

COSMIC: Geodetic Applications in Improving Earth's Gravity Model

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ABSTRACT

The routine GPS tracking data that will be collected for the precise orbit determination of the eight COSMIC spacecraft will contain valuable information about the terrestrial gravity field. Numerical simulations based on current straw-man mission scenarios have shown: (1) For the static model of the gravity field, significant improvement is possible over our present knowledge embodied in the EGM96 model, out to harmonic degree as high as 40. (2) With respect to time-varying gravitational signals, large-scale mass transport processes in the geophysical fluids (e.g., atmosphere and oceans) can be detected or monitored during the mission, providing important global change information. Further sophisticated simulations incorporating more realistic force models will be needed once COSMIC mission scenario and spacecraft design are completely defined.

(Key words: Gravity field, Gravity model, Orbit determination, Satellite tracking)

1. INTRODUCTION

COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) is a scientific space mission jointly planned by the National Space Program Office of Taiwan, the Republic of China, and the National Science Foundation of the United States. Its primary goal is atmospheric research, but its operation requires precise orbit determination for the eight COSMIC spacecraft via GPS (Global Positioning System) tracking. These tracking data have additional value to geodetic research in that they contain valuable information which can

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be used to advance our current knowledge about Earth's gravity field. That is the subject of this paper.

Mapping of the terrestrial gravity field has seen great advances in data acquisition and modeling techniques over the past 4 decades ever since the first days of the space age (e.g., King-Hele, 1992). The driving impetus of these advances is the quest for higher precision, higher spatial resolution, as well as the prospect of reasonable temporal resolution for time-varying gravitational signals.

Note first that putting a gravimeter in orbit is of no use in measuring gravity, because the gravimeter would be in free fall along with the spacecraft and hence experience zero gravity. An equivalent way of stating this is that the centrifugal force completely cancels the gravity the orbiting gravimeter tries to measure.

The method for "measuring" the terrestrial gravity from space that has been successful is by obtaining precise orbit determination (POD) for low-Earth orbit (LEO) satellites. A satellite orbit is a manifestation of Earth's gravitational pull to which the satellite is subject, hence contains information about the gravity field. To first order, a satellite orbit is a simple Keplerian elliptical orbit governed by Earth's total mass (more specifically, the mass "monopole", or equivalently a spherically symmetric Earth). It is the small departures from an elliptical orbit, typically in the hundreds of meters to kilometer range and in some cases secular in nature, that is of geophysical interest — they reflect the (non-spherical) gravity anomalies and hence mass anomalies in the Earth. A particularly prominent and interesting example (in this case a secular perturbation) is the nodal precession of the satellite orbit plane caused by Earth's oblateness, of which COSMIC will take advantage in its orbit adjustment design (see Section 2 below).

The external gravity field U is customarily expressed in terms of spherical harmonic expansion:

$$U(\mathbf{r}) = \frac{GM}{r} \left[1 + \sum_{l=2}^{\infty} \sum_{m=0}^l \left(\frac{a}{r}\right)^l \bar{P}_{lm}(\cos\theta) (\bar{C}_{lm} \cos m\lambda + \bar{S}_{lm} \sin m\lambda) \right], \quad (1)$$

where G is the gravitational constant, M and a are respectively the mass and the mean radius of the Earth, θ and λ are respectively the co-latitude and longitude of the field point \mathbf{r} , and \bar{P}_{lm} denotes the 4π -normalized associated Legendre function of degree l and order m . The first term in (1) of course is simply the "monopole" term mentioned above. The second double-summation term represents the "anomalous" gravity field specified by the harmonic expansion coefficients, or so-called Stokes coefficients, \bar{C}_{lm} and \bar{S}_{lm} . Note that the degree $l=1$ ($m=0, 1$) terms are excluded because they vanish as the coordinate origin is chosen to coincide with the center of mass of the Earth. The zonal (l,m)=(2,0) term, often referred to as J_2 , is by-far the largest anomaly term representing the ellipticity, or oblateness, of the Earth, while J_3 represents the pear-shapedness, etc.

When one speaks of a global "gravity model", one refers to a table of Stokes coefficients up to certain maximum degree L (rather than the infinity indicated in Equation 1) and order supported by, e.g., the POD data that are available and utilized. The spatial resolution increases with the value of L , according to the relation that the spatial resolution is roughly the Earth circumference (40,000 km) divided by $2L$.

