Global landing site access using atmospheric skip trajectories

L. Bryant

Abstract

Mars direct entry, without going into orbit, does not provide global access to all landing site latitudes. Latitudes accessible via direct entry trajectories consist of a ring around the backside of the planet, centered about V infinity. Landing sites outside this ring can be achieved using a modified approach trajectory entering the atmosphere over the South Pole "aerocapture fashion" that will skip out to an altitude above the atmosphere and then re-enter the atmosphere a second time and continue to toward the North Pole. The first aerocapture maneuver is aligned to provide an exit orbit that contains the desired landing site with an apoapsis computed to provide proper ranging for the second entry. A powered maneuver is utilized during the exoatmospheric phase to remove altitude and flight path deviations due to uncertainties in the atmosphere occurring during the first entry. Three guidance schemes are required for global landing site access analysis. Aerocapture guidance was used for the first atmospheric entry, Shuttle Powered Explicit Guidance was used for the exoatmospheric maneuver, and Apollo Derived Entry Guidance was used for the second atmospheric entry. An altimeter to update the onboard navigation state after the first atmospheric entry, was required to remove accumulated dead-reckoning navigation errors and achieve reasonable range errors at chute deploy.

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Skip Trajectory Analysis
(Provide Mars Global Site Access)

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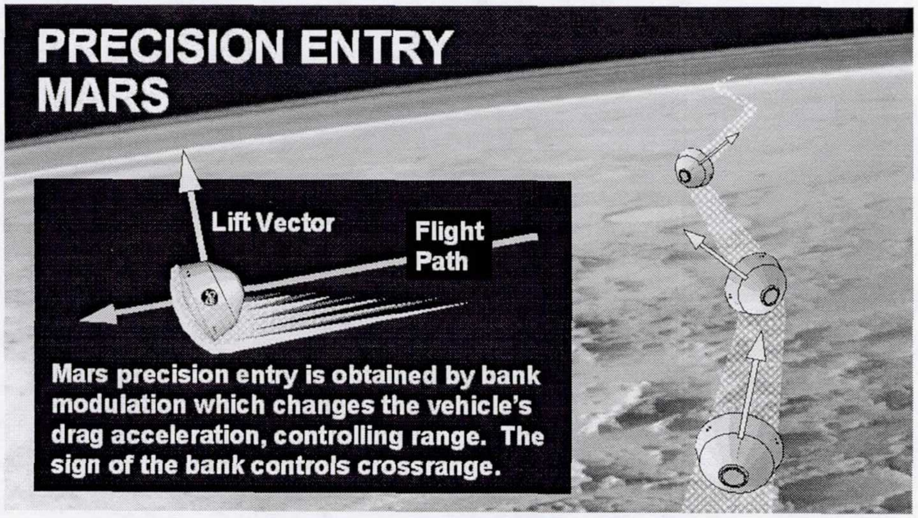
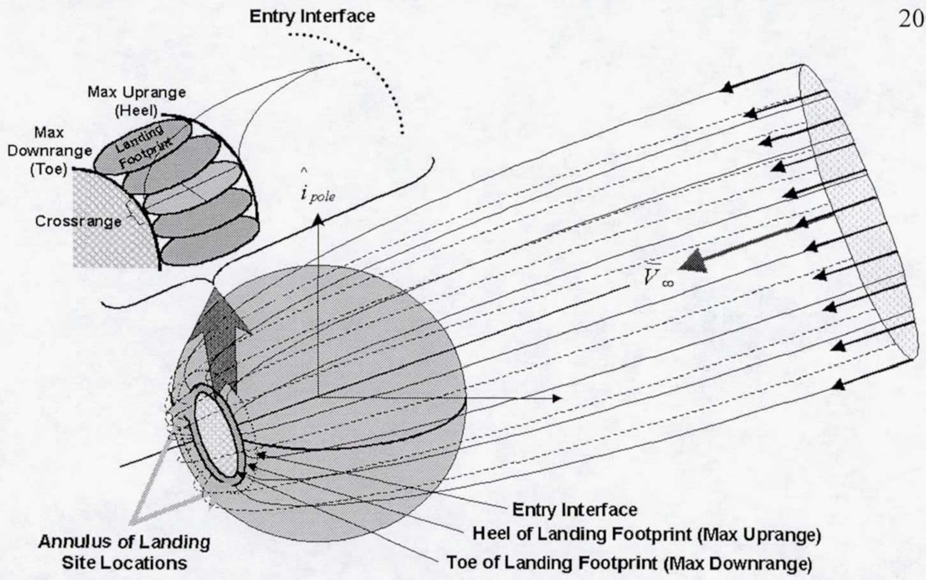
2/8/02



PRECISION ENTRY MARS

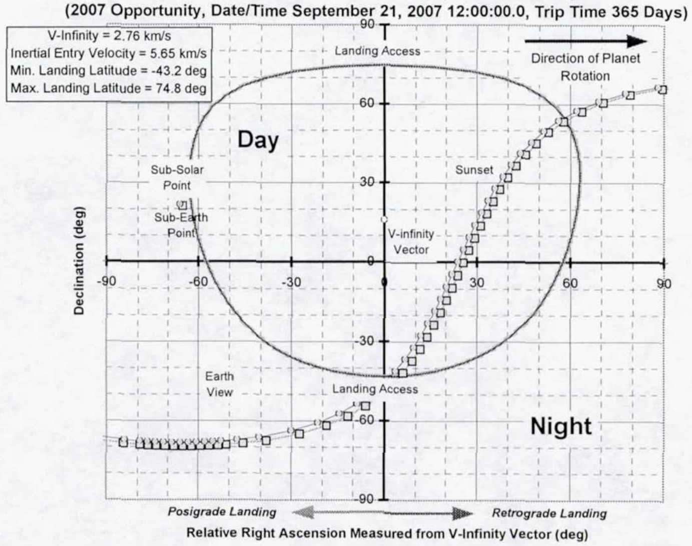
Mars precision entry is obtained by bank modulation which changes the vehicle's drag acceleration, controlling range. The sign of the bank controls crossrange.

