111129

N95- 17544

31949

p. 11

Implementation of a Low-Cost, Commercial Orbit Determination System

July 22, 1994

Jim Corrigan
Storm Integration, Inc.
2025 Gateway Place, Suite 118
San Jose, CA 95110
(408) 451-0620 FAX (408) 451-0622

Abstract

Traditional satellite and launch control systems have consisted of custom solutions requiring significant development and maintenance costs. These systems have typically been designed to support specific program requirements and are expensive to modify and augment after delivery. The expanding role of space in today's marketplace combined with the increased sophistication and capabilities of modern satellites has created a need for more efficient, lower cost solutions to complete command and control systems.

Recent technical advances have resulted in Commercial-Off-The-Shelf products which greatly reduce the complete life-cycle costs associated with satellite launch and control system procurements. System integrators and spacecraft operators have, however, been slow to integrate these commercial based solutions into a comprehensive command and control system. This is due, in part, to a resistance to change and the fact that many available products are unable to effectively communicate with other commercial products.

The United States Air Force, responsible for the health and safety of over 84 satellites via its Air Force Satellite Control Network (AFSCN), has embarked on an initiate to prove that commercial products can be used effectively to form a comprehensive command and control system. The initial version of this system is being installed at the Air Force's CEnter for Research Support (CERES) located at the National Test Facility in Colorado Springs, Colorado. The first stage of this initiative involved the identification of commercial products capable of satisfying each functional element of a command and control system. A significant requirement in this product selection criteria was flexibility and ability to integrate with other available commercial products.

This paper discusses the functions and capabilities of the product selected to provide orbit determination functions for this comprehensive command and control system.

Precision Orbit Determination System™ (PODS™)

Introduction

The Precision Orbit Determination System (PODS), developed by Storm Integration, Inc., is a workstation-based orbit determination system. PODS is layered on top of the commercially-available Satellite Tool Kit (STK)® produced by Analytical Graphics, Inc. PODS also incorporates the Workstation/Precision Orbit Determination (WS/POD)™ product offered by Van Martin Systems, Inc. The STK graphical user interface is used to access and invoke the PODS capabilities and to display the results. WS/POD is used to compute a best-fit orbit solution to user-supplied tracking data.

The Precision Orbit Determination System (PODS)™ grew out of a need to process antenna tracking data to determine a spacecraft orbit. The determined orbit can then be used to generate antenna pointing commands to control a ground antenna. Such a system is necessary for full "closed-loop" satellite command and control (i.e., from processing of telemetry and tracking data to the transmission of commands) and augments commercial command and control systems such as Storm's Intelligent Mission Toolkit (IMT)™.

PODS provides the capability to simultaneously estimate the orbits of up to 99 satellites based on a wide variety of measurement types including angles, range, range rate, and Global Positioning System (GPS) data. PODS can also estimate ground facility locations, Earth geopotential model coefficients, solar pressure and atmospheric drag parameters, and measurement data biases. All determined data is automatically incorporated into the STK data base, which allows storage, manipulation and export of the data to other applications.

PODS supports three levels of processing: Standard, Basic GPS and Extended GPS. Standard allows processing of non-GPS measurement types for any number of vehicles and facilities. Basic GPS adds processing of GPS pseudo-ranging data to the Standard capabilities. Extended GPS adds the ability to process GPS carrier phase data.

Requirements

A workstation-based capability is desired for compatibility with other workstation-based products (such as Storm Integration's IMT). The system should function stand-alone, but offer interfaces for integration with other products. A Commercial Off-the-Shelf (COTS) product approach is desirable for potential resale either alone or integrated with other command and control products. Finally, the development and certification costs must be kept low, which suggests incorporation of existing, proven COTS products in the implementation as much as possible.

Solution Approach

Storm chose two commercial products for incorporation into PODS: Satellite Tool Kit (STK)® by Analytical Graphics, Inc. (AGI), and Workstation/Precision Orbit Determination (WS/POD)™ by Van Martin Systems, Inc. (VMSI). PODS consists of these products as well as the additional code and data required to integrate the products, accept user inputs and provide output data in operationally useful formats.

