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JPL

Mars Exploration Rover

Using Inertial Measurements for the Reconstruction Of 6-DOF Entry, Descent, and Landing Trajectory and Attitude Profiles (AAS 02-164)

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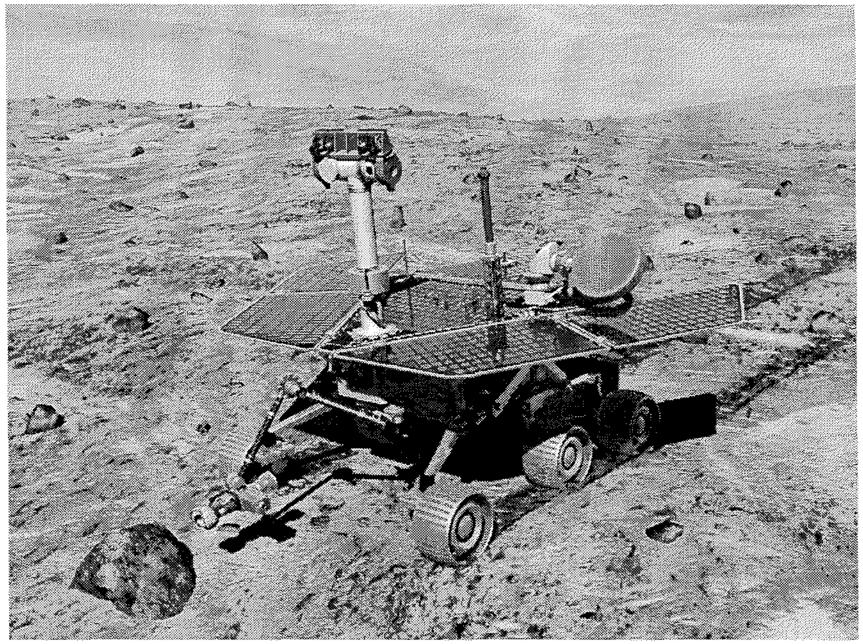
Outline

- Introduction
- Motivation
- Mars Exploration Rover Entry, Descent, and Landing (MER EDL)
- Airbag Testing
  - Objectives
  - Facilities
  - Equipment and Instrumentation
  - Video of Drop Test (facilities permitting)
- Trajectory Reconstruction (REDLand)
  - Objectives
  - Algorithm and Method
  - Results
- Conclusions and Future Work
- Questions

Introduction

- MER missions to Mars
  - Two identical space vehicles and rovers
  - Doubles scientific return for minimal added effort
  - Launching summer of 2003
  - Arriving 21 days apart on Mars at different locations
- Similar to Mars Pathfinder (not the same, though)
  - Rover concept
  - Parachute -- retrorocket -- airbag EDL
- Rovers expected to travel up to 1 km
- Determine history of climate and water in two areas that may once have been favorable for life
- Instruments will help give better understanding of Martian geology
  - 360° panorama
  - Rock and soil samples
  - RAT (Rock Abrasion Tool) exposes fresh surfaces of rock



Motivation for Trajectory Reconstruction

- Need to determine the "stroke" of the airbags at impact to within 10 cm (3σ) from airbag drop tests
  - Airbag physics is a black art
  - Stroke is the amount of airbag compression
  - No direct measurement exists for measuring stroke
  - Bottoming out, or "full stroke" is caused by inadequate pressure in the airbags
  - Too high of a pressure, and the airbags could pop on impact

- Need to reconstruct EDL trajectory of 1st MER within seven days of its arrival
  - 2nd MER will arrive 21 days later

- REDLand (Reconstruction of Entry, Descent, and Landing) software developed by authors to accomplish first objective
- REDLand is prototype for IPANEMA (Interim Planetary Atmosphere Navigation for Estimation and Mission Analysis)
- IPANEMA, also written by the authors, will be used to reconstruct the EDL of the MER mission

