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NSWCDD/TR-17/229

HISTORY OF SATELLITE ORBIT DETERMINATION AT NSWCDD

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14. ABSTRACT

This document provides a detailed technical history of the satellite orbit determination and prediction capabilities developed and the associated satellite programs and analyses supported by the Naval Surface Warfare Center, Dahlgren Division, and its predecessor organizations since the late 1950s. This work started with computing orbits for the first Navy Transit satellites launched, and the establishment of the Space Surveillance Operations Center at the Naval Weapons Laboratory in May 1959 to take advantage of the resident Naval Ordinance Research Calculator computing resource. The Operations Center separated from the Naval Weapons Laboratory in 1961, but the satellite work continued and expanded. Four major generations of orbit determination software systems have been developed over the years: ASTRO, CELEST, OMNIS, and EPOCHA, along with several minor dependent and independent systems. Details of each system's capabilities are provided along with the specific satellite programs each system supported.

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The author would like to acknowledge two retirees who provided historical information through the early 1970s: Bob Hill and Patricia Smith. Bob was one of the principal analysts who used ORKI [Orbital Runge-Kutta Integration for Ephemeris] for early satellite launches, helped formulate, develop, and use ASTRO, and contributed to the development and application of CELEST to several satellite programs. Patricia wrote the code for the initial orbit determination program, ORKI, and worked on the Transit satellite project.

PREFACE

A variety of formal and informal historical material from various sources was reviewed in writing this technical report. No attempt was made to cite references throughout the text but a comprehensive bibliography is contained at the end of the report. The authors identified in this bibliography comprised a large majority of the individuals who participated in satellite orbit determination work over more than 50 years. Many other individuals not cited in this bibliography also contributed significantly to this work. The author has become the custodian of this historical information and would like to thank all the individuals who took the time to document and save their work along the way. Countless individuals have devoted their entire professional careers to this work and have left a lasting legacy. In the mid-1980s, around 65 Naval Surface Warfare Center, Dahlgren Division, personnel were working on satellite-related projects. This decreased to less than 10 personnel at one point in time, but has been increasing in recent history. The author would also like to thank the numerous National Geospatial-Intelligence Agency technical personnel who have used the Naval Surface Warfare Center, Dahlgren Division-developed software systems in production over the years. Their success and feedback contributed significantly to this legacy. The author accepts full responsibility for any inaccuracies and omissions present in this history.

FOREWORD

This document was written with the support of the National Geospatial-Intelligence Agency (NGA). The NGA and its predecessor organizations—the National Imagery and Mapping Agency and the Defense Mapping Agency—have been the primary sponsors of the satellite work done at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD), and its predecessors since 1972. The Naval Research Laboratory sponsored significant satellite work at NSWCDD, primarily in the 1960s and 1970s. The Navy's Strategic Systems Program Office also sponsored all GPS [Global Positioning System]-related SATRACK [Satellite Tracking] work. Other organizations that supported this work during the early years were Headquarters Navy, Navy Bureau of Weapons, Naval Air Systems Command, and the intelligence community.

The *National Reconnaissance Office Review and Redaction Guide for Automatic Declassification of 25-Year-Old Information, Version 2.0,* 2012 edition (approved for public release 8 May 2013), provided the basis for writing about the now-declassified satellite work that was carried out at NSWCDD.

This document has been reviewed by Rebecca Moffitt, Head, Space Tracking and Control Branch; and Cornealius Flakes, Head, Combat Control Division.

Approved by

MIKE TILL, Head
Warfare Systems Engineering and Integration
Department

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GLOSSARY

Acronym	**Definition**
NSWCDD	Naval Surface Warfare Center, Dahlgren Division
AII	Accuracy Improvement Initiative
ANNA	Army, Navy, NASA, Air Force
ANTEX	Antenna Exchange
AOD	age of data
ARL:UT	Applied Research Laboratories at The University of Texas at Austin
ARP	antenna reference point
ASCII	American Standard Code for Information Interchange
ATS	Advanced Technology Satellite
BIH	*Bureau International de l'Heure*
BINEX	binary exchange
CCID	Continuous-Count Integral Doppler
CDP	carrier-derived pseudorange
Cs	cesium
DARCUS	Determination and Refinement of the Coordinates of an Undetermined Station
DASO	Demonstration and Shakedown Operations
DAWG	Data Analysis Working Group
DB	Doppler Beacon
DMA	Defense Mapping Agency
DMAAC	DMA Aerospace Center
DMAHTC	DMA Hydrographic/Topographic Center
DMATC	DMA Topographic Center
DoD	Department of Defense
DTM	Drag Temperature Model
ECAT	Editing and Clock Automation Tool
ECI	Earth-centered-inertial
EDL	EPOCHA Development Laboratory
EGM	Earth Gravitational Model
ENV	east-north-vertical
EOP	Earth-orientation parameters
EPOCHA	Estimation and Prediction of Orbits and Clocks to High Accuracy
ERD	estimated range deviation
ERM	Exact Repeat Mission
ESSP	External Satellite/Station Parameters
GEOCEIVER	geodetic receiver
GEOS	Geodetic Earth Orbiting Satellite and Geodynamics Experimental Ocean Satellite
GEOSAT	Geodetic Satellite
GM	Gravitational Constant times Mass of Earth
GMF	Global Mapping Function
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPSPAC	GPS Package
GUI	graphical user interface
HILAT	High-latitude Research Satellite
HV	host vehicle
IAU	International Astronomical Union

GLOSSARY (CONT'D)

Acronym	**Definition**
ICS	Interim Control Segment
IDL	Interactive Data Language
IERS	International Earth Rotation and Reference Systems Service
IGS	International GNSS Service
JHU APL	Johns Hopkins University Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
KH	Keyhole
LAGEOS	Laser Geodynamics Satellite
LCC	Launch And Checkout Capability
LTP	Long-Term Predictor
mas	milliarcseconds
MESA	Miniature Electrostatic Accelerometer
MSF/S	Multisatellite Filter/Smoother
MSN	Monitor Station Network
MSNCC	Monitor Station Network Control Center
NASA	National Aeronautics and Space Administration
NAVPAC	Navigation Package
NAVSAT	navigational satellite
NAVSPASUR	Naval Space Surveillance System
NAVSTAR	Navigation Satellite Timing and Ranging System
NCE	National Geospatial-Intelligence Agency (NGA) Campus East
NGA	National Geospatial-Intelligence Agency
NGR	Normalized Group Residual
NIMA	National Imagery and Mapping Agency
NMR	Navigation Message Replacement
NORC	Naval Ordnance Research Calculator
NRL	Naval Research Laboratory
NSOP	New System of Programs
NSWC	Naval Surface Weapons (or Warfare) Center
NSWCDD	Naval Surface Warfare Center, Dahlgren Division
NTS	Navigation Technology Satellite
NWL	Naval Weapons Laboratory
OCS	Operational Control Segment
ODF	OCS Data Facility
OMNIS	Orbit Mensuration and Navigation Improvement System
OPNET	Operational Network
OPROG	Operational Program
ORKI (or ORKIE)	Orbital Runge-Kutta Integration for Ephemeris
OT	Operational Test
PAGEOS	Passive Geodetic Earth Orbiting Satellite
PAWG	Performance Analysis Working Group
PCT	Product Comparison Tool
PDS	Product Distribution System
PREFER	Precision Recursive Estimator for Ephemeris Refinement
PO	Preprocessed Observation

GLOSSARY (CONT'D)

Acronym	Definition
PRN	pseudorandom noise
RAC	radial, along-track, cross-track
Rb	rubidium
RINEX	Receiver Independent Exchange
RK	Runge-Kutta
RMS	root mean square
RMT	residual magnitude threshold
RTS	Rauch-Tung-Striebel
RVC	radial, velocity, and cross-track
SA	Selective Availability
SAMSAP	SATRACK Multiple Satellite Processor
SATRACK	Satellite Tracking
SCOPE	Supervisory Control of Program Execution
SECD	Satellite Ephemeris And Clock Data
SMTP	Special Mission Tracking Program
SNR	signal-to-noise ratio
SOLRAD	Solar Radiation
SST	satellite-to-satellite tracking
STARLETTE	*Satellite de Taille Adaptée avec Réflecteurs Laser pour les Etudes de la Terre*
STP	Short-Term Predictor
TCA	time of closest approach
TED	Tracked Ephemeris Data
TIMATION	Time Navigation
TOPEX	Ocean Topography Experiment
TRANET	Tracking Network
URE	User Range Error
USNO	U.S. Naval Observatory
UT1	Universal Time
UTC	Coordinated Universal Time
VAFB	Vandenberg Air Force Base
WGS	World Geodetic System
ZAOD	Zero Age of Data

Supplemental Information

Throughout Dahlgren's history, its name has changed several times. This document covers some of the decades during which the shore-based facility was renamed more than once. To alleviate readers' confusion, all name changes, abbreviations, and corresponding dates are listed below.

Naval Weapons Laboratory (NWL) 1959–1974
Naval Surface Weapons Center (NSWC) 1974–1987
Naval Surface Warfare Center (NSWC) 1987–1992
Naval Surface Warfare Center, Dahlgren Division (NSWCDD) 1992–present (publication date)

In 1972, the Defense Mapping Agency (DMA) was established, combining the mapping, charting, and geodesy organizations from the Army, Navy, and Air Force. In 1996, the DMA was combined with elements of the intelligence community to form the National Imagery and Mapping Agency (NIMA).In 2003, the NIMA was renamed the National Geospatial-Intelligence Agency (NGA).

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INTRODUCTION

Four major and several minor dependent and independent software systems for estimating and predicting satellite orbits have been developed and used extensively by the Naval Surface Warfare Center, Dahlgren Division (NSWCDD), and its predecessors—the Naval Surface Warfare Center (NSWC), the Naval Surface Weapons Center (NSWC), and the Naval Weapons Laboratory (NWL)—since the late 1950s. This report is an attempt to summarize each of these systems, their modeling and estimation capabilities, and the specific satellite systems and associated analyses each was used to support. The software systems were not an end in themselves but they provided the tools necessary to do the more important analyses and production processing required to maximize the potential of each satellite system. For most of these systems, NSWCDD formulated the mathematical models for the physical forces, the transformations between the inertial and Earth-fixed reference frames, the observations and their associated editing techniques, and the estimation equations; designed, developed, integrated, and tested the associated software; conducted prototype and actual production; improved the models and associated physical constants; transferred all of this technology, both hardware and software, to operational groups at the National Geospatial-Intelligence Agency (NGA) and its predecessor organizations; monitored these operations and assisted in troubleshooting issues; and continually improve operation efficiency and product accuracy.

Historical information on the software developed in the late 1950s and 1960s was minimal, especially for the first orbit determination system developed by the NWL: the Orbital Runge-Kutta (RK) Integration for Ephemeris (ORKI or ORKIE). ORKI was followed by the four major systems, listed in chronological order: ASTRO (not an acronym), CELEST (not an acronym), OMNIS (Orbit Mensuration and Navigation Improvement System), and EPOCHA (Estimation and Prediction of Orbits and Clocks to High Accuracy). All four major systems used the method of special perturbations (involving numerical integration of the equations of motion and their associated variational equations) to improve initial orbit parameter estimates. The last two systems, OMNIS and EPOCHA, also had to estimate both satellite and station clock parameters as stochastic processes and not just as pass bias parameters.

The early software systems processed mainly station Doppler frequency data from low-to-medium altitude satellite systems, one satellite at a time, until CELEST, which was modified extensively to process satellite-to-satellite tracking (SST) data (providing the first multisatellite processing capability) and GPS [Global Positioning System] pseudorange and range difference data. Up until OMNIS, all systems used batch weighted-least squares estimation in a differential correction mode. Iterations were required because the problem is nonlinear, and the initial orbits were not very accurate. OMNIS was the first to use a Kalman filter followed by a Rauch-Tung-Striebel (RTS) smoother for estimation, when iteration was not normally needed, and had an extensive GPS processing capability for both data collected by ground stations and on-board low-altitude satellites. A Kalman filter with zero process noise is equivalent to sequential weighted-least squares estimation. OMNIS also included a separate limited weighted-least squares orbit estimation capability similar to CELEST. EPOCHA, the current software system, is also a Kalman filter and RTS smoother and was designed to be operated mainly in real-time to generate accurate short-term predictions as either standalone predictions or corrections to the navigation messages broadcast by the satellites.

After some early history related to ORKI and the NWL’s role in assisting in the development and operation of the Naval Space Surveillance System (NAVSPASUR), the complete capabilities of each of the four major orbit estimation and prediction software systems will be discussed, followed by the satellite programs and analyses supported by each system. Several other minor software systems will also be discussed. Comparable system processing diagrams will be presented for all four major systems and summary tables comparing the capabilities of these four major software systems are provided in the Summary.

EARLY ORBIT COMPUTATIONS AT THE NAVAL WEAPONS LABORATORY

Beginning in the late 1950s and early 1960s, NWL personnel developed the ORKI program, principally to support the Johns Hopkins University Applied Physics Laboratory (JHU APL)-initiated Transit navigation satellite project and other Transit-like projects. ORKI was executed on the Naval Ordnance Research Calculator (NORC) and was written in the NORC's own native programming language. As its name indicated, ORKI used an RK Gill numerical integration algorithm to integrate a satellite orbit based on six initial conditions, a simple force model, and a true-of-date inertial reference frame assuming a constant Earth rotation rate and no polar motion. The force model consisted of Earth's central force term and the first two even zonal harmonics ($C_{2,0}$ and $C_{4,0}$), perturbations due to the Sun and the Moon as point masses, and atmospheric drag. In 1960, by manually plotting the motion of perigee of the Transit 1B satellite, a refined value for the first odd zonal harmonic ($C_{3,0}$) corresponding to the pear-shaped Earth was determined at NWL and included in the force model. ORKI could process Doppler observations, optical observations (azimuth and elevation), National Aeronautics and Space Administration (NASA) Minitrack observations (direction cosines), NAVSPASUR fence observations (direction cosines), and radar observations (range, elevation, and azimuth). There was automatic polynomial fitting and editing for Doppler observations. Most editing was done manually with the assistance of a Kelvin Hughes Limited™ camera online to view passes, data, and residuals. Individual points or entire passes could be edited. Frequency biases were determined for each pass but not very accurately. Physical magnetic tapes were used for all inputs and outputs. Weighted-least squares fits were used to refine an initial orbit, usually requiring several iterations during which a reference orbit was reintegrated in each iteration. A typical orbit computation for a daily fit took up to three hours.

When the attempt to launch the first Transit 1A satellite in September 1959 failed, ORKI and other related software were not quite ready to be used. NWL personnel were planning to do the computations without this software. However, most of the software was ready to support the first successful Transit 1B satellite launched in April 1960. The responsibility for preparing station alerts for Transit satellites was assigned to the NWL within a few days after this first launch. Station alerts are predictions of when a satellite will first come into view at a station and the duration of the contact. Besides the Transit satellites, ORKI was used to determine orbits for some Sputnik satellites, SAMOS [Satellite and Missile Observation System] film readout satellites, and the Soviet Union's Venus Probe satellite. For some early satellite launches, the NWL competed with the Massachusetts Institute of Technology Lincoln Laboratory, JHU APL, and Aerospace Corporation® on computing the first definitive orbit after a successful launch. Most of the time, the NWL was first. These orbit determinations were sometimes based on a single pass or a few passes of Doppler data. Many launch failures occurred during these early years.

In parallel with the ORKI-related work at the NWL, the Naval Research Laboratory (NRL) established the Space Surveillance Operations Center at NWL in Building 111 in May 1959 to take advantage of the NORC and of the NWL staff. The NRL was developing a Naval Space Surveillance program to meet fleet tactical requirements and needed Navy computing support to routinely process the data collected by an electronic fence deployed across the southern part of the United States. The radio frequency radiation from the fence was reflected from any satellite that passed overhead and was received by other parts of the fence to provide the observations. The observations consisted of the angles of arrival of the reflected signals at each receiving site. The NORC was chosen to compute and predict the orbits of all objects that passed over this fence to maintain a catalog of space objects.

The mathematical formulation for the orbit determination algorithm used by this Center was primarily the responsibility of outside consultants hired by the U.S. Naval Observatory (USNO). However, analysis, programming, and some mathematical formulation for orbit estimation and prediction were completed by NWL personnel. Using both empirical and analytical equations for the ephemeris model, least-squares fitting to the fence observations were used to estimate a set of orbital elements and rates of change of certain orbit-related quantities to make the predictions. The NORC took approximately 15 minutes to process and update the orbit for a single satellite plus additional time for preprocessing the raw fence data and updating the catalog.

Space Surveillance Operations Center operations began in June 1960, and by September 1960, the Center had become a separate branch of K Laboratory, and in October moved to Building 218 with the NWL's new computer, an IBM™ 7090. In February 1961, NAVSPASUR was officially established as an independent command under the North American Defense Command and another IBM 7090 computer was added to its computing facility. Forty-three NWL civilian personnel were transferred to NAVSPASUR, and in July 1961, an additional twenty-one were detailed to NAVSPASUR. The NWL continued to provide study support to NAVSPASUR for many years after this transition.

Prior to its completion, the NORC became well known in the scientific community as the most powerful computer ever assembled. The NORC was delivered to the NWL in March 1955 to use for ballistics computations. The NORC originally had a 2000-word Williams tube electrostatic memory, which was augmented with a 20,000-word magnetic core memory to complete the expanding orbit computations. The NORC had a word size of 16 digits plus a check digit. Storage access time was 8 microseconds, multiplication time was 31 microseconds, and addition time was 15 microseconds. There were eight magnetic tape units operating at 70,000 characters per second and three printers. Two mechanical printers operated at 300 characters per second and one optical printer operated at 15,000 characters per second. Follow-on IBM 7090 computers used transistors, and had a 36-bit word length, a 32K-word address space, a 2.18-microsecond memory cycle time, and a processing speed of about 100 Kflops. They included card readers, tape drives, and line printers.

ASTRO (1960–MID-1970S)

ASTRO was a single-satellite, pass-oriented, after-the-fact processing system. It was formulated beginning in 1960 and the system was first used in 1962. Its main purposes were to estimate orbits and their associated atmospheric drag and solar radiation pressure parameters, preliminary geodetic coordinates for stations, and the two coordinates of Earth's pole. Earth's spin axis and axis of figure (pole) are not at the same location, and the spin axis moves slowly with both annual and Chandler (435-day) periods. ASTRO was used in conjunction with the GEO (not an acronym) system of programs to generate general geodetic solutions for gravity field model coefficients and station coordinates. Improved gravity field models were needed for both satellite orbit determination and long-range missile trajectory computations for both intercontinental and submarine-launched ballistic missiles. Station coordinates were determined for the tracking stations used for orbit determination, for computing interdatum ties, and for ground-based missile launch locations.

ASTRO performed an iterative weighted-least squares solution for the orbit parameters, equipment biases, and positions of observing stations (with or without *a priori* weights), and operated using the UTC [Coordinated Universal Time] system. The estimation procedures used a linearized state vector that required calculating the state transition matrix, the diagonal weighting matrix representing the *a priori* state uncertainties, and the matrix of observation partial derivatives. The dynamical parameters were the epoch osculating orbital elements or position and velocity, up to four sets of four parameters corresponding to the atmospheric drag model (each in effect for multiples of one day), up to four solar radiation pressure scale parameters (each in effect for multiples of one day), station coordinates, and two polar motion parameters. The osculating orbital element set most used is determinate at zero eccentricity and consisted of the semi-major axis, eccentricity times the sine of the argument of perigee, eccentricity times the cosine of the argument of perigee, inclination, mean anomaly plus the argument of perigee, and right ascension. The classical osculating orbital element set could also be used. Each set of four drag parameters consisted of two used in computing the drag coefficient and two used in computing the atmospheric diurnal bulge amplitude. Various constraints on these drag parameters could be specified via inputs. ASTRO processed various kinds of satellite observations and used numerical integration of the equations of motion and variational equations to generate a starting orbit and corresponding state transition matrices and the orbit at any other time after improvement. It included segments for filtering and aggregating Doppler satellite observations and segments for updating orbital elements, and conversion among three representations: position and velocity, osculating orbital elements, and mean orbital elements. It produced summary reports in both tabular and graphical form.

ASTRO consisted of ten segments for performing program control, orbit integration, orbit improvement, data filtering, data evaluation, report generation, and station coordinate estimation. The chief functions of each of the segments were:

Segment 11	controlled system flow
Segment 10	integrated the equations of motion and variational equations
Segment 20	processed the observations and did the orbit improvement
Segment 30	filtered and aggregated the observed Doppler frequency data
Segment 40	did station navigation and error of fit analysis
Segment 45	plotted the residuals generated by *Segment 20*
Segment 50	prepared result reports
Segment 60	TRIDON (applied ephemeris corrections)
Segment 70	DARCUS [Determination and Refinement of the Coordinates of an Undetermined Station] combined data from several arcs and solved for station coordinates
Segment 80	extracted or accumulated observational data

Typically, *Segment 10* was used for integrating a preliminary orbit and for integrating the variational equations to get the necessary partial derivatives, *Segment 30* followed, and *Segment 20* then computed the orbit improvements with *Segments 10* and *20* iterated until convergence.

Segment 10 was then used to create a minute vector (a trajectory at a one-minute interval) based on the final orbit solution, and *Segment 20* generated input for the next run. *Segment 40* did pass editing and its use was optional after *Segment 20*. *Segment 30* needed to be run before *Segment 80*. *Segment 70* was run as needed. Physical magnetic tapes were used for all inputs and outputs, just like for ORKI. The diagram in Figure 1 gives the typical ASTRO data processing flow.

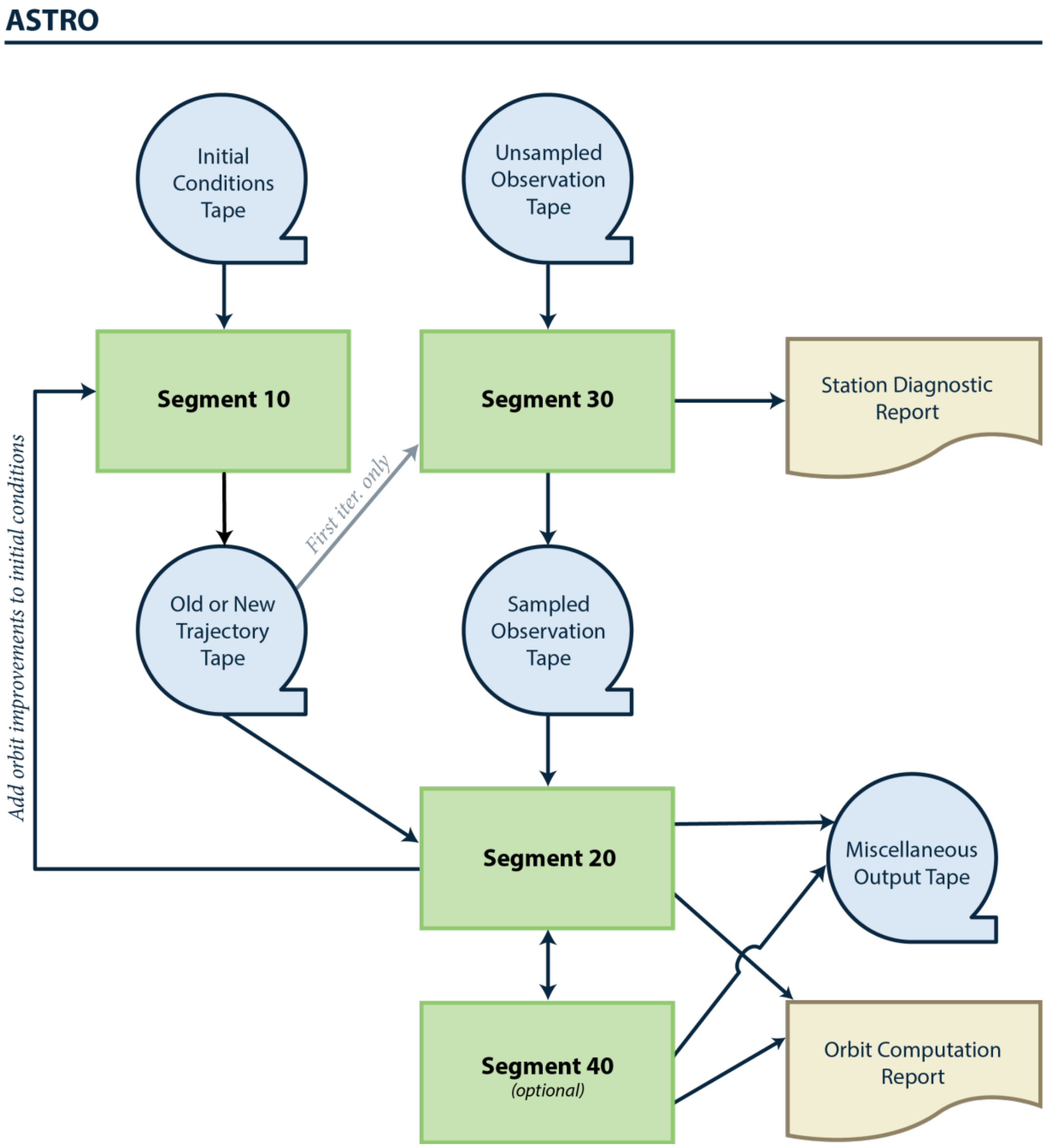

Figure 1: ASTRO Data Processing Flow

In measuring the Doppler shift, the received frequency from the satellite was beat against a frequency generated by the station receiver oscillator. The method of counting these beat cycles differed. Until 1971, most of the Doppler data were taken by counting a preset number of cycles and recording the time required for the count. The count was typically done every four seconds and the number of cycles to count was chosen so that the count interval would last just under one second. This type of Doppler data was called Sampled Doppler. The counting was later changed so that the time of completion of one count was the beginning of the next count and the number of cycles counted was set so that the intervals lasted 10–30 seconds. This type of Doppler data was called Continuous-Count Integral Doppler (CCID). The Sampled Doppler data were treated as frequency data (number of cycles counted divided by the count interval) in the orbit determination process. The CCID (also called integrated Doppler) data were treated as range differences over time. The tracking networks collecting the Doppler data were the Operational Network (OPNET) and Tracking Network (TRANET), which are described in the following subsection.

The primary data type used in ASTRO prior to the conversion to CCID data was Sampled Doppler frequency data. The raw Doppler data were preprocessed at the stations to apply any corrections for known instrumentation calibration biases. A pre-ASTRO program processed the frequency data from a collection of stations and did some preliminary editing and reformatting of the data. Originally the program processed the raw tracking data by converting it from teletype five-channel paper tapes to NORC input tapes. Transmission and format errors were identified and tagged, and all data tapes were merged onto one tape. The raw data were then converted to Doppler frequency data, corrected for errors due to ionospheric refraction, and bad data points were eliminated. Weights were computed for individual data points and the data were aggregated and put into the ASTRO input format. Inconsistent station-pass combinations were then eliminated. Once in ASTRO, the time tags were corrected and data were deleted if collected below a minimum elevation angle.

Time of closest approach (TCA) was computed for each pass and used for the time ordering of the passes. A minimum number of data points were required for each pass to be accepted after an elevation angle tolerance was applied. For the Doppler frequency observations, the transmission time correction and the tropospheric refraction correction, based on the Hopfield model and either default or measured weather data, were made. The observation weights for Doppler frequency data depended on whether or not the tropospheric refraction correction was made. All input data variances could be scaled by an input sigma multiplier. Preliminary filtering (editing) was done using a linear fit to the data for each pass with elimination of observations associated with fit residuals exceeding an input multiple of the standard deviation. An entire pass was deleted if the convergence criteria for this test were not satisfied. A pass frequency bias plus an optional pass frequency drift were estimated for this data type. Also, a pass tropospheric refraction scale parameter and time tag offset could be estimated. Bias parameters were eliminated before the pass normal equations were combined. Final pass filtering was implemented using a station navigation technique involving linear fits to the slant range and tangential direction navigations over all passes.

ASTRO could also process the following data types (number of components is given in parentheses): right ascension (1); declination (1); directional cosine data (2); projection of range vector along the velocity vector (1); range or range difference (1); previously computed position and velocity (6); directional cosine data time derivatives (2); reflected Doppler data (1); geodetic datum constraint (3); and reference station longitude, latitude, and radial distance from Earth’s center (3). Each of these data types had their own weights. An eight-digit name or number for each satellite was required along with the gravity coefficient set ID, station coordinate set ID, and time standard.

In integrating the equations of motion for a satellite, the following accelerations were modelled: Earth gravitational; Sun and Moon gravitational; solar and lunar tidal bulges using Love’s tidal constant; atmospheric drag assuming a spherical satellite, drag coefficient, and a simple exponential atmospheric density model that involved a diurnal atmospheric density maximum on the equator but lagging the Sun's meridian by a fixed angle; and solar radiation pressure assuming a spherical satellite, a simple shadow model (full Earth shadow or full sunlight), and a scale factor. Earth's gravitational model could include both zonal and tesseral spherical harmonics up to degree and order 25.

The inertial coordinate system used in the orbit computations was based on the mean of date system (mean equator and equinox) at the beginning of the day of the initial orbital conditions. Precession, nutation, and Earth rotation were defined by the 1961 version of the *Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac.* Precession is used to convert from the mean equator and equinox at one epoch to another and used a reference epoch on 1 January 1950, usually designated B1950 to indicate the start of the Besselian solar year. Nutation is used to convert from mean equator and equinox of date to true equator and equinox of date. The longitude of the Greenwich meridian from the apparent equinox was based on the mean Greenwich hour angle at 0. Hours 1 January of the reference year obtained from the appropriate *American Ephemeris and Nautical Almanac* plus the integrated correction to Earth's rotational rate due to nutation and the effect of Earth's mean sidereal rotational rate from the beginning of the year with a seasonal correction made. Linear interpolation on daily Earth-orientation parameters published by the Bureau International de l'Heure (BIH)[1] was also used in this transformation to get to the axis of figure of the Earth.

The integration segment was a Corrector/Predictor type that used the 12th order Adams and Cowell algorithms in the Corrector and a difference extrapolation scheme in the Predictor. It also integrated a set of variational equations to generate the state transition matrix of the transformation relating the state vector at any time to the state vector at epoch. The time required for integrating these variational equations could be reduced, when appropriate, by truncating the number of gravity terms while using all terms in the force equations.

The weighted-least squares estimation was done iteratively and included a short cycle mode in which the numerical integration was deleted for a given number of iterations to save computer time. ASTRO inputs included an un-sampled observation tape, an old trajectory tape, and control cards. ASTRO outputs included a new trajectory tape, a miscellaneous output tape, station diagnostic reports, an orbit computation report, a control or history tape, and a sampled observation tape for use in DARCUS and GEO. ASTRO also contained a Delta R plot program for comparing two trajectory tapes, resolving the differences into the RAC [radial, along-track, cross-track] frame, plotting the differences, and computing the mean and root-mean-square (RMS) differences. Numerous other special purpose programs were part of the ASTRO system, including programs to compute daily average classical orbital elements at zero hours of the day, sub-satellite point and height above Earth's surface as a function of time, equator crossings, Sun angle at each time and percent of time in sunlight during a nodal cycle, and station alerts and times of NAVSPASUR fence crossings.

In the 1960s, NAVSPASUR, with NWL assistance, implemented a version of ASTRO on its computer systems to use in special projects, and further NWL assistance was made available as needed. NAVSPASUR used ASTRO until the early 2000s.

ASTRO was initially developed on the NORC with the 20K magnetic core memory (last reference to its use on the NORC was January 1965) and moved to the IBM 7090 (1961–1963),

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[1] The BIH preceded the International Earth Rotation and Reference Systems Service, which was set up in 1988.

and the IBM 7030 STRETCH computer system (1962–1972). In August 1965, the IBM 7030 STRETCH computer included 48,000 64-bit words of core storage, 10 magnetic tape drives, and a 2,000,000 word store used for GEO (see below). ASTRO and GEO were both written in Fortran IV (available on the IBM 7030 STRETCH in 1962) and ran from a punched card deck and magnetic tapes. ASTRO was ported to the Control Data Corporation[2] CDC 6700 mainframe computer when this machine became available in 1971 and was used until 1974. CDC 6700 card decks included SCOPE [Supervisory Control of Program Execution] control cards required to run the program. These included a CHARGE card related to usage charges and various REQUEST, ATTACH, and CATALOG cards related to copying, attaching, and saving files.

GEO

The GEO system received filtered and aggregated satellite Doppler observation data from ASTRO as input, formed normal matrices involving partial derivatives for station coordinates, orbit parameters, gravity field model harmonic parameters, atmospheric drag, and solar radiation pressure; accumulated these normal matrices over a period of time; and solved the accumulated matrices for corrections to the parameters. GEO used two computational phases. Phase I included an orbit integrator that integrated the orbits and the variational equations for all parameters, including the necessary gravity field harmonic coefficients, and formed the normal equations for each arc. Phase II combined and solved the normal equations for all arcs considered based on the selected options and applied the corrections to all parameters. The solution of the normal equations began with eliminating the arc parameters from each contributing arc, while saving the back-substitution equations for each arc so the arc parameters could be recovered after solving for the gravity field model and station coordinate parameters. These reduced normal equations were then combined after the station parameters were eliminated and solved to get the gravity field parameter corrections. Then the station coordinate solutions and individual arc parameters were recovered using the saved equations. Communication among the various programs was carried out using magnetic tapes. Both phases generated large volumes of output on tape. A GEO Library program stored a required subset of the data and released tapes that contained data no longer required.

ASTRO and GEO included many common routines so were not independent software systems. GEO evolved from ASTRO. Common data were communicated over magnetic tapes. ASTRO calculated day-to-day orbital computations and provided inputs for interim station coordinate solutions. It also filtered and aggregated Doppler data for GEO. GEO was primarily used to produce accurate geodetic solutions based on months of processing time and months of observational data. GEO was also ported from the NORC to the IBM 7090 and then to the IBM 7030 STRETCH computers.

Satellite Programs and Analyses Supported by ASTRO and GEO

The primary satellite tracking systems of interest to the NWL during this era were OPNET and TRANET. The OPNET stations were in Maine, Minnesota, California, and Hawaii, and comprised the operational tracking and control system developed by JHU APL for the Transit satellites described below. The TRANET station network was also developed by JHU APL and was used to track Transit and many other satellites and record Sampled Doppler frequency

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[2] Control Data Corporation (CDC), a supercomputer firm incorporated in Minnesota in 1957, was one of the nine major U.S. computer companies through most of the 1960s; the others were IBM, Burroughs Corporation, DEC, NCR, General Electric, Honeywell, RCA, and UNIVAC.

observations. Six stations were deployed in 1959 and were augmented with five stations in mobile vans by 1967. These stations communicated with a control center resident at JHU APL using a teletypewriter communications network. The tracking stations were provided satellite alerts and the stations returned Doppler data, satellite time data, and optional weather data to JHU APL. It was estimated that the TRANET system could simultaneously handle 10 near-Earth satellites. The data were preprocessed daily and distributed to users, including the NWL. TRANET receivers evolved to collect CCID data. In 1967, the JHU APL began developing the GEOCEIVER [geodetic receiver] to track satellites broadcasting on either the 400/150 MHz pair or the 324/162 MHz pair. This receiver was portable, integrated the Doppler signal over about 30–60-second intervals, had separate outputs for each of the two frequencies, used Transit timing signals for clock calibration, and outputted data on punched paper tape. ASTRO was modified to process CCID Doppler observations as range difference observations over time as opposed to the previous Sampled Doppler frequency observations.

Transit

The Navy Navigation Satellite System’s Transit satellites were originally developed to provide a two-dimensional positioning capability for ballistic missile-carrying submarines, but they were also used for various geophysical purposes, such as gravity field determination and station positioning in the applicable World Geodetic System (WGS) Earth-fixed reference frame. The station positions included those for the intercontinental missile launch sites and corresponding missile tracking stations. The first Transit satellite launched did not achieve orbit in September 1959 but did transmit useful signals. The first successful satellite launch, Transit 1B, occurred on 13 April 1960 and the satellite was put into an orbit with a 51° inclination, an apogee height of about 640 km, and a perigee height of about 360 km. It operated for 89 days.

Other Transit research and development satellites were launched during the early 1960s. The estimated accuracy of the Transit-predicted daily orbits at this time was about 5 km. In July 1963, the NWL derived the NWL-3B gravity field model with 13 gravity coefficients; this resulted in predicted orbits accurate on the order of 100 m.

The first operational Transit satellite was not launched until 5 December 1963, and the system was fully operational in 1967. The Operational Control System was established by the Naval Astronautics Group at Pt. Mugu, CA in 1964. The orbits of the Transit satellites were first estimated using ASTRO at the NWL for all available satellites for use in surveying the positions of the mainly portable receivers that tracked the Transit satellites. These orbits were called the “precise ephemeris” for each satellite. This nomenclature has endured over the years even though this is the incorrect use of the word “precise.” Precision typically describes the resolution of the orbital positions computed, not their accuracy. The computed orbits were the most accurate that could be determined given the limitations of the models and the distribution and quality of the station tracking data.

After 1965, the Transit satellites were sometimes called NAVSATs [navigational satellites]. Approximately 14 TRANET stations were available at that time along with a few roving stations. These stations were biased toward the northern hemisphere, so in 1965 a station was deployed to McMurdo Station at the edge of Antarctica, where each satellite was tracked on every revolution. In 1965, after refining Earth’s geodetic parameters, the NWL was given the new mission of exploiting the Transit program to meet the mapping, charting, and geodesy requirements of the Navy Hydrographic Office, Army Map Service, and Air Force Aeronautical Chart and

Information Center and, when these organizations were combined on 1 July 1972, the joint Defense Mapping Agency (DMA).

At one point in time the NWL also had a special Navy site survey requirement to locate ship anchorages using Transit observations. Surface ships collected range difference data called SRN-9 data, and submarines collected frequency difference data called PRN-3 data with the data type named after the on-board equipment. The data were printed on “grocery” paper tapes and were manually transferred to punched cards for input to the pre-ASTRO program. The data were then processed in ASTRO, holding the previously determined orbits fixed and estimating the ship anchorage coordinates.

Typically six Transit satellites were always available. These satellites had polar orbits at an altitude of about 1000 km (about a 107-minute orbit period) and broadcast on two frequencies—400 MHz and 150 MHz offset by -80 ppm [parts per million]. The raw Doppler data from the two frequencies were combined to remove the first-order ionospheric effects. Passes were 10–15 minutes long. Two-day fit spans were typically used, solving for six epoch orbital elements, one drag coefficient, two pole coordinates (starting in 1969), one frequency bias per pass, and one tropospheric refraction parameter per pass. The Transit orbits were primarily used to derive coordinates for mobile tracking stations, but the Transit tracking data were also used to refine Earth’s gravity field model. Over 100 stations had been positioned using Transit by the end of 1969 starting with just 10 stations in 1962. In 1965, the estimated accuracy of the coordinates derived using the DARCUS part of ASTRO was 25 m, which improved to 10 m a few years later.

