ORBIT DETERMINATION THROUGH GLOBAL POSITIONING SYSTEMS: A LITERATURE SURVEY

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5. Reduced Dynamic Strategy
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6. Low Circular Orbiters
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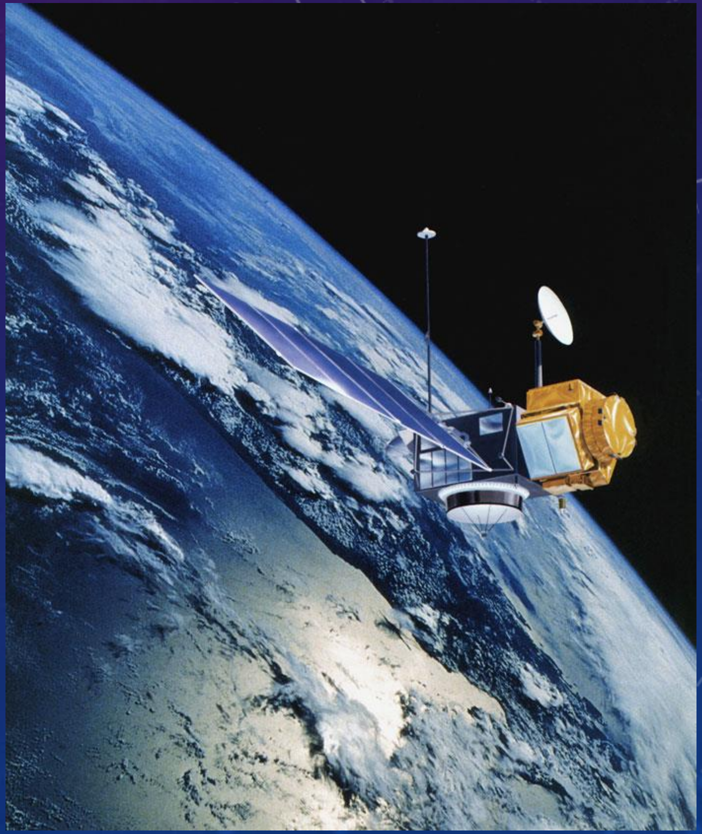
INTRODUCTION

- The Global Positioning System (GPS) was developed by NASA to track remote sensing satellites at altitudes below 3,000 km with accuracies better than 10 cm
- Equipment required for GPS includes ground receivers operating in conjunction with a receiver onboard a satellite
- Satellite accuracies became stringent to a decimeter in the 1990's
- One example is TOPEX which includes a primary laser tracking system and a French Doppler instrument
- Data from TOPEX and ground receivers will be combined to recover TOPEX and GPS satellite orbits in a reference frame defined by selected ground sites
- The ground network for the TOPEX experiment includes NASA's three deep-space tracking sites in California, Spain, and Australia, and at least three complementary sites operated by other government agencies.



TOPEX in space (credit JPL)

TWO ORBIT SOLUTION STRATEGY

- GPS orbit solutions are dynamic, which means they are governed by the laws of motion
- User satellite orbit solutions can range from purely dynamic to purely kinematic
- To achieve decimeter tracking accuracy, a joint solution must be applied for the user and GPS satellite orbits
- If GPS orbits are held fixed, user accuracy is typically limited at the meter level by GPS orbit error
- Non-NASA ground-site locations and parameters such as atmospheric propagation delay and solar radiation pressure are also adjusted
- A dynamic strategy exploiting the laws of motion is always preferable for the GPS orbit solutions
- This provides ample accuracy and maximizes data strength for the more demanding user solution, which is our primary interest.

DYNAMIC ORBIT DETERMINATION

- Until 1989 the classical dynamic solution technique was the only technique available for precise orbit determination
- This technique estimated satellite position and velocity at a single epoch with an extended arc of data
- Observations at different times were related to the epoch state parameters by integrating the equations of motion, a process requiring accurate models of the forces acting on the satellites
- Errors in the force models naturally introduce errors in the epoch state solution
- The effect of force model errors tends to increase with increasing arc length

