Getting Started Processing DSN Data with ODTK

1 Introduction

ODTK can process several types of tracking data produced by JPL's deep space network (DSN): two-way sequential range, two- and three-way Doppler, and two- and three-way total count phase. In the context of the DSN, *two-way* indicates observations where the signal is transmitted and received by the same ground station. *Three-way* measurements involve the signal being transmitted from one ground station and being received by a different ground station.

The DSN is the primary tracking system for NASA's deep space missions and uses antennae of several sizes: 11 meters, 26 meters, 34 meters, and 70 meters. The antennae are located in California, Spain, and Australia, providing excellent coverage of deep space missions. The ODTK algorithms for processing DSN measurements are based on measurements after the completion of the Network Simplification Program.

DSN observations are designed to be zero-bias measurements. To achieve this result, DSN stations perform a self-calibration process prior to each tracking pass. This process determines and removes system delays from the reported observations. The calibrations are effective in removing biases larger than approximately 14 range units (about 4 meters for typical X band processing) in the sequential ranging. The smaller remaining biases should be unique for each pass and should be estimated. You can consider the phase measurements to be unbiased. You can remove transponder delay effects from the reported observation, but more commonly this is not the case and you should account for it during orbit determination.

2 ODTK configuration

The simplest way to work with DSN tracking data in ODTK is to import the DSN tracking system object that comes with the product. The measurement statistics associated with each of the tracking stations are based on the processing of actual DSN tracking data for at least one spacecraft. If particular measurement types are not included in the measurement statistics list for a certain ground station, this only means that no live data was processed to determine the statistics and it is not an indicator that the tracking station cannot support that measurement.

Since large measurement biases are removed from DSN observations, and transponder effects are accounted for, the typical estimation state includes

- the troposphere near the ranging facility
- the trajectory of the spacecraft
- force model parameters, specifically solar pressure states

The DSN tracking system object includes Az-El masks for some DSN tracking stations in the system. AGI obtains Az-El masks from the JPL 301N report for ground stations. You can use the masks during measurement simulation. The JPL report may specify two or more Az-El masks for a facility, depending on whether the system is using the station to receive data, transmit data in a low-power configuration, or transmit data in a high-power configuration. ODTK defaults to using the "receive data" mask for each station that has masks. To use one of the other masks, go to ProgramData\AGI\ODTK7\Databases\Facilitiy\AzEl, select another mask, and use it to replace the Receive Data mask in the DSNetwork.tso file. You can disable mask usage on a per-facility basis by setting AzElMask.Enabled=false in the Facility properties.

3 DSN tracking data

ODTK can process DSN two-way sequential range, two- and three-way Doppler, and two- and three-way total count phase provided in the TRK-2-34 format. ODTK also provides limited capability for generating simulated DSN observations. The simulation capability is limited to generating observations in the ODTK generic observation format.

The DSN *sequential ranging* measurement is an ambiguous range. The length of the unambiguous part of the observation is supplied in the tracking data file in conjunction with the observation value. During the simulation of measurements, the ambiguity is set to be 1.0×10^{99}, which results in generation of unambiguous ranges.

The DSN *total count phase* (TCP) measurement is the total number of accumulated cycles of the carrier frequency observed since a starting epoch. Each observation of total phase count is supplied in the tracking data file with two epochs: the time that the total phase count was observed, and the starting time when the count was zero. ODTK differences the adjacent total count phase measurements as it reads the tracking data file, thus creating a sequence of derivative measurements equal to the number of cycles elapsed during adjacent time intervals. This makes ODTK's processing of total count phase observations nearly equivalent to processing Doppler observations (discussed in the sequel). When simulating TCP measurements, ODTK assumes a constant transmit frequency for the transmitting ground station, and it maintains the simulated measurements as the number of cycles over adjacent time intervals rather than the total number of accumulated cycles since a starting epoch.

The DSN *Doppler* measurement is the number of cycles of the carrier frequency observed over a specified time interval. Each observation of Doppler count is supplied in the tracking data file with the time interval over which the count is taken, and the time of the center of the time interval. A Doppler measurement differs slightly from a TCP measurement in that the time of a Doppler measurement is referenced to the center of the time interval, while the time of a TCP measurement is referenced to the end of the time interval. When simulating Doppler measurements, ODTK assumes a constant transmit frequency for the transmitting ground station.

