# Current Topics in Astrodynamics

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**rev 1**

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# Outline

- SSA Challenges & Opportunities
- Astrodynamic Knowledge
- SSA Limitations
- Open Source Project
- Astro Algorithms for the open source tool
- S/W considerations

# SSA Challenges & Opportunities

# The Time Period 1940-60 Saw the Advent of …

- Radar
- Computers
- Ballistic Missiles
- Ballistic Missile Warning & Defense
- Space Launch Vehicles
- Artificial Earth Satellites
- Large 'Institutional' Projects

# Space Situational Awareness (SSA) Challenges & Opportunities

- **Challenges and opportunities of 2011 are very different from those of 1959**
- **In 1959, the challenge was to maintain the space catalog for a small number of simple, non-maneuvering space objects using limited:**
  - **Tracking assets**
  - **Communication capabilities**
  - **Knowledge of the space environment**
  - **Knowledge of orbit estimation technology**
  - **Computing resources (hardware and software)**
  - **Astrodynamical expertise (people)**

# SSA Challenges and Opportunities 2011

- **In 2011, the challenge is to maintain the space catalog and <u>support collision avoidance</u> for a much larger number of complicated, frequently-maneuvering space objects using:**
  - **Sophisticated radar and optical sensors**
  - **High speed communication networks**
  - **Improved knowledge of the space environment**

    **Geopotential (the shape of the Earth)**

    **Third-body point masses**

    **Neutral atmosphere density**

    **Solar Radiation Pressure**

# SSA Challenges and Opportunities 2011 Cont'd (2 of 4)

– **Sophisticated <u>orbit propagation</u> technology**
  - **General Perturbations (Brouwer, Deprit)**
  - **Special Perturbations (numerical integration)**
  - **Semi-analytical Satellite Theories**
– **Sophisticated <u>orbit estimation</u> technology**
  - **Weighted least-squares, recursive Kalman Filter, recursive Non-linear Filter**
  - **Position and velocity and mean equinoctial element solve-for vectors**
  - **Reduced dynamic techniques – 1 cm accuracy demonstrated for geodynamics applications**
– **<u>Moore's Law growth</u> in computing thru-put**
  - **Mainframes (IBM)**
  - **Mini-computers (VAX)**

# SSA Challenges and Opportunities 2011 Cont'd (3 of 4)

- Moore's Law growth in computing thru-put Cont'd
  - Workstations
  - PCs
  - PVM & MPI-based parallel computing
  - High Performance Computing (HPC)
  - Multi-core CPU
  - Graphical Processing Units (GPU)
  - Cloud
- Software Factors
  - Assemblers
  - Fortran compilers (F77)
  - Objected-oriented design (F90, F95, C++, JAVA)
  - Version control

# SSA Challenges and Opportunities 2011 Cont'd (4 of 4)

- Software Factors Cont'd
  - Integrated Development Environments (IDE)
  - Software Development Standards (Carnegie Mellon)
  - Markup Languages (XML, SysML)
  - CUDA or TBD parallel computation tools
  - Role of legacy software in time of economic constraint
  - Proprietary software packages
  - Open Source software
- Astrodynamics Expertise
  - US Astrodynamical knowledge in 1959
  - Astrodynamics in 2011

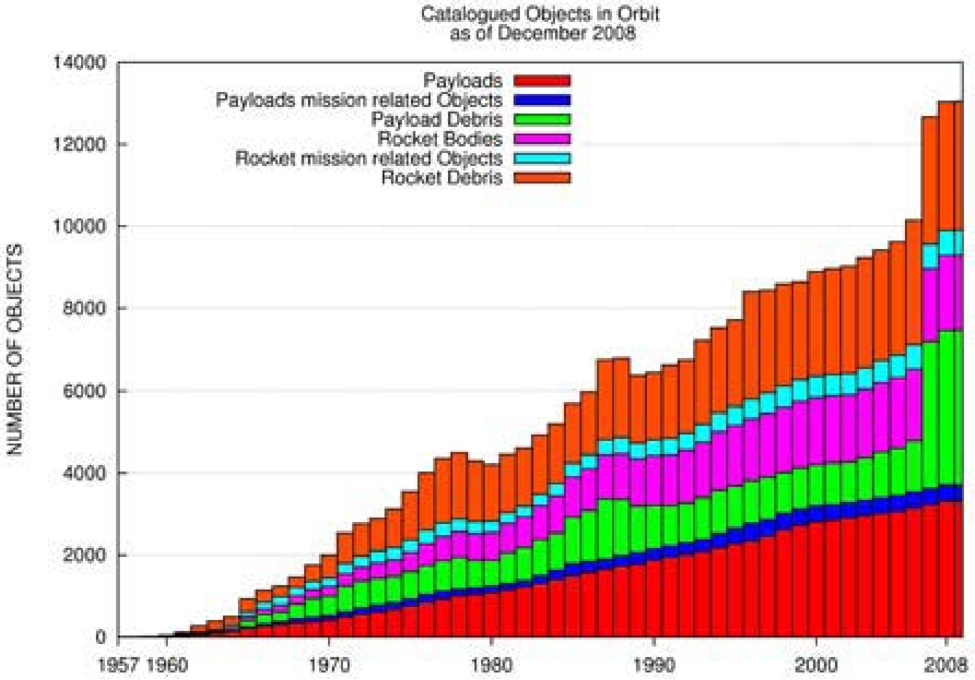
# Number of Objects

- **Presently 22000 objects are presently tracked**

  **16000 are known, identifiable space objects**

  **6000 are known analyst sats**

- **These satellites are distributed between LEO, MEO and GEO**



# Number of Objects Cont'd

- 22000 objects are presently tracked—thought to be 10 cm
- Several estimates of 500,000 or more space objects if we count down to 1 cm
- Observation data flow to increase to million per day or more

