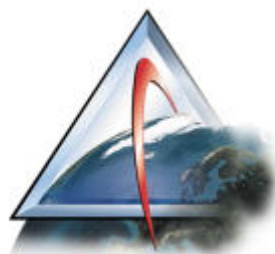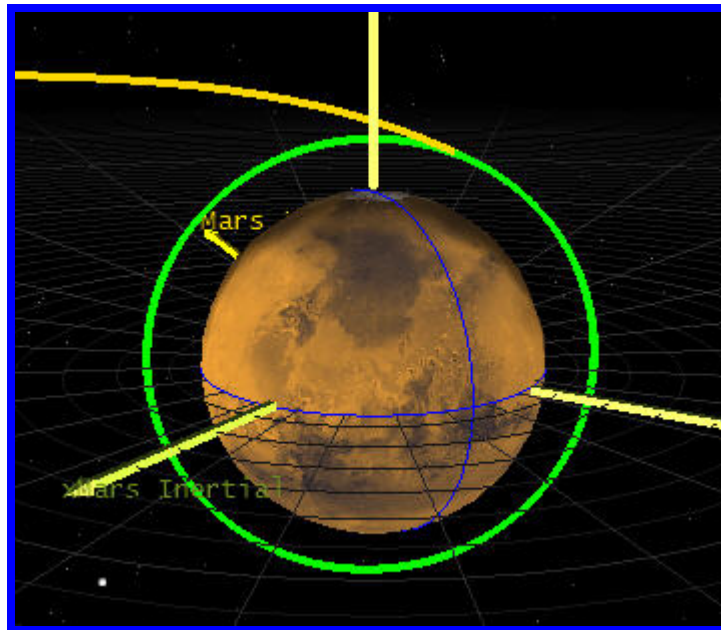# Trajectory Design with STK/Astrogator

Mars Orbit Mission Tutorial

Mission Overview

In this tutorial, we will model a Mission to Mars. Starting from the Earth, we will:

1. Use the Target Vector Outgoing Asymptote parameters to specify our outgoing state.
2. Use a Trajectory Correction Maneuver to target Mars approach parameters.
3. Coast to Mars Periapsis
4. Perform an impulsive Mars Orbit Insertion (MOI) maneuver.
5. Circularize our orbit at 90 degrees.

At the end of this exercise we will have:

1. Used a TCM maneuver in a Mission Control Sequence.
2. Used Multiple Profiles to achieve our desired Martian parameters
3. Used Constraints to help us target.
4. Created Mars-Centered views in STK.
5. Created a trajectory that leaves the Earth enters heliocentric space, and then orbits Mars.

NOTES

Setting Up the Scenario

Setting up to Scenario and Animation Times

1. Open a new scenario in STK. By default, you should get a 3D Window and a 2D Map. We will configure these windows later for our Mars mission.

2. Name the scenario 'Mars_Mission'.

3. Specify the timeframe of the mission. This is important since the objects that don't fall within the interval of the scenario will not be displayed. The orbit epoch of this particular mission is July 15th, 2003. This is a good reference time for our scenario; therefore, we will use it as our start time.

   a. Right click on the 'Mars_Mission' scenario and select **Basic Properties**. On the **Time Period** page, enter the follow parameters:

   Time Period

Element	Value
Start Time	15 Jul 2003 00:00:00.00
Stop Time	16 Jul 2003 00:00:00.00
Epoch	15 Jul 2003 00:00:00.00

   b. Select the **Animation** page and introduce the following dates:

   Animation

Element	Value
Start Time	15 Jul 2003 00:00:00.00
Stop Time	16 Jul 2003 00:00:00.00
Time Step	60 sec

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You can access the Basic Properties of any object in STK by double-clicking on its object icon.

Note

Setting up the 2D and 3D Windows

We are now ready to configure the 2D and 3D windows for our mission to Mars. We will use the following settings to visualize the orbit from a Mars equatorial position.