The gravity model used in the Transit orbit computations was changed several times as it was improved: NWL-8D in February 1967; NWL-9H in April 1968; NWL-9B in February 1970; and NWL-10E in January 1973. As the gravity field model was improved, the resulting improvement in orbit estimation accuracies meant that higher accuracy station coordinates could be estimated. The station coordinate set used in the Transit orbit computations was also changed several times as the accuracy of the coordinates was improved: NWL-8E in February 1967; NWL-8F in January 1968; NWL-9C in December 1970; and NWL-9D in October 1971. The NWL-9D station coordinates were the basis for defining the WGS 72 reference frame. The longitudes of the NWL-9D coordinates were adjusted by +.260 arcsec and the heights were changed by -5.27 m. The latitudes were left unchanged. These adjustments were made to align WGS 72 with the international reference frame maintained by the BIH. These WGS 72 coordinates were also referred to as NWL-10F. The estimated accuracy of these coordinates was 0.7–0.9 m. It was believed the origin of this coordinate system was consistent with the center of mass of Earth to about one meter.

In 1969, the NWL started routinely estimating the two pole coordinates using Transit satellite data. After improvements were made in the processing, the agreement with astronomical determinations of the pole coordinates was shown to be better than one meter during 1969 and 1970. The pole coordinates determined for 1971 had standard errors of about 0.5 m for a five-day mean. However, for some time periods a bias of about 0.5 m also existed between the Doppler pole positions and positions reported by the BIH based on astronomical data. In 1972, the typical standard error in the pole position for the five-day means was about 20 cm.

In the early 1970s, near the end of the ASTRO’s processing of Transit data, the NWL primarily received its Doppler observations from a globally distributed network of 13 permanent and four mobile van stations of the TRANET system and from the four OPNET stations. Tracking data were normally collected above 5° in elevation. In ASTRO, numerical integration of the equations of motion was carried out using a one-minute time step. The accelerations considered were due to Earth's gravitational field (all terms through degree and order 19 plus many pairs of higher order resonance coefficients for a total of 478 terms), accelerations due to the Sun and Moon, accelerations due to atmospheric drag with a scale factor estimated, accelerations due to solar radiation pressure (treated as a step function that was off while in shadow and a coefficient of 3.622 held fixed with an associated nominal area-to-mass ratio of .811E-8 km^2/kg), and accelerations due to the solar and lunar tidal bulges with a Love's number of 0.3 with a zero lag angle. Two-day fits were done in the inertial frame corresponding to the mean equinox and equator at the fit epoch. The two pole coordinates were estimated starting with pole coordinates and Universal Time (UT1)-UTC based on the USNO's weekly extrapolation of values. The least squares solution included the six orbital elements, a drag coefficient, two pole coordinates, and frequency and tropospheric refraction biases (with a 10% *a priori* sigma) for each pass. The output ephemeris was given in Earth-fixed reference frame at one-minute intervals. All computations were performed in the UTC time system. The orbit accuracy was estimated to be about 5 m.

Studies were done for selected satellites mentioned below to examine the effects on their orbit determination due to neglected higher order and degree gravity field terms. Gravity field models specific to individual satellites were derived as required optimizing their orbit determination accuracy.

POPPY

The POPPY satellites were some of the earliest electronic intelligence satellites and the first mission launched in late 1962 used two co-orbiting satellites to record data from Soviet radar installations and Soviet navy ships at sea. The NWL did some type of orbit modeling for these satellites.

MIDAS [Missile Defense Alarm System]

The extent of NWL's participation in this first missile early-warning satellite program could not be determined based on the available declassified information.

Discoverer/Corona

The extent of NWL's participation in this first film-return reconnaissance satellite program could not be determined based on the available declassified information.

ANNA [Army, Navy, NASA, and Air Force] 1B

ANNA included a Doppler transmitter, a SECOR [Sequential Collation of Range] transponder, and flashing lights for optical tracking. In late October 1962, ANNA was launched into an orbit with an approximate altitude of 1100 km and an inclination of 50.1°. The Doppler system operated on either the 162/54 MHz or 324/216 MHz frequency pairs. Baker-Nunn and Wild BC-4 camera systems optically tracked the satellite. The NWL used the tracking data to compare the use of the various tracking systems for both absolute and relative station positioning and used the Doppler data for gravity field model determination.

BE-B [Beacon Explorer-B]

BE-B was launched in October 1964 into a slightly eccentric orbit with a mean altitude of about 960 km and inclination of 79.7°. It included a Doppler system transmitting on the 324/162 MHz frequency pair and laser retroreflectors. This satellite’s main mission was to provide worldwide observations of total electron content, but the NWL used its tracking data for gravity field model determination.

BE-C [Beacon Explorer-C]

BE-C was launched in April 1965 and the spacecraft and its main mission were identical to those for BE-B. However, its orbit was again slightly eccentric with a mean altitude of 1120 km and an inclination of 41.2°. This satellite’s slightly different altitude and completely different inclination made its tracking data useful to the NWL for gravity field model determination.

GEOS [Geodetic Earth Orbiting Satellite]-A

In November 1965, GEOS-A was launched into a slightly eccentric orbit with a mean altitude of 1700 km with a perigee height of 1115 km and an inclination of 59.4°. The satellite included a Doppler system transmitting on the 324/162 MHz pair, laser retroreflectors, a SECOR transponder, an optical beacon, and a C-band transponder. Again its primary purpose for NWL was using its tracking data for gravity field model determination.

PAGEOS [Passive Geodetic Earth Orbiting Satellite]

PAGEOS was a 100-ft. diameter balloon launched in June 1966 into an eccentric orbit (3000 x 5200 km altitude range) and an inclination of 84.4°. The balloon appeared as a fast moving star and was tracked optically. Again, its primary purpose for the NWL was using its tracking data for gravity field model determination because of its unique orbit.

Diademe A and B

Two French Diademe geodetic satellites were launched in February 1967 carrying Doppler transmitters and laser retroreflectors into elliptical orbits with inclinations of around 40° and an altitude range of 570 to 1350 km for the first satellite, and 590 to 1880 km for the second satellite. Their tracking data were used by the NWL for gravity field model determination.

TIMATION I [Time Navigation I]

TIMATION I was launched in May 1967 into a circular orbit with an altitude of 925 km and an inclination of 70°. It broadcast on the 399.4/149.5 MHz frequency pair to enable Doppler tracking for orbit determination. It used a stable quartz-crystal oscillator and a side tone ranging capability for time transfer experimentation. The NWL provided the precise ephemeris for this satellite to the NRL.

GEOS [Geodetic Earth Orbiting Satellite]-B

GEOS-B was launched in January 1968 into a slightly eccentric orbit with a mean altitude of 1300 km with a perigee height of 1080 km and an inclination of 105.8°. It included the same tracking systems as GEOS-A. Again, its primary purpose for the NWL was for gravity field model determination because of its different altitude and inclination.

TIMATION II [Time Navigation II]

TIMATION II was launched in September 1969 into an orbit with the same altitude and inclination as TIMATION I. It was just an updated version of the spacecraft and was used to continue the time transfer experiments. The NWL also provided the precise ephemeris for this satellite to the NRL. Tracking data for both TIMATION satellites were used for gravity field model determination at the NWL.

Geodesy with Transit and Other Satellites

The NWL used early satellites to verify the pear shape of Earth (as represented by the third-order zonal gravitational harmonic) and then to determine other zonal harmonics and tesseral harmonics, which introduced longitudinal variations into the gravity field model. Transit satellite results contributed significantly to the Department of Defense's (DoD) WGS 66 and were a major part of WGS 72 along with the other satellites mentioned above. The original WGS 84 reference frame was based on Transit data also and was not replaced by one based on GPS data until 1994.

The first NWL satellite data-based global geodetic solution, NWL-2, was generated in March 1963 using data from the ANNA 1B and Transit 4A and 4B satellites. The NWL-5E gravity field was based on adding data from three polar orbiting satellites to data from the previous three satellites; thus providing data from four distinct inclinations. Further refinement of this field by adding a few coefficients to account for resonance effects resulted in 25 m accuracy in determining the absolute positions of the tracking stations with 5 m accuracy for relative station coordinates. The NWL-8D solution used data from seven distinct inclinations and yielded station positions, datum shifts, and geoid heights with an estimated accuracy of 15 m in any linear dimension with 90% confidence. Table 1 gives a summary of the various gravity field solutions generated at NWL with the GEO software through the early 1970s. The NWL-8 fields were complete through degree and order 12. The NWL-9 and -10 fields were complete through degree and order 19. The WGS 72 gravity field model was complete through degree and order 19 and included zonal coefficients through degree 24 and additional resonance terms through order 27.

Table 1: Gravity Field Models Developed through Early 1970s

Gravity Field Name	Date Generated	No. of Gravity Coefficients	No. of Stations
NWL-2	March 1963	15	15
NWL-3B	July 1963	13	18
NWL-5E	August 1964	50	29
NWL-5K	September 1965	66	29
NWL-8B	September 1966	209	39
NWL-8D	February 1967	209	50
NWL-9B	October 1969	478	60
NWL-10C	February 1971	462	75
NWL-10E/ WGS 72	January 1973	479	>100

CELEST (1971–EARLY 1990S)

CELEST was a single-satellite, pass-oriented, after-the-fact processing system like ASTRO. The system was originally designed to more efficiently process Doppler observations collected by the TRANET, OPNET, and Special Mission Tracking Program (SMTP) networks from Transit, geodetic, and primarily low-altitude satellites. CELEST was similar to ASTRO in that iteration was almost always needed with fit spans typically of a day or more, and observations were processed in passes with bias parameters estimated per pass. The bias parameters were formally eliminated from the pass matrices; then the reduced pass matrices were combined for computing the arc solution. Once the arc solution was completed, the pass bias solutions were computed using information saved during the elimination process. For low-altitude satellites, CELEST also had a short-arc mode in which multiple overlapping arcs per day (of two revolutions each) could be done in a single run after the long-arc solution had converged. These short arcs used the pass matrices from the long-arc run in their solutions. This was necessary to support the so-called Doppler Beacon series of satellite launches (discussed below), which started out with up to three per year and were then reduced to once per year as the spacecraft hardware's reliability improved and missions were extended. The first operational use of CELEST was for these satellites.

CELEST was also used to process other satellites, including two Navigation Technology Satellites (predecessors to GPS), GPS Block I and II satellites, and the Doppler Beacon satellites augmented with Navigation Package (NAVPAC) receivers, which simultaneously tracked up to three Transit satellites. As the number of GPS Block I satellites to be processed increased as launches occurred, it was necessary to write additional software programs, called NSOP (new system of programs), to replace the CELEST editing and solution portions for efficiency reasons. The details of all of these uses of CELEST are presented below.

The CELEST software system consisted of seven overlays that performed the following processing:

1. *Integrator* integrated a reference trajectory for the time span of interest
2. *Pre-processor* edited and time corrected raw Doppler observations
3. *Pre-processor* applied ionospheric refraction corrections when required
4. *Filter* determined weights to use in the least-squares procedures
5. *Filter* formed pass normal equations that then had biases eliminated
6. *Matrix Combiner-Solver* combined the pass normal equations and then solved the arc normal equations
7. *Short-arc Selector* selected the short-arc fit spans
8. *Propagator* computed the updated ephemeris and associated covariance information
9. *Orbit Computation Report* produced reports and diagnostics

The input section of CELEST included reading the Gravity File containing the gravity field harmonic coefficients needed by the *Integrator*. The *Integrator* read the Sun-Moon File to get their positions as needed and generated the Perturbed Trajectory File for input to the *Filter*, *Matrix Combiner-Solver*, and *Propagator*. The *Integrator* could also generate an Earth-Fixed Trajectory File and an Inertial Standard Trajectory File. The *Pre-Processor* read the Raw Observation File and optionally, the Station Table File containing clock corrections, and generated the Time Corrected Observation File for input to the *Filter*. The *Filter* generated a Pass Matrix File for input to the *Matrix Combiner-Solver* and also output an O-C [Observed-Computed] File containing residuals for each pass. The *Matrix Combiner-Solver* generated the B-Inverse Matrix File for input to the *Propagator* and also generated the Data Class/Pass Diagnostics File and the Station Analysis Report. The *Propagator* output the Propagated Trajectory File.

The whole process, beginning with the *Integrator,* could be iterated until convergence was obtained. In Short-Arc mode, the Perturbed Trajectory File and Pass Matrix File were input to the *Matrix Combiner-Solver,* and multiple short arcs were estimated with a Diagnostic File and B-Inverse File generated. The B-Inverse file was then used by the *Propagator* to generate the Short Arc Ephemeris File. Multiple Pass Matrix Files based on the same Perturbed Trajectory File could be merged together and also input to the *Matrix Combiner-Solver*. An Initial

Conditions File could be written to by various overlays including the input section when the initial conditions were read in, the *Matrix Combiner-Solver* after each improvement cycle, and the *Propagator* at the epoch of the next fit span. The following diagrams give the CELEST data processing flow for the long-arc and short-arc modes, respectively, for a low-altitude satellite being tracked by multiple ground stations:

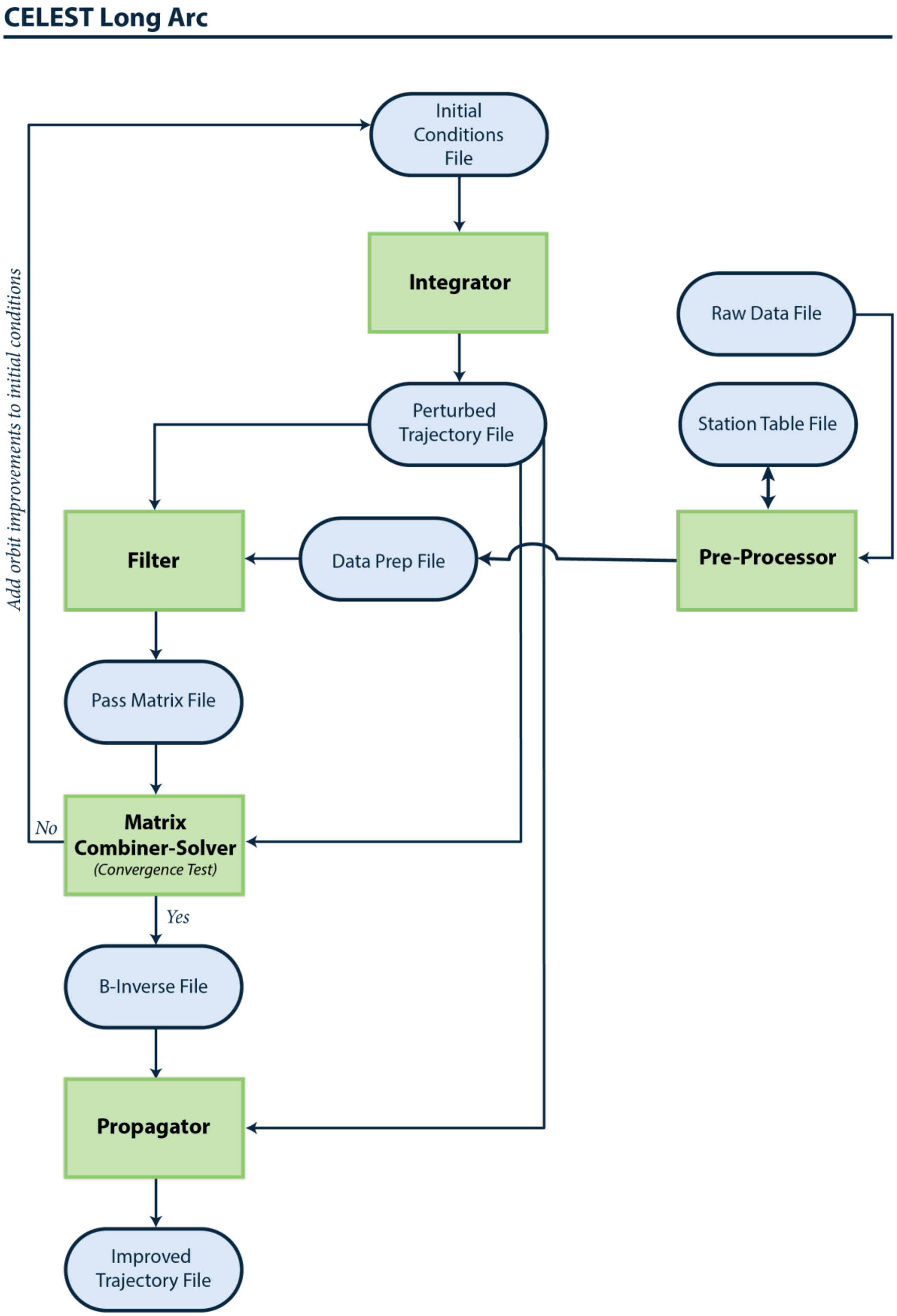

Figure 2: CELEST Long Arc

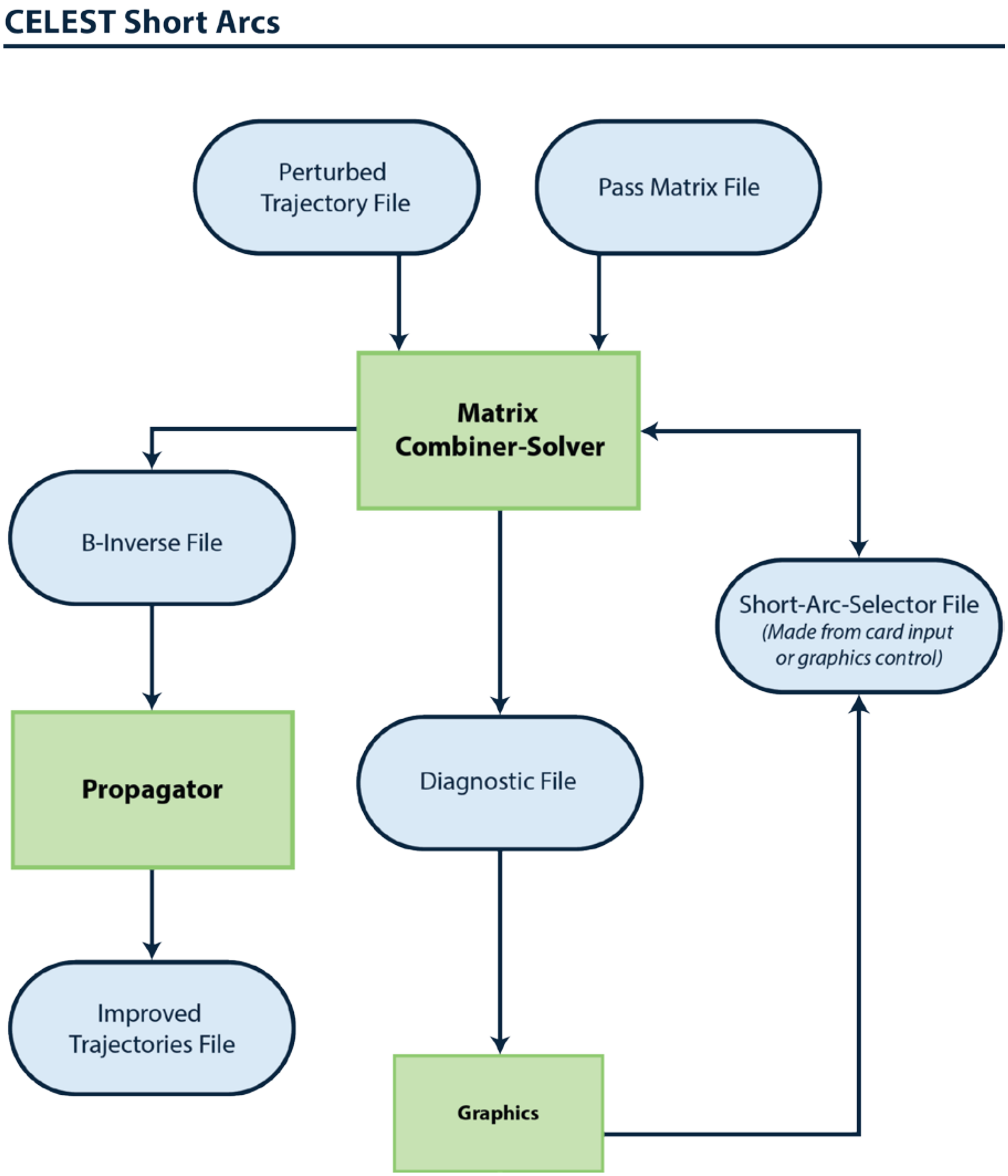

Figure 3: CELEST Short Arcs

The *Integrator* was a 10th-order, Adams-type predictor/corrector with an iterative start routine and used backward differences. It included the capability of integrating backward in time to provide addition trajectory timelines at the beginning of an arc to accommodate the eight-point Lagrangian interpolation scheme. The partial derivatives of position and velocity—with respect to epoch osculating orbital elements or epoch position and velocity—were also derived by integrating the variational equations. Two sets of six osculating orbital elements at epoch were possible. The first set was the elements that are determinate at zero eccentricity; the second set was the classical elements. The *Integrator* also used a technique for integrating variational equations for canonical drag and thrust parameters. The resulting partial derivatives were used to derive the partial derivatives needed for time-segmented drag parameters and a specific thrust profile in the *Matrix Combiner-Solver* section. The initial reference frame used for integration was an inertial frame defined by the mean equator and equinox of B1950.0. Rotation of the gravity field accelerations from Earth-fixed to inertial did not use UT1-UTC initially.

The following accelerations were modelled:

1. Earth gravitational
2. Sun and Moon gravitational
3. Solar and lunar solid-Earth tidal distortions of the gravitational field
4. Atmospheric drag assuming a spherical satellite with a given mass and cross-sectional area, drag coefficient, and a simple atmospheric density model
5. Solar radiation pressure assuming a spherical satellite with a given mass and cross-sectional area, a simple shadow model, and a scale factor
6. One or more vehicle thrusts in the radial, velocity, and cross-track (RVC) or RAC body-fixed frame if needed.

The Earth gravitational model included zonal and tesseral spherical harmonics up to an input degree and order. Partial derivatives for up to 32 gravity coefficient parameters could be integrated so that these could be estimated along with the arc orbit parameters. Sun and Moon positions were initially available in the mean inertial system of B1950.0 time-tagged with Ephemeris Time. A shape factor was used to adjust the solar radiation pressure force when the satellite was in Earth’s penumbra and umbra. Both a simple exponential and a modified Jacchia-Bass atmospheric density model were available to account for the atmospheric drag on low-altitude satellites. This second model required inputs of daily solar flux and geomagnetic index data.

The reference epoch of the basic inertial system used in CELEST was either B1950.0 or zero seconds of the day of the trajectory epoch. The transformation between the inertial Cartesian and Earth-fixed Cartesian frames, using precession, nutation, and Earth rotation was based on the formulas from the 1961 *Explanatory Supplement to the Astronomical Ephemeris and the America Ephemeris and Nautical Almanac.* This was the same transformation as used in ASTRO. Linear interpolation within the day was used for the precession matrix, and the nutation matrix was computed at the time of interest as was the longitude of the Greenwich Meridian from the true vernal equinox. The Earth-orientation matrix-before solution was based on predicted values for the pole coordinates and UT1-UTC; the after-solution matrix included the effects of estimating Earth orientation. The predicted values for the pole coordinates were based on fitting a constant and a Chandler period of 420 days to each coordinate using the most recent 200 days of Transit-based estimates and predicting seven days forward. UT1-UTC was also predicted for seven days using the most recent three-week USNO estimates of UT1-UTC.

CELEST could initially process both Doppler frequency observations and integrated Doppler observations treated as range differences, all time-tagged using UTC. The *Pre-Processor* converted the raw data into Doppler frequency or range difference observations, performed preliminary editing by deleting garbled data records and tagging questionable data, applied an ionospheric refraction correction if needed, computed and applied observation time tag corrections, stored average time tag corrections for each station on a daily basis, and output an unfiltered Time-Corrected Observation File. CELEST could also process the range observation data type, but such data were preprocessed outside of CELEST and input using the common

Time-Corrected Observation File format. CELEST also accepted inertial positions and velocities as observations.

The *Filter* (not really a filter in either the Kalman filter or low-pass filter sense) read the Time-Corrected Observation File and the Perturbed Trajectory File and formed the normal equations for each pass, edited the data in each pass, and determined best estimates of each observation's standard error and iterated this procedure until convergence. It then output a Pass Matrix File based on the good observations and an optional Observation File consisting of the good observations and their standard errors. Minimum elevation angle tests were applied to each individual observation and to the elevation at the TCA of the pass. Corrections were made for transmission time (data were either time-tagged at time of emission or time of reception) and tropospheric refraction using the Hopfield model. The fit used in each iteration solved for the most well-determined parameters from the tropospheric refraction scale parameter, frequency bias, frequency drift, and the six position and velocity parameters resolved into a local frame at the TCA of the pass. This local frame was based on the slant range vector from the station to the satellite, the velocity vector, and the cross-product of these two vectors. The adjusted residuals from this fit were used to edit the data and determine a sigma multiplier for the previous iteration's sigmas. Each canonical pass matrix output from the *Filter* always contained a bias parameter section that included equations for three Earth-fixed station coordinates, a refraction scale parameter, frequency bias, and frequency drift.

The *Matrix Combiner-Solver* generated the arc normal equations using the pass normal equations from *Filter*, solved the equations, and computed the associated diagnostic information. Options existed to delete data by station number and pass number. This overlay read the Pass Matrix File and the Perturbed Trajectory File. Forming the arc normal equations involved expanding the pass matrices from *Filter* to include parameters not already present and possibly updating the pass matrices to reference a different epoch. The expansion to include parameters not already present pertained to solving for time-segmented drag coefficients (up to 16), for multiple possible thrusts during the arc fit span (up to 4), for Earth orientation and for possible gravity field model coefficients. The two coordinates of the pole and the UT1-UTC rate could be estimated. After referencing the matrices to the proper epoch and including the additional parameters, the bias parameter portion of each pass matrix was augmented with *a priori* sigmas and was eliminated; back-substitution equations were saved. The pass matrices were added together making sure any portions related to solving for station coordinates were handled properly. If station coordinate parameters were present, they were also eliminated from the normal equations and additional back-substitution equations were saved. The resulting arc matrix was then inverted to obtain all satellite-related parameter solutions. Station coordinates (if present) and pass bias parameter solutions were then computed using saved back-substitution equations.

Once the initial arc solution was obtained, a "navigation solution" for each pass was performed. These navigation solutions gave the station movement that minimized the residuals of an individual pass while keeping the orbit fixed. Since the station coordinates were well-known, the resulting movement was an indication of the ephemeris error. The pass matrices were adjusted to reference the updated trajectory and the station bias section was then rotated into the local frame based on the slant range vector from the station to the satellite, the velocity vector, and the cross-product of these two vectors. The navigation solution was then done using just the slant-range (Radial) and velocity (Tangential) components along with the other bias parameters.

The magnitudes of the individual pass Radial and Tangential navigations were tested against absolute values and those passes failing were tagged. Separate straight line fits to the untagged pass Radial and Tangential navigations were then computed, and each navigation residual (including those for passes that did not enter into the previous arc solution) was compared against an input multiple of the RMS residuals to determine which passes were to be tagged for this iteration. The arc equations were adjusted based on these navigation tests and the solution repeated. This procedure was iterated until either a maximum number of iterations were reached or the same passes were tagged on two successive iterations. The resulting solution obtained after this cross-pass filtering was the solution for this cycle, where a cycle was based on reintegrating the reference trajectory. Various signal-to-noise quantities and an expected percent change in variance for the arc were computed and these were used to determine if recycling was needed.

The *Short-Arc-Selector* determined the fit spans to use for each revolution of a low-altitude satellite and the proper drag segmentation and saved this information to a file. In this mode, it was assumed that the recycling done during the long-arc convergence resulted in no linearization issues so the last generated set of pass matrices could be used in one cycle. No cross-pass filtering was done in Short-Arc Mode.

The *Propagator* time-updated the orbit improvements using the partial derivatives from the Perturbed Trajectory File with additional manipulation to accommodate drag segments and thrusts, then added them to the reference values at each trajectory timeline. The improved values were output to the Improved Trajectory File in both the inertial and Earth-fixed reference frames. The *Propagator* also propagated the orbit covariance matrix and scaled it, if required, to the desired times in both the inertial and Earth-fixed reference frames. The Earth-fixed position, velocity, and position covariance were output at the trajectory interval; and the inertial position, velocity, and covariance were output at a specified multiple of the trajectory interval. Additional output of the position uncertainties in the radial, tangential, and out-of-plane directions were provided for diagnostic purposes.

CELEST was originally implemented on the CDC 6700 mainframe computer, which had 60-bit, single-precision words (corresponding to 14 decimal digits), two high-speed central processors with a 32K central memory with an access time of around 100 nanoseconds, 10 peripheral processors to handle inputs and outputs, system and user-specific disk packs for storage, seven-track tape drives, and a display console all operating under the SCOPE operating system. It also included a punched card reader, a punched card punch, and printers. CELEST was easily ported to the CDC Cyber 170-865 system in late 1984 and eventually to the CDC Cyber 170-875 system and to the final CDC 995 system. The CELEST computer program originally (in October 1976) occupied 130 octal units of memory, was structured as nine major overlays, was written in Fortran IV, and was file-oriented. This was prior to implementing the two sets of changes described next.

Satellite-to-Satellite Tracking (SST)

In support of processing satellite-to-satellite tracking data in CELEST, a data simulator was developed to generate four data types: one-way range and range difference between a low-altitude and several higher-altitude satellites, and two-way elapsed time for ranging and elapsed time for accumulating a given number of Doppler counts involving geostationary satellites. This software was used to simulate data for prelaunch studies for the NAVPAC system and to check out all capabilities of the multisatellite version of CELEST. The two-way observations were required to allow CELEST to process tracking of a satellite via the experimental geostationary Advanced Technology Satellite (ATS)-F used by NASA.

NAVPAC was a satellite-borne data collection system developed for the DMA by the JHU APL. It consisted of a receiver/data system capable of simultaneously tracking up to three NAVSATs (another name for the Transit satellites) and recording integrated Doppler, first-order ionospheric refraction, and timing information, and a miniature electrostatic accelerometer (MESA) capable of measuring accelerations due to atmospheric drag, winds, solar radiation pressure, and orbit adjust thrusts. The MESA units were built by Bell Aerospace[3] under contract to the Air Force Geophysics Laboratory (AFGL). The NAVPAC units contained magnetic core memory for storing data temporarily until it was written to analog tape on-board the host vehicle (HV). (Satellites that carry receivers for tracking other satellites for orbit determination purposes are referred to as HVs in this report.) The NAVPAC program was developed to improve the low-altitude host satellite orbit accuracy and to improve time calibration of events on the satellite. The NAVPAC system was included on-board six Doppler Beacon satellites launched starting in 1977 with the last mission ending in 1984. The NAVPAC receivers counted the Doppler frequency shift and the ionospheric refraction effects over 30-second intervals. The reception times of the two-minute time marks broadcast by the Transit satellites were also recorded to convert observation time tags to calibrated UTC times in the preprocessing software. The satellite tracking data were used operationally along with the tracking data from the TRANET and SMTP networks for orbit determination for these satellites using CELEST. The MESA accelerations were used for atmospheric density determination by the AFGL and experimentally in CELEST for orbit determination.

All CELEST sections were modified to accommodate up to eight satellites simultaneously—the host satellite and up to seven NAVSATs. The orbit *Integrator* was expanded to integrate up to eight trajectories of the same type in one run done sequentially. This capability was used for simulation studies only. In production, all NAVSAT trajectories required for NAVPAC data preprocessing and CELEST processing were determined independently by running CELEST in the single-satellite mode using station tracking data. For processing the two-way tracking data collected through the ATS-F satellite, its orbit was obtained from NASA.

Two modifications were made to CELEST in support of NAVPAC processing that involved the ground tracking of the host satellite and the NAVSATs. The first modification was made because the transmitting antenna was displaced from each satellite's center of mass. Prior to this change, CELEST computed orbits for a satellite's transmitting antenna and not its center of mass. The second modification was made to use temperature and pressure values as functions of station height as input to the modified Hopfield tropospheric refraction correction model whenever measured weather data were not available.

NAVPAC SST data were processed using basically the same procedures as the ground tracking data but modified to account for the fact that the data were collected by an orbiting satellite instead of a ground station. A TCA was computed for each pass along with the associated rotation matrix for converting from the inertial reference frame to the navigation reference frame at this time.

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[3] Textron, Inc.® purchased Bell Aerospace in 1960.

For each observation in a pass:

1. an SST observability test was done to edit out observations that had passed through the troposphere,
2. the time transmission correction was applied at the transmitter since the data were time-tagged with UTC receive time,
3. the NAVSAT's inertial position was adjusted because NAVSAT trajectories were computed using NWL-11Z station coordinates while the host satellite station tracking data were processed using WGS 72 station coordinates,
4. the antenna offsets for both the transmitting and receiving satellites were accounted for in generating the computed observation, and
5. a residual and its associated partial derivatives (including partials for the NAVSAT parameters) were computed.

After processing all the observations in a pass, the pass normal equations were formed and the standard data editing and weight determination iterations were done.

The solution and diagnostic section of CELEST was modified to process the NAVPAC SST data separately or simultaneously with station tracking data for the host satellite. It could also accommodate parameters for up to seven NAVSATs along with the host satellite parameters. The arc normal equations were first formed using the NAVPAC SST and the ground-tracking pass matrices. Two modifications were implemented to improve the long-arc fit diagnostic capabilities. The first was an option to compute navigations before fit without doing cross-pass filtering. The second was an option to cross-pass filter based on ratios of navigations to their estimated uncertainties instead of just navigations. To combine the SST pass matrices, they were adjusted to reference the fit epoch and expanded to accommodate the drag segmentation and any thrusts present. The frequency bias parameter was then formally eliminated from each pass, and all passes for a given NAVSAT were summed. The ground-tracking arc normal equations were then combined with the NAVPAC SST arc normal equations accounting for the fact that NAVSAT parameters were present for several satellites. *A priori* information was then introduced into the normal equations, and the equations were inverted and the arc parameters solutions computed. Signal-to-noise quantities were then computed along with the expected percent change in variance. Navigations were computed for each pass, and the cross-pass filtering was extended to include the SST data and the solution was iterated until convergence. If needed, a long-arc fit could be recycled for the HV by integrating a new Perturbed Trajectory based on the previous cycle's solution. CELEST's short-arc mode was run after the long-arc solution converged.

A unique multiple-velocity pass-matrix expansion technique was implemented in CELEST for experimental host satellite processing. The technique allowed a simultaneous solution for epoch position and velocity and additional small velocity increments at equally spaced times along a host satellite trajectory. The velocity increments were solved for in the RAC reference frame at each time. This expansion could be used for long arcs as well as short arcs. There was no reintegration possible after a multiple-velocity fit; only propagated trajectories after fit could be computed. This meant that a converged orbit using standard techniques needed to be obtained before this expanded solution was performed.

The *Propagator* section of CELEST was also modified to accommodate NAVPAC processing. This section still operated in a single satellite mode so only the host satellite solution parameters and its covariance matrix were used. However, the following changes were made:

1. The covariant ephemeris was changed to include the Earth-fixed velocity vector and a full 6x6 Earth-fixed covariance matrix.
2. An option was included to apply an NWL-11Z-to-WGS 72 rotation matrix to the propagated inertial positions and velocities at each trajectory timeline. This was required if NAVPAC orbits were carried out using NWL-11Z coordinates. In this case, the rotation would not have been applied to NAVSAT trajectories when filtering SST data.
3. An option to output the trajectory of a reference location on the host satellite instead of the center-of-mass location was included.
4. The NAVPAC SST data fits required a special form of NAVSAT trajectory called a Hybrid Trajectory. A Hybrid Trajectory was identical to the original Perturbed Trajectory except the positions were updated to reflect the results of an orbit fit; the partial derivatives remained unchanged. An option was added to generate this type of trajectory for NAVSATs.
5. The propagation section was modified to output a Propagated Trajectory and covariance matrix when the multiple-velocity expansion was used in the solution section.

The NAVPAC accelerometer data were only used experimentally in CELEST for host satellite orbit determination. Average RAC accelerations over 2.045-second intervals based on low-pass filtered instantaneous accelerations were measured. The data were preprocessed to obtain input for plotting programs and the *Low-Pass Filter* program. The preprocessing included time-tagging the data, converting it to the appropriate units, applying known corrections, and editing it to ensure there were continuous records and no wild points. The *Low-Pass Filter* program output accelerations every 30 seconds for input into the CELEST *Integrator*. These accelerations replaced the atmospheric drag, solar radiation pressure, and orbit-adjust thrust accelerations normally computed from models in integrating the equations of motion for the host satellite. Variational equations were also integrated to improve scale factors and biases associated with the accelerometer data. By assuming separate biases but a common scale factor for the three axes, a one-to-one correspondence between scale factor and drag coefficient and between bias and continuous thrust resulted. Therefore, only the *Integrator* had to be modified to accommodate the accelerometer data in CELEST, and the scale factors could be segmented in both the long-arc and short-arc fits like drag coefficients.

A sequential processor for low-altitude orbit determination consisting of a Kalman filter followed by an RTS Smoother was formulated in 1977 for processing both station and NAVPAC observations for the Doppler Beacon satellites with the possible addition of accelerometer data, but it was never implemented.

GPS [Global Positioning System]

The GPS Joint Program Office was formed in 1973 with the Air Force as the lead service and with Deputy Program Managers from the three services and the DMA. The DMA decided it wanted to be part of GPS and to eventually replace Transit with GPS for all geodetic quality positioning work. The planned NRL TIMATION III and IV satellites were renamed Navigation Technology Satellite (NTS)-1 and NTS-2, respectively, and were pathfinder spacecraft for the GPS Block I satellites. The NRL was the agency designated as responsible for all GPS atomic clock technology development and testing.