# Space object characteristics

- Size – many organizations are building small satellites
- Satellite Smallness represents a challenge for SSA
- GEO satellite clusters represent a difficult challenge because angular separation of the of the vectors from the sensor to cluster elements may be small making the task of associating cluster obs with the correct satellite difficult
- Formations of small satellites such as the Prisma Mango and Tango may be difficult for SSA
- Fractionated spacecraft concepts now being developed may propose a challenge to SSA.
- Detection of station-keeping maneuvers may challenge SSA.  Spacecraft with low thrust ion propulsion systems may be a particular challenge

# Space Object Characteristics Cont'd

- **High Area to Mass Ratio (HAMR) objects may exhibit unusual motion**
- **QB50, a 50 satellite constellation is being proposed to study atmosphere density**
  - **Each satellite will be a double cubesat.**
  - **Some of the satellites will have maneuver capability**

# Observation Residual, $O_o$ - $O_c$

- $O_o$ **= actual measurement at time** $t$
- $O_c$ **= computed measurement at time** $t + \delta t$ **based on a previous estimate of the solve-for parameter vector where**

$$O_c = f_0\left[\vec{R}(t+\delta t,\vec{p}),\vec{R}-dot(t+\delta t,\vec{p}),\vec{r}_s\right]+b+RF_c$$

$f_0$ **is the observation geometry**

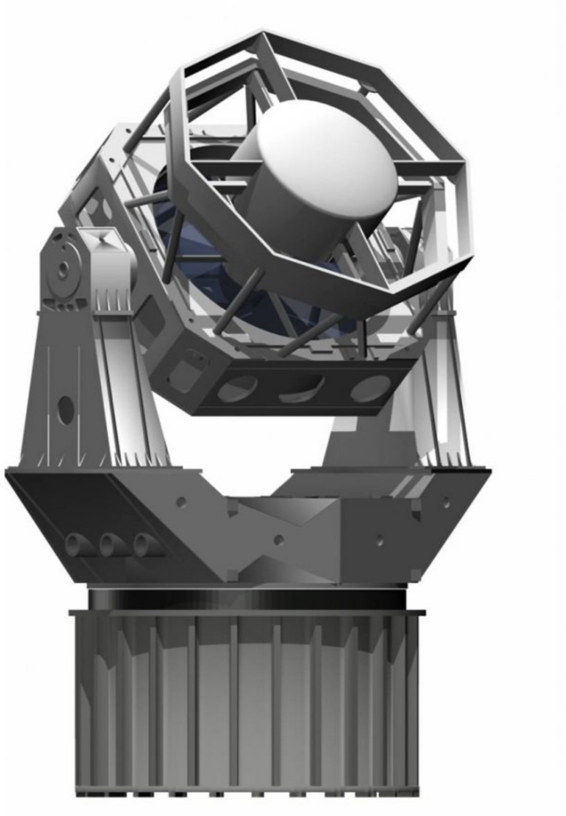
***R,R-dot*** **are the local topocentric (position, velocity) vectors**