Commercial Products

Satellite Tool Kit

STK is a workstation-based, interactive system for analyzing the relationships among satellites, Earth-bound vehicles, ground stations and targets. STK incorporates both text-based tables and graphics to display satellite orbits, periods of visibility, access times, and sensor coverage patterns for multiple satellites, ground stations and targets. The graphics allow animation of satellite constellations to see how sensor coverage and visibilities change over time and with orbital position.

STK allows the input of initial orbit conditions for satellites, facility and target coordinates, and Earth- and satellite-based sensor parameters via ASCII text file or Motif-based user interface panels. Output is displayed via graphical ground traces on a variety of map projections, and tables of access angles and ranges over windows of visibility. Both text and graphics output can be sent to files for printing and/or incorporation into other systems.

The STK user interface uses an object-oriented approach for defining and manipulating data. For example, a Scenario object consists of multiple Vehicle, Facility and/or Target objects. Each of these in turn may have one or more Sensor objects. Objects are created, saved, and restored separately. Data for objects are stored in individual ASCII files with pre-defined extensions (e.g., ".v" for vehicle files, etc.).

STK Programmer's Library

The Satellite Tool Kit/Programmer's Library (STK/PL)™ offers C application programmers access to the underlying functionality of the STK runtime version. The STK/PL includes header files and selected source code modules to allow programmers to develop add-on applications that are seamlessly integrated with the STK user interface, or stand-alone applications that use STK/PL as a library of functions. The STK/PL includes access to the object manager, user interface, and graphics, as well as astrodynamics libraries, time and coordinate conversion functions, and the orbit propagators. The STK/PL is written in an object-oriented manner which allows rapid modification and addition of new functionality. The PODS User Interface is being developed using the STK/PL.

Workstation/Precision Orbit Determination

WS/POD is a state-of-the-art precision orbit and geodetic parameter determination software system derived from the GEODYN II Version 8609 software used by NASA's Goddard Space Flight Center (GSFC). Van Martin Systems, Inc. has ported the GEODYN II software to numerous workstation platforms, enhanced it in the area of GPS data processing, and packaged it as a commercially available and supported product.

WS/POD processes satellite tracking data using a Bayesian weighted least-squares data reduction algorithm and detailed environmental modeling using a Cowell-type numerical integration scheme to determine precisely various quantities related to the satellite orbit and tracking stations. Specific capabilities include the following:

Physical Models
- Atmospheric drag using the Jacchia 1971 atmospheric density model
- Solar radiation pressure
- Earth gravitation (up to 180 x 180 geopotential matrix)
- Polar motion
- Earth rotation
- Solid Earth tides
- Third body gravitation
- Earth precession and nutation
- Tropospheric refraction

Measurement Types
- Laser and radar range
- Radar range rates and dopplers (including single and double differences)
- Radar altimeter range
- Topocentric right ascension and declination
- East and north direction cosines
- X/Y angles relative to the tracking station
- Azimuth/elevation angles relative to the tracking station
- GPS pseudo-range and carrier phase, including single, double and triple differences

Parameters Estimated
- Orbit state vectors
- Parameters of atmospheric drag and solar radiation pressure
- Measurement and time tag biases
- Tropospheric refraction scale parameters
- Satellite and station clock polynomials
- Earth gravitational coefficients
- Tracking station coordinates

Algorithms and Capabilities
- Cowell-type numerical integration
- Bayesian weighted least-squares estimation algorithm
- Batch data processing
- Automatic data editing with criteria specified by the user
- Simultaneous estimation of up to 99 satellite orbits in a single run

WS/POD receives inputs and produces outputs exclusively through files. There is no user interface provided. Program control is provided by input files of 80-column card images with data in rigidly-defined column format. Data is provided and produced in ASCII text and binary files, with the file formats defined in the WS/POD documentation.