MER-A EDL Sequence

MER-A Sequence

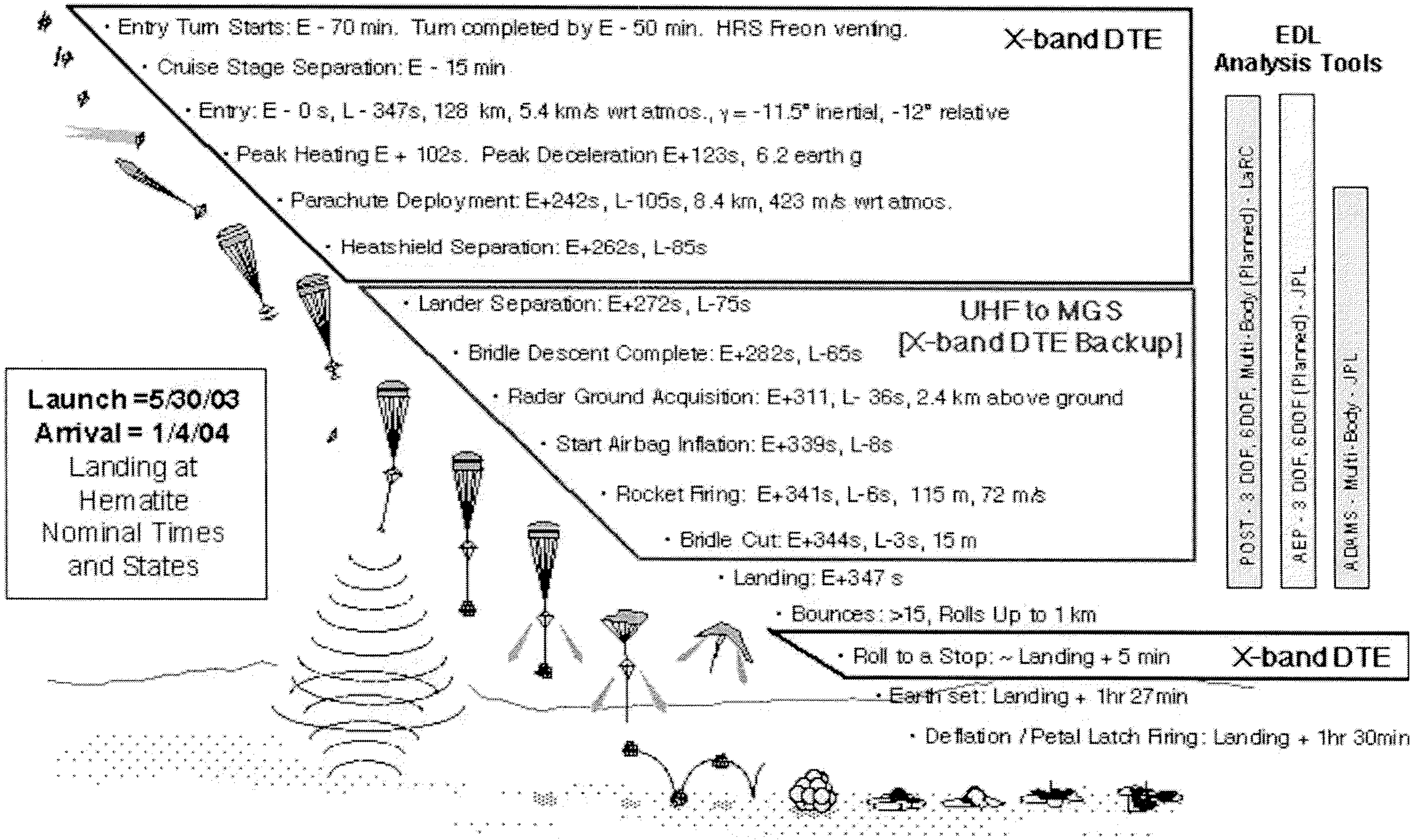


Illustration courtesy of Phil Knocke, JPL

MER-B EDL Sequence

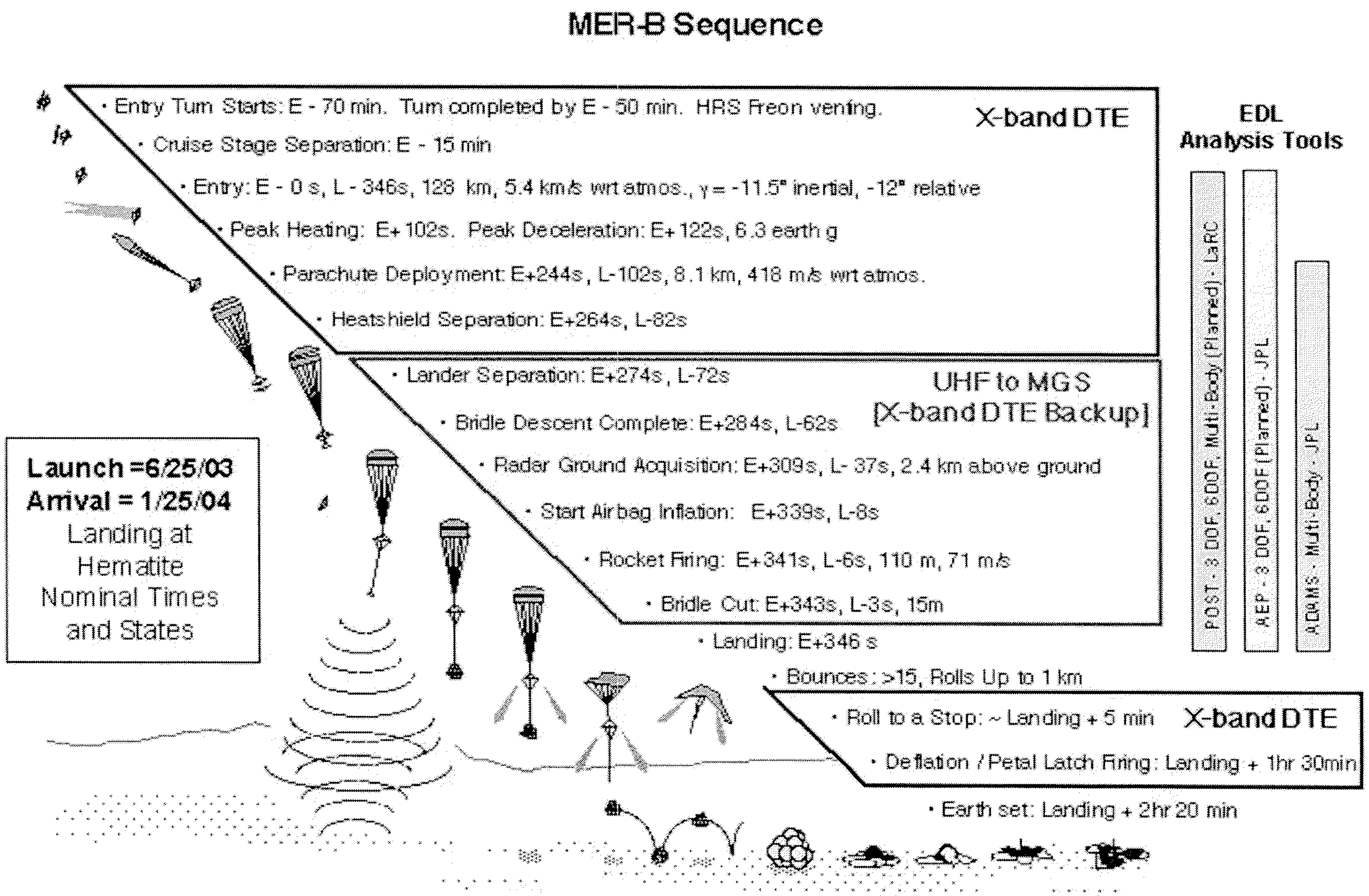


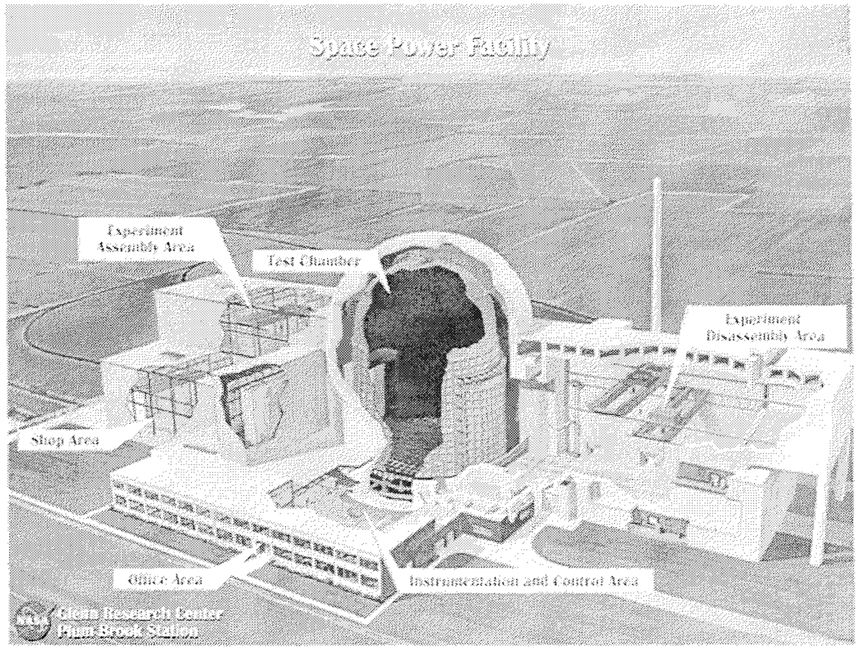
Illustration courtesy of Phil Knocke, JPL

Airbag Drop Test Objectives

- Evaluate the performance of MPF heritage airbag design under the higher landing mass conditions
  - MPF mass was 385 kg
  - MER drop test mass is 535 kg
- Evaluate the relative performance between abrasion layers constructed from 100 denier and 200 denier fabrics
  - Denier is a thread count (or fabric thickness)
  - Trade-off is between number of layers and denier of airbag
- Evaluate the MER petal to airbag interface
- Measure tendon loads, acceleration and stroke

Airbag Drop Test Facilities

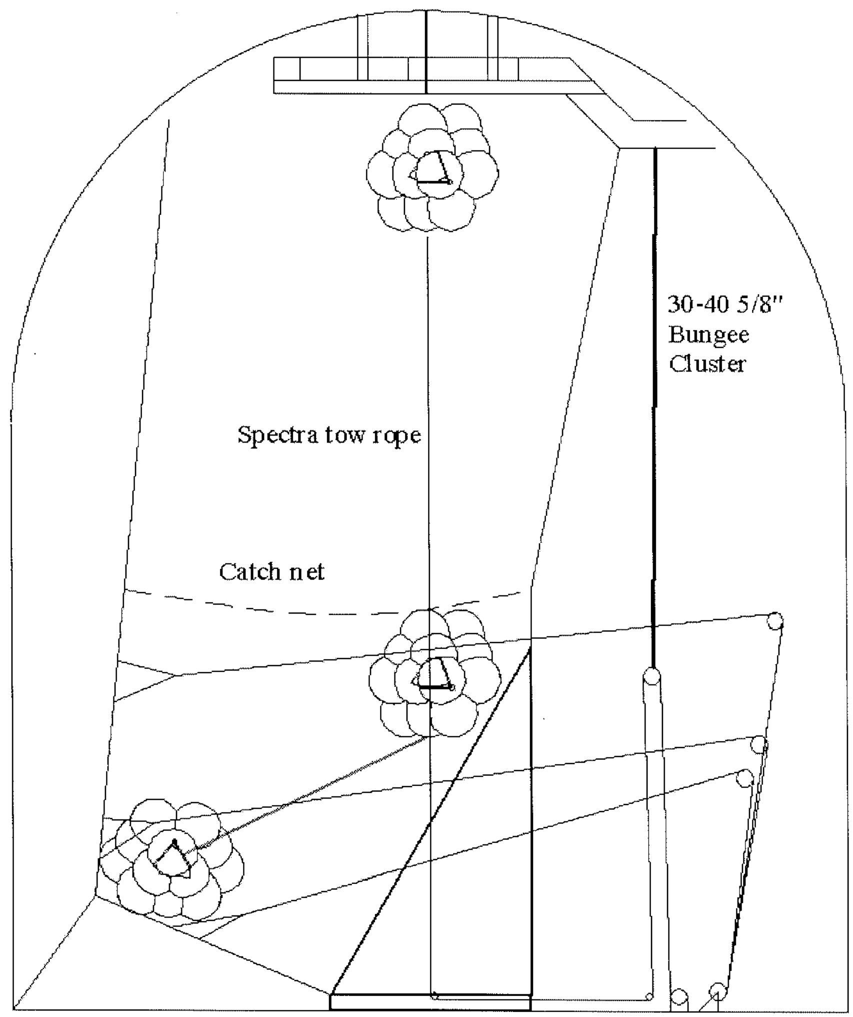
- Drop tests are conducted at the Space Power Facility (SPF) at NASA Glenn Research Center, Plum Brook Station, Sandusky, Ohio
- Only place in the world that can simulate Martian landing environment and conduct drop tests of scale models
  - Largest vacuum chamber on Earth
- Chamber is 100 feet in diameter, 122 feet high
- Center of the chamber is a ramp with a rock field to simulate the Martian surface



From ``World Class Facilities CD-ROM", NASA Glenn Research Center at Lewis Field Productions, Cleveland, OH, 2000