$p$ **is the solve-for vector**

$r_s$ **is the station location**

# Evolution in the Observation Data

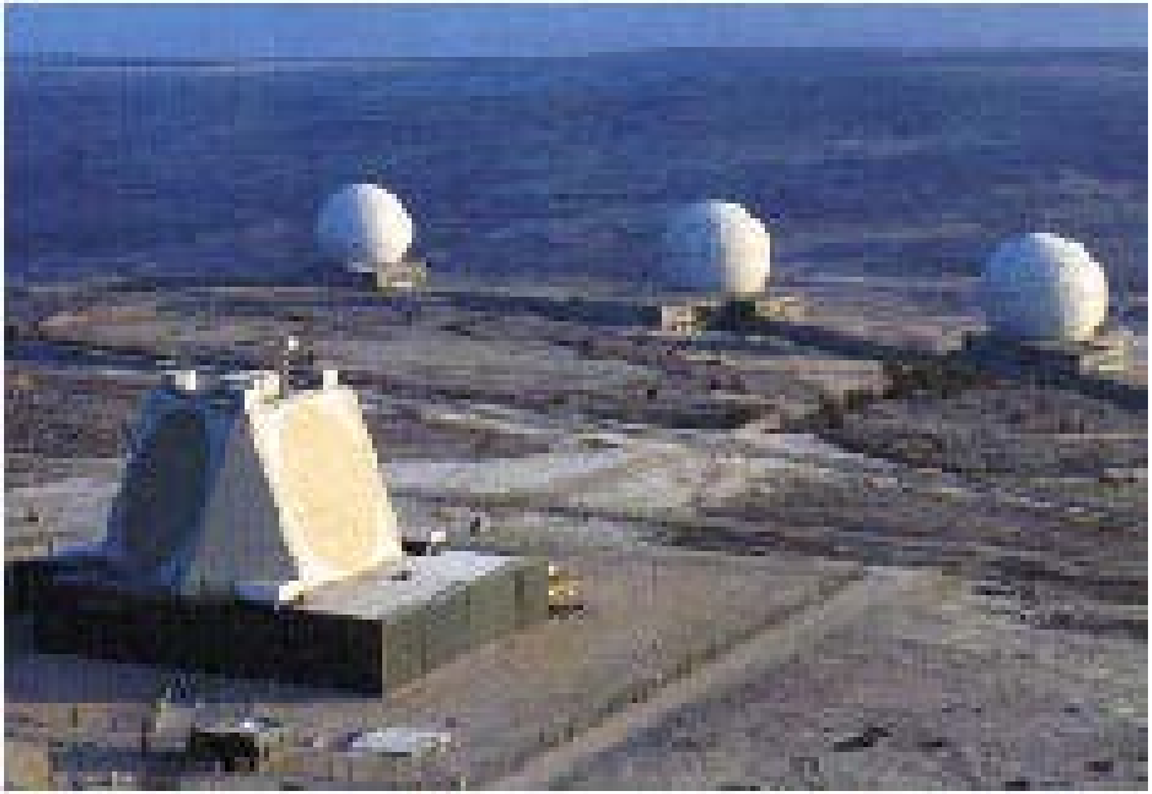
- **Space Surveillance Telescope**



- **Space-Based Space Surveillance System**

**This agile sensor mount enables SBSS to find and track objects in space -- even new spacecraft launches and maneuvers -- with significantly greater speed, capacity and sensitivity than previous space sensors, including:**
**twice the sensitivity**
**twice as fast at detecting threats**
**three times improvement in the probability of detecting threats, and ten times improvement in capacity**

# Phased-array surveillance radar and tracking radars at Fylingdales, UK

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# The Shape of the Earth, 1964

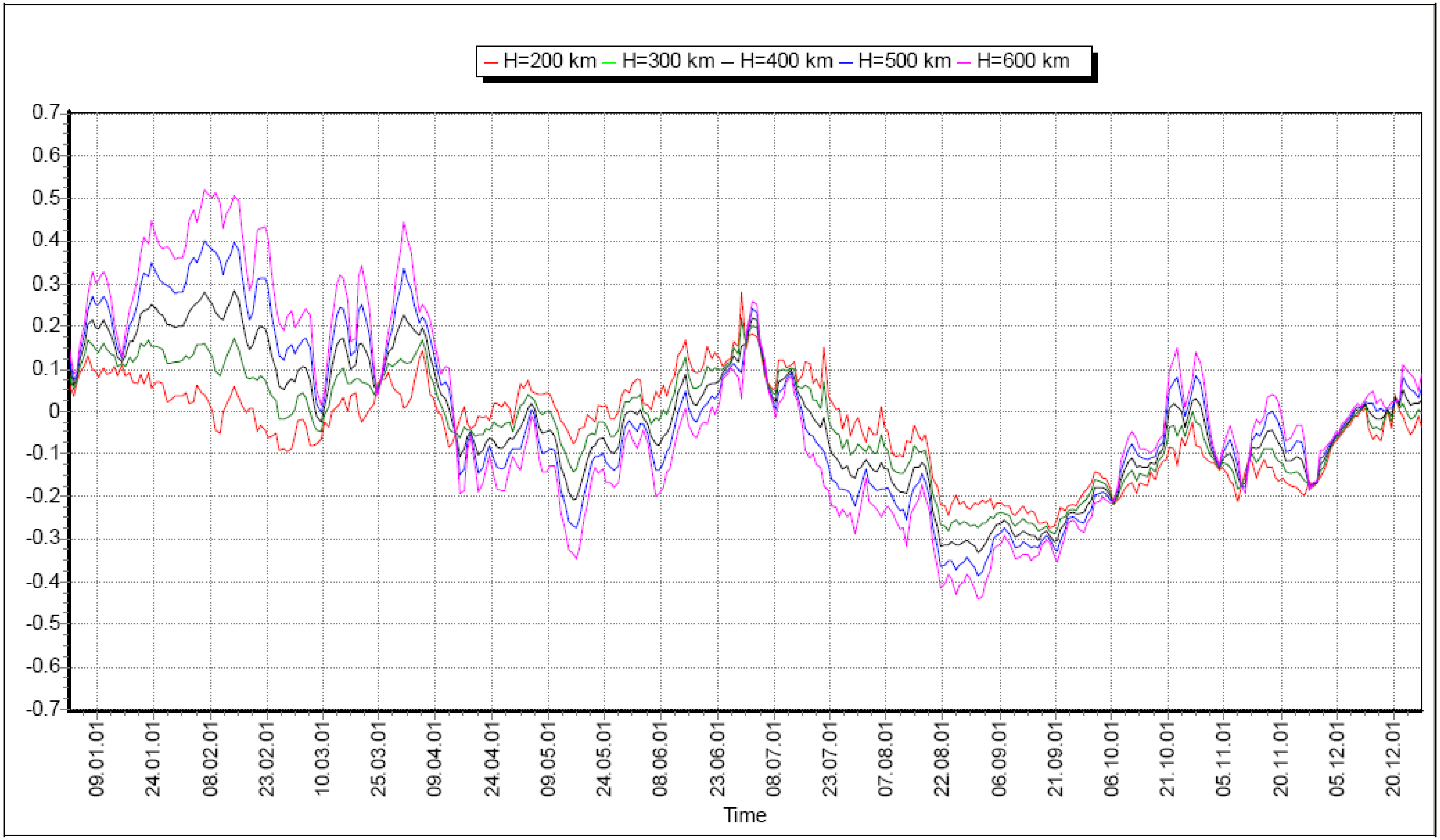
- **Duke of Edinborough Lecture given by D. G. King-Hele:**

$$U = \frac{GM}{r}\left\{1 - \sum_{n=2}^{\infty} J_n \left(\frac{R}{r}\right)^n P_n(\sin\varphi)\right\}$$