2-D WINDOW SETTINGS

4. Select the 2-D window, and click on the **Central Body** button 🌐 from the 2-D Graphics toolbar.

5. Change the Central Body to **Mars**.

6. Select the 2-D window, and click on the **Properties** button 🖳 from the default toolbar.

7. From the **Details** Page**,** Turn off Image and **deselect** all the high resolution detail Items.

8. From the **Projection** page:

    a. Change the **Type** to **Orthographic.**

    b. Change the **Display Coordinate System Frame** to '**CBI**' (Central Body Intertial).

    c. Change the **Display Height** to **40000 km.**

    d. Change the **Center** to **Lat** = 0 deg & **Lon** = 115 degrees.

    e. Turn on **Show Axes** and click on the **Format**… button.

        i.   Turn on All Axes.

        ii. Change the color to Green for Plus and Red for Minus.

        iii. Change the **scale** to **30** for both Axes.

        iv. Change the **coordinate frame** to **CBI**

    f. Click on Apply when done and on the reset button to refresh the 2D Map.

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9. Dock the 2-D window to the top of your application (Select the window, and right click on the upper blue bar of the window for these options). We'd like the windows to be visible during targeting so it's best not to leave them Integrated, or Floating.

3D WINDOW SETTINGS

10. Select the 3-D window, and click on the **Properties** button.

   a. From the **Globe** page, change the Central Body to Mars.

   b. From the **Details** page, select **Show Equator** and **Show Prime Meridian**.

   c. On the **Celestial** page, turn the 'Ambient Level' to zero, in the Global Lighting area.

   d. On the **Advanced** Page, change the Visible Distance to 1e+009 km

   e. On the **Grids** page, turn the CBI grid on, change the color to dark gray, and show radial lines.

   f. On the **Vector** page, activate the Sun vector and the Mars J2000 Axes.

11. From the View menu, Create a new 3D Graphics Window.

   a. From the **Globe** page, change the Central Body to the Sun.

   b. On the **Advanced** Page, change the Visible Distance to 1e+012 km

12. Dock your 3Ds window to the top as well, and try to position things to that you can see them.

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Populating the Scenario

In this particular scenario, we only need two types of STK objects: Planets and Satellites.

CREATING PLANETS

13. With the scenario selected, from the **Insert** menu, select **New** and then **Planet**.

    a. From the **Basic Properties** of the new planet, on the **Definition** page, select '**Mars**' as the central body.

    b. From the 2-D Graphics/Attributes page, deselect **Inherit from Scenario**, **Show Subsatellite Point**, and **Show Subsatellite Label** and select the **Show Orbit** box, and select the color to be red.

14. Copy and Paste Mars into the scenario again, and then redefine it to be 'Earth'.

    a. Configure the planet the same as Mars, except select the color to be blue and change the name to 'Earth'.

CREATING THE SPACECRAFT

15. With the scenario selected, from the Insert menu, select New and then Satellite. Dismiss the orbit wizard.

16. Name the satellite 'Mars_Probe'.

17. Select the Basic Properties of the satellite.

18. From the Orbit page, change the propagator to ASTROGATOR.

19. Remove all the segments in the Mission Control Sequence (MCS) using the Delete Segment button .

20. On the **2-D graphics page/Pass** page turn the **Orbit Track/Lead Type** to **All** and set the **Ground Track/Lead Type** to **None.**

21. On the **3-D graphics page/Pass** page turn the **Orbit Track/Lead Type** to **All**.

22. From the **3-D graphics/Model** page:

    a. Change the Marker to 'Point'

    b. Change the scale to 7.

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    c.   For the Detail Thresholds, slide the Marker label and the Marker bars to the maximum.

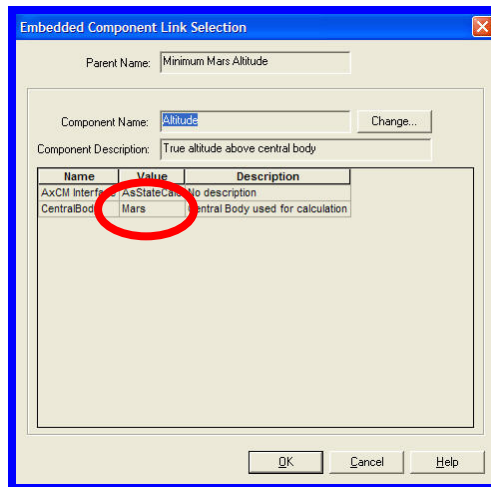# Building the Mission Control Sequence (MCS)

Get out of Orbit.