Summary

STK offers a state-of-the-art graphical user interface that has been perfected through many years of development, upgrades and customer feedback. WS/POD offers more algorithmic and data processing capabilities that any other commercially-available orbit estimation system. WS/POD also benefits from its NASA heritage, which assures that the algorithms have been tested using a wide range of operational scenarios over a span of decades

PODS Solution Approach and Features

PODS is separated into two components: PODS User Interface and PODS External Procedure (PODS/XP). PODS User Interface is implemented using STK/PL. PODS/XP is a stand-alone program independent from STK and provides a C-language interface to WS/POD. The PODS functional breakdown is shown in Figure 1: PODS Functional Breakdown and is described below.

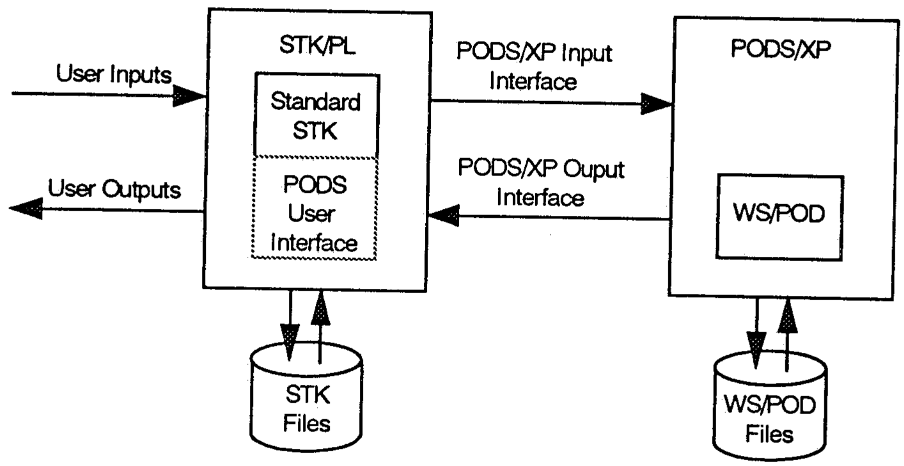

Figure 1: PODS Functional Breakdown

PODS User Interface

STK provides an object-oriented user interface in which the data applies to a selected object (either Vehicle, Facility or Scenario). PODS data is treated as an extension to the data for the existing STK object class. This allows STK to store the PODS user inputs in the STK object files and use previously-entered values as defaults for subsequent runs. This approach also allows PODS input data to be specified in the ASCII object files instead of through the user interface.

PODS operations are implemented as extensions to the existing STK operations and are invoked via the standard STK user interface. The PODS input panels are similar to existing STK panels, providing Motif pull-down menus, on-line help, and standardized range and data format checking.

Numerical outputs from PODS are displayed in standard STK output data windows, which allow scrolling through the output data, exporting to files, queuing to a system printer, and real-time units and time format conversions. Selected PODS data (e.g., ephemeris and facility locations) are entered into the existing STK data structures, allowing STK to display the data graphically and use it as the basis for accesses and other computations.

PODS External Procedure

The PODS External Procedure (PODS/XP) provides a C-language interface to the WS/POD product. It is designed to be independent from the specifics of the user interface, which allows the use of other user interfaces or calls from external applications. The interface data are consolidated in a series of structures in header files that are incorporated by the application providing the data (initially STK/PL). PODS/XP is designed such that calls to it can be made from any C program that makes use of the PODS structures.

