Spaceborne Ranging System

David E. Smith
Goddard Space Flight Center
Greenbelt, Maryland 20771

Abstract. A spaceborne laser ranging system is described that could survey a large network of ground reflectors, and provide, their relative locations to a precision of ± 1 cm. This performance is believed realizable for networks covering up to 10^6 square kilometers and from only a few days of observations. This system could be used to monitor crustal movements in many areas of the world and has the potential to provide an almost real-time system for detecting precursory ground motions before large earthquakes.

Introduction

During the last decade or so improvements in our ability to measure precise positions on the earth's surface by conventional ground based techniques has made us more aware of the existence of crustal motions taking place at the centimeter level. This has become particularly apparent for seismic regions such as California where the existence of sizable geodetic motion, both horizontal and vertical, have been observed (e.g., Castle et al. 1974) and the majority of earth scientists now seem ready to accept that motions at the centimeter level are probably occurring in many regions, not only those considered seismically active or undergoing well-documented subsidence. The extension of conventional surveying at the centimeter level into larger areas presents difficulties from a point of view of accuracy and the frequency with which re-surveys of the areas can be reasonably accomplished. With only limited knowledge of the time scales on which motions along plate boundaries and plate interiors are occurring it seems highly desirable to be able to make these geodetic measurements almost synoptically, or at least on an "as required" basis. Ground deformation preceding large earthquakes is known to occur (Scholz et al., 1973) but little seems to be known about the time scale or the magnitude of the deformation nor, of course, precisely where it will occur. Thus techniques capable of monitoring large areas on a scale that could detect possible precursory motion and able to re-survey the area quickly in order to confirm the initial observation could play a very important role in the detection and understanding of this type of crustal phenomenon; at least in so far as indicating where intensive ground based measurements might be concentrated.

Space techniques involving mobile ground based systems, such as very long baseline interferometry (VLBI) and laser ranging to satellites and the moon can be expected to provide a capability close to the required accuracy in the next several years but it is not clear if the measurement and re-measurement of hundreds, or perhaps thousands, of points by these methods is practical in an operational role. For these reasons it was proposed several years ago (Mueller et al., 1975; Vonbun et al., 1977; Smithsonian Astrophysical Observatory, 1977), that putting a laser system into space and putting simple unmanned reflector systems on the ground might have a distinct advantage when the scale of monitoring ground motions grew to a level of becoming a global problem or the frequency of re-surveys coupled with areal size become too large for the mobile space techniques. Furthermore