1. Create a new Target segment, and label it 'Target_Mars'.

2. Inside the target segment, add an initial state segment.

    a.   Set the **Element type** to Target Vector Outgoing Asymptote.

    b.   Set the Orbital Elements as follows:

        i.   Orbit epoch = 6 Jun 2003 18:18:28.00 UTCG

        ii.   Radius of Periapsis = 6778 km.

        iii.   C3 Energy = 8.7949 km^2/Sec^2.

        iv.   RA of Outgoing Asymptote = 348.941 deg.

        v.   Declination of Outgoing Aysmptote = -6.4025 deg.

        vi.   Velocity Azimuth at Periapsis = 0 deg.

        vii.   True Anomaly = 0 deg.

    c.   Set C3, RA and Declination as Controls.

3. After the initial state segment, add a propagate segment named 'Prop to SOI'. Change the color as you see fit.

    a.   Leave the stopping condition as 'Duration'.

    b.   Change the **Trip value** to 1 Day.

    c.   Set the **Propagator** to 'Cislunar'.

4. Add a propagate segment named 'Prop to TCM'. Change the color as you see fit.

    a.   Change the stopping condition to 'Altitude', and make the altitude relative to Mars.

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b. Change the **Trip value** to 40,000,000 km. This will stop the propagation when the satellite gets within 40 million km of Mars.

c. Set the **Propagator** to 'Heliocentric'.

5. After the Propagation segment, add an impulsive burn segment named 'TCM'.

a. Change the **Attitude Control** to **Thrust Vector.**

b. Change the thrust axes to **'Sun VNC'.**

c. Set X, Y and Z as Controls.

6. After the TCM segment, add a propagate segment named 'Prop to Mars'.

a. Change the propagator to Heliocentric.

b. Give the segment a stopping condition of altitude (WRT Mars) of 50 km. This will prevent the trajectory from impacting Mars.

c. Give the segment a 2nd stopping condition of periapsis:

   i. Give the periapsis a condition a constraint that it's altitude (above Mars) be less than 200,000 km. (Bring up the Altitude Calculation object and make sure it's central body is Mars)

We constrain our periapsis condition to prevent the stopping condition from being met when we haven't actually encountered a periapsis. Periapsis is measured within STK by following

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the altitude along the orbit track. If the altitude reaches a minimum and starts rising again, STK thinks it has achieved periapsis. Since it is possible that we could encounter this condition before actually getting near Mars, we can constrain this condition and only accept periapses that are within 200,000 km of Mars.

Hit Mars

7. Add 3 results to the 'Prop to Mars' segment:

    a. From the 'MultiBody' Calc Object folder, **Delta Right Asc**.

    b. From the 'MultiBody' Calc Object folder, **Delta Declination**

    These constraints are the targeted differences in the right ascension and declination angles between the spacecraft at the end of the segment and the selected central body (Mars) with respect to its parent body (Sun). Note that both of these default to a selected central body of the Moon.

    c. Epoch.

8. Select the 'Target Mars' targeter, and name the default Targeting Profile 'RA Dec'.

9. Set the **Profile Mode** to **Iterate**, and set the **Action** for the targeter to '**Run Active Profiles Once'**.

10. Select the Properties button for the profile, and activate the Controls and Constraints

    a. Activate the Controls:

        i. **C3**. **Perturbation** of 0.0001 km^2/sec^2, **Max Step Size** of 0.05 km^2/sec^2.

        ii. **RA of Outgoing Asymptote**. **Perturbation** of 0.1 deg, **Max Step Size** of 1 deg.