Processing Levels

PODS provide three levels of support for users with a variety of mission requirements: Standard, Basic GPS, and Extended GPS All levels provide the STK-based graphical user interface and input/output capabilities. The different levels are licensed externally, allowing users to upgrade without re-installation of the PODS software. Each level is described in more detail below:

- Standard - Provides the capability to determine the parameters and process the measurement types listed in the section titled Workstation/Precision Orbit Determination, including processed GPS position/velocity data. Depending on the quality of the data and models used, sub-meter orbit positional accuracies are achievable.
- Basic GPS - Includes the Standard capabilities plus the ability to process GPS pseudo-range data from any number of GPS satellites and receivers. To achieve a more accurate solution using GPS data, PODS estimates the orbits of the GPS satellites based on tracking data from ground receivers rather than using the downlinked GPS navigation data.
- Extended GPS - Includes Basic GPS capabilities and the ability to process carrier phase data. Orbit position accuracies within 10 cm and ground station coordinate accuracies within 1 cm are achievable.

Inputs

This section summarizes the available inputs.

Inputs from User

PODS user inputs are provided per STK object (Scenario, Vehicle, or Facility). Scenario inputs apply to all vehicles and facilities in the Scenario. Inputs per object type are listed below.

<u>Scenario Inputs</u>

- Input tracking data file names and formats
- Selection criteria for tracking data by time span, measurement type, vehicle or facility, etc.
- Earth flattening coefficient
- Earth gravitational constant and sigma
- Maximum geopotential model degree and order for all vehicles

<u>Vehicle Inputs</u>

- Transponder delay
- Geopotential model degree and order to be used in the force model for this vehicle
- Vehicle area and mass
- Initial orbit state vector in a variety of coordinate systems and element forms (Cartesian, Keplerian, non-elliptical forms, etc.)
- Span for orbit estimation and/or propagation

- Earth gravitational model coefficients and sigma values
- Solar flux data and times
- Magnetic flux data and times
- Coordinate system reference date
- Data pass definitions
- Minimum and maximum number of iterations
- Convergence criteria
- Sigma editing criterion
- Initial RMS values
- Orbit integrator step size
- Selection of optional output reports as listed in the section titled Outputs to User
- Optional unmodeled acceleration and sigma values
- Solar pressure coefficient and sigma
- Atmospheric drag coefficient and sigma value
- Biases and sigma values for all measurement types
- Covariance matrix for initial orbit elements
- Selection of optional output files

<u>Facility Inputs</u>

- Minimum elevation angle before data is rejected
- Facility coordinates (in a variety of coordinate systems) and sigma values
- Coordinate system for station adjustments
- Facilities which are constrained in position relative to one another
- Earth semi-major axis and flattening overrides for geodetic conversion per station
- Antenna mounting type and displacement
- Nominal received wavelength
- Turn-around factor (ratio of wavelength transmitted to wavelength received)
- Biases and sigma values for all measurement types
- Override sigma values for normal equations and data editing
- Temperature, pressure and humidity at facility and time spans over which the data applies

<u>Additional GPS Inputs (GPS options only)</u>

- Names of RINEX files containing GPS tracking data
- Names of navigation files containing GPS navigation data
- Time span and/or measurement type criteria for selection/deletion of GPS data
- Radiation pressure model name for GPS orbit perturbations
- Identification of hub receivers used in construction of single differences
- Allowed tolerances between receiver times when forming differences
- Selection of optional output data

Inputs from Files

- Tracking Data Files - Files containing tracking data (formats described in PODS documentation.
- Environmental Files - Files containing Earth geopotential matrix; time system, polar motion and flux data; and planetary ephemeris.
- STK Object Files - ASCII files containing the STK and PODS data (user inputs, estimated parameters, orbit ephemeris, etc.) stored between runs.

Outputs

Outputs to User

All user outputs are displayed through the STK user interface. STK provides the ability to change display units and time systems, export data into a format suitable for use by a spreadsheet program, and send data directly to a system printer. The Mandatory Outputs are displayed during or after every PODS run, and the Optional Outputs can be displayed in addition to the Mandatory Outputs at the user's choice. The items in each output type are listed below.