How are satellite orbits determined? POD of a LEO satellite relies on optical or radio tracking of the satellite from ground-based and/or space-borne platforms whose positions themselves are well determined. Many LEO satellites at different inclinations and altitudes, whether launched as geodetic missions or not, have been tracked over the years by means of a variety of techniques. Traditional tracking techniques are primarily ground-based, and include optical directions, range and Doppler tracking by radar, and laser ranging, all from ground stations (e.g., Lemoine et al., 1998). One newer technique that involves no ground tracking and has been proposed as especially suited for gravity mapping applications is the satellite-to-satellite tracking (SST). SST is effected through range and/or range-rate observations between a pair of satellites orbiting either in tandem, separated by several hundred km in the same low orbit ("low-low" configuration), or between a LEO satellite and a satellite in high orbit ("high-low" configuration). A latter scheme using NASA's geo-synchronous TDRSS satellites has already proved useful in some recent cases (Rowlands et al., 1997). But the prime example of the high-low SST is the tracking of LEO missions from the Global Positioning System (GPS) constellation of satellites. COSMIC belongs to this category.

The GPS constellation comprises 24 satellites transmitting coded radio signals to Earth for the purpose of navigating users equipped with proper receivers. GPS satellites orbit at roughly 20,000 km in altitude with 12-hour orbital periods. Thanks to the low cost and many operational advantages of space-borne GPS receivers, POD by GPS tracking has prevailed for LEO satellites in recent years (Pavlis and Olson, 1995). Examples include the German/DARA-US joint space mission CHAMP to be launched in 2000 (Reigber, et al., 1997), and another joint US-German SST mission called GRACE scheduled for a 2001 launch (Tapley, 1997). GRACE consists of two LEO spacecraft in tandem undergoing both low-low microwave SST between them and high-low tracking by GPS. We mention in passing that GRACE promises to deliver unprecedented precision in monitoring minute time-varying gravitational signals to a spatial resolution of several hundred km every 15-20 days. Yet even higher precision can conceivably be achieved using optical laser interferometry, instead of microwave, in the SST (e.g., Colombo and Chao, 1996; NAS, 1997). We should also mention that, in contrast to a gravimeter, a gravity gradiometer does measure locally the spatial *gradient* of gravity, hence would be sensitive to gravity in its own way, particularly to the short-wavelength components. In this case, POD is not required (as data source) any more than just to know the location of the field being mapped at a given time. Space-borne gradiometer missions have been proposed in recent years. One such mission, GOCE, is currently under development by the European Space Agency for a possible 2003 launch.

Satellite tracking data inevitably contain certain amount of non-gravitational signals, which if left untreated during the data reduction will masquerade as gravity signal and corrupt the solution for U . The main source of such contamination is the atmospheric drag experienced by the satellite. Atmospheric drag reduces with altitude, but so does the gravitational signal (see Equation 1). Drag also varies with the solar cycle, as high solar activity would expand the upper atmosphere. Other non-gravitational contamination comes from mis-modeling of radiation pressure on the satellite body from the Sun, Earth albedo, and the satellite's own thermal emissions.

Smaller surface-to-mass ratio and aerodynamic shape inasmuch as feasible help reducing

the non-gravitational effects on a satellite. A direct, active way to eliminate non-gravitational forces makes use of a drag-free system, where on-board thrusters maintain the satellite orbit in pace with an on-board encased proof mass which is shielded from the non-gravitational forces. Although proposed since early on, such scheme has yet to be tested in space. An alternative is to carry an on-board accelerometer to record, and hence correct for the non-gravitational forces. The gravity satellite missions CHAMP and GRACE, for the first time, will be equipped with a three-axis vector accelerometer for this purpose. Falling short of such active means but taking advantage of the fact that satellites flying in tandem experience similar non-gravitational forces, COSMIC will use yet another scheme of reducing the influence of such forces, namely the common-mode cancellation (see Section 2 below).

Using the satellite PODs as source data one can then solve for U , based on methods developed by, e.g., Kaula (1966). The numerical procedure is basically a large least-squares solution of the Stokes coefficients to fit the variety of the tracking data. In practice, large softwares have been developed over the years that carry out this solution, such as the GEODYN program (see below) developed at NASA's Goddard Space Flight Center. Such effort has led to a series of global gravity models, a most recent example being EGM96 (Lemoine et al., 1998), a spherical harmonic expansion complete to degree and order 360 which correspond to a spatial resolution of about 50 km. Such high resolution models incorporate terrestrial surface gravity data and ocean altimetry data for short and medium wavelength components of U , but the "back bone", long-wavelength signals are derived from the analysis of the tracking data from LEO satellites. The spatial resolution of "satellite-only" gravity models is limited by the minimum altitude of the considered tracking data, typically not less than 300 km. The current state-of-the-art satellite-only models hence reach up to harmonic degree and order 70, corresponding to a spatial resolution of about 300 km.