A GPS version of CELEST was developed in parallel with the development of the NAVPAC (satellite-to-satellite) version of CELEST to aid the transition to GPS. A preprocessor required to convert raw data received from the GPS Master Control Station at Vandenberg Air Force Base (VAFB) was developed for the Magnavox™ X-set receiver tracking data collected at each of the three remote stations in Guam, Hawaii, and Alaska, and the one at VAFB. A solar radiation pressure model specific to the NTS-2 satellite was implemented. The GPS Block I satellite solar radiation pressure model ROCK4, developed by the spacecraft manufacturer Rockwell International Corporation[4], was also implemented. A y-bias acceleration parameter was not introduced into the force model until 1980. Both a radiation pressure scale parameter and the y-bias acceleration could be estimated. The eclipsing model was enhanced to include the effects of the lunar penumbra and umbra. The *Integrator* was also modified to do smoothing at the penumbra/umbra entrances/exits. The y-bias acceleration was eclipsed also. An option to estimate three RAC radiation pressure scale parameters was added. A body-fixed XYZ thrust model was added. Station coordinate displacements due to solid-Earth tides were included for the first time.

To prepare for Air Force implementation of the GPS Operational Control Segment, CELEST was modified in 1983 to include an option to use the mean equator and equinox of J2000 (Julian epoch of 2000) for its inertial reference frame. This modification involved implementing the International Astronomical Union (IAU) 1976 precession model, the IAU 1980 nutation model, and the 1982 definition of UT1. This change was associated with the generation of the *Project MERIT Standards,* which eventually evolved into the International Earth Rotation and Reference Systems Service (IERS) Conventions. Also, Earth orientation (x, y, and UT1-UTC) was first included in the transformation of the gravity field accelerations from Earth-fixed to the inertial reference frame.

The GPS range and range difference data types were incorporated. CELEST was modified to include a third clock term—frequency drift or aging—and to allow clock parameters to be treated as arc parameters instead of pass parameters (arc clock parameters could be segmented in time). The periodic relativistic correction to pseudorange and range difference data was included. In 1977, the NSWC merged the CELEST SST and GPS versions into a single version.

In 1978, the NSWC developed the initial methodology for predicting Earth orientation for the GPS program using BIH estimates of polar motion and UT1-UTC. The x pole prediction model consisted of a constant and Chandler (435-day) and annual periods fitted using least squares to 435 days of data of past estimates. The y pole prediction model included an additional semiannual term and also used 435 days of past data. The UT1-UTC prediction model used a least-squares fit to one year of data to determine a straight line plus coefficients of a trigonometric series with periods of 91, 121, 182, and 365 days. CELEST was modified to accommodate this new form of Earth-orientation predictions.

A DARCUS II program, similar to the DARCUS program based on ASTRO, was developed based on CELEST pass matrices and was used for determining coordinates of GPS stations based on multiple arcs. Both satellite and station clock models could be treated as arc parameters with up to three parameters possible—range, range drift, and aging biases—in DARCUS. It combined pass matrices from several arcs after bias elimination, included appropriate *a priori* uncertainties, and solved for station coordinates.

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[4] North American Rockwell Corporation became Rockwell International in 1973 and, in 1996, sold its defense electronics and aerospace businesses to the Boeing Company™.

NSOP [New System of Programs] for GPS Only

NSOP was a system of interactive programs developed and used to provide a rapid orbit determination capability for GPS satellites. CELEST processed data pass by pass, since it was previously and primarily used for low-altitude satellite orbit determination. When the first GPS satellites were launched starting in 1978, CELEST computed their weekly orbit fits and generated 18-day predictions for use by the GPS Control Segment at VAFB. Since a rapid turnaround in processing was required, using CELEST for multiple satellites became very time consuming. NSOP shortened the time required to complete orbit fits and predictions for all GPS satellites, and became operational in 1981.

Because GPS satellites orbit at a high altitude, the pass matrix approach used in CELEST was not ideal. Therefore, NSOP used point-by-point processing but still operated on one satellite at a time. NSOP estimated the orbital initial conditions, force model parameters (radiation pressure scale and y-bias acceleration), satellite and station clocks assuming a master clock (station clocks could include a range bias, frequency bias, and frequency drift and satellite clocks could include these three parameters plus an orbit period sinusoid) and, on option, station positions and Earth orientation (pole coordinates and UT1-UTC rate) using a weighted least-squares algorithm. Pass-structured observation files had to be merged into a single time sequential observation file that contained station positions and, for each observation, the observation time, observation value, observation standard error, and weather data. The observations for a given satellite over a given time span were extracted, and residuals and partial derivatives were computed using a Perturbed Trajectory File generated by the CELEST *Integrator*.

The system could process both range and two types of range difference observations. Range differences could either be based on differencing successive pseudorange observations or obtained directly by counting Doppler cycles. Only observations collected above an input minimum elevation angle were used, and corrections for satellite antenna offset from the center of mass (z-direction only), time transmission effects (could process observations time-tagged with time of emission or time of reception), tropospheric refraction effects, and periodic relativity effects were applied. Individual observations and/or whole passes could be tagged and not used in the solution. The CELEST-generated Perturbed Trajectory File contained the 3x3 transformation matrix to go from the inertial to Earth-fixed reference frames except for the contributions from Earth-orientation parameters. Predicted Earth-orientation parameters were input in the form of a coefficient set as defined above.

Using the residuals and partial derivatives for all untagged observations, the weighted least-squares arc normal equations were formed and solved. Residuals after fit were then computed and additional data tagging could be done interactively and the solution repeated. The final orbit solution was then propagated and a new Perturbed Trajectory File was generated starting with the improved initial conditions from the fit.

SAMSAP (SATRACK Multiple Satellite Processor)

SAMSAP (also called the Operational Program [OPROG]) was used in conjunction with CELEST to provide a special GPS product to JHU APL for its Satellite Tracking (SATRACK) GPS tracking system. The JHU APL developed the SATRACK system and a post-flight processor to determine the accuracy of the Navy’s fleet ballistic missile systems using GPS. This system required GPS translators integrated into each missile for tracking. The SAMSAP software generated Tracked Ephemeris Data (TED) tapes for delivery to the JHU APL.

SAMSAP was a system of programs that computed a multisatellite solution for GPS satellites using single-satellite Pass Matrix Files based on both range and range difference data types and Perturbed Trajectory Files from the single-satellite CELEST program. The multisatellite solution included solutions for both satellite and station clocks (time offset, frequency offset, and frequency drift) and possibly four Earth-orientation parameters, up to 20 gravity parameters, and station positions. To form the solution normal equations, CELEST pass matrices were tested to determine if they should be included. Accepted passes were then expanded to include the possible bias parameters, the expanded matrices were summed into the appropriate sections of the full solution matrix, and bias parameters were eliminated. A station was selected to treat its clock as the master clock. The solution and its full covariance matrix were then determined and diagnostic information was computed. The orbit for each satellite and the full covariance matrix were then propagated as required for generating a TED tape.

TERRA

TERRA (not an acronym) replaced GEO for all general geodetic solutions involving solving for gravity field model harmonics in parallel with CELEST-T, a special version of CELEST used just for these general geodetic solutions. The force model included point mass terms in addition to the usual harmonics in the model of Earth’s gravitational potential. The purpose of these terms was to reflect isolated features in Earth’s potential field. This was important because TERRA could process both surface anomaly data and surface geoid height data. The TERRA equations of motion also accounted for atmospheric drag, solar radiation pressure, the albedo of Earth using a simple model, and the effects of both solar and lunar tides of the solid Earth, ocean, and atmosphere. TERRA included both a *Surface* program for forming normal equations for surface and astrogeodetic data and a *Satellite* program for forming normal equations for satellite data. A separate *Matrix Combiner/Solver* overlay was also part of TERRA. TERRA was originally developed on the CDC 6700 system and was converted to the CDC Cyber 170-865 and completed in late 1985.

Satellite Programs and Analyses Supported by CELEST, NSOP, SAMSAP, and TERRA

For most of the satellite systems discussed in the following subsections, the NSWC conducted simulated orbit determination studies prior to launch to establish the expected orbit error levels as a function of the size of the gravity field model used and whether resonance coefficients should or should not be included in the model. Also studied was the best combination of integration interval/write interval and interpolation order needed to represent the trajectory with minimal loss of precision.

Transit (Navy Navigation Satellite System, NAVSATs)

The operational orbit determination conducted for these satellites using ASTRO was transitioned to CELEST in the early 1970s. Precise satellite ephemerides were provided to the DMA and allied mapping agencies in the United Kingdom, Canada, Belgium, France, and Australia for geodetic positioning applications. The total number of Transit satellites launched over the years was 46, although there were a few failures. Seven or eight satellites were always operational with several on-orbit spares. Transit satellites were used to determine precise coordinates of mobile tracking stations. Two-day fits were done for the orbits and accuracies improved to about the 3 m level. With continual CELEST modeling improvements, the absolute positioning accuracy reached the one meter level around 1980. Un-modeled higher order ionospheric refraction effects limited the accuracies attainable using the Transit satellites.

The Transit satellite named Triad was launched in September 1972 into a 788 km altitude orbit with an eccentricity of .006. This satellite included a three-axis Disturbance Compensation System (DISCOS) to account for all atmospheric drag and radiation pressure surface forces acting on the satellite. This system operated for about one year. This experimental satellite resulted in the single-axis compensation system flown on all of the then-future Transit Nova satellites.

In April 1975, the operational Transit processing using CELEST was transitioned to the DMA's Topographic Center (DMATC) in Bethesda, MD. The NSWC continually monitored the center's efforts and provided software upgrades and troubleshooting assistance as required. By the end of 1977, the polar coordinates computed using the Doppler observations were accurate to 40 cm for the two-day solutions and 20 cm for the five-day means. In 1980, Earth's semi-major axis, based on Doppler observations of Transit satellites, was estimated to be 6378136.0 with an uncertainty of 0.1 m. This semi-major axis value was never used in production and was only one of many estimates available at the time.

From 1979–1982, Transit precise orbits were computed using Doppler observations from 19 TRANET stations and the four OPNET stations. The original TRANET receiving systems were replaced with TRANET II equipment during this time period. Positioning results using the precise orbits were eventually reported to be below the one meter level. The Doppler reference frame was determined to be biased relative to other geodetic reference frames.

Transit satellite-derived positions for several sites over the years 1973–1983 were used to estimate plate motion for 25 sites spread over eight tectonic plates and compared against their geological model rates. These results for determining the rates of change of station position were inconclusive with height variations highly influenced by uncompensated higher order ionospheric effects.

The next generation Transit satellite, Nova, contained a single-axis DISCOS, based on the Triad satellite experiment discussed earlier, which continually corrected for any non-conservative forces affecting the satellite's along-track motion. The first satellite with this capability was launched in May 1981 followed by two more in 1984 and 1988.

Doppler-derived WGS 84 station coordinates for the TRANET, SMTP, and OPNET stations became available in September 1986.

SOLRAD [Solar Radiation]

The NWL's role in the NRL's SOLRAD program was to conduct long-term orbit stability, launch scenario, and station keeping analyses; and orbit computation simulations. This work was done in support of two SOLRAD-HI satellites, which were launched together in March 1976 into a 26° inclination orbit at an orbital radius of over 18 Earth radii. No actual orbit determination was done for these satellites.

STARLETTE [Satellite de Taille Adaptée avec Réflecteurs Laser pour les Etudes de la Terre]

France's STARLETTE satellite was launched in June 1975 into a 50° inclination orbit at an altitude of 800 km. The satellite was a sphere covered with laser retroreflectors used for geodesy purposes. The NSWC's interest in this satellite was for use in gravity field model determination.

LAGEOS [Laser Geodynamics Satellite]

The LAGEOS was launched in May 1976 into a 110° inclination orbit at an altitude of 5900 km. This satellite was also a sphere covered with laser retroreflectors used for geodesy purposes. The NSWC's interest in this satellite was again for use in gravity field model determination.

HILAT [High-latitude Research Satellite]

The HILAT satellite was launched in June 1983 to study the structures in the high-latitude ionosphere that produces radio wave scintillation effects. It was launched into an 82° inclination orbit at an altitude of 800 km. It broadcast on four coherent frequencies from 138–447 MHz for its ionospheric mission. The NSWC's interest in this satellite was again for use in gravity field model determination.

Doppler Beacon (DB)

Precise satellite ephemerides were initially provided for these low-altitude satellites to both the DMA's Aerospace Center (DMAAC) in St. Louis, MO and DMATC. These satellites broadcast on the 324/162 MHz pair of frequencies for tracking by TRANET and the SMTP network. The SMTP was a collection of over 40 portable receivers the DMA deployed worldwide to support these missions. The NSWC had previously conducted a study to predict the low-altitude satellite orbit accuracy obtainable vs. the number of SMTP stations deployed. These DB missions involved the now declassified Keyhole (KH)-9—also known as HEXAGON program—which had a first launch in June 1971. A Mapping Camera System (MCS) and an associated Doppler Beacon transmitter were added on the fifth mission, launched in March 1973. Typical orbits for these satellites were Sun-synchronous orbits at 96.4° inclination with altitudes ranging from 150 to 270 km and with orbital perigee at about 45° north latitude. The DMA used the photography from these missions to develop maps and to provide strategic target locations in the WGS 72 reference frame.

Thrusts were required for these satellites approximately every three days to keep atmospheric drag from causing them to re-enter. Twelve missions included the MCS, which were followed by three additional missions that used photography from the stereo panoramic cameras augmented with stellar sensors for the DMA's mapping and target location missions. The Air Force determined the operational orbits for these satellites using Space-Ground Link System tracking data from its six worldwide stations. The initial MCS mission lasted 42 days; the last two missions lasted around 118 days each.

To determine the orbits for these satellites using CELEST, long-arc fits were computed daily followed by overlapping three-hour (two-revolution) short-arc fits for each revolution. For the short arcs, the six orbital elements at epoch and four drag coefficients with *a priori* sigmas of .05 each were estimated along with a frequency bias and tropospheric refraction parameter per pass. Thrusts were estimated in the long-arc fits as required. Using the TRANET and SMTP tracking data only, the orbits were determined using CELEST to an approximate accuracy of 20 (6.1), 60 (18.3), and 40 (12.2) feet (meters) one sigma in the radial, along-track, and cross-track directions, respectively, in the WGS 72 reference frame. The version of CELEST used for this DB satellite processing, based on just station tracking data, was ported in 1974 to the DMAAC Univac™ 1108 mainframe computer it was first used operationally in 1975.

NSWC personnel conducted studies to determine the expected improvement in the orbit estimation accuracy for these satellites by adding the SST data type based on Transit satellites. The resulting NAVPAC system was developed to provide these additional data for orbit determination and to improve modeling atmospheric density at low altitudes. NAVPAC also included a three-axis accelerometer system for measuring the non-conservative (atmospheric drag, wind, radiation pressure, and thrusts for both attitude control and orbit maintenance) forces acting on the satellite. The NAVPAC data were downloaded daily from the on-board analog tape recorder, and the NWL received half-inch-wide analog tapes that contained a 128 Kbs bi-phase level PCM [pulse-code modulation] bit stream recorded in FM (900 KHz). The NWL developed a system to read these tapes, convert the data, and write nine-track tapes for use on the CDC 6700 mainframe.

Beginning in June 1977, six missions included the NAVPAC system. The last NAVPAC system was launched in June 1983 and operations ended in March 1984. Using the TRANET and SMTP tracking data along with the NAVPAC tracking data, the orbits were determined using CELEST in its long-arc/short-arcs mode to an approximate accuracy of 20 (6.1), 30 (9.1), and 30 (9.1) feet (meters) one sigma in the radial, along-track, and cross-track directions, respectively. One reason the accelerometer data were never used operationally was due to an initial hardware problem resulting from a proof-mass housing design deficiency: the instrument measured a significant transient acceleration every time the HV crossed the night-to-day boundary. Eventually, it was determined that an asymmetry in the internal venting associated with the proof mass caused this effect. However, the AFGL did use the data from the later missions for atmospheric density modeling after this problem was fixed. In July 1979, an AFGL representative came to the NWL and monitored the accelerations being measured by the MESA unit operating prior to reentry for NASA’s Skylab space station and advised those trying to predict the exact reentry time.

The NAVPAC Preprocessor calibrated the time tags for the Doppler observations using the NAVSAT two-minute time marks. A byproduct of this calibration was the calibration of HV time marks to an accuracy of better than 35 microseconds. These time marks corresponded to exposure times for the photography collected by both the mapping camera and panoramic camera systems. This accuracy corresponded to less than 30 cm of satellite motion. The previously available time tags were truncated at the one millisecond level; thus, were biased on average by .5 milliseconds, corresponding to almost 4 m of satellite motion. It is believed that this demonstrated timing accuracy was the best achieved for satellite events prior to the flight of the first GPS receivers on satellites.

The 1983 NAVPAC mission (the 18th KH-9/HEXAGON mission) also included the first GPSPAC [GPS Package] to fly on these satellites. (A description of GPSPAC is given in the PREFER /GALAXY Section on page 34.) The tracking data from the first two NAVPAC missions were processed at the NSWC and transitioned to the DMAAC in 1979 for the third and subsequent missions. The NSWC received the daily analog tapes for the third mission. After that mission ended, the associated hardware and software systems were transferred to the DMAAC, and the NSWC provided software updates and troubleshooting for the last four missions. During the six NAVPAC missions there was only one minor hardware failure. The hardware used magnetic core memory for storing data. A single magnetic core memory unit got stuck and the NWL determined what value (1 or 0) should be used for that bit and modified the software to make this correction.

White Cloud

The orbits of this cluster of three satellites were designed so that a certain relative configuration could be maintained for several years. Studies were completed at the NSWC prior to the first launch to determine the size of the gravity field model, including resonance coefficients needed to obtain the required orbit determination and prediction accuracies. The first satellites were launched in April 1976 into an 1100 km circular orbit inclined at 63.5°, the critical inclination. After launch, large unpredicted orbital perturbations in the argument of perigee and eccentricity of the three satellites were observed. A study determined that the zonal harmonics of degrees five and seven were the cause of most of these perturbations. However, it was shown that the cluster configuration remained unaffected by these large orbital perturbations.

NTS-1

The NTS-1 (formerly TIMATION III) satellite was launched in July 1974 into an orbit with an eight-hour period (approximately a 13,000 km altitude) at an inclination of 125°. It transmitted at 1580 and 335 MHz. There were minimal un-modeled gravity effects at this altitude. The satellite operated using a Rubidium (Rb) clock and generated both side-tone and pseudorange noise (PRN) ranging signals. Doppler measurements were also collected. The NSWC-generated ephemeris provided to the NRL was based on the side-tone ranging observations. Fits of four to five days were done using CELEST. However, the satellite never stabilized in attitude so the tracking data were very sparse.

NTS-2

This satellite was launched in June 1977 and carried both cesium (Cs) and Rb clocks. The NSWC was involved in determining the transfer orbit after launch with CELEST so that a rocket burn could be made at apogee to circularize the orbit at a 12-hour period. After orbit circularization, several more thrusts were needed to get the satellite into its final orbit. The NSWC determined a new orbit after each thrust to provide the NRL with the information needed for each subsequent orbit adjustment. The NSWC continued to generate orbits for this satellite as needed in support of NRL clock and ranging tests. The PRN ranging system failed shortly after launch while the satellite was operating on a Cs clock.

Altimetry Satellites

The NSWC used the altimetry data associated with these satellites to derive Launch Region Gravity Models for fleet ballistic missile submarines consisting of gravity anomalies, geoid heights, and deflections of the vertical. These models were used for both submarine navigation and initial missile guidance. The tracking data for these satellites were also used for global gravity field modeling.

GEOS [Geodynamics Experimental Ocean Satellite]-C

GEOS-C was launched in April 1975 and operated until July 1979. This satellite operated a radar altimeter at an altitude of 840 km altitude and an inclination of 115°. GEOS-C contained multiple tracking systems—laser retroreflectors, a Doppler transmitter, a C-band transponder, and an S-band transponder for tracking through the ATS satellites. The NSWC conducted orbit determination experiments using two-way tracking data collected via the ATS-F satellite. Doppler observations of the GEOS-C satellite were used in two-revolution fits (approximately three hours) at the NSWC to determine the orbital radius of the satellite to an accuracy of 2 m using a satellite-specific gravity field model, NWL-1G6. Other longer orbit fits were done for this satellite for estimating the coordinates of Earth’s pole.

Seasat

Seasat was launched in June 1978 into an 800 km Sun-synchronous orbit inclined at 108°, and was operational for a little over 100 days. Seasat also operated a radar altimeter and a Doppler transmitter broadcasting on the 324/162 MHz frequency pair. The NSWC again computed orbits for the radar altimeter data reduction. The radial orbit accuracy obtained was 1.4 m and again was obtained using three-hour orbit fits.

A formulation for a sequential Kalman filter/RTS smoother orbit determination program was written in 1978 for the Seasat mission but never implemented. It would have used a Perturbed Trajectory File, a Pass Matrix File based on range difference data, and a Short-Arc Selector File from CELEST as inputs.

GEOSAT [Geodetic Satellite]

GEOSAT was launched in March 1985 into an 800 km altitude 108°-inclined orbit for an 18-month classified geodetic mission. It also operated a radar altimeter and had a Doppler transmitter broadcasting on the 324/162 MHz frequency pair. In November 1986, it began its Exact Repeat Mission (ERM) for oceanographic studies after being put into an orbit whose ground track repeated every 17 days. The ERM ended in January 1990. The radial orbit accuracy obtained was 75 cm.

GPS

Prior to the establishment of the GPS Program Office in 1973, the NWL conducted studies under NRL sponsorship on the TIMATION, 621B, and TIV (Two-in-View) programs. The TIMATION was the NRL’s proposal for a constellation of 27 satellites in three orbit planes in eight-hour period orbits at an inclination of 125° and planned to use atomic clocks. Remote tracking stations were to be located in Guam, Alaska, Samoa, and the Virgin islands. 621B was the Air Force’s proposal that advocated using one geostationary and four inclined (60° with eccentricity = .25) geosynchronous orbits for each of four regions around the world and PRN ranging. TIV was JHU APL’s proposal to launch more Transit satellites so that two were always in view at any location. This system, however, did not allow for real-time three-dimensional positioning. Both the TIMATION and TIV proposed constellations were studied by the NWL in terms of configuration stability and expected orbit determination and prediction accuracy along with its associated navigation accuracy. When the GPS program was established, the best features of the TIMATION and 621B programs were combined and the planned TIMATION satellites were renamed Navigation Technology satellites. After an initial GPS program agreement was reached among the NSWC, DMA, and GPS Joint Program Office, the NSWC conducted accuracy studies, developed software (including modifications to CELEST as described earlier), and conducted “end-around” tests with other agencies in preparation for the satellite launches. These tests reduced differences in computer programs from meters to centimeters.

A simulation study was done before the first GPS Block I satellites were launched using modified CELEST pass matrices and additional custom software so that up to six satellites tracked by five stations could be processed simultaneously with arc parameters for all satellite and station clocks using standard weighted-least squares. This was the first attempt to show the benefits of simultaneously processing multiple satellites. This idea was expanded upon and eventually implemented operationally into the SAMSAP software.

In February, May, October, and December 1978, the first four GPS satellites (Satellite Vehicle Number [SVN] 1–4) were launched into two orbit planes (two satellites in each plane) inclined at 63° so that they clustered once per day over the western United States enabling user equipment testing at the Army's Yuma (AZ) Proving Ground and on the west coast. With the first launch, the NSWC began weekly reference trajectory generation using CELEST by doing orbit fits based on 15-minute data with a selected clock as the master and predicted the orbit for 18 days. These predictions were provided to the Master Control Station at VAFB for use in its real-time Kalman filter. Magnetic tapes were shipped back and forth between VAFB and the NWL by transport airplanes. The computations were done in the WGS 72 reference frame and used range differences derived from successive smoothed pseudoranges collected at four stations in California (at VAFB), Guam, Hawaii, and Alaska. The Air Force stations tracked the Block I satellites using Magnavox 4-channel X-sets, which tracked the P [precision] code on L1 and L2. The initial prediction accuracies were 50–300 m/day. With the elimination of the satellite roll momentum dump thrusts in November 1979 (by dumping momentum magnetically), the prediction accuracies improved to 20–200 m/day. SVN 5 and SVN 6 were launched in February and April 1980, respectively, and SVN 2 failed in December 1980. The y-bias acceleration was introduced into the orbit computations in 1980 and resulted in prediction accuracies of 20–50 m/day. The weekly fitted part of each trajectory was distributed as the precise ephemeris. NSWC personnel participated in the Control Segment-sponsored Data Analysis Working Group (DAWG) meetings and gave many presentations on GPS prediction and precise ephemeris estimation work.

In 1981, the interactive orbit fitting software NSOP was implemented, and prediction accuracies were reduced to < 10 m/day. Eventually, predictions were conducted every other week and extended to 41 days in length. DMA Doppler Van data were first used experimentally in GPS ephemeris work in 1981. Each Doppler Van consisted of a receiver developed by Stanford Telecommunications, Inc. (STI)[5] and supporting hardware integrated by the NSWC consisting of a Cs frequency standard, time interval counters, a digital clock, a full-cycle counter, a microprocessor controller, a video display, a cassette recorder, and an L-band antenna. The outputs were recorded on cassette tapes. Doppler Vans were deployed to the Seychelles and Australia in April 1981. Orbit fits using data from the four operational GPS stations augmented with data from these two Doppler Vans were then were computed for the first time. An additional Doppler Van was deployed to Argentina in May 1983 and its data were added to the orbit fits. The Air Force also gave the DMA an X-set, which was operated in England and provided some useful tracking data.

IBM's Federal Systems Division took over operations of the General Dynamics®-developed Control Segment in 1982, establishing the Interim Control Segment (ICS). The IBM-developed Operational Control Segment (OCS), which was part of the Consolidated Space Operations Center at Falcon Air Force Station (AFS)[6] (east of Colorado Springs, CO), replaced the ICS in July 1985. The tracking stations were located at Falcon AFS (called Colorado Springs), Ascension, Diego Garcia, Kwajalein, and Hawaii. During OCS development, the NSWC

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[5] In 1996, Stanford Telecommunications, Inc. was purchased by a consortium of Intel, Alcatel, Flextronics, and ITT.

[6] In June 1988, Falcon Air Force Station was re-designated Falcon Air Force Base, and in June 1998, renamed Schriever Air Force Base.

participated in the Trajectory Standards Working Group in which GPS orbit integrators from Aerospace Corporation, IBM, and the NSWC were compared. The agreement reached between CELEST and TRACE (Aerospace Corporation's program) was less than 6 cm after 30 days (20 cm for an eclipsing trajectory), but both programs disagreed with IBM's integrator by about 70 cm (84 cm with solar radiation pressure). It was determined that IBM was using a 64-bit IBM mainframe computer and the NSWC and Aerospace Corporation were using 60-bit CDC mainframe computers; this was the main cause of the differences. Experiments were also conducted using the NSWC-developed *Multisatellite Filter/Smoother* (*MSF/S*) system based on CELEST (describe in the OMNIS section below) in 1984 and early 1985 and agreement with a filter developed by the Aerospace Corporation was better than one meter for both the orbit and clock estimates. All of these results were reported at various DAWG meetings. NSWC's orbit prediction role ended in mid-September 1985 when the ICS was decommissioned. By the end of October 1985, a total of 11 GPS Block I satellites had been launched, but at most seven were operational at any given time.

After the NSWC's prediction role in GPS ended, the NSOP processing continued without the predictions. At all times the fitted portion of each final orbit was considered the NSWC precise ephemeris for that satellite. These estimates were converted to the Earth-fixed reference frame and distributed to users. The NSOP was used to estimate the precise ephemerides for all operational GPS Block I satellites up until December 1985, when the CELEST-based MSF/S system was first used for production.

During the late 1970s and early 1980s, the NSWC was also involved in writing the specifications for and development and testing of the first two generations of geodetic quality GPS receivers built by Stanford Telecommunications Inc. (STI) and Texas Instruments (TI)®. The STI receiver development began in 1977, and the first receiver (STI-5007) was delivered to the NSWC in August 1978. The purposes of this program were to gain GPS experience, demonstrate potential for geodetic applications, and provide additional monitor stations. It was integrated into a Doppler Van system and tested locally. Field tests were then conducted in 1979 at the Yuma Proving Ground; Las Cruces, NM; Austin, TX; and at the USNO. An STI-5010 was received in August 1980 and integrated into a second Doppler Van and tested. Doppler Van 1 was shipped to the Seychelles and Doppler Van 2 was shipped to Australia in February 1981 and started providing data in April 1981. A second STI-5010 was received in late 1982, integrated into a third Doppler Van, and deployed to Argentina to provide data starting in May 1983. The Applied Research Laboratories at The University of Texas at Austin (ARL:UT) led the writing of the specifications for a field portable GPS geodetic receiver in early 1981, and the JHU APL completed a design study for the geodetic receiver in April1981. In September 1981, Texas Instruments was selected to develop the receiver. The first field tests of the resulting TI-4100 receiver were conducted in January 1984 with further testing throughout 1984 and early 1985. The NSWCDD-developed Doppler Van systems were retired in 1985 and replaced by ARL:UT-developed systems based on the TI-4100 receivers. This was the beginning of the NGA's official Monitor Station Network (MSN), which ARL:UT has maintained and enhanced over the years.

SATRACK

The CELEST/SAMSAP combination of programs was used to support the JHU APL SATRACK program for evaluating test firings of the Navy's fleet ballistic missiles. Tests of the program interfaces were conducted along with accuracy studies prior to the first test flight in the late 1970s. TED tapes for both Trident C4 Demonstration and Shakedown Operations (DASO) flights and Operational Test (OT) flights were provided to JHU APL under SATRACK I for use in its Post-flight Processor software used to reconstruct missile trajectories using translated GPS signals.

WGS 72-to-WGS 84 Transition

For many years prior to the first derivation of the WGS 84 gravity field and realization of the WGS 84 reference frame, the NSWC and DMA were using the NWL-10E Earth gravity field model and the NWL-9Z2 station coordinate set for Transit satellite computations. When the WGS 84 gravity field model for orbit determination was derived using the TERRA software, it had spherical harmonic coefficients up to degree and order 41 and was based on several data types: Doppler satellite tracking data for seven medium altitude satellites with various inclinations and perigee heights; satellite laser ranging data for two satellites; surface gravity data; oceanic geoid heights determined by satellite radar altimetry data; GPS tracking data; and "lumped coefficients." Medium altitude satellites with perigee heights between 700 and 1200 km were used because they were high enough to experience minimal atmospheric drag effects but low enough to be sensitive to the gravity field harmonics to be estimated. In 1992, NSWCDD reported on a study that used CELEST to compare orbits determined using the WGS 84 gravity field model versus orbits determined based on nine other gravity field models for four satellites: OSCAR-20, Nova-3, GEOSAT, and Seasat.

For the first WGS 84 reference frame realization, the NWL-9Z2 coordinates were geometrically transformed by applying +0.814 arcsec in longitude, -0.6 ppm in scale, and +4.5 m to the Z axis to get the starting coordinates. An iterative process of estimating orbits with CELEST and then station coordinates using the GEOCEIVER point positioning program was conducted. The adopted coordinates were consistent with the geometrically transformed NWL-9Z2 coordinates to within a meter in the scale and z-axis parameters and consistent in longitude. The z-axis differences had a periodic variation related to the seasons so the adopted coordinates were chosen to minimize this difference. The scale difference was attributed to uncompensated ionospheric refraction effects. The resulting determinations of the position of Earth's pole using Transit observations had no systematic differences relative to the BIH pole positions.

The permanent GPS tracking stations operating at that time and used for the precise ephemeris were surveyed and positioned in WGS 84 based on Transit tracking data collected at each site and the precise ephemerides for Transit satellites generated with this new WGS 84 realization.

PULSAR (1981–1983)

The PULSAR (not an acronym) software system was a prototype for processing tracking data in support of a planned new satellite program. The system was to receive raw Doppler tracking data from the TRANET and SMTP station networks and process it to obtain time-corrected point and pass edited data for use in separate orbit determination software along with other types of tracking data. The system also had to provide mean orbital elements to the tracking stations.

PREFER/GALAXY (1980–1986)

The Precision Recursive Estimator for Ephemeris Refinement (PREFER) program was developed by Business and Technological Systems, Inc. under contract to NSWC for use primarily on the GPSPAC project. Renamed GALAXY (not an acronym) by NSWC, PREFER was a linearized Kalman filter and an RTS smoother used for estimating the orbit of a low-altitude satellite. The filter and smoother were implemented using a square root covariance algorithm. Pass parameters were added to and deleted from the filter as stations and satellites changed visibility. PREFER required input of a converged CELEST Perturbed Trajectory File for the low-altitude satellite containing inertial positions and state transition matrices for the orbit, drag coefficient, and possible thrust parameters. It also required input of a GPS Trajectory File containing inertial positions and velocities of all GPS satellites. (An equivalent Transit Trajectory File was needed when processing NAVPAC observations.) Earth-orientation input was required and it had to be the same as what was used in CELEST.

The observations types PREFER could process were range, range difference, and Doppler collected by stations, GPSPAC pseudorange and delta-range, and NAVPAC range difference. It could estimate osculating epoch orbital elements, an atmospheric drag coefficient, perturbing RAC gravitational accelerations, up to two RAC thrusts, and the host satellite's clock time offset and frequency offset parameters. For the orbital elements, it was optional to input state noise as the expected standard deviation of the time derivative of the parameter. For the atmospheric drag coefficient, PREFER accounted for steps due to segmented drag coefficients in the CELEST-estimated trajectory file and estimated a correction as a first-order Gauss-Markov process. Perturbing RAC gravitational accelerations were also modeled as first-order Gauss-Markov processes. The host satellite's frequency offset was modeled as a first-order Gauss-Markov process, and the time offset was obtained by integrating the frequency offset. PREFER could also estimate, if required, ground station measurement bias and tropospheric refraction parameters, ground station Cartesian position errors, and GPS satellite RAC position errors and a clock offset error. All of these parameters were treated as pass parameters with no process noise.

In processing the observations transit time, corrections were made, an elevation cutoff test was defined for both stations and the host satellite, and tropospheric refraction corrections were applied for station-based observations. Observations were processed in mini batches in the filter and state noise was only included in going from one mini batch to the next.

PREFER/GALAXY output a CELEST Inertial Standard Trajectory File from the smoother and an optional file containing smoother covariance matrices. The covariance matrices corresponding to orbital elements were transformed from epoch osculating elements to current state Earth-Centered-Inertial (ECI) Cartesian position and velocity for this optional file. PREFER/GALAXY was ported to a computer at the DMAAC once it had successfully processed actual downlinked satellite-borne GPSPAC data at the NSWC.

Starting in 1978, the GPSPAC hardware development began under joint funding from the DMA and NASA. It was designed by JHU APL and built by Magnavox, resulting in an integrated GPS receiver/processor assembly and data system capable of tracking a single GPS satellite at a time but cycling through all satellites in view. The receiver tracked the C/A [Coarse Acquisition] code on L1 and the P code on L2. It switched satellites every 6 seconds and collected the delta-range measurement over a 0.6-second interval. The GPSPAC computed an on-board navigation solution using a nine-state extended Kalman filter running on a Digital Equipment Corporation LSI-11 computer. The GPSPAC also time-tagged timing marks from other on-board equipment and downlinked the filter solution, raw measurements, and time-tag measurements. The first GPSPAC was flown on Landsat-4, which was launched in July 1982 into a 700 km altitude circular orbit at an inclination of 98.3°. The first DB (KH-9/HEXAGON) satellite carrying a GPSPAC was launched in June 1983 and operated until March 1984. This satellite also carried the last NAVPAC. The NSWC processed the GPSPAC data for this mission and transferred the updated software to the DMAAC. The third GPSPAC was flown on Landsat-5, which was launched in March 1984 into a similar orbit to Landsat-4. The fourth GPSPAC was flown on a DB satellite launched in June 1984 and operated until October 1984, and the data were processed by the DMAAC. The last GPSPAC was on a DB satellite that suffered a failed launch attempt in April 1986.

In July 1986, the NASA Goddard Space Flight Center sent one week of Landsat-5 flight data to NSWC for analysis. Changes had to be made to PREFER/GALAXY to process this dataset. NSWC’s work on GPSPAC ended in late 1986. It is not known how long the GPSPAC units on the two Landsat satellites operated; however, in 1992, the NSWC processed a sample dataset collected by a second-generation GPSPAC developed by NASA to evaluate the receiver’s performance and utility for DoD spacecraft.

A 1982 study compared low-altitude satellite orbit determination using NAVPAC and Doppler Beacon tracking data processed in CELEST vs. PREFER/GALAXY. The objective was to evaluate the use of a sequential processor to possibly replace the CELEST short-arc method. The initial work involved making changes to both programs so that equivalent cases could be run. With PREFER/GALAXY set up to emulate a batch processor, agreement with CELEST was obtained with a peak difference of 20 cm. Introducing the stochastic processing capability in PREFER/GALAXY resulted in significant RAC orbit differences of 4, 7, and 9 m, respectively, for the rev of interest out of a two-rev fit span. Increasing the orbital process noise resulted in even larger differences. Longer fit spans were tried for PREFER/GALAXY and the results were somewhat degraded. The PREFER/GALAXY covariance estimates were optimistic and many numerical problems were present so no further studies were done.

OMNIS [ORBIT MENSURATION AND NAVIGATION IMPROVEMENT SYSTEM] (1980–2012)

In early 1980, it was decided the NSWC needed to develop a batch, after-the-fact GPS processing system based on a Kalman filter and smoother with the station tracking data for all satellites processed simultaneously. The previous emphasis had been on doing accurate predictions, but now the emphasis was on generating the most accurate fitted orbits and clocks so the DMA could switch to using GPS in place of Transit for its surveying work. This decision resulted in the GPS *MSF/S* system with the initial formulation completed in January 1981. It was a linearized Kalman filter with a pseudo-epoch state formulation, a square root information implementation, and included mini batch processing. The original version used CELEST Perturbed Trajectory Files as reference trajectories. A *Reformat/Merge* program was developed to combine the tracking data from the OCS and DMA stations and put them into a time-ordered file. A *Corrector/Editor* system of programs was also developed to correct and edit the station tracking data before being input to the *MSF/S* system.

In parallel with the initial *MSF/S* system development, discussions on CELEST’s future were taking place between the NSWC and DMA. There were several reasons why CELEST needed to be replaced, including its age and difficulty in being modified, its inefficient processing, its lack of transportability, new computer systems, new satellite systems, and new software development techniques. In July 1982, a task force first discussed the status and future of CELEST. At that time, the status of CELEST and two related programs were summarized as follows in Table 2.