Airbag Drop Test Facilities

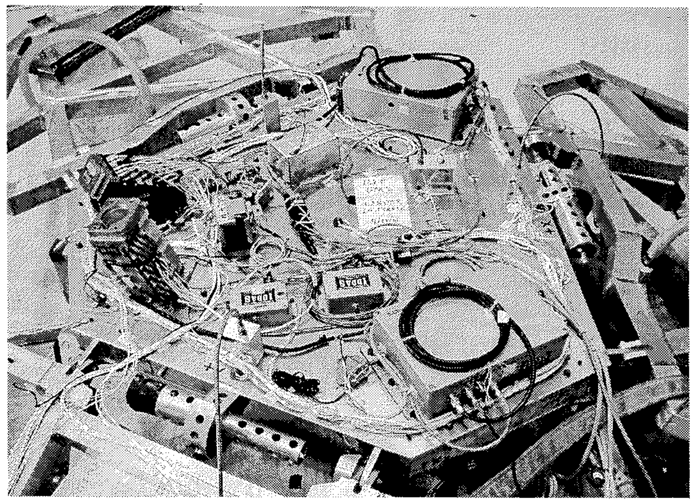
- At right is a figure of the drop test chamber
  - Z-axis is up
  - Y-axis is right
  - X-axis is out of page
- Pyro is fired to release lander from the hanging sling
- Bungee accelerates lander towards the 60° ramp
  - Simulate Mars EDL horizontal velocity component from the wind
- Airbags encounter the ramp and compress
- Airbags and lander bounce off the ramp into catch net
- Entire sequence from release to net takes less than 2 seconds
- Drop captured by numerous cameras situated around the chamber

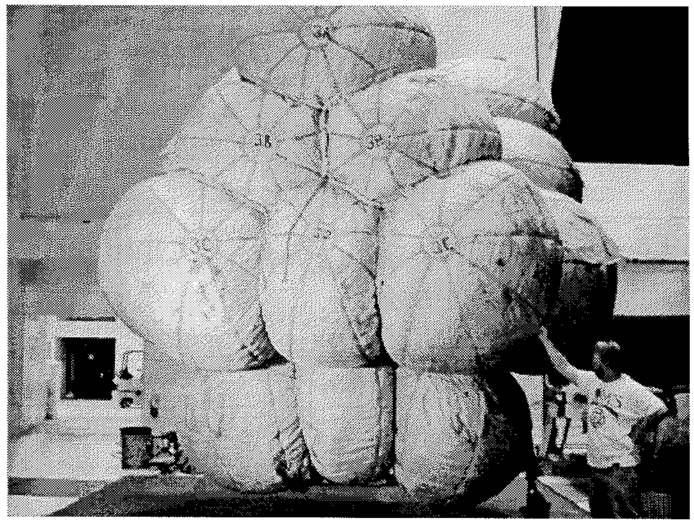


Drawing courtesy of Tom Rivellini, JPL

Equipment and Instrumentation

- Drop test lander is similar in size, shape and mass of flight lander
- Base petal of test lander holds instrument panel
  - IDDAS (Intelligent Dummy Data Acquisition System)
  - Accelerometers
  - Rate gyroscopes
  - Pressure transducers
  - Tendon load cells
  - Latch pin load cells
  - String potentiometers
  - Orientation Sensor
- Ballast mass added to side petals
- Lander is approximately 1 meter tall
- Inflated airbags on lander are 4 meters tall





Photos courtesy of ILC Dover, Inc.

(movie)

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

REDLand Trajectory Reconstruction

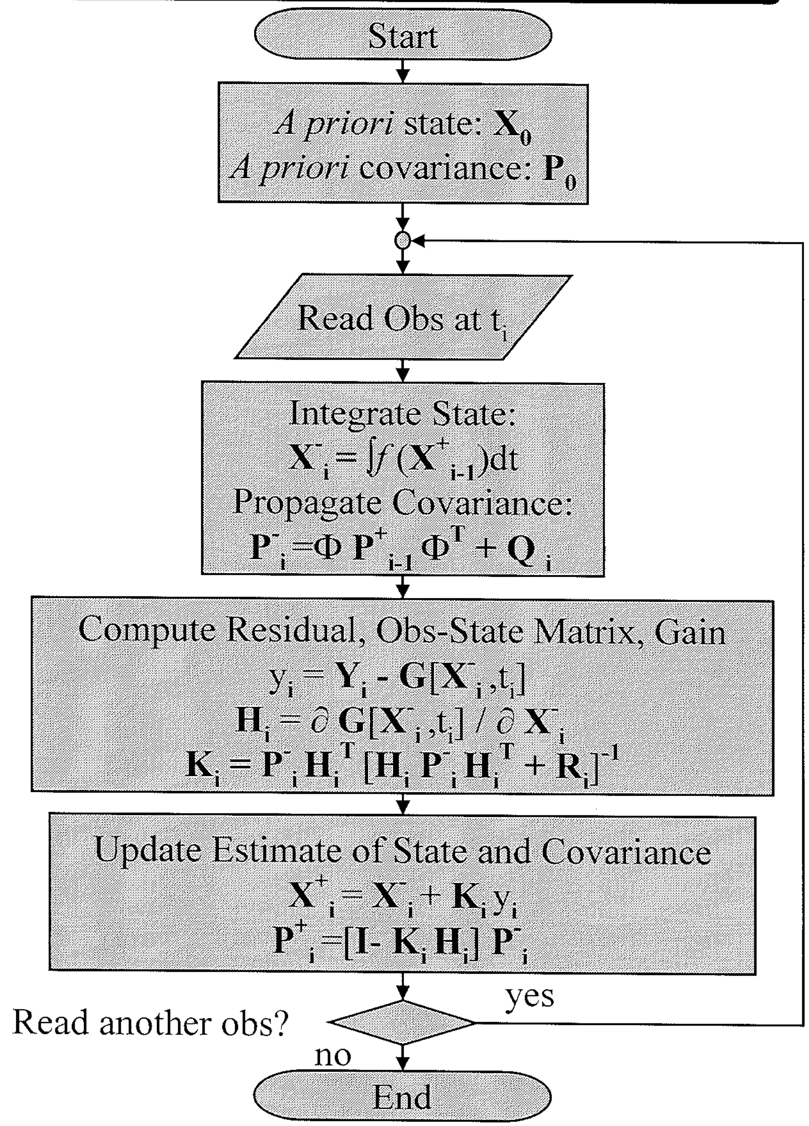
- Objectives
  - Determine acceleration environment of lander
  - Indirectly determine airbag stroke
  - Learn how to model IMU measurements for MER EDL using IPANEMA (Interim Planetary Atmosphere Navigation for Estimation and Mission Analysis)
- REDLand uses IMU data as measurements in EKF
  - Traditional route of dead reckoning integrates IMU data
- REDLand estimates (of the CG and as functions of time):
  - Position (SPF reference frame)
  - Velocity (SPF reference frame)
  - Translational Acceleration (Body frame)
  - Quaternion (SPF to Body)
  - Rotational Rate (Body frame)
  - Rotational Acceleration (Body frame)
- Quaternion relates SPF and Body reference frames
- The rotation to the Mars frame from the SPF frame is a -60° about the SPF X-axis

Extended Kalman Filter

- The trajectory and attitude reconstruction will be performed using an Extended Kalman Filter (EKF)
- At right is a flowchart of a typical EKF

- *A priori* values are from the initial conditions
- Φ is the state transition matrix
- Q is the process noise matrix
- Y is the observed measurement, G is the modeled measurement. Their difference is the residual, y
- H is the state-observation matrix
- R is the measurement noise matrix
- K is the gain

- The next slides discuss each of these elements of an EKF in more depth



Measurement Types (Y in EKF)

- **Accelerations from a number of three-axis accelerometers positioned in the lander**
  - **Current 1σ noise assumption is 0.1 g**
  - **DC offsets are averaged and removed**
  - **1 g is added to unbiased accelerometer tri-axis**
    - This will lead to a propagated error if initial orientation is miscalculated
  - **Modeled kinematics (**G **in EKF) of acceleration at a point "*a*" relative to a reference point "*o*" is:**

    $a_a = a_o + \omega \times \omega \times r_{a/o} + \alpha \times r_{a/o}$
  - **Small error may arrive from $\Delta r_{a/o}$ uncertainty (most apparent during max rotation rate and acceleration)**
    - Max(ω) ~ 12 r/s, Max(α) ~140 r/s^2 ,Set a_o = 0
    - $a_a(r_{a/o}$ = 50cm) = 142 m/s^2, $a_a(r_{a/o}$ = 51cm) = 144.84 m/s^2
    - Difference of 0.3 g
  - **Small errors may also arrive from orientation of accelerometers wrt lander axes**
    - 20g * sin(1°) = 0.35 g
- **Rotational rates from a three-axis gyroscope in the lander**
  - **Current 1σ noise assumption is 0.4 mV**
  - **1 mV ~ 1 deg/sec**