The next section describes COSMIC's orbit evolution and configuration, and the details of the tracking scheme for its POD. Section 3 then presents our simulation results of how useful these POD data will be in solving for U .

2. TRACKING DATA FOR COSMIC ORBITS

The eight COSMIC satellites will be placed in orbit in a single launch in 2003. The initial orbit is 400 km in altitude with an inclination of about 78 degrees. Then different satellites will be boosted by on-board thrusters to different altitudes ranging from 400 to 800 km. A nominal scenario is that 3 pairs will be raised to 500 km, 600 km, and 700 km altitudes, respectively, while a single satellite is boosted up to 800 km and one remains at 400 km. The corresponding different rate of orbit nodal precession at different altitudes will then gradually drift the five orbit planes apart. (Remember that the nodal precession is a slow drift of the satellite orbit plane in space caused by the Earth's oblateness which is about 1 part in 300. The drift rate is a function of the orbit altitude and inclination, typically amounting to a fraction of a degree per day with higher orbit drifting slower.) After a few months, the paired satellites will take turns to be separated by raising one of the two to about half way to the next higher orbit. The differential precession (now eight orbits) continues until a more-or-less even distribution of

the eight orbit planes around the globe is achieved. This whole process will take about a year, during which time the satellites would already start collecting atmospheric data. At the end of this orbit adjusting phase all eight satellites will be raised to the final altitude of 800 km while keeping the same inclination of 78 degrees, thus begin the normal operation phase. Of course, the nodal precession will still be going on, but all satellites now drift at the same rate, so the entire constellation remains an entity.

As far as obtaining gravity information is concerned, it is the first few months when pairs of satellites orbit in tandem that is most valuable, for the following reason. COSMIC satellites are not drag-free designs and will not carry accelerometers. For COSMIC, we use the GPS double-difference scheme to take advantage of the “common-mode cancellation” as an alternative way of treating non-gravitational forces. The double-difference scheme, depicted in Fig. 1, is a standard technique used in reducing GPS tracking data (Pavlis and Olson, 1995). The original purpose was to eliminate any difference, and hence resultant errors, of the receiver clocks relative to the GPS satellite clocks. We, however, here take the additional advantage of the following: When flying closely in tandem (less than a few hundred km apart in

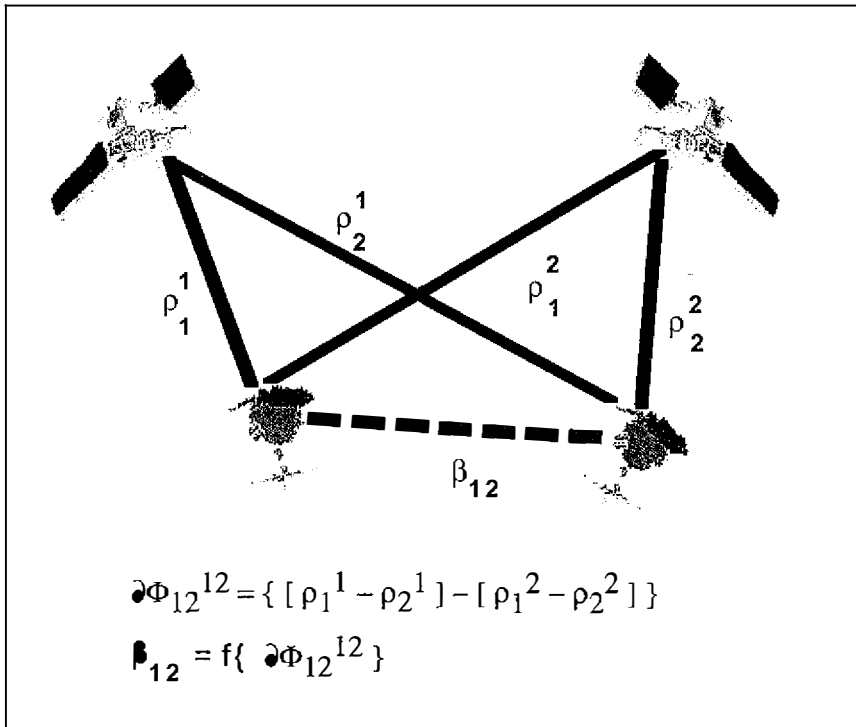


Fig. 1. Schematic diagram depicting the operation of GPS double-difference range/range-rate for two LEO satellites: Two single differences are first formed, one each between one GPS spacecraft and the two LEOs, and then the double difference is formed by differencing the two single differences.

distance, or no more than a minute apart in time), a pair of satellites are subject to similar non-gravitational forces (e.g., air drag and solar radiation pressure), which largely cancel as common mode errors in a GPS double-difference scheme. Note further that during this period the relatively low altitude orbits (compared with the final orbit) are advantageous in obtaining higher spatial resolutions.