Table 2: Orbit Determination Program Comparison Summary

Program and Version	Primary New Capability Supported	Status
CELEST V15	TRANET, SMTP, and OPNET Doppler ground stations	Operational at DMAHTC*
CELEST V16	NAVPAC	Operational at DMAAC
CELEST V17	GPS (NSWC's V17 had been modified to include the V16 NAVPAC capability)	Operational at NSWC and being tested at DMAHTC and DMAAC
NSOP	GPS (Interactive)	Operational at NSWC
PREFER/GALAXY	GPSPAC	Operational at NSWC and DMAAC
* DMA Hydrographic/Topographic Center		

In May 1983, there was another review about what to do next and, by August, the NSWC had developed a list of special studies that needed to be completed relative to a new orbit determination program. This resulted in a set of recommendations that were discussed at the January 1984 OMNIS development meeting. OMNIS was supposed to be a portable, computationally efficient modular system developed using top-down design, under configuration control, written in Fortran 77, and have extensive technical documentation and a user's guide. Work on OMNIS began in 1984 and several planning documents for development and testing were written. A Preliminary Design Review was held in January 1985 and a Critical Design Review was held that October. OMNIS system requirements definition, system requirements analysis, system development plan, configuration management, quality assurance test plan, and test plan documents were completed.

All CELEST-based GPS-related programs were converted to the OMNIS system of programs once the new OMNIS *Orbit Generation* program was completed in 1985, resulting in the GPS/Sequential Processor. A batch processor was developed in parallel to support the traditional station tracking data types for low-altitude satellites. The OMNIS system was continually updated to provide more capability and utilities were generated as needed to satisfy various requirements.

OMNIS was a system of programs designed to determine the orbits of several classes of satellites in a non-real-time mode. A GPS/Sequential Processor system was developed that used a Kalman filter and smoother to determine orbits and clocks for GPS satellites and/or HV satellites that tracked GPS satellites. It could simultaneously estimate parameters and covariances for many satellites using station tracking data and/or SST data involving GPS. It could also be used to simultaneously conduct station coordinate solutions for one or many stations. A Batch Processor was also developed to do weighted least-squares fits for orbit determination of Transit and other low-altitude satellites using station tracking data only. Therefore, the Batch Processor had a subset of the capabilities implemented in CELEST and used the same pass matrix approach but without a Short-Arc mode. Both processors required reference trajectories for all satellites to be processed and shared the *Orbit Generation* program for this purpose.

The OMNIS system of programs consisted of a series of programs that communicated with each other through files written to and read from mass storage devices. It was originally written in Fortran 77 and used a simple graphical user interface (GUI) for starting the various programs and analyzing the results. It was initially developed on the CDC 6700 mainframe computer system and operated on other CDC mainframes all under the SCOPE operating system and was modified to run on a Sperry 1100/82 computer at the DMA facilities (November 1986). It was eventually ported to run on IBM R/S 6000 workstations under the AIX [Advanced Interactive eXecutive] operating system and Hewlett Packard® workstations under the HP-UX operating system. OMNIS software Revision Control System configuration control was initiated at NSWCDD in late 1994. OMNIS was converted to using Fortran 90 in 1998.

In the following subsections, summaries of the various processing capabilities implemented in OMNIS are given first followed by detailed descriptions of each of the individual programs developed and their interfaces.

GPS Orbit Determination

The orbit determination process for GPS was divided into three separate functions: orbit integration; data correction and editing; and estimation and prediction. The first function was handled by the *Orbit Generation* program. The second function was handled by the *Corrector/Editor* system of four programs: *Corrector*, *Editor*, *Editing and Clock Automation Tool* (*ECAT),* and *Corrector/Editor Residual Plot*. The third function was handled by the *MSF/S* system of programs: *Filter*, *Smoother*, *Trajectory Propagator*, *Smoother Residual Generator*, *Diagnostic Plot*, *Signal-to-Noise Plot*, *Filter/Smoother Residual Plot*, *Carrier-Derived Pseudorange Editor*, *TagRes*, *Clock Event Utility*, *Least Squares Orbit Fit*, and *Clock Fit*. The collection of programs required for the second and third functions were called the GPS/Sequential Processor. The *Orbit Generation* program was the only one run in single-satellite mode, though a script was available to execute several runs sequentially to provide integrated orbits for all satellites. Other programs for data extraction, preprocessing, and reformatting were required. The *GPS Data Prep* program extracted information from the Smoothed Measurement, Master Clock, and Nominal Clocks and Events ASCII [American Standard Code for Information Interchange] files to generate a binary Observation File and ASCII Master Clock and Nominal Clocks and Events files for input to the *Corrector* program. The *GPS Report Generator* program read information from a binary file written by the first four programs in the *MSF/S* system, labeled it, and wrote a run summary file that could be viewed on a terminal or printed.

The GPS/Sequential Processor could process three types of station tracking data. The first was pseudorange, the second was range difference, and the third was carrier-derived pseudorange (CDP). The range difference data type was derived from differencing two successive Doppler count (phase) measurements (provided that no loss of lock had occurred) from the same satellite-station pair. The *GPS Data Prep* program formed these differences from the Smoothed Measurement File. A two-stage processing approach was eventually adopted. Generating CDP observations could not take place until the final first stage *MSF/S* orbit run had been completed. This was done in a separate program called the *Carrier-Derived Pseudorange Editor (CdpEdt)* program. This program required a special Biased Residual File produced by the *Smoother Residual Generator* and the Edited Observation File from the first stage *MSF/S* run. The Biased Residual File contained the differences between the computed pseudoranges, based on orbit and clock estimates from the first-stage *MSF/S* run, and the corresponding carrier phase measurements. *CdpEdt* estimated and removed the biases from the carrier phase measurements for each continuous tracking segment between a satellite and a station. Each bias was estimated by taking the mean over the residuals in each segment. CDP observations were formed by removing the biases from the carrier phase measurements. These CDP observations were written to an output Edited Observation File for use in the second-stage *MSF/S* run for clock estimation.

The *Filter* processed the tracking data initially in mini batches, which were typically longer than the data interval. This meant all observations in a mini batch were simultaneously processed, and process noise was only added in when propagating from one mini batch timeline to the next. One-hour mini batches were used with 15-minute tracking data in eight-day *Filter/Smoother* runs for each week in the early days of OMNIS processing. All programs were compiled to handle a maximum of 32 satellites and 80 stations. The *Filter* could process up to 1600 measurements per mini batch.

The *MSF/S* system of programs was initially designed to simultaneously estimate orbits, satellite and station clocks relative to a master clock, and Earth-orientation parameters. The first four programs were run in sequence in this mode. The orbit corrections could be modeled either stochastically or deterministically. In the first case, the *Filter*, *Smoother*, and *Trajectory Propagator* had to be run to obtain fitted trajectories. In the second case, only the *Filter* and *Trajectory Propagator* had to be run since the final corrections computed in *Filter* were equivalent to those obtained in a weighted-least squares orbit fit. After-fit residuals could be computed for the first case by running the *Smoother Residual Generator*. To compute after-fit residuals for the second case, the *Smoother* also was run to obtain the smoothed estimates for the clock parameters. For evaluation purposes, the resulting orbits and satellite clocks from either case could be held fixed, and the *MSF/S* system run again with station coordinates and clocks estimated and with the same or different edited measurements.

As more capabilities were added to OMNIS for GPS processing, users contributed less effort and time and the accuracy of the estimates increased. The user-intensive process of editing the data and identifying clock anomalies was automated, first by introducing the *ECAT* program and then by using iterative estimate-and-tag sequences using *TagRes* and the *Clock Event Utility*. With these additions, user intervention was minimized but not completely eliminated. The accuracy of the OMNIS orbit and clock estimates was improved by using the *MSF/S* in two stages. The first “orbit” stage used the pseudorange and range difference data to generate propagated orbits using an interferometric technique for handling the clock estimates. This was done by setting the statistics that characterized the satellite and station (except master) clock behavior to a large value (white noise clocks) and was equivalent to solving for independent solutions for each clock at each mini batch time. Using the orbits and other information generated from this first stage, the carrier-derived pseudorange observations were derived and used in a second “clock” stage *MSF/S* run to re-estimate the clocks, with the clock statistics set to reflect their actual behavior.

HV Orbit Determination

The *MSF/S* system of programs could handle up to three HVs simultaneously with all GPS satellites. GPS satellite observations from the tracking stations could be simultaneously processed with SST observations. Both pseudorange and range difference HV data could be processed. Orbits and clocks could be estimated for both HV and GPS satellites, or for HV satellites only. When estimating HV orbits/clocks only, three different modes existed regarding the treatment of the GPS orbit and clock estimates. In the first mode, the GPS trajectories and clock estimates were held fixed with only HV-related states present in the estimation equations. In the second mode, range and range rate error states were estimated to account for the remaining errors present in the GPS trajectories and clock estimates. This was performed through modeling the clock time and frequency offset states as current state first-order Gauss-Markov processes and allowed the software to estimate these errors without adding the full set of orbit and clock states for each GPS satellite. In the third mode, both GPS pseudoepoch satellite clock and orbital element parameters were present in the estimation equations. These GPS parameters were estimated using realistic *a priori* uncertainties to account for orbit and clock errors that grow with time when using predicted values.

Several options specific to HV estimation were implemented. These included options to propagate HV orbits only even if GPS orbits were estimated, to put direct process noise on the HV pseudo-epoch orbital elements using either the acceleration method or an alternative method, to select one of two indirect process noise methods (either drag or un-modeled acceleration parameters), and to output Earth-orientation corrections and HV covariance matrices. The *Filter* and *Smoother Residual Generator* programs also accepted GPS total clock offsets at a larger interval than the HV mini batch step as input when estimating HV orbits and clocks only.

Depending on the HV estimation technique, different GPS trajectory and clock file types could be used. When estimating orbits and clocks for both HV and GPS satellites, reference orbits for each satellite and a Nominal Clock and Events File were provided. When estimating HV orbits and clocks only, GPS orbit and clock estimates or predictions were provided. In these two modes, precise orbit and clock estimates derived using OMNIS were normally used. In the third mode, the OCS nine-hour predictions of GPS orbits and clocks and associated covariance matrices were used. Nine-hour predictions are generated by OCS every three hours. To use the most recent predicted quantities, extended GPS trajectory and clock files in a specific format for OMNIS were produced offline from the overlapping nine-hour prediction files. This reformatting included adjusting the square root error covariance matrices so the parameters were in the correct order and units for use by the *Filter*.

SATRACK

OMNIS was modified to generate Satellite Ephemeris and Clock Data (SECD) files for the SATRACK program. An SECD File contained ephemeris and clock estimates for all GPS satellites plus covariance matrices for these estimates at select times. The orbit and clock estimates were identical to the precise estimates generated normally for production, except the clock estimates were given relative to a master station (not adjusted to GPS time) and the span length was only 12 hours. Orbit integration and data correction and editing were done normally. The *Filter* had to have additional inputs to specify generating a primary SATRACK File, the SATRACK File covariance time(s), and the reduced step time span information. The covariance times were provided by the JHU APL. The reduced step time span defined the 12-hour span for which the orbit and clock estimates were required and was centered on the covariance time(s). For *Smoother*, users had to specify generating both the Primary and Secondary SATRACK files. The Primary SATRACK File was passed from the *Filter* to the *Smoother* where additional information was written. After the *Smoother* ran, both files contained the necessary information for the *SECD File Generator* to generate the SECD File. Multiple covariance times and generation of inter-time covariance matrices were supported by the program.

GPS Point Positioning

Two types of station coordinate estimation were available using the OMNIS programs. The first method was used for sites that were fixed in place over long spans of time. The second method was used for sites that were occupied for a short time, either hours or a few days.

For a new or recently moved fixed-site station, the coordinates were estimated simultaneously with the standard parameter set in the first-stage processing but with the coordinates for all other stations de-weighted. This was done for at least a week of daily spans and the daily solutions were averaged to get the final coordinates. No second-stage processing was required, but the appropriate plate motion name for the station was required and the epoch of the coordinates was set to the epoch in use for all the other stations.

For stations occupied for a short time, OMNIS could compute high accuracy absolute point positions starting with Receiver Independent Exchange Format (RINEX)-formatted Observation and Navigation Message files. Both two-frequency pseudorange and carrier phase observations sampled at the same interval as the mini batch interval were required. This capability required the use of the Propagated Trajectory Files and the first-stage Satellite Clock File from a production run, which provided all quantities held fixed in the computations.

The RINEX data were first processed by the *RTOOM [RINEX-to-OMNIS]* program, which sampled the data, calibrated time tags, applied the two-frequency ionospheric refraction correction, and completed preliminary editing. It output an ASCII Smoothed Measurement File, a Nominal Clocks and Events File, and a Station Coordinate File. This program was run for each station to be positioned and then the ASCII output files are merged and input into the *GPS Data Prep* program. *GPS Data Prep* extracted the pseudorange data and formed the range difference data. The *Corrector* was run next and made the usual corrections except that the data were time-tagged with reception time and a plate motion correction may not have been necessary depending on which epoch was required for the coordinates. *Corrector* used the Propagated Trajectory Files and the first-stage Satellite Clock File. *ECAT* and possibly the *Corrector/Editor Residual Plot* program were then used to edit any wild points, but station clock event detection was not necessary. The *MSF/S* system was then run using the same trajectory and clock files as *Corrector*. Only station coordinates, tropospheric refraction corrections, and station clock offsets were estimated. Appropriate *a priori* statistics were used on the first two sets of parameters, but large *a priori* statistics were used for the station clocks, similar to those used in the first-stage production processing. The *TagRes* program was then used to further edit the data and the *MSF/S* system was rerun. The GPS Report File then contained the starting and updated station coordinates in both geodetic and Cartesian form and the east-north-vertical (ENV) corrections to the starting coordinates along with their formal uncertainties.

Several computer programs outside of OMNIS were written by NSWC personnel for various GPS-based absolute and relative positioning applications. These included combining GPS observations with inertial measurement unit outputs for dynamic positioning and attitude determination applications.

WGS 84 Reference Frame Realization Method

Realization of the WGS 84 reference frame using GPS was done using similar techniques to the first point positioning method discussed above but on a much larger scale, with coordinates for a large number of fiducial stations held fixed. GPS tracking data collected by a worldwide distribution of International GNSS [Global Navigation Satellite Systems] Service (IGS) stations were processed simultaneously with the tracking data from the OCS and NGA station networks. The coordinates for a core set of IGS stations given in the latest International Terrestrial Reference Frame (ITRF) were held fixed, while OCS and NGA station coordinates were estimated. Daily fits were done and the individual solutions were averaged over 10–14 days to provide the final coordinates. Several techniques were then used to evaluate these new coordinates, including comparing orbit and clock estimates based on the new coordinates against the IGS estimates, and holding OCS and NGA station coordinates fixed while estimating the IGS station coordinates.

Crosslink Ranging

Three crosslink ranging data types were incorporated into the *MSF/S* system of programs so that a preliminary study of their effect on the GPS orbit and clock estimation accuracies using simulated data could be completed. These changes included the ability to estimate crosslink bias parameters for each satellite. No real crosslink observations were ever provided to NSWCDD for the Block IIR satellites.

Orbit and Clock Prediction

Orbit and clock predictions could be generated based on the three-day first-stage *Smoother* output. A least-squares fit was computed over the three days and the estimated parameters propagated forward in time for the predictions. The *Clock Fit* (*Clkfit*) program performed the clock fits using the first-stage Satellite Clock File as input and made the prediction based on this fit. Various clock models, including possible sinusoidal terms, and fit spans could be selected. The resulting coefficients were evaluated prior to the fit span to perform backward predictions, with the clock model providing the smallest RMS differences versus the clock estimates selected. These selected coefficients were then used to predict forward for the specified time span. The *Least Squares Orbit Fit* (*Lqfit*) program performed the orbit fitting needed to generate initial conditions for orbit prediction. Initial conditions extracted from the *Smoother* orbits were used to generate the reference trajectories needed for input to this program, one satellite at a time. Then for each satellite, the reference orbit was fit to the *Smoother* orbit and improved initial conditions were generated and written to an OMNIS Parameter Correction File. The *Trajectory Propagator* was then used with the reference trajectory and the Parameter Correction File as input to generate the predicted orbit.

Transit and Low-Altitude Orbit Determination

The Batch Processor augmented by the *Orbit Generation* program was used for Transit and other low-altitude satellite orbit determination. This Processor used the same pass matrix-based editing and estimation techniques as CELEST but only included the capability to process station range difference data based on a few different receiver types. Iterations could be performed by passing improved initial conditions back to the *Orbit Generation* program and integrating a new reference trajectory.

Extensive efforts were required when OMNIS had to be changed from using two-digit years to using four-digit years because of the century rollover at the beginning of 2000.

Orbit Generation

The *Orbit Generation* (*OrbGen*) program was common between the GPS/Sequential and Batch Processors. This program computed the position and velocity of a satellite as a function of time in a specified reference frame, given an initial position and velocity and models for the accelerations acting on the satellite. It also computed partial derivatives of position and velocity with respect to the osculating orbital elements at epoch or the epoch position and velocity and other orbit-related parameters, such as drag coefficients and radiation pressure parameters. All of this information was written to an Integrated Trajectory File. It could also output Earth-fixed positions and velocities. Integrated Trajectory files were used by the *Corrector*, *Filter*, and

Trajectory Propagator programs in the GPS/Sequential Processor and by the *Point Editor*, *Solution*, and *Trajectory Propagator* programs in the Batch Processor.

OrbGen used a Gauss-Jackson second-sum predictor/corrector method to simultaneously integrate the satellite equations of motion and the associated variational equations. It was a fixed-step/multistep algorithm using backward differences of accelerations and first and second sums. It was not self-starting, so accelerations were first computed using an approximate position and velocity based on Taylor series expansions. An iterative process was then used to generate a converged backward difference table. Once converged, the difference table was extrapolated forward to the next timeline. Using the extrapolated difference table, the satellite's position and velocity were computed, then accelerations were computed using the new position and velocity. Acceleration corrections were then computed and used to correct position and velocity. This computation of acceleration, corrections, and new position and velocity was iterated a specified number of times, and the difference table was then corrected based on the last set of corrections. Typically, the program options were set to use a single correction of accelerations (differences) and position (sums) at each time step. This was believed to be more efficient than using larger time steps with multiple corrections. The integration technique was augmented by various partial restart capabilities to account for force discontinuities due to thrusts and solar radiation pressure forces during eclipse seasons.

The inertial reference frame used was defined by the mean equator and mean equinox at the J2000 epoch using the IAU 1976 Precession, the IAU 1980 Theory of Nutation, and the 1982 definition of UT1 and corresponded to the 1996 IERS Conventions. A daily table of polar motion and UT1-UTC was generated based on coefficient sets provided by the DMA/National Imagery and Mapping Agency (NIMA), with the most recent set prior to the orbit epoch used. The DMA implemented its Earth-orientation prediction service in mid-1984 in preparation for the upcoming transition to the GPS Operational Control Segment. Zonal tide variations computed from the Yoder model with 41 terms were added to the UT1-UTC values in the daily table. Optionally, IERS final values for Earth orientation, which already included zonal tides in its UT1-UTC values, could be used. Quadratic interpolation in this daily table was used to get the three Earth-orientation parameters at a given time and then diurnal and semidiurnal variations to all three parameters could be applied on option.

Several time systems were used in OMNIS. Integration time was in GPS Time for trajectories to be used in the GPS/Sequential Processor and UTC Time for trajectories used in the Batch Processor. GPS Time is independent of leap seconds, but UTC is not. (The Batch Processor could not compute a fit over a leap-second transition unless it was ignored and the observation time tags after the leap second did not include its effects.) Terrestrial Time was used for the Sun, Moon, and planetary ephemerides. The time systems are related to each other through constants and/or quadratic polynomials.

The satellite equations of motion modeled in OMNIS included:

1. Gravitational Earth accelerations expressed in spherical harmonics using up to 2500 terms (up to 70th degree and order)
2. Solid-Earth lunar and solar tidal accelerations and ocean and atmospheric tidal accelerations
3. Atmospheric drag (not used for GPS)
4. Constant thrust acceleration in the RAC frame or the GPS XYZ body-fixed frame over a specified interval

5. Solar radiation pressure acceleration (including y-axis acceleration)
6. Gravitational attraction of the Sun, Moon, and the other planets

Each acceleration component was evaluated in its reference frame and rotated if necessary into the inertial frame. Partial derivatives, with respect to a drag coefficient, a radiation pressure scale factor and y-axis acceleration, thrusts, and selected gravity field harmonic coefficients could be generated by *OrbGen* based on integrating the variational equations.

For GPS, a five-minute integration step was used and information was written to the trajectory file every 15 minutes. For low-altitude satellites, either a 60- or 30-second integration step was used; the trajectory file written at the same interval. An integration step size of 10 seconds was typically used to restart the integration routine at discontinuities due to thrusts, drag coefficient boundaries, and eclipse shadow boundary crossings. Eight additional timelines were written before and after the integration span to accommodate the eight-point Lagrangian interpolator used in programs that read the trajectory files.

The Earth Gravitational Model 1996 (EGM96) was used after it became available to replace the original WGS 84 Earth gravity model. The tidal potential model computed the gravitational acceleration on the satellite due to changes in Earth in response to Sun and Moon tidal forces. Either the NSWCDD second-order Legendre polynomial representation with a Love’s number multiplier or the IERS 96 tidal potential models were used for the solid-Earth tide effects. IERS96 ocean and atmospheric tidal effects models were used. Pole tide and permanent tide variations in the solid-Earth tide effects were optional. For atmospheric drag, an atmospheric density model option allowed using an exponential density model developed by the NWL, the Jacchia-Bass 1977 model, or the Barlier Drag Temperature Model (DTM) model. The last two models were required to use a current Geophysical Database File of daily solar flux values and geomagnetic indices. The possible reference frames for a thrust were RAC and the body-fixed GPS XYZ frame. The options available for the solar radiation pressure acceleration models were:

1. Spherical
2. Rock4: original Rockwell International model for the GPS Block I satellites
3. Rock42: original Rockwell International model for the GPS Block II/IIA satellites
4. T10: Aerospace Corporation’s Block I model
5. T20: Aerospace Corporation’s Block II/IIA model
6. T30: Aerospace Corporation’s Block IIR model
7. BLKIIR: Lockheed Martin™ OCS table look-up model for Block IIR
8. T20JPL: NASA Jet Propulsion Laboratory’s (JPL’s) first Block II/IIA model
9. T20JPL2: variation of the T20JPL model
10. TJPLIIA: an updated JPL model
11. TJPLIIR: JPL’s first Block IR model
12. TJPLIIA2: variation of the TJPLIIA model
13. TJPLIIR2: variation of the TJPLIIR model
14. BLKIIF: Boeing Company™ OCS table look-up model for Block IIR

Controls were present to select a beta angle limit and option for use in conjunction with several of these models. Satellite eclipses due to Earth and the Moon were accommodated by computing a shape factor with a value between zero and one to account for penumbra passages. A shape factor of 0 indicated a satellite was completely in the umbra; a shape factor of 1 indicated it was in full Sun. Another control was present to select whether or not to apply the shape factor to the y-axis acceleration. The JPL Development Ephemeris DE403 was used for

Sun, Moon, and planetary ephemerides for both the point mass acceleration and shape factor computations after it became available.

GPS/Sequential Processor

GPS Data Prep

The *GPS Data Prep* program extracted required observations from the archived ASCII Smoothed Measurement Data File, including the pseudorange, range difference, and carrier phase data types. OCS Accumulated Delta Range observations were converted into range differences. Observation tags from the previously processed span that overlaps in time with the current span were transferred. The final station clock estimates from the previous span were incorporated into the Nominal Clocks and Events File, as were any clock events and associated offsets from the previous span that occurred during the overlap. This program generated the binary Uncorrected Observation File needed by the *Corrector* program. Other programs outside of OMNIS were used to put satellite-to-satellite and crosslink ranging observations into the Uncorrected Observation File format.

Corrector/Editor (C/E) Subsystem

The *Corrector* program corrected the observations for known effects and computed residuals for each observation and the corresponding elevation angle. Corrections related to a satellite’s clock and antenna position, the signal path time delay and an additional delay due to the troposphere, and station’s motion were applied. The following corrections were made to each observation:

1. Time Transmission: The observations were time tagged with either time of emission by the satellite or time of reception by the station. For the first case, a station’s motion during the signal transit time was accounted for in making this correction. For the second case, a satellite’s motion during the signal transit time was accounted for by interpolating on the satellite’s trajectory at the appropriate time. This correction resulted in the formation of an instantaneous measurement necessary for the *Filter* program.
2. Tropospheric Refraction: Each observation was corrected for the effects of the troposphere on the transit time using either measured or default weather data and either the Hopfield or the Neill tropospheric refraction model.
3. Antenna Offset: Each observation was measured from a satellite’s antenna phase center while its trajectory was for the satellite’s center of mass. This correction adjusted the observation so that it appeared to come from the satellite’s center of mass. The yaw motion of each GPS satellite was accounted for in this correction. No adjustment was made for the station antenna offset since it was assumed that station coordinates referred to its antenna phase center.
4. Periodic Relativistic: Each observation was corrected for the periodic relativity effect and was an adjustment to the time offset converted to distance units.
5. Solid-Earth Tide: Each observation was corrected to account for the movement of the station due to tidal motion of Earth’s crust, using either the NSWC or the IERS model.
6. Ocean Loading: Each observation was corrected to account for the time-dependent motion of the station due to ocean tides.
7. Pole Tide: Each observation was corrected to account for station displacement station due to rotational deformation caused by polar motion.

8. Plate Tectonic Motion: Each observation was corrected to account for the station's motion due to Earth's tectonic plate movement. Three models were available: AM0-2 (12 plates), NUVEL NNR [no-net rotation]-1 (14 plates), and NNR-NUVEL-1A (16 plates).
9. Phase Windup: Both the range difference and carrier phase observations were corrected to account for the relative motion of right-hand circularly polarized satellite and station antennas during the time interval of the observation. This was a change in phase and did not affect the pseudorange observations.

Corrector had an option to write orbit partials to the Corrector Residual File for use in adjusting orbits as part of the editing process in *Editor*. It also had an option allowing users to override the station coordinates obtained from the Observation File. Changes to *Corrector* to accommodate laser ranging observations were also included as two of the GPS Block IIA satellites had laser retroreflectors on their Earth-facing side.

The *HV Corrector* program corrected the observations for known effects and computed residuals for each observation and the corresponding elevation angle from the HV to the GPS satellite. Negative elevation angles were possible. A minimum ray path distance prevented the use of GPS-to-HV measurements that passed through the troposphere. Observations that passed closer to Earth than this minimum distance were tagged as bad. Corrections related to each satellite's clock and antenna position and the signal path time delay were applied. All corrections resulted in the formation of instantaneous measurements necessary for the *Filter* program.

The following corrections are made to each observation:

1. Time Transmission: The observations were time tagged with either time of emission by the GPS satellite or time of reception by the HV satellite. For the first case, HV satellite motion during the signal transit time was accounted for by interpolating on the HV satellite's trajectory at the appropriate time. For the second case, the GPS satellite's motion during the signal transit time was accounted for by interpolating on the GPS satellite's trajectory at the appropriate time.
2. Antenna Offsets: Each observation was measured from the GPS satellite's antenna phase center to the HV satellite's antenna phase center. The trajectory for each satellite was for each satellite's center of mass. This correction adjusted the observation so that it appeared to come from the center of mass of the GPS satellite to the center of mass of the HV satellite. The yaw motion of each GPS satellite was accounted for in this correction. The attitude of the HV satellite was also accounted for in this correction through an RAC model for low-altitude satellites and a specific attitude model for the TOPEX [Ocean Topography Experiment] satellite.
3. Periodic Relativistic for GPS: Each observation was corrected for the periodic relativity effect at the GPS transmit time and was an adjustment to the time offset converted to distance units.
4. Periodic Relativistic for HV: Each observation was corrected for the periodic relativity effect at the HV receive time and was an adjustment to the time offset converted to distance units.
5. Phase Windup: The range difference observation was corrected to account for the relative motion of the right-hand circularly polarized GPS satellite and HV satellite antennas during the time interval of the observation. This was a change in phase and did not affect the pseudorange observations.

The *ECAT* program was developed to minimize the user-intensive process of editing outlier residuals and identifying clock anomalies. *ECAT* read a sorted, coded version of the Residual File from *Corrector* and, based on certain criteria, determined if there were any outliers, clock events, or orbit events in the time span being processed. This involved an iterative process applied to each satellite/station pair. A polynomial fit to the residuals was used to identify outliers and to detect clock events. If the RMS fit residual was greater than an input tolerance, the outliers were identified and removed (tagged) from the data. Another fit was done and the process continued until the RMS was less than the input tolerance, five iterations had been performed, or no outliers were detected. After the outliers were removed, a test was performed to detect clock events. If a clock event was detected, its information was written to the Nominal Clocks and Events File. The effect of the clock event was then removed from the residuals after that time, and the original fit was redone for further detection of outliers and possible later events. This process was continued until the RMS was less than an input tolerance or five iterations had occurred. A check was then done to detect an orbit event. *ECAT* was originally used to remove outliers and detect events prior to using the *Corrector/Editor Residual Plot* program to interactively tag or untag observations. Later on, *ECAT* was used in conjunction with *TagRes* in an iterative estimate and tag sequence. In either case, a Residual File was used to identify and tag data outliers in the Corrected Observation File. *ECAT* was not used for the carrier phase data. HV tracking data could be processed by *ECAT* but had to be processed in a run separate from the GPS station tracking data.

The *Editor* program used the observation residuals from the *Corrector* program to solve for clock parameters and edit data. It had an option to adjust the orbit parameters as part of the editing process, and allowed users to add new clock parameters to account for station or satellite clock events. A quadratic weighted least-squares fit was used to solve for all clocks relative to a master clock. All after-fit residuals (both tagged and untagged) were then tested against user-defined absolute and consistency tolerances. All observations and adjusted residuals not meeting the tolerances were tagged as bad by negating the sigma value. An Edited Observation File was written, and then it, along with the Residual File, was used by the *Corrector/Editor Residual Plot* program to interactively edit any remaining bad points. Improvements in the nominal clock values and information defining new clock parameters added during the editing process were used to update the Nominal Clocks and Events File. Carrier phase data were ignored by the *Editor* program. HV tracking data could be processed by *Editor*, but it had to be done in a separate run from the GPS station tracking data if present.

The *Corrector/Editor Plots* (*QikPlt*) program allowed users to interactively view plots of observation residuals by satellite/station/data type combination. A user could zoom in on a portion of the plot and tag or untag individual or all points displayed, or tag points based on a tolerance. Initially, the program was used after the *Corrector* program for editing data and identifying clock event information for the *Editor* program. The program could also be used after running the *Editor* program for the same purposes. An Interactive Data Language (IDL) version of this program (*ResPlt*) was later written to replace *QikPlt*; it featured both two- and three-dimensional plots with the latter having a user capability to rotate the plots to better review the residuals.

MSF/S Subsystem

The *Filter* program consisted of a square root information implementation of a linearized Kalman filter that could simultaneously accommodate data and parameters for many satellites and stations. The *Filter* required reference trajectories for all satellites, nominal clock and clock event information for all stations and satellites (this essentially provided a reference trajectory for each clock), corrected and edited observations, and other information required to initialize and control the operation of the filtering algorithm and the selection of data. *Filter* states were corrections to the nominal model parameters, and the measurements were processed as residuals. Therefore, partial derivatives were required that related the states at one time to another time (state transition matrices) and that related the measurements to the states (measurement matrices). All partial derivatives were evaluated based on the reference trajectories and nominal parameter values. All orbit-related partial derivatives were obtained from the reference trajectories or computed based on information obtained from these trajectories.

Each run was a cold start of the *Filter* with a fixed parameter set using input *a priori* sigmas and process noise statistics, if needed, for the solution parameters. For radiation pressure estimation of a third parameter (the angle between the GPS satellite's x and y axes, nominally 90°) was included but was always de-weighted.

Fit span information including the mini batch interval and the reduced span information for possible generation of an SECD File were input. Seven data types could be processed by the *Filter* program: station pseudorange and range difference, HV satellite pseudorange and range difference, and three crosslink ranging measurement types. The parameter set selected for the *MSF/S* system was divided into three categories:

1. Stochastic parameters
    a. Orbit-related, including radiation pressure and RAC gravitational accelerations
    b. Measurement-related, including tropospheric refraction, satellite and station clocks, and crosslink ranging biases
2. Time-varying but nonstochastic parameters, including orbital elements (two direct orbit process noise options were added for use by HVs only)
3. Bias parameters
    a. Station-related, including station coordinates (ENV) and Earth orientation
    b. Orbit-related, including radiation pressure, thrusts (up to four), and gravity coefficients

The stochastic parameters represented random processes, with state or process noise added to the parameter states at each mini-batch step. Each stochastic parameter was assigned particular statistical assumptions. The Radiation Pressure (included the Y-Axis Acceleration) and Gravitational Accelerations parameters were treated either as Gauss-Markov processes or random walk processes. For the Tropospheric Refraction parameter, an option existed to either estimate a single wet zenith delay correction using either the 1/sine (elevation) or the Neill wet-mapping function or to add two additional tropospheric east and north gradient parameters. All three parameters were modeled as either first-order Gauss-Markov processes or random walk processes. All clocks were modeled as either third- or second-order linear systems with white noise inputs. When the processing was converted to use two stages, the clocks were treated differently in the first "orbit" stage. The clock statistics were set to large values (white noise clocks), which resulted in solving for independent estimates for each clock, except the master, at each timeline. This only worked because the mini batch and observation intervals were set the same. The orbits and Earth orientation estimated in this first stage were then held fixed while the clocks were re-estimated in the second stage with the clock statistics set to reflect actual clock behavior. Estimated Earth-orientation parameters were the two pole coordinates and their rates and the UT1-UTC rate and acceleration.

Categories were used to specify minimum sigma values for each data type. Sigma values coming from the Edited Observation File that were smaller than the corresponding minimum sigma were replaced with this minimum. An option existed to de-correlate and whiten range difference data types. Coordinates for individual stations could be overridden through inputs. Categories were also used to specify both satellite and station clock process noise statistics. Several HV processing options could be selected, and the corresponding statistics had to be provided.

The *Filter*–produced Filter Output/Smoother Input File contained all the information required by the *Smoother* program except for the nominal clock for each satellite at each mini batch time, which was in the Filter Nominal Clock File. The *Filter* estimated corrections, in the form of a Filter Diagnostic File, which were saved and could be plotted using the *Diagnostic Plot* program to analyze the quality of the estimates. When solving for station coordinates, an option existed for saving a Filter Station Solution File. This file contained various types of information, including the initial and final station coordinates and the covariance matrix for the coordinates and all Earth-orientation parameters. The *Filter* could also be operated in a “batch” orbit determination mode. This mode was primarily used for improving a reference trajectory that contained a thrust. In this mode, no orbit-related stochastic parameters were estimated, and the orbit was completely determined after the filtering was completed. An improved set of initial conditions was written to the Initial Conditions File, which was then input into the *OrbGen* program and an improved reference trajectory integrated. If a Propagated Trajectory File based on the *Filter* program estimates was required, the Filter Parameter Correction File could be input into the *Trajectory Propagator* program.

The *Smoother* program was run after the *Filter* program to smooth the estimates using the Rauch-Tung-Striebel equations. It processed the information saved by *Filter* in the Filter Output/Smoother Input Files in reverse time order. Two fixed-interval smoothing algorithms, State-Only Smoother and Array Smoother, based on the square root information implementation were available. The State-Only Smoother did not provide any covariance information but ran much faster than the Array Smoother. The Array Smoother had to be used in conjunction with providing an SECD File for the SATRACK program. The *Smoother* required a Filter Nominal Clock File to generate a Smoother Satellite Clock File. The *Smoother* always generated a Smoother Parameter Correction File and could optionally generate a Smoother Diagnostic File for *Diagnostic Plot* program plotting.

The *Trajectory Propagator* program used the reference trajectories from *OrbGen* and the orbit-related parameter corrections from either the *Filter* or *Smoother* programs and converted them into inertial position and velocity corrections at each trajectory timeline by linear propagation techniques. These corrections were then added to the reference trajectory positions and velocities. Earth-fixed positions and velocities were obtained by transforming these improved inertial coordinates, with the improved values for Earth orientation used if also solved for. The propagated trajectories corresponded to the fit span with at least four extra timelines added at both ends to accommodate the interpolation method. The program could be operated in one of three modes—Batch, Filter, or Smoother. The Smoother mode was the usual operational mode and required a Smoother Parameter Correction File. The other two modes required a Filter Parameter Correction File. The Batch mode corresponded to the Batch orbit determination mode described for the *Filter* program. In this mode, only one set of epoch orbital element and constant force model corrections were required. In the other two modes, corrections to epoch orbital elements and stochastic orbit-related parameters at each mini batch step were required. The Propagated Trajectory Files also contained the updated Earth-orientation table. Improved initial conditions at up to three times could be generated after the propagation and written to the Initial Conditions File. In the Smoother mode, the radiation pressure and y-axis estimates are averaged over the fit span and added to the nominal values to get improved values. These initial conditions could be used to integrate orbits through *OrbGen* for generating orbits for subsequent spans. An option existed for propagating HV orbits only for a combined HV/GPS fit.

The *Smoother Residual Generator* program used edited observations from the Edited Observation File and computed after-fit residuals using the Propagated Trajectory files and the Smoother Parameter Correction File. The latter file provided corrections for the measurement-related stochastic parameters. The residuals were formed by differencing computed geometric range or range difference values, derived from a mathematical model based on smoothed estimates, with the observations from the Edited Observation File. If pseudorange observations were processed in the *Filter*, this program could, on option, compute residuals for any other data type contained on the Edited Observation File. This program generated a statistical summary of the residuals by satellite, by station, and over all measurements, and output individual residuals and signal-to-noise ratios (SNRs) for each mini batch to the Smoother Residual File. This file was the input file for both the *Signal-to-Noise Plot* and *Filter/Smoother Residual Plot* programs.

The original *Diagnostic Plot* program could plot the corrections and sigmas (if present) for any parameter from either a Filter or Smoother Diagnostic File. By default, the program plotted everything on the file for the entire fit span and automatically selected the scale limits. Parameters could be selected by satellite, by station, or individually and plotted for the entire fit span or a subspan on option. In addition, the scale limits could be manually set for individual parameter types. This program was eventually replaced by an *Interactive Diagnostic Plot* program written in IDL. It was much more user friendly and flexible for viewing diagnostic plots.

The *Signal-to-Noise Plot* program plotted the SNRs for each mini-batch interval for the entire fit span from a Filter or Smoother Residual File.

The *Filter/Smoother Residual Plot* program plotted residuals grouped by day number. By default, the program plotted everything on the input Filter or Smoother Residual File by satellite and data type with all stations on each daily plot for the entire fit span, and automatically selected the scale limits. Tagged points were plotted as Bs and did not enter into determining scale limits. Upon option, residuals for a subset of the data types, satellites, or stations could be plotted. In addition, the scale limits for each data type could be specified.