Process Noise Matrix (Q) Assumptions

- The propagated covariance matrix is:

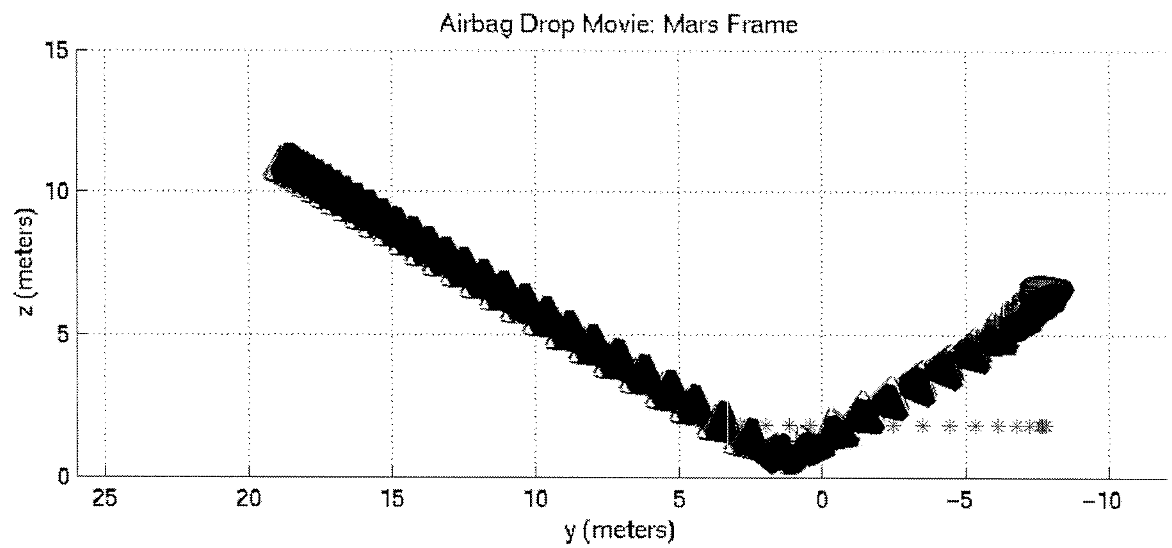
$$P^-_i = \Phi P^+_{i-1} \Phi^T + Q_i$$

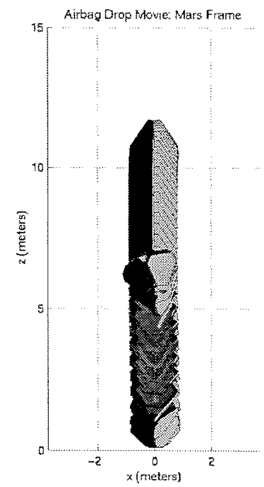
- Q is a diagonal matrix that can be thought of as a lower bound on the propagated covariance matrix
- Non-zero Q prevents the estimator from converging
- Tuning of an EKF is the black art of balancing the uncertainty of the dynamics model and the uncertainty of the measurements, or Q/R
- Q should only be applied to states where and when there are dynamics uncertainties
  - Release and impact
  - Velocities predicted using a constant value for g
  - Translation and rotation accelerations
  - Rotation rates
- The measurement update to the covariance matrix,

$$P^+_i = [I - K_i H_i] P^-_i,$$

will correct for the added process noise (Q)

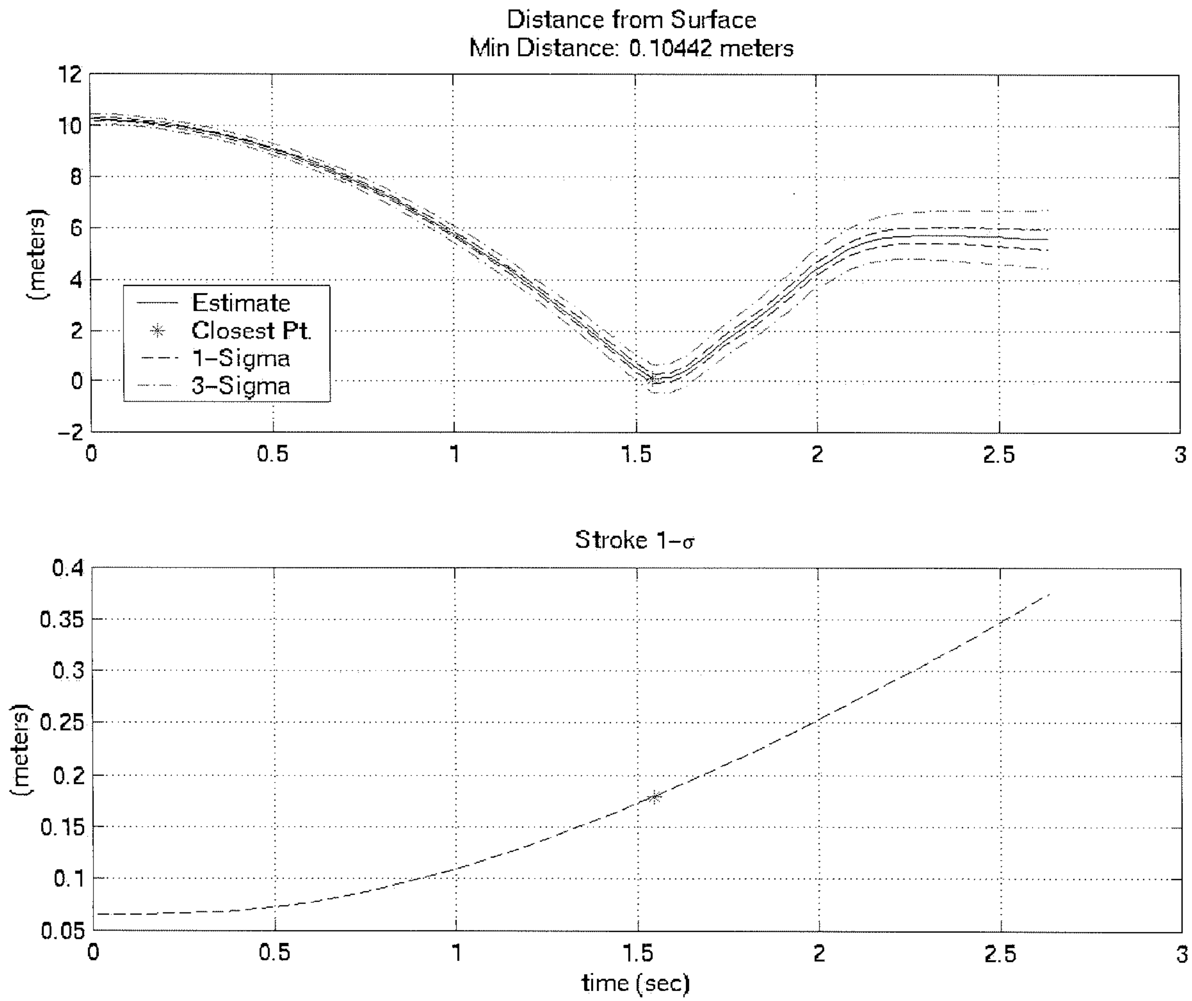
Results: Mars view animation frames



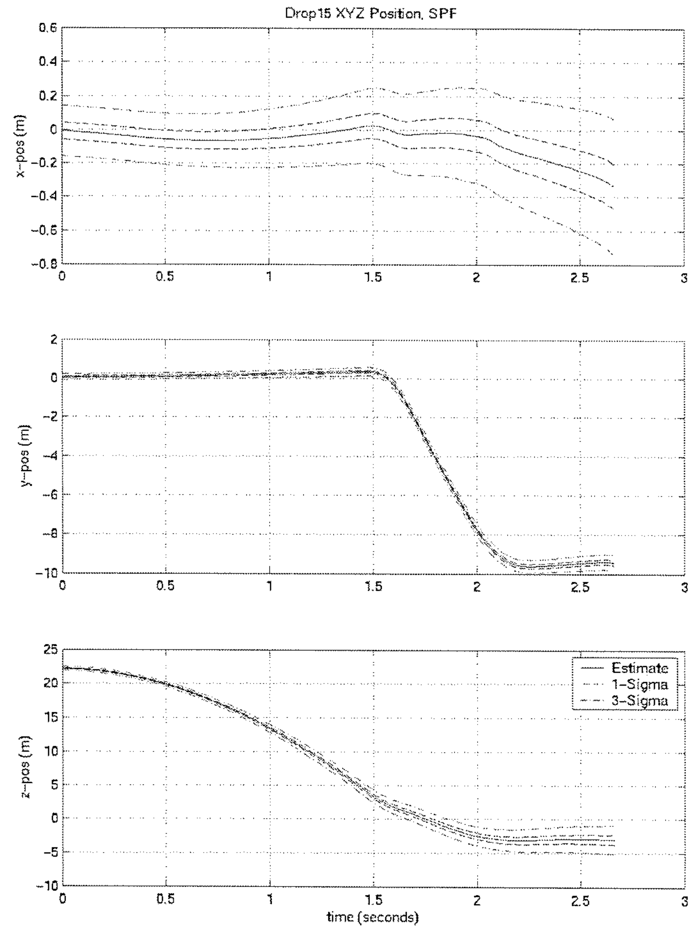


* Roll Line. This movie was played at 20 frames per second.