The normal operation will last for at least another year, dependent upon instrument condition (the satellites are actually designed for a lifetime of 5 years), orbit stability (the year 2003 is just off the peak of the solar maximum), and the availability of continuing funding support. Obviously a longer lifetime, say up to 5-10 years, would be highly desirable scientifically. In terms of the POD/gravity data that would be collected, this period of time represents another phase, in which the common-mode cancellation of non-gravitational effects is no longer available. Nevertheless, at the high altitude of 800 km, atmospheric drag, which at low altitude is the largest non-gravitational force, is much weaker so that "standard" empirical modeling can be invoked. Higher altitude of course means the sacrifice of spatial resolution. However, with the low-degree gravity field already well resolved, these data can reveal slight temporal variations in the low-degree, long-wavelength U caused by global mass transports that go on in the Earth system (see below).

3. SIMULATIONS AND RESULTS

The simulation results that we describe herein fall in two categories: results from simplified *analytical* evaluations of various configurations; and more elaborate, *dynamic* solutions using the same software and models that are used for real data analysis, approximating reality as much as it is feasible. The second, dynamic type are far more time consuming and labor intensive processes, and are reserved for the study of the configurations and spacecraft designs that seem likely to materialize.

(1) The first, analytical approach, being fast but still accurate enough, is used for the quick relative evaluation of mission designs with regard to the type and accuracy of the observed quantity, the sampling rate, the orbit altitudes, and mission lifetime. Analytical simulations with simplified assumptions can be very useful to the mission design team in evaluating (in a relative sense) the various options and mission scenarios (Pavlis et al., 1996). These simulations by their nature make a lot of simplifications in describing both the signal as well as the measurement error spectra. As such, their results must be taken with more than a grain of salt and never to be used as absolute and deterministic.

To give an example, we explain here how the highest possible resolved signal is determined. The orbit is assumed circular polar and its period is taken as that of a perfect Keplerian orbit. That determines the number of revolutions within the given mission duration and from that a uniform distribution of orbits in longitude. Using the sampling rate then, the latitudinal distribution of the observations on each orbit is determined. The two spacings (latitude and longitude) are then used to determine the size of the area "covered" by each observation. Using this information, a covariance function for the gravitational signal, and the prescribed error spectrum of the measurements, a degree-by-degree computation is started for both signal and error. These components are accumulated and at each degree a signal-to-noise ratio is

computed. When that ratio becomes or exceeds unity, the maximum resolvable degree has been reached. It is obvious from this description that reality differs from it in several respects. For example, many missions are in repeating orbits, or near repeat orbits. This immediately makes some of the assumptions less valid. If however the same approach is taken while varying for instance the mission altitude, then the relative comparison of the results is valid and useful in order to select one or the other scenario. We simply should not take these numbers in the absolute sense and should not compare them to dynamic simulations (see below) where the problem has been described in much higher detail and fidelity.

We used the analytical approach to examine the interrelationship between measurement precision, mission altitude and duration, highest resolution reached and the corresponding cumulative commission error mapped in geoid space. For the measurement precision we have used three values, 0.10, 0.05 and 0.01 mm/s, that we expect to be the most conservative estimates (i.e., worst case scenario) for SST range-rate measurements with the GPS technology likely to be used. The range of altitudes we consider is from the lowest feasible at 300 km up to 700 km. In terms of mission duration we chose three values, one month, six months and one year, to be representative of various stages in the orbit adjusting phase described above.

The results are summarized in Figs. 2 and 3. Note that these results are for a single pair of COSMIC spacecraft. Three independent pairs should improve the situation by a factor of 3 (although ideally the maximum number of independent pairs of spacecraft is 7, only the three pairs in tandem are useful as stated above). Each graph within each figure is for a different mission length. Within each graph, there are three different curves, one for each of the selected measurement noise levels. The graphs in Fig. 2 show the maximum resolution as a function of the mission altitude. Those in Fig. 3 differentiate the various scenarios on the basis of the cumulative geoid commission error; they are mapped into more easily visualized geoid space, i.e., either as equivalent error or signal of geoid height undulations.

The utility of these graphs is to aid the mission design team in evaluating scenarios and trade-off alternatives. For example, if we are interested in the static part of gravity solution but concerned about the altitude of the spacecraft, we can trade one for the other in the following way: we can extend the period of time we collect data from one month to six months for instance (since we are after static signals this is not a problem), and raise the spacecraft orbits from 300 to about 400 km. Alternatively, if we were initially assuming the lowest (worst) measurement precision, we may consider upgrading our receivers (small, fixed cost) in exchange for data collection of the same duration (1 month) but at a higher orbit.