Approach

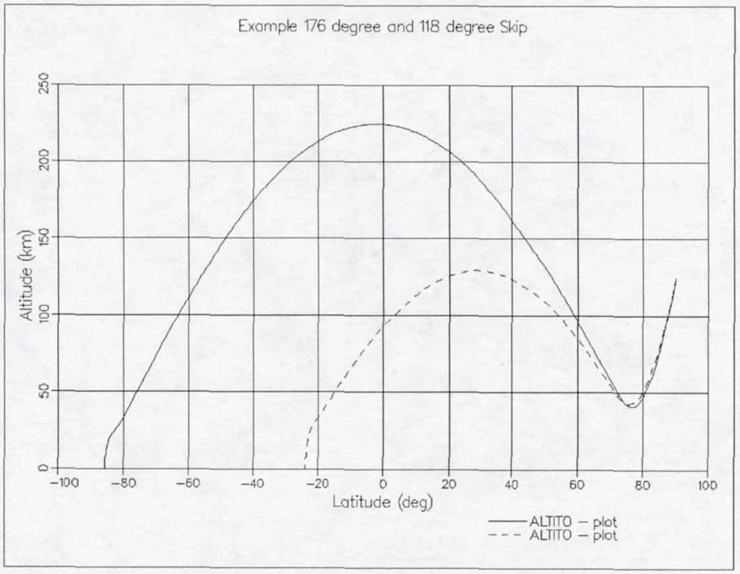


2007 Opportunity, Depart Earth 9/21/07, Trip Time = 365 days, C3 = 12.8 km^2/s^2

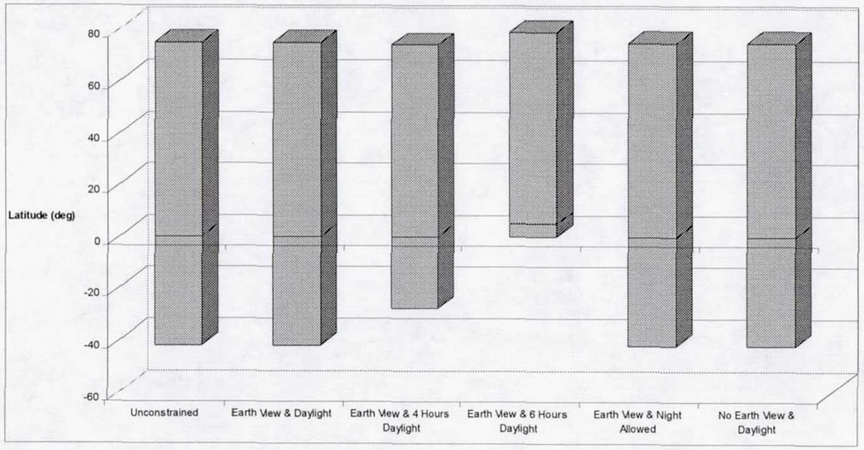
Type II


Landing Lighting and Latitude for Direct Entry JSC Mars Sample Return
(2007 Opportunity, Date/Time September 21, 2007 12:00:00.0, Trip Time 365 Days)

V-Infinity = 2.76 km/s
Inertial Entry Velocity = 5.65 km/s
Min. Landing Latitude = -43.2 deg
Max. Landing Latitude = 74.8 deg


Example 176 degree and 118 degree Skip

Type II



Evaluation of Type I - IV

Opportunity	Maximum To opposite pole (deg)	Minimum Across annulus (deg)	Inside annulus (deg)
Type I	184	135	68
Type II	164	$\boxed{118}$	$\boxed{59}$
Type III	168	153	77
Type IV	$\boxed{196}$	157	79

Aerocapture Guidance (HYPAS)

HYPAS = Hybrid Predictor-corrector Aerocapture Scheme

Capture Phase - Provides bank angle command, ϕ_{cmd}, to stabilize the trajectory and drive the vehicle toward equilibrium glide conditions.

$$\cos\phi_{cmd} = \cos\phi_{eq.gl.} - G_{\dot{h}}\left(\frac{\dot{h}-\dot{h}_{ref}}{\bar{q}}\right) + G_{\bar{q}}\left(\frac{D/m-(D/m)_{ref}}{\bar{q}}\right) \qquad (D/m)_{ref} = K\left(\frac{V^2}{R}-g\right)\frac{C_D}{C_L}$$

D/m is measured, filtered

$\dot{h}_{ref} = 0$

Exit Phase - Analytically predicts the velocity vector at atmospheric exit altitude, then adjusts bank command so that the velocity achieved at exit altitude will produce an orbit with the target apoapsis.

$$\Delta V = -\left[\frac{\dot{h}_{ref}m}{C_D S h_s \bar{q}_{est}} + \frac{1}{V_r}\right]^{-1}$$

$$V_{exit} = V_I + \Delta V$$

$$V_p = \sqrt{\frac{2\mu R_a}{R(R+R_a)}}$$

$$\dot{h}_{factor} = \frac{-1}{2V_p\left(\frac{R_a^{\,2}}{R^2}-1\right)}$$

$$V_{desired} = V_p + \dot{h}_{factor}\dot{h}_{ref}^{\,2}$$

$$V_{miss} = V_{desired} - V_{exit}$$

$$\dot{h}_{ref} = \dot{h}_{ref} + \frac{V_{miss}}{(dV_{miss}/d\dot{h})}$$

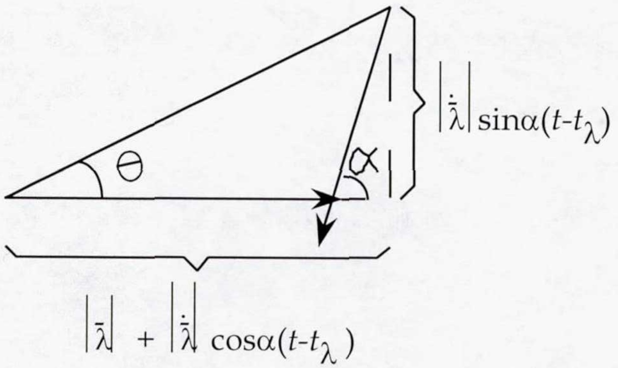
$$\cos\phi_{cmd} = \cos\phi_{eq.gl.} - G_{\dot{h}}\left(\frac{\dot{h}-\dot{h}_{ref}}{\bar{q}}\right)$$

Lateral logic - Bank reversal when inclination error exceeds deadband limits. Deadband limits specified as a function of velocity.

$$i_{allowable} = \max\left[i_{min}, \min\left(i_{min} + m(v - v_{min}), i_{max}\right)\right]$$

Powered Explicit Guidance (PEG)

If gravity is assumed to be constant, theory shows that optimal thrust vector time history is a linear function of time.