Stroke Estimate

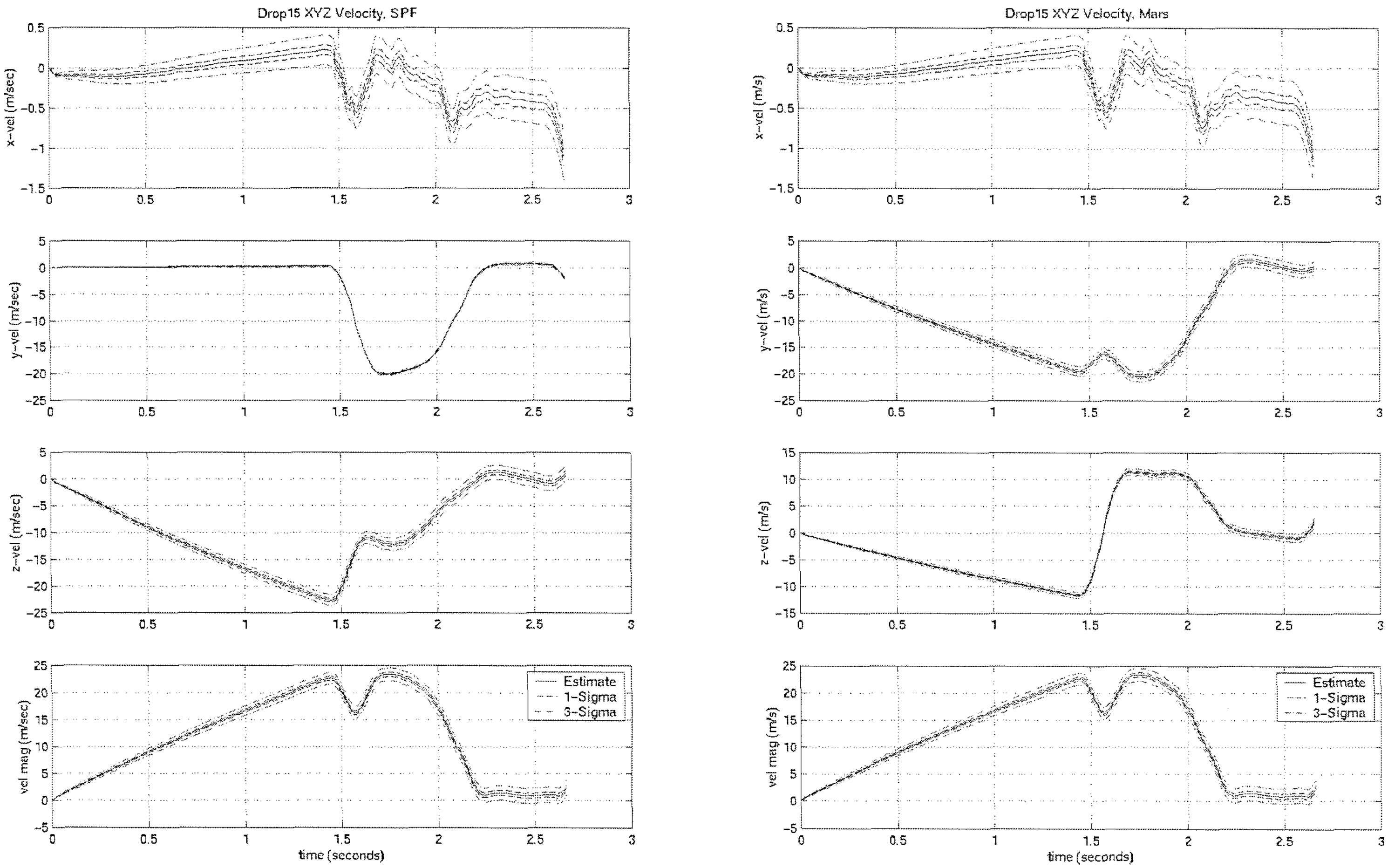


Results: Position (SPF frame)



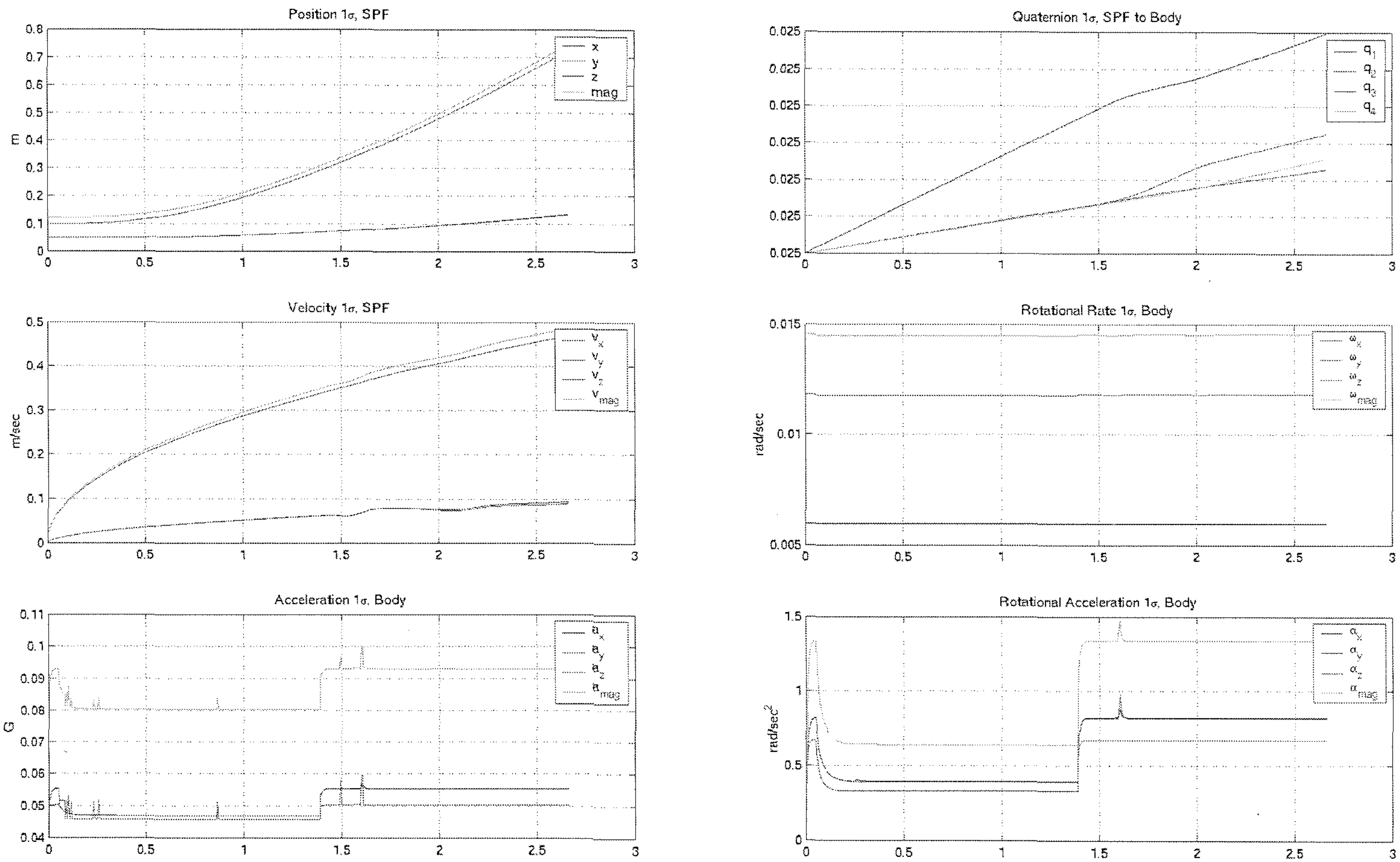
XYZ Positions in the SPF frame

Results: Velocity (SPF and Mars frames)



XYZ Velocities in the SPF (left) and Mars (right) frames

Uncertainties: Translational & Rotational



Translational (left) and Rotational (right) Uncertainties

Initial Conditions

- Previous slide of estimate 1σ uncertainties illustrates need for accurate initial conditions
- Uncertainties of unmeasured states grows as a value of its derivative state
  - Position uncertainty grows at a rate equal to the value of the velocity uncertainty, etc.
- If stroke measurement is needed to be know to within 10 cm (3σ), initial conditions must be an order of magnitude more accurate
- Initial position and initial attitude are important since no measurements of height or attitude are made during the drop (only acceleration and rotation rate are measured)
- Navigators are involved in precision measurements of the SPF chamber's layout and magnetic field
  - We (navigators) are dealing with hardware and getting our hands dirty!

