PRESENT STATUS AND FUTURE TRENDS IN NEAR-EARTH SATELLITE ORBIT DETERMINATION

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ABSTRACT

The paper describes the present status and future trends in near-Earth satellite orbit determination from the author's perspective. The scope of the paper is limited to unmanned artificial satellites and near-Earth is defined to include satellites within the geosynchronous distance of the Earth. The major components of an orbit determination system and the evolution of the elements making up each component is reviewed. Typical accuracies presently achievable in the orbit determination process are summarized as well as the factors limiting the accuracies and some interesting examples of recent improvements made in the dynamic models used in the process. Some future trends for near-Earth satellite orbit determination are presented which includes a number of concepts and experiments for onboard and real-time orbit determination.

Keywords: Orbit Determination, Spacecraft Observations, Computational Techniques, Dynamic Models

1. INTRODUCTION

This paper deals with near-Earth satellite orbit determination which is defined to include artificial satellites within the geosynchronous distance of the Earth. The problem of orbit determination consists of comparing measurements taken on a satellite trajectory to a model representing that trajectory. The model is generally represented by a system of differential equations whose constants of integration define the satellite trajectory as a function of time. Thus, given an a priori estimate of these constants of integration (state parameters), the problem is to update or correct the a priori state parameters as a function of the measurements. For artificial Earth satellites there generally exist many more measurements than state parameters to be estimated. Therefore, the comparison process or estimation process is one that satisfies some statistical principles such as least squares, maximum likelihood or minimum variance. The determination of very precise near-Earth satellite orbits requires the continual development of models, data systems, and computational techniques. Our present ability to determine orbits has not yet achieved the same level of accuracy as that of our data systems and computational techniques. Historically orbital accuracy has lagged behind the observational accuracy because improved observations are needed to improve upon the models which predict the spacecraft's behavior. Figure 1 portrays the evolution of near-Earth satellite orbit determination which for convenience is broken down into the following systems:

(a) Data systems or measurements (such as radars, Doppler, interferometry, etc., Refs. 1-6).

(b) Dynamic Models (such as gravity, atmospheric drag, etc., Ref. 6).

(c) Computational Techniques which include trajectory propagation techniques (general perturbations and special perturbations) and estimation techniques (batch processing and sequential processing, Refs. 7 and 8).

Figures 2 and 3 depict the evolution of definitive and predictive orbital accuracies, respectively. Definitive orbit accuracy is defined to be the orbital accuracy within the time interval that tracking data was utilized (data arc) in the orbit determination solution. Predictive orbit accuracy is defined to be the accuracy which is attained when the orbit state is predicted beyond the data arc. The orbital accuracies in each case are portrayed for three general classes of Earth satellite orbits. Geosynchronous satellites are clearly defined and the orbital errors are dominated by uncertainties in solar radiation pressure models, the gravitational constant for the Earth (GM), tracking station location errors, etc. Drag dominated satellites are in Earth orbits whose altitude remains about 500 km ± 200 km and whose orbital errors are dominated by uncertainties in modeling atmospheric drag effects. Stable satellite orbits represent that class of satellites whose altitude from the surface of the Earth is approximately 1000 km and whose orbital errors are dominated by Earth gravity models.

Section 2 reviews the data systems utilized in the orbit determination process, section 3 describes the computational techniques and section 4 the dynamic models employed for near-Earth satellite orbit determination. In each section the recent advances and future trends of the major components are presented.

2. DATA SYSTEMS

The key feature that distinguishes orbit determination from other aspects of orbital mechanics is the use of measurement data from which the trajectory state is derived. The measurement data consists of discrete observations which are subject to random errors or noise and frequently to systematic errors or biases. The observations are modeled as non-linear functions of the trajectory state and are used to estimate the state of the orbit through a statistical or estimation process. The data systems which are used to generate the observations are typically radars, Doppler, interferometry and optical measurement systems.