Tip: You cannot combine real DSN tracking data with simulated DSN tracking for the same ground stations in the same scenario. ODTK generates simulated tracking data based on a constant frequency taken from the ground station properties, while the real tracking data contain frequency ramp information in the tracking data file. During estimation, ODTK always uses the frequency ramp information from the real data if it exists; this will result in the rejection of all simulated data.

4 Orbit determination example

The distribution of actual DSN tracking data is highly regulated, so in this exercise you will work with simulated data. You should have a basic knowledge of ODTK and of how to navigate its GUI menus before attempting this exercise.

4.1 Configuring the tracking system

1. Start ODTK.
2. Load the GS_DSN demonstration scenario located in your ODTK install area under the directory:

   `<install directory>\ODTK\UserData\DemoScenarios\ Processing DSN Data`

   After loading the scenario, perform a Save As operation to save a copy of the scenario to your local user area. The scenario contains a satellite configured to mimic the MAP spacecraft orbiting near the Earth-Sun L_2 point.
3. Double-click the MAP satellite in the Object Browser to bring up the properties of the satellite in the object properties window. The initial conditions are specified in the Earth-centered J2000 reference frame. Scroll down to view the force modeling settings. Since MAP is very far from the Earth, AGI truncates the geopotential at a low degree and order. The geopotential includes the full list of third-body perturbations.
4. With the scenario highlighted in the Object Browser, click the File menu and select Import -> Import Object(s).

   In the Open dialog box, first select "TrackingSystem Files (*.tso)" as the file type and then browse to and select:

   `<install directory>\ODTK\AppData\Databases\ TrackingSystems\DSNetwork.tso`

   This tracking system is preconfigured with all of the appropriate DSN tracking.
5. MAP is tracked using the DSN 70-meter antennae, DSS14 and DSS43. Double-click either of these facilities in the Object Browser to view its properties in the object properties window. The description indicates the general location and type of antenna. DSS14 is at Goldstone, CA, and was the first of the 70-meter dishes to be built, initially supporting

Mariner 4. DSS43 is in Spain. All of the DSN 70-meter antennae were originally constructed as 64-meter dishes. Scroll down and notice the setting of the AntennaCorrectionType. DSN_70_AE indicates that ODTK will apply the antenna correction model for DSN 70-meter antennae with an azimuth/elevation mount when processing observations from this antenna.

6. DSS65 is included twice. This station was relocated after March 2005.
7. To keep the scenario simple, delete all facilities other than DSS14 and DSS43 by highlighting them in the object browser and pressing the delete key.
8. Save the scenario file before proceeding.

4.2 Simulating tracking data

1. Add a simulator object to the scenario and double-click it to open its properties. Set the MeasTypes list on the simulator to contain DSN TCP, DSN 3W TCP, and DSN Seq Rng.
2. Verify that the time period for the simulation is two weeks long by checking the start and stop times. Change the simulator time step to be two minutes.

Tip: The simulator was created with a time period of two weeks based on the DefaultTimes settings on the scenario object.

3. Set the TrackingStrandList to contain all of the following:
    - DSNetwork.DSS14 - *
    - DSNetwork.DSS43 - *
    - DSNetwork.DSS43 - * - DSNetwork.DSS14

   The first two tracking strands enable the simulation of the two-way measurement types (DSN TCP and DSN Seq Rng), while the three-element strand enables the simulation of three-way total count phase. The sequence of the three-element strand indicates that the signal will be transmitted from DSS43, pass through a satellite of interest, and then be received at DSS14.
4. Change the Output.Measurements.Filename to point to a file with the .gobs extension. The generic observation format is the only format that you can use to simulate DSN measurements. Apply all changes.
5. You are now configured to simulate tracking data. Generate the simulated observations by clicking the Run button while the simulator is highlighted in the object browser. This may take several minutes.
6. When the simulator is finished, you can view the generated observations by clicking the View Measurements button.
7. Save the scenario file before proceeding.