DYNAMIC ORBIT DETERMINATION

- TOPEX error studies illustrate the importance of accurate dynamic models
- Figure 1 is taken from a covariance study of the altitude error for a single TOPEX orbit, at 1334 km, using GPS carrier data only
- A critical assumption is the gravity error model, which consists of the differences between more than 300 coefficients (20-by-20) from two gravity models, GEML10 and GEML2
- This reflects the approximate accuracy of the best gravity models in the early 1980's
- With a perfect gravity model this would fall to less than 6 cm
- Efforts at the Goddard Space Flight Center have substantially refined the gravity model, which approached the required accuracy around 1992

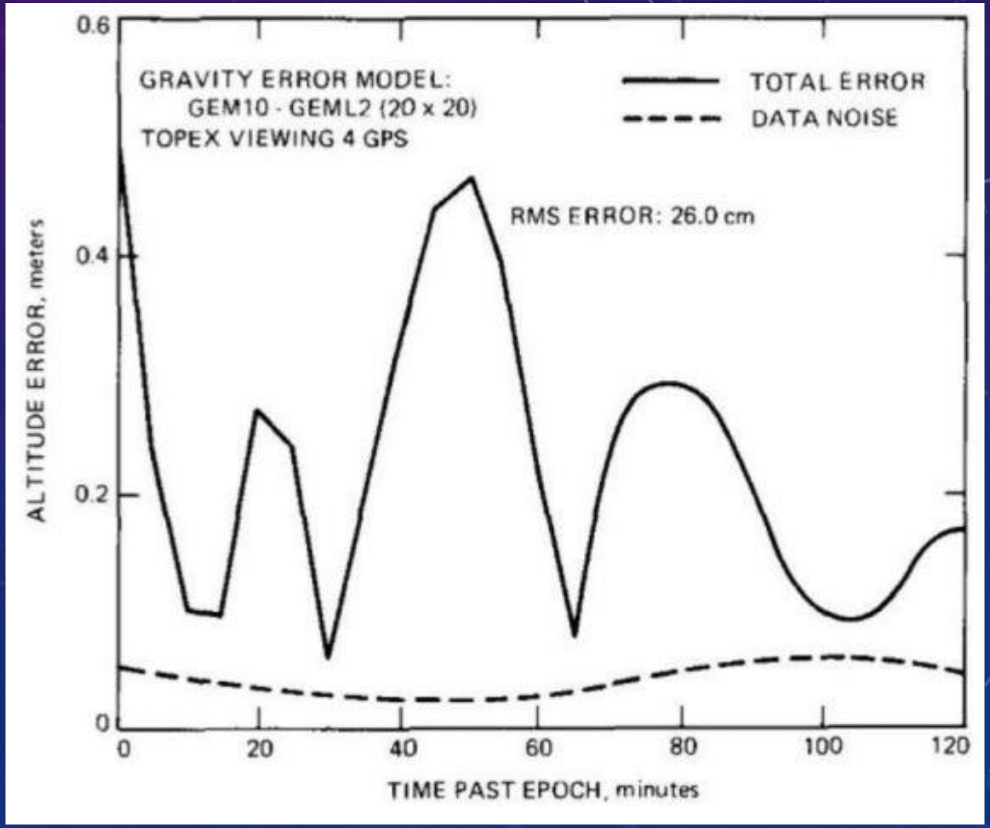


Figure 1. Predicted TOPEX altitude error with a dynamic solution using a gravity error model reflecting the estimated gravity model quality in the early to mid-1980's [2]

KINEMATIC ORBIT DETERMINATION

- This approach to precise orbit determination developed in the late 80’s was made possible by two features of GPS:
  - Pseudo-range measurements from many directions provide continuous geometric position determination
  - Simultaneous carrier phase and pseudo-range data enabled long-term kinematic smoothing
- Together, these offer a solution technique that is entirely geometric
- The kinematic technique smooths a series of pseudo-range-based position solutions against the continuous record of position change obtained from carrier phase
- Carrier phase empirically supplies the state transition previously obtained from dynamic models as illustrated in Figure 2.