2.1 Background

As shown in Figure 1, the earliest of the data systems was the Minitrack system. This system refers to an interferometer tracking technique and was used to support the first United States Vanguard satellites and many of the early scientific artificial Earth satellites. The early manned spaceflight program was supported by C-Band radars and the Unified S-Band (USB) system was introduced to support the Apollo and

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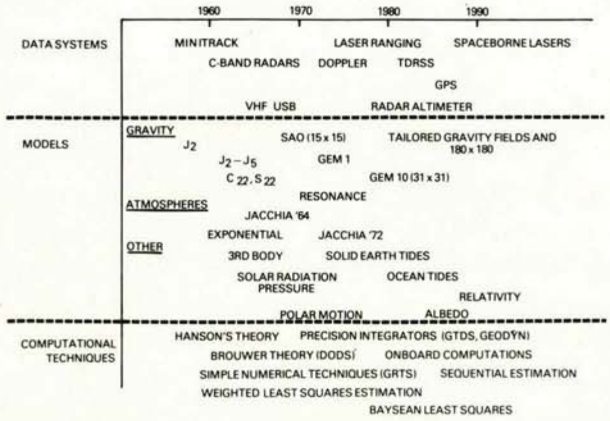

Figure 1. Evolution of Orbit Determination Elements

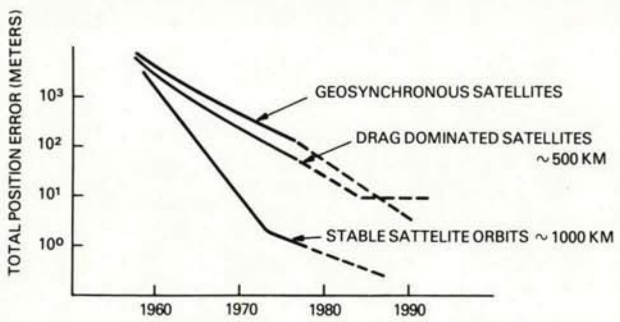

Figure 2. Definitive Orbit Accuracy Evolution

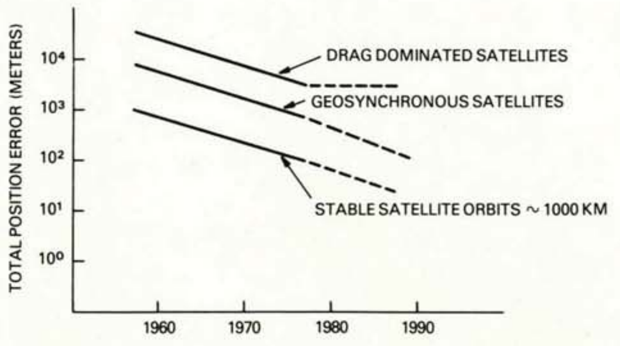

Figure 3. Evolution of Predictive Orbit Accuracy (1 Week)

Skylab programs. In addition the USB system increasingly replaced the Goddard Range and Range Rate (GRARR) system. The GRARR was designed and implemented as an element of the original unmanned Space Tracking and Data Network (STADAN) to provide spacecraft tracking for orbits where interferometer tracking was inadequate. The USB and GRARR systems and a few C-Band radars and interferometers were consolidated to be known as the Spaceflight and Tracking and Data Network (STDN).

2.2 Current Developments and Future Trends

Currently the STDN consists of approximately fourteen ground stations which provide telemetry, tracking and command satellite support. With the development of the Tracking and Data Relay Satellite System (TDRSS) the STDN will consist of a ground segment i.e. the Ground Spaceflight Tracking and Data Network (GSTDN) and a space segment (TDRSS). The GSTDN will be phased down to a core network to be used only for supporting highly elliptical and geosynchronous satellites; and launch and landing support until TDRSS proves it can also provide this capability (Ref. 9). The prime GSTDN ground stations will be located at Goldstone, California; Madrid, Spain; and Orroral Valley, Australia. Current plans also call for consolidation of the GSTDN with the Deep Space Network in the 1983–1985 timeframe. The optical tracking network will also be retained to support the Earth and ocean dynamics programs. The TDRSS will consist of a ground station at White Sands, New Mexico and two operational Tracking and Data Relay Satellites (TDRS) located in geosynchronous orbits at 41 degrees and 171 degrees west longitude. The system will also include an in–orbit spare and the capability for rapid launch replacement should an in–orbit failure occur.

