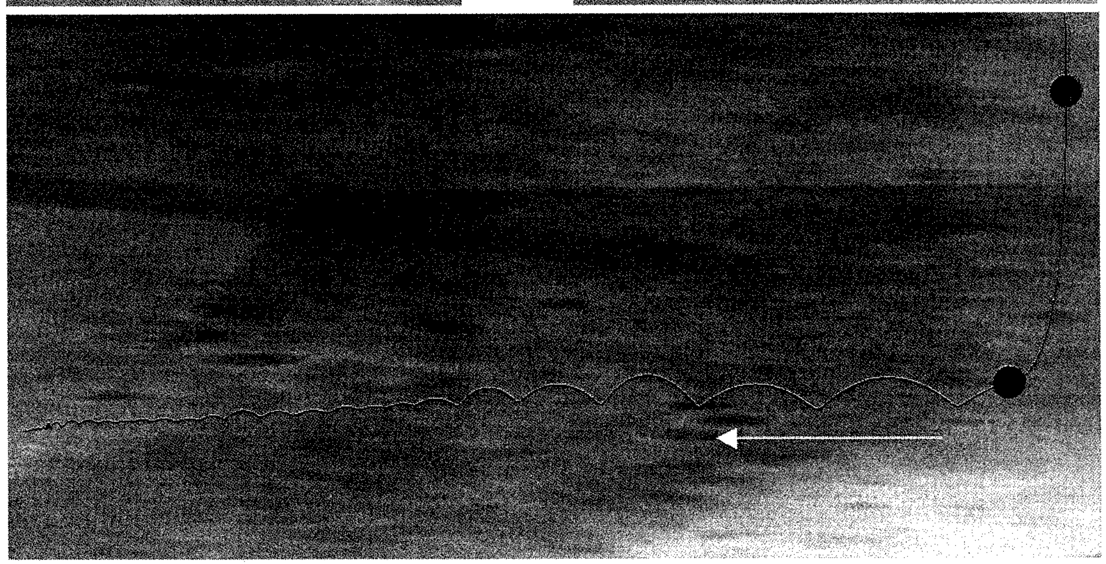
Spirit Trajectory over DIMES images

Mars Exploration Rover



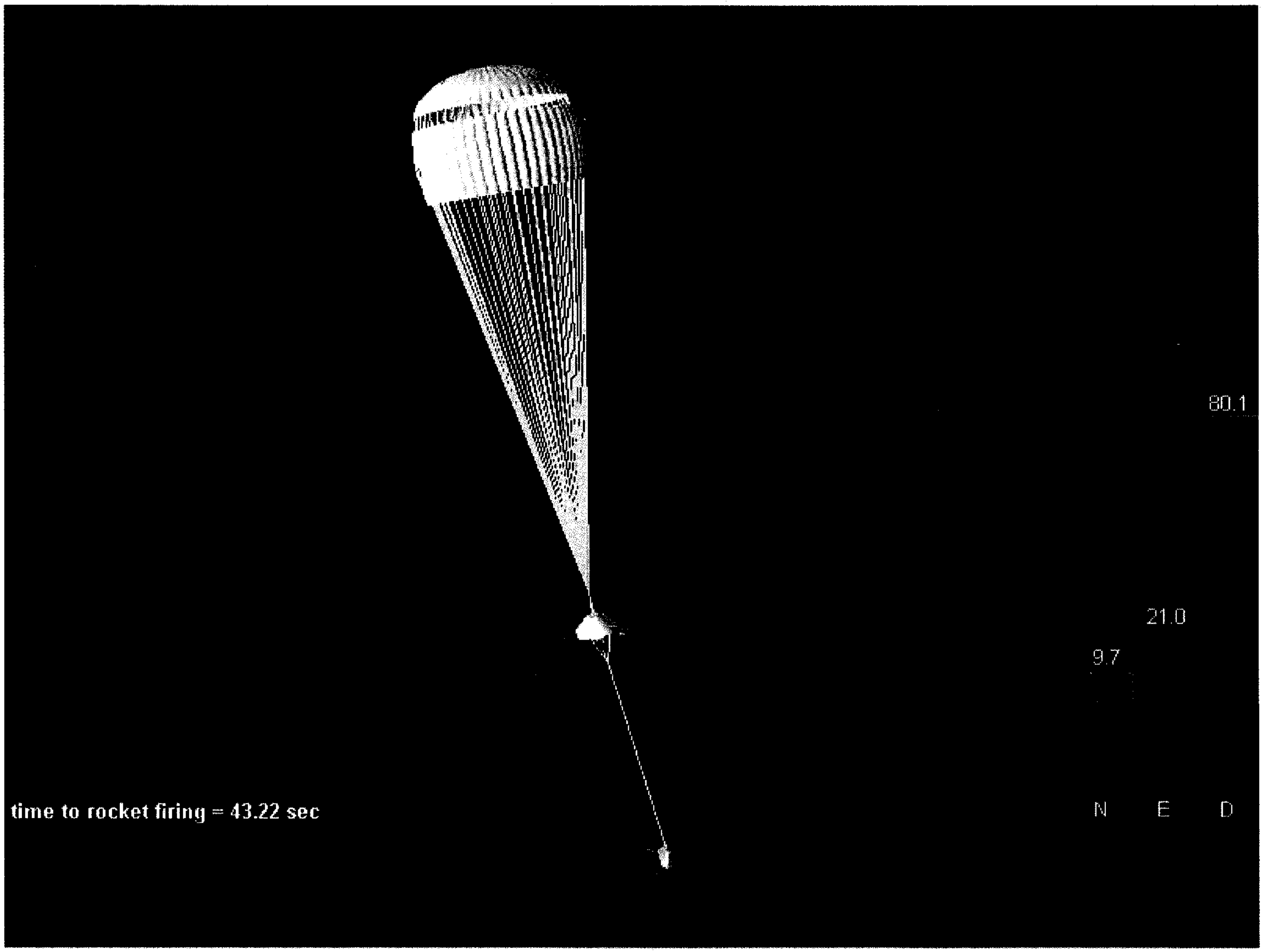






