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AN INTERNET-BASED TRAJECTORY DATABASE FOR THE MESSENGER MISSION TO MERCURY

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The MESSENGER Trajectory Database provides an informative and captivating means of depicting the planned trajectory and mission plan for the NASA Discovery Program's MESSENGER mission to Mercury. With a successful launch on August 3, 2004, the MESSENGER spacecraft is en route to a March 2011 Mercury orbit insertion. The web-based trajectory database utilizes state-of-the-art information retrieval techniques to effectively serve the MESSENGER mission operations team, science team, and education and public outreach. In addition, the trajectory database minimizes site maintenance through the automation and creation of standard format files during post-launch operations. Discussion of the design and implementation of the MESSENGER Trajectory Database Web Service will focus on the architectural design and its integration with the SPICE (Spacecraft Planet Instrument Camera-matrix Events) toolkit and associated data files using XML and J2EE technologies. Of primary importance are descriptions of post-launch usage (user community and how they apply retrieved trajectory data) and updating (ephemeris upload and key event identification) of the trajectory database.

INTRODUCTION

The rationale for developing the MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) Trajectory Database Web Service (identified as "MESSENGER Trajectory Database" throughout this paper) was to provide MESSENGER team members with a user-friendly means of generating commonly requested trajectory data at their leisure. Using the MESSENGER Trajectory Database is one of several methods for disseminating details of the "current best trajectory" (a merged version of the most accurate reconstructed and predicted spacecraft ephemeris files) to the MESSENGER team. By updating the MESSENGER trajectory database with up to three spacecraft ephemeris files, Mission Design personnel now reap time savings via a significant reduction in special and routine data requests. A detailed description of MESSENGER's trajectory design and maneuver strategy is found in [1].

Flight controllers and the space science community desire to minimize the number of information systems they must learn to efficiently operate the spacecraft, plan data acquisition, and interpret data returned from the many active and planned spacecraft missions. In the 1980s

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NASA's Jet Propulsion Laboratory (JPL) established the Navigation and Ancillary Information Facility [2] (NAIF), the group responsible for design and implementation of the SPICE toolkit [3]. The SPICE acronym, which comes from (S – Spacecraft, P – Planet, I – Instrument, C – Camera-matrix, E – Events), provides an open-source, reliable means for archiving, distributing, and accessing observation geometry and related ancillary data used in mission design, mission evaluation, observation planning, and science data analysis. The toolkit consists of proven software routines written in C and FORTRAN. A growing number of spacecraft mission planners, operators, and scientists use the SPICE toolkit of subroutines, utility programs, and astrodynamics constants to develop mission analysis, scientific data analysis, and observation tools.

Many of these software tools suffer from at least one of three main limitations. First, the tools are often stand-alone programs that cannot provide information to users at other locations without the transmission of huge data files. Before the completion of recent upgrades, the Satellite Orbit Analysis Program (SOAP) from The Aerospace Corporation shared this limitation. The SOAP package is extremely flexible and very fast. A licensed version of SOAP [4] served as the primary tool for verifying and validating the results generated by the MESSENGER Trajectory Database. Second, many tools are not open source and do not exploit software reuse. Software developed as open source and based on component reuse would allow different missions to develop data analysis and observation tools faster and at a lower cost. Lastly, extremely capable web-accessible tools such as the "JPL HORIZONS On-Line Solar System Data and Ephemeris Computation Service" [5] are somewhat cumbersome to learn, and they place less emphasis on having a user-friendly graphics user interface (GUI).

Most planetary space missions utilize the SPICE library of astrodynamics data files and software. The MESSENGER Trajectory Database maximizes its use of the standard SPICE data files and software modules to both minimize computation time and offer reliable data query results. This paper describes the design and implementation of the MESSENGER Trajectory Database, a web service for the NASA Discovery Program's MESSENGER mission to orbit Mercury. The MESSENGER Trajectory Database, based on J2EE technology, utilizes a three-tier architecture where the back end interacts with the SPICE library through native method calls to C. The MESSENGER Trajectory Database development team included the MESSENGER Mission Design Lead Engineer from The Johns Hopkins University Applied Physics Laboratory (JHU/APL) and a professor and several graduate students from Howard University's Systems and Computer Sciences Department.

MESSENGER TRAJECTORY DATABASE CAPABILITY

The MESSENGER Trajectory Database provides an informative and captivating means of obtaining data using the reconstructed and planned trajectory (Figure 1) for the NASA Discovery Program's MESSENGER mission to orbit Mercury. The service uses state-of-the-art information retrieval techniques to effectively serve engineers, scientists, and public relations personnel during MESSENGER's development (pre-launch) and operations phases. The MESSENGER Trajectory Database provides an interactive GUI with immediate-response error checking and an easy-to-use ephemeris update tool for the systems administrator. To facilitate users' data analysis needs, data output formats include Excel, ASCII, and HTML. The user-friendly GUI enables the submission of data queries that may not require any keystrokes (100% mouse/cursor controlled). In order to ensure that the user obtains reliable results, error messages may appear prior to data query submission to indicate problems such as an input parameter falling outside an acceptable range. The MESSENGER Trajectory Database is an ITAR-approved tool that gives spacecraft mission analysis data without revealing the attitude of either the spacecraft or any movable part.

MESSENGER Trajectory Database users can specify, via a web interface, complex queries that return a variety of output quantities. The system supports seven distinct data query types:

1. Distance – Calculates the straight-line distance between any combination of the Sun, Mercury, Venus, Earth, and spacecraft. It can also calculate the distance traveled by one of these bodies relative to another body. Spacecraft altitude relative to a planet is offered.
2. Scalar Velocity – Calculates the scalar velocity of the spacecraft relative to the center of the Sun, Mercury, Venus, or Earth; or the velocity of Mercury, Venus, or Earth relative to the center of the Sun.
3. Position/Velocity Vector – Gives the Cartesian position and/or velocity vectors of the target Sun, Mercury, Venus, Earth, and spacecraft relative to a planet or the Sun. Several commonly used coordinate systems and reference epochs may be specified.
4. Angles – Calculates the angle formed by three bodies, usually the Sun, spacecraft, Mercury, Venus, or Earth, as well as the angular diameter of the Sun, Mercury, Venus, Earth, and Moon as viewed from the spacecraft, and solar phase (Sun – sub-spacecraft Mercury or Venus surface – spacecraft). Figure 2 shows the Angles page.
5. Orbital Elements – Computes classical orbital elements and related quantities (e.g., orbit period) relative to the Sun, Mercury, Venus, and Earth with different reference equator planes and a specified reference epoch.
6. Earth-Based Antennas – Calculates the elevation, azimuth, and range of the spacecraft, Sun, Mercury, or Venus relative to 34-m and 70-m diameter Deep Space Network (DSN) Earth-based antennas (locations come from [6]). This data helps determine potential communication windows for transmitting and receiving telemetry to/from the spacecraft.
7. Event-Based Output – Finds the time various spacecraft events occur. These events may be entry or exit of an eclipse or Earth occultation, periapsis or apoapsis, user-specified altitude relative to Venus or Mercury, or a range of Sun-planet-spacecraft angle. Any of the previous six query output types can be displayed at the instant an event occurs.