In addition to the TDRSS current plans are being implemented to utilize the Department of Defense Global Positioning System (GPS). The GPS in its operational phase is currently projected to consist of 18 satellites, placed in 12 hour, 56 degrees inclination, circular orbits. Each of the GPS satellites radiate pseudorandom noise (PN) signals at two L–Band frequencies. Encoded within the signal is a precision ephemeris for the transmitting GPS satellite, satellite clock bias and relativity corrections, and an almanac for all other GPS satellites. A coded train of pulses emitted from four satellites determines the position of a receiver by the relative time of arrival. The navigation accuracy anticipated from the GPS is approximately 5 to 10m (Ref. 4).

3. COMPUTATIONAL TECHNIQUES

The main computational processes of orbit determination are the trajectory generation process and the estimation process (Refs. 7 and 8).

3.1 Background

Trajectory generation is performed through the integration of the orbital equations of motion. Analytic and numerical theories may be used for trajectory generation. As shown in Figure 1, analytical theories such as the Hanson and Brouwer theories were used in the early days of the space program when precision orbits were not required. The chief advantage of analytic techniques is their high efficiency and the understanding provided by the closed form formulations. However, in order to gain an analytical solution some approximations are required. For example in the Brouwer theory, the perturbation model includes only the effects of a point mass Earth and the low–order zonal harmonics in the gravitational potential. When more precise modeling is required, the numerical integration approach is utilized.

In the high precision numerical integration approach, the perturbing accelerations which act on the satellite are modeled as accurately as possible. These models and attempts at improving the models are described in the next section. The GEODYN and GTDS computer programs (Refs. 7 and 8) both provide high order, extremely precise numerical integration methods with fixed and variable step size control.

Because the data systems and dynamic models are both imperfect, no trajectory can be computed which fits the observations exactly. Thus, one desires to obtain a 'best estimate' of the trajectory from the data in some statistical sense. The estimation techniques may be divided into two broad but related classes, namely: Batch estimation and sequential estimation. Batch estimation derives its name from the approach of accumulating a "batch" of data over some time span (data arc) and solving for the orbital state given an observational model so as to minimize the squares of the differences between a computed and an observed trajectory. Since many data types may be used in the observational data set some weighting is assigned to each data set, and since a priori information may be available as to the uncertainty of the initial estimate (initial conditions) it is also added to the estimation process. Thus, the name given to this technique is called the weighted least squares with a priori, or Bayesian weighted least squares algorithm. Since a linearization takes place in relating the computed and the observed values, the process is an interactive one, whereby "differential corrections" are applied to the state parameters until convergence to the weighted least squares solution is reached. Due to the ease with which bad data may be edited with the weighted least squares algorithm, and due to its reliability in the presence of long time intervals between data sets, this algorithm has been found to be most suitable for Earth satellite orbit determination over the first two decades.

3.2 Future Trends

A trend which is currently appearing in Earth satellite orbit determination is the movement towards onboard satellite orbit determination. This trend is motivated by new data/information management concepts which are emerging to accommodate the increased volume of experimental data, the greater sensor resolution required by experimenters, and a decrease in the delivery time being requested by the experimenters. The availability in the mid–1980's of some new data types such as the GPS data and the TDRSS data discussed earlier along with advances being made in micro–electronic data processing systems, make onboard orbit determination feasible in this time frame (Ref. 11). Figure 4 illustrates the functional scenario of performing onboard navigation with GPS data (Ref. 10). The first GPS user set flown by NASA will be a spaceborne GPS navigation set (GPSPAC) which will be included as an experiment on Landsat–D. The Landsat–D spacecraft is currently scheduled to be launched in the 3rd quarter of 1982. The GPSPAC is being developed by the Johns Hopkins University Applied Physics Laboratory and the major subsystem of this assembly, namely the receiver/processor assembly, is being developed by the Magnavox Advanced Products Division. A block diagram (Ref. 3) of the GPSPAC is shown in Figure 5.