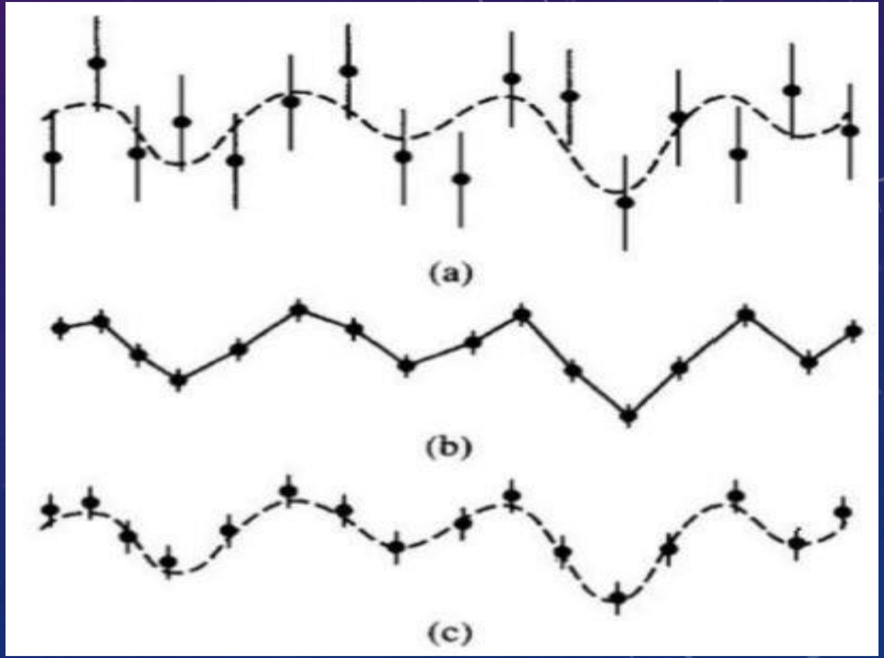


Figure 2. Conceptual illustration of GPS orbit determination via geometric point positioning and kinematic smoothing. (a) Independent position solutions obtained from pseudo-range. (b) Precise track position change obtained from carrier phase. (c) Final position solutions after adjusting (b) against (a) [3]

REDUCED DYNAMIC STRATEGY

- Kinematic tracking has one critical limitation: Performance is dependent upon the momentary observing geometry.
- Observing geometry depends upon the number and arrangement of ground receivers, the receiver viewing capacities, and the GPS satellite constellation.
- User dynamics can carry the solution through geometric weak spots while adding strength throughout

REDUCED DYNAMIC STRATEGY

REDUCED DYNAMIC FORMULATION

- To put this idea into practice begin with a dynamic formulation and introduce a kinematic component by adding process noise to the user force models
- The GPS orbit solution remains fully dynamic, while the user solution becomes partly dynamic and partly kinematic
- Different solution characteristics, ranging from fully dynamic to kinematic, can be achieved by varying the parameters defining the process noise
- A time update, which uses a state transition model to propagate the state estimate and covariance from one time batch to the next, and a measurement update, which incorporates a new batch of measurements
- These steps alternate until all batches are processed

REDUCED DYNAMIC STRATEGY

REDUCED DYNAMIC ANALYSIS

- Figure 3 shows the estimated TOPEX altitude error as a function of the gravity error (which was varied by scaling GEM10-GEML2 from 0 to 100 percent) for different U
- For any finite dynamic model error (in this case dominated by the gravity), a range of U exists within which the altitude error is lower than with either the dynamic or kinematic solutions
- the reduced dynamic technique is superior, provided that the dynamic model is properly weighted
- With TOPEX observing all satellites, the geometry is consistently strong and kinematic tracking yields about an 8 cm accuracy, only 1 cm above the optimal