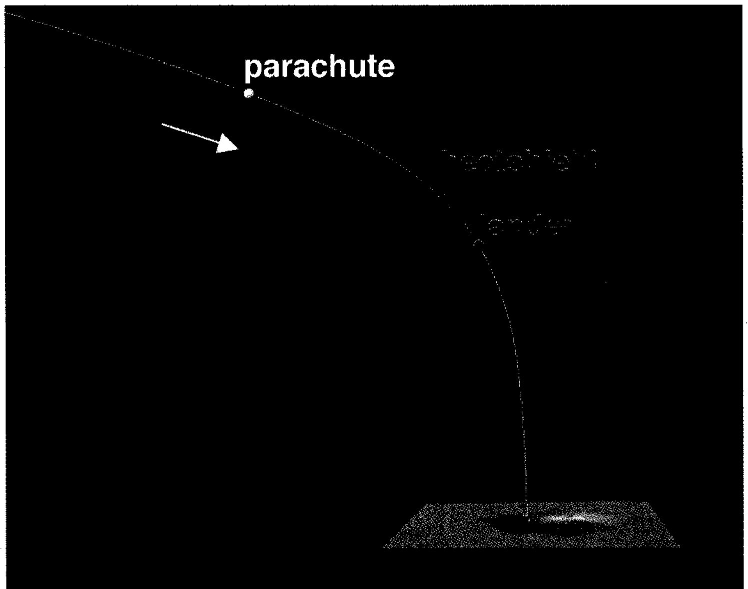
Spirit Reconstruction Movie

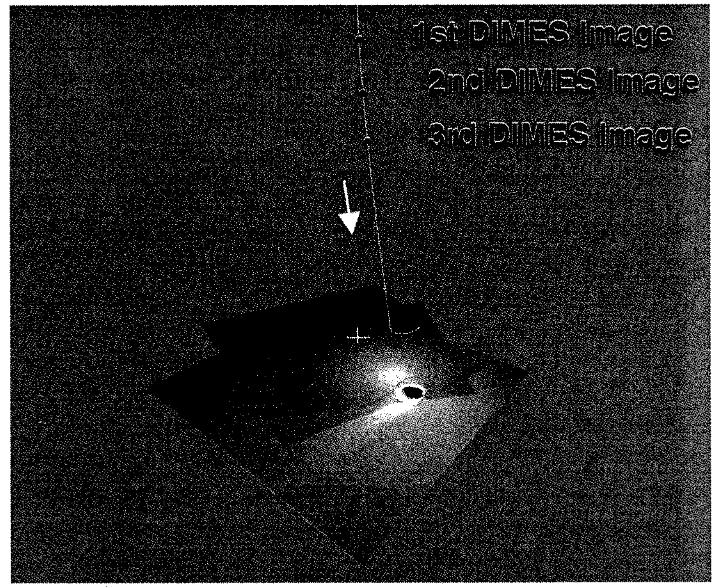
Mars Exploration Rover