Mandatory Outputs

- Tracking data summary, including:
  - Vehicles, facilities and measurements types for which tracking data exists in the selected files
  - Start and stop time of selected tracking data by vehicle, facility and measurement type
  - Number of passes
  - Time span for each pass
  - Vehicle, facility and measurement types per pass
- Convergence status (converged/diverged) for solutions
- Convergence criterion for solution
- Number of iterations performed
- List of parameters estimated
- For each estimated parameter:
  - A priori value
  - Estimated value before last iteration
  - Final estimated value
  - Difference between final and a priori values
  - Difference between final and last iteration values
  - Final sigma value
  - Final sigma value multiplied by the RMS value
  - Epoch times (for estimated orbits)
- List of STK objects updated
- Ephemeris data (including ground traces) for each estimated orbit
- New locations for each estimated facility

Optional Outputs

- Correlation and covariance matrices for solved-for parameters
- Last iteration residuals
- Number of measurements per type used in each iteration
- Summary per measurement type, including:
  - Name
  - Units
  - Total number of measurements in tracking data
  - Number used
  - RMS and mean value of both the residual and weighted residual
- RMS history per iteration
- GPS vehicle orbit elements (GPS options only)
- WS/POD TDF Run File
- WS/POD TDF Block Summary File
- WS/POD GDF Run File (for GPS options only)
- WS/POD FixClock Run File (for GPS options only)
- WS/POD CNTL Run File
- WS/POD EXEC Run File (132-column)
- WS/POD EXEC Terminal Output File (80-column)

Outputs to Files

- Solution Files - WS/POD output files saved after the PODS run. File formats are outlined in the PODS documentation.
- Environmental Files - Updates to the Environmental Files used by WS/POD.
- STK Object Files - Updates to the ASCII object files with the latest object data.

Applications

Single Satellite Maintenance

One potential application for PODS is the Air Force Satellite Control Network (AFSCN), which determines the orbit of individual satellites using azimuth, elevation and S-band range and range-rate from a world-wide network of Remote Tracking Stations (RTSs). Tracking data is generated by the stations and sent to a Mission Control Complex where an orbit estimation is performed. The new orbit is used to generate antenna pointing angles, which are in turn sent to the RTSs to drive the antenna for subsequent contacts with the vehicle.

A typical sequence of events using PODS is as follows:

- The analyst creates the vehicle in the STK database including the initial orbit estimate. This can either be the result of a previous PODS run propagated to the present time, or generated by STK using NORAD 2-Line Mean Element Set (2LMES) inputs.
- The tracking data from the RTSs are reformatted into a PODS data format. This can be accomplished using a database management system, custom program, or text formatting tool such as UNIX awk.
- The analyst produces a tracking data summary as necessary to display the types and spans of tracking data available.
- After approval of the tracking data contents, the analyst sets the estimation parameters and performs a PODS estimation run, resulting in a display of solution data and a ground trace for the new vehicle orbit.
- After examination of the output, the analyst can elect to accept the results by saving the vehicle object in STK, or can overwrite the results by reloading the original vehicle object from the data base.
- The analyst invokes the standard STK *Access* operation against the saved orbit ephemeris data to generate antenna pointing angles for the RTSs.
- After viewing the pointing angles, the analyst can export the data to a file for use in controlling an antenna in real-time.

The saved PODS results supply the input field defaults for the next PODS run for the same vehicle. The PODS-generated ephemeris data is used by other STK utilities and/or optional add-on STK products. The analyst can also at any time extend the ephemeris span of a PODS orbit by invoking the PODS orbit propagator from the STK *Vehicle/Orbiting* menu.

Automated Constellation Management

One of the powerful features of the PODS implementation is the ability to process the data for many satellites simultaneously. This allows management of entire constellations from a single workstation. The nature of the STK interface and object file storage capability allows inputs to be specified by an automatic process, eliminating the need for a user to manually enter data for each run.