TABLE II. VALUES OF THE COEFFICIENTS $J_n$ OBTAINED FROM ANALYSIS OF SATELLITE ORBITS

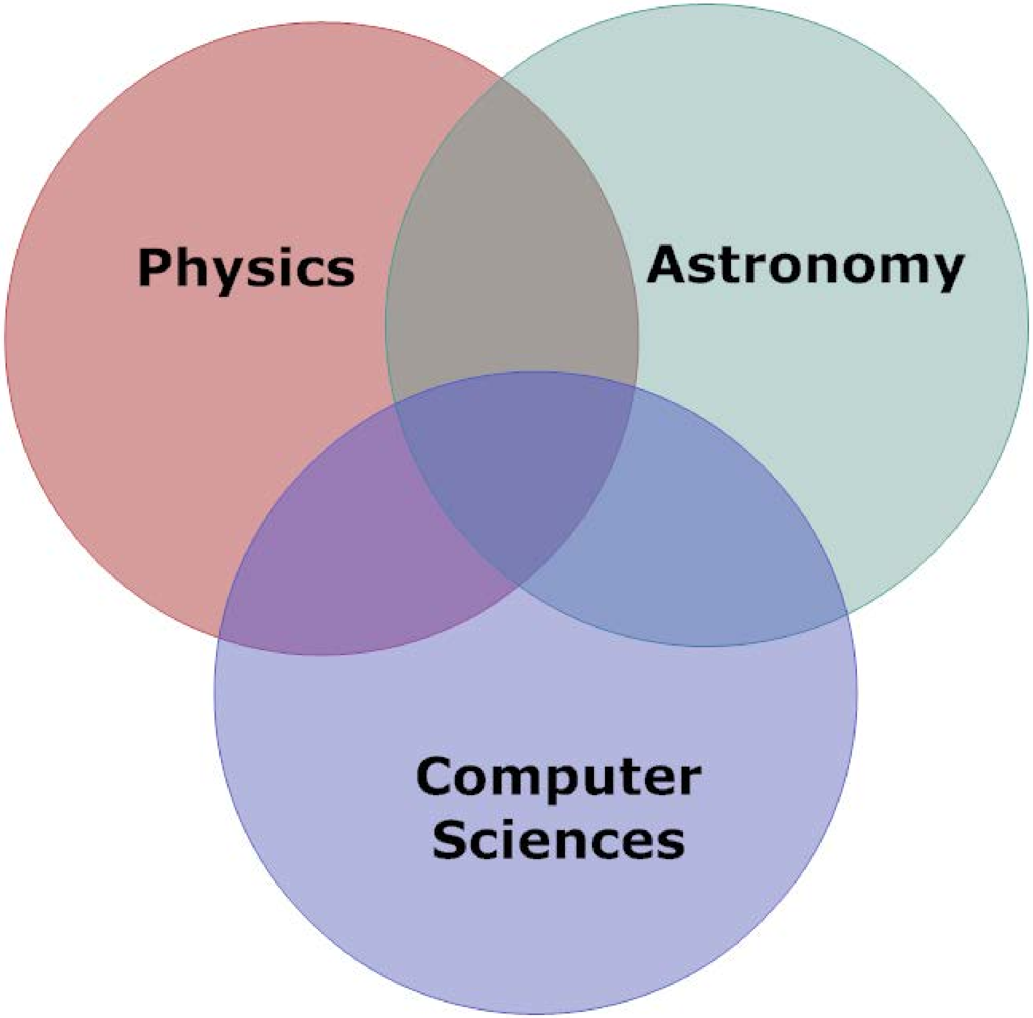
| | | | |
|---|---|---|---|
| $10^6 J_2$ | 1082.86 | $10^6 J_3$ | −2.45 |
| $10^6 J_4$ | −1.03 | $10^6 J_5$ | −0.05 |
| $10^6 J_6$ | 0.72 | $10^6 J_7$ | −0.41 |
| $10^6 J_8$ | 0.34 | | |
| $10^6 J_{10}$ | −0.50 | | |
| $10^6 J_{12}$ | 0.44 | | |

# Errors in the NRL MSIS-2000 Atmosphere Density over 2001



# Astrodynamic Knowledge

# Astrodynamics exists at the interface between physics, astronomy, & computer sciences




- **Physics is concerned with the physical processes and phenomena of a particular system**
- **Astronomy is the study of objects and matter outside the earth's atmosphere and of their physical and chemical properties**
- **Computer Science is the domain of computer software and the more abstract domain of problem solving**

# Space Situational Awareness and Astrodynamics

- **The fundamental requirement of space situational awareness (SSA) is to provide actionable knowledge about events and activities in Earth orbit. A key component of SSA is space surveillance -- determining the present position of space objects and the ability to predict their future orbital paths. Related requirements are the detection of new space objects, the detection of spacecraft maneuvres, and the prediction of when one space object may interfere with another space object.**

- **Identify the portions of Astrodynamics that contribute to SSA.**

- **Identify research topics in Astrodynamics that support improved SSA capabilities.**

# Astrodynamics Technical Areas relevant to SSA

- **Orbital Perturbations and Satellite Theory**
- **Orbit Determination**
  - **Batch Least Squares and Kalman Filter**
- **Orbit and Constellation Design and Maintenance**
- **Atmospheric Density Correction**
- **Operational Orbit Determination**
- **Attitude Estimation**
- **Parallel Processing**
- **Application of modern software paradigms**
- **Systems Design**

# U.S. Astrodynamical Knowledge, 1959

- **Dynamical Astronomy Community**

| Brouwer | Kozai |
|---|---|
| Vinti | Hori |
| Herget | Herrick |
| Danby | Musen |

- **Ph.D. programs in Aerospace Engineering/Astrodynamics were uncommon**
  - **Robert M. L. Baker's PhD in Engineering (UCLA, 1958) with specialization in Aerospace is thought to be the first such degree in the US**
- **The first Astrodynamics Specialist Conference was held in 1961 at UCLA**
- **Industrial Research**
  - **Lockheed, TRW, Aerospace Corp**