Conclusions and Future Work

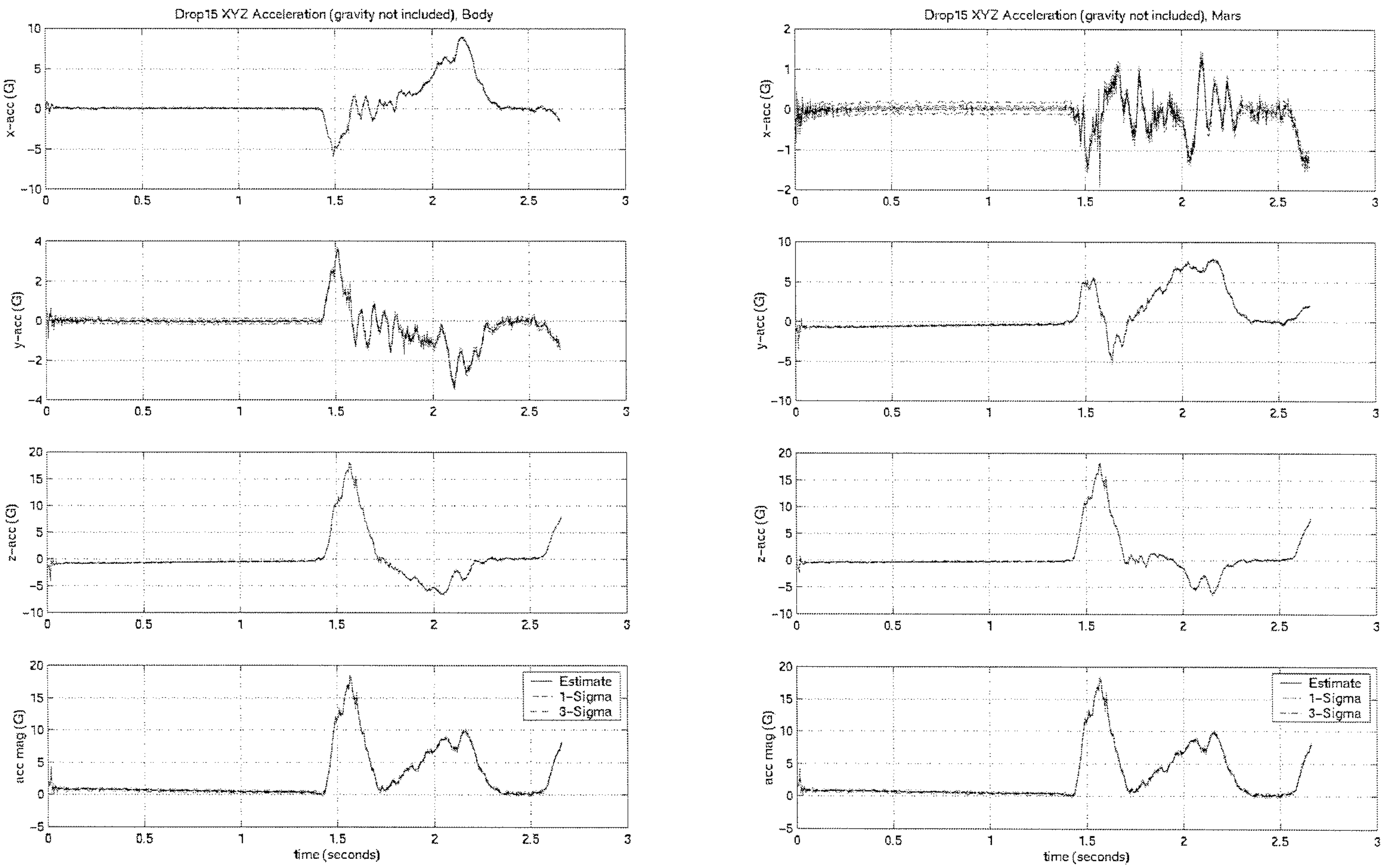
- REDLand demonstrates that IMU data can be used as measurements in a Kalman filter
- JPL is on course to have a high-fidelity EDL reconstruction application for the MER missions

- Must get better estimate of stroke
- Must get accurate measurements of the initial conditions

- Future drop tests will include distance measurement

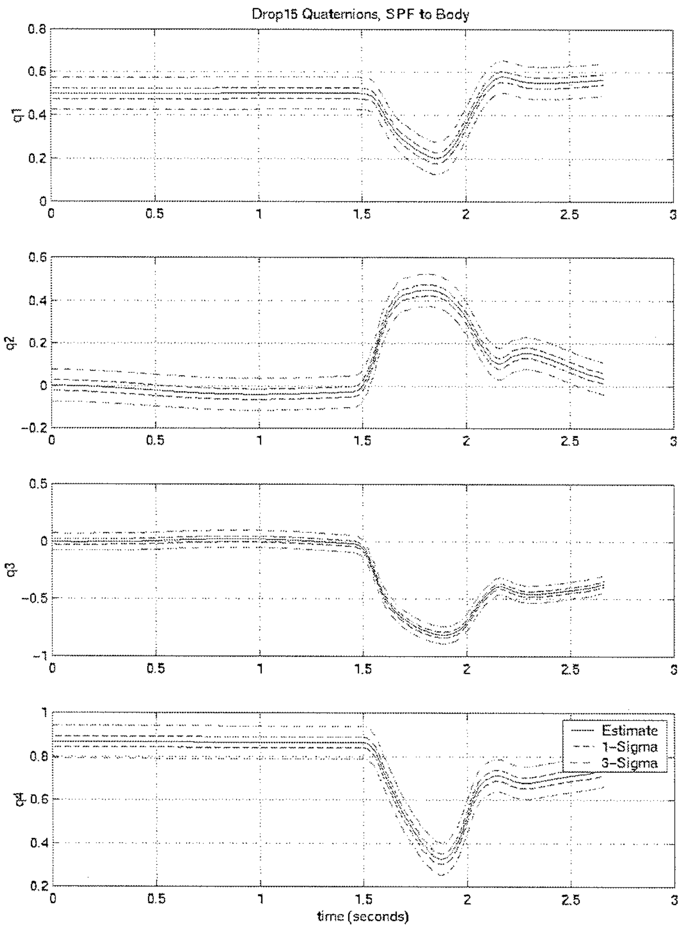
Backup Slides

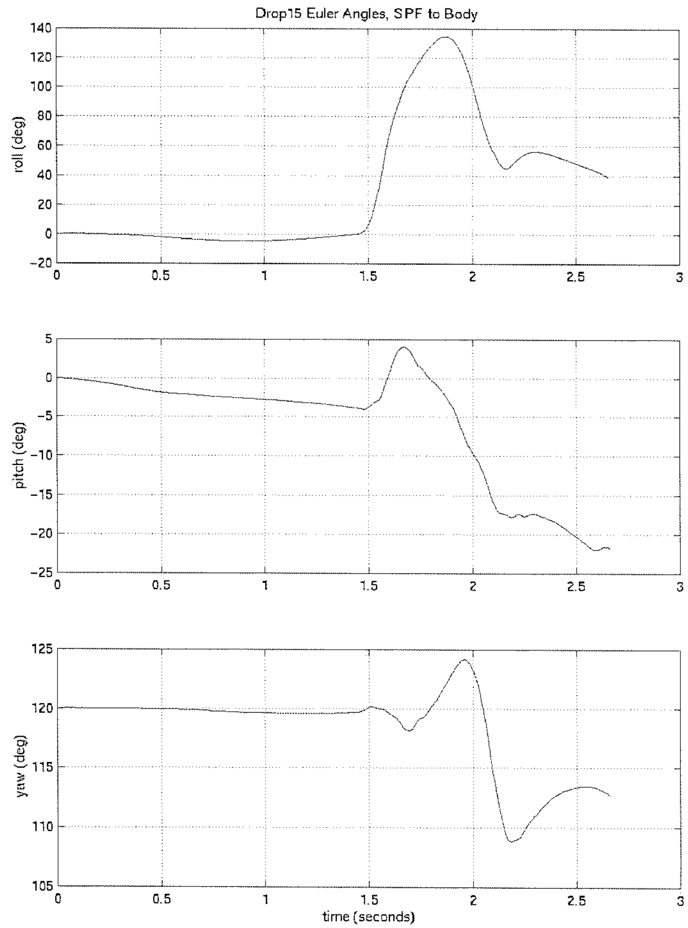
Results: Acceleration (Body and Mars)