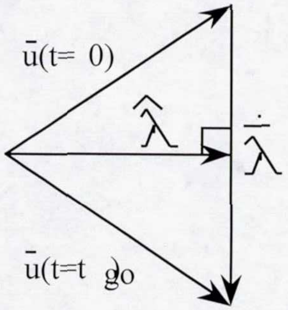
$$\tan\theta = \frac{|\dot{\bar\lambda}|\sin\alpha(t-t_\lambda)}{|\bar\lambda| + |\dot{\bar\lambda}|\cos\alpha(t-t_\lambda)}$$

Linear Tangent Guidance

For tanθ to be linear, its second derivative must be = 0

$$\frac{d^2\tan\theta}{dt^2} = -2\frac{|\dot{\bar\lambda}|\cos\alpha(\sin\alpha-\cos\alpha\tan\theta)}{\left[|\bar\lambda| + |\dot{\bar\lambda}|\cos\alpha(t-t_\lambda)\right]^2} = 0$$

Can only be true if $\alpha = +/- 90$



$$\bar\lambda_F = \bar\lambda + \dot{\bar\lambda}(t-t_\lambda)$$

$$\hat u_F = \frac{\hat\lambda + \dot{\bar\lambda}(t-t_\lambda)}{\sqrt{1+\dot\lambda^2(t-t_\lambda)^2}}$$

Unit Thrust direction

Prediction Phase

Given the definition of R and V predicted

$$\bar{r}_{THRUST} + \bar{r}_{grav} = \bar{r}_p - \bar{r} - \bar{V}\, t_{go}$$

$$\bar{V}_{THRUST} + \bar{V}_{grav} = \bar{V}_p - \bar{V}$$

The R and V thrust (also known as RGO and VGO) can be computed in terms of the first and second integrals of acceleration including integrals with t and t^2

$$\bar{r}_{THRUST} = \left[S - \frac{1}{2}\dot{\lambda}^2 (P - 2t_\lambda Q + t_\lambda{}^2 S) \right] \hat{\lambda} + (Q - S t_\lambda)\, \dot{\lambda} \qquad \bar{V}_{THRUST} = \left[L - \frac{1}{2}\dot{\lambda}^2 (H - 2t_\lambda J + t_\lambda{}^2 L) \right] \hat{\lambda} + (J - L t_\lambda)\, \dot{\lambda}$$

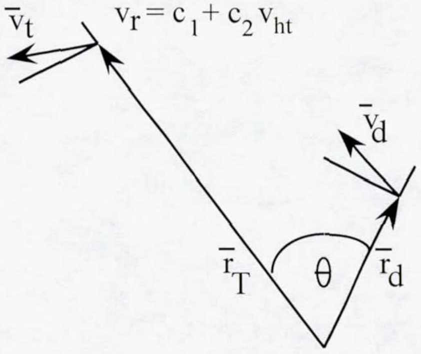
$$\bar{r}_{grav} = \int_0^{t_{go}} \int_0^{t_{go}} \bar{g}(t)\ \mathrm{dt}\,\mathrm{dt} \qquad \bar{V}_{grav} = \int_0^{t_{go}} \bar{g}(t)\ \mathrm{dt}$$

And R grav and V grav are computed by

Using a first guess of tgo we can compute R and V predicted

PEG Corrector & LTVC

Using Linear Terminal Velocity Constraint at Entry Interface, you can compute the velocity desired (vd) and update vgo and tgo and iterate until converged



LTVCON SCHEMATIC

$$\bar{v}_{miss} = \bar{v}_p - \bar{v}_d$$

$$Vgo = vgo - vmiss$$

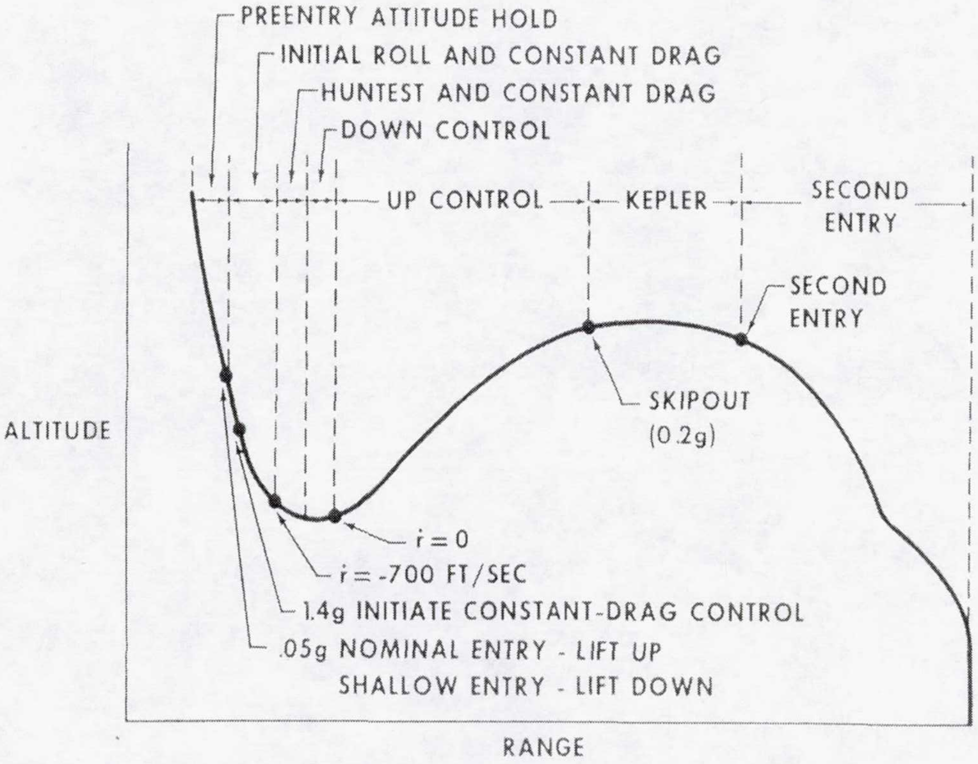
$$t_{go} = (m/\dot{m})\left[1 - \exp^{(-v_{go}/v_{ex})}\right]$$

Method to compute c1 and c2

Use a fixed entry profile and increment the velocity at EI
Iterate to find the gamma which gives the same range

c2 = (vr1 – vr2)/(vh1 – vh2)
c1 = vr1 – c2 * vh1

Apollo Derived Entry Guidance



Second entry phase guidance equations

Predicted range:

$$R_p = R_{ref} + \frac{\partial R}{\partial D}\left(D - D_{ref}\right) - \frac{\partial R}{\partial \dot{r}}\left(\dot{r} - \dot{r}_{ref}\right)$$

Vertical *L/D* command:

$$\left(\frac{L}{D}\right)_C = \left(\frac{L}{D}\right)_{ref} + \frac{K_3\left(R - R_p\right)}{\partial R/\partial\left(L/D\right)}$$