(2) For the second type, or dynamic simulation, one case was studied based on some early descriptions of the constellation configuration. This simulation was done at NASA's Goddard Space Flight Center (GSFC) using the POD software GEODYN (Pavlis et al., 1996). At the time we assumed a near circular, near polar orbit at an altitude of 420 km, with 8 COSMIC spacecraft all in tandem at spacing of 400 km. In addition to white noise we included some atmospheric error in the form of the atmospheric density model: the data were simulated using the French DTM87 model, while the recovery was performed using GSFC's MSIS86 model.

The data we simulated were doubly differenced GPS range signals for reasons we explained above, and we assumed that they were collected with GPS receivers similar to the GPS/MET-class design but with the capability to track up to 12 GPS spacecraft simultaneously

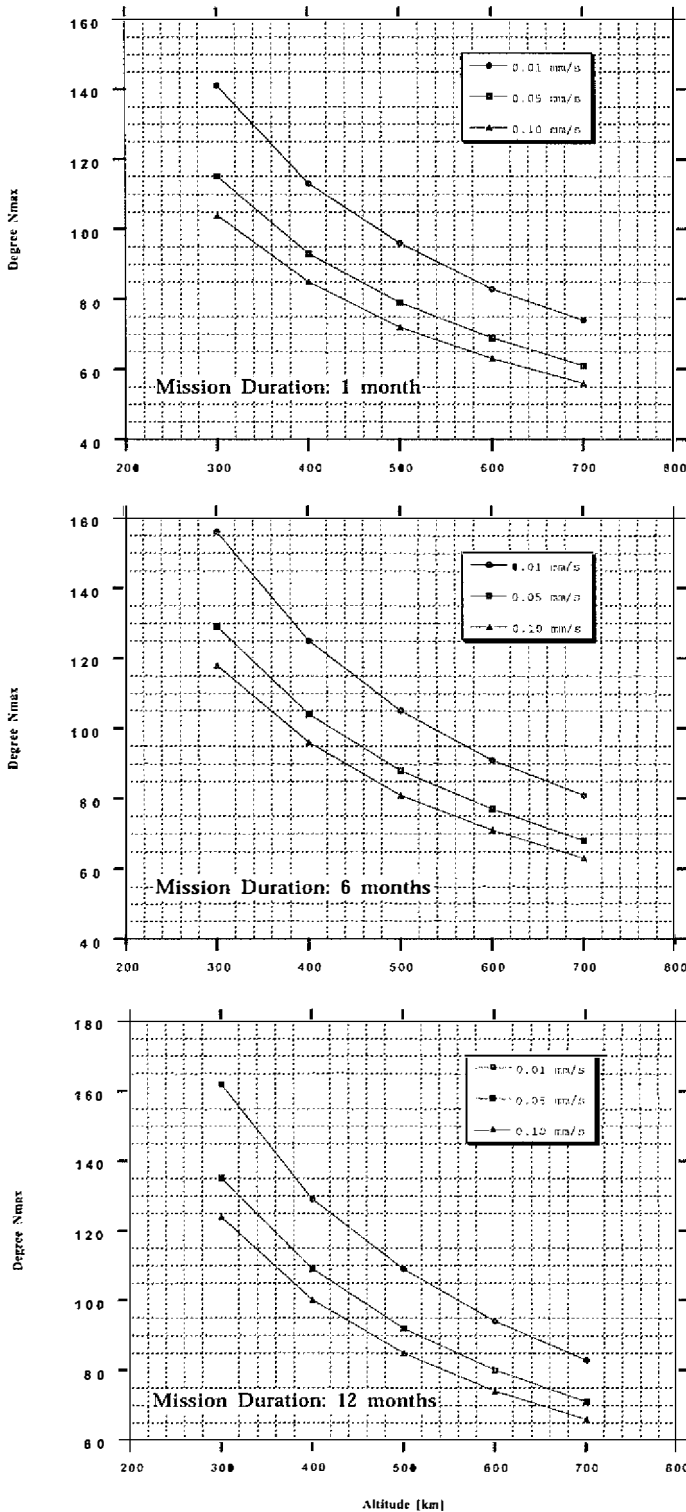


Fig. 2. Maximum spatial resolution of the geoid solution (in terms of the maximum harmonic degree achievable) from a pair of COSMIC spacecraft, as a function of mission altitude for three different mission durations at three assumed GPS range-rate tracking errors.