        iii. **Dec of Outgoing Asymptote**. **Perturbation** of 0.1 deg, **Max Step Size** of 1 deg.
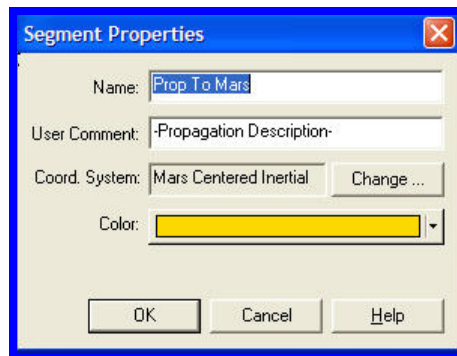
    b. Activate the Constraints

        i. **Delta Right Asc**. Leave as defaults.

        ii. **Delta Declination**. Leave as defaults.

        iii. **Epoch**. 25 Dec 2003 20:36:26, tolerance of 1 hr.

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11. Run the sequence. Check the 3-D window to see how close the trajectory appears to be to Mars.

12. Set the Targeter Action to Run Active Profiles.

13. Turn on **Draw Trajectory as it is Calculated** under the MCS Options button on the Astrogator Toolbar.

14. Run the targeter.

15. Right Click on the 'Prop to Mars' segment, and change the coordinate system to 'Mars Centered Inertial'.

16. Bring up the Summary Report on the 'Prop to Mars' segment, and inspect both the 'Stopped On' condition (which identifies which stopping condition ended the segment) and the altitude (above Mars) at the time. Given that we targeted Delta RA and Delta Dec to be zero, we should have produced an impact trajectory. Did we?

17. Note the end of segment time for Prop_to_Mars segment. Paste this time (and then subtract one second) into the Animation toolbar and look at the trajectory in the 3-D windows.

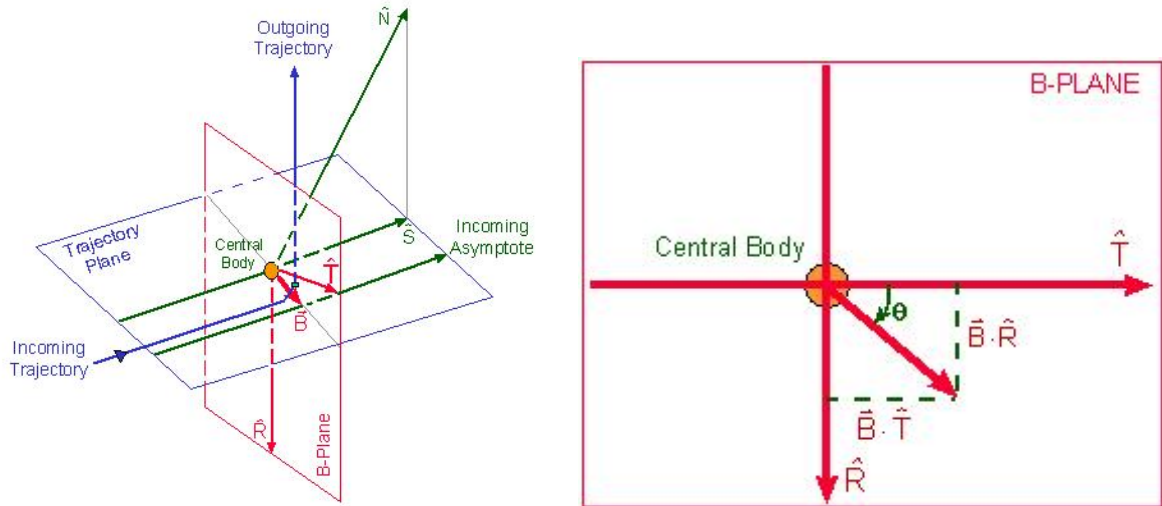18. Run the animation to watch the trajectory.

Target the B-Plane

Now we have an impact trajectory, which is close, but we want to get to orbit. The best way to do that is target the B-plane. The B-plane is a planar coordinate system that allows targeting during a gravity assist or for planetary orbit insertion. It can be thought of as a target attached to the assisting body. If you have a trajectory that is close to the encounter planet, the B-plane

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gives you targets that behave very linearly, which is important with the differential corrector targeting scheme in Astrogator. However, had we targeted the B-plane before we had proper initial conditions (i.e. we were pointing in some random direction) this would not have worked since we may never have crossed the plane. We first had to target to get close to Mars, and only then were we close enough to Mars with our trajectory to use B-plane targeting.