Many of the output quantities shown above are available in a choice of units (e.g., orbit period in seconds, minutes, hours, or days; semi-major axis in kilometers, miles, or astronomical units).

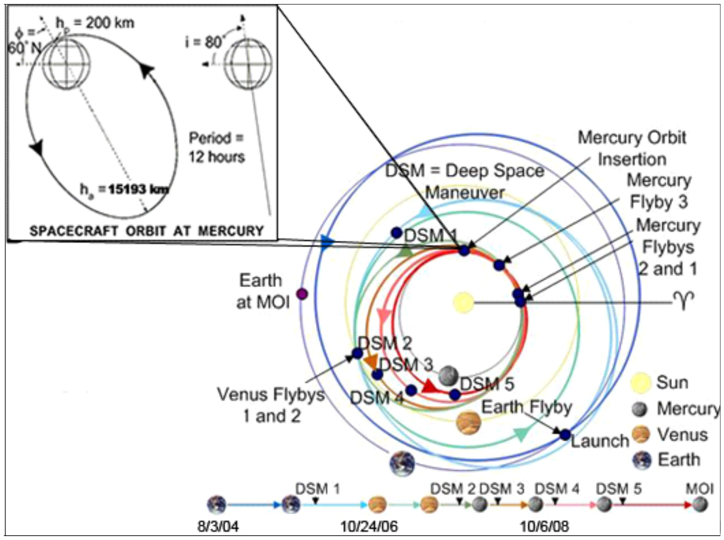
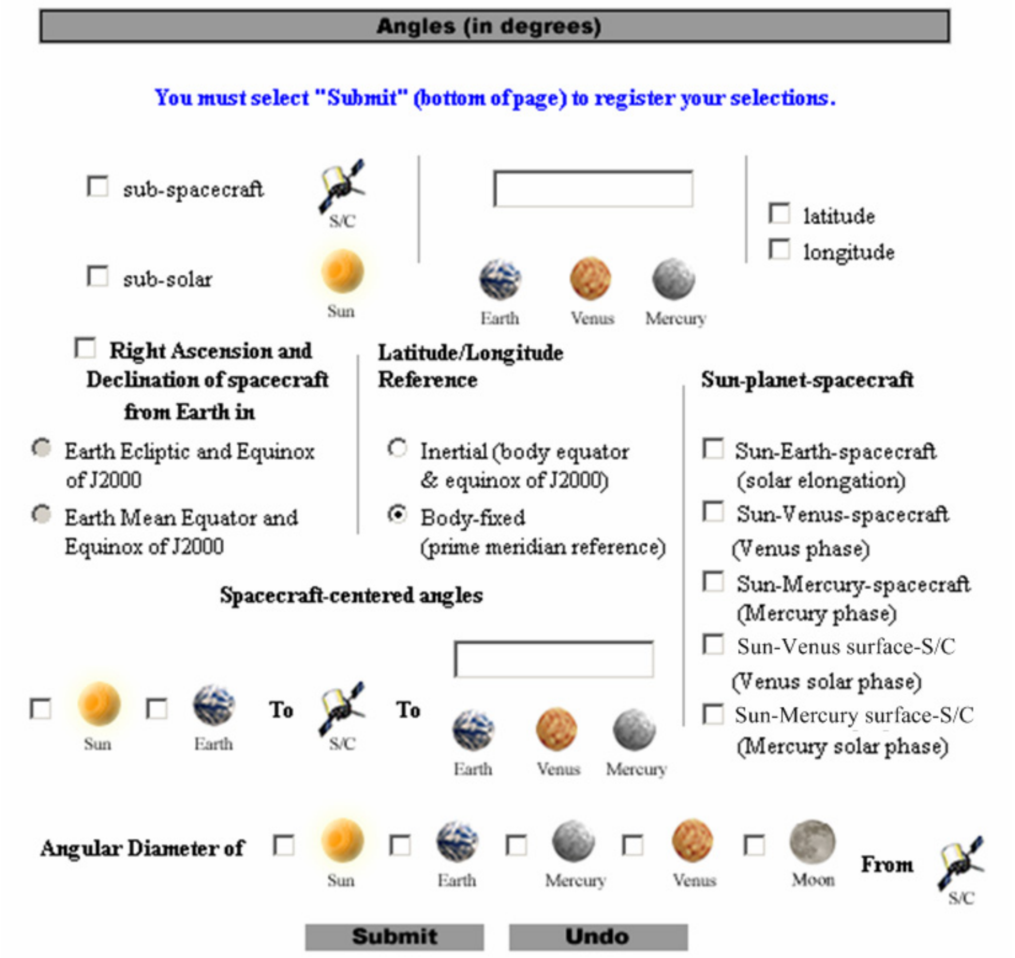


Figure 1. Views of MESSENGER's heliocentric and Mercury-centered trajectories



Angles (in degrees)

You must select "Submit" (bottom of page) to register your selections.

□ sub-spacecraft S/C

□ sub-solar Sun

Earth Venus Mercury

□ latitude

□ longitude

□ **Right Ascension and Declination of spacecraft from Earth in**

○ Earth Ecliptic and Equinox of J2000

○ Earth Mean Equator and Equinox of J2000

Latitude/Longitude Reference

○ Inertial (body equator & equinox of J2000)

● Body-fixed (prime meridian reference)

Sun-planet-spacecraft

□ Sun-Earth-spacecraft (solar elongation)

□ Sun-Venus-spacecraft (Venus phase)

□ Sun-Mercury-spacecraft (Mercury phase)

□ Sun-Venus surface-S/C (Venus solar phase)

□ Sun-Mercury surface-S/C (Mercury solar phase)