The *Carrier-Derived Pseudorange Editor* program was run once in between the final first-stage *MSF/S* orbit run and the second-stage *MSF/S* clock run when estimating final satellite and station clocks using carrier-derived pseudorange observations. This program estimated and removed the biases from the carrier phase measurements and saved the resulting carrier-derived pseudorange observations in the output Edited Observation File to be used in the second-stage *MSF/S* run.

The *TagRes* program automated observation tagging, using after-fit residuals generated by the *Smoother Residual Generator* program, observations from an Edited Observation File, and user-specified tolerances to automatically tag or untag observations. Observations could also be marked as killed, so they could never be untagged. This program could also transfer tags from a fully edited file to an unedited or partially edited file.

The *Clock Event Utility* program identified time and frequency offset jumps in satellite and station clocks using the Filter Diagnostic File, Residual Output File, and Nominal Clocks and Events File. The program was executed after convergence of the automatic *TagRes* procedure and prior to the second-stage clock estimation, and searched the Filter Diagnostic File for times when satellite or station clock corrections exceeded input tolerances. Newly identified events were written to the Nominal Clocks and Events File.

The *Least Squares Orbit Fit* (*Lqfit*) program performed orbit fits independently for each satellite using orbits from *Smoother* as observations and integrated reference trajectories and solved for orbital element and constant force model parameter corrections at the epoch of each reference trajectory. These corrections were then reformatted and written to a Parameter Correction File for input to the *Trajectory Propagator* to generate the final predicted orbits.

The *Clock Fit* (*Clkfit*) program performed clock fits independently for each satellite using *Smoother* clock estimates as observations. Several models for the clock could be considered consisting of either a linear or quadratic model augmented by sinusoidal periods of 6, 12, or 24 hours. A fit was done for each model selected and evaluated by predicting backward and comparing against the corresponding *Smoother* estimates. The model that provided the best backward prediction was then used to predict forward in time, and a clock file was generated.

The *GPS Report Generator* program summarized information from a binary file created and updated by the *Filter*, *Smoother*, *Trajectory Propagator*, *and Smoother Residual Generator* programs and from a *TagRes* output file, labeled it, and wrote a text file that could be viewed on a terminal or printed.

The *SECD File Generator* program produced a file containing precise GPS orbit, clock, and covariance estimates for the SATRACK program. The inertial orbit and clock estimates were identical to the precise estimates normally generated in production, except the span length was only 12 hours. A reduced step time defined the 12-hour span for which orbit and clock estimates were required; this span was centered on the covariance times. Covariance matrices relating eight parameters for each satellite to every other satellite were also provided at up to three times, and inter-time covariances could be generated on option. The eight parameters for each satellite were position, velocity, and two clock parameters (time and frequency offsets). An inertial-to-Earth-fixed matrix was provided at each covariance time.

The following two diagrams indicate the complicated processing flow used for the OMNIS GPS/Sequential Processor once the two-stage method was adopted and the carrier-derived pseudorange data type was added. OMNIS passed multiple files from program to program. Figure 4 includes the generation of the reference trajectories, preparation of the pseudorange, range difference, and carrier phase tracking data, and correcting and editing of the tracking data for use in the *Filter*. The interactive *Corrector/Editor Plot* program is not shown but could be used after either *Corrector* or *Editor* for additional data editing. Figure 5 includes the sequence of programs (left) required for the orbit estimation, the calibration of the carrier-derived pseudorange observations in the Edited Observation File (center), the sequence of programs for clock estimation (right), and the adjustment of the clocks to GPS Time and creation of the SP3 File (bottom). A binary Report File could be initially output by *Filter* and then added to by *Smoother*, *Trajectory Propagator*, and *Smoother Residual Generator,* but is not shown in this diagram.

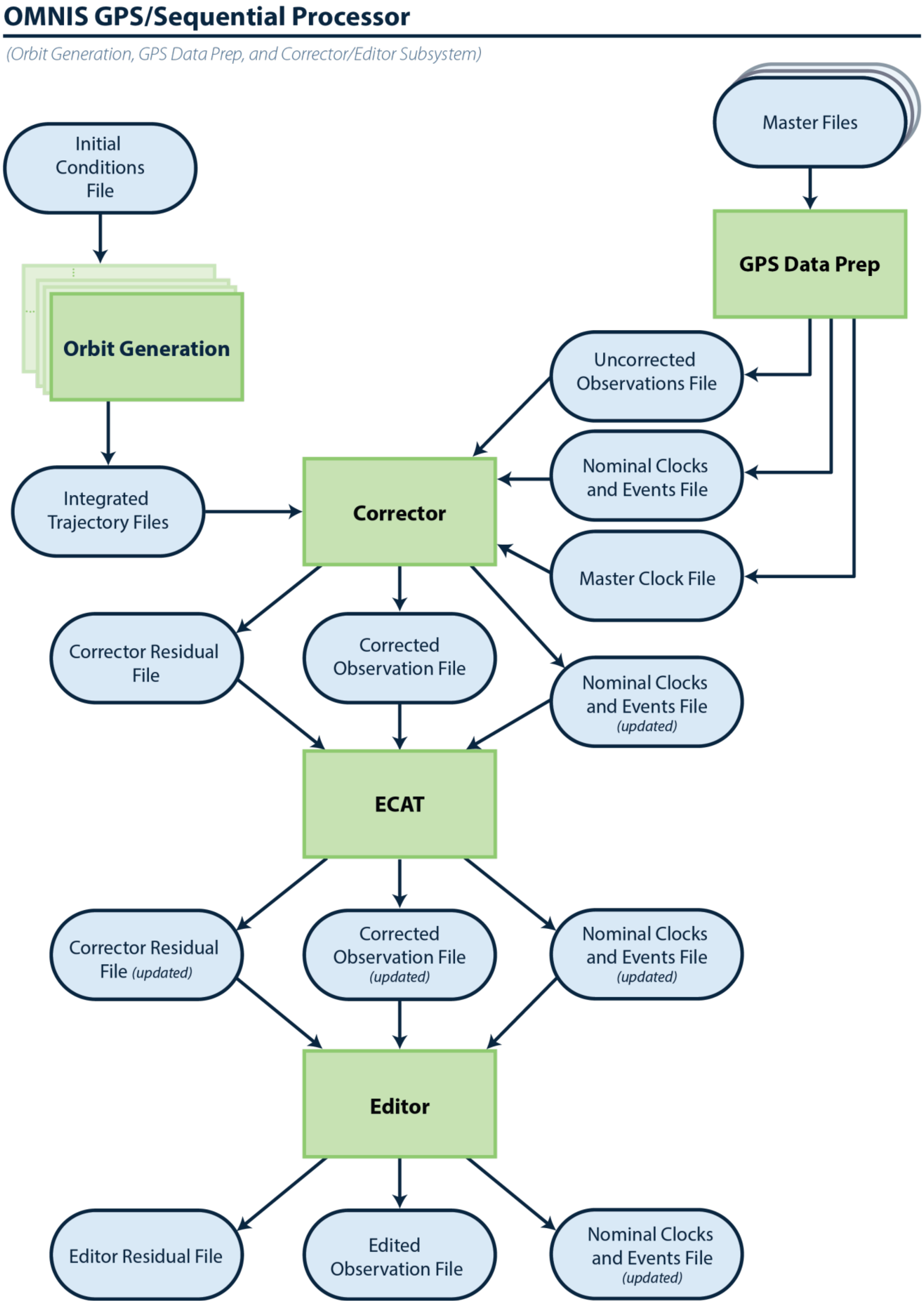

Figure 4: OMNIS Orbit Generation, GPS Data Prep, and Corrector/Editor Subsystem

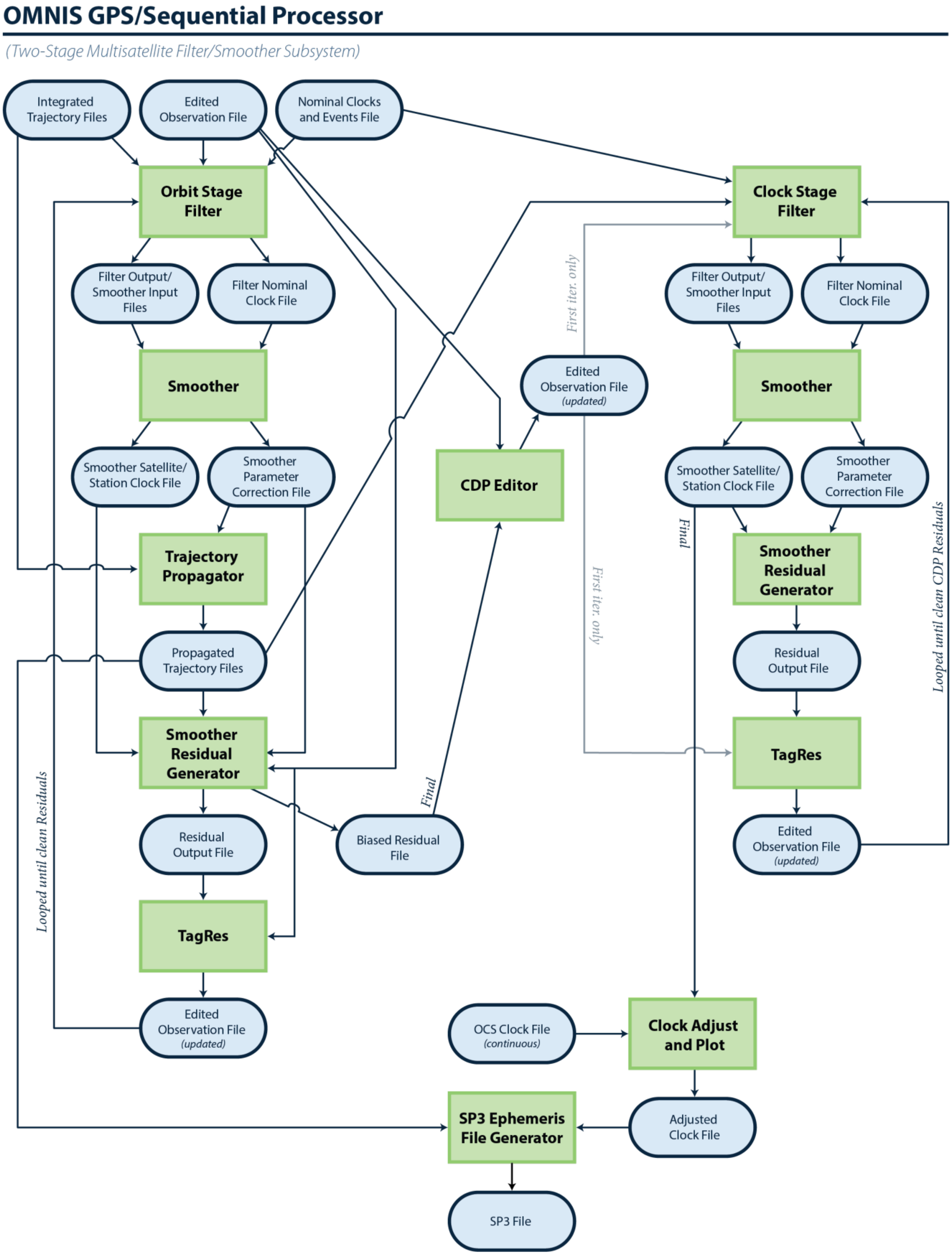

Figure 5: OMNIS Two-Stage Multisatellite Filter/Smoother Subsystem

Batch Processor

The Batch Processor consisted of six programs required to process the station-based range difference data types that were previously processed in CELEST for a single satellite. These programs were: *Two-to-Five*, *Data Prep*, *Point Editor*, *Solution*, *Orbit Computation Report*, *Trajectory Propagator*, and *Batch Plots*.

The *Two-to-Five* program maintained a database of NAVSPASUR elements for each NAVSAT in time order. This program performed minor conversion and satellite number mapping to produce elements in a form similar to the two- and five-card elements used in CELEST. A Satellite Characteristics File was needed as input.

The *Data Prep* program read a file of Clean-Checked Source Data, processed the data, performed time corrections, and wrote out an Observation File. The NAVSAT (i.e., Transit) data contained time marks that were extracted and used to compute daily corrections for each station. The data for other satellites, called GEOSATs, did not have time marks so their observation time tags were corrected using values based on NAVSATs. The program could process data from OPNET, TRANET2, and MX1502 stations. A Satellite Characteristics File mapped various satellite numbers to a common set, and a Station File was needed to get station coordinates. The NAVSPASUR elements database provided elements to make time of transmission corrections. This program could process up to five NAVSATs and five GEOSATs in one run.

The *Point Editor* program edited the data, determined the data weights, and formed pass matrices for every contact between a station and satellite over the fit span very similar to how the *Filter* section of CELEST worked. Three data types could be processed: range difference (primary), frequency, and range. The maximum number of editing iterations was specified, and passes could be deleted by pass number. A minimum elevation angle test was conducted, and corrections were made to the tracking data for time transmission effects (for either receive or transmit time tags), tropospheric refraction effects, solid-Earth tide effects on station positions, satellite antenna offsets, and relativity effects. There was no plate motion adjustment to the station positions and station coordinates were assumed to be for the antenna phase center. Up to three bias parameters could be selected for each pass: tropospheric refraction, frequency bias (or time bias for range data), and frequency drift (or frequency bias for range data). A Pass Matrix File was written for input into the *Solution* program.

The *Solution* program computed the parameter improvements for the orbit fit. Parameters that could be estimated included epoch position and velocity (or epoch osculating elements), a single drag coefficient, three thrust components for a single thrust, one or three radiation pressure scale parameters, Earth orientation (two coordinates of the pole, UT1-UTC, and UT1-UTC rate), and station coordinates. Biases were first eliminated from the pass matrices, and the resulting equations summed to form the arc normal equations. The solution was then computed and navigation solutions were generated and cross-pass editing was done using these navigation solutions. The solution was repeated using all untagged passes, and this procedure was iterated until two successive iterations had the same good passes or the maximum number of iterations was reached. The program wrote an improved set of initial conditions and printed the navigation solutions for each iteration of the cross-pass editor, the parameter solutions, the station solution (if present), and the bias solutions for each pass.

The *Solution* program created and updated a binary file from which the *Orbit Computation Report* program read information, labeled it, and wrote a text file that could be viewed or printed.

The *Trajectory Propagator* program used the Integrated Trajectory File from *OrbGen* and the orbit-related parameter corrections from the *Solution* program and converted them in inertial position and velocity corrections at each trajectory timeline by linear propagation techniques. These corrections were added to the reference trajectory positions and velocities, and the updated quantities were transformed into Earth-fixed frame and a new trajectory written for the satellite. Earth-fixed positions for either the satellite center of mass or an antenna reference point could be output.

The *Batch Plots* program was generated for the RADCAL/DMSP orbit determination (discussed below). It plotted the two navigation components and the signal-to-noise for all passes in time order based on TCAs.

Utilities

The following lists all the OMNIS utility programs that performed various functions needed for manipulating files in the OMNIS system of programs:

1. *Trajectory Comparison (Delta R Plot)*
2. *Get Initial Conditions*: This program extracted initial conditions from am ASCII file written by the ODF [OCS Data Facility]. The ODF read information from the OCS, reformatted it, and stored it in databases.
3. *List Files*
4. *Initial Conditions Cleanup*
5. *Create Sun-Moon File*
6. *Clock File Utilities*
    a. *Satellite/Station Clock Comparison Plot*
    b. *Merge Clock Files*
    c. *Extract Clock Files* extracted satellite and station clock offsets from an ODF ASCII file.
    d. *Clock File Gap Filler* filled in gaps in the extracted clock file using linear interpolation.
    e. *Clock Adjust and Plot*: The *Clock Adjust* program adjusted the *Smoother*-estimated clock offsets to be consistent with GPS Time and Frequency. The clock offsets were estimated in OMNIS relative to a master clock, at either the USNO or Colorado Springs. When the OCS converted to using a Composite Clock in 1990, this program, along with the supporting utility programs, were written to provide adjusted clock estimates to the OCS. The program used a sliding window technique in which all clock differences between OMNIS and the OCS for the selected satellites were formed each 15 minutes and for each timeline averaged over the 24 hours centered on this timeline. The average adjustment was then applied to all OMNIS clock estimates at this timeline for both satellites and stations. This was repeated for all timelines and was done independently for the time and frequency offsets.
    f. *Clock File Print*
    g. Allan Variance Utilities merged together several Satellite/Station Clock Files and then computed and plotted Allan variances.
7. *Observation File Utilities*
8. *Binary-to-Coded File Utilities*
9. *Update Solar Geophysical Database*

10. *Trajectory/Clock Difference and URE [User Range Error] Statistics* generated tables of statistics summarizing the comparisons between two sets of orbit and clock estimates. Quantities computed included mean, RMS, and peak statistics for RAC orbit and clock differences and RMS and peak statistics for total, orbit, and clock UREs. A satellite was not included in the overall statistics if it had a clock event during the span of interest. Several selection options were included, such as Earth-fixed or inertial positions and antenna phase center or center-of-mass positions. The next utility program was used to plot the differences and UREs produced by this program.
11. *Trajectory/Clock Difference and URE Plots*
12. *Yaw Rate File Utility* computed average yaw rates for Block II/IIA satellites to make yaw attitude corrections in the Corrector, HV Corrector, and Trajectory Propagator programs. JPL-provided yaw rate estimates from the previous eclipse season for each satellite were used to obtain the averages used for the next eclipse season.
13. *RINEX-to-OMNIS (RTOOM) Utility* converted RINEX-formatted observations into the OMNIS Smoothed Measurement File format.
14. *SP3-to-OMNIS Utility*
15. *RINEX Navigation Message-to-OMNIS Utility* converted RINEX-formatted navigation messages into OMNIS-formatted trajectory and clock files.
16. *OCS Kalman-to-OMNIS Conversion Utility* created OMNIS-formatted trajectory and clock files from OCS information contained in the ODF output databases.
17. *Seven-Parameter Transformation Programs*: Two programs existed for computing seven-parameter Helmert transformations (three translations, three rotations, and scale), one based on two sets of station coordinates, and the other based on two sets of Earth-fixed satellite orbits.
18. *Ephemeris SP3 Comparison Plotting Program* compared two SP3 Files directly and created plots using the IDL software.

OMNIS also had a *Menu-Oriented Manager* (*MOM*) program for selecting input files, naming output files, selecting options and input values, and generating the corresponding run stream. *MOM* was run on an interactive terminal session and provided extensive menus for selecting various options and inputs. The menus were organized under four high-level groupings: Orbit Generation, GPS/Sequential Processor, Batch Processor, and Utilities. *MOM* always used a Default Values File to display nominal values for most menu items. These values could be overridden by a user as required to set up the appropriate run. During the interactive session, *MOM* would check the input entered by a user to see if it was within a predefined range. Entering a value out of range two times would cause it to be accepted. A user could save a modified Default Values File for use in a special series of runs. *MOM* built a shell script to execute the programs either in the foreground or in the background and the associated Process Files for each program. SCRIPTGEN, an interactive tool, was developed to assist in the generation of NIMA's precise GPS orbit and clock estimates. Input specific for generating daily precise orbit and clock estimates was requested and substituted in the appropriate shell scripts and process files.

Satellite Programs and Analyses Supported by the OMNIS GPS/Sequential Processor

GPS

The CELEST-based versions of the *Corrector/Editor* and *MSF/S* systems running on a CDC mainframe computer were used in studies prior to the OCS becoming operational in 1985. RMS differences between the *MSF/S* orbits (based on 15-minute smoothed pseudorange from the four GPS monitor stations and Australia and range difference data from the Republic of Seychelles) and the fitted portion of the standard NSOP-derived reference trajectories for five satellites over six weeks from the summer of 1984 ranged from 0.8 to 1.8 m in the radial direction, 7.9 to 15.3 m in the along-track direction, and 6.8 to 10.5 m in the cross-track direction. All *MSF/S* fits were done over one week with a mini-batch interval of one hour. The RMS residuals for the pseudorange data were 85 cm with a 16 cm RMS for the range difference data from Seychelles.

These CELEST-based versions were used for generating GPS precise ephemerides starting in December 1985 (GPS Week 309). There was a backlog in receiving OCS data so it took many months for the processing to catch up to shortly after each week ended. The original fit spans were eight days long (the week of interest plus half a day on either end) and a mini-batch interval of 60 minutes with a data interval of 15 minutes was used. The first four weeks were processed using the WGS 72 station coordinates and gravity field model in the J2000 inertial system. Starting in January 1986 (GPS Week 313), WGS 72 Doppler-derived coordinates for the GPS stations transformed to WGS 84, and the WGS 84 (8x8) gravity field model were first used. The initial *MSF/S* runs used 15-minute smoothed pseudorange data only. There were three DMA tracking stations operating, which were equipped with new receivers around this timeframe as discussed below.

Early in 1982, the DMA, with the assistance of ARL:UT, JHU APL, and NSWC, finished a specification for a field portable four-channel GPS geodetic receiver. During Texas Instruments' development of this receiver, the NSWC formulated, coded and, with the assistance of ARL:UT, tested the navigation software (called GESAR [Geodetic Satellite Receiver]) that allowed users to collect and record the tracking data. The NSWC also participated in the field test program for this receiver during 1984. Data collected by this receiver was also extensively analyzed at NSWC. This development and testing resulted in a deployable TI 4100 NAVSTAR [Navigation Satellite Timing and Ranging System] Navigator receiver system. TI 4100 receivers and supporting hardware were deployed to Argentina in late 1985 and to England and Australia in early 1986. A GE™ Mark III system received TI 4100 data, which was preprocessed on the CDC Cyber 170/865 computer system at the NSWC.

Early results of using the *MSF/S* system for computing the precise ephemerides were reported at meetings with the DMA and at the Performance Analysis Working Group (PAWG) meetings starting in July 1986. These follow-on meetings to DAWG meetings began after the switch to the OCS.

In early 1987, the NSWC presented results indicating the combined radial orbit and satellite clock accuracy for an eight-station network was better than 1.5 m and the horizontal orbit accuracy was better than 5.0 m. Initial runs using satellite clock process noise indicated that orbit-period sinusoidal variations were occurring in the clocks. Interferometric fitting techniques (white noise clock estimation for all clocks except a master) were used in experiments to try to quantify the magnitude of these orbit-period sinusoidal satellite clock variations and to determine process noise levels that would let the *Filter* track these variations. The worst case peak-to-peak variations for a Block I satellite Rb clock were 100ns with less than 20ns peak-to-peak variations for the Cs clocks. These clock variations were attributed to thermal clock variations during each orbit and were difficult to separate from the radial orbit variations. The OCS was using smaller process noise than the NSWC in order for the radial orbit estimates to compensate for these periodic variations in the clock so that they were predictable, even though they were really a clock variation and not a radial orbit variation. The NSWC gave several PAWG presentations on this work during this time period.

The NSWC used an IBM Series/1 minicomputer for OCS data preprocessing. Originally, OCS log files were provided and software on an IBM Series/1 computer had to extract the desired information. Initially, this consisted of both orbital initial conditions for all satellites and clock offsets for the satellites and stations. The clock offsets for the OCS master clock were used for steering to GPS time with special processing required whenever there was a master station switch. The OCS-developed Kalman Report Tool (KRTOOL) software provided data in a new ASCII format; it was implemented in August 1987 and upgraded in October 1988.

The OMNIS GPS/Sequential Processor was first used operationally at the NSWC for GPS orbit and clock estimation in August 1987. A few weeks prior to this date, TI 4100 receiver tracking data were added to the processing from new DMA stations in Ecuador and Bahrain, for a total of 10 stations. At that time only seven Block I satellites were available. In 1988, the first attempt to use range difference data (differences of consecutive carrier phase measurements) for orbit determination in the *MSF/S* systems was unsuccessful. The integrated effect of both the satellite and station clock noise was contained in each range difference measurement, but there was no way to account for this in the *Filter* other than to increase the measurement sigma to an appropriate level.

Initially, 12-hour orbit and clock overlap differences (middle 12 hours of the one-day overlap from noon Saturday to noon Sunday) were computed to get an idea of the accuracy of the estimates. For all of 1987 and 1988, based on six Block I satellites, the RMS overlap differences were 1.4 m for the clocks and 1.2 m, 2.7 m, and 1.9 m for the orbit RAC components, respectively. In January 1988, satellite clock process noise values were adjusted to better separate orbit period clock variations from the orbital eccentricity, the solid-Earth tide correction to the station coordinates was first implemented, and the minimum observation sigma for pseudorange was reduced to 75 cm from 100 cm. The overlap differences remained at the above level through the end of 1989. The weekly mean radiation pressure scale and y-axis bias acceleration estimates were monitored to try to understand how these estimates varied over time starting in 1987. Yearly reports containing these plots and supporting comments were generated.

Earth-orientation estimates for the middle day of each week were also differenced with the BIH final values. For weekly estimates from 1987, the mean x pole difference with BIH was 22 cm with a standard deviation of 12 cm. The mean y pole difference with BIH was -6 cm with a standard deviation of 9 cm. The mean UT1-UTC difference with BIH was 1.0 msec with a standard deviation of 2.4 msec. For weekly estimates from 1988, the mean x pole difference with the newly-formed IERS final value was 15 cm with a standard deviation of 10 cm. The mean y pole difference with IERS was -10 cm with a standard deviation of 10 cm. The mean UT1-UTC difference with IERS was -0.4 msec with a standard deviation of 3.2 msec. Studies indicated there was a scale difference between the Transit and GPS systems and a possible height bias in the WGS 84 reference frame used for GPS of approximately -1.2 m. This was based on the ten-station tracking network operating at the time.

The DMA was responsible for Earth-orientation predictions for the OCS; these were also provided to the NSWC. For the two pole coordinates, the functional representation included a bias plus annual (365-day) and Chandler (435-day) periods. These functions were fit to the past 435 days of USNO pole estimates. For UT1-UTC, the functional representation included a straight line plus four periodic components of 365 days and its first three harmonics. These functions were fit to the past 365 days of USNO UT1-UTC estimates. The DMA generated a new set of coefficients weekly based on the latest inputs from USNO. Daily coefficient set generation was initiated in 2009.

The IBM Series/1 was moved to the DMAHTC in September 1988 and, in October, the DMA station tracking data collection and preprocessing was also transferred to DMAHTC. The OMNIS precise ephemeris processing transitioned to the DMAHTC in January 1989 and run on its Sperry mainframe computer.

The first Block II satellite was not launched until February 1989. The original plan was to launch two satellites at a time on a NASA Space Shuttle out of VAFB. After the Challenger explosion in January 1986, the decision was made to launch them one at a time out of Cape Canaveral on Delta II rockets. The Block I satellites had all been launched out of VAFB on Atlas rockets into 63° inclination orbits. The maximum inclination reachable from Cape Canaveral was 55°.

Once Block II satellite launches began, the NSWC was tasked to do the orbit and clock estimation for the first few satellites for two reasons. The first was because this was a different spacecraft design; therefore, a different model for solar radiation pressure effects had to be implemented and tested in OMNIS. The second concerned the DMA Sperry mainframe computer's limitation for handling no more than seven satellites simultaneously in the *Filter* and *Smoother*. The NSWC received observation files containing just Block I observations from the DMAHTC and merged in the Block II observations to simultaneously estimate all GPS satellites on the CDC mainframe computers. The NSWC then studied how best to partition the satellites because of the DMAHTC computer limitations. At the beginning of 1990, Block II processing was transferred to the DMAHTC using two partitions, and this ended all NSWC GPS production processing. When needed, the NSWC modified its version of the OMNIS code to simultaneously handle more GPS satellites and stations. The *OMNIS User's Guide* was first published in April 1989. A second TI 4100 receiver was deployed to each of the existing five DMA stations in late 1989. The same selected satellite was tracked by both receivers at each station to collect the information required for adjusting the data from the second receiver to be consistent with the first receiver.

Fitting problems were encountered for each Block II satellite during the first few months after launch. Large overlap differences and an exponential decay in the radiation pressure scale estimates were observed. Outgassing was proposed as the source of these problems. A study was conducted in 1989 to determine how to reduce the increase in overlap differences present for all satellites experiencing eclipse seasons. The conclusion was that increasing the steady-state uncertainty on the radiation pressure scale parameter (modeled as a Gauss-Markov process with a de-correlation time of four hours) by an order of magnitude reduced the overlap differences. This change was adopted by the DMAHTC for production beginning in early 1990 along with estimating a stochastic tropospheric refraction parameter and reducing the minimum observation sigma for pseudorange to 55 cm. For 1990, the RMS overlap differences were reduced to 1.2 m for the clocks and 0.8 m, 1.9 m, and 1.9 m for the orbit RAC components, respectively. The accuracy of Earth-orientation differences versus IERS was estimated to be 5 cm or better in 1990, except for biases owing to reference frame differences. The average rotational rate over a week was estimated to an accuracy of better than 0.1 msec/day (5 cm/day).

Also in 1990, Block II satellite Selective Availability (SA) was turned on for 22 weeks. During this period, Block II satellite fits were based on OCS data only, since the DMAHTC did not yet have the capability to remove SA effects from the tracking data. There were six Block I and nine Block II satellites during most of 1990. Ignoring these weeks, the RMS overlap differences for all of 1990 overall satellites were 1.1 m for the clocks and 0.7 m, 1.8 m, and 1.8 m for the orbit RAC components, respectively.

In December 1989, the NSWC first learned the OCS was going to switch to operating in Composite Clock mode starting no earlier than February 1990. The OMNIS capability to adjust estimated clocks relative to a master clock to be consistent with GPS Time was developed to handle this change. The IBM Series/1 software was modified to extract the satellite clock offsets every 15 minutes in April 1990, but the actual OCS switch from Master Clock mode to Composite Clock mode did not occur until June. This was when the new clock adjustment process was first used in OMNIS to adjust the *Smoother* satellite and station clock estimates to be consistent with GPS Time.

The switch from two partitions (7 and 7) to three partitions (5, 5, and 5) at the DMAHTC took place on in October 1990 (GPS Week 563) when the 15th satellite became operational. The RMS overlap differences at this time were 1.2 m for the clocks and 0.8 m, 1.8 m, and 1.7 m for the orbit RAC components, respectively.

In January 1991, plate motion corrections to station coordinates were first implemented using the AM0-2 model, the zonal tide effects on UT1-UTC were added, and three additional Earth-orientation parameters were first estimated (x and y pole rates, and UT1-UTC acceleration). At the beginning of 1991, the following force models were being used: WGS 84 EGM [Earth Gravitational Model] truncated to 8th degree and order, Sun and Moon as point masses using the JPL DE200 ephemerides, 2nd-degree Legendre polynomial for the solid-Earth tide model (Love’s number = .29), ROCK4 for Block I satellites, ROCK42 for Block II satellites, y-axis acceleration (also eclipsed), and thrusts as needed. For Earth-fixed to inertial rotation, the following were used: J2000 epoch, 1976 IAU precession, 1980 IAU nutation, 1982 definition of UT1, and DMAHTC Earth-orientation predictions. The following corrections were applied to the tracking data: two-frequency ionospheric refraction applied to the raw data, signal propagation time, tropospheric refraction using the Hopfield model with measured weather data if available and a 1/sine(elevation angle) mapping function, periodic relativity, satellite antenna offsets, and station displacement due to solid-Earth tides.

Tracking data collected during the GPS IERS and Geodynamics (GIG) 1991 campaign were used for the first reference frame comparisons between WGS 84 and SV5, which was a reference frame developed in 1990 by the Massachusetts Institute of Technology for use in monitoring crustal deformation with GPS. There were five OCS and five NGA stations and 15 satellites at the time of this approximately three-week data collection period. Orbits in the SV5 reference frame—based on tracking data from 13 globally distributed JPL-designed Rogue receivers—were also computed to compare the WGS 84 and SV5 reference frames. The three translation parameters ranged from 12–16 cm in magnitude, and the largest rotation parameter was around the z axis of -11.3 milliarcseconds (mas), equivalent to -35 cm at Earth’s surface. Coordinates for the 10 OCS and NGA stations were derived using the SV5-based orbits and compared against the original Transit-derived WGS 84 coordinates. A mean height difference of approximately -1.5 m was obtained, meaning the WGS 84 heights were 1.5 m too high. A rotation about z of -13.8 mas was also obtained. Extensive studies were done on this dataset and included comparisons between OMNIS-estimated Earth orientation and the IERS estimates.

The GPS Joint Program Office-sponsored PAWG meetings were suspended after the spring of 1989 until November 1991, when the Air Force Space Command started sponsoring the meetings. The NSWC presented a series of comparisons of the OCS Kalman filter estimates vs. the DMA precise ephemerides and showed how the DMA estimates would change due to different modeling assumptions.

In May 1992, the OMNIS GPS processing was initiated on UNIX-based IBM RISC [reduced instruction set computer] System/6000 (RS/6000) workstations, then partitioning was eliminated and all satellites were estimated in a single partition starting in January 1993. In June 1993, the GPS orbit production processing moved from the DMAHTC in Bethesda, MD to the DMAAC in St. Louis, MO. A PC-based replacement for the IBM Series/1, the ODF, had become operational in February 1993, and was also moved to the DMAAC. In December 1992, Ashtech® Z-12 receivers were deployed to the five existing DMA tracking stations to replace the dual TI 4100 configurations. These receivers were upgraded to the Z(Y)-12 versions using Precise Positioning Service Security Modules (PPSSMs) in late 1994 and early 1995. The PPSSM module removed the SA effects from the GPS signals and allowed the receiver to track the Y-code. Random jumps in the computed residuals for the smoothed pseudorange data for a single satellite from the Ashtech receivers were encountered. These “channel events” were the result of a receiver problem and not real clock jumps. *ECAT* and *Editor* both had problems with these events.

Extensive comparisons were made between the weekly average radiation pressure scale and y-axis acceleration parameters from the OMNIS *Smoother* and weekly samples of the same quantities from the OCS Kalman filter for the Block I and II/IIA GPS satellites through 1993. There was a clear correlation of the variations with eclipse seasons and transients for the Block II/IIA satellites after each launch.

The NSWC first computed Allan variances based on the OMNIS *Smoother* GPS satellite clock estimates in 1994 to be able to better tune the clock estimation process noise. Several consecutive clock files output from OMNIS were merged prior to computing these Allan variances.

The first realization of the WGS 84 reference frame using GPS was done at NSWCDD in 1993. At the time there were five Air Force and five DMA tracking stations whose Transit-derived coordinates defined WGS 84. Starting in 1991, the DMA had adjusted the Transit-derived coordinates to account for plate motion effects using the AM0-2 plate motion model and an epoch of 1988.0 in their orbit computations. The Air Force continued to use the unadjusted coordinates. An improved set of WGS 84 coordinates was derived using smoothed pseudorange and range difference observations from the 10 stations processed simultaneously with the same data types collected at 22 globally-distributed Rogue receiver sites during the 1992 IGS Geodynamics campaign. There were 17 active GPS satellites at the time. The newer NUVEL NNR-1 plate motion model was used to derive coordinates at the 1988.0 epoch. The Gravitational Constant times Mass of Earth (GM) value was changed from 398600.5 to 398600.4418 km^3/sec^2 in deriving the new coordinates. Eight of the 22 IGS stations were held fixed using their ITRF91 coordinates in deriving the Air Force and DMA station coordinates. Antenna phase center coordinates were used for all stations. The white noise clock estimation method was used with a master clock selected that did not have any clock events. The most significant estimated Helmert transformation parameters between the Transit-derived and GPS-derived coordinates were a z translation of -28 cm, a scale of -21.8 parts in 10^8 (corresponds to -139 cm at Earth's surface), and a rotation about z of -15.6 mas (corresponds to -48 cm at Earth's surface). The estimated uncertainty in these station coordinates was 10 cm. The x and y pole coordinate estimates using these new coordinates still had mean differences vs. IERS of 10–20 cm in magnitude but standard deviations of about 2 cm.

In early 1994, the NUVEL NNR-1 plate motion model was implemented at the same time the first GPS-based WGS 84 realization of the reference frame, WGS 84 (G730), was implemented in the DMAAC's precise ephemeris processing. Also at this time, the minimum observation sigma for pseudorange was reduced to 45 cm. In early 1995, the Total RMS UREs of the precise orbit and clock estimates versus IGS for a 10-station network were 0.5 m. The WGS 84 (G730) station coordinate set was not implemented by the Air Force until July 1994.

In a 1995 study based on tracking data from 32 IGS stations, it was determined that by adopting a station network consisting of between 17 and 19 globally distributed stations, the DMA could improve the accuracy of its orbit and clock estimates by a factor of two. It also stated that additional improvements were possible by changing the estimation procedures, including using range difference data and double differencing techniques.

In the summer of 1995, the NSWCDD developed its first orbit and clock comparison capability that computed Orbit, Clock, and Total RMS UREs and provided the corresponding plots. The correlation between the radial orbit differences and the satellite clock differences was also computed for the first time. This capability was used extensively for evaluating the precise orbit and clock estimates and for numerous studies.

Starting in October 1995, the fit span was changed to three days (day of interest plus a day on either side) and 15-minute mini batches were first used. *ECAT* was implemented at the same time. WGS 84 (G730) coordinates for ten stations and DMA Geodetic Absolute Sequential Positioning (GASP)-determined coordinates for the USNO and China were used until late September 1996. The DMA developed the GASP program to estimate station coordinates using GPS observations. Also in 1995, Ashtech Z(Y)-12 receivers had been deployed to the USNO and to China.

In 1996, NSWCDD personnel completed the second realization of the WGS 84 reference frame using GPS. At the time there were five Air Force and seven NIMA tracking stations with USNO and China added since the first realization done using GPS. The Australia and England antennas had been moved since the first realization so had starting coordinates based on relative positioning from their previous locations. Ten days of tracking data from late 1995 were used and included data from 18 IGS stations using either Rogue or Turborogue receivers. ITRF94 coordinates were used for the IGS stations. There were 24 active GPS Block II/IIA satellites at the time. The NNR-NUVEL1A plate motion model was used to derive coordinates at the 1997.0 epoch. The coordinates for 11 of the 18 IGS stations were held fixed in deriving the Air Force and NIMA station coordinates. Antenna phase center coordinates were used for all stations. The white noise clock estimation method was used with a master clock selected that did not have any clock events. For the ten stations in common between the last realization and this one, a seven-parameter Helmert transformation was computed. The x, y, and z translations were -0.3, -1.2, and -1.1 cm, respectively. The scale parameter was 0.51 parts in 10^8 (corresponded to 3.3 cm at Earth's surface). The x, y, and z rotations were -1.47, -0.38, and -0.07 mas, respectively. The rotation about x of -1.47 mas corresponded to -4.6 cm at Earth's surface. The estimated uncertainty in these station coordinates was 5 cm. The x and y pole coordinate estimates derived using these new coordinates both had mean differences vs. IERS of 2.8 cm with standard deviations of about 2 cm.