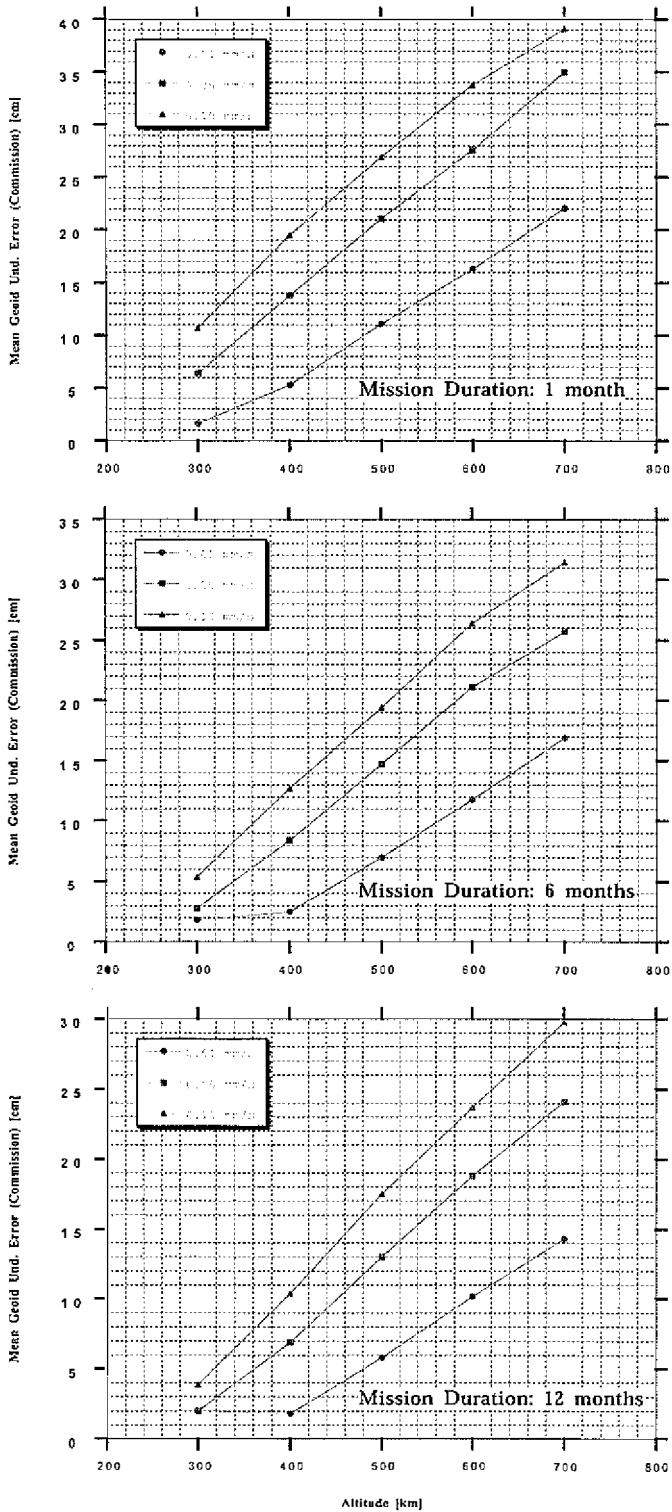


Fig. 3. Same as Fig.2, but for the cumulative geoid undulation errors.

on both frequencies. We assumed that a minimum of 8 GPS spacecraft were in sight at every event and we postulated a 1 cm noise (to include some systematics, which otherwise would be too difficult to do) per observation collected at the rate of 1 Hz. The actual data were grouped into 5-min normal points, given the appropriate accuracy. This made the problem far more manageable in terms of data and required computer time. The data were generated between 7 independent spacecraft pairs using an elevation cut-off angle at the spacecraft horizon of 0° . This might need to be re-evaluated in future designs to verify that there is no systematic and significant obstructions for any azimuth around the receiving antenna. In this simulation there are no data that involve ground tracking, but in the future, this should be investigated since such data exist independent of COSMIC (IGS network) and are free to the international science community. In fact, in the reduction of the data we assumed that the GPS spacecraft orbits will be provided by the IGS service and we adopted a very conservative 50 cm error in each component (calibrations of these products indicate that their accuracy is closer to an order of magnitude lower than what we assumed, see Pavlis, 1995).

Four 8-day arcs were simulated, spanning 32 consecutive days, or simply a month. They resulted in some 300,000 doubly differenced ranges. During the reduction process we formed normal equations (one for each arc). In addition to the usual spacecraft state-vector and ambiguity parameters, the latter allowed for static gravity harmonic coefficients up to $(l,m) = (20,20)$ and time-varying terms of seasonal periods for the full (4,4) part of the gravity field U .