Bank angle command:

$$\Phi_C = \cos^{-1}\left(\frac{L/D_C}{L/D}\right) * K2ROLL$$

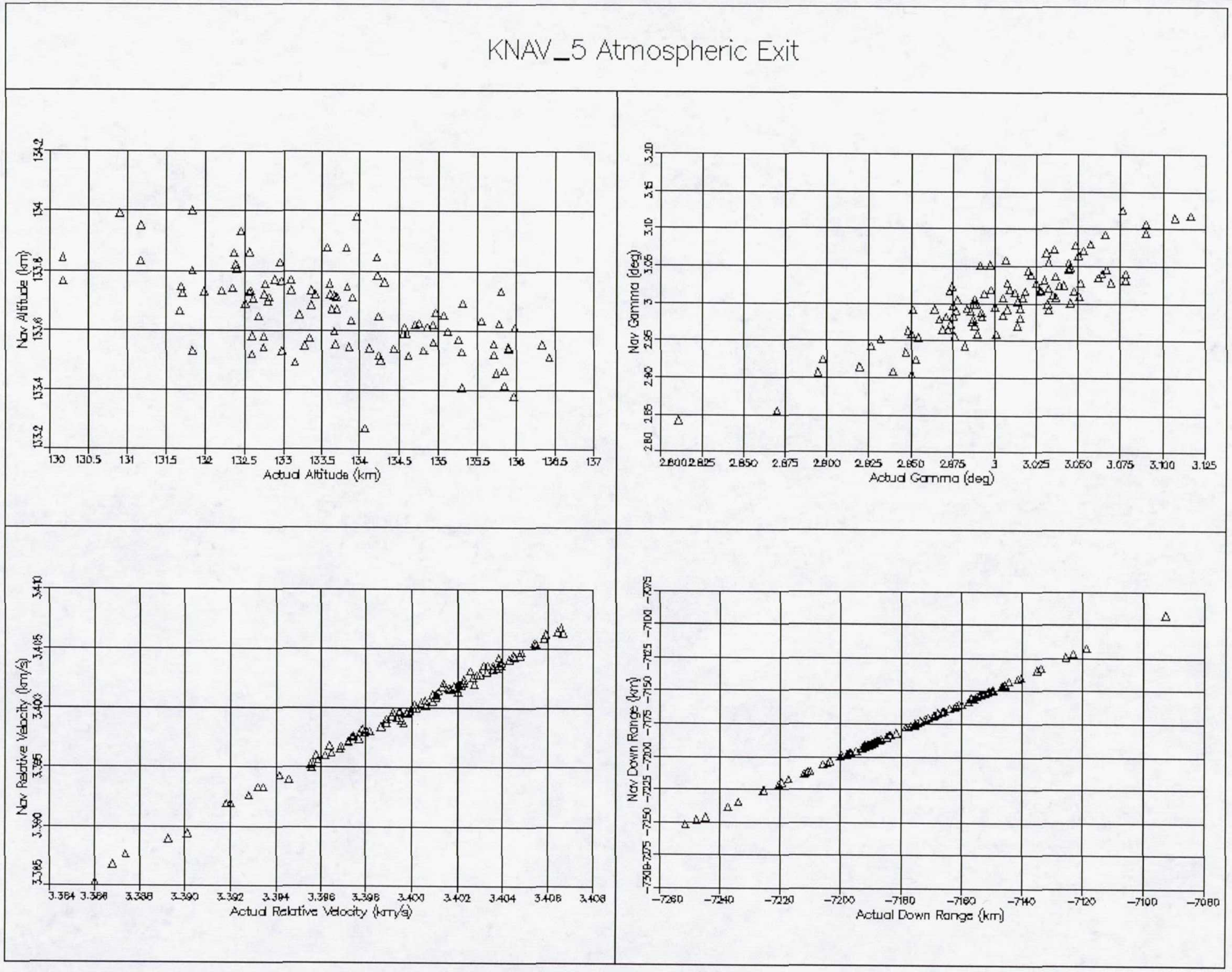
Navigation Model

- Nav dispersions modeled from 2005 knowledge covariance applied at EI with 111μ rad per axis star camera alignment
- Dead reckoning accomplished via LN100S IMU located at vehicle CG
  - Sensor scale factors, biases, axial misalignments, and noise modeled in simulation
- Altimeter Updates
  - Simulations run ~3000 seconds which induces a large vertical channel nav error in dead-reckoning
  - Some studies use a high altitude altimeter and a Kalman filter to reduce vertical channel error after first aeropass
- Calibration assumed to be 90% of bias values in some studies