The b-plane is defined to be the plane that contains the focus of an idealized two-body trajectory (assumed to be a hyperbola) that is perpendicular to the incoming asymptote of that hyperbola. The incoming and outgoing asymptotes, $\hat{S}$ and $\hat{O}$, and the focus are contained in the trajectory plane, which is perpendicular to the b-plane. The intersection of the b-plane and the trajectory plane defines a line in space. The b-vector is defined to lie along this line, starting on the focus and ending at the spot where the incoming asymptote pierces the b-plane. The vectors $\hat{T}$ and $\hat{R}$ lie in the b-plane and are used as axes.

Now that we have found the right direction of our transfer trajectory, we can adjust our first guesses of Outgoing Asymptote RA, Dec and C3 to target in on the desired final orbit. To do so, we will use the B-Plane parameters BdotT and BDotR. In this example, we are interesting in capturing around Mars in a 90 degree inclination orbit. Thus we will target a BdotT = 0 km and a BdotR = -10000 km that will bring our orbit along the North (BdotT is negative to the North). Ultimately we will target an orbit of 90 degrees with a periapsis of 1000 km altitude. However, altitude and the b-plane parameters do not directly match, so we will guess a value

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that gets us well off the surface of the planet above the north pole of Mars knowing that the Martian radius is 3386 km. For our purposes, we will guess 10000 km.

Let's set up another targeting profile to achieve these goals.

19. Add two new results to the 'Prop to Mars' panel.

   a. From the 'MultiBody' Calc Object folder, **BdotT**. Reconfigure this result to be Mars centered.

   b. From the 'MultiBody' Calc Object folder, **BdotR.** Reconfigure this result to be Mars centered.

20. In the targeter panel, create another profile named 'Bplane'.

   Recall that in our first profile, we targeted using our Outgoing Asymptote conditions. While we can do that in a real mission, there is a limit to the accuracy we can achieve in our launch state.   In a real mission, any errors in our launch conditions would be taken out using a Midcourse Correction. In order to simulate this:

   a. Apply corrections from the first profile **RA Dec**, and make the profile inactive.

   b. Truncate the Outgoing Asymptote Ra and Dec down to the first digit after the decimal point to simulate the maximum precision available in a launch vehicle. Leave the C3 value the way it is.

21. Select the Properties button for the new Bplane profile, and activate the Controls and Constraints

   a. Activate these Controls from the TCM segment:

      i. **Cartesian.X**. **Perturbation** of 0.0001 km/sec, **Max Step Size** of 0.001 km/sec.

      ii. **Cartesian.Y**. **Perturbation** of 0.0001 km/sec, **Max Step Size** of 0.001 km/sec.

      iii. **Cartesian.Z**. **Perturbation** of 0.0001 km/sec, **Max Step Size** of 0.001 km/sec.

   b. Activate the Constraints

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i. **BdotT**. Value of –10000. **Tolerance** of 1 km.

ii. **BdotR**. Value of 0.0. **Tolerance** of 1 km.

iii. **Epoch**. 25 Dec 2003 20:36:26, tolerance of 1 hr.

22. Set the Mode for the 'Bplane' profile to 'Iterate'.

23. Set the Targeter Action to Run Active Profiles Once.

24. Run the targeter.

25. Check the results window and see that our initial B-Plane parameters are reasonable.

26. Set the Targeter Action to Run Active Profiles.

27. Run the targeter again.

28. Bring up the Summary Report on the 'Prop to Mars' segment, and inspect both the 'Stopped On' condition (which identifies which stopping condition ended the segment) and the altitude (above Mars) at the time. Given that we targeted the b-plane at 10000 km, we should have some reasonable altitude above Mars, and we should be stopped on periapsis.