As an example of such a process, consider a constellation of several dozen low-flying satellites at high inclination (as is proposed for several commercial global cellular communications networks). Tracking data for the satellites is collected by multiple ground stations around the world. A process utilizing PODS is as follows:

- Collect the tracking data for the different stations.
- Using a network management system (such as Storm Integration's IMT) perform the following:
  - Reformat into PODS tracking data types. Data from multiple stations and/or vehicles can be included in a single PODS tracking data file.
  - Automatically generate the PODS inputs and build the STK ASCII object files containing the PODS inputs per object.
  - Invoke PODS for the entire constellation. Graphical results for the entire constellation appear in STK.
  - Automatically save the estimated results for the entire constellation.
  - Use the Inter-process Communication (IPC) features of STK to automatically generate scheduling information, ground station access times and antenna pointing angles for the constellation.
- The analyst can perform periodic updates of the solar and magnetic flux information, Earth polar motion and UT1 coefficients using the PODS database management utilities, or these can also be automated.
- Manual overrides can be used at any time, entered either through the user interface or the object files.

Initial orbit estimations may require multiple passes of data in order to accurately estimate the effects of solar pressure, atmospheric drag, and the Earth gravitational field per vehicle. Longer data spans using multiple stations can also be used to precisely determine the location of the tracking stations as well as any biases associated with the measurements from the individual tracking stations. The best estimates of these parameters can be used in the automated scenario described above and can be updated at any time.

GPS Data Processing

PODS provides a variety of options for GPS data processing. The simplest option is supported by the Standard level and involves incorporation of GPS receiver point position vectors into an orbit solution. Vehicles with on-board GPS receivers generally telemeter the position vectors computed by the receiver. These position vectors can be combined with ground-based measurement types (e.g., range, range-rate, etc.) to form a single set of data for which PODS will compute the orbit that best fits the available data. The GPS receiver data can supplement ground-based measurement types, which can reduce the number and/or required coverage areas of ground stations while still achieving high accuracy. The GPS data can also be used as a reference to calibrate the ground-based receivers.

A more sophisticated approach can be supported when the on-board GPS receiver passes along the raw pseudo-range and carrier phase data. The GPS options of PODS can process these data types directly to obtain user satellite position solutions with 10 cm accuracy. Processing of pseudo-range and carrier phase data from ground-based receivers allows determination of ground receiver locations as well as orbit solutions for the entire GPS constellation with uncertainties below 1 m.

Summary

PODS combines two powerful COTS products, STK and WS/POD, into a single integrated system combining ease-of-use with high-fidelity algorithms. STK provides a modern graphical user interface and seamless integration of the estimated parameters with a wide range of existing mission planning and analysis tools. The integration with STK makes PODS a natural extension of existing STK capabilities. WS/POD provides powerful computational capabilities with demonstrated reliability due to the heritage from NASA programs. The system is designed so that it can be entirely configured by the end user with minimal assistance from the vendor.

Applications of PODS range from single satellite control to constellation management. The three different processing levels based on inclusion of different types of GPS data allow the user to choose the level of support appropriate for mission requirements. The open nature of the PODS/STK interfaces allow easy integration with existing command and control systems.

References

- Volume 1, MicroCosm® Systems Description, Version 9302.00, February 1993 published by Van Martin Systems, Inc., Rockville, MD.
- Volume 2, MicroCosm® File Description, Version 9302.00, February 1993 published by Van Martin Systems, Inc., Rockville, MD.
- Volume 3, MicroCosm® Operations Description, Version 9302.00, February 1993 published by Van Martin Systems, Inc., Rockville, MD.
- Volume 1, MicroCosm® Installation and Tutorial, Version 9302.00, February 1993 published by Van Martin Systems, Inc., Rockville, MD.
- Satellite Tool Kit® User's Manual, Version 2.0 for Engineering Workstations, published by Analytical Graphics, Inc., King of Prussia, PA.
- Satellite Tool Kit/Programmer's Library (STK/PL)™ Programmer's Guide, published by Analytical Graphics, Inc., King of Prussia, PA.
- Satellite Tool Kit/Programmer's Library (STK/PL)™ Programmer's Reference, published by Analytical Graphics, Inc., King of Prussia, PA.