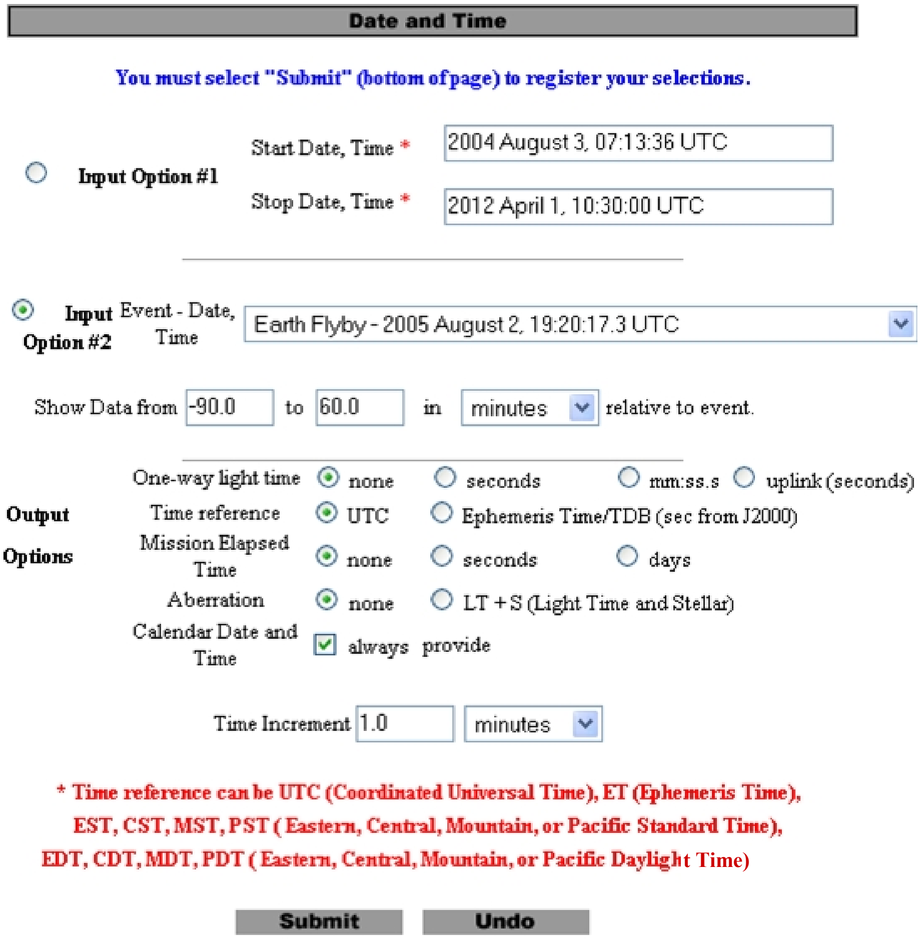
Spacecraft-centered angles

□ Sun □ Earth **To** S/C **To** Earth Venus Mercury

Angular Diameter of □ Sun □ Earth □ Mercury □ Venus □ Moon **From** S/C

Figure 2. "Angles" query form for the MESSENGER Trajectory Database

An additional capability of the MESSENGER Trajectory Database involves specifying time formats for the query output. How time-related outputs and their units are chosen is apparent from Figure 3. For the user-selected ephemeris file, the user may choose from the "start/stop date and time" (input option #1) or the "mission event/relative time" (input option #2). The "default" start and stop date and time values, shown in Figure 3, are the earliest and latest allowable options for any query. Time reference options for entered values of start and stop dates and times are listed at the bottom of the page. The U.S. time zone labels will not appear in the output data tables. Selecting any date before the start date and time or after the stop date and time will produce an error message that directs the user to re-enter the unallowable date(s) and time(s). The time increment, with unit choice of seconds, minutes, hours, or days, applies equally to either of the selected input options. Input option #2 provides a means of selecting from a pull-down list a "mission-critical" (e.g., major course-correction maneuver or close approach of a planetary flyby) event, along with choosing pre-event and post-event relative times as the start and stop times. Other time-related outputs such as one-way light time and mission elapsed time (e.g., time since a reference epoch near the moment of launch) may be specified. The only absolute time reference options are UTC (Universal Time, Coordinated) and Ephemeris Time. The user may choose to account for light-time and stellar aberrations, which account for the motions of the observer ("from" location) and the target ("to" location) and the finite speed of light, or no aberration. Without aberrations, the geometric states are used as if the speed of light is infinite.



You must select "Submit" (bottom of page) to register your selections.

○ Input Option #1
Start Date, Time * 2004 August 3, 07:13:36 UTC
Stop Date, Time * 2012 April 1, 10:30:00 UTC

● Input Option #2
Event - Date, Time Earth Flyby - 2005 August 2, 19:20:17.3 UTC

Show Data from -90.0 to 60.0 in minutes relative to event.

Output Options
One-way light time ● none ○ seconds ○ mm:ss.s ○ uplink (seconds)
Time reference ● UTC ○ Ephemeris Time/TDB (sec from J2000)
Mission Elapsed Time ● none ○ seconds ○ days
Aberration ● none ○ LT + S (Light Time and Stellar)
Calendar Date and Time ☑ always provide

Time Increment 1.0 minutes

* Time reference can be UTC (Coordinated Universal Time), ET (Ephemeris Time),
EST, CST, MST, PST (Eastern, Central, Mountain, or Pacific Standard Time),
EDT, CDT, MDT, PDT (Eastern, Central, Mountain, or Pacific Daylight Time)

Figure 3. “Date/Time” query form for the MESSENGER Trajectory Database

MESSENGER TRAJECTORY DATABASE DESIGN

The MESSENGER Trajectory Database was designed using the model-view-controller (MVC) design; which separates the system architecture into three distinct tiers (Figure 4). This arrangement allowed for any of the tiers to be ported to different platforms or languages with little or no significant change to any other tier. Tier one consists of the web application used for building and submitting queries. Tier two is the SPICE server which accepts queries, processes them, and generates output. Finally, tier three contains mission data in the form of kernel files in a relational database. This design was implemented with a combination of Java technologies for the web application (e.g., Tomcat and Xerxes XML Java parser), the C Language and the libXML library for the SPICE server and additional computations [7], and a mySQL database to store mission parameters used in calculations.

Web Application Design

The web application component (Figure 5) is used to build and submit queries with an option to save queries for later retrieval. Since users can submit multiple queries as a single job, a standard shopping-cart model accumulates queries. Users can build queries using forms with standard html elements and intuitive images representing planetary bodies and spacecraft (Figure 2). To maximize performance, more query validation is done on the client side than on the server.