# Astrodynamical Community, 2011

- Astrodynamics is a well established technical discipline
  - American Astronautical Society (AAS) Space Flight Mechanics Committee
  - American Institute of Aeronautics & Astronautics (AIAA) Astrodynamics Technical Committee
  - American Astronomical Society (AAS) Division on Dynamical Astronomy
- Astrodynamics is supported by the owner/operator side of space industry and by SSA
- Astrodynamics is taught at many major universities: e.g. MIT, U. Colorado, U. Texas, Texas A&M, Purdue, Lille U., TU Delft, BUSA
- 'Open' technical interchange facilitated by a robust network of conferences, journals, electronic libraries
- 'Other than open' technical interchanges

# Semi-analytical Satellite Theory

- Conventional Cowell equations of motion are replaced with the equations of motion for the mean equinoctial elements and the short-periodic expressions. Both of these are obtained by the Generalized Method of Averages (Krylov-Bogoliubov-Mitropolsky) perturbation method.
- The short-periodic formulas are Fourier series with slowly varying coefficients and trignometric variables related to the satellite phase angle and the rotation of the Earth.
  - The slowly varying coefficients are evaluated at the output times using low order interpolators
- Compatible semi-analytical concept for the partial derivatives (the state transition matrix)
- Interpolator structure and strategy

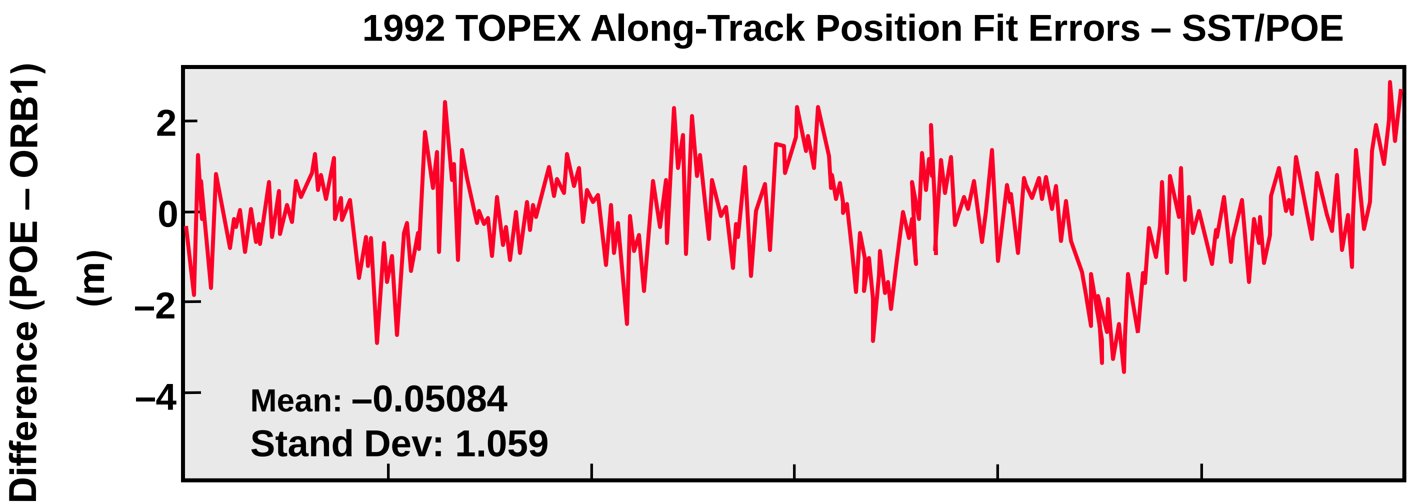
# Why should we be interested in the Semi-analytical Satellite Theory?

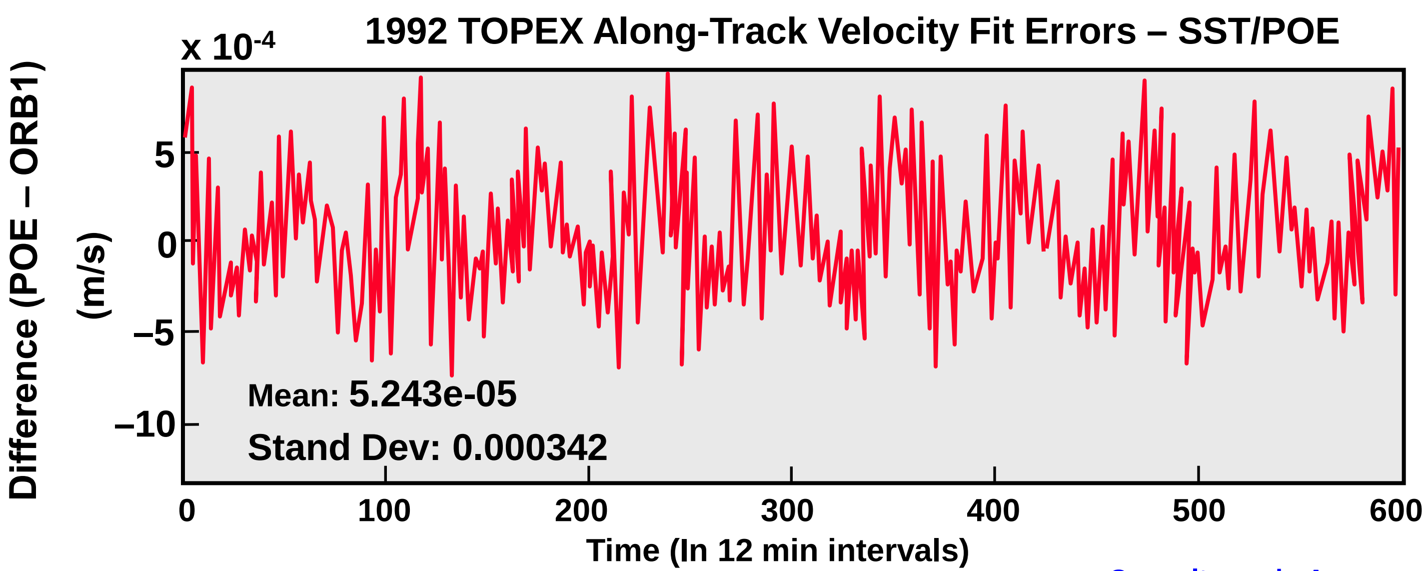
- Very high accuracy
- Great flexibility because the spherical harmonic expansions have been passed through the perturbation transform
- Non-conservative perturbations of atmospheric drag and solar radiation pressure
- Employs a variant of the GP theory architecture of one-time initialization and output at multiple request times
  - The initialization is refreshed on the mean element grid
- The computational cost does not increase significantly for dense output at request time grids
- Portions of the Semi-analytical Satellite Theory can be added to a GP theory