XYZ Accelerations in the Body (left) and Mars (right) frames

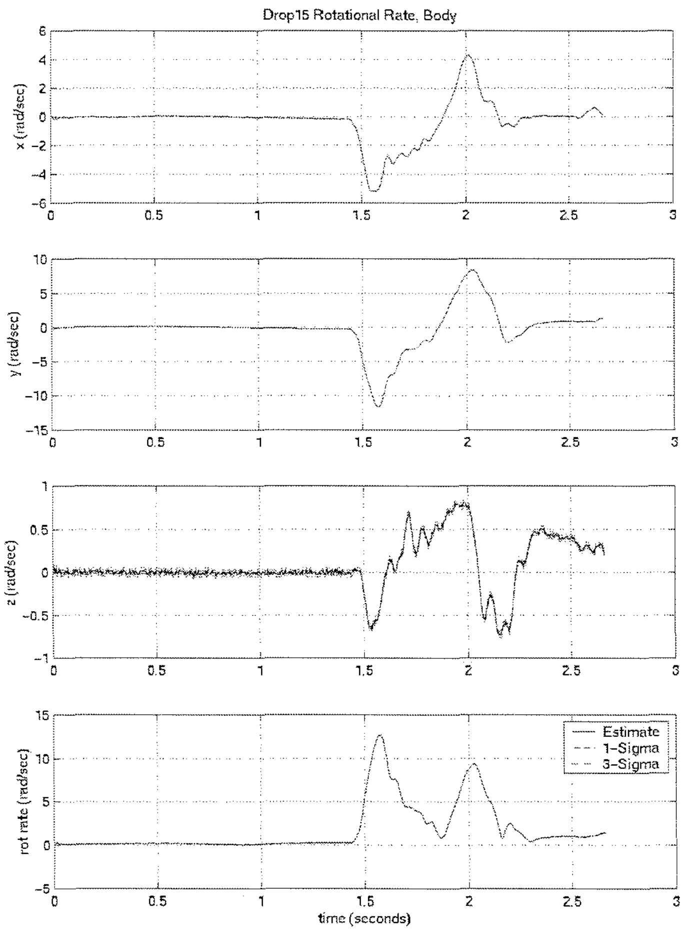
Results: Quaternion and Euler Angles

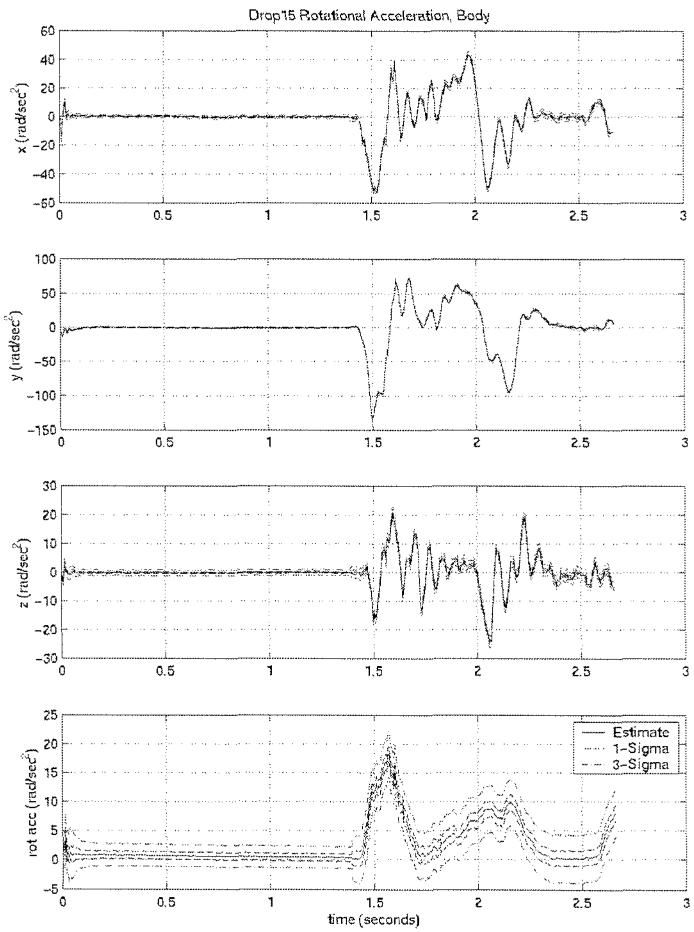




SPF to Body rotations: Quaternion (left) and 1-2-3 Euler Angles (right)

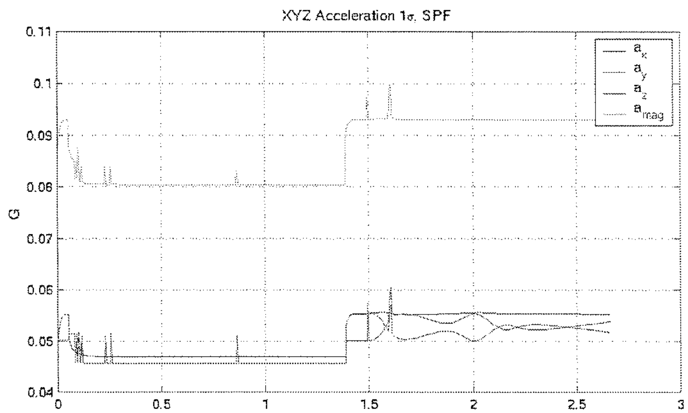
Results: Rotational Rate and Acceleration

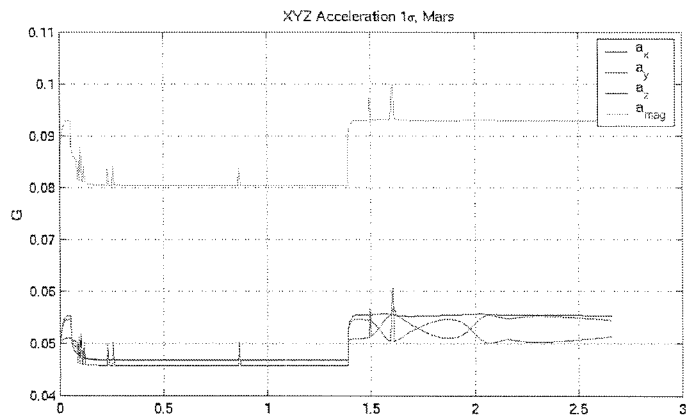




XYZ Rotational Rate (left) and Rotational Acceleration (right)

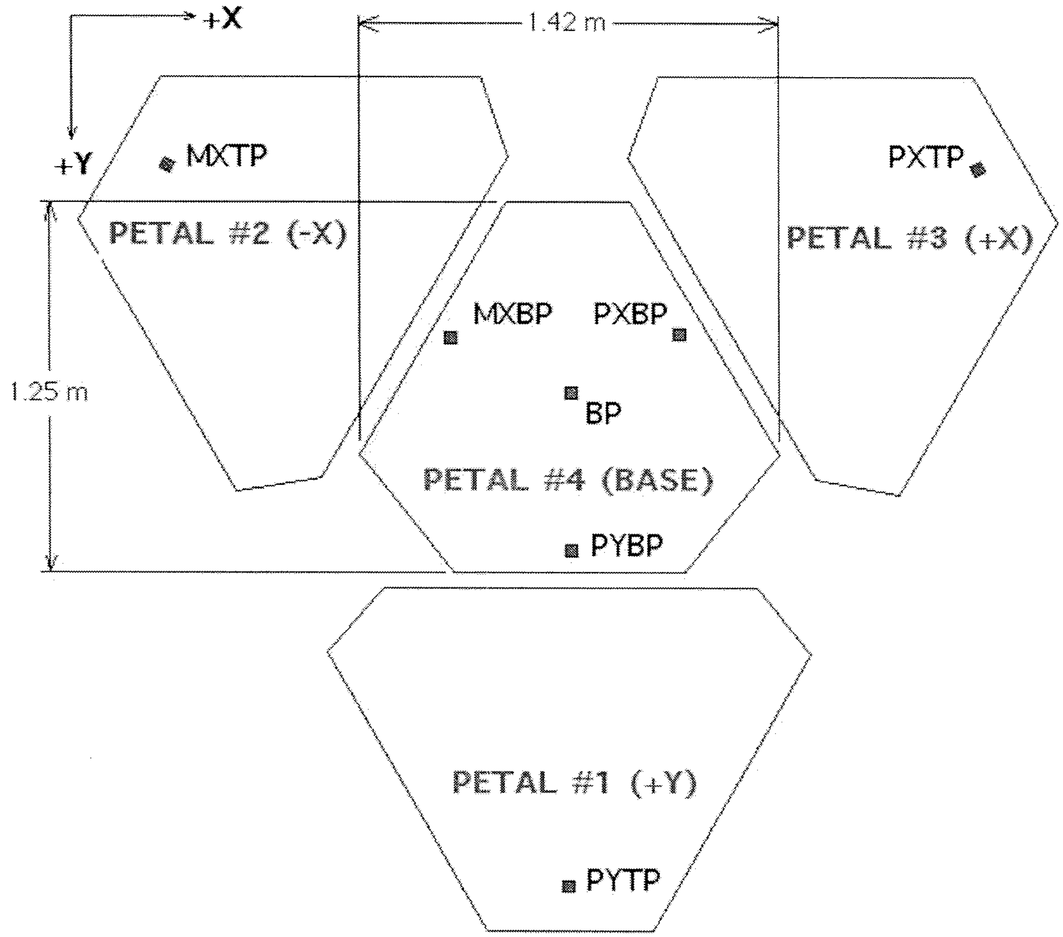
Acceleration Uncertainty (SPF & Mars)