In late September 1996, this second realization of the WGS 84 reference frame, WGS 84 (G873), was implemented in production at NIMA. At the same time, the processing was changed to use range difference data formed by differencing two successive carrier-phase observations for the same satellite/station pair in a process that used white noise clock estimation for all clocks except a master clock. This was equivalent to double-difference or interferometric processing and resulted in slightly noisier clock solutions. A two-stage processing method was implemented six weeks later with only smoothed pseudorange data used for clock estimation in the second stage. The second stage held fixed the improved orbits and Earth orientation from the first stage and only estimated the satellite and station clocks relative to a master, with realistic clock process noise used, and tropospheric refraction corrections. Significant improvement in the comparisons with the IGS resulted from these changes. The Orbit RMS UREs were now less than 10 cm and had been around the 30-cm level prior to these improvements. The clock estimates from the second-stage processing were less noisy than using just a single-stage estimation technique for both orbits and clocks. Their estimated accuracy was on the order of 25 cm or slightly better than one ns. In December 1996, an error in the solid-Earth tide correction implementation was fixed.

In support of the planned OCS Accuracy Improvement Initiative (AII), NSWCDD conducted a study in 1996 using OMNIS to predict the expected improvements in the OCS Kalman filter estimates and predictions resulting from adding smoothed pseudorange data from the six DMA stations and using a single partition for estimation. The study indicated a 50 percent improvement in the OCS Kalman filter estimates and a 20–35 percent improvement in the OCS 3-hourly predictions. Most of the improvement was because the DMA tracking data were included and not because a single partition was used. These results were presented at a PAWG meeting in August 1996.

The first successful Block IIR satellite launch occurred in July 1997 after a January failure. The OMNIS version resident at NIMA/St. Louis had previously been updated with the attitude and table look-up radiation pressure models for the Block IIR satellites. Estimation began as soon as tracking data became available. Additional changes (detailed below) were implemented in late November 1997 (GPS Week 934) and resulted in a further but smaller improvement than that obtained with the original two-stage processing implementation. Changes in the statistical assumptions for most of the stochastic parameters, including the satellite and station clocks, were made along with changes to the minimum observation sigmas. The EGM96 (12x12) gravity field model replaced the WGS 84 (8x8) model, and selected physical constants were changed to their IERS values if WGS 84 values were not defined. The JPL ephemerides DE403 was used for Sun, Moon, and planetary ephemerides. The Hopfield tropospheric refraction model was replaced by the Saastamoinen zenith dry and wet tropospheric refraction models and Neill mapping functions. The Neill wet-mapping function was used to estimate tropospheric refraction corrections. Random walk process noise replaced the Gauss-Markov process noise in the tropospheric refraction correction estimation. The minimum observation sigma for pseudorange data was changed from 45 to 40 cm except for Colorado Springs, which had its sigma increased to 100 cm. The minimum observation sigma for range difference data was changed from 3 to 1.5 cm. The steady-state sigmas on the radiation pressure scale and y-axis acceleration parameters were halved.

After these changes were in production, tracking data from several more stations were added to the NIMA processing: Alaska in September 1998, New Zealand in January 1999, South Africa in January 1999, South Korea in October 1999, and Tahiti in September 2000. The OCS also made the tracking data from its Cape Canaveral station available in 2001.

Two of the Block II satellites, SVN35 launched in August 1993 and SVN36 launched in March 1994, had laser retro-reflectors aboard. For the three-month period from December 1997 to February 1998, SLR [Satellite Laser Ranging] residuals were calculated using NASA-provided normal point data, with better than centimeter precision, from the NIMA precise ephemerides. The SLR data were corrected for tropospheric refraction effects, relativistic effects, the laser retro-reflector's offset from the satellite's center of mass, and station tide and plate motion effects. The RMS residuals were 8.2 cm for SVN35 using 576 points and 7.5 cm for SVN36 using 819 points. Both satellites had mean residuals of around -3 cm. The corresponding RMS residuals using the IGS precise ephemerides were 6.7 and 5.9 cm, respectively, with similar means.

In 1996, NSWCDD obtained the code for JPL's Block II/IIA attitude model and incorporated it into OMNIS. This model improved the modeling of the yaw attitude during each eclipse period and a half hour after exit from eclipse. This was needed because of the x component of the satellite's antenna offset was 28 cm and for the as-yet unimplemented carrier phase windup correction. Studies indicated that using the average JPL-estimated yaw rates from the previous eclipse season were adequate, and capability was implemented in *Corrector* and *HV Corrector* and first used in production in January 1999 (GPS Week 991). In April 1999, a correction to this implementation was made. NSWCDD used Analytical Graphics, Inc.'s Satellite Tool Kit software to visualize GPS attitude variations and solar radiation pressure effects during this time period.

As of June 1999, the Orbit RMS UREs were typically less than 7 cm, Clock RMS UREs were around 0.5 to 0.7 ns (15–21 cm), and all systematic differences between WGS 84 and ITRF96 were less than 3 cm. Orbit RMS UREs decreased to around 5 cm by mid-2000 as stations were added. In mid-September 1999 (GPS Week 1028), the process noise levels on all satellite and station clock parameters were adjusted. In November 1999, NIMA started removing zonal tides from the USNO UT1-UTC values before the predictions were done. In June 2000 (GPS Week 1066), diurnal and semidiurnal Earth-orientation corrections were first introduced into the OMNIS processing. Monitoring of Earth-orientation solutions and mean radiation pressure scale and y-axis acceleration estimates was transferred to NIMA in late 2000. In August 2001, the China station was decommissioned.

The third realization of the WGS 84 reference frame using GPS was done at NSWCDD in 2001. At the time there were five Air Force stations and 12 NIMA stations used in precise ephemeris computations. Stations in Alaska, New Zealand, South Africa, South Korea, and Tahiti had all been deployed since the second realization. WGS 84 (G873) coordinates for these five stations had been obtained by holding the coordinates of the other pre-existing NIMA and Air Force stations fixed while estimating the coordinates for each new station. For this realization, fifteen days of tracking data from February 2001 were used and included data from 49 IGS stations. The 30-second raw data from all IGS stations was processed to remove receiver-dependent biases before being smoothed. ITRF2000 coordinates were used for the IGS stations.

ITRF2000 velocities were adopted for all stations for the first time. For the Air Force and NIMA tracking stations, ITRF2000 velocities of nearby IGS stations were adopted as were a few provided by Dr. Demets from the University of Wisconsin. Antenna phase center coordinates were used for all stations. There were 28 active GPS Block II/IIA and IIR satellites at the time.

The reference trajectories for all satellites included the effects of ocean tides and the pole tide for the first time. The ROCK42 solar radiation pressure model was again used for the Block II/IIA satellites and the Lockheed Martin lookup table radiation pressure model was used for the Block IIR satellites. Diurnal and semidiurnal Earth-orientation corrections were included for the first time. The coordinates for 43 of the 49 IGS stations were held fixed in deriving the Air Force and NIMA station coordinates. The white noise clock estimation method was used with a master clock selected that did not have any clock events. For the first time, three tropospheric refraction parameters were estimated for each station to accommodate elevation- and azimuth-dependent variations in the troposphere. The 14 individual station coordinate solutions were combined formally for the first time using each solution’s full covariance matrix. A seven-parameter Helmert transformation was computed to examine the systematic differences between the starting WGS 84 (G873) coordinates for the NIMA and Air Force stations, and the refined coordinates at the adopted 2001.0 coordinate epoch. All the translation parameters were less than 0.8 cm in magnitude and the largest rotation parameter was a y rotation of -0.54 mas. This corresponded to about -1.7 cm at Earth’s surface. The scale parameter was -6.0 parts in 10^9, corresponding to about -3.8 cm at Earth’s surface. The estimated uncertainty in these station coordinates was 1 cm. The x and y pole coordinate estimates using these new coordinates had mean differences vs. IERS of -0.3 cm and 0.3 cm, respectively, with standard deviations of 0.3 and 0.5 cm.

The resulting WGS 84 (G1150) coordinates for all stations with an epoch of 2001.0 and their adopted velocities were used in the OMNIS processing starting in January 2002. In January 2003, ocean loading and pole tide corrections to station coordinates were first implemented. The IERS 1996 solid-Earth tide model also replaced the NSWC model in January 2003. The initial capabilities in OMNIS Version 9 were delivered to NIMA/St. Louis in July 2003 and a user’s guide in December. Version 9 included the carrier-derived pseudorange data type, a phase wind-up correction to both the carrier phase and range difference data types, and an orbit and clock prediction capability based on least squares fits to *Smoother* outputs. Additional JPL-developed solar radiation pressure models for both Block IIA and IIR satellites were added in 2004. This version was put into production use in early 2004 and the orbit prediction capability was first used to generate eight-day predictions. Prior to including the carrier-derived pseudorange for clock estimation, the RMS clock differences vs. IGS had been reduced to less than 15 cm. After this change, the RMS clock differences vs. IGS were around 10 cm with larger excursion (up to 20 cm) for days where the differences were dominated by either one or a few poorly estimated satellite clocks.

A GPS Improvement Study was initiated in July 2003 to examine how to improve both the Zero Age-of-Data (ZAOD) estimation and prediction capabilities of GPS. In support of this study, NSWCDD generated, evaluated, and distributed various GPS products including “truth” orbit and clock estimates, Earth-orientation estimates, as well as emulations of the OCS AII processing for a 17-day span. The “truth” included both 15-minute orbit and clock estimates and 30-second clock estimates. The OCS emulations were generated for the baseline Legacy AII case and for various cases with successive processing improvements included. ZAOD filter estimates and one-, two-, and three-hourly predictions were evaluated. These OCS emulation products were evaluated by various organizations. This study demonstrated the extensive capabilities and flexibility of the GPS/Sequential Processor part of OMNIS and NSWCDD's role in the greater GPS community that uses the ZAOD and prediction products.

A study was done in 2004 with OMNIS using IGS stations to examine the expected increases in orbit and clock estimation accuracies for station networks containing beyond 20 stations; 30-. 40-, 50-, and 80-station networks were analyzed. The results for 50 stations were essentially the same as for 80 stations. In going from 20 to 50 stations, the Orbit RMS UREs decreased from 4.2 to 3.5 cm, the Clock RMS UREs decreased from 8.1 to 6.0 cm, and the Total RMS UREs decreased from 7.7 to 5.6 cm. With a 30-station network, it was determined that at least eight stations could view each satellite nearly 90 percent of the time.

Fall of 2005 was when the AII version of the OCS legacy software was implemented and the NGA tracking data was first used in the OCS Kalman filter. The Architecture Evolution Plan version was implemented in September 2007 and involved moving from a 1970s-era mainframe computer to a distributed information technology infrastructure with advanced automation features.

In late spring of 2006, NSWCDD received its first data set from a prototype of new ITT, Inc.® receivers from ARL:UT. By the end of June 2007, NSWCDD had successfully processed a four-day smoothed data set collected with the latest prototype of this receiver and determined that the noise levels were comparable to those of the operational Ashtech Z(Y)-12 receivers. NSWCDD analyzed a five-day span of data collected by a prototype of the new ITT receiver in early 2009. The quantity and quality of the data set were both excellent. All NGA stations were updated to include two ITT MSN GPS receivers by mid-2010. Each receiver included the Selective Availability/ Anti-Spoofing Module so that they were unclassified when keyed.

The final updates to OMNIS Version 9, the last version, were delivered to NGA/St. Louis in March 2010 along with a user's guide. This version included the attitude and table lookup radiation pressure models for the Block IIF satellites and an option to eclipse the y-axis acceleration. The first Block IIF satellite was launched in May 2010. All Block I, II/IIA, IIR, and two Block IIF satellites (50 satellites in all) were processed in OMNIS before it was replaced by EPOCHA in February 2012.

WGS 84 (G1674), derived by the NGA using OMNIS with assistance from NSWCDD, was implemented on 8 February 2012 when the next generation EPOCHA software system became operational at the NGA. This was the first alignment of WGS 84 with the ITRF2008 reference frame, and it was achieved differently than any previous solutions. Since the NGA had been providing 30-second RINEX data to the IGS from its 11 monitor stations since 1996, ITRF2008 coordinate velocities had been computed by the IGS. However, by mid-2010 ITT receivers and antennas had replaced the Ashtech Z(Y)-12 receivers and antennas at all of NGA's stations. The ITRF2008 coordinates of the antenna reference point (ARP) for each station were first adjusted for any changes that had occurred, since several antenna locations had been changed, and then moved to the antenna phase center (APC). After this adjustment, there was still an unexplainable height difference for the Bahrain antenna location so its coordinates were estimated in the new realization along with the coordinates for the six OCS stations, which did not have ITRF2008 coordinates available. The NGA had evidence that its station in South Korea had moved significantly eastward after the March 2011 Japanese earthquake, so South Korea's east coordinate was estimated, but the other two directions were constrained. ITRF2008 velocities were adopted for all NGA and OCS stations.

A two-week period of data collected in late October 2011 was processed in OMNIS solving for daily coordinates for the OCS and two NGA stations while holding fixed the adjusted ITRF2008 coordinates of the other nine NGA stations. IERS96 Conventions were used along with a 2003 JPL model of the solar radiation pressure forces for the Block II/IIA satellites and table lookup models for all Block IIR and IIF satellites. White noise clock estimation was used with the USNO station clock designated as the master clock. The last three weeks of December 2011 were used to compare both the WGS 84(G1150) and the new WGS 84(G1674) reference frames against the ITRF2008 reference frame based on the OMNIS orbits computed in each WGS 84 frame and the IGS final orbits. All translation and rotation parameters decreased in going from WGS 84(G1150) to WGS 84(G1674) to be equivalent to 1 cm or less. The scale parameter for each comparison corresponded to a magnitude of 1.2 cm at GPS altitude.

NSWCDD obtained various IBM RS/6000 computer systems for OMNIS development, testing, and analysis after the switch from the CDC mainframes. The largest system was a Model 580 with 160 MB of memory, 7 GBs of hard disk storage, an 8 mm tape drive, a nine-track tape drive, and a ¼-inch tape drive. Both X-stations and 486 PCs running Windows™ 3.1, PC-X View, and TCP/IP were used to interface with the IBM RS/6000 systems for running OMNIS.

SATRACK

The capabilities of the CELEST-based *MSF/S* system were first briefed to JHU APL SATRACK personnel in early 1983. Comparisons were made in early 1985 between using SAMSAP (OPROG) and the CELEST-based SECD File generation using both simulated data and real SATRACK I data from a 1982 DASO flight and a 1984 OT flight. In September 1985, the JHU APL recommended replacing the TED file with the SECD file in SATRACK I processing. The first missile test flight event was a DASO flight in December 1985. The changes required to handle the then-future SATRACK II (for the Trident D5 missile test flights) update were documented in early 1984. The first SATRACK II-related processing did not occur until January 1987, and 19 D5X flights had been processed by the end of January 1989. Ten performance evaluation missile flights were supported in 1989 and 1990 followed by many Trident D5 DASO and OT tests and navigation tests.

Once the OMNIS version of the *MSF/S* system was available and thoroughly tested, it replaced the CELEST-based system in supporting the SATRACK program. In 1991, a comprehensive set of results for over 20 events was compiled that used static missile analyses to quantify the accuracy of the orbit and clock estimates and their covariance matrices. The orbit and clock estimates usually resulted in range errors below 1.0 m and range-rate errors under 0.6 mm/sec. The covariance estimates were also determined to be good representations of the actual errors in the orbit and clock estimates. The NSWC supported SATRACK for several more years, even after GPS production had been transferred to the DMAHTC. Eventually, after DMAHTC production had been transferred to the DMAAC, NSWCDD’s SATRACK participation ended in the fall of 1997, and support by NIMA/St. Louis using OMNIS was initiated. This transition required some changes to the SECD File format and used second-stage satellite clock offsets but first-stage covariance information. These changes were needed to accommodate the production processing methodology in effect at the time. Over the years, other missile programs such as ERIS [Exoatmospheric Reentry-vehicle Interceptor System] and MX [Missile-eXperimental] were also supported by this SECD File generation capability.

Host Vehicles (tracking GPS)

The initial planning for integrating a host vehicle (HV) orbit determination capability in OMNIS began in the early 1990s when the DMA requested a study. An *HV/Station Data Simulator* was written to assist in checkout of the *HV Corrector* and HV modifications to the *MSF/S* system. Both simulated and real data were processed. The real data were time-tagged with GPS time of emission and adjusted to account for ionospheric, SA dither, and antenna offset effects. All processing was done in GPS Time, but a Lagrangian interpolator was used to change the output trajectory and covariance information from GPS Time to UTC Time. Two HP Model 750 workstations, one unclassified and one classified, were originally used to check out the software and do the processing. A sensitivity analysis using the first real data set was performed to show how the estimated HV orbits varied based on different modeling and process noise assumptions. Additional real data sets were processed using a subset of the cases studied for the first data set.

A set of SA-free GPS tracking data collected on board the TOPEX radar altimeter satellite during November 1993 were also used in these studies. TOPEX included an experimental six-channel L1/L2 GPS demonstration receiver developed by Motorola®. During this time period, 19 GPS satellites had SA turned off, but only 17 of these were tracked by TOPEX. The TOPEX tracking data were sampled to approximate the tracking scenario for the HV under study. An attitude model for TOPEX was implemented in *HV Corrector* and used to make the antenna offset correction. Additional real data sets were obtained in the mid-1990s and processed using OMNIS. The 3-hourly predict messages were used for the first time in processing these data sets. For an AII-related study, NSWCDD evaluated the expected accuracy improvement in the OCS Kalman filter estimates and the 3-hourly prediction messages due to adding the DMA tracking data from six stations and using a single partition for estimation. These improved estimates and predictions were generated for these additional real data set days and used in the HV studies.

The purpose of an additional study was to evaluate the future HV positioning accuracy attainable using data from a state-of-the-art GPS receiver and both differential and non-differential estimation approaches. Two HV orbital configurations were studied. An additional goal was to determine the minimum number of ground-based tracking stations required for the differential approach. The real data from the TOPEX mission described above were processed in differential and non-differential modes using a subset of the available station tracking sites. Simulated data were used to extend the results to the two HV orbital configurations of interest, which involved different altitudes and inclinations. These simulations used realistic HV force model, GPS orbit and clock, and measurement-related errors. Enhancements to the existing WGS 84 models were also incorporated into this study. Two sources of GPS orbits and clocks were used in a mode that did not require station tracking data but did include estimating stochastic range biases to account for the GPS orbit and clock errors: OCS Kalman estimates and DMA precise estimates. Estimating the HV and GPS orbits and clocks simultaneously in both differential and non-differential modes was also studied. These modes did require station tracking data.

A 30-hour data set, consisting of five-minute smoothed GPS pseudorange and carrier phase data converted to range difference data from November 1993, was analyzed in detail to study how well OMNIS could be used to estimate precise orbits for the TOPEX satellite. The force model used to process the data set consisted of the JGM [Joint Gravity Model]-2 (70x70) gravity field model, a solid-Earth tide model, Sun and Moon point mass gravity effects, the Jacchia-Bass atmospheric density model and a geophysical database with a single drag coefficient assuming a spherical spacecraft model, and a single radiation pressure coefficient assuming a spherical spacecraft model. Corrections were made to the data for signal propagation delays, periodic relativity for both TOPEX and GPS, GPS antenna phase center offsets, and the TOPEX antenna phase center offset. GPS orbit and clock estimates were generated using a five-minute data set from fifteen IGS Rogue receiver sites and a 15-minute data set from the ten OCS/NGA tracking stations. The OCS Kalman filter ZAOD orbit and clock estimates were also used in this study. The RMS agreement between the two network solutions was 0.7, 0.4, 1.2, and 0.9 m for the clock, radial, along-track, and cross-track components, respectively. The agreement between the OCS estimates and the 10-station OCS/NGA smoothed solution was 1.3, 1.2, 4.6, and 3.4 m for the clock, radial, along-track, and cross-track components, respectively. Several solution techniques were evaluated for the TOPEX orbit determination involving simultaneous GPS and TOPEX estimation and with each set of GPS orbit and clock estimates held fixed. TOPEX RMS orbit differences versus the JPL precise TOPEX orbits were typically 5, 15, and 14 cm in the radial, along-track, and cross-track directions, respectively. The study conclusions were that non-simultaneous GPS and TOPEX estimation gave similar results to simultaneous estimation, and solving for stochastic biases to account for errors in the OCS Kalman filter estimates did not significantly improve the TOPEX orbit estimates.

Additionally, HV UREs were analyzed along with OCS-provided covariance matrices for the ZAOD and 3-hourly prediction products. Spaced-based TOPEX satellite orbit UREs were computed for the OCS Kalman filter estimates with the DMA precise orbit and clock estimates used as “truth.” The space-based RMS UREs was approximately 15 percent larger than the ground-based RMS UREs.

The Shuttle Radar Topography Mission (SRTM) was a joint effort by NASA and NIMA to provide a digital elevation model for the land masses from 56° south latitude to 60° north latitude using orbiting interferometric synthetic aperture radar. The radar system, using an antenna in the payload bay and one on a 60 m mast, flew on the Space Shuttle Endeavour STS-99 mission from February 11–22, 2000. Two JPL-designed GPS receivers with separate antennas and clocks collected observations for orbit determination. NSWCDD was tasked to generate orbits for the Space Shuttle to validate the official JPL-determined orbits. Thirty-second observations, which were corrupted by SA effects, were corrected by ARL:UT and became classified. A classified computer system was therefore used to compute the Shuttle’s orbits. Thirty-second GPS satellite clock offsets were estimated using 30-second RINEX data from the 12 NIMA stations while holding fixed the production GPS orbits. These satellite clock estimates and the production orbits provided the GPS satellite estimates for processing the SRTM 30-second GPS tracking data. Satellite attitude data in the form of quaternions were received from JPL, and an interpolation technique was added to the *HV Corrector* to use this information to correct the data to be instantaneous at the center of mass of the Shuttle. OMNIS had to be modified to handle two on-board receivers, each with its own clock. Orbits were computed for 19 spans varying in length from 3.1 to 27.1 hours and compared against the JPL-derived orbits; one-revolution overlaps were also computed for each source of orbits. Except for a few limited time spans, the level of agreement validated and supported the SRTM mission positioning accuracy requirement of 60 cm RMS error per RAC orbit component.

For the classified processing using OMNIS, NSWCDD used HP9000-755 workstations with 96 MBs of memory, 4 GBs of hard disk storage, a 4 mm tape drive, and a printer. NSWCDD also used a Sun Microsystem, Inc. Scalable Processor Architecture (SPARC) II with 32 MBs of memory, 3 GBs of hard disk storage, and a ¼-inch tape drive. 486 PCs running Windows 3.1, PC-X View, and TCP/IP were used to interface with the HP9000 systems to run OMNIS. The HP workstations were later decommissioned and replaced by an IBM workstation.

Satellite Programs Supported by the OMNIS Batch Processor

Transit

The OMNIS Batch Processor capability was available at the DMAHTC by the late 1980s with support provided as needed by the NSWC. The DMAHTC continued to generate precise ephemerides for all Transit satellites until the SMTP network was shut down at the end of September 1993. Shutting down the over 40-station tracking network also resulted in terminating estimation of orbits for the Polar Orbiting Geomagnetic Survey (POGS) satellite. Transit's navigation mission ended in 1996.

POGS

POGS was launched in April 1990 into a 690 km altitude circular orbit at an inclination of 90°. It transmitted on the 400/150 MHz frequency pair, was tracked by the TRANET and SMTP networks, and the DMAHTC computed the orbits for the Navy. The NSWC supported the DMAHTC whenever there were orbit determination problems for this satellite.

GEOSAT Follow-on

This was a Navy-sponsored satellite launched in February 1998 into the same orbit the GEOSAT ERM used. The satellite included a Doppler transmitter that was tracked by the TRANET system and Magnavox MX-1502 receivers. The orbits for this satellite were computed by NIMA/St. Louis for several years. The satellite was not decommissioned until October 2008.

RADCAL [Radar Calibration]/DMSP [Defense Meteorological Satellite Program]

RADCAL was launched in June 1993 into a slightly eccentric orbit with a mean altitude of 840 km and an inclination of 89.5°. It was used to calibrate C-Band radars as part of the DoD's Radar Performance Monitoring capability. The orbits were first computed at NSWC, then the computations were transferred to NIMA/St. Louis in October 2000. Because of the reliability of the aging RADCAL satellite, the NGA started computing orbits in parallel for the DMSP F15 satellite in August 2007. This satellite also had a C-Band transponder and was launched in 1999 into an 840 km altitude Sun-synchronous orbit inclined at 98.9°. The RADCAL orbit determination processing was stopped in early May 2013. Orbit determination for this DMSP satellite is continuing at NGA/St. Louis using the OMNIS Batch Processor running on a virtual machine using the AIX operating system. At least one IBM workstation was maintained at NSWCDD until 2013 in support of the use of the OMNIS Batch Processor for the NGA's RADCAL and DMSP satellite orbit determination.

ASTER [ADVANCED SATELLITE TRAJECTORY ESTIMATION ROUTINE] (1989–1993)

The objective of a project initiated in the late 1980s was to develop engineering software for precise ephemeris estimation for a mid-altitude, mid-inclination satellite using relay, Space-Ground Link System, and auxiliary tracking data. ASTER was supposed to operate in both near-real-time and post-processing modes. The software system was to consist of a *Filter/Smoother* module, a *Point Editor* module, a *Solution* module, a *Propagation* module, and a *Diagnostic/Planning* module developed over a three-year period. This software development was the NSWC's first use of the C++ programming language for orbit determination. The OMNIS *Orbit Generation* program was modified to write C-formatted trajectories and Earth-rotation matrix files. Development was started using C++ on PCs.

A prototype system was developed using object-oriented program design with C++ to meet DMA requirements to provide an interim capability for precise satellite ephemeris determination. This development involved a PC-based software package and validation of the entire system in a simulated operational environment. A laboratory acceptance test of the hardware and software system occurred at the NSWC in April 1991. This was followed by a system transfer and a site acceptance test at DMAAC in St. Louis. The software was ported to a SPARC II workstation in early 1992 for further development. The SPARC computer, manuals, and the existing ASTER software were delivered to the DMAAC in March 1993. Work was then terminated after it was learned in mid-1994 that an alternative source of ephemerides that met mission requirements would be made available to the DMAAC.

EPOCHA [ESTIMATION AND PREDICTION OF ORBITS AND CLOCKS TO HIGH ACCURACY] (2002–PRESENT)

In early 2002, NSWCDD began work on defining requirements for a real-time version of the OMNIS/GPS Sequential Processor. An NSWCDD Real-Time OMNIS (RTO) Requirements Working Group was established and a system requirements specification (SRS) document including preliminary requirements was written and discussed extensively with NIMA and ARL:UT during the spring and summer of 2002. After many revisions, the SRS was then considered complete, and the name of the program to be developed was changed from RTO to EPOCHA to differentiate it from OMNIS. EPOCHA development and implementation used objective-oriented principles and was written in C++. Like OMNIS, it was a Multisatellite sequential estimation *Filter* but with the addition of a short-term (up to nine hours) prediction capability for real-time use and a *Smoother* augmented with a long-term (3–9 days) orbit prediction capability for batch use. A long-term clock prediction requirement was added later. Every OMNIS run used a Cold Start to initialize the *Filter*, but EPOCHA had both Cold Start and Warm Start capabilities. In its evolving form, EPOCHA processed GPS pseudorange and carrier phase observations with estimation of the carrier phase biases and included extensive automatic observation editing along with clock event detection and accommodation. Because of these carrier phase biases, the number of parameters being estimated continually changed, contrary to the fixed parameter set used in OMNIS. EPOCHA was also implemented so that either a Master Clock mode or a Composite Clock mode (both with steering/adjustment to GPS time and frequency) could be used.

Because of the learning curve required to use object-oriented design and C++ and the use of databases instead of files, an incremental approach to EPOCHA development was implemented and is described first; details of the various EPOCHA modules developed are subsequently presented. The result of this approach, and the use of a GUI for all interactions with the computational modules and their databases, has provided an extremely user-friendly and flexible GPS data processing and analysis capability.

The Unified Modeling Language (UML) was used to generate diagrams of the use cases

EPOCHA had to handle. Three users were defined in early 2003: Operational Analyst, Monitoring Analyst, and Offline Analyst. Use cases were defined for each task to describe how each user could interact with the EPOCHA software. Operational Analysts would control the real-time process while several Monitoring Analysts would also view and analyze the results. Offline Analysts would operate EPOCHA in either real-time or batch mode. A Domain Dictionary was generated to define the terms used in the design effort. Activity Diagrams for more complex use cases were generated to visualize the sequence of activities and identify any parallel steps involved. An EPOCHA software development plan was written that contained proposed schedules for design, development, test, delivery, and training. A requirements, analysis, and design document was also generated that included use cases and the Domain Dictionary. Conceptual class diagrams were also generated to identify concepts that needed to be modeled in the software and associations between classes. An EPOCHA coding standards document was also written and updated as needed.

A decision was made early on to use SPARC workstations for EPOCHA development and operations to be consistent with NGA Monitor Station Network Control Center (MSNCC) processing. In mid-2004, a Sun Fire V880 server and a Sun Blade 2000 workstation were delivered to NSWCDD, and EPOCHA code development was initiated. EPOCHA development was planned to be incremental and was to include a *Filter* and a *Smoother* just like OMNIS. However, a decision was made to use an extended Kalman filter with a square-root covariance (UD) implementation in place of the linearized Kalman filter with a square-root information implementation adopted for OMNIS, primarily because the EPOCHA *Filter* had to run in real time and have replay/restart capabilities. The initial draft of the EPOCHA *Filter*/*Smoother* formulation was completed in early 2004. The initial database-oriented version of EPOCHA was to be written in C++ with some wrapped Fortran 90 from OMNIS. EPOCHA also used an extensive GUI for starting/restarting program modules, entering events, and analyzing results.

Defining the real-time interface for getting the OCS tracking data and Kalman filter outputs and the NGA tracking data into EPOCHA using the associated binary exchange (BINEX) files began in 2004, and was documented in the *MSNCC/EPOCHA Interface Definition Document.* The first working copy was available in January 2005. Work also started on defining the Static database and databases for storing the tracking data (the Preprocessed Observation [PO] database) and the OCS Kalman filter information (the External Satellite/Station Parameters [ESSP] database). Oracle Corporation’s Berkeley DB database software was eventually used instead of a full relational database management system, and initial GUI table layouts were developed. All of this work resulted in an EPOCHA Software System Design Review with NGA/St. Louis and ARL:UT personnel in February 2005. All documentation was updated after this review.

In the summer of 2005, the first discussions took place on what was to become the classified EPOCHA Development Laboratory (EDL), and a decision was made for NGA analysts to use ORACLE® Sun Ray thin clients to operationally interface with EPOCHA. The initial requirements for the GUI time history plots from *Filter* and *Smoother* were also written this summer. Initial EPOCHA event definitions were also written during this time period; any change to the *Filter* processing had to be made through an event. The first comparison between orbits generated by OMNIS and EPOCHA occurred in late 2005. Extensive unit testing began, and a draft system test plan was written.

By early 2006, all forces except for thrusts had been implemented in the C++ orbit integration code for both the multi-step and the RK integrators. The station propagation model, except for the ocean loading model, was completed in C++, and the first three clock events (Reinitialization, Time Change, and Frequency Change) were defined.

The first EPOCHA Change Review Board meeting was held in May 2006. The OMNIS Fortran code used for computing the rotation matrix between the ECI frame and the Earth-Centered-Earth-Fixed frame, following the IERS96 Conventions, was rewritten in C++ and thoroughly tested around this time. By the end of 2006, significant progress had been made in developing and testing the EPOCHA *Filter*. This included the capability of estimating most of the parameters, designating a master clock, incorporating thrusts into the force model, processing a limited set of orbit and clock event types, and defining and designing the Filter Database. A utility was written to extract information from this database and write OMNIS-formatted trajectory and clock files. All of this work resulted in the development, testing, and delivery of Version 0.9 to the NGA in January 2007. Version 0.9 assumed all observation correcting and editing and event identification had already been done by OMNIS. This version could also only process pseudorange and carrier-derived pseudorange observations. Training was provided to NGA personnel so they could begin experimenting with EPOCHA.

The classified EDL was established in April 2007 and consisted of three SPARC workstations. EPOCHA Version 0.10 was developed, tested, and delivered to the NGA in October 2007. This version included significant efficiency improvements in the *Filter*, a state-only *Smoother*, and an upgraded GUI. Excellent agreement was obtained between both the EPOCHA *Filter* and *Smoother* results and the equivalent OMNIS results. Two-day fit spans for each day of interest using observations at a five-minute rate were adopted as EPOCHA's initial processing mode.

Development of Version 1.0, the first version of EPOCHA to be independent of OMNIS was next. In late 2007, the first warm starts were successfully completed, and multiple batch sessions could be run simultaneously by a single user. In April 2008, the proposed contents of the output of the EPOCHA *Products Manager* were first discussed with the ARL:UT. The first comparison of EPOCHA *Smoother* results with the IGS final orbit and clock estimates was completed in the summer of 2008. The Total, Orbit, and Clock RMS UREs versus IGS were 8.3, 7.1, and 10.4 cm, respectively. The OMNIS precise RMS UREs versus IGS for the same case were 8.9, 5.4, and 10.0 cm, respectively.

A preliminary capability for reading and using MSNCC/EPOCHA data messages was developed and successfully tested in late 2008. Prior to this time, the same tracking data and OCS Kalman filter ASCII files that fed OMNIS were imported into the PO and ESSP databases. NSWCDD delivered Version 1.0 to the NGA in February 2009. This version included carrier phase processing for the first time but still no covariance *Smoother*. Version 1.1 contained the following additional capabilities: the covariance *Smoother* option; enhancements to the *Filter* Warm Start and Restart processing; satellite/station pair masking by data type; input of clock Reinitialization time offsets in meters or ns; thrust input in the form of a delta-v (in ft./sec), a prograde/retrograde indicator, a start time in Hr:Min:Sec, and a duration (in seconds); *Long-Term Orbit Predictor* (*LTOP*); and numerous GUI enhancements. A special capability was added to EPOCHA in 2009 for processing SVN49, which was the first GPS Block IIR satellite launched to broadcast on the L5 frequency but had on-board frequency interference issues.

Most of the detailed requirements for Version 2.0, the first real-time version, were finalized by June 2009. Version 2.0 development began and included the following additional capabilities: *Short-Term Predictor* (*STP*), *STP Evaluator*, *Products Manager*, use of a Composite Clock in *Filter*, the *Weekly Transition Tool*, the *New Session Wizard*, and several GUI upgrades including auto-refreshing *Filter* plots. Version 2.0 also included an update for transforming orbit covariance matrices from inertial to Earth-fixed by properly accounting for the uncertainties in Earth orientation and its correlations with the inertial orbit parameters. The NGA started using Version 1.1 for data analysis and training in October 2009, and NSWCDD delivered a patch release Version 1.2 in March 2010. By mid-summer 2010, tracking data were flowing to NSWCDD in real time to both the unclassified development workstations and the classified EDL workstations. The unclassified stream only included the data from the 11 NGA tracking stations. The classified stream also included the data from the six OCS tracking stations and OCS Kalman filter estimates for the orbits and satellite and station clocks. These OCS clock estimates were first used in Version 2.0 in late 2010 to steer the EPOCHA Composite Clock to GPS Time. Version 2.0 was the first system to undergo a 30-day real-time system test that included running *Filter*, *STP*, *STP Evaluator*, *Smoother*, *LTOP*, and *Products Manager*.

In July 2011, Version 2.0 was delivered to the NGA. Training on this real-time version was conducted in September and the NGA starting using this version for experimental real-time processing. While NSWCDD was developing Version 2.0, the NGA was running extensive tests on EPOCHA Version 1.2, which finally replaced OMNIS for precise ephemeris estimation in late February 2012. Version 2.1, delivered in the fall of 2012, included rewriting all the remaining Fortran code in C++, implementing IERS 2003 Conventions and IERS 2010 Conventions, implementing the phase center variations (Antenna Exchange [ANTEX]) Format File for satellite and station antenna offset computations, generating a *Smoother* Report File, implementing a Change Station Properties event, and the first version of the *Product Comparison Tool* (*PCT*). Version 2.1.1 was then developed to include adjusting *Smoother* clock estimates to GPS Time, a fix to the handling of leap seconds in UTC, and the first version of the Normalized Group Residual (NGR) carrier phase editing algorithm. Version 2.1.2 included an enhancement to the clock adjustments in *Smoother*, a *Clock Extractor* utility, and an *SP3 File Writer* utility. It was delivered in early 2013. For Version 2.2, all database interactions were switched to the Oracle® MySQL; the Berkeley DB software had proven unreliable. Conversion to MySQL was an extensive effort. This version was the first to run on a virtual machine operating the Oracle® Solaris operating system on an Intel™ platform.

ARL:UT installed unclassified and classified Virtual Host Environment hardware based on Intel™ processors at NSWCDD in the summer of 2013. The NGA switched EPOCHA production from using Version 1.2 to using Version 2.1.2 in the fall of 2013. Version 2.2 was delivered to the NGA in January 2014 and experimental use of this version began that spring.

In June 2015, EPOCHA Version 2.3 was delivered to the NGA and installed on the recently deployed x86 legacy sustainment hardware using virtual machines. Version 2.3 included a GPS III processing capability; a *Launch and Checkout Capability (LCC) File* creation utility; automatic removal/addition of OCS-masked/unmasked platforms that were part of the Composite Clock, automatic generation of Set EO [Earth Orientation] Reference Model and IERS UT1-UTC Rapid Parameter events; an EPOCHA High-level Summary; maintenance of open plots and tables during a restart, using computed pseudorange observations on option to initialize the carrier phase biases; *PCT* enhancements, and several new user features. EPOCHA Version 2.4 was delivered to the NGA in September 2015, followed by two minor patch versions. The initial capabilities for the Data Availability Metrics were included along with predicting clocks in the *LTP*. This was the first version to be installed on the virtual machines at NGA Campus East (NCE). Version 2.4 was first used in production in early 2016.