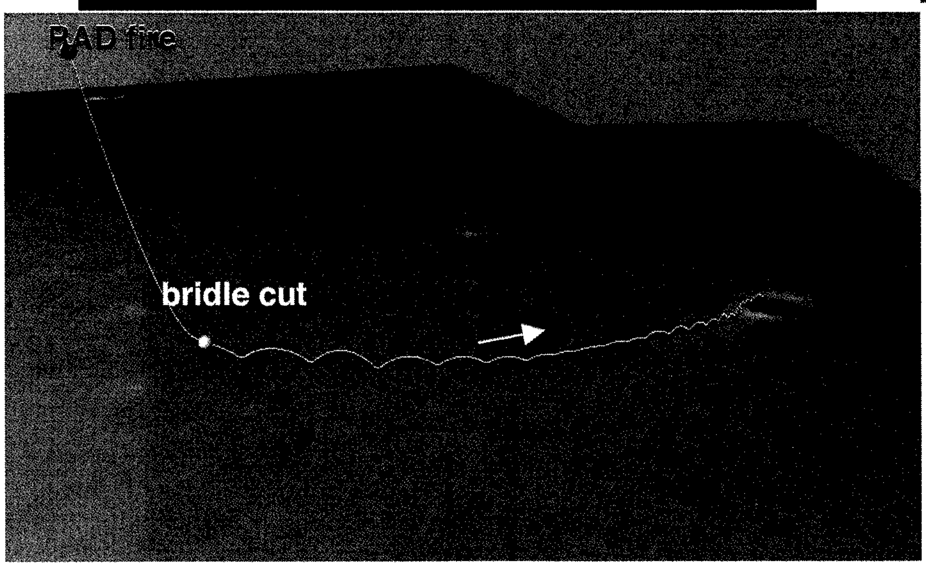


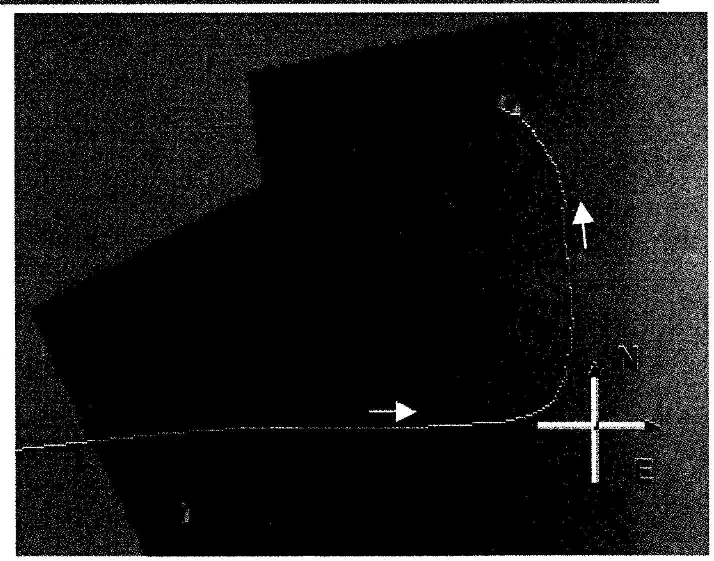
Opportunity Trajectory over DIMES images