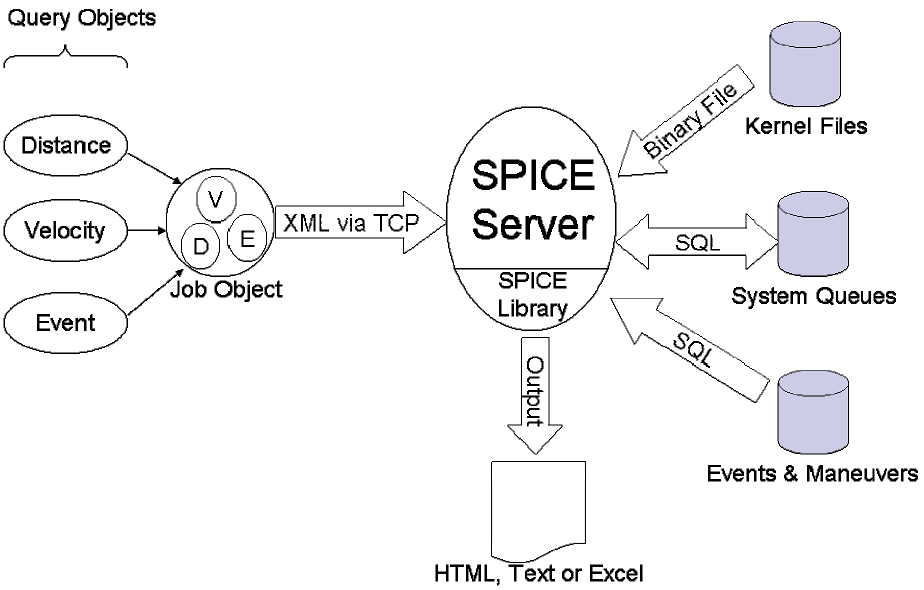
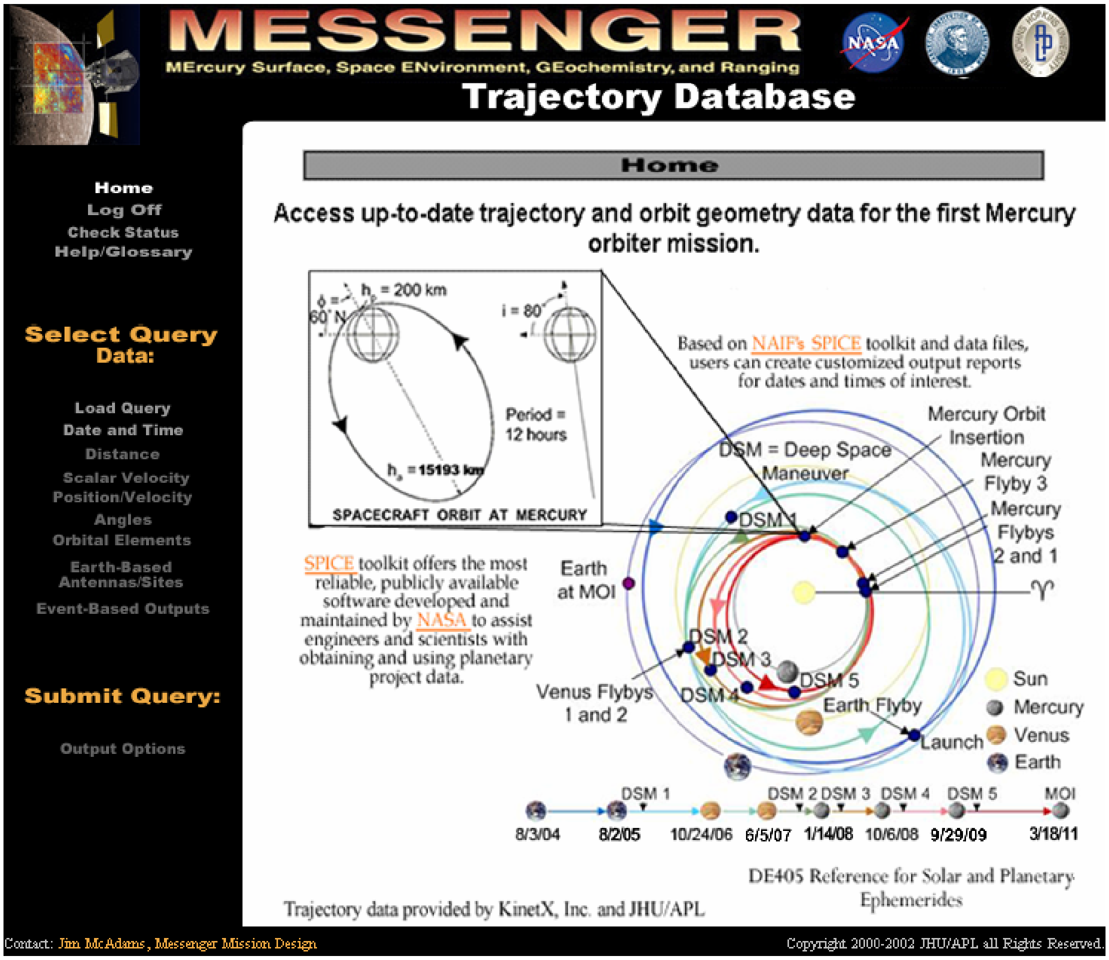


Figure 4. Architecture design for the MESSENGER Trajectory Database



Access up-to-date trajectory and orbit geometry data for the first Mercury orbiter mission.

Based on NAIF's SPICE toolkit and data files, users can create customized output reports for dates and times of interest.

SPICE toolkit offers the most reliable, publicly available software developed and maintained by NASA to assist engineers and scientists with obtaining and using planetary project data.

Trajectory data provided by KinetX, Inc. and JHU/APL

DE405 Reference for Solar and Planetary Ephemerides

Contact: Jim McAdams, Messenger Mission Design

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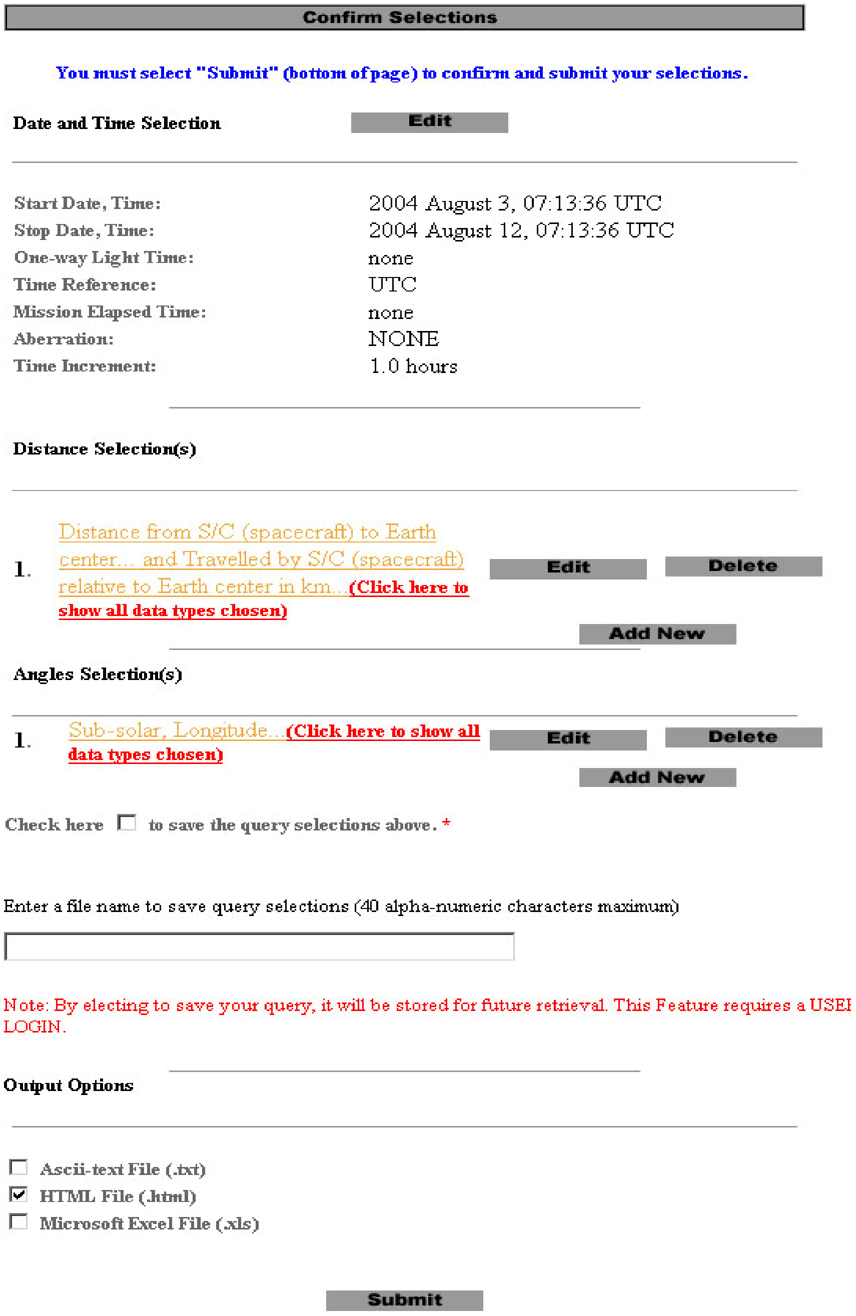
Figure 5. Home page for the MESSENGER Trajectory Database