# Why should we be interested in a Semi-analytical Satellite Theory Cont'd?

- Several estimation algorithms have been built for estimating the Mean Elements directly from the tracking data
  - Conventional Weighted Least Squares
  - Extended Semi-analytical Kalman Filter (ESKF)
  - Square-Root Information Filter (SRIF)
  - Backward-Smoothing Extended Semi-analytical Kalman Filter (BSESKF)
- The Semi-analytical Satellite Theory can take advantage of modern computer architectures
  - e.g. Picard-Chebyshev iteration integrator and current graphical processor

# Least Squares Fit of SST Theory to TOPEX Orbit – Along-Track Fit Errors



# SSA Limitations

# USG SSA system shortcomings (1)

- Observation compression concepts are not available for either radar or optical sensors
- Fast <u>and</u> accurate orbit propagator concepts are not available
- Fast <u>and</u> accurate state transition matrix concepts are not available
- Kalman filter-based orbit estimation concepts are not available
- Kalman filter-based sensor calibration processes for are not available
- Realistic process noise and measurement error models are not employed
- The orbit uncertainty as represented by and propagated by the orbit determination systems is not well understood
- The processes developed by the Air Force Space Command for real time tracking of the atmospheric density variations are limited and narrow in scope

# USG SSA system shortcomings (2)

- There is no process for re-acquiring a significant portion of the catalog, as would be required in the event of a major geo-magnetic storm (such as 1989)
- There is no mathematically ‘strong’ theory for the general concept of observation association
- There is no concept for taking advantage of frameworks that can be massively parallelized on distributed computing clusters. (or multi-core CPU with GPU).
- There is no web services-based architecture for SSA**
- There is no capability for organizing the very large databases that will result from large catalogs and improved sensors
- There is only a limited cooperative, positive relationship between the U.S. military SSA community and the broader international astrodynamics research community
- The strict acquisition and operational requirements resulting from the NORAD ITW/AA certification process

** See poster: Development of a Web Front End for ESA’s CRASS system”

# Goals of the Open Source SSA Project

- Begin to create the software tools for basic Space Situational Awareness (SSA) and Space Traffic Management (STM) that could be used by any satellite operators, anywhere in the world, to improve the safe and efficient use of Earth orbit.

- This promotes international cooperation, responsible behavior, and the availability of essential data and tools to make space operations safer.

- The intent is to add at least one viable community open source project to the current market of SSA in order to drive innovation and provide alternative price points and feature sets.

# Requirements

- Correctly predict the orbit determination performance of future tracking and orbit determination systems
- Correctly predict the performance of existing SSA systems (and combinations of such systems)
- Generate high accuracy reference orbits
- Include conventional weighted least squares, Kalman Filter, and modern Nonlinear filters
- Flexible with respect to the choice of orbit propagator and solve-for variables
- Flexible with respect to the available observation models including ground-based and space-based observation types and realistic errors
- Flexible with respect to the total number of allowable sensors

# Current Space Computational Software Environment

- **Tremendous legacy of scientific space software (mostly Fortran 77) whose development was initiated in the 1970s and 80s**
- **Tremedous evolution in scientific computing hardware**
  - **Connection Machines**
  - **Mainframes**
  - **VAXSystems**
  - **Reduced Instruction Set Computers (RISC)**
  - **Net worked clusters of PC's**
  - **Current machines with multi-core CPUs and Graphic Processor Units (GPU) with hundreds of processing elements**
- **Tremendous evolution in scientific software development tools**
  - **Fortran 90, 95, 2003**
  - **C++**
  - **Java**

# Current Space Computational Software Environment Cont'd

- Parallel Processing software tools
  - Parallel Virtual Machine (PVM)
  - Message Passing Interface (MPI)
  - OpenMP
- Graphical Processor Units (GPUs)
  - CUDA C (requires your program to be compatible with C++)
  - CUDA Fortran (requires your program to be compatible with Fortran 90 or better)
- Web Application issue

# Orbit Propagator and Orbit Determination Programs

| Organization | Software program | Primary application |
|---|---|---|
| Aerospace Corporation/USAF | TRACE | Operational OD evaluation and covariance analysis<br>www.aero.org/publications/crosslink/summer2002/04.html |
| Analytical Graphics Inc. | STK/HPOP | Integrated graphics and numerical processing<br>www.agi.com/products/desktopApp/odtk |
| Charles Stark Draper Laboratory | DSST<br><br>DGTDS | Precision semianalytical OD technique<br>www.csdl.org<br>POD |
| APL | OIP/ODP | Transit Doppler post-processing OD used in the 1960s through the 1980s |
| MICROCOSM | MICROCOSM | Commercial software OD package of the NASA GEODYN program<br>www.vmsi_microcosm.com |
| MIT/LL | DYNAMO | POD, specifically for HEO and GEO satellites<br>www.ll.mit.edu |
| NASA/GSFC | GTDS<br><br><br>RTOD | Operational OD for LEO, MEO, and GEO orbits (TDRSS) and lunar and interplanetary orbits<br>fdab.gsfc.nasa.gov/live/Home/Tools_Nav_GTDS.html<br>Precision real-time OD for onboard spacecraft using Kalman filtering<br>nctn.oact.hg.nasa.gov/ft-tech-GEONS.html |
| NASA/GSFC | GEODYN II | POD for geodesy and geophysics<br>bowie.gsfc.nasa.gov/697/POD/POD.html |
| NASA/JPL | MIRAGE | Multiple satellite OD using GPS |
| NASA/JPL | DPTRAJ | Interplanetary OD |