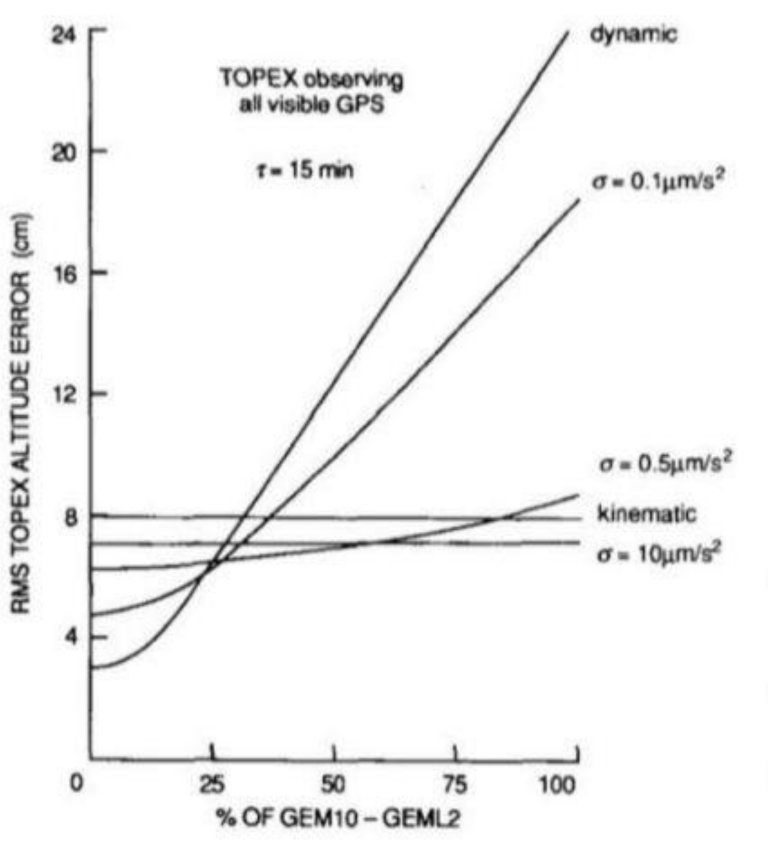


Figure 3. Predicted TOPEX altitude error using dynamic, kinematic and reduced dynamic strategies, shown as a function of the gravity model quality [8]

REDUCED DYNAMIC STRATEGY

REDUCED DYNAMIC WEIGHTING

- The optimum initial weight for the reduced dynamic process noise can be estimated through a covariance analysis using a realistic dynamic error model
- Misjudgment of the dynamic model error, which at some level is inevitable, will yield a suboptimal weight
- Performance is fairly insensitive to significant departures (a factor of two) from the optimum weight

LOW CIRCULAR ORBITERS

- TOPEX has a circular orbit at a nominal altitude of 1,336 km
- Although a formal accuracy requirement of 13 cm has been set for the continuous determination of its altitude, TOPEX ocean science would benefit from an altitude accuracy comparable to the 2.5-cm precision of its radar altimeter
- The experimental GPS receiver onboard TOPEX was equipped with six dual-frequency channels allowing simultaneous observation of six GPS satellites
- TOPEX nicely illustrates the benefits of reduced dynamic tracking since its ~1300-km altitude, its six-satellite receiver capacity, and its relatively compact dimensions permit both good observing geometry and reasonably well modeled dynamics

ELLIPTIC ORBITS

- Elliptical orbits pose unique orbit determination challenges, since the viewing geometries and dynamics can vary considerably with the altitude of the satellite
- Orbit requirements for the Japanese VLBI Space Observatory Program (VSOP) MUSES-B spacecraft were examined
- The highly elliptical orbit of VSOP will have its apogee at -20,000 km and perigee at -1,000 km in altitude, as shown alongside a circular GPS orbit in Figure 4