Confirm Selections

You must select "Submit" (bottom of page) to confirm and submit your selections.

Date and Time Selection

Start Date, Time:	2004 August 3, 07:13:36 UTC
Stop Date, Time:	2004 August 12, 07:13:36 UTC
One-way Light Time:	none
Time Reference:	UTC
Mission Elapsed Time:	none
Aberration:	NONE
Time Increment:	1.0 hours

Distance Selection(s)

1. Distance from S/C (spacecraft) to Earth center... and Travelled by S/C (spacecraft) relative to Earth center in km...(Click here to show all data types chosen)

Angles Selection(s)

1. Sub-solar, Longitude...(Click here to show all data types chosen)

Check here ☐ to save the query selections above. *

Enter a file name to save query selections (40 alpha-numeric characters maximum)

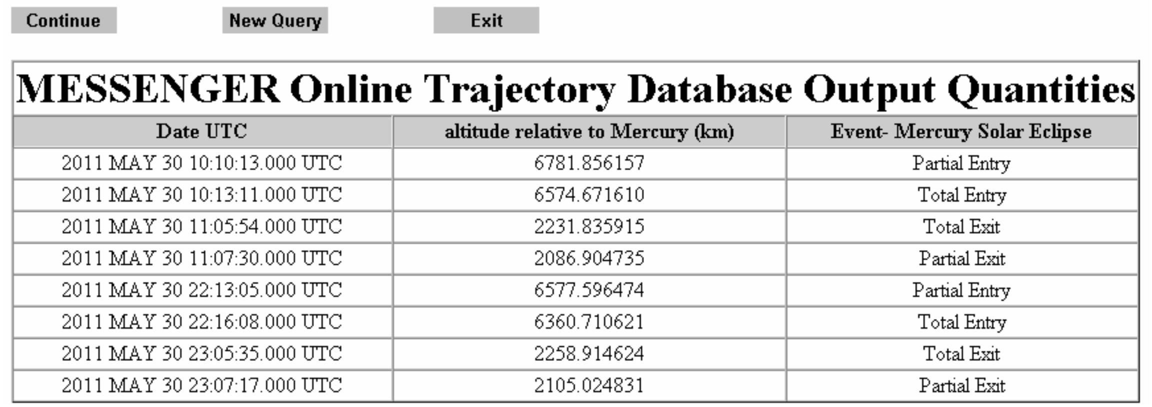
Note: By electing to save your query, it will be stored for future retrieval. This Feature requires a USEI LOGIN.

Output Options

☐ Ascii-text File (.txt)
☑ HTML File (.html)
☐ Microsoft Excel File (.xls)

Figure 6. "Output Options" page for the MESSENGER Trajectory Database

After "submit" is clicked at the bottom of any data query page, a message directs the user to either continue requesting more data or to select "Output Options" in the lower right of the screen. Figure 6 is an example of the display seen after selecting "Output Options." This display offers a summary of data types and times chosen. The user may see a complete summary of data type specifications by clicking on the red text "(Click here to show all data types chosen)" messages. The user may also check a box and enter a name by which to save the query. At the bottom the user may select any number of the three output formats for the query results. Figure 7 is an example of the HTML output format from a submitted query. The term "partial entry" indicates when Mercury begins to obscure a portion of the solar disk from the spacecraft's view. The moment that the Sun's view is fully occulted by Mercury is labeled "total entry."