Mars Exploration Rover



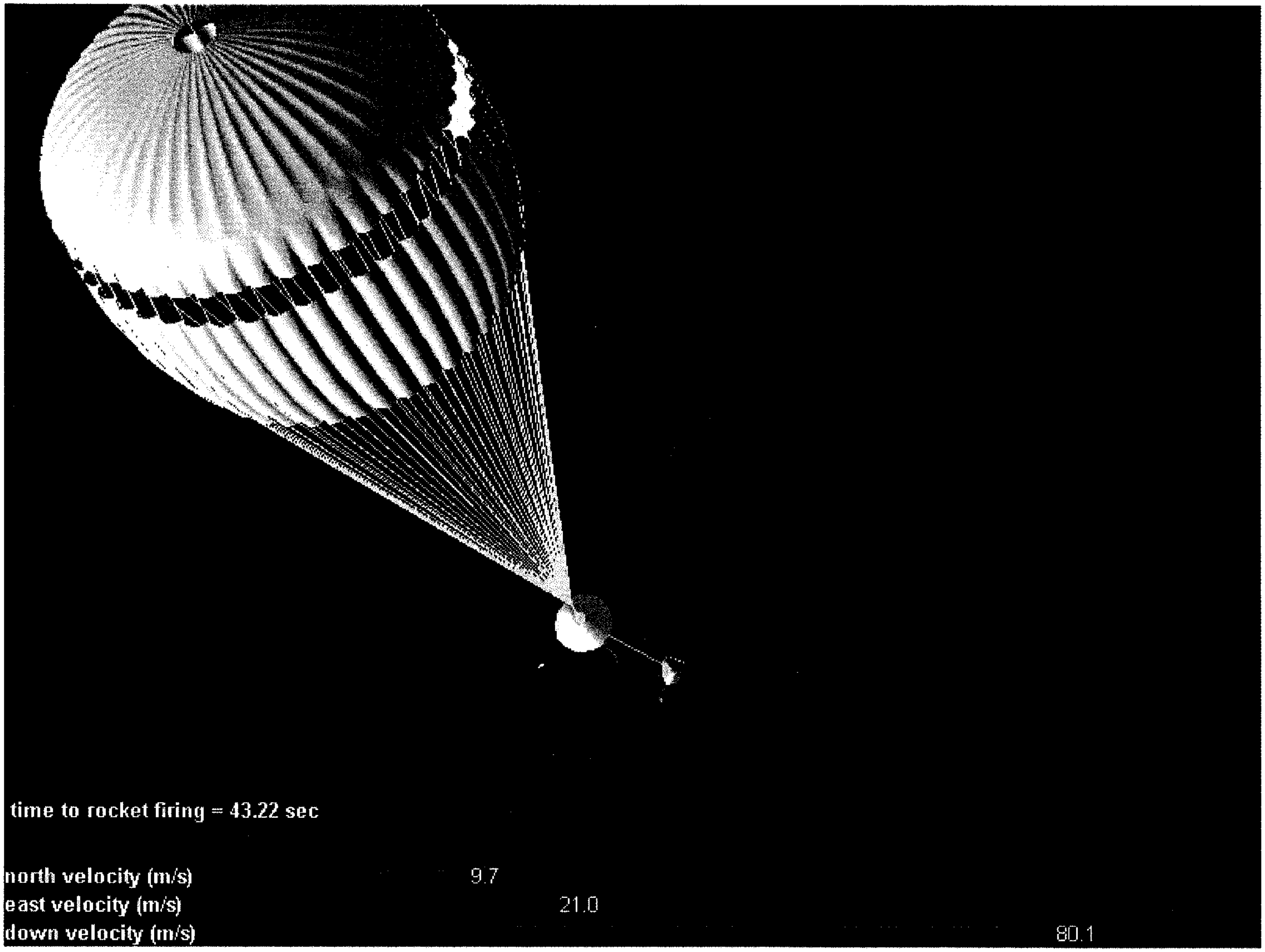






Spirit Reconstruction Movie

Mars Exploration Rover



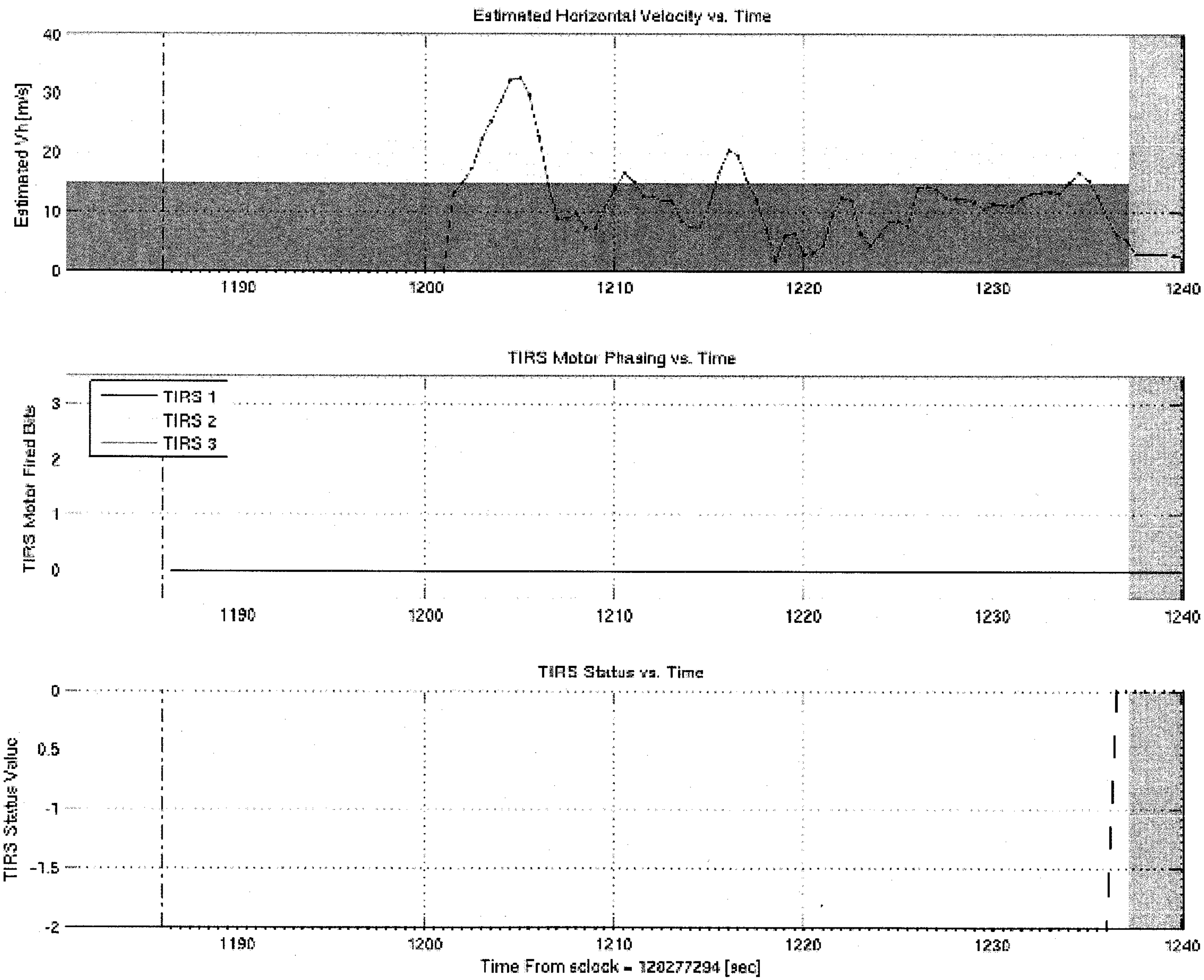
Opportunity TIRS Flight Performance

- **TIRS DID NOT FIRE**

- **Predicted RAD Induced Hor. Velocity without TIRS:**
  - North = -7.70 m/sec , East = 3.92 m/sec
- **Hor. Velocity at RAD Ignition (DIMES):**
  - North = 10.42 m/sec, East = -2.76 m/sec
- **Total Predicted Hor. Velocity without TIRS:**
  - North = 2.71 m/sec, East = 1.16 m/sec
- **Reconstructed Hor. Velocity:**
  - North = 9 m/sec, East = -2 m/sec

Opportunity Predicted Total Horizontal Velocity Magnitude

Mars Exploration Rover



Conclusions

- **In a very short period of time the MER project successfully developed and tested a system, TIRS/DIMES, to improve the probability of success in the presence of large Martian winds**
- **The successful development of TIRS/DIMES played a big role in the landing site selection process by enabling the landing of Spirit on Gusev crater, a site of very high scientific interest but with known high wind conditions**
- **The performance of TIRS by Spirit at Gusev Crater was excellent**
  - Velocity prediction error was small
  - Big TIRS was fired reducing the impact horizontal velocity from ~23 m/sec to ~11 m/sec, well within the airbag capabilities
- **The performance of TIRS by Opportunity at Meridiani was good**
  - Velocity prediction error was rather large (~6 m/sec, a < 2 sigma value)
  - But TIRS did NOT fire which was the correct action