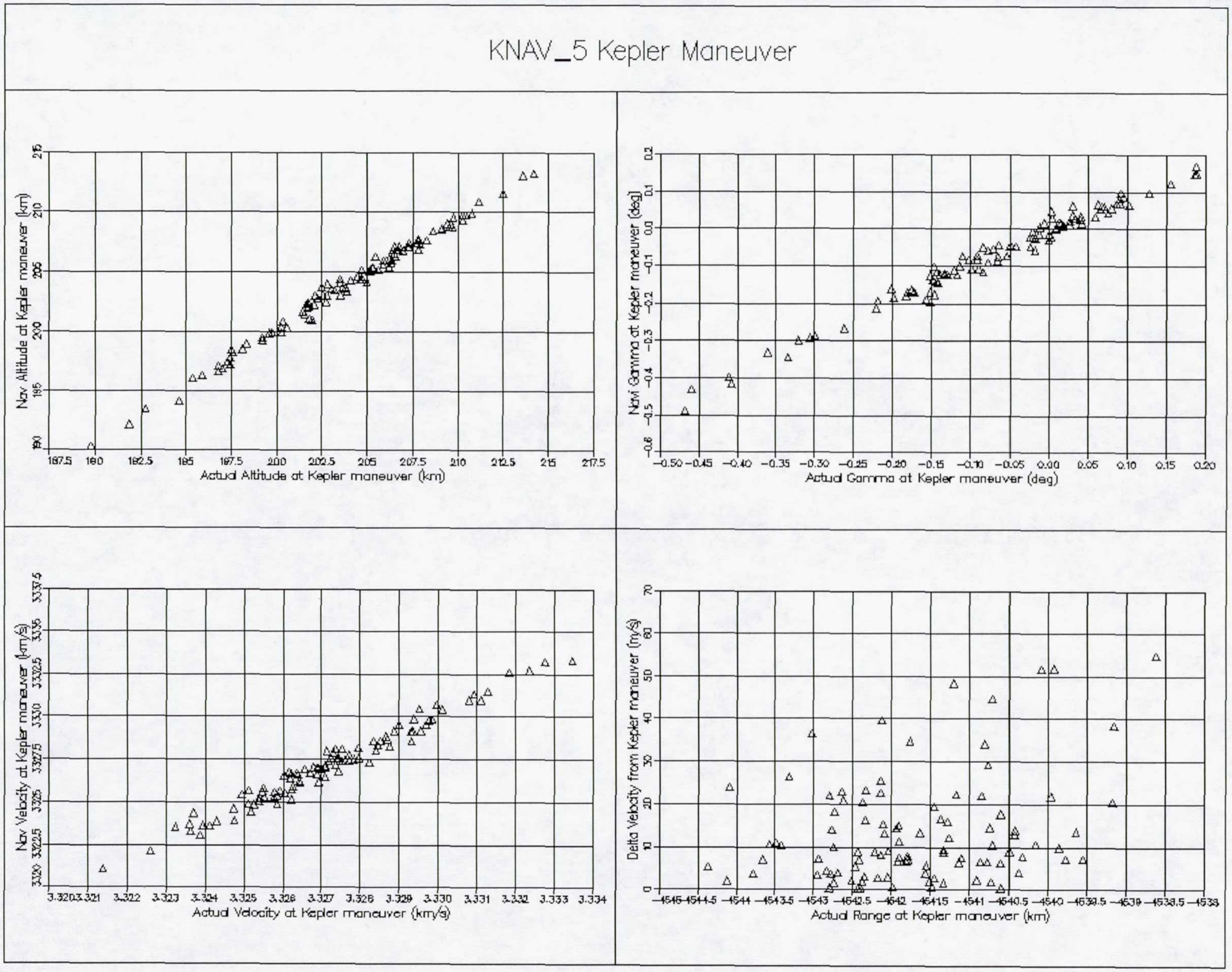
Vehicle

- **Vehicle Weight 1950 kg**
- **L/D 0.25 (trim tab)**
- **Mars Gram 2000**
- **Phase Plane Dap**
  - 5 deg/s2 angular acceleration
  - 20 deg/s angular rate
- **Thrust 172 lbs**
  - Acceleration 0.04 Earth g's
- **ISP 310**
  - 55 m/s = 35 kg fuel and burn time of 139 seconds
- **Ballistic number 111 (mach 34)**

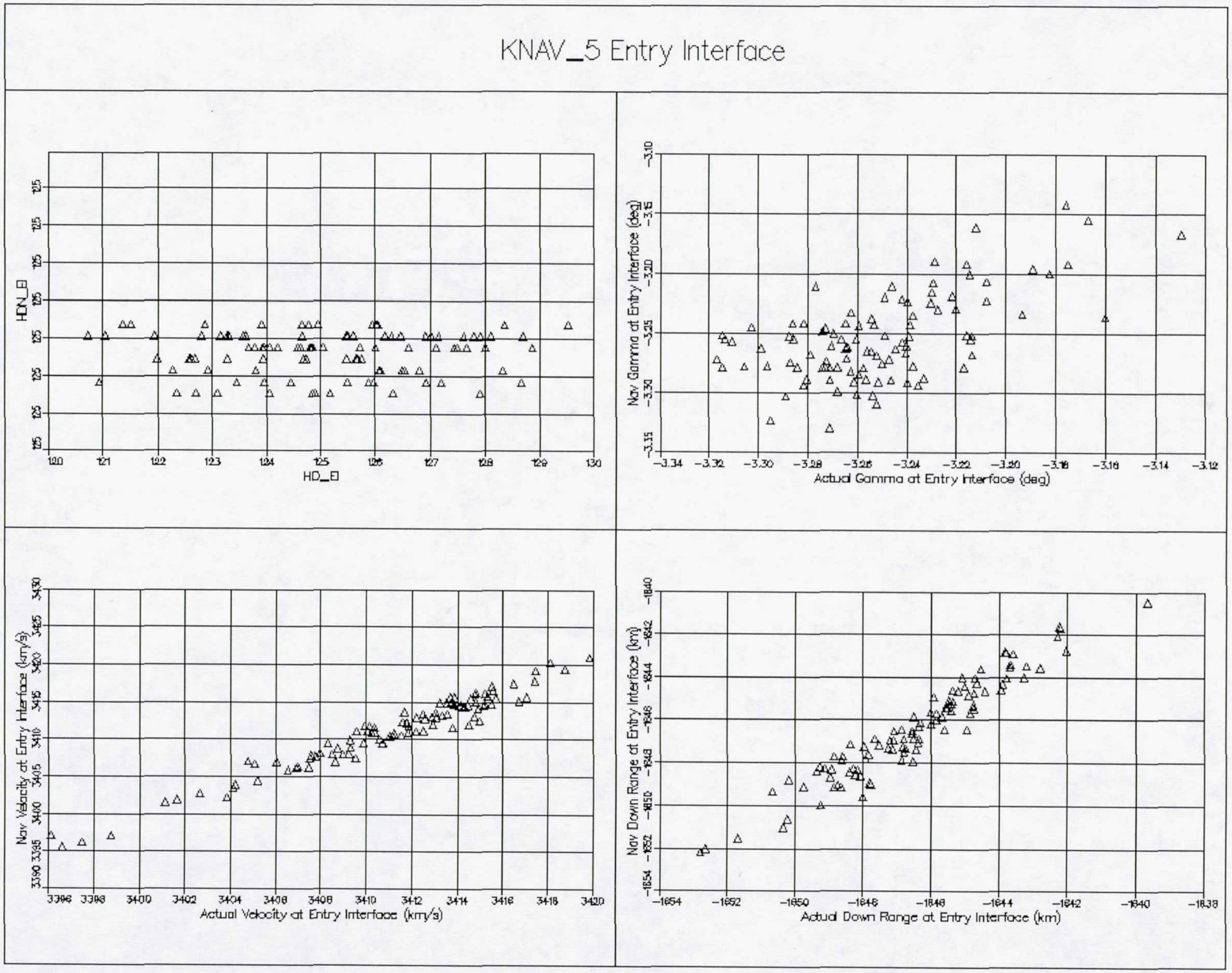
Monte Carlo Atmospheric Exit (100 cases)