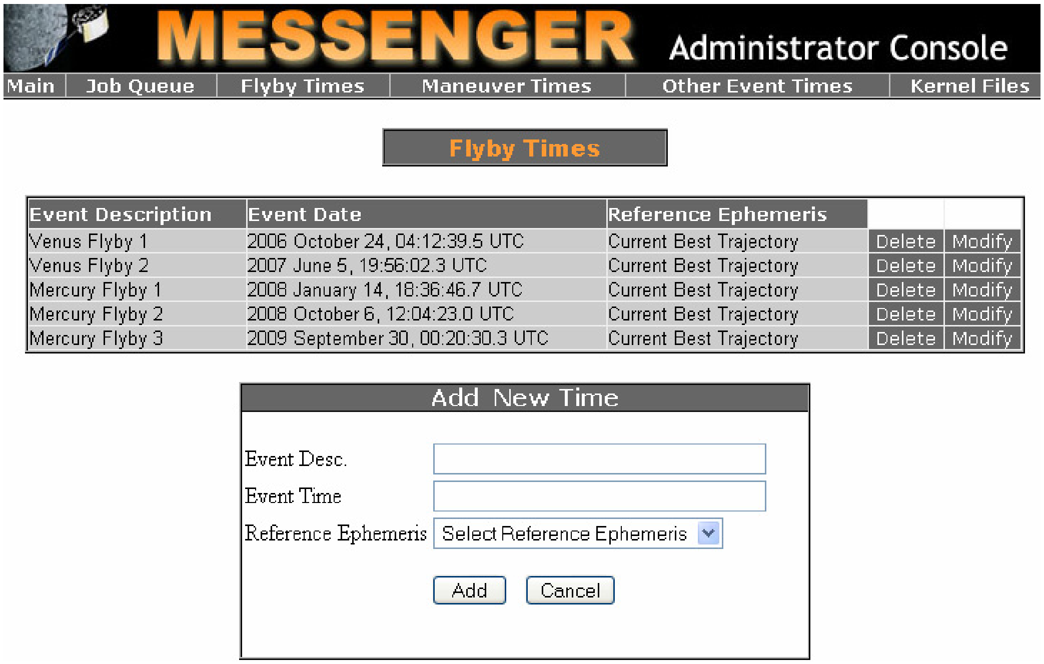


MESSENGER Online Trajectory Database Output Quantities

Date UTC	altitude relative to Mercury (km)	Event- Mercury Solar Eclipse
2011 MAY 30 10:10:13.000 UTC	6781.856157	Partial Entry
2011 MAY 30 10:13:11.000 UTC	6574.671610	Total Entry
2011 MAY 30 11:05:54.000 UTC	2231.835915	Total Exit
2011 MAY 30 11:07:30.000 UTC	2086.904735	Partial Exit
2011 MAY 30 22:13:05.000 UTC	6577.596474	Partial Entry
2011 MAY 30 22:16:08.000 UTC	6360.710621	Total Entry
2011 MAY 30 23:05:35.000 UTC	2258.914624	Total Exit
2011 MAY 30 23:07:17.000 UTC	2105.024831	Partial Exit

Figure 7. Sample HTML output from the MESSENGER Trajectory Database

Users may also save queries before submitting them to the system, thereby allowing them to return another time and build a similar query by loading the previous query and making small changes. Additionally, users can check the status of their queries (i.e., when the query was submitted, how long it's been sitting in the queue, and how long it's been running). All users register once by entering their email address. In the event that a query reply requires more than 30 seconds, an email with a link to the tabular output results is sent to the user. The MESSENGER Trajectory Database also supports mission reconfiguration (i.e., loading new spacecraft trajectory files) and job queue management through the use of an administration tool. This web-based administration tool allows the administrator to add or change the reference trajectory by uploading SPICE kernel files, or by specifying new event dates and times (Figure 8). This administrator may also delete queries with long run times.



Event Description	Event Date	Reference Ephemeris		
Venus Flyby 1	2006 October 24, 04:12:39.5 UTC	Current Best Trajectory	Delete	Modify
Venus Flyby 2	2007 June 5, 19:56:02.3 UTC	Current Best Trajectory	Delete	Modify
Mercury Flyby 1	2008 January 14, 18:36:46.7 UTC	Current Best Trajectory	Delete	Modify
Mercury Flyby 2	2008 October 6, 12:04:23.0 UTC	Current Best Trajectory	Delete	Modify
Mercury Flyby 3	2009 September 30, 00:20:30.3 UTC	Current Best Trajectory	Delete	Modify

Add New Time

Event Desc.

Event Time

Reference Ephemeris: Select Reference Ephemeris

Figure 8. "Flyby Times" page from the "Administrator Console" maintenance tool

Web Service Interaction Using XML

Queries built within the web application are in the form of JAVA objects. These objects are eventually serialized to XML in order to be transmitted to the SPICE server. Queries that are saved on the system for later retrieval are also stored in XML. This procedure allows queries to be persistent even during system failure. In addition, utilizing XML helped avoid potential future problems that may occur if the system was ported to another platform or language.

A typical query for the distance traveled by the spacecraft may look like this:

```
<?xml version="1.0" encoding="UTF-8"?>

<trajectory email="wikka@lotek.net">
  <distance>
    <distance_from>Earth center</distance_from>
    <distance_to>Venus center</distance_to>
    <distance_units>km</distance_units>
    <sp_alt>Earth</sp_alt>
    <sp_alt_unit_metric>km</sp_alt_unit_metric>
  </distance>
</trajectory>
```

The output file name and format for the output are transmitted in XML as shown below:

```
<OutputFile>
  <file option="1" format="htm">511603.htm</file>
  <file option="1" format="xls">511603.xls</file>
</OutputFile>
```

Protocol between the Front End and the SPICE Server

After building a data query in the web application, the user submits the query for processing. This request is made through a simple plain-text protocol that is implemented over a TCP/IP channel [8]. For the following description, transmissions by the web application are prefixed with "CLIENT" and responses by the SPICE server are prefixed with "SERVER." The actual text transmitted is enclosed in parentheses.

CLIENT: Sends a query submission request (QUERY)
SERVER: Responds with an acknowledgement (QUERY:OK)
CLIENT: Transmits the query as a continuous XML string
The SPICE server then validates the XML against its DTD.
SERVER: Replies with either a confirmation (XML:OK) or failure (ERROR:XML)
CLIENT: Sends the output file name and format in the form of an XML string
The SPICE server then validates the XML against its DTD.
SERVER: Replies with either a confirmation (FILE:OK) or failure (ERROR:FILE)
SERVER: Sends the process ID (PID:<id>) if the query was immediately scheduled for execution, or (QUEUED) if the query was scheduled for delayed execution.

The SPICE Server Queuing System Design

The first version of the MESSENGER Trajectory Database utilized a First-in First-out (FIFO) scheduler. This scheduler was chosen to simplify the system design and to focus on the

SPICE-based computational design component. This version schedules jobs using a priority ready queue and a run queue. Queries submitted to be processed are queued and processed based on their priority. Once the run queue is full, queries are placed in the ready queue. A query's priority is based on the estimated time to complete (i.e., *Query Burst*) and how long the query has been in the ready queue. Small queries that can be completed in a few seconds are given priority over longer queries that may take minutes or hours to complete. In order to estimate the time to complete a query, benchmarks were obtained for each output quantity. A series of tests provided averaged results for worst-case processor burst times for each of the seven data query types (see the "MESSENGER Trajectory Database Capability" section). These results were obtained by executing queries from the system log over a one-week time span (from start date to stop date) with output generated at a 60-s time increment. The longest calculation times came from the data query types that most often utilize data interpolation – Earth-based Antennas/Sites and Event-based Outputs. The shortest calculation times came from the data query types that most efficiently utilize SPICE toolkit routines – Scalar Velocity and Orbital Elements.

Once a job is submitted to the system, its *Query Burst* is calculated based on Eq. (1):

$$Query\ Burst = \sum_{i=0}^{(stopTime\ - startTime\ )/increment} Q_f(i) \qquad (1)$$

where *stop Time* and *start Time* denote the query's time duration, *increment* denotes how often to output results, and $Q_f(i)$ is the maximum processing time (ms) for the ith output quantity *f.* The *Query Burst* time is estimated to determine if the results can be provided to the user interactively (within 30 s). For most cases this estimate provides a useful indicator of the actual run time. This estimate is not as accurate for queries that involve large numbers of output quantities and require data mining (i.e., Event-Based Outputs and Earth-Based Antennas/Sites queries). As a result, methods such as data caching must be utilized to process the queries more efficiently.