An alternative to onboard orbit determination with GPS data is being pursued utilizing TDRSS data and the functional scenario of this concept is shown in Figure 6. A block diagram of the major components of a user system with TDRSS is shown in Figure 7. A comparison of onboard navigation features with GPS and TDRSS data is depicted in Figure 8.

Another area which is gaining increased popularity is the navigation of Earth–referenced satellites with imaging data rather than, or in addition to, conventional radio tracking data and attitude sensor data (Ref. 12). Driving forces for the capability include the trend towards data automony, the need for timely and highly accurate annotation and correction of the images, and a growing awareness of the presence of high quality navigation information contained in such data. Navigation systems utilizing imaging data have been developed and implemented

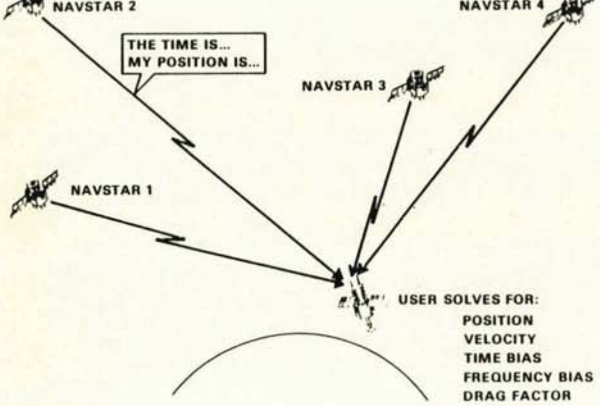

Figure 4. Onboard Navigation with GPS

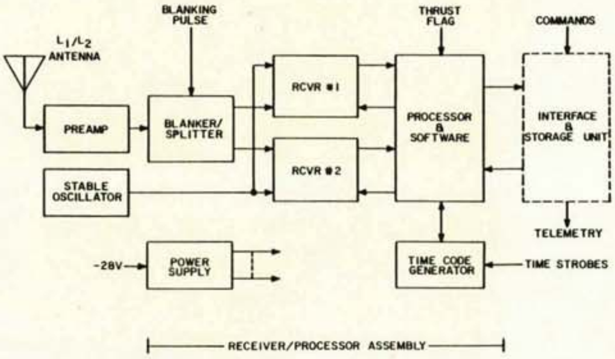

Figure 5. GPSPAC Block Diagram

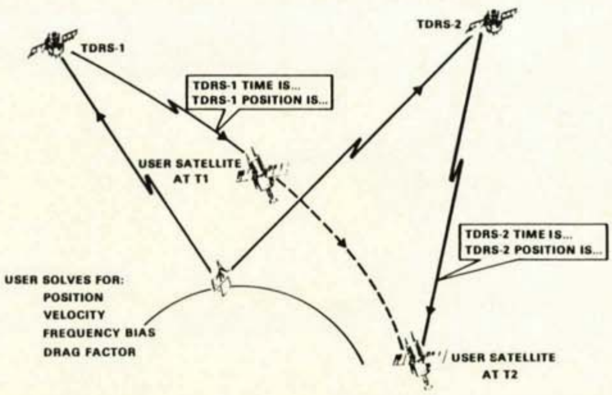

Figure 6. Onboard Navigation with TDRSS

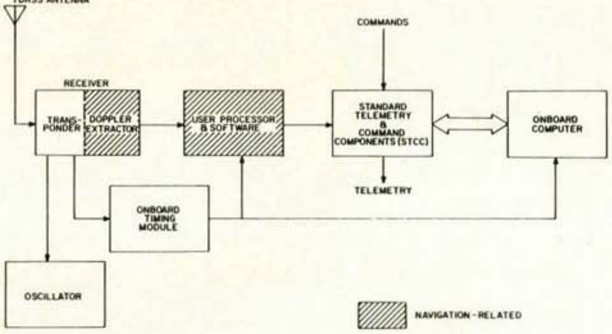

Figure 7. User Systems with TDRSS

for geosynchronous meteorological satellites and are currently being pursued for the Landsat class of satellites.