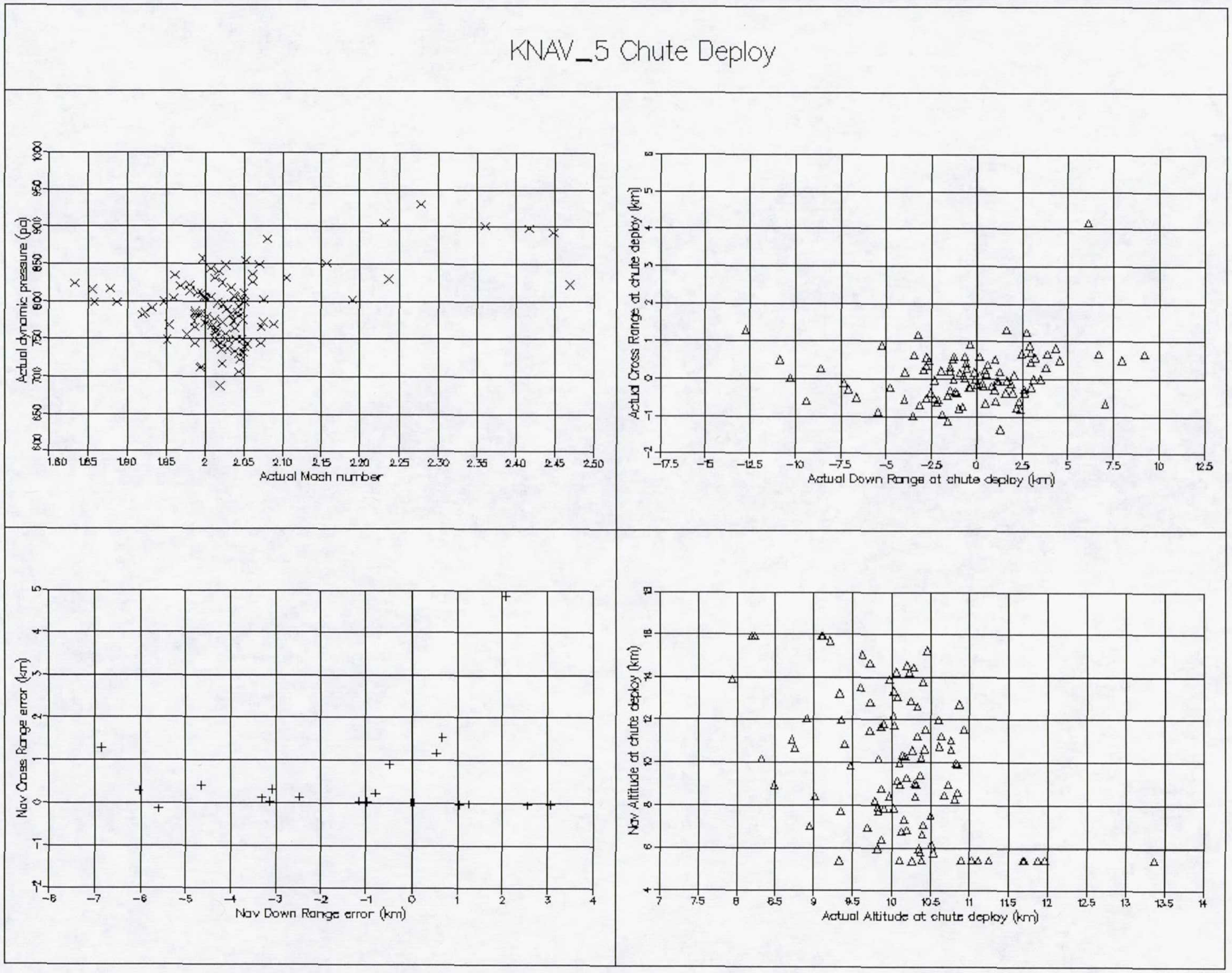
Monte Carlo Kepler Maneuver (100 cases)

- 

Monte Carlo Entry Interface (100 cases)



Monte Carlo Chute Deploy (100 cases)



KNAV_5 Chute Deploy

Delivery Errors

Delivery errors which cause 4 cases to be greater that 10km in actual range are:

Downtrack	18 - 36 km
Crosstrack	120 km
Hd	3.0 km
Gamma	0.3 - 0.45 deg
Azimuth	1.5 – 3.0 deg

Appendix

References

REFERENCES: HYPAS

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2. Bryant, L., Tigges, M., Ives, D. "Analytic Drag Control for Precision Landing and Aerocapture," AIAA-98-4572, AIAA Atmospheric Flight Mechanics Conference, Boston, MA, Aug. 1998.

3. Masciarelli, J., Rousseau, S., Fraysse, H., Perot, E. "An Analytic Aerocapture Guidance Algorithm for the Mars Sample Return Orbiter," AIAA-2000-4116, AIAA Atmospheric Flight Mechanics Conference, Denver, CO, Aug. 2000.

REFERENCES: PEG

1. McHenry, R. L., et al: "Space Shuttle Ascent Guidance, Navigation, and Control," The Journal of Astronautical Sciences, Vol. XXVII, No. 1, pp. 1-38, January-March, 1979.
2. Long, A. D., McHenry, R. L.: "Shuttle Powered Flight Guidance Equations Development," 84-FM-37, JSC-19995, Mission Planning and Analysis Division, NASA Lyndon B. Johnson Space Center, Houston, TX, August 1984.

REFERENCES: Apollo Derived

Carman, G., Ives, D., Geller, D., "Apollo-Derived Mars Precision Lander Guidance," Paper No. 98-4570, AIAA Atmospheric Flight Mechanics Conference, Boston, MA, August 1998.

Mosely, P. E., "The Apollo Entry Guidance: A Review of the Mathematical Development and It's Operational Characteristics," TRW Note No. 69-FMT-791, Task MSC/TRW A-220, December, 1, 1969.

Ro, T. U., Queen, E. M., "Mars Aerocapture Terminal Point Guidance," Paper No. 98-4571, AIAA Atmospheric Flight Mechanics Conference, Boston, MA, August, 1998.

Dispersions

SWGT01 = 5.4467 / 0.38% 3 sigma Weight
DSPC1 = 0.050 / 10% 3 sigma Cl
DSPC2 = 0.0048 / 4% 3 sigma Cd
ALONG DEG = 0.1 / Longitude
GDLAT DEG = 0.1 / Latitude
VI = 5.0 / Velocity ft/sec
GAMI DEG = 0.05 / Gamma
AZI DEG = 0.1 / Azimuth
HD KM = 0.5 / Altitude

RNCPOS(1) = 1.0
RNCPOS(2) = 1.0 / Random number in covariance, position
RNCPOS(3) = 1.0
RNCVEL(1) = 1.0
RNCVEL(2) = 1.0 / Random number in covariance, velocity
RNCVEL(3) = 1.0

AABIAS(1) MTR = 2.4525e-4
AABIAS(2) MTR = 2.4525e-4 / Accelerometer biases
AABIAS(3) MTR = 2.4525e-4
AMISAL(1) = 4.84814e-6
AMISAL(2) = 4.84814e-6
AMISAL(3) = 4.84814e-6 / Accelerometer nonortho/misalign
AMISAL(4) = 4.84814e-6
AMISAL(5) = 4.84814e-6
AMISAL(6) = 4.84814e-6
AASCAL(1) = 1.0e-4
AASCAL(2) = 1.0e-4 / Acceleration scale factor
AASCAL(3) = 1.0e-4