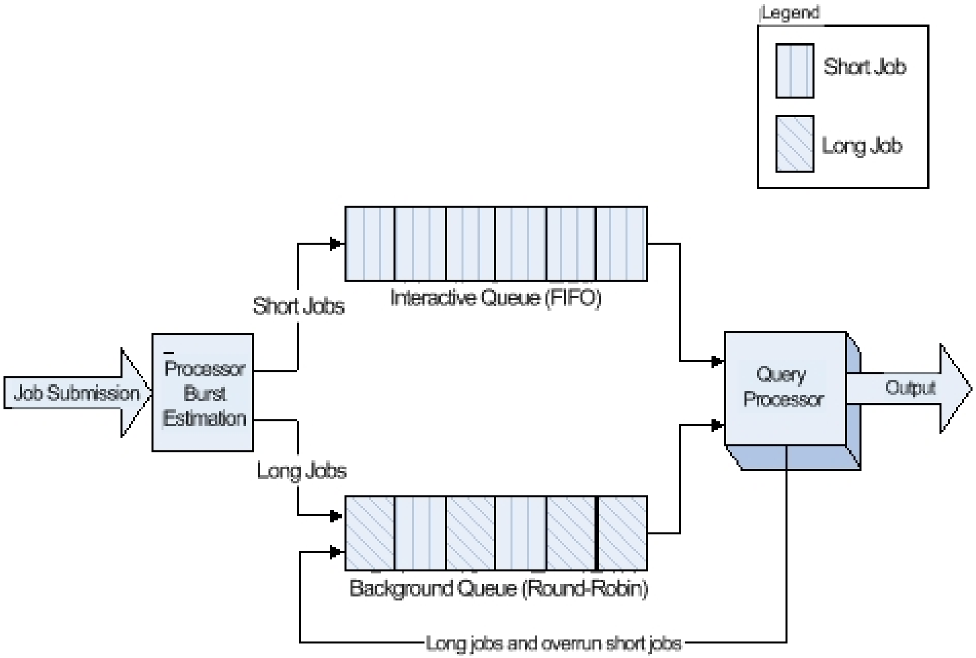


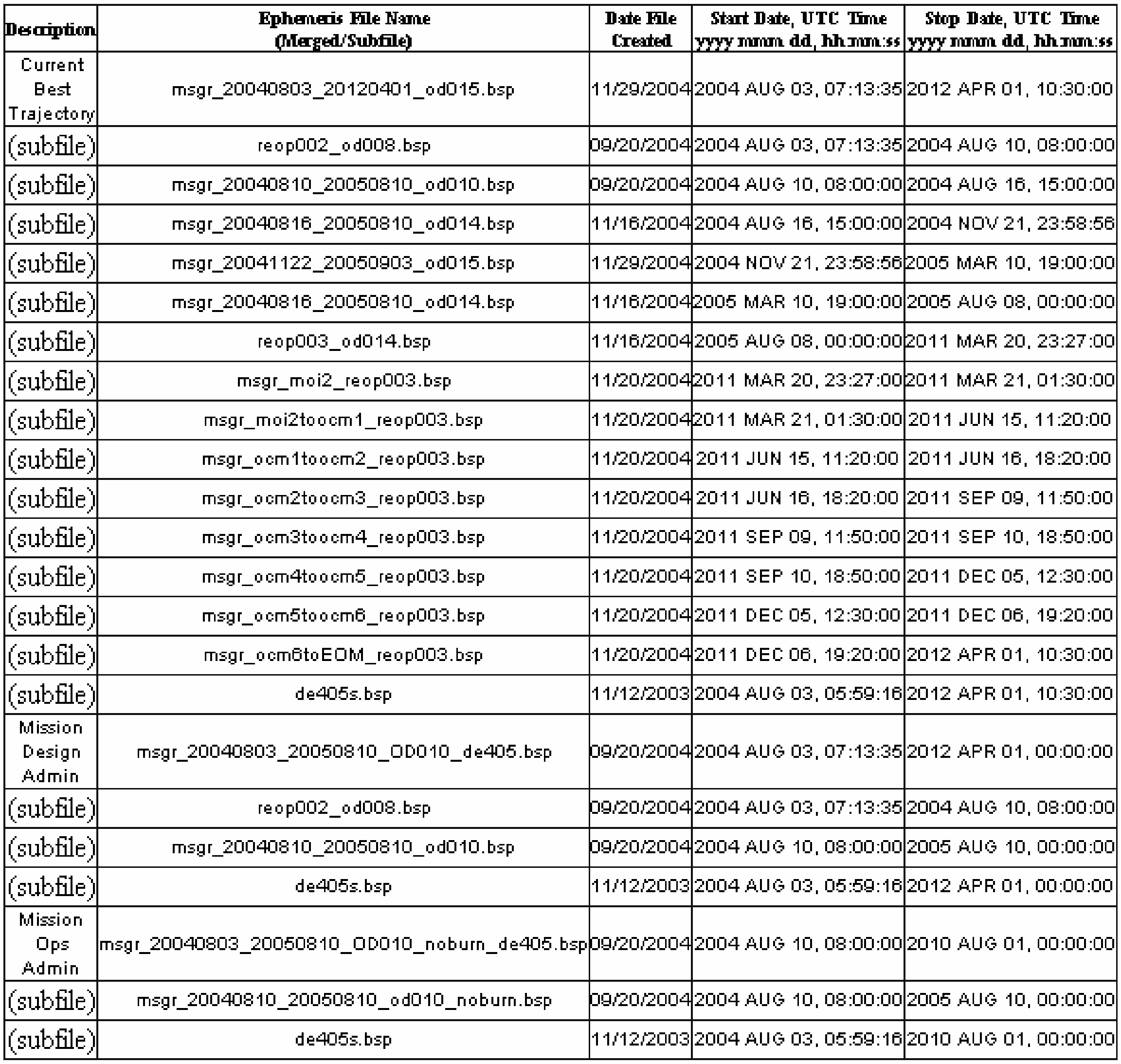
Figure 9. System job queue (multi-level feedback, FIFO/round-robin)

As shown in Figure 9, the current system utilizes a multi-level feedback queue. If the job can be processed interactively, it is placed in the interactive queue. Otherwise it is placed in the background queue and the user is notified that they will receive an email once the job is complete. The interactive queue provides a FIFO schedule to reduce turnaround time. Jobs from the interactive queue are processed for a maximum of 30 s. If they are not complete by this time, they become "long jobs" and move to the background queue. The background queue provides a round-robin schedule to maximize throughput. Once a job from this queue is complete, an email is sent to the job owner, notifying them that the job is complete and providing a reference to the storage location for the results.