4.3 Running the Filter

1. Add a Filter object to the scenario. In its properties, set the MeasTypes list on the Filter to contain DSN TCP, DSN 3W TCP, and DSN Seq Rng.
2. Configure the Filter to generate smoother input data by setting the Output.SmootherData.Generate flag to true.
3. Change the name of the filter output file to “GS_DSN_Earth.filrun”. Apply all changes.
4. From the ODTK LaunchPad, select the ODTK Utilities tab. Expand the Installed Utilities directory and open the **StateContent** utility. Select the filter object and then click the **Display State Contents** button to verify that the following states are being estimated:
    - spacecraft position and velocity
    - spacecraft solar-radiation pressure
    - troposphere biases for each DSN facility
5. Save the scenario before proceeding.
6. Run the filter. This may take several minutes.
7. On completion, check the Message Viewer to verify that there are no error or warning messages.

4.4 Running the Smoother

1. Add a Smoother object to the scenario. Add the rough file generated by the filter to the input file list for the Smoother.
2. Change the name of the smoother output file to “GS_DSN_Earth.smtrun”. Apply all changes.
3. Save the scenario file before proceeding.
4. Run the Smoother. This may take several minutes.
5. On completion, check the Message Viewer to verify that there are no error or warning messages.

5 Analysis of results

5.1 Residual analysis

1. Open the Static Product Builder. Click the Inputs tab and add the filter output file GS_DSN_Earth.filrun as a data source. Select DSN Seq Rng in the data limiting area for measurement types. Click the Outputs tab and select the Residuals graph style. Click the **Run Selected** button to generate a new graph.

2. For better readability of the plot, double-click the plot to reveal the customization dialog box. Click the Axis tab, and then click the Y-Axis Min/Max radio button. Set Min to -20 and Max to 20; then click OK.
3. Return to the Inputs tab of the Static Product Builder and change the data limiting selection to produce similar graphs for the DSN TCP and DSN 3W TCP measurement types. A scale of +/- 1 will work well for these plots.
4. Keep these graphs available, as you will use them for comparisons in a later part of the exercise.

Tip: During estimation, ODTK ignores measurements with residual-ratio magnitudes greater than the value set in MeasurementProcessing.ResidualEditing.NominalSigma. ODTK's default value is three (3). Rejected residuals are graphed with different colored symbols.

5.2 Accuracy analysis

1. Remove all data limiting selections and return to the Outputs tab of the static product selector. Generate a Position Uncertainty graph. Change the scaling of the Y axis or use the zoom capability on the graph to examine the difference in the filter accuracy for the radial direction versus the in-track and cross-track directions. Also, while the filter appears to have reached a steady-state condition in radial accuracy, the in-track and cross-track are still improving.
2. Change the input file for the Static Product Builder to be the smoother output, GS_DSN_Earth.smtrun, and regenerate the Position Uncertainty graph. The level of improvement is approximately a factor of two in the in-track and cross-track directions. Also note the bow-tie shape of the smoother uncertainty in the in-track and cross-track directions, which indicates that the smoother never achieved steady state performance. Why do you think that neither the filter nor smoother achieved steady-state performance over the two weeks of data?

5.3 Quality analysis

1. From LaunchPad, select the ODTK Utilities tab. Expand the Installed Utilities directory and open the **StateDiffTool** utility. For the target, select the .smtrun file created by the smoother object. For the reference, select the .filrun file created by the filter object. Change the name of the output file to be GS_DSN_Earth_FilSmt.difrun. Click **Go!** to create the difference (.difrun) file.
2. Return to the Static Product Builder window. Choose the Inputs tab. Change the data source to be the .difrun file you just created.
3. Choose the Outputs tab of Static Product Builder and select the Pos Consistency graph style as the output product. Click the Run Selected button to generate a new graph.
4. Examine the position consistency graph. All component statistics remain within +/-3 almost all the time. We expect this type of behavior for a simulated data scenario. An

experienced analyst would consider the filter's total modeling as adequate upon seeing similar results for real data processing.

Tip: "Filter-smoother consistency" is a test statistic equal to the difference between the filter estimate and the smoother estimate, divided by the variance of the difference. Theoretically, this statistic is normally distributed with unit variance, such that when the filter-smoother modeling is adequate, large values of the statistic (greater than about 3) should be rare.