Finally, a computational technique which has benefited from a great deal of interest and research in the past twenty years is the use of sequential estimators for orbit determination. The use of sequential estimators for onboard and real–time orbit determination is becoming a reality. The GPSPAC described earlier will utilize a UDU sequential filter and work is in progress for devising sequential filters for onboard usage with TDRSS data and for real–time applications.

4. DYNAMIC MODELS

The accuracy with which a trajectory can be generated in the orbit determination process is dependent upon the integration process itself and the perturbation forces which influence the

FEATURES	GPS	TDRSS
STATE SOLUTION	GEOMETRIC	DYNAMIC
FILTER MEMORY	SHORT	LONG
ONBOARD HARDWARE REQUIREMENTS	ANTENNA, RECEIVER, CLOCK, FREQUENCY STANDARD, RANGE AND RANGE DIFFERENCE EXTRACTOR, NAVIGATION COMPUTER, FREQUENCY SYNTHESIZER	DOPPLER EXTRACTOR, SYNTHESIZER, NAVIGATION COMPUTER
REALTIME ACCURACY	5-10M	50-100M
ADVANTAGES	RAPID STATE VECTOR RECOVERY (MANEUVERING VEHICLES) (2.3 MIN.), HIGH ACCURACY, KEEPS ACCURATE ONBOARD TIME, GLOBAL COVERAGE	LOW INCREASE IN POWER, WEIGHT, SPACE NO ADDITIONAL ANTENNA, RECEIVER, CLOCK, OR FREQUENCY STANDARD REQUIRED, SIMPLIFIES ACQUISITION PROCEDURES AT WHITE SANDS (NO FORWARD COMPENSATION REQUIRED)
DISADVANTAGES	ADDITIONAL EQUIPMENT INCREASE, POWER, WEIGHT, SPACE, APPENDAGES. POSSIBLE DENIAL OF ACCURACY, TIED TO DOD NEEDS	LESS ACCURATE, LONGER STATE RECOVERY TIMES (SEVERAL HOURS), TIME MAINTENANCE MUST BE EXTERNAL, SPARSE TRACKING COVERAGE

Figure 8. GPS vs. TDRSS for Onboard Navigation

trajectory motion. The ways in which the perturbative forces are represented are referred to as dynamic models. The perturbative forces which are modeled for near-Earth satellite orbit determination are:

(a) Gravitational forces
(b) Atmospheric drag
(c) Solar radiation pressure
(d) Thrust accelerations
(e) Albedo radiation pressure
(f) Earth and Ocean tides
(g) Polar motion

4.1 Background

The perturbative forces which are modeled for near-Earth satellites are illustrated chronologically in Figure 1. Analysis of data from the first satellite launched by the United States yielded some immediate and significant improvements in our knowledge of dynamic models. Calculations for the oblateness of the Earth, J_2 (Ref. 13) showed it to be significantly different and much improved over those values determined from geodetic information. Subsequent calculations showed the Earth to be pear shaped. Likewise it was found that atmospheric density was significantly greater (about a factor of 5) at satellite altitudes than that assumed prior to the launch of the first artificial satellites. By the mid-1960's the zonal harmonics (J_2 - J_5) of the Earth's gravitational field had been determined and the determination of the ellipticity of the Earth's equator (C_{22}, S_{22}) had been made. Atmospheric models (Jacchia 1964) which included the fact that the atmosphere bulges in the direction towards the Sun and which included the dependence of atmospheric density on solar activity (solar flux tables and the geomagnetic index) were also discovered from the analysis of satellite data.

4.2 Recent Advances and Future Trends

As the accuracy requirements for near-Earth satellites becomes more stringent (Figure 9), the requirement to improve the accuracy of the dynamic models and to model more effects so as to minimize the unmodeled effects increases.