Target Final Approach Conditions

Now that we have refined our trajectory, we would like to achieve the exact Martian altitude and inclination we desire for our orbit. We are interested in capturing around Mars in a circular, 90 degree inclination orbit with an altitude of 1000 km.

29. Add two new conditions to the 'Prop to Mars' segment.

   a. Inclination (set this to the 'Mars Centered Inertial' coordinate frame).

   b. R-Mag (set this to the 'Mars Centered Inertial' coordinate frame).

30. Create another profile, called 'Rp Inc'

   a. Activate these Controls from the TCM segment:

      i. **Cartesian.X**. **Perturbation** of 0.0001 km/sec, **Max Step Size** of 0.001 km/sec.

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ii. **Cartesian.Y**. **Perturbation** of 0.0001 km/sec, **Max Step Size** of 0.001 km/sec.

iii. **Cartesian.Z**. **Perturbation** of 0.0001 km/sec, **Max Step Size** of 0.001 km/sec.

b. Activate the Constraints

i. **Inclination**. Value of 90. Default tolerance.

ii. **R-Mag**. Value of 4386 km. Default Tolerance.

iii. **Epoch**. 25 Dec 2003 20:36:26, tolerance of 1 hr.

31. Set the Mode for the 'Rp Inc' profile to 'Iterate'.

32. Run the targeter.

33. Bring up the Summary Report on the 'Prop to Mars' segment, and inspect the 'Stopped On' condition (which identifies which stopping condition ended the segment) the altitude (above Mars) and the inclination (WRT Mars). We should now have the parameters we desired.

34. Select the 'Target Mars' targeter, and select 'Clear all corrections'. This should clear out everything we've targeted so far.

35. Run the targeter again, and watch how the profiles converge sequentially, each time setting up the results slightly closer for the next profile.

Get Into Orbit

Now that we've gotten ourselves where we want at Mars, it's time to get into orbit.
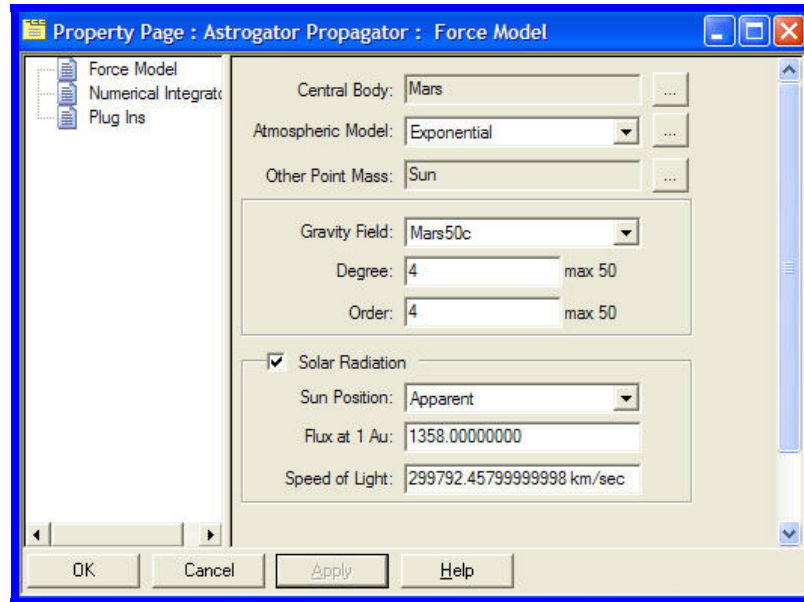
36. Apply the corrections in the 'Target Mars' targeter, and change the Action for the targeter to Run Nominal Sequence. Run the sequence again to make sure you did this in the right order.

37. Create a new targeter after 'Target Mars' called 'Get into Orbit'.

38. Add an Impulsive Burn to the segment and name it 'MOI'.

39. Change the **Attitude Control** to **Thrust Vector**, and the **Thrust Axes** to **Mars VNC**.

40. Activate the **X(Velocity)** vector as a control.

41. Add two results to the MOI segment

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    a. **Eccentricity** (WRT Mars) from the Keplerian Elements Folder.

    b. **C3** Energy (WRT Mars) from the Target Vector Folder.