The primary result of this simulation is shown in Figs. 4a, b in the form of an error spectrum for the recovered coefficients and the associated geoid error. In the figures we included several other geophysical signals spectra that are useful in the evaluation of the results. In Fig. 4a we show the signal spectra of the ocean and atmospheric circulations, and the post-glacial rebound, while 4b is the associated geoid error spectra in terms of geoid height, where we have included the signal spectra of the dynamic ocean topography and that of the expected effect of vertical datum errors (systematic errors due to different land surface survey systems) on the low degree and order terms of U . Both are prime examples of areas where geodesy, oceanography and other scientific disciplines would like to see significant improvements in the very near future.

In Fig. 4 we also show the error spectra of the latest, state-of-the-art gravity model, EGM96 (Lemoine et al., 1998), and the expected error spectra of a model that would be derived on the basis of the future gravity mapping mission GRACE (see Section 1 above). From the figure we can summarize that the static part of the model will be improved significantly over EGM96 (by about an order of magnitude) for the low degree and order terms up to 40 or so, with lesser but still significant improvement extending as high as out to degree 60.

The above simulations assume the absence of direct non-gravitational effects. In the case of COSMIC this is equivalent to the ideal case where such effects are canceled in common-mode fashion as described above. It should also be pointed out that the current spacecraft design is by geodetic standards quite prone to non-gravitational force errors. We will need to reconsider and re-do the simulations once COSMIC mission and spacecraft design are better defined.

Ideally, using the individual model estimate from a single month's data set, we can deduce a (low-degree) U solution if it were possible to produce such an estimate every month.