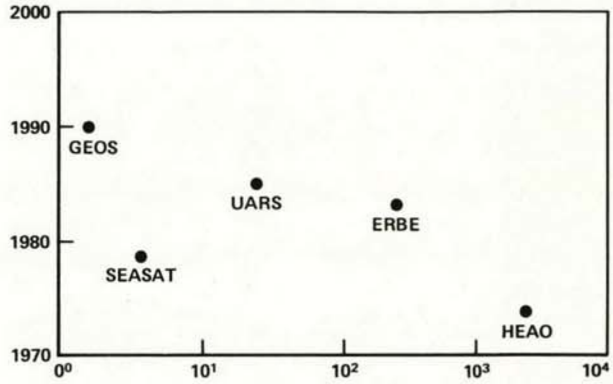

Figure 9. Representative Orbital Accuracy Requirements Present and Future

One of the areas that has shown greatest improvement during the last decade has been our knowledge of the gravity field of the Earth. The inclusion of high precision range measurements from laser tracking systems and Unified S-Band doppler data and, more recently, altimeter data has enabled our definition of the gravity field to extend out to a degree and order 36. These new fields Goddard Earth Models (GEM) developed at GSFC have permitted improvements of at least an order of magnitude in orbit determination over the past decade. Figure 11 shows a comparison of the abilities of three gravity models, GEM's 1, 7 and 9, to fit five consecutive passes of laser data (with a single 7.75 hour orbit) from a single tracking station. These five passes, obtained at GSFC in 1974 on the BE-3 satellite, (same as data shown in Figure 10) when analyzed by the GEM 1 gravity field developed in 1970-71 (Ref. 14) could only be satisfied at the 2 meter level even though the data was of 10cm quality. The same data analyzed a few years later with GEM 7 model (Ref. 15) could be satisfied to about the 50 centimeter level and more recently the GEM 9 (Ref. 16), model fits to 12cm. The improvement from GEM 1 to GEM 9 has been brought about largely by the inclusion in the later models of large quantities of laser tracking data on several satellites, particularly GEOS-3, but not the data shown in Figure 11. The slight curvature of the GEM 9 results in Figure 11 show that some gravitational signature still exists in the data and that some improvement still remains to be made although this may well be the most difficult to achieve. The present plans at GSFC are to continue to improve our knowledge of the gravity field by the addition of the current data as well as data from the newer systems.

The product of the Gravitational Constant, G, and the Earth's mass, M, is a fundamental constant of geophysics. It can be determined as a by-product in obtaining the Earth's gravity field from satellite data. The current value being derived from near-Earth satellites is $398600.44 \pm 0.02 \, km^3/sec^2$ for a velocity of light, $C = 299792.458 \, km/sec$ (Ref. 17). This result implies knowledge of GM to five parts in 10^8. Figure 12 shows how these results compare with other published values of GM. For certain geophysical applications it has been estimated that a knowledge of GM of one part in 10^8 is necessary.

At the present time the density models used in computing the drag acceleration are based on the work of Jacchia and include variations in solar activity, diurnal terms, geomagnetic effects, and semi-annual and seasonal latitude variations. In order to improve the responsiveness of the model to unmodeled changes in density, a time dependent parameter ($\dot{\rho}$) has been introduced that enables accounting for systematic changes during the orbital arc. Currently drag is only being calculated to an altitude of 2500km. The Lageos satellite, launched May 5, 1976, into a 6000km orbit has been tracked by lasers and found to have a decreasing semi-major axis. Figure 13 shows this decrease to vary from 1.1mm per day in