# Orbit Propagator and Orbit Determination Programs Cont'd

| | | |
|---|---|---|
| NASA/JPL | GIPSY/OASIS II (GOA) | POD of satellites using GPS, SLR, and DORIS observations<br>gipsy.jpl.nasa/orms/goa |
| Navy/NSWC | OMNIS/EPICA | GPS precision orbits<br>earth-info.nga.mil/GanG/sathtml/gpsdoc2006_11a.html |
| Navy/NSWC | PPT3[a] | Surveillance and space debris tracking and propagation |
| Navy/NSWC | Special-K | Operational numerical OD program |
| Navy/NRL | OCEANS | Orbit studies, covariance analyses, and GPS orbits<br>www.nrl.navy.mil |
| SAO | DOI | Used in the early 1960s for OD of Baker-Nunn camera data and development of standard Earth gravity models |
| USAF/SPACECOM | MCS | GPS operational orbits |
| USAF/SPACECOM | SGP4[a] | Surveillance and space debris tracking and propagation |
| USAF/SPACECOM | SPADOC/ SPECTR | Operational numerical OD program used by Shreiver and Kirkland AFBs |
| USAF/SPACECOM | ASW | Workstation numerical OD program |
| University of Texas | UTOPIA, MSODP | Precision orbits using GPS, SLR, and DORIS observations; TRANET, OPNET, altimetry<br>www.csr.utexas.edu |

# Space Situational Awareness Tool Requirements

- Model the orbital motion to varying accuracy levels
- Model and update the space environment
- Simulate tracking measurement data for multiple sensor networks and sensor types including space-based sensors
- Process actual and simulated tracking measurement data for multiple sensor networks and sensor types with multiple orbit determination algorithms
- Consider chemical and electric on-board propulsion technologies
- Rigorous treatment of the orbit determination uncertainty estimates
- Be affordable both in the developmental sense and in the operational sense given the current economic circumstances and given the current baseline capabilities
- Be maintainable over many years with the programming and computer science skills likely to be available

# Astrodynamic Algorithms for the SSA Analysis tool

- Satellite Theories
  - Numerical integration
  - Draper Semi-analytical Satellite Theory
  - NORAD GP (SGP, SGP4, SGP8, and HANDE)
  - NAVSPASUR PPT2 and PPT2 enhanced
  - Russian GP (A and AP)
  - Russian Numerical-Analytical (NA)
  - Others tbd
- Orbit Estimation Algorithms
  - Batch Least Squares
  - Extended Kalman Filter
  - Modern Nonlinear Filter
  - Both perturbed position and velocity and mean nonsingular element solve-for parameter options

# Software Development Considerations

- Migration to modern language platform(s) employing object-oriented and component technologies such as C++/CORBA
  - Anticipated for key algorithms
  - Costly in programming effort
  - Accounting for the evolutionary effort to date
- Encapsulation
  - Noninvasive approach to employ the legacy binaries in predefined but configurable workflows
  - Data exchange between binaries continuing to take place through file I/O
  - Devising an extensible encapsulation of the software components that treats them as black boxes with a set of inputs/outputs and a set of valid types and ranges of compile time and run-time parameters
  - Automatically generated GUI based on XML

# Software Development Considerations Cont'd

- Web 2.0 Architecture for SSA
- Adaptation of the algorithms to take advantage of GPU
  - Take advantage of work done for the SIMD machine-assumption

# Risk Reduction Plan for the SSA Analysis Tool

- Migration of the Standalone DSST from Fortran 77 to Object-Oriented C++
- Non-invasive encapsulation of the Linux GTDS R&D Orbit Determination system using Legacy Computing Markup Language (LCML) and LEGacy Encapsulation for Network Distribution (LEGEND)
  - LCML and LEGEND tools were developed in the Ocean Engineering Department at MIT (campus)
  - Linux GTDS development is ongoing
    - 100 sensors in Differential Correction
    - Refinements to the DSST State Transition Matrix capability to support covariance studies
    - PPT2 enhanced with tesseral m-dailies real data testing (CHAMP)
- Develop a Web 2.0 architecture for a selected SSA service based on the human-provided services (HPS) paradigm
  - Schall (Technical University, Vienna)

# Risk Reduction Plan for the SSA Analysis Tool Cont'd

- **Demonstrate the capability of the GPU to improve astrodynamic processing via a Picard-Chebyshev implementation of the DSST**
  - **Take advantage of the work on Picard-Chebyshev DSST orbit propagation by Jeff Shaver (MIT, 1980)**