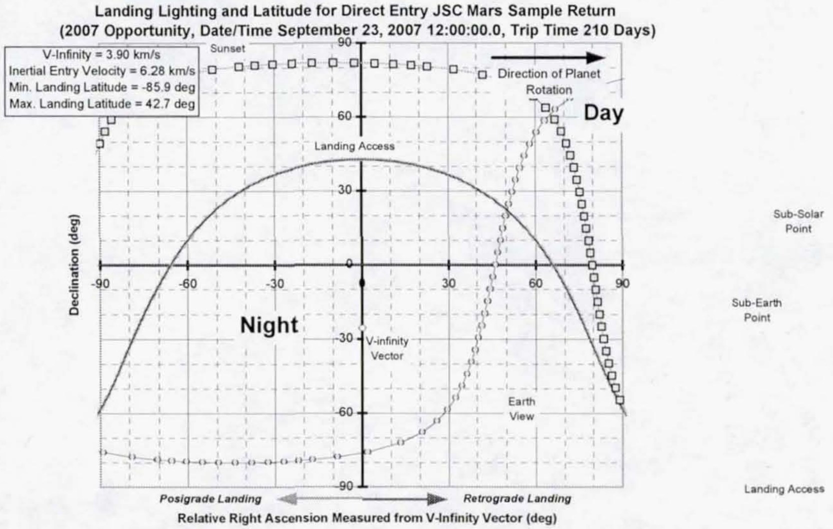
GDRIFT(1) DEG = 8.3333e-7
GDRIFT(2) DEG = 8.3333e-7 / Gyro bias drift
GDRIFT(3) DEG = 8.3333e-7
GSFERR(1) = 1.0e-6
GSFERR(2) = 1.0e-6 / Gyro scale factor
GSFERR(3) = 1.0e-6
GMISAL(1) = 4.84814e-6
GMISAL(2) = 4.84814e-6
GMISAL(3) = 4.84814e-6 / Gyro nonortho/misalign
GMISAL(4) = 4.84814e-6
GMISAL(5) = 4.84814e-6
GMISAL(6) = 4.84814e-6

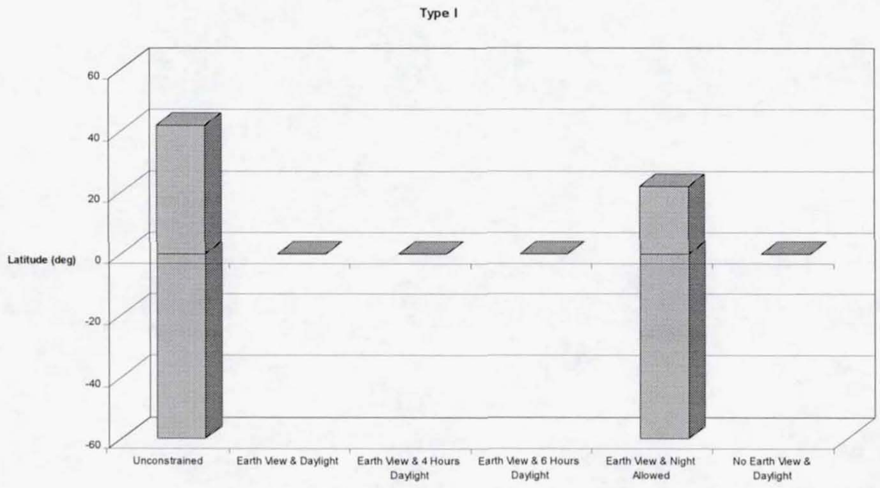
ROTN(1) = 111.0e-6
ROTN(2) = 111.0e-6 / Navigated attitude
ROTN(3) = 111.0e-6