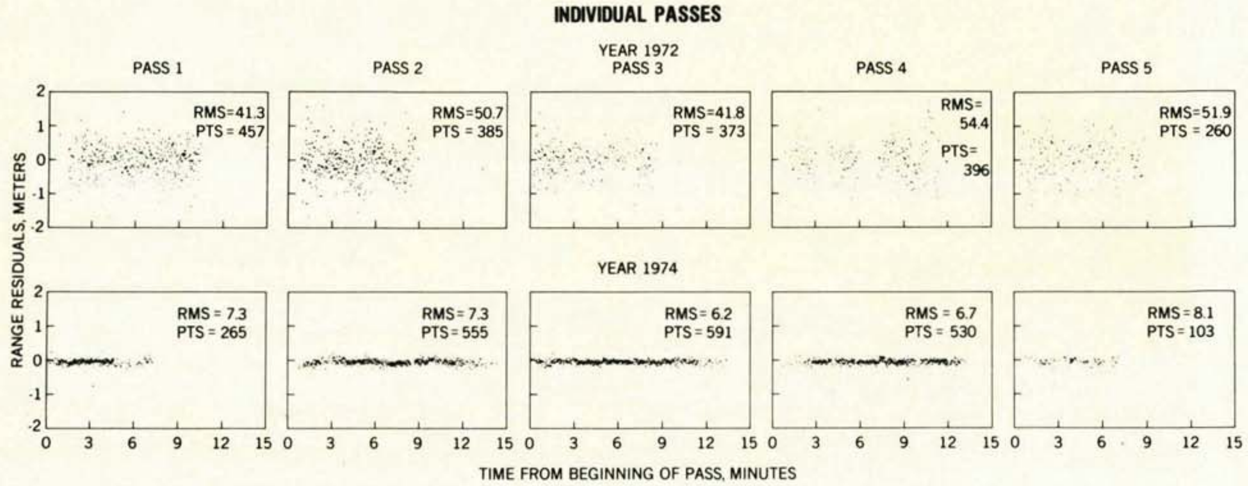

Figure 10. Example of Data System Improvement (Laser Ranging for BE - 3 in 1972 and 1974)