EPOCHA Version 3 was delivered to the NGA in May 2016. Version 3 included a GUI for editing the Static Database, advanced user features, improved data editing through implementation of the residual magnitude threshold (RMT) test and data reprocessing, additional *PCT* enhancements, use of navigation message-derived initial conditions (Navmic) messages for initializing a satellite that does not yet have OCS Kalman filter estimates and an *Events Transfer* utility (needed for initial GPS III processing, and adding sinusoidal satellite clock parameters for improving *STP* clock prediction accuracies for selected satellites. An EPOCHA Version 3, Release 1, was developed and delivered to the NGA in July 2016 for future support of OCX [Next-Generation Operational Control System] testing activities in July 2016. This version included updated GPS Block IIA and IIR radiation pressure models made available by the JPL and fixed the problem with the phase center variations computations. The NGA transitioned to using this version in production in October 2016. It was also installed shortly thereafter on NCE virtual machines. A few minor revisions to Version 3 have been since been provided to the NGA.

EPOCHA Version 4 development, the first version to run under Red Hat® Enterprise Linux 7®, has been completed. This version includes the following features: capability to allow operations to be shifted from a virtual machine at NGA/St. Louis to one at NCE with minimal interruptions; the ability to delete products while product forwarding is paused for troubleshooting purposes; enhancements to the Data Availability Metrics based on *Filter* information; EPOCHA Help features; a utility to output station-related information for verifying what is currently being used by the *Filter*; SVN-centric processing in EPOCHA; a standalone *Station Coordinate Calculator* to access station coordinates from various sources, move them to a different epoch, and output quantities to a file; a redesign of the Events Database and the *Events Database Editor*; and an initial version of a clock event detector that automatically identifies clock events and completes the necessary reprocessing to handle them appropriately. System testing of Version 4 is currently underway.

Analyst Types

There are three analyst types available for operating EPOCHA: Operational, Monitoring, and Offline. There can be only one Operational Analyst at a time, and this analyst always does real-time processing. There can be several Monitoring Analysts simultaneously viewing real-time results with their own GUIs. The Real-time Operational Analyst is automatically logged off after a certain length of time without GUI activity. Any Monitoring Analyst can easily switch to Operational Analyst if one is not active through an icon. All previously opened displays remain open when switching between these two user types and when the Operational Analyst is doing a Restart. Events to handle anomalies or other required changes can only be entered by the Operational Analyst. There can be several Offline Analysts running simultaneously either in Real-time or Batch modes. A New Session Wizard assists an Offline Analyst set up a session in either Real-time or Batch mode using either the current operational real-time stream and associated PO and ESSP databases or archived PO and ESSP databases for input data.

Session Editor

Each use of EPOCHA is called a Session, and can be either Real-time or Batch. The *Session Editor* enables users to set up their desired session either starting without any prior information or based on any user's existing session. Through the *Editor,* a user can specify whether the session is Real-time or Batch, all input and output databases, and output file directories. These databases include: Static, ESSP, PO, Events, and Filter Input if doing a Warm Start (New). The input database names for the real-time ESSP and PO databases are not under user control. Warm Start (New) means warm starting the *Filter* from an existing database but storing its output in a new database. The name of the output Filter Database is based on the Session name. There is one output file directory for all program outputs and if the Generate Products option in the *Session Editor* is selected, a products directory for Offline Analysts is required. The Operational Analyst products have a predefined method for storing products. All sessions require a *Filter* Start Time, a processing interval, and a *Filter* End Time or Processing Span for Batch mode runs. For *Filter,* users must also specify whether the start mode is Cold Start, Warm Start (New), or Warm Start (Existing). An option exists for warm-starting the *Filter* at the last Filter Database timeline for the last two start modes. For a cold start, users must also specify the source and identification for Earth-orientation model information to be used. If running in Master Clock Mode with a Cold Start, the *Session Editor* requires users to specify the identification for the station or satellite that will serve as the initial master clock.

Separate tabs exist on the *Session Editor* window for entering information for *Smoother/LTP* and for the two *STP* modes of operation. For *Smoother,* the inputs include whether to use the State-Only or Covariance *Smoother*, the start time and span of the first *Smoother* associated with the session, and the interval for running future *Smoothers*. Typically the *Smoother* for a given day of interest starts a half day before and ends a half day after this day of interest, and each successive *Smoother* runs a day later. The name of the output Smoother Database is based on the Session name. For *LTP,* the inputs include the Observation Type (either position only or position and velocity), the Fit Times information, and the Output Times information. Typically, *LTP* will fit over the entire two-day *Smoother* span and predict nine days forward. The name of the output LTP Database is based on the Session name. For each of two *STP* modes, the input includes Output Times (start time of the first *STP* run), Run Interval (how often the predictions are done), and Output Interval (the internal interval associated with each prediction). Options allow users to compute or not compute covariance predictions and whether to repeat existing predictions if *Filter* is restarted in the past. The name of the output STP Database is based on the Session name.

Icons exist for starting and stopping a Session, restarting a Session involving backing up in time to process a newly defined event, and pausing product forwarding for real-time Sessions.

Static Database Editor

The Static Database contains all the inputs required to run all programs except for those inputs specified in the *Session Editor.* Each version of EPOCHA has a default Static Database, and the *Static Database Editor* will update a previous version's Static Database to the current version. The *Static Database Editor* provides a user-friendly interface for changing default values, including additional satellites and stations, and adding processing information through categories. Categories are used extensively to group inputs for satellites and/or stations that have common characteristics. There are several inputs for constants common to all satellites related to gravitational, tidal, and radiation pressure forces. There are controls for the *Filter* and *Smoother* and time system options related to the use of either a Composite Clock mode with steering to GPS Time and Frequency or a Master Clock mode. Earth-orientation model, estimation, and prediction inputs are present. For each satellite all orbit- and clock-related model, estimation, and prediction inputs are also present. For each station inputs for all estimated parameters are required along with observation types to use and their corresponding minimum observation sigmas, corrections to be made, and possible station tracking obstructions to account for. The station coordinates are input in terms of epoch position and velocity of either a geodetic mark, the ARP, or the two-frequency electrical APC, and may require input of the height above the mark and the height of the APC above the ARP. An ANTEX file can be specified and options exist to use or not use the phase center offsets and variations for either satellites or stations. Station displacement model options include the effects of the solid-Earth tide, ocean loading, and pole tide. There is also a tool for comparing two Static databases for the same EPOCHA version.

Filter

Since EPOCHA uses an extended Kalman filter algorithm, the *Filter* must do almost everything the OMNIS *Orbit Generation*, *Corrector/Editor* Subsystem, and *Multisatellite Filter* did. For a cold start with any satellite's initial conditions not at the designated epoch, orbit integration is required to update the position and velocity for each affected satellite to this epoch. An RK integrator is usually used for this update and for routine integration from one *Filter* timeline to the next. It also has to integrate the variational equations for each satellite to get the partial derivatives required to propagate the orbit-related part of the covariance matrix to the next timeline. Typically, the RK78 version is used, but RK24, RK45, and RKSHANKS8 versions are also available.

The inertial reference frame used is selectable through the Static Database from three frames as defined by either the IERS 96, 2003, or 2010 Conventions. Earth-orientation information is usually obtained from NGA-predicted coefficient sets but can use IERS daily values on option. Cubic interpolation in the corresponding daily table of Earth-orientation parameters is used to get values at arbitrary times each day. Diurnal and semidiurnal perturbations to all three Earth-orientation parameters can be applied on option. The GPS Time system is used throughout EPOCHA, except that the time associated with the Sun, Moon, and planetary ephemerides is Terrestrial Time (TT), and TT = GPS Time + 51.184 seconds. A Leap Seconds file is input and used as needed.

The satellite equations of motion modeled in EPOCHA include:

1. Gravitational accelerations of Earth expressed in spherical harmonics using up to 2500 terms (up to 70th degree and order)
2. Solid-Earth lunar and solar tidal accelerations and ocean and atmospheric tidal accelerations
3. Constant thrust acceleration in the RAC frame over a specified interval
4. Radiation pressure acceleration (including y-axis acceleration)
5. Gravitational attraction of the Sun, Moon, and the planets

Each acceleration component is evaluated in its reference frame and rotated if necessary into the inertial frame. Partial derivatives, with respect to a solar radiation pressure scale factor (one or two) and y-axis acceleration and thrusts, can be generated based on integrating the variational equations. A five-minute integration step is used most of the time but an integration step size of 10 seconds is used to handle discontinuities due to thrusts and eclipse shadow boundary crossings.

The EGM2008 Earth gravity model (12x12) is used. A tidal potential model computes the gravitational acceleration on the satellite due to changes in Earth in response to the Sun and

Moon's tidal forces. The selected IERS Conventions controls which tidal potential models are used. The options available for the radiation pressure acceleration models are:

1. JPL_XYZ03_IIA—corresponds to the last Block IIA JPL model used in OMNIS
2. JPL_XYZ03_IIR—corresponds to the last Block IIR JPL model used in OMNIS
3. TABULAR_IIF—table look-up model for Boeing Block IIF satellites
4. TABULAR_III—table look-up model for future Lockheed Martin GPS III satellites
5. GSPM04—includes JPL Block IIA and Block IIR models
6. GSPM13—includes JPL Block IIA, Block IIR, and Block IIF models

An attitude model is associated with each satellite Block type with two being available for Block IIA satellites. Additional inputs include a beta angle limit and a corresponding beta angle limit option (either to keep one term constant or to not compute this term in the low-beta region). Eclipses due to Earth and the Moon are accommodated by computing a shape factor with a value between zero and one to account for penumbra passages. A shape factor of 0 indicates a satellite is completely in the umbra; a shape factor of 1 indicates it is in full Sun. Another control is present for each radiation pressure model to select whether or not to apply the shape factor to the y-axis acceleration. An Earth radiation pressure model is currently being implemented. The JPL Development Ephemeris DE430 is currently used for Sun, Moon, and planetary ephemerides for both the point mass acceleration computations and the shape factor computations.

The EPOCHA *Filter* and *Smoother* can estimate the following current state parameter set:

1. Satellite position and velocity (acceleration process noise can be specified)
2. Satellite radiation pressure (either a single radiation pressure scale factor or separate X and Z scale factors and a y-axis acceleration)
3. Satellite RAC thrust (no process noise possible)
4. Satellite clock (up to three terms: time offset, frequency offset, and frequency drift)
5. Station clock (up to three terms: time offset, frequency offset, and frequency drift)
6. Station tropospheric refraction (either a wet zenith delay correction by itself using either the Neill Mapping Function (NMF) or the Global Mapping Function (GMF), or with east and north gradients included)
7. Station Cartesian coordinates (input *a priori* sigmas are specified in the east, north, and vertical frame, no process noise possible)
8. Earth orientation (x pole, y pole, and UT1-UTC and their rates of change, daily independent observations of UT1-UTC from USNO are processed to control the estimates since UT1-UTC is not directly observable)
9. Carrier phase pass biases (initialized at the start of a pass or reinitialized at a timeline following a break in the observations because of either loss-of-lock or edited data)

The parameter set for each satellite and station is independently selectable. For radiation pressure and tropospheric refraction parameters, either random walk or Gauss-Markov process noise can be selected and the appropriate statistics provided. For the clock estimation, a white noise spectral density can be specified for each parameter, and a full process noise covariance matrix is generated and used. Rb and quartz crystal clocks usually require estimation of all three clock parameters; Cs and hydrogen maser clocks only require estimation of two parameters. The number of clock parameters estimated for a given satellite or station can be changed by an event. The Earth-orientation reference model is usually updated at the beginning of each day; however, the estimated parameters are adjusted at this time so the total Earth orientation is continuous. This adjustment, along with the UT1-UTC observation, puts steps into offset estimates at the beginning of each day. Random walk process noise can be specified for each Earth-orientation parameter and for carrier phase pass biases. Most process noise categories can be changed by events.

At the *Filter* epoch for a cold start, the estimation equations are initialized using the *a priori* sigmas for all estimated parameters from the Static Database. These parameters are augmented with carrier phase bias parameters for all passes present. For each observation, an elevation angle test is done and observations below the minimum allowable elevation angle are discarded. If obstructions are defined for the station involved, additional tests are performed that could result in the observation being discarded. For each observation, a computed value is derived based on the current estimates of all associated parameters. These estimates include parameters for the orbit, clock, tropospheric refraction, Earth orientation, and station coordinates, if being improved. All observations are assumed time-tagged with GPS time of signal emission. Each computed observation also includes the effects of transmission time, tropospheric refraction, antenna offsets and possibly phase center variations for both the satellite and station, periodic relativity, carrier phase windup (for carrier phase observations only), and displacement of the station due to its velocity and solid-Earth tide, atmospheric tide, ocean loading, and pole tide effects. The tropospheric effects can use the Saastomonien zenith dry and wet models with either the NMF or GMF. All tidal effects are computed using the selected IERS Conventions model options. An additional adjustment is applied to the pseudorange data for the Block IIR SVN49 satellite. The computed observation is then subtracted from the actual observation to compute the predicted or *a priori* residual. In addition, the predicted residual uncertainty is computed as a combination of the covariance matrix projected along the line-of-sight and the observation uncertainty. If the input observation uncertainty is greater than a minimum specified in the Static Database, this input uncertainty is used. Otherwise the minimum uncertainty is used, which is the usual case.

Once the *a priori* residuals and their uncertainties for all observations at a given timeline are computed, automatic editing takes place. In Real-time mode, the Session contains an Observation Wait interval to determine when editing can start. Observations that arrive in *Filter* after this wait interval are not processed but have already been saved in the PO Database and are available for use if the *Filter* is restarted prior to this time. In this case, all previously processed observations are reprocessed along with any additional observations received after the initial real-time processing. An SNR threshold test is performed on each observation followed by NGR editing for the carrier phase data and also an RMT test for each observation. The SNR test only compares the ratio of each *a priori* residual divided by its uncertainty against a threshold value. Observations that exceed the threshold are tagged and not used in the measurement update. The RMT test is similar except it uses just the *a priori* and/or *a posteriori* residual itself. The NGR editing tests each individual carrier phase residual against statistics based on all the other carrier phase residuals. *Filter* examines *a posteriori* residuals to identify observations that were used but should have been tagged and observations that were tagged but should have been used. For the first case, all observations at a given timeline must be used in a new measurement update. If only the second type of observations are identified, then only these observations need to be used in a new measurement update. This is an iterative process that usually converges in a single iteration, but there is an input limit to the number of iterations. Once properly tuned, this editing procedure removes almost all anomalous data. However, if an anomalous point gets through, it can be tagged through a user input masking event and the *Filter* restarted at or before this timeline.

There are other types of masking events to accomplish various results and each event can be applied over multiple timelines. All observation-, clock-, and orbit-related events defined below must be detected either while the *Filter* is running or after it has completed (for Batch Mode only), and the appropriate events entered and the *Filter* restarted before the earliest event time. If a user is running in real-time and a station clock jump is detected and observations are being tagged, a clock event can be placed at a future time so the *Filter* does not have to be restarted, as long as a user is willing to accept the minor effects of the tagged data not being included.

The possible events that can be created in the *Events DB Editor* and processed by *Filter* are grouped as follows along with a brief description of what needs to be specified:

1. Observation
    a. Observation Masking Change: time, duration, single or pair masking, satellite and/or station IDs, and masking option for each measurement type
    b. Change Observation Category: time, station ID, and category containing pseudorange and/or carrier phase minimum observation sigma, and related information
2. Clock
    a. Set Master Clock: time and satellite or station ID
    b. Reinitialization: time, satellite or station ID, option to input adjustments or total offsets, adjustments or total offsets, and delta process noise (from an existing category but can be changed) and duration
    c. Time Change: time, satellite or station ID, and known time change
    d. Frequency Change: time, satellite or station ID, and known frequency change
    e. Change Clock Type: time, satellite or station ID, and a category with number of estimated parameters and associated clock process noise values specified
    f. Unusable Clock Flag: time, satellite ID, and duration (used in making SP3 files to indicate bad satellite clock values)
3. Orbit
    a. Thrust Maneuver: start time, duration, satellite ID, thrust estimation duration, RAC delta-v or accelerations, prograde or retrograde if delta-v, *a priori* sigmas, and delta process noise on position and/or velocity (from an existing category but can be changed) and its duration
    b. Orbit Process Noise: time, satellite ID, and delta process noise on position and/or velocity (from an existing category but can be changed) and its duration
    c. Change Radiation Pressure Parameters GPS Category: time, satellite ID, and category
    d. Change Orbital Statistics Category: time, satellite ID, and category
4. Earth Orientation
    a. Set Earth Orientation Reference Model: time, type, source file, and effectivity date or bulletin number, if NGA coefficients
    b. Use IERS UT1-UTC Rapid Parameter: time, predicted UT1-UTC value and sigma, and source file (usually the USNO Daily File)
    c. Change Process Noise for Earth Orientation Parameters: time and up to six process noise values
5. Station
    a. Estimate Station Coordinates: start time, duration, station IDs selected, and *a priori* sigmas (from an existing category but can be changed)
    b. Change Station Coordinate Properties: time, station ID, and new position, velocity, and/or antenna properties

    c. Change Station Observation Rate: time, station ID, observation rate, and carrier phase bias process noise and *a priori* sigma
    d. Change Troposphere Category: time, station ID, and category
6. Platform
    a. Decouple Platform: time, satellite or station IDs
    b. Recouple Platform: time, satellite or station IDs
    c. Activate Platform: time, satellite or station IDs
    d. Deactivate Platform: time, satellite or station IDs
7. Composite Clock
    a. Add Clock to Composite Clock Ensemble: time, satellite or station IDs
    b. Remove Clock from Composite Clock Ensemble: time, satellite or station IDs

Shortcuts allow users to quickly define Reinitialization, Thrust Maneuver, Observation Masking Change, Activate Platform, Deactivate Platform, Add Clock to Composite Clock Ensemble, and Remove Clock from Composite Clock Ensemble events. Any Static Database quantity can be updated based on a change implemented through an event by running the *Session Updater*. In this way, the Static Database always contains the most up-to-date modeling information, and events that changed the information are removed from the Events Database.

After the measurement update segment of each *Filter* timeline is completed, and if the Composite Clock Mode is selected, two computations take place. A pseudo-observation is processed that assumes the weighted sum of all of the clocks in the composite is zero. This is needed to keep the clock variances from growing. Also, the differences between the *Filter* clock time offset and frequency offset estimates for both satellites and stations and the most recent equivalent estimates obtained from the OCS Kalman filter are computed and used to compute the GPS time and frequency steering applied to all clock estimates. Typically, the OCS uses 18 satellites and all OCS and NGA station clock estimates in deriving its Composite Clock. The *Filter*-computed differences for these platforms are combined using weights based on the *Filter a priori* covariance matrix for the clocks; the resulting weighted average is run through a smoothing process, and this smoothed result is applied to all satellite and clocks. After convergence, this results in very small changes in time and frequency being applied to the *Filter* estimates. The last available OCS clock estimates are simply extrapolated forward in time if a gap is present until the next available set of estimates. Membership in the Composite Clock is kept as close as possible to what the OCS is using by automatically processing OCS-provided information. Occasionally a change in the OCS Composite Clock membership will not be received and a manual event or events may be needed to reconcile any differences.

To complete the *Filter* processing at a given timeline, the last sets of *a priori* and *a posteriori* residuals are written to the Filter Database, the diagnostics are computed and written to the database along with Composite Clock-related information, and all matrices needed by the *Smoother* are written. If the *Products Manager* is active, it reads information from the Filter Database and computes whatever other quantities are needed and sends the resulting products to the Product Distribution System (PDS). Product forwarding can be paused while troubleshooting an issue in *Filter* and then questionable products can be deleted and not sent to the PDS. All open GUI plots and tables will automatically be updated if this option is on. If pass bias parameters are no longer needed for certain passes, they are removed from the estimation equations. The *Filter* then updates all of its information to the next timeline. This involves integrating the equations of motion based on the estimated orbit-related parameters to get the position and velocity at the next timeline, propagating the clock estimates and other parameters, and propagating the square root covariance matrix and adding in the appropriate process noise covariance matrices. Since the EPOCHA *Filter* executes for long periods of time without cold starts, direct process noise on the orbit velocity parameters and Earth-orientation parameters are usually included.

STP

The *STP* has two modes of operation: Navigation Message Replacement and Prediction modes. The first mode is used to predict for two hours, which corresponds to a typical navigation message page length of applicability. The second mode is used to predict either six or nine hours to support other products. As mentioned earlier, the *Session Editor* provides the information on when to run each mode. The *Filter* signals the *STP* when it has completed a timeline and written its information to the Filter Database. If this is a timeline for either or both of the *STP* modes to run, the required mode or modes are initiated. The orbits are predicted by integrating forward using a second sum multi-step integrator based on the most recent *Filter* estimates of all orbit-related parameters and the current Earth-orientation reference model and its associated parameter estimates. Both inertial and Earth-fixed positions and velocities are computed at the required time interval. The corresponding covariance matrix is also propagated forward in time. Two options exist for predicting the satellite clock parameters. The first option is just to extrapolate the most recent time offset, frequency offset, and frequency drift (if present) parameter estimates forward. Both the time offsets and frequency offsets at the required time interval are computed. This is the usual method used for Cs clocks because of their statistical behavior and estimation of just their time and frequency offset parameters. The second option involves using a Kalman filter operating on the past history of the time offset parameter estimates as observations. The states of the Kalman filter are usually time offset, frequency offset, frequency drift, and up to three optional sinusoidal parameters (with 6-, 12-, and 24-hour periods). Both the time offsets and frequency offsets at the required time intervals are computed based on the Kalman filter estimates of all states at the prediction timeline extrapolated forward. The corresponding covariance matrix is also propagated forward in time. This is the usual method used for Rb clocks, which have low noise characteristics but orbit-period thermal variations. For this mode, the last timeline *Filter* estimates and the equivalent *STP* prediction at this time do not agree because of the prediction method. In each mode, *STP* cycles through all of satellites and writes the results to the STP Database for each mode as it is completed. The *Products Manager* then computes the associated prediction products and writes them to the PDS.

After each *Filter* timeline is completed, and if *STP* is running, the *STP Evaluator* computes the orbit and clock differences between the latest *Filter* timeline estimates and all orbit and clock predictions at this same time from all predictions that included this timeline in either of the two *STP* modes. These differences are written to the STP Evaluator Database for GUI viewing to evaluate the quality of the predictions. All open GUI displays containing *STP Evaluator* results are automatically updated after the new evaluations are written to the STP Evaluator Database.

Smoother

The *Filter* continually sends a signal to the *Smoother* as to what timeline it has just completed. The *Smoother* knows from the *Session Editor* what times it is supposed to run and initializes when the *Filter* completes the required timeline. The *Smoother* needs information the *Filter* has written to its database. The *Smoother* runs backward in time, usually for a two-day period for each day of interest. If the *Filter* is backed up to a time before the start time of the *Smoother,* an option exists for determining whether to rerun the *Smoother* for this span or not. The *Smoother* writes information to its database as each timeline is processed. GUI plot and table displays, which read from the Smoother Database, can be opened based on a completed or running *Smoother*. These displays do not automatically update when the *Smoother* completes additional timelines but can be manually reopened. After a *Smoother* completes, the *Build Trajectory and Clock Files* utility automatically writes SP3-formatted files to the appropriate output directories for the day of interest and for the entire *Smoother* time span. The *Products Manager* also computes the associated *Smoother* products and writes them to the PDS.

LTP

The *Smoother* signals the *LTP* whenever it completes a span, and the *LTP* initializes and computes its long-term predictions. For orbits, the *LTP* does a least-squares fit to the *Smoother* position (and possibly velocity) time history for each satellite and integrates forward using the second sum multi-step integrator from the start of the *Smoother* time span, typically for 11 days. The parameters of fit for each satellite include the position and velocity at the epoch of the *Smoother* time span and whatever radiation pressure parameters are selected. The *Smoother* Earth-orientation reference model and its associated parameter estimates at the last timeline in *Smoother* are used to predict Earth orientation for orbit prediction and in converting the inertial positions and velocities into the Earth-fixed frame. For satellite clocks, the *LTP* does a least-squares fit to the complete two-day *Smoother* time offset time history for each satellite and extrapolates forward from the fit epoch for typically 11 days using the resulting function. The parameters of fit for each satellite usually include the time offset, frequency offset, frequency drift (optional), and up to three optional sinusoidal parameters (with 6-, 12-, and 24-hour periods). An exponentially correlated measurement noise model with a correlation time of six hours is used for time offset observations. The corresponding covariance matrix is also propagated forward in time to get the time and frequency offset uncertainties. Scale factors as a function of satellite Block type and clock type have been determined to make the covariance matrix more realistic. The computed *LTP* information is written to the LTP Database and the *Products Manager* computes the associated *LTP* products and writes them to the PDS. A GUI table display reads from the LTP Database and can be opened after *LTP* completes to evaluate the available results. After *LTP* completes, the *Build Trajectory and Clock Files* utility automatically writes daily SP3-formatted files to the appropriate output directory for each of the nine days starting after the day of interest.

PCT

The *PCT* is used to compare EPOCHA products stored in the PDS, external files, and quantities from the ESSP Database, which are the ZAOD information from the OCS. Products from *Filter*, *STP*, *Smoother*, and *LTP* can be input. The external files supported are SP3 files (for orbits and clocks), RINEX Clock files (for clocks only), SP3 files (for orbits) and RINEX Clock files (for clocks), RINEX Nav Message, and Earth-orientation parameter files from the NGA, IERS (finals daily), and IGS. All EPOCHA products include both satellite Earth-fixed and inertial positions and velocities for both the center of mass and antenna phase center, satellite time and frequency offsets, and Earth-orientation parameter values and rates. Antenna phase center refers to the two-frequency offset from the center of mass and may be different between IGS and EPOCHA products. *Filter* and *Smoother* products also include radiation pressure parameters, station time and frequency offsets, and tropospheric refraction parameters. IGS SP3 files contain satellite center of mass positions only in the Earth-fixed frame and satellite time offsets. NGA SP3 files can contain either satellite center of mass or antenna phase center positions and velocities in the Earth-fixed frame and satellite time and frequency offsets. Only satellite time offsets are used from an IGS RINEX clock file. The RINEX Nav Message file provides satellite positions and velocities for the antenna phase center in the Earth-fixed frame and satellite time and frequency offsets. The ESP database contains both Earth-fixed and inertial positions and velocities for both the center of mass and antenna phase center of all satellites. It also contains satellite time and frequency offsets and station time and frequency offsets.

Two product sources for comparison must be specified for the *PCT*. Multiple products can be selected for *Smoother*, *STP*, and *LTP*. Typically, the day of interest is extracted from each *Smoother* span. The overlap in the two products is determined and users can select a subset of this time span. An option also exists to compare *STP* and *LTP* products against other products as a function of age of data (AOD). Once the products and time span have been selected, users can restrict the satellite and/or station lists involved in the comparisons and specify tagging conditions for satellites and stations. These are usually used to remove outliers from the comparisons. For instance, they can be used to remove a time span around a satellite thrust maneuver in the comparisons. Undefined clock values are ignored in all computations. Options exist to select the orbit reference frame (Earth-fixed or inertial) for comparison (if applicable) and to remove a seven-parameter Helmert transformation between two sets of orbits. Either center of mass or antenna phase center reference points can also be selected for each source (if applicable). An option exists to adjust satellite clocks for zenith antenna offset differences by specifying the antenna option used for each source. To accommodate differences in time systems used for referencing clock offsets, either a linear or quadratic fit to all satellite clock differences over the entire time span can be computed or the average satellite clock difference at each timeline can be computed and these effects removed from the differences. Typically, the orbit seven-parameter Helmert transformation and satellite clock fits are computed daily. An option exists to remove individual satellite clock biases to account for clock biases resulting from mixing receiver types in their determination.

Both plots and tables of the various differences, along with their corresponding statistics, are provided through the *PCT* GUI. Orbit differences are given in the radial, along-track, and cross-track directions along with the magnitude of the differences. Clock time offset differences are given in both nanoseconds and meters. Total, Orbit, and Clock RMS UREs are given in meters based on the standard formulas. RMS UREs vs. AOD are available for comparisons involving the *STP* and *LTP* predicted products. Information on orbit and clock fit parameters and individual satellite clock biases can be viewed. A selection tool exists for easily comparing subsets of the total comparisons based on Block type (IIA, IIR, or IIF), orbit plane (A-F), and clock type (Cs or Rb) for satellites and based on groups (OCS, NGA, and IGS) for stations. Tabs used on the plots allow users to view components grouped together or individually. Plots and tables can be printed or saved to files. Extreme flexibility has been built into the *PCT* to allow users to make desired comparisons.

Output Display GUI

Extensive plots and tables can be displayed to indicate the quality of estimation and prediction results and how these are evolving if operating in real time. All *Filter* and *STP* displays can be set to automatically refresh with a moving display as a new timeline is processed. A custom time span can also be defined for these displays. All plots can have custom vertical and horizontal (time) scales and be zoomed if desired. Most tables display results for the most recent timeline but previous timelines are easily accessible. For residual plots by satellite, there is usually a selection tool that allows users to reduce the number of plots based on station group (OCS, NGA, or IGS) and individual station. For residual plots by station, there is usually a selection tool that allows users to reduce the number of plots based on satellite Block type, orbit plane, and individual satellite. The *Filter* and *Smoother* have identical plots except for two extra for *Filter*, which do not change for *Smoother*.

Filter Plots:

1. Signal-to-Noise: includes separate SNRs after fit for pseudorange and carrier phase data and the combined SNR.
2. Residual: *a posteriori* residuals are plotted by both satellite and station for both pseudorange and carrier phase data with statistics given for each. Tagged and masked points are indicated appropriately as are unhealthy satellites. *A priori* residuals can be plotted on option.
3. ERAT [EPOCHA Residual Analysis Tool]: includes on one display plots of residuals for all satellites or stations for a given data type with common scales by data type. Four tabs allow pseudorange and carrier phase residuals to be displayed separately for satellites and for stations. Double clicking on a single plot opens the Residual plot for this satellite/station pair discussed above.
4. Diagnostic: all plots include a parameter value and its *a posteriori* sigma. *A priori* sigmas can also be included on option. All have multiple components that are displayed on one screen and individually using tabs.
    a. Radiation Pressure: the mean value of each parameter is removed and displayed at the top of each plot.
    b. Satellite Position: RAC position adjustments are plotted. These adjustments and the velocity adjustment below are usually very small after convergence because of the use of an extended Kalman filter.
    c. Satellite Velocity: RAC velocity adjustments are plotted.
    d. Satellite Clock: either a two- or three-parameter fit is made to total clock time offsets, and its effects are removed from all clock parameters. Any clock Reinitialization event resets the fit, and an indicator for these events is given. The associated fit parameters are given on the plots by component.
    e. Thrust: the total estimated RAC thrust components are plotted and are zero before the thrust starts and after its estimation span has been passed.
    f. Station Clock: either a two- or three-parameter fit is made to total clock time offsets, and its effects are removed from all clock parameters. Any clock Reinitialization event resets the fit, and an indicator for these events is given. The associated fit parameters are given on the plots by component.
    g. Tropospheric Refraction: the wet zenith correction and east and north gradients (if present) are plotted.
    h. Earth Orientation: the two pole coordinate corrections and the UT1-UTC correction are plotted. All corrections show steps at the day boundaries when the underlying Earth orientation model is changed. The effects of processing UT1-UTC observations at each day boundary can be seen by a slight decrease in the corresponding sigma.
    i. Earth Orientation Rates: the two pole coordinate rate corrections and the UT1-UTC rate correction are plotted.

5. Common Clock Offset and Frequency: the weighted offset value and its sigma and the smoothed offset value and its sigma are plotted for both the time and frequency offsets.
6. Clock Offset and Frequency Differences: four plots on one display and individual tabs give the differences vs. OCS for satellite time, station time, satellite frequency, and station frequency offsets. Differences not used in the steering, either because of OCS masking or being tagged, are indicated. Any gap since the last set of OCS clock estimates was received is indicated by colors. The background color is used to indicate whether the differences were computed in real time or not.
7. Composite Clock Weights: individual weights for satellites and stations are plotted, along with sums for all satellites, for all NGA stations, for all OCS stations, and combined, which should always be 1.
8. Phase Bias: includes plots of the carrier phase bias parameter values, state estimates, and their sigmas by satellite or by station.
9. Station Weather: includes plots by station of the pressure, temperature, dew point temperature, and the derived relative humidity. Measured and default weather data are indicated by color and are usually available every 15 minutes.
10. Radiation Pressure: includes plots of radiation pressure-related quantities by satellite. These quantities are the Sun rotation angle, beta angle, Sun-vehicle-Earth angle, yaw angle, yaw angle rate, and a shadow indicator if relevant. Symbols are also used to identify timelines when the satellite is in the umbra, in the penumbra, and experiencing a noon turn.

Filter Tables:

1. Satellite Summary: available at each timeline with the most recent one usually displayed. For each satellite, the following quantities or indicators are displayed: membership in both the EPOCHA and OCS Composite Clocks; PRN number; SVN; orbit plane and slot; eclipse indicators; event indicator; number of stations with untagged pseudorange observations, their RMS residuals, and number of tagged observations; number of stations with untagged carrier phase observations, their RMS residuals, and number of tagged observations; and number of late observations (for real time). The eclipse indicator includes Earth umbra, penumbra, and noon turn; and lunar umbra and penumbra. The possible events are: Clock Reinitialization, Time Change, Frequency Change, Change Clock Type, Set Master Clock, Thrust, and Orbit Process Noise. Colors are used to indicate an unhealthy satellite, a decoupled satellite, a satellite used as a master clock, observation masking type in effect, RMS over an input threshold, no observations, and observations all tagged. A tool tip also gives the satellite status, clock ID and type, estimated states, and the geodetic latitude and longitude of the sub-satellite point. Tool tips also contain detailed information for events and information about the late data.
2. Station Summary: available at each timeline with the most recent one usually displayed. For each station the following quantities or indicators are displayed: membership in both the EPOCHA and OCS Composite Clocks; station number, name, and longitude; event indicator; number of satellites with untagged pseudorange observations, their RMS residuals, and number of tagged observations; number of satellites with untagged carrier phase observations, their RMS residuals, and number of tagged observations; and number of late observations (for real time). The possible events are: Clock Reinitialization, Time Change, Frequency Change, Change Clock Type, Set Master Clock, and Change Station

Coordinate Properties. Colors are used to indicate a decoupled station, a station used as a master clock, observation masking type in effect, RMS over an input threshold, no observations, and observations all tagged. A tool tip also gives the receiver ID and type, clock ID and type, information on data smoothing, estimated states, and the geodetic and geocentric station coordinates. Tool tips also contain detailed information for events and information about the late data.

3. Observation Residuals: available at each timeline with the most recent one usually displayed. There is a separate display for each plane that contains all the residuals for both data types by station with RMS residuals for the plane, overall planes, and overall stations per satellite and data type. Colors are used to identify residuals and RMS values over their input thresholds. For each residual, a tool tip is available containing the observation sigma, elevation angle, azimuth angle, loss-of-lock indicator, and other indicators.
4. Parameter Estimate: available at each timeline with the most recent one usually displayed. A display is available for every satellite, every station, and Earth orientation. The following information is given: parameter name; the state, its sigma, and its total value at the measurement update time; and the *a priori* total value at the time update time (the prediction to the next timeline). Thrusts for satellites only appear during their estimation time spans. Station coordinates only appear during their estimation time spans.
5. IERS UT1-UTC Events: contains the results of incorporating UT1-UTC observations at the beginning of each day. The table includes the observation value and its sigma, the *a priori* residual and its sigma, and the *a posteriori* residual and its sigma.
6. Station Coordinate Estimation Results: contains the station coordinate estimation results at the end of the estimation time span for any station whose coordinates were estimated during the time span selected. For each station coordinate estimation case, the following information is given: station number/name; time span for estimation; coordinate epoch; ENV corrections and sigmas; XYZ corrections, sigma, and total coordinates; and geodetic coordinates.

Smoother Plots

All plots are the same as for *Filter* except as noted. The *Smoother a priori* sigmas are the same as the *a posteriori* Filter sigmas and cannot be plotted.

1. Signal-to-Noise
2. Residual
3. ERAT
4. Diagnostic
    a. Satellite Position and Velocity: the plotted RAC adjustments are corrections the *Smoother* computes relative to the *Filter* estimates, because an extended Kalman filter is used.
    b. Satellite Clock: clock offsets not adjusted to GPS Time can be plotted.
    c. Station Clock: clock offsets not adjusted to GPS Time can be plotted.
5. Common Clock Offset and Frequency
6. Clock Offset and Frequency Differences: the real-time indicator does not apply.
7. Composite Clock Weights
8. Phase Bias

Smoother Table:

1. RMS Observation Residuals: available only once for each Smoother. There is a separate display for each plane that contains all RMS residuals for both data types by station with RMS residuals for the plane, overall planes, and overall stations per satellite and data type. Colors are used to identify RMS values over their input thresholds. Tool tips give the number of observations that were used in computing each RMS value.

STP Evaluator Plots:

1. Orbit/Clock Evaluations: for both the Navigation Message Replacement (NMR) and Prediction modes of *STP*, plots of the most recent evaluations and single evaluations are available. For both types of plots there is one plot per satellite. The orbit and clock differences are presented in terms of estimated range deviations (ERDs) using the standard formulas. The uncertainties associated with all predictions are also plotted. Color is used to designate time spans when old evaluations are plotted, which occur when the *Filter* is restarted in the past but the predictions are not recomputed.
2. EOP Evaluations: for both the NMR and Prediction Modes of *STP*, plots of the most recent evaluations and single evaluations are available. Earth-orientation differences for the two pole coordinates and UT1-UTC are presented along with prediction uncertainties.

STP Evaluator Tables:

1. Orbit/Clock Evaluations: for both the NMR and Prediction modes of *STP*, a table provides the most recent evaluations in terms of ERDs. Previous most recent evaluations are also available for viewing. For each satellite the following are given: PRN number, SVN, Block type, orbital plane and slot, and the Total, Orbit, and Clock ERDs and corresponding prediction uncertainties. A separate table gives the combined ERDs overall satellites, by plane, and by Block type.
2. EOP Evaluations: for both the NMR and Prediction modes of *STP*, a table provides the most recent evaluations in terms of differences for the two pole coordinates and UT1-UTC. Previous most recent evaluations are also available for viewing.

LTP Table:

1. Long-Term Predictor Results: for each execution of LTP there is a table that gives RMS residuals by satellite and overall satellites for position (and velocity if used) both before and after the final iteration fit. These before- and after-fit RMS residuals are also available for all iterations.

Utilities

The following is a list of all EPOCHA utility programs that perform various functions needed to manipulate files and databases in the EPOCHA system of programs:

1. Static Database Editor: see above
2. *ESSP Database Maker:* creates or adds to an ESSP Database based on ASCII files received from the OCS containing orbit, clock, and clock event information or based on a BINEX file
3. *PO DB Maker:* creates or adds to a PO Database based on ASCII smoothed measurement files or based on a BINEX file
4. *Events DB Editor:* provides users the ability to incorporate events into the *Filter* processing as described above. It allows users to select a new event, to duplicate an event

so only parts of it can be changed, to delete an event, to transfer events from one Events Database to another, to print an Events Database, and to save the Events Database to the same or a different name.