42. Create a new propagator, called 'Mars 4x4' in the Astrogator Browser, and configure it as follows (use the default integrator):

43. Add a propagation segment after the targeter called 'Prop twice around'

    a. Set the **Propagator** to **Mars 4x4**

    b. Set the stopping condition to **Periapsis** (WRT Mars)

    c. Set the **Repeat Count** to **2**.

> **Note**
>
> C3 is the energy of the orbit, computed as $-\mu/a$, where μ is the gravity constant of the central body and a is the Semi-major axis. A negative C3 indicates that a spacecraft is captured and in orbit, while a positive C3 indicates a hyperbolic trajectory.

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We'd like to target an eccentricity of 0.0 to get a circular orbit, but eccentricity switches sign when a spacecraft goes from being hyperbolic to being in orbit, so first we'll target our MOI to get our C3 negative, and then we'll set the eccentricity to 0.

44. Create two profiles in the targeter:

   a. Target C3

      i. Use X(Velocity) of MOI to hit C3 of −0.1 using default settings.

   b. Target Ecc

      i. Use X(Velocity) of MOI to hit Eccentricity of 0.01 within a tolerance of 0.01
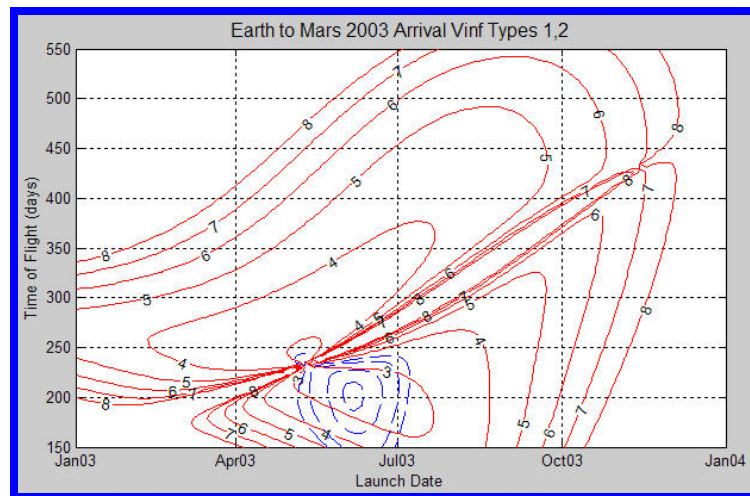
45. Set the modes of both Profiles to 'Iterate'.

46. Set the Action of the Targeter to 'Run Active Profiles'.

47. Run the targeter.

48. Change the properties of the 'Prop Twice Around' propagator to use Mars Centered Inertial coordinates.

49. Get the summary report from this segment and inspect the orbital elements.

The initial state we used came from a 'Porkchop' plot of Earth-Mars opportunities for 2003:

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Try out some alternate trajectories. Remember that your targeting profiles will need the new arrival date in addition to the initial state modifications.

Mission	Mariner 9	Viking 1	Viking 2
Launch date	30 May 1971 22:36:00	20 Aug 1975 21:22:00	9 Sep 1975 18:39:00
Arrival	14 Nov 1971 00:00:00	19 Jun 1976 00:00:00	7 Aug 1976 00:00:00
C3	9.374 km^2/sec^2	21.4905 km^2/sec^2	15.2799 km^2/sec^2
RA	-35.8077 deg	85.6871 deg	79.2051 deg
Dec	-28.3369 deg	-11.4433 deg	-3.4004 deg

Mission	Mars Global Surveyor	Mars Odyssey	Mars Express
Launch date	7 Nov 1996 17:00:00	7 Apr 2001 15:02:00	2 Jun 2003 17:45:00
Arrival	12 Sep 1997 00:00:00	23 Oct 2001 02:26:00	20 Dec 2003 00:00:00
C3	9.8677 km^2/sec^2	10.8186 km^2/sec^2	8.8435 km^2/sec^2
RA	173.2313 deg	-124.803 deg	-8.705 deg
Dec	22.4338 deg	-50.5085 deg	-8.142 deg

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