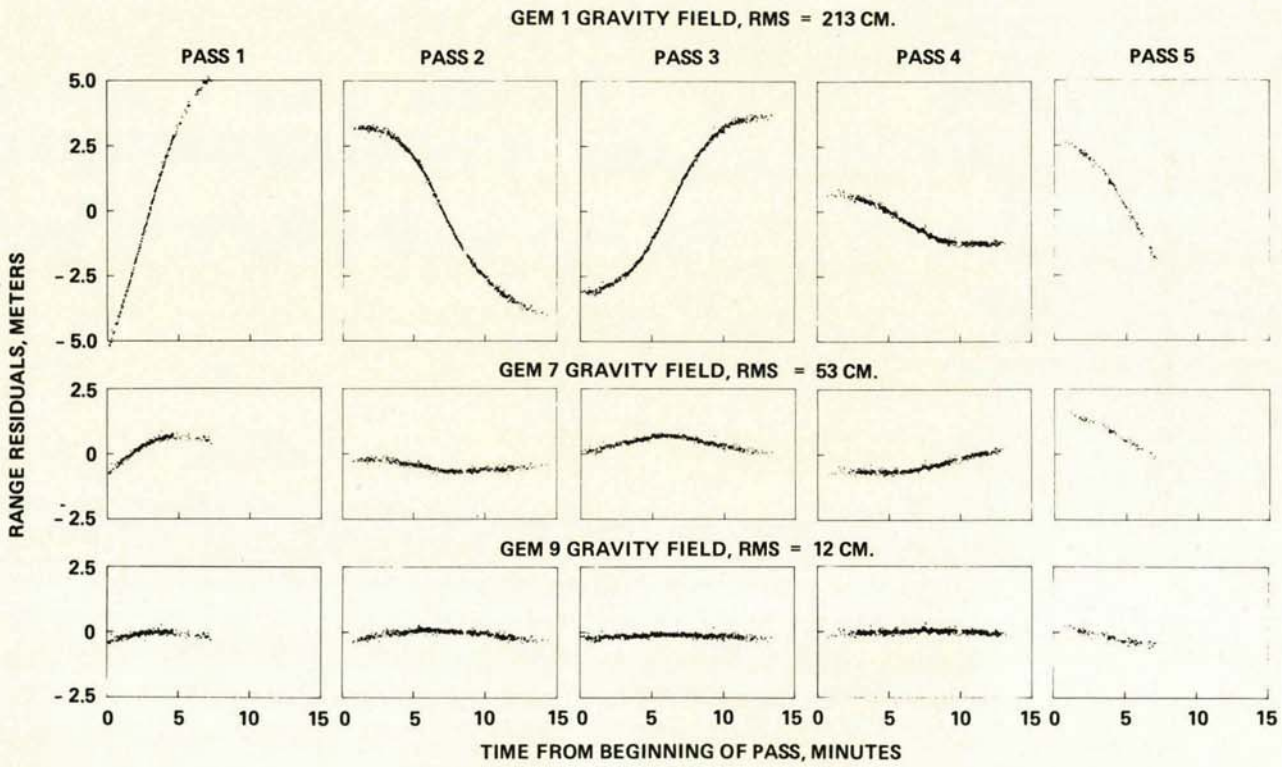

Figure 11. Example of Gravity Field Improvement (Laser Residuals from Five Pass Orbits for BEC in 1974)

1976 through 1978 and again in 1980 and 1981 to about 1.8 mm per day in 1979. The most likely cause of this effect is currently thought to be charged particle drag (Ref. 18). However, an accurate model for this effect is yet to be determined. This is an example of how precision measurements and a precision orbit determination program can lead to the discovery of an effect that should be modeled by the orbit determination program.

Other models which are currently being incorporated into orbit determination programs for precision calculations include a time varying area for solar radiation pressure; a time varying model for albedo radiation pressure; Earth tides which account for the distortions in the Earth's body due to Sun and Moon attractions; and ocean tides which affect satellite altimeter data as well as gravitational effects on the satellite motion (Ref. 19).

Acknowledgment

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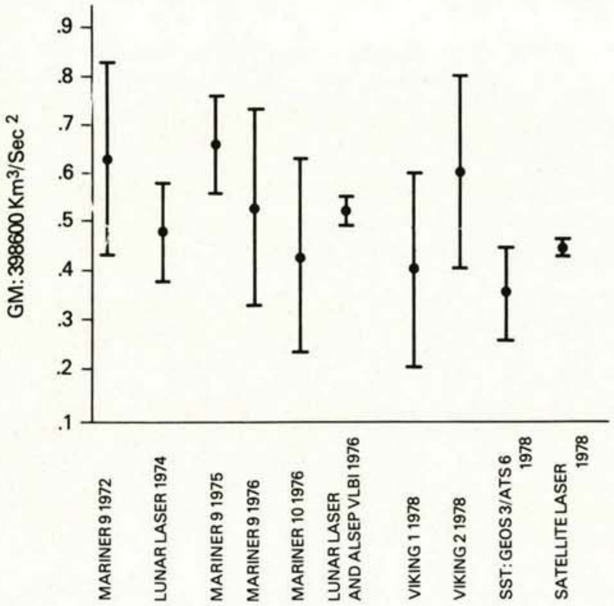

Figure 12. Comparison of Recent GM Values (Velocity of Light = 299792.458 km/sec)

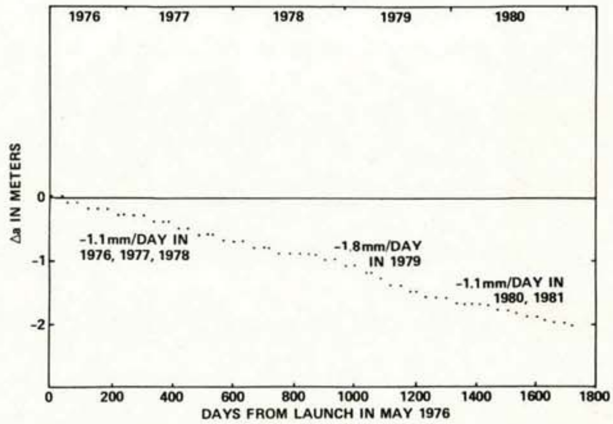

Figure 13. Unmodelled Changes in Lageos Semi-Major Axis

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