5. *Observation File Maker:* creates a daily corrected and edited ASCII observation file containing both smoothed pseudorange and carrier phase data types based on both the Smoother and Filter databases to the NRL for analyzing satellite clock stability
6. *EOP File Maker:* creates an ASCII output file of Earth-orientation information based on a Filter, Smoother, or LTP database. The file contains model values, either estimates or predictions of corrections to these model values, and total values at a specified time interval.
7. *Smoother Report File Maker:* creates an ASCII output file summarizing the radiation pressure and clock parameter estimation and other information primarily from *Smoother*, but also requires input of the corresponding Filter Database.
8. *SECD File Maker:* creates an ASCII Satellite Ephemeris and Clock Data File based on *Smoother* results for use by JHU APL’s SATRACK program. This utility also requires input of the corresponding Filter Database for additional information.
9. *LCC File Maker:* creates an ASCII Launch and Checkout Capability File containing information from *Filter* at one timeline for upcoming GPS III satellite launches
10. *Trajectory and Clock File Maker:* creates SP3 files from Filter, STP, Smoother, or LTP databases and runs automatically in a predefined way after both *Smoother* and *LTP* complete
11. *Clock Extraction Utility:* creates an ASCII output file containing satellite and station clock estimates from either *Filter* or *Smoother* or both with estimates prior to adjustment to GPS Time also available from *Smoother*
12. *PoQA [Preprocessed Observation Quality Assurance] Tool:* initially used to create an ASCII output file containing either daily summaries or weekly statistics on observations, weather observations, and clock parameters saved in the PO and ESSP databases. It is being extended to provide additional information stored in the Filter Database.
13. *Sun-Moon-Planet File Maker:* generates a Sun-Moon-Planets file for multiple years based on an input JPL Development Ephemerides
14. *Copy Database:* copies an input database to a different name
15. *Session Updater:* incorporates events that have changed quantities originally read from a Static Database into a new Static Database and then removes these events and others with event times prior to the input time and creates a new Events Database
16. *Session Database Extractor:* extracts information from a Session’s databases to a file that can then be reimported into databases needed to restart the Session using a *Session Importer*
17. *Weekly Transition Tool:* archives a weekly Session plus an input-defined overlap time span and retains the current reduced databases for use in the following week. It uses the *Session Updater* to update the Static and Events databases to apply to the current week.

Tools also exist to assist users in managing sessions and databases, to delay the start of a batch run by an input time interval, and to specify individual GUI preferences.

Viewers

The following is a list of all EPOCHA viewers that allow users to view certain databases and files from EPOCHA either during real-time processing or after the fact.

1. *ESSP Data Viewer:* lets users examine a selected time span and information contained in the ESSP Database. It allows for selecting satellites, stations, and whether the information came from OCS or other sources.
2. *PO Database Viewer:* lets users examine a selected time span and information contained in the PO Database. It allows for selecting from the two data types, satellites, and stations at two levels of detail.
3. *Real-Time Preprocessor Viewer:* only applies to real-time users and displays information about the data as they arrive from up to three data streams—OCS, NGA, and IGS.
4. *Real-Time OCS Messages Viewer:* only applies to real-time users and displays information received from OCS about changes in routine processing
5. *Preprocessor HLS[High-Level Summary]:* only applies to real-time users and displays information about when each station last reported observational data or clock data, indicates which satellite/station pairs had observations, and provides alerts
6. *Alerts:* intended for real-time use and displays indicators at each timeline, e.g., No Platform Observations, Late Data, All Data Tagged for Type X
7. *User GUI Log Files:* lets users review processing comments generated by the GUI code
8. *Session Log Files:* lets users review comments generated by the various processing modules' code (e.g., *Session*, *Filter*, *Smoother*)
9. *Messages:* provides messages from the Session as each module in the session starts or stops executing

In going from OMNIS to EPOCHA, passing data between modules transitioned from using multiple files to using just a few databases. The following diagrams illustrate the typical data processing flow for EPOCHA Batch Processing and Real-Time Processing modes:

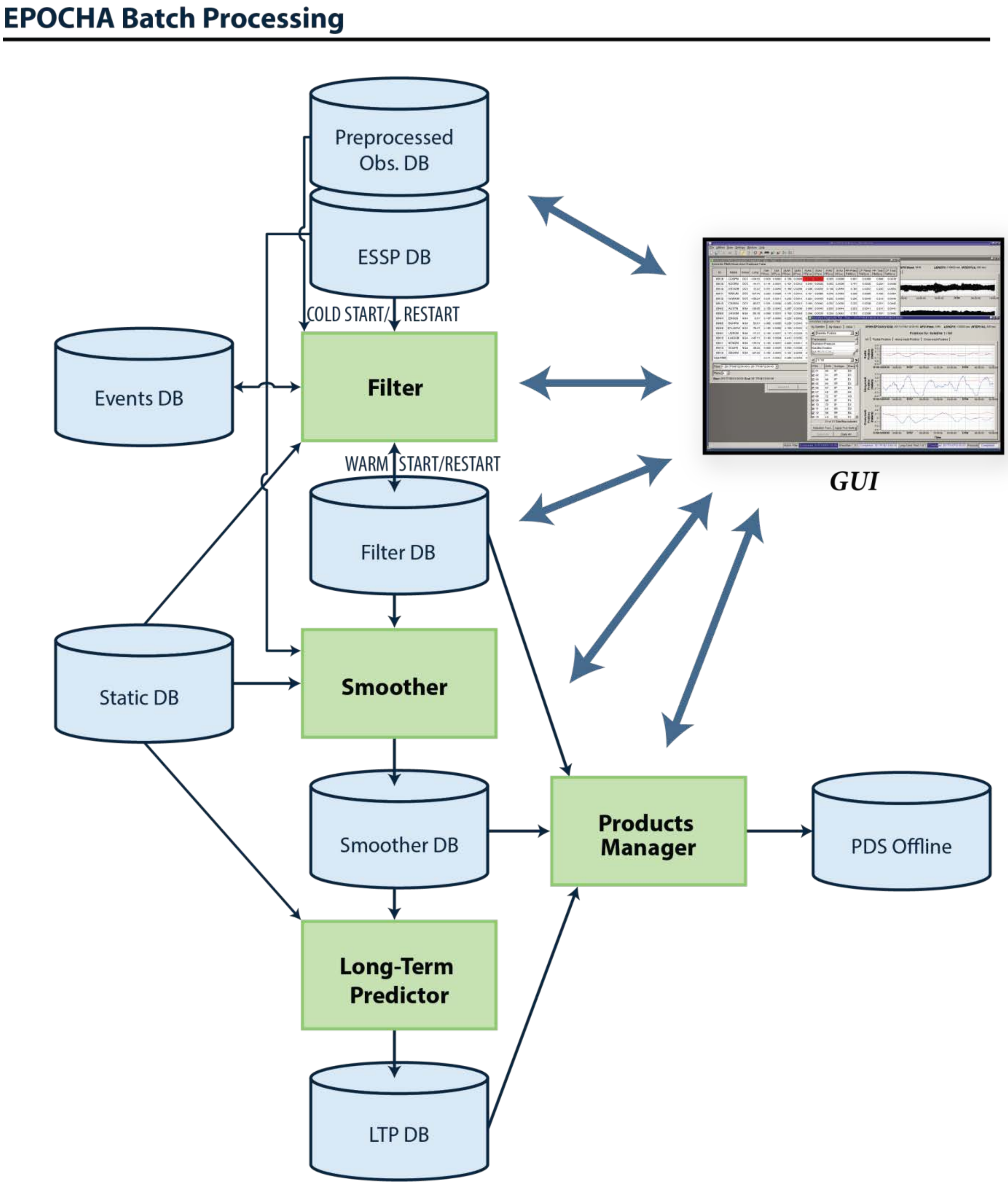

Figure 6: EPOCHA Batch Processing

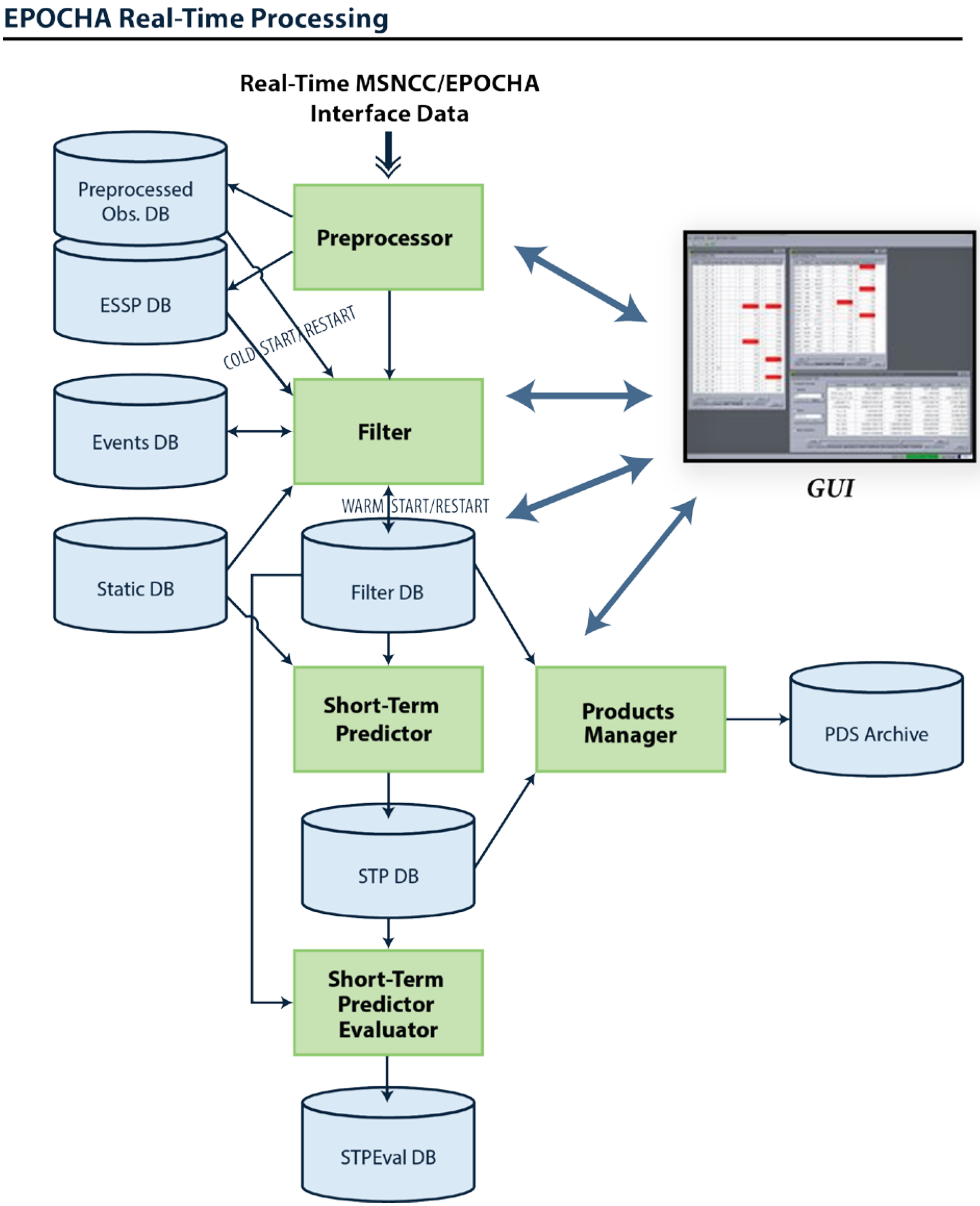

Figure 7: EPOCHA Real-time Processing

NSWCDD continually enhances EPOCHA’s capabilities and automation. High-rate GPS clock estimation (at intervals of 30 seconds or less) for both real-time and after-the-fact applications needs to be added. A HV/GPS estimation capability equivalent to that which was present in OMNIS also needs to be added.

Satellite Programs and Analyses Supported by EPOCHA

GPS

In 2009 after EPOCHA Version 1.1 was developed and was completely independent of OMNIS outputs, NSWCDD conducted extensive tuning exercises to refine the accuracy of EPOCHA *Filter* and *Smoother* products. These exercises resulted in Total, Orbit, and Clock RMS UREs versus the IGS final orbit and five-minute clock estimates of 9.5, 6.4, and 9.0 cm, respectively, for the *Filter*, and 6.3, 4.3, and 7.5 cm, respectively, for the *Smoother*. To evaluate the EPOCHA processing, the NGA conducted extensive comparisons of OMNIS and EPOCHA Version 2.1.2 in 2011 for a 10-week time span. Table 3 gives the RMS UREs for the OMNIS *Smoother* results and the EPOCHA *Filter* and *Smoother* results versus the IGS final orbit and clock estimates for this time span. The OMNIS estimates were generated at a 15-minute interval while EPOCHA estimates were generated at a five-minute interval. Seven-parameter Helmert transformations were removed prior to these comparisons. The three translation parameters were all reduced with means around zero going from OMNIS to EPOCHA. The x- and y-rotation parameters were similar, but the z-rotation parameters were reduced from a mean of around -1.0 mas to near zero going from OMNIS to EPOCHA. The mean scale parameter was around 0.3 ppb [parts per billion] for both comparisons.

Table 3: Smoother and Filter RMS UREs

RMS User Range Errors (in cm)	**OMNIS *Smoother***	**EPOCHA *Filter***	**EPOCHA *Smoother***
Clock	11.7	15.9	9.7
Orbit	5.0	8.8	3.9
Total	8.2	10.5	7.2

No actual production work has been done at NSWCDD using the EPOCHA software system, unlike all previous orbit determination software systems. After extensive testing and training, EPOCHA Version 1.2 replaced OMNIS for precise ephemeris estimation at the NGA on 26 February 2012 (during GPS Week 1676). Prior to this change, the NGA conducted another extended comparison of OMNIS and EPOCHA production results from late August 2011 to the end of March 2012. Table 4 gives the RMS UREs for both the OMNIS and EPOCHA *Smoother* results for these comparisons. This time span included ion pump maintenance events for Block IIA satellites, the year rollover, clock failures, several thrusts, and numerous satellite and station clock events. This testing demonstrated the improved accuracy and better anomaly handling of the EPOCHA system.

Table 4: Smoother RMS UREs

RMS User Range Errors (in cm)	**OMNIS *Smoother***	**EPOCHA *Smoother***
Clock	10.8	9.5
Orbit	6.2	4.9
Total	9.5	8.6

As GPS Block IIF satellites were launched from mid-2010 through early 2016, NSWCDD noticed using EPOCHA that for most of the satellites there were large orbit estimation differences initially in going from *Filter* to the *Smoother* estimates. These were orbit-period radial differences with amplitudes from approximately 20–40 cm and along-track differences with amplitudes of 40–80 cm. This was an indication that some un-modeled force was acting on the satellites, which apparently decreased as each satellite's time on orbit increased. These differences may have been caused by outgassing from materials on the satellite. No attempt was made to model this effect since so little was known about its origin. Eventually this behavior disappeared for all 12 Block IIF satellites.

The WGS 84 (G1762) realization was the first one the NGA computed with EPOCHA. It used a 16-day data set from May 2013 and the resulting coordinates for the 17 active OCS and NGA stations were implemented in NGA production on 16 October 2013. This data set included data from approximately 40 IGS stations smoothed using the legacy five-minute smoothing algorithm. ITRF2008 coordinates at the 2005.0 epoch, with minor updates provided by the IGS, were used for all IGS stations and all IGS and starting OCS and NGA coordinates were for the ARPs. ITRF2008 velocities were adopted for all stations. The ANTEX file containing satellite and station phase center offsets and phase center variations was used for this realization. The IERS 2010 Conventions were used in this processing and included ocean loading coefficients for all stations. White noise clock estimation was used with the USNO station clock assumed to be the master clock. The minimum observations sigma for pseudorange was 1.0 m and for carrier phase was 1.0 cm. The coordinates for the IGS Core sites were held fixed. Sixteen sets of daily coordinate estimates were averaged to come up with the final coordinates. Seven-parameter Helmert transformations were computed between the IGS final orbits and orbits computed by the NGA using the new station coordinates. All translations were less than 9 mm in magnitude and all rotation parameters were less than 0.2 mas in magnitude, which corresponds to 6 mm at Earth's surface. However, there was a 1.9 cm scale difference in the orbits at GPS altitude. The resultant Orbit RMS UREs vs. the IGS final orbits was 4.1 cm.

After the WGS 84 (G1762) coordinates were implemented in the NGA orbit computations, the ARL:UT discovered an approximately +2 cm bias in the NGA station heights by using IGS final orbit and clock estimates and their Precise Point Positioning algorithm to estimate the coordinates of the NGA stations. The ARL:UT also determined in early 2014 that there were daily periodics in the six-hour overlapping Precise Point Positioning results, mainly in the vertical solutions and mainly for stations in the southern hemisphere. NSWCDD conducted independent analysis of this last issue later that year. NSWCDD has discovered that phase center variations for both the satellites and stations were not properly being applied in deriving the WGS 84 (G1762) station coordinates. It has not yet been determined whether or not this was the complete cause of the ARL:UT-observed height bias. Both issues will be studied when the NGA derives the next WGS 84 reference frame realization.

In late 2013, the NGA switched to using Version 2.1.2 and then activated the Composite Clock mode with steering/adjustment to GPS Time on 1 December 2013 (GPS Week 1769).

From 2013–2014, studies were conducted to analyze the suitability of using monitor stations operating on Rb clocks in place of Cs clocks; mainly because of the high cost of a Cs vs. a Rb clock and the desire for redundancy at each station. The studies were designed to determine the long-term behavior of this type of clock and the optimal way to process tracking data collected by a monitor station using one of these clocks. Both the ARL:UT and NSWCDD participated in these studies. There were no issues discovered relative to the continuous operation of Rb clocks. Using the appropriate process noise levels, NSWCDD showed there were no issues with estimating the time offset, frequency offset, and frequency drift parameters for this type of clock either.

In late 2013, the differences between using the IERS96 and IERS 2010 Conventions on the

GPS orbit estimation results were examined. In the Earth-fixed reference frame, the RMS RAC differences vs. the IGS final orbit estimates were almost identical so the accuracy of the resulting orbits was unchanged. However, the two sets of Conventions resulted in different inertial frames. Seven-day *Filter*-derived orbits were compared directly for the two sets of Conventions. The mean inertial RAC position differences over all satellites were 1.0, 6.2, and 0.2 cm, respectively. However, each satellite's position difference plot included an along-track bias and a periodic cross-track effect. Total position RMS differences ranged from 327–419 cm. Total position peak differences ranged from 464–475 cm. After removing a seven-parameter Helmert transformation from the differences, the total position RMS differences now ranged from 5.1–7.4 cm. For this time period, most of the differences were accounted for by an x rotation of -12.92 mas and a y rotation -33.39 mas. These rotations are equivalent to -168 and -434 cm, respectively, at GPS altitude. This brief study indicates that inertial GPS product users need to use the same Conventions as those used in estimating the GPS orbits.

Also in late 2013, NSWCDD began investigating the nature of the clock time offset differences when comparing against IGS final clock estimates. NSWCDD personnel noticed these differences seemed to be getting larger with time. Since the IGS uses a different time system to reference its clock estimates than EPOCHA, a daily quadratic clock model is always fit to all satellite clock differences and then removed from each individual satellite's clock estimates. The remaining differences for a typical weekly span exhibited satellite-dependent biases ranging from -14 to +17 cm with an overall RMS of about 9 cm. The biases did not vary much from one day to the next; removing these daily biases by satellite reduced the overall RMS to < 6 cm. Upon further investigation and discussions with the IGS, it was determined that most of these satellite biases are due to the mixture of receiver types and clock estimation methods the IGS uses in deriving its final clock estimates. It is believed that removing these biases gives a better estimate of the quality of NGA clock estimates, so this option was implemented in EPOCHA's *Product Comparison Tool.*

On 16 February 2014, the NGA switched its EPOCHA processing to the IERS 2010 Conventions, except the existing Earth-orientation predictions based on the IERS96 Conventions were still used as the reference model. The Gross zonal tide model with 41 terms was used in place of the Yoder model with 41 terms to restore zonal tide effects on UT1-UTC in EPOCHA. Studies indicated that this small difference had no noticeable effect on the orbit estimation and prediction accuracies. This was done because the GPS OCS was not yet ready to accept UT1-UTC predictions based on removing and then restoring the Gross zonal tide modal with 62 terms.

In early 2014, NSWCDD personnel examined the changes in the orbit and clock differences vs. IGS of using both smaller and larger values than the 1.0 m in use for the smoothed pseudorange minimum observation sigma. One centimeter was used for the carrier phase minimum observation sigma and was left unchanged. Values for the pseudorange sigma from 0.5 to 8.0 m were tried. Decreasing the sigma to 0.5 m increased the Total RMS UREs by a little over 1 cm, while increasing the sigma from 1.5 m to 8.0 m resulted in an approximately linear growth by over 3 cm, primarily because of growth in the Clock RMS UREs. The decision was made to leave the minimum sigma at 1.0 m. Another brief study in 2014 examined the changes in orbit differences vs. IGS of using both smaller and larger values for the orbit process noise level. Decreasing the level by a factor of 0.4 resulted in about a 0.5 cm increase in the Orbit RMS UREs; increasing the level by a factor of 10 also resulted in just less than a 0.5 cm increase. Again, the decision was made to leave the orbit process noise level unchanged.

Also in the spring of 2014, the NSWCDD began receiving real-time IGS tracking data for over 20 stations. Initial processing, in conjunction with the existing OCS and NGA tracking data, indicated that no corrections were being made to the data collected by receiver types that tracked the C/A code on L1 instead of the P/Y code. Mixing tracking data from different types of receivers requires adjusting pseudorange observations for consistency with each other. All OCS- and NGA-operated receivers track the P/Y code on L1. Since this issue was resolved, the NSWCDD has continually processed real-time IGS data from approximately 24 stations. The new RMT editing worked well with the IGS tracking data. NSWCDD then developed clock process noise models to better handle the tracking data from receivers operating on internal quartz clocks and poorly performing Rb and Cs clocks. Several clock process noise categories were defined to be used as needed for the IGS stations. The combination of improved editing and better clock modeling resulted in minimal manual IGS data editing and a significant reduction in the number of clock events needed.

Also in 2014, NSWCDD compared the results of using three different pseudorange smoothing algorithms. The first algorithm was the standard continuous pass smoothing algorithm in which the bias between the raw 1.5-sec pseudorange and carrier phase observations is continuously averaged during the pass as long as there is no loss of lock. For this algorithm a span of 7.5 minutes of continuous data has to be available before the first smoothed pseudorange can be computed at the beginning of the pass or after a break. The second algorithm was identical except that this 7.5 minute span was reduced to 0.25 minutes. The third algorithm was the legacy smoothing algorithm in which only the last five minutes of differences before the observation time are used to estimate the bias. No significant differences were observed between the *Smoother* results for all three data sets and the final IGS estimates. The method of using the computed pseudoranges to initialize the carrier phase biases instead of the observed pseudoranges was also evaluated for these three data sets. This resulted in a slight degradation in the orbit estimates, but the number of tagged carrier phase observations decreased significantly for all three data sets using the editing options available at the time of this study.

In December 2014, the NGA's station in Argentina was decommissioned and a new station in Uruguay was activated.

In late 2014 and early 2015, NSWCDD conducted a brief study to understand the effects of using different GM and a_{Earth} values with the EGM2008 and EGM96 gravity field model coefficients for GPS. The TOPEX values for these two quantities were used in deriving both gravity field models while the official WGS 84 values are both slightly larger—398600.4415 vs. 398600.4418 km^3/s^2 and 6378.1363 vs. 6378.1370 km. Orbit integrations using the WGS 84 values resulted in an along-track runoff of approximately 50 cm in one day with a mean radial difference of -2 cm plus a sinusoidal variation. After orbit estimation, all orbit differences were very small with the largest being a 7 mm radial difference present whenever different GM values were used for the two-body term.

Studies have also been done at NSWCDD to quantify the accuracies of both the *STP* and the *LTP*. For the *STP*, the Total RMS UREs at the two-hour AOD was typically around 20 cm with a worst case of 60 cm for a satellite operating on a Cs clock. At the nine-hour AOD, the equivalent numbers were 50 cm and 130 cm, respectively. For the *LTP*, the Total RMS UREs at the nine-day AOD was 13 m for satellites operating on Rb clocks and 100 m for satellites operating on Cs clocks.

The NGA's station in Tahiti was decommissioned in August 2015, reducing the total number of combined Air Force and NGA stations to 16.

Version 2.4 was first used in production at the NGA in early 2016. This was the start of the NGA providing nine-day predictions for satellite clocks in addition to orbits. For the first three months of 2016, the NGA comparisons vs. IGS had Total, Orbit, and Clock RMS UREs of 10.0, 3.6, and 9.3 cm, respectively, without the daily satellite clock biases removed from the Clock and Total RMS UREs.

The NGA has been monitoring the seven-parameter orbit Helmert transformations of WGS 84 vs. ITRF since October 1995 based on the precise ephemerides for GPS and the IGS final orbit estimates. For the first 198 days of 2016, the largest mean of all translation parameters was for the z direction (-0.8 cm with a sigma of 0.6 cm). The largest mean of all rotation parameters was for the z rotation (-0.142 mas with a sigma of 0.135 mas), which corresponds to less than 0.5 cm at Earth's surface. The mean scale parameter was -0.176 ppb with a sigma of 0.093 ppb, which corresponds to less than 0.5 cm at GPS altitude.

On 14 June 2016 (GPS Week 1901/Tuesday), the NGA switched its Earth-orientation predictions and EPOCHA processing to use the Gross zonal tide model with 62 terms, implementing the full IERS 2010 Conventions. The prediction coefficients also were modified to include an expanded resolution on the UT1-UTC rate term. The GPS OCS switched to the new coefficient sets at the same time, included this zonal tide model, and also started using the diurnal and semidiurnal model for both pole coordinates and UT1-UTC.

The NGA transitioned to using Version 3, Revision 1 in production in late October 2016.

NSWCDD has been running EPOCHA in real-time since 2010, after Version 2.0 was developed, to determine and anticipate any changes required to make real-time processing as automated as possible. Properly corrected IGS tracking data were added in 2015. The NGA has been running EPOCHA in real-time off and on since late 2011. Continual improvements have been made and minimal interaction is now needed for real-time processing.

SATRACK

EPOCHA has supported all SATRACK missile events since February 2012 when it replaced OMNIS for the NGA's precise ephemeris generation.

Note: Operational GPS Satellites

Altogether, there have been 28 Block II/IIA operational satellites with the first one launched in February 1989, and the last one launched in November 1997. The last operational satellite, SVN23, was decommissioned in January 2016. There are currently 19 operational Block IIR satellites. The first launch in January 1997 was unsuccessful but was followed by the first successful launch in July 1997, prior to the launch of the last Block IIA satellite. The last Block IIR satellite was launched in August 2009. The Block IIR satellite, SVN49, has never been used operationally because of on-board interference associated with adding the L5 frequency. The first of 12 Block IIF satellites was launched in May 2010, and the last one was launched in February 2016. All 12 are currently operational.

SUMMARY

NSWCDD’s contributions to the field of satellite orbit determination have been extensive since the first satellites were launched in the late 1950s. Over the years, the algorithms used have increased in complexity. Integration methods for the equations of motion have been adapted to handle discontinuities, and the associated force models have been expanded and become more detailed. Observations processed into pass matrices with arc orbit-related parameters and clock-related and tropospheric refraction parameters treated as pass biases were replaced by time-ordered observations with stochastic estimation of orbits, clocks and tropospheric refraction parameters. Earth-orientation modeling and estimation has become more advanced. Observation editing and clock event detection techniques have become more complex and automated. Processing a single satellite at a time was followed by simultaneously processing all GPS satellites (and HVs if required), first after the fact, and now all GPS satellites can be processed in real time using EPOCHA. Estimation using weighted-least squares techniques was followed by using linearized Kalman filters and RTS smoothers, and later by an extended Kalman filter and RTS smoother. Highly accurate, both short- and long-term orbit and clock prediction algorithms were also developed. Orbit and clock estimation accuracies are now measured in centimeters instead of meters or kilometers. NSWCDD will continue to enhance state-of-the-art orbit and clock estimation and prediction into the future.

Over the years, hundreds of individuals at NSWCDD have contributed to the formulation, development, testing, analysis, production, delivery, training, and troubleshooting associated with orbit determination and related software systems. Probably an equivalent number of individuals at NSWCDD’s primary sponsoring organization, the NGA, have conducted production using these software systems with continual NSWCDD support. This has been an extensive collective endeavor and speaks to the dedication and expertise of all of those who contributed to this effort for at least part of their careers, with many for their entire careers.

Comparing the Four Major Orbit Determination Software Systems’ Capabilities

Force Models	Orbit Determination System			
	ASTRO	**CELEST**	**OMNIS**	**EPOCHA**
Gravity Field	Many before and including WGS 72 (up to 25x25)	WGS 84 (up to 41x41, 8x8 used for GPS)	EGM96 (up to 70x70, 12x12 used for GPS)	EGM2008 (any size, 12x12 used for GPS)
Tides	Lunar and solar tidal bulges with Love’s constant	Lunar and solar tidal distortions with Love’s constant	NSWCDD solid-Earth tides with Love’s constant (same as CELEST) or IERS96 solid-Earth, ocean, and pole tides Permanent tide used with both solid-Earth tide models	IERS96,IERS2003, or IERS2010 models for all tides
Atmospheric Density/Drag	Exponential	Exponential, Jacchia-Bass 1977 with daily solar flux and geomagnetic index data	Jacchia-Bass 1977 and DTM, both with daily solar flux and geomagnetic index data	HV orbit estimation not yet implemented
Solar Radiation Pressure	Spherical Eclipse model: Earth’s shadow or full sunlight	Spherical, NTS-2, ROCK4 for GPS Block I, and ROCK42 for GPS Block II/IIA Eclipse model: Earth and lunar penumbra and umbra	Spherical, ROCK4 for GPS Block I, ROCK42 for GPS Block II/IIA, Table look-up for Block IIR, Numerous JPL empirical models for GPS Blocks IIA and IIR, and Table look-up for Block IIF Eclipse model: Earth and lunar penumbra and umbra	JPL empirical models for GPS Block IIA and IIR, Table look-up model for GPS Block IIF, and JPL GSPM04 and GSPM13 models (GSPM13 includes first empirical Block IIF model) Eclipse model: Earth and lunar penumbra and umbra
Earth Radiation Pressure	None	None	None	UT/Knocke model being implemented
Thrust	None	RVC, RAC, or GPS XYZ accelerations	RAC or GPS XYZ accelerations	RAC accelerations
Sun/Moon/Planets	Sun/Moon only	Sun/Moon only	Sun/Moon and all planets, DE403	Sun/Moon and all planets, DE430

Transformation from Inertial to Earth-fixed Reference Frames	**Orbit Determination System**			
	ASTRO	**CELEST**	**OMNIS**	**EPOCHA**
Reference Epoch	B1950.0	B1950.0 then J2000	J2000	J2000
Precession Model	Based on the Explanatory Supplement to *The American Ephemeris and Nautical Almanac 1961*	Same as ASTRO for B1950.0 epoch, 1976 IAU precession, 1980 IAU nutation, and 1982 definition of UT1 for J2000 epoch	Same as CELEST for J2000 epoch initially then updated with minor revisions to the IERS96 model	IERS96, IERS2003, or IERS2010 model
Nutation Model	Same as above	Same as above	Same as above	IERS96, IERS2003, or IERS2010 model
Earth Rotation and Polar Motion Reference Models	Same as above, daily pole coordinates input and linear interpolation used. UTC was adopted in 1960 and 100 msec steps were applied to keep it close to UT1 until 1972, when leap seconds were introduced	Same as above for Earth rotation, daily pole coordinates input and linear interpolation used. For GPS added NSWC Earth Orientation Parameter Prediction (EOPP) coefficients converted to daily table with linear interpolation	Same as above for Earth rotation, NGA EOPP coefficients converted to daily table or IERS daily table both with quadratic interpolation	IERS96, IERS2003, or IERS2010 model for Earth rotation, NGA EOPP coefficients converted to daily table or IERS daily table both with cubic interpolation
UT1-UTC Zonal Tide Model	None	None	None initially then IERS96 model (Yoder with 41 terms)	IERS96, IERS2003, or IERS2010 model (Gross with 62 terms)
Diurnal and Semidiurnal Tide Models for x, y, and UT1-UTC	None	None	None initially then IERS96 model	IERS96, IERS2003, or IERS2010 model

Tracking Data Types	**Orbit Determination System**				
	ASTRO	**CELEST**	**OMNIS (Batch)**	**OMNIS (GPS/Sequential)**	**EPOCHA**
Doppler	X	X			
Range Difference	X	X	X	X	
Carrier Phase					X
Carrier-Derived Range				X	
Range	X	X	X	X	X
HV Range				X	
HV Range Difference		X		X	
HV Two-Way Range and Range Rate*		X			
Right Ascension and Declination	X				
Directional Cosines and Rates	X				
Position and Velocity	X	X	X	X**	X**

*Involved tracking of an HV through a geostationary relay satellite

** Involved least squares fits with position and optionally velocity as observations to predict GPS orbits for several days

Station Displacements and Observation Corrections	**Orbit Determination System**			
	ASTRO	**CELEST**	**OMNIS**	**EPOCHA**
Station Tectonic Motion	None	None	Plate motion models with epoch initially, then adopted station velocities with epoch starting in 2002	Adopted station velocities with epoch
Solid-Earth Tide	None	None, NSWC model added for GPS processing	NSWC model initially then IERS96 model	IERS96, IERS2003, or IERS2010 model
Ocean Loading	None	None	None initially then IERS96 model	IERS96, IERS2003, or IERS2010 model
Atmospheric Tide	None	None	None	IERS96, IERS2003, or IERS2010 model
Atmospheric Loading	None	None	None	Not yet implemented
Pole Tide	None	None	None initially then IERS96 model	IERS96, IERS2003, or IERS2010 model
Observation Time Tags for Transit Time Correction	UTC time of emission or time of reception	UTC or GPS time of emission or time of reception	(GPS/Sequential) GPS time of emission or time of reception (Batch) UTC time of emission or time of reception	GPS time of emission
Satellite Antenna Offset	None	Vertical only except for HVs which required an attitude model	Yaw attitude required for GPS satellites, HVs required an attitude model	Yaw attitude required for GPS satellites
Station Position Reference Point	APC*	APC*	APC*	APC*, ARP*+PCO*, or Mark+Ht. of ARP above Mark+PCO
Antenna Phase Center Variations	None	None	None	Satellite elevation dependent and/or station elevation and azimuth dependent
Ionospheric Refraction	Two-frequency correction using raw data	Two-frequency correction using raw data	Two-frequency correction using raw data	Two-frequency correction using raw data
Tropospheric Refraction	Hopfield model using measured or default weather data	Hopfield model using measured or default weather data	Hopfield or Saastomonien zenith models with Neill mapping functions using measured or default weather data	Saastomonien zenith models with NMFs or GMFs using measured or default weather data
Periodic Relativity	None	Applied for GPS	Applied for GPS and HV tracking of GPS	Applied for GPS
Carrier Phase Windup	None	None	Applied to range difference data and carrier phase data prior to being converted to CDP data	Applied to carrier phase data

*APC = two-frequency antenna phase center
ARP = antenna reference point
PCO = vertical phase center offset

Parameters That Can Be Estimated	**Orbit Determination System**			
	ASTRO	**CELEST**	**OMNIS**	**EPOCHA**
Orbit	Epoch state position and velocity, zero-eccentricity elements, or classical orbital elements	Epoch state position and velocity, zero-eccentricity elements, or classical orbital elements	Pseudoepoch state position and velocity or zero-eccentricity orbital elements without process noise for GPS, same with direct process noise included for HVs	Current state position and velocity with acceleration process noise
Gravity Field Model	None. Done in GEO	Selected spherical harmonics (up to 32)	Selected spherical harmonics	None
Atmospheric Drag	Daily or multi-day sets of four drag parameters (up to 4 sets)	Segmented drag coefficients (up to 16)	Stochastic drag coefficient	HV orbit estimation not yet implemented
Radiation Pressure	Daily or multi-day radiation pressure scale parameters (up to 4)	Segmented radiation pressure scale and y-bias acceleration (up to 4 pairs)	Stochastic radiation pressure scale (1 or 2) and y-axis acceleration	Stochastic radiation pressure scale (1 or 2) and y-axis acceleration
Thrust	None	RVC, RAC, or GPS XYZ accelerations (up to 4)	RAC or GPS XYZ accelerations (up to 4)	RAC accelerations (unlimited)
Clocks	Possible pass bias parameters– frequency offset, frequency drift (aging), time tag offset, and range bias	Possible pass bias parameters – time offset, frequency offset, frequency drift (aging) Possible arc parameters for GPS–range bias (equivalent to time offset), frequency offset, and frequency drift (aging)	(GPS/Sequential) Stochastic satellite (1 to 3) and station (1 to 3) clock parameters except for a master clock. Adjustment to GPS time and frequency after the fact. (Batch) Same pass bias parameters as CELEST	Stochastic satellite (1 to 3) and station clock (1 to 3) parameters, Either Composite Clock steered/adjusted to GPS Time and Frequency or a Master Clock with adjustment after the fact
Tropospheric Refraction	Pass scale bias parameter	Pass scale bias parameter	Stochastic zenith and optional east and north gradient parameters using the Neill wet mapping function	Stochastic zenith and optional east and north gradient parameters using the wet NMFs or GMFs

Parameters That Can Be Estimated	**Orbit Determination System (Continued)**			
	ASTRO	**CELEST**	**OMNIS**	**EPOCHA**
Earth Orientation	x and y pole offsets relative to model	x and y pole offsets relative to model	x and y pole offsets and rates and UT1-UTC rate relative to model (one model only)	Stochastic x and y pole offsets and rates, stochastic UT1-UTC offset and rate with daily observation with sigma for UT1-UTC, estimates adjusted at model changes to ensure continuity
Station Coordinates	Cartesian XYZ coordinate corrections	Cartesian XYZ coordinate corrections	Cartesian ENV coordinate corrections	Cartesian XYZ coordinate corrections with ENV *a priori* sigmas
Carrier Phase Biases	None	None	None	For each continuous tracking segment between a satellite and station pair

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