# First step: Open use of DSST through Internet (Nonlinear dynamical Web Tool project)

## Astrodynamics Web Tools

HOME | SOFTWARE | REPORTS | USER AREA | LINK | STAFF | CONTACT

### Astrodynamics Tools

Universidad de La Rioja

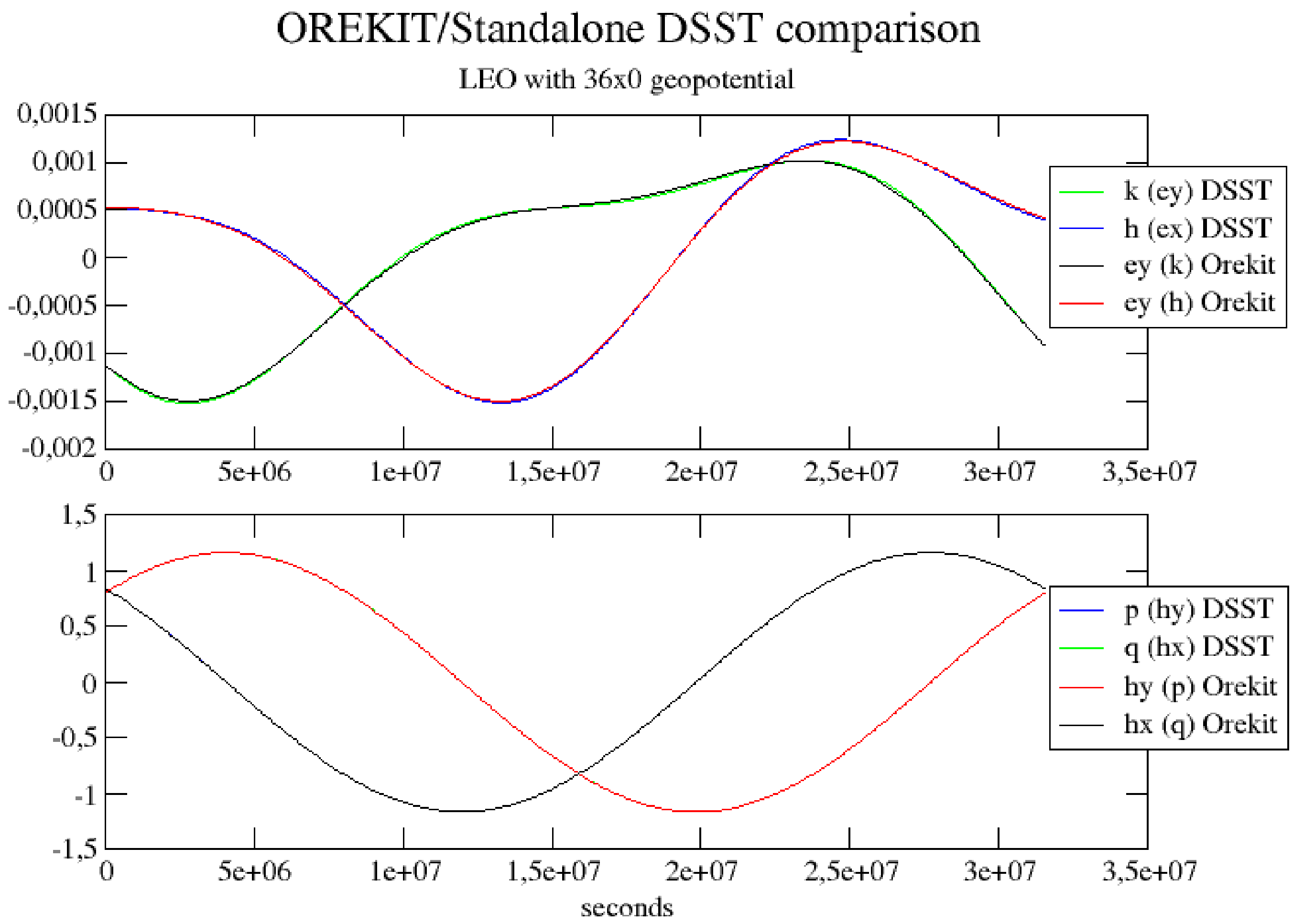
Dr. Juan Félix San Juan (juanfelix.sanjuan@unirioja.es)

**Orbit Propagator Programs**

Twelve mathematical zonal and tesseral models for prediction of satellite position and velocity using state vector are available:

| Model | Coefficient | Order | Name | Real-Time |
|---|---|---|---|---|
| Zonal | $J_2$ | 2 | ppkbJ2or2 | **Yes** |
| | $J_2$ | 3 | ppkbJ2or3 | **Yes** |
| | $J_2$ | 4 | ppkbJ2or4 | No |
| | $J_2 \cdots J_4$ | 2 | ppkbJ4or2 | No |
| | $J_2 \cdots J_4$ | 3 | ppkbJ4or3 | No |
| | $J_2 \cdots J_6$ | 2 | **ppkbJ6or2** (1) | No |
| | $J_2 \cdots J_6$ | 3 | **ppkbJ6or3** (1) | No |
| | $J_2 \cdots J_9$ | 2 | ppkbJ9or2 | No |
| Tesseral | 2 x 2 | 4 | tes2x2 | **Yes** |
| | 4 x 4 | 4 | tes4x4 | No |
| | 6 x 6 | 4 | tes6x6 | No |
| | 8 x 8 | 4 | tes8x8 | No |
| DSST | 50 x 50 | 2 | DSST | Yes |

# Port of the Precision DSST to the Orekit java environment



# Summary

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- Astro Algorithms for the open source tool
- S/W considerations

# Acknowledgement


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# An Astrodynamic Researcher's Point of View:

- **"In September 1976, I visited Dr. Max Lane [at the USAF in Colorado Springs] and his collaborators. The conversations were friendly, but never totally open, even in matters pertaining to what belongs to the public domain in the arts and techniques of orbit generation and prediction. On leaving the base, I resolved to wait for the opportunity of meeting the managers of the Space Computational Center and of sharing with them, if they were willing to do so, my concern about what I perceived that day as the crucial issue:**

***Research and development at the interface of computer software and mathematical astronomy is too shy, too slow, and too little informed to meet the fast progress in computer and communication hardware and the expanding responsibilities within the DoD. "***

**- Dr. Andre Deprit, NBS/NIST, 1977**