5. Choose the Outputs tab of Static Product Builder and select the SRP Coeff Consistency graph style as the output product. Click the Run Selected button to generate a new graph.
6. Examine the SRP coefficient consistency graph. The statistic is well distributed within ±3.

EXTRA CREDIT:

Go to the satellite properties and change the nominal value of Cp to 0.75. Based on the original value of 0.45 and the stated uncertainty of 0.05, this is a six-sigma deviation. Change the name of the filter output (.filrun) file so that you don’t overwrite your earlier result, which you will use again below. Now rerun the Filter, Smoother, and difference operations. Generate the position consistency graph again. It indicates potential modeling problems. Generate the SRP coefficient consistency graph to see if the solar pressure mismodeling might have been detectable with real tracking data. Reset Cp to 0.45 prior to proceeding to the next step.

6 Going heliocentric

1. Up to now, you have considered the MAP spacecraft to be in orbit about the Earth. It should be equally valid to consider MAP to be in orbit about the Sun, since it is located in the vicinity of the Sun-Earth L_2 point. From LaunchPad, select the ODTK Utilities tab. Expand the Installed Utilities directory and open the ChangeCentralBodyTool utility. Use the Central Body selector to choose the Sun as the new central body for MAP. Click **Execute** to make the change.
2. Double-click the satellite object to expose its properties window to verify that it has been repopulated. The state should now be a Sun-centered inertial frame.
3. In the Satellite properties, scroll down to the force modeling section. The degree and order of the gravity field has been updated to a value of 4. This reflects the smaller gravity field size available for the Sun.
4. Change the name of the filter output file to “GS_DSN_Sun.filrun”.
5. Rerun the filter to create the new .filrun file.
6. Go to the Static Product Builder. Click the Outputs tab and select the Residuals graph style. Click the Inputs tab and set the new *.filrun file from the filter run as the data

source. Use the data limiting capability to generate a residual graph for each measurement types. Compare these to the residual graphs that you generated earlier. Are the plots similar?

7. In LaunchPad, use the StateDiffTool utility to create a difference run that produces a comparison between the two filter output files, “GS_DSN_Earth.filrun” and “GS_DSN_Sun.filrun”. Prior to clicking **Go**, change the name of the output file to be “GS_DSN_Earth_Sun.difrun”. The first filter output file was generated using an Earth-centered integration of the spacecraft and the second used a Sun-centered integration of the spacecraft.
8. Return to the Static Product Builder. Click the Outputs tab and select the Differenced Pos R graph style. Click the Inputs tab and set the new *.difrun file from the difference run as the data source. Generate the selected graph; then generate graphs for the Differenced Pos I and Differenced Pos C graph styles. Do the ephemeris differences lie within the uncertainty bounds of the estimates? Would you expect the estimates to be different? Would you expect the uncertainties to be different?

7 Exploring the effects of force modeling

1. The original scenario contained the MAP spacecraft with a force model configured to use third-body perturbations from all available solar system bodies. This seems excessive, so you will try to process the simulated tracking data using a smaller number of perturbing bodies. Return to the ChangeCentralBodyTool utility and use the Central Body selector to choose the Earth as the new central body for MAP. Click **Go** to make the change. Making this change automatically changes the content of the third body perturbations list.
2. Double-click the Satellite object to expose its properties window to verify that it has been repopulated. Review the contents of the third-body perturbations list to verify that it has been changed to include only the Sun and the Moon, which are the normally desired settings for an Earth-centered trajectory.
3. In the Satellite properties, scroll down to the force modeling section. The degree and order of the gravity field is still set to a value of 4. Update this setting to 8.
4. Change the name of the filter output file to “GS_DSN_Earth_2TB.filrun”.
5. Run the Filter to create the new .filrun file.
6. Go to the Static Product Builder. Click the Outputs tab and select the Residuals graph style. Click the Inputs tab and set the new *.filrun file from the filter run as the data source. Use the data limiting capability to generate a residual graph for each measurement types. Compare these to the residual graphs that you generated earlier. Are the plots similar?
7. Use the StateDiffTool utility to create difference run which produces a comparison between the new filter output file, GS_DSN_Earth_2TB.filrun, and simulator output file

GS_DSN.simrun. Prior to clicking **Go**, change the name of the output file to be “GS_DSN_Earth_2TB.difrun”.