Translational Acceleration Uncertainties in the SPF (top) and Mars (bottom) frames

Accelerometer Layout



Accelerometers on Tri-axial Block

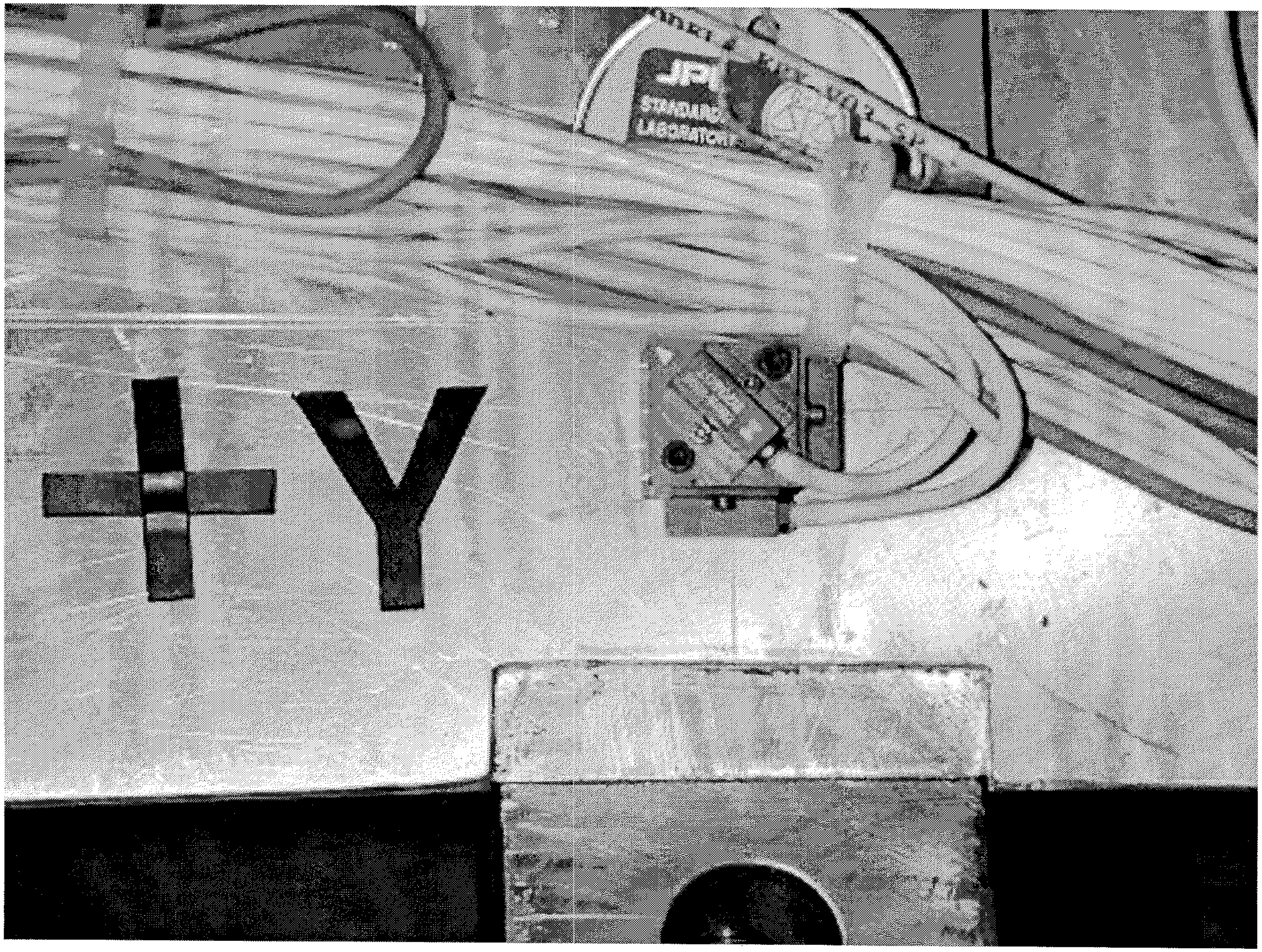


Photo courtesy of ILC Dover, Inc.

Closed Lander

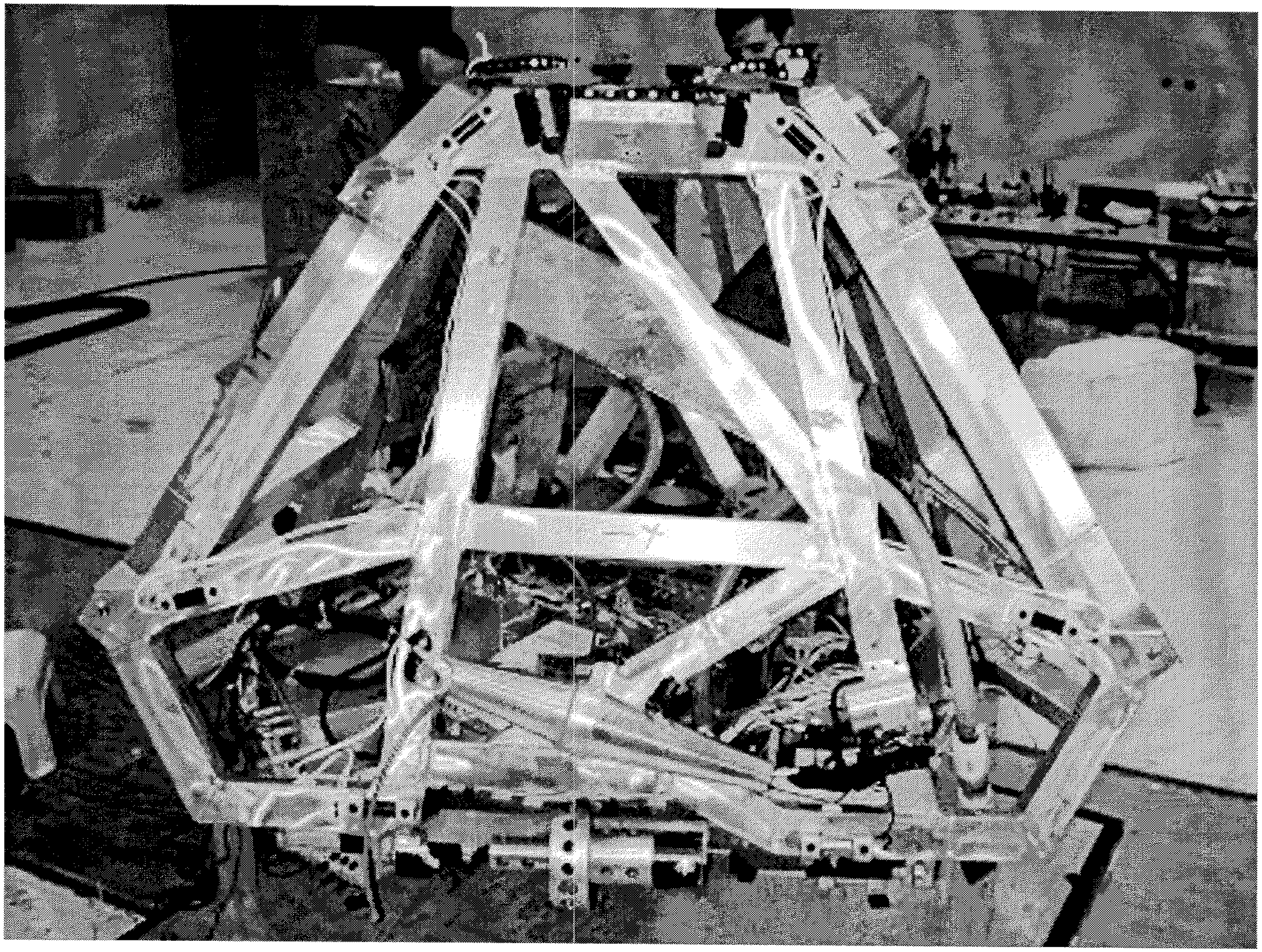


Photo courtesy of ILC Dover, Inc.