Type I and Type II

2007 Opportunity, Depart Earth 9/23/07, Trip Time = 210 days, C3 = 18.8 km^2/s^2

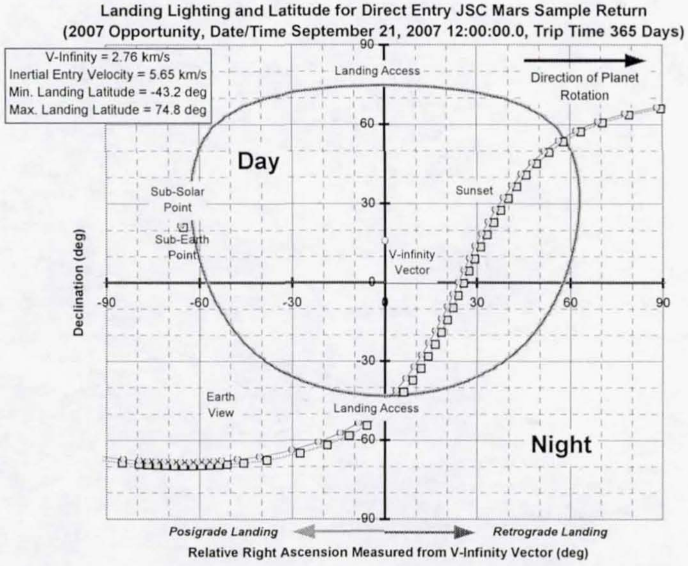
Type I

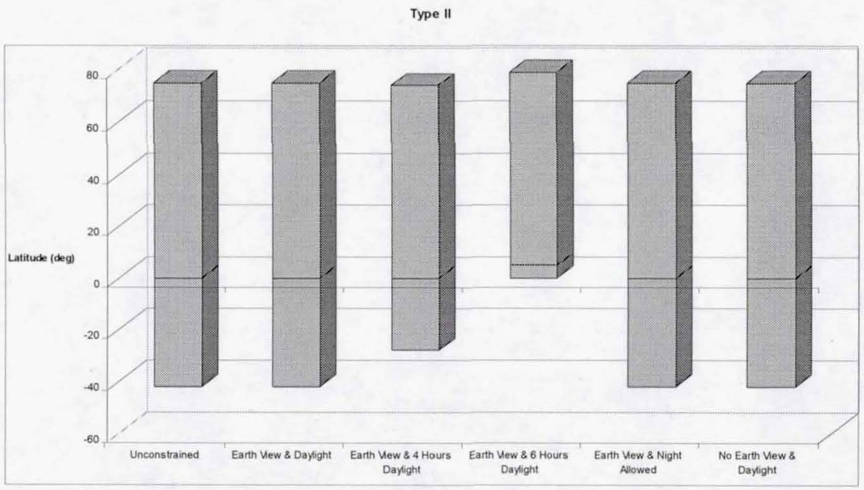




2007 Opportunity, Depart Earth 9/21/07, Trip Time = 365 days, C3 = 12.8 km^2/s^2

Type II

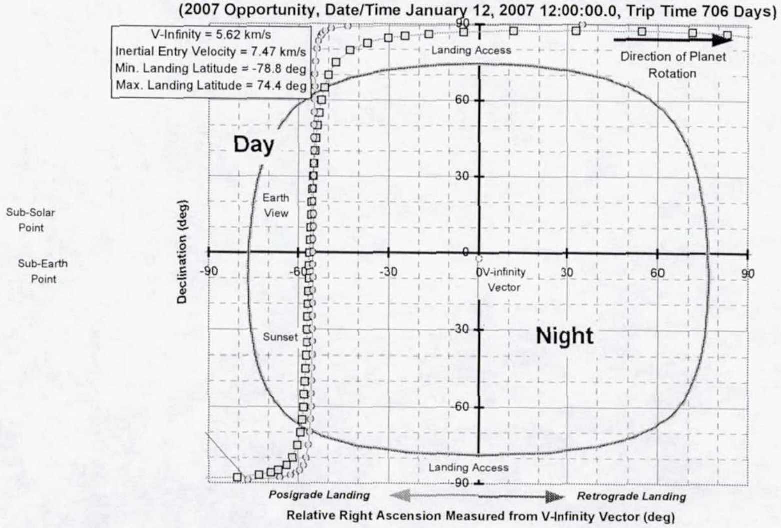


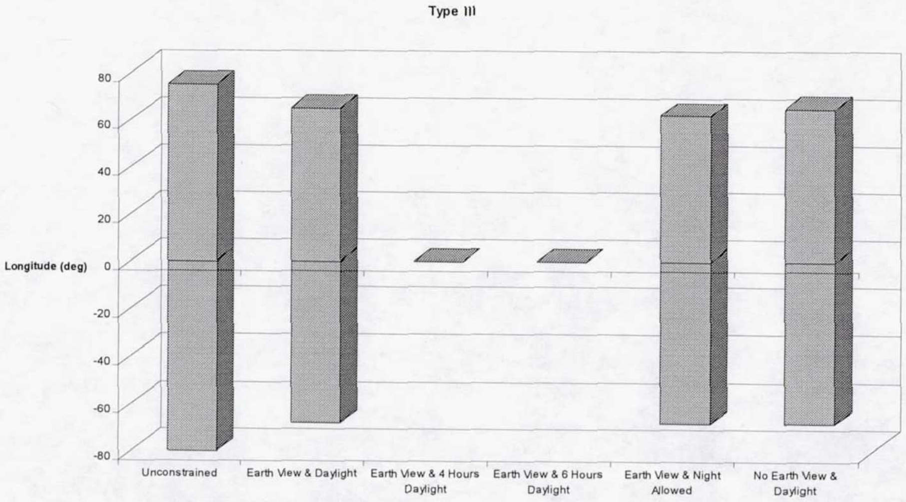


Type III and Type IV

2007 Opportunity, Depart Earth 1/13/07, Trip Time = 706 days, C3 = 9.0 km^2/s^2

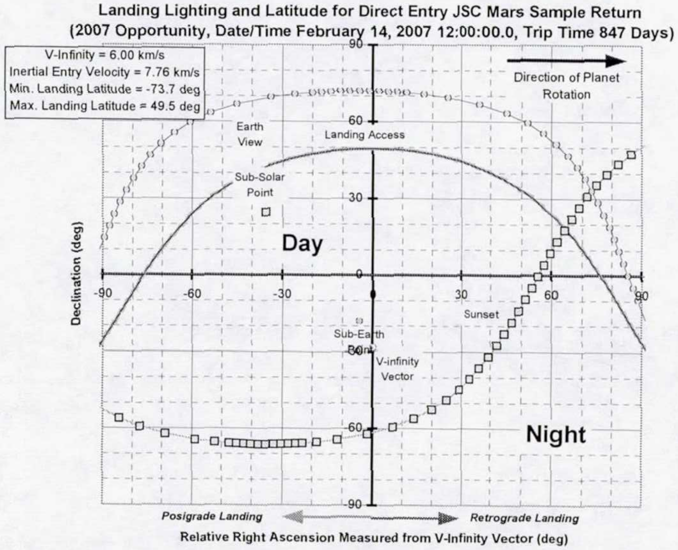
Type III

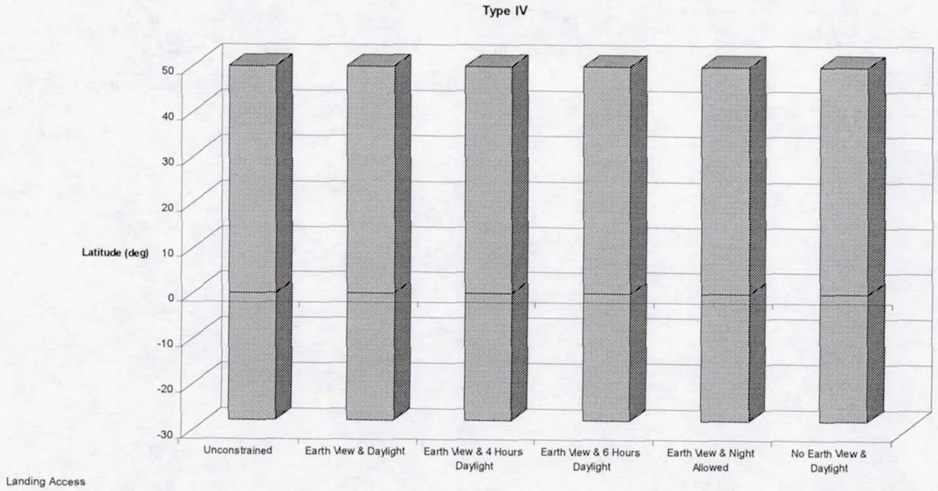

Landing Lighting and Latitude for Direct Entry JSC Mars Sample Return
(2007 Opportunity, Date/Time January 12, 2007 12:00:00.0, Trip Time 706 Days)



2007 Opportunity, Depart Earth 2/14/07, Trip Time = 847 days, C3 = 8.7 km^2/s^2

Type IV


Landing Lighting and Latitude for Direct Entry JSC Mars Sample Return
(2007 Opportunity, Date/Time February 14, 2007 12:00:00.0, Trip Time 847 Days)



Additional Peg Equations

$$L = \int_0^{t_{go}} \frac{f}{m(t)}\,\mathrm{dt}$$

$$S = \int_0^{t_{go}} \int_0^{t_{go}} \frac{f}{m(t)}\,\mathrm{dt}\ \ \mathrm{dt}$$

$$J = \int_0^{t_{go}} \frac{f}{m(t)}\,t\,\mathrm{dt}$$

$$Q = \int_0^{t_{go}} \int_0^{t_{go}} \frac{f}{m(t)}\,t\,\mathrm{dt}\ \ \mathrm{dt}$$

$$H = \int_0^{t_{go}} \frac{f}{m(t)}\,t^2\mathrm{dt}$$

$$P = \int_0^{t_{go}} \int_0^{t_{go}} \frac{f}{m(t)}\,t^2\mathrm{dt}\ \ \mathrm{dt}$$