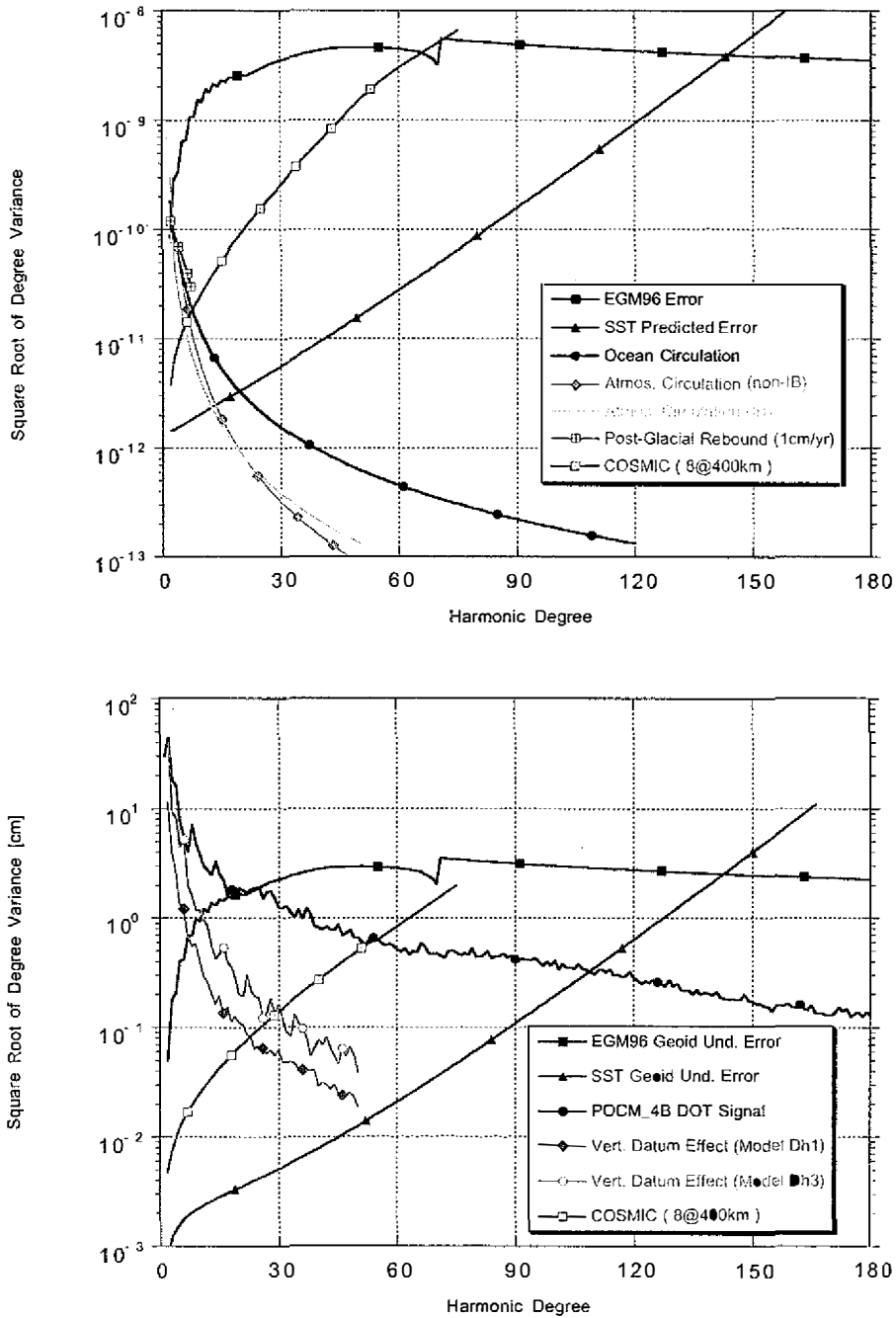


Fig. 4. Error spectrum (per harmonic degree) for the COSMIC-derived geoid solution, in comparison with the error spectra for the current EGM96 model and a future SST mission, and some geophysical gravitational signal spectra, for (a) harmonic coefficients, and (b) geoid undulation.

Then after certain time we can use these solutions to deduce the temporal variation of the low degree components of U . Based on our results for the precision of a monthly solution we can forecast the expected decrease in the standard deviation (i.e., increase in precision) of the amplitudes of these terms as a function of the mission duration. Table 1 shows that in the case of signals with an intra-seasonal frequency (period of, say, three months), a mission that produced monthly solutions for five consecutive years would give us estimates that have a standard deviation as small as 4% of that of the monthly estimate; in other words, 25 times more precise. The gain in precision is of course less for lower frequency terms since we would have observed fewer cycles during the same fixed five year period. Based on these estimates for the expected secular rates for the very low degrees, it seems possible that signals as low as $\sim 5 \times 10^{-13}$ could be reliably resolved within the first five years. If the mission were to survive for up to ten years, then this limit in sensitivity would improve to $\sim 2 \times 10^{-13}$.

Obtaining information about the (small) temporal variation of the gravity field U would address to important meteorological and geophysical problems, such as those associated with climate change and the derivation of constraints on the climate-driven mass redistribution on Earth at intra-seasonal to secular scales. Our results shows, in particular, that after a 5-year mission, a majority of large-scale, temporal geophysical signals (e.g., Chao, 1994; NAS, 1997) could be encompassed in the signals observed by COSMIC. For example, Figure 4 shows that low-degree atmospheric and oceanic circulations, which represent the largest meteorological signals (Chao, 1994), can be detected up to degree at least 6 at monthly intervals. In terms of the number of Stokes coefficients this is an order of magnitude improvement over the present satellite laser ranging technique which can only resolve the lowest zonal harmonic coefficients (e.g., Cheng and Tapley, 1999).

Table 1. Predicted Precision Estimate vs. Mission Lifetime.

Component	% Gain in Precision of Estimated Components*				
	1	2	3	4	5
Secular	89	33	18	12	9
Annual	63	23	13	8	6
Semi-annual	51	19	10	7	5
Quarterly	40	15	8	5	4

*With respect to the monthly error estimate

4. SUMMARY

The geodetic utility of COSMIC is to provide new sets of SST data that will be used in the improved solution for Earth's gravity field U . The scenario is characterized by:

- (1) Continuous "high-low" GPS tracking of a constellation of 8 LEO satellites in 78° inclination circular orbits;
- (2) During the orbit adjusting phase, data reduction in terms of double-differences will be done on GPS tracking of satellite pairs in tandem at altitudes of 500 km, 600 km, and 700 km, each for a period of a few months;
- (3) Common-mode cancellation of non-gravitational forces will be exploited during configuration (2);
- (4) The COSMIC tracking data will provide new information to improve our knowledge of the static model for U ;
- (5) During the subsequent operational phase (1-5 years) at 800 km altitude, the 8 satellites are tracked by GPS independently without the benefit of common-mode cancellation (3), however, they experience less non-gravitational effects due to the higher altitude;
- (6) The GPS tracking data collected during the operational phase will be used to solve for the (relatively small) temporal variations in U for geophysical purposes.

In this scenario, (4) and (6) are our anticipated scientific products. For the static model, i.e., (4), significant improvement is possible over our present knowledge embodied in the EGM96 model. Realistic simulations have demonstrated an improvement by an order of magnitude up to harmonic degree as high as 40, depending on the actual configurations during the orbit adjusting phase. With respect to time-varying gravitational signals, i.e., for (6), geophysical processes that involve large-scale mass transports can be detected and monitored during the mission duration to an unprecedented precision and resolution, providing important global change information.

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