MESSENGER TRAJECTORY DATABASE USAGE AND MAINTENANCE

The potential set of users for the MESSENGER Trajectory Database is limited for a number of reasons. The information that may be retrieved by MESSENGER Trajectory Database data queries is considered in the public domain, i.e., it has received legal approval from a JHU/APL export control authority. However, the level of funding for developing and testing the MESSENGER Trajectory Database fell short of that needed for formal software configuration control. With formal configuration control, support would have been provided to produce a requirements document, user's guide, software revision log, and other documents. Formal code reviews involving JHU/APL and experts from outside JHU/APL, also part of configuration control, would be required before the URL of the MESSENGER Trajectory Database were released to the general public. Therefore, the only MESSENGER Trajectory Database users are the developers from Howard University and MESSENGER team members. None of the data obtained from the MESSENGER Trajectory Database is used directly in the establishment of flight commands or observation sequences. The MESSENGER Trajectory Database is primarily used by managers, public relations staff, lead engineers, and scientists as a full-mission reference tool that easily and quickly provides data for preliminary planning and for periodic mission status reports.

During MESSENGER post-launch (flight) operations the Mission Design Lead Engineer performs all MESSENGER Trajectory Database maintenance. Maintenance tasks include using SPICE utility programs to merge the most accurate spacecraft ephemeris files (also called kernels) available for each time span of the mission. Since many MESSENGER ephemeris files overlap, the file most recently created usually takes precedence when considering how to build the "current best trajectory" option for the MESSENGER Trajectory Database. The "current best trajectory" and up to two other spacecraft ephemeris files are checked using other software in order to identify the time of major mission events such as planet flyby close approaches and major course correction maneuvers. Since MESSENGER's Navigation team issues all official spacecraft ephemeris files, the Navigation Team Chief also approves the selection of ephemeris files and their corresponding start and stop epochs for the "current best trajectory." Figure 10 is a table that appears on the user's screen after clicking "Date/Time" once. On the screen just above this table appears a pull-down menu which enables the user to select one of the three ephemeris options: current best trajectory, mission design admin, or mission ops admin. The naming convention for each binary SPICE file (*.bsp) includes the year, month, and day at the beginning and end of the valid time span. Files that do not use this naming convention, usually long-term ephemeris predicts, come from trajectory optimization software equipped with high-precision trajectory propagators. The table shows all the "subfiles" that are merged into the primary ephemeris file, even including the "de405" version of the lunar, solar, and planetary ephemerides.



Description	Ephemeris File Name (Merged/Subfile)	Date File Created	Start Date, UTC Time yyyy mmm dd, hh:mm:ss	Stop Date, UTC Time yyyy mmm dd, hh:mm:ss
Current Best Trajectory	msgr_20040803_20120401_od015.bsp	11/29/2004	2004 AUG 03, 07:13:35	2012 APR 01, 10:30:00
(subfile)	reop002_od008.bsp	09/20/2004	2004 AUG 03, 07:13:35	2004 AUG 10, 08:00:00
(subfile)	msgr_20040810_20050810_od010.bsp	09/20/2004	2004 AUG 10, 08:00:00	2004 AUG 16, 15:00:00
(subfile)	msgr_20040816_20050810_od014.bsp	11/16/2004	2004 AUG 16, 15:00:00	2004 NOV 21, 23:58:56
(subfile)	msgr_20041122_20050903_od015.bsp	11/29/2004	2004 NOV 21, 23:58:56	2005 MAR 10, 19:00:00
(subfile)	msgr_20040816_20050810_od014.bsp	11/16/2004	2005 MAR 10, 19:00:00	2005 AUG 08, 00:00:00
(subfile)	reop003_od014.bsp	11/16/2004	2005 AUG 08, 00:00:00	2011 MAR 20, 23:27:00
(subfile)	msgr_moi2_reop003.bsp	11/20/2004	2011 MAR 20, 23:27:00	2011 MAR 21, 01:30:00
(subfile)	msgr_moi2toocm1_reop003.bsp	11/20/2004	2011 MAR 21, 01:30:00	2011 JUN 15, 11:20:00
(subfile)	msgr_ocm1toocm2_reop003.bsp	11/20/2004	2011 JUN 15, 11:20:00	2011 JUN 16, 18:20:00
(subfile)	msgr_ocm2toocm3_reop003.bsp	11/20/2004	2011 JUN 16, 18:20:00	2011 SEP 09, 11:50:00
(subfile)	msgr_ocm3toocm4_reop003.bsp	11/20/2004	2011 SEP 09, 11:50:00	2011 SEP 10, 18:50:00
(subfile)	msgr_ocm4toocm5_reop003.bsp	11/20/2004	2011 SEP 10, 18:50:00	2011 DEC 05, 12:30:00
(subfile)	msgr_ocm5toocm6_reop003.bsp	11/20/2004	2011 DEC 05, 12:30:00	2011 DEC 06, 19:20:00
(subfile)	msgr_ocm6toEOM_reop003.bsp	11/20/2004	2011 DEC 06, 19:20:00	2012 APR 01, 10:30:00
(subfile)	de405s.bsp	11/12/2003	2004 AUG 03, 05:59:16	2012 APR 01, 10:30:00
Mission Design Admin	msgr_20040803_20050810_OD010_de405.bsp	09/20/2004	2004 AUG 03, 07:13:35	2012 APR 01, 00:00:00
(subfile)	reop002_od008.bsp	09/20/2004	2004 AUG 03, 07:13:35	2004 AUG 10, 08:00:00
(subfile)	msgr_20040810_20050810_od010.bsp	09/20/2004	2004 AUG 10, 08:00:00	2005 AUG 10, 00:00:00
(subfile)	de405s.bsp	11/12/2003	2004 AUG 03, 05:59:16	2012 APR 01, 00:00:00
Mission Ops Admin	msgr_20040803_20050810_OD010_noburn_de405.bsp	09/20/2004	2004 AUG 10, 08:00:00	2010 AUG 01, 00:00:00
(subfile)	msgr_20040810_20050810_od010_noburn.bsp	09/20/2004	2004 AUG 10, 08:00:00	2005 AUG 10, 00:00:00
(subfile)	de405s.bsp	11/12/2003	2004 AUG 03, 05:59:16	2010 AUG 01, 00:00:00

Figure 10. Sample ephemeris file architecture for the MESSENGER Trajectory Database

CONCLUSIONS AND FUTURE WORK

If this project were to continue, it would benefit from a reconfiguration using an XML configuration file. This will allow users to easily configure new missions or reconfigure an existing mission by simply submitting an XML configuration file that contains all the data, events and parameters for the new mission. It would help to mark up all output as XML natively. This XML can then be transformed into several formats specified by the user. These formats may include HTML, plain text, Microsoft Excel, and PDF. In order to use less storage for output in several different formats, this transformation should be done using Extensible Style-sheet Language Transformation or XSL/T. Another development option, providing animations of selected query output, would give the user a visual context showing the physical representation of tabular data represented in the query results, for instance, the motion of a spacecraft around a planetary body.

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