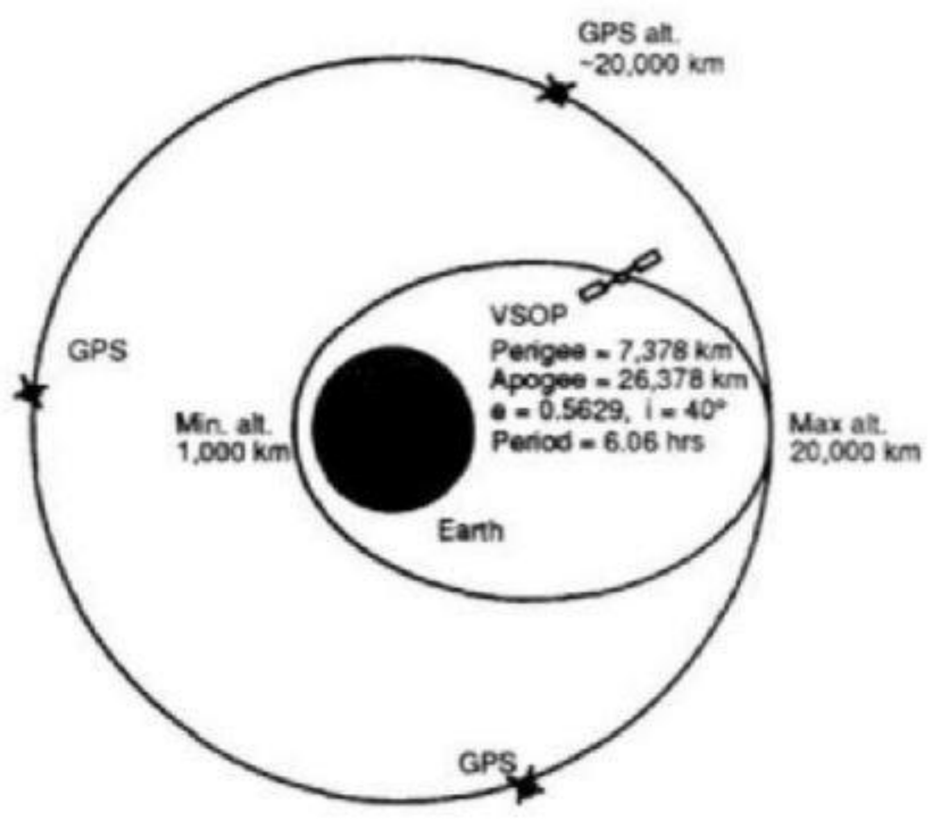


Figure 4. VSOP orbit geometry [1]

ELLIPTIC ORBITS

- While ground-based GPS measurements can be used to calibrate the Doppler data for improved tracking, the inclusion of differential GPS measurements between VSOP and a global network of ground sites should be even better
- For altitudes below 2,000 km, reduced dynamic tracking (with a steady-state sigma of 0.5 µm/sec2 and a 15-minute time constant, which were the same as used in Figure 9 for TOPEX) was utilized
- At higher altitudes, the acceleration parameters were still adjusted, but treated as constant instead of process-noise parameters

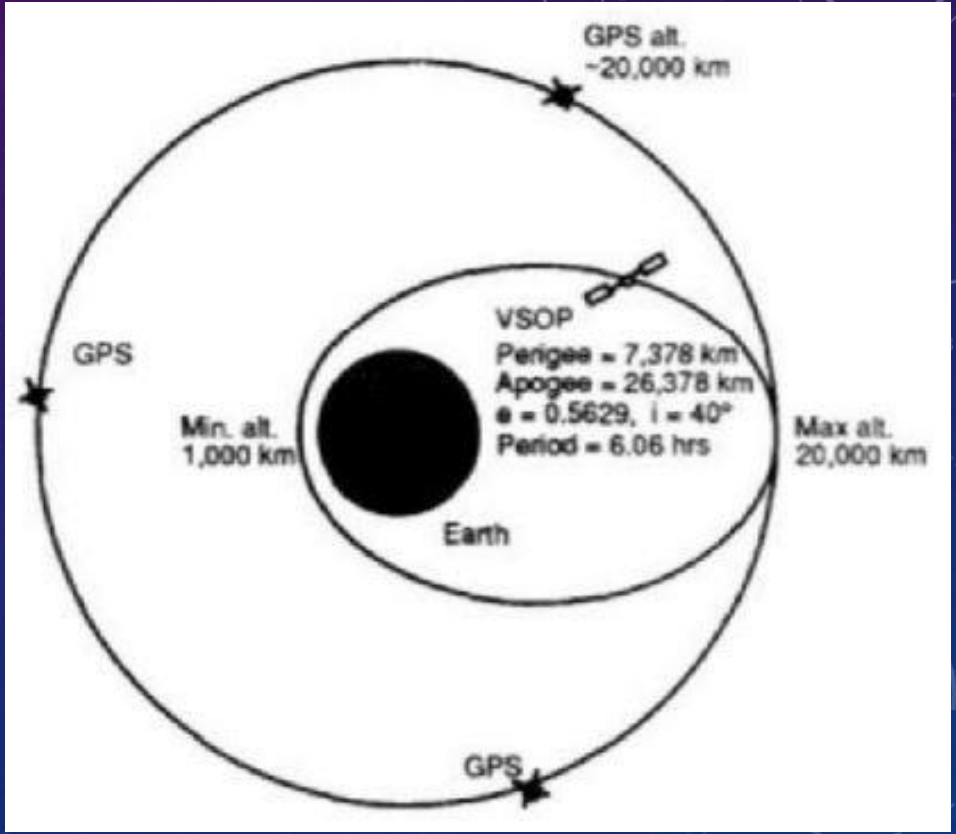


Figure 4. VSOP orbit geometry [1]

QUESTIONS?

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