Tip: Generating difference runs between the Filter and Simulator outputs is a simple way to check the validity of the Filter estimate for simulated tracking data.

8. Return to the Static Product Builder. Click the Outputs tab and select the Differenced Pos R graph style. Click the Inputs tab and set the new *.difrun file from the difference run as the data source. Generate the selected graph; then generate graphs for the Differenced Pos I and Differenced Pos C graph styles. Do the ephemeris differences lie within the uncertainty bounds of the estimates?
9. Change the name of the smoother output file to “GS_DSN_Earth_2TB.smtrun”. Run the smoother.
10. Return to the StateDiffTool utility. For the target, select GS_DSN_Earth_2TB.smtrun. For the reference, select GS_DSN_Earth_2TB.filrun. Change the name of the output file to be GS_DSN_Earth_2TB_FilSmt.difrun. Click **Go** to create the difference (.difrun) file.
11. Return to the Static Product Builder window. Choose the Inputs tab. Change the data source to be the .difrun file you just created.
12. Choose the Outputs tab of static product builder and select the Pos Consistency graph style as the output product. Click the Run Selected button to generate a new graph.
13. Examine the position consistency graph. All component statistics remain within +/-3 almost all the time. You should expect this type of behavior for a simulated data scenario. An experienced analyst would consider the filter's total modeling as adequate upon seeing similar results for real data processing.
14. Return to the ChangeCentralBodyTool utility and use the Central Body selector to choose the Sun as the new central body for MAP. Click **Go** to make the change. Making this change automatically changes the content of the third-body perturbations list.
15. Double-click the Satellite object to expose its properties window to verify that it has been repopulated. Modify the contents of the third body perturbations list to include only the Earth and the Moon.
16. Change the name of the filter output file to “GS_DSN_Sun_2TB.filrun”.
17. Run the filter to create the new .filrun file.
18. Go to the Static Product Builder. Click the Output" tab and select the Residuals graph style. Click the Inputs tab and set the new *.filrun file from the filter run as the data source. Use the data limiting capability to generate a residual graph for each measurement types. Compare these to the residual graphs that you generated earlier. Are the plots similar?

19. Use the StateDiffTool utility to create difference run which produces a comparison between the new filter output file, GS_DSN_Sun_2TB.filrun and simulator output file GS_DSN.simrun. Prior to clicking **Go**, change the name of the output file to be "GS_DSN_Sun_2TB.difrun".
20. Return to the Static Product Builder. Click the Outputs tab and select the Differenced Pos R graph style. Click the Inputs tab and set the new *.difrun file from the difference run as the data source. Generate the selected graph; then generate graphs for the Differenced Pos I and Differenced Pos C graph styles. Do the ephemeris differences lie within the uncertainty bounds of the estimates? With good-looking residual plots, was there a way to detect that something was wrong?
21. Change the name of the smoother output file to "GS_DSN_Sun_2TB.smtrun". Run the Smoother.
22. Return to the StateDiffTool utility. For the target, select GS_DSN_Sun_2TB.smtrun. For the reference, select GS_DSN_Sun_2TB.filrun. Change the name of the output file to be "GS_DSN_Sun_2TB_FilSmt.difrun". Click **Go** to create the difference (.difrun) file.
23. Return to the Static Product Builder pane. Choose the Inputs tab. Change the data source to be the .difrun file you just created.
24. Choose the Outputs tab of static product builder and select the Pos Consistency graph style as the output product. Click the Run Selected button to generate a new graph.
25. Examine the position consistency graph. Note the significant excursions of the test statistic outside the desired region of +/-3. This type of behavior of the filter-smoother consistency test is indicative of a modeling error. Why do the modeling simplifications appear to be valid for Earth-centered estimation but not for Sun-centered estimation?

EXTRA CREDIT:

Try adding third bodies using only the filter-smoother consistency test to determine when your modeling is adequate. Once you have a good-looking consistency test, regenerate the difference between the filter output and the simulator output and see if the filter estimate and uncertainty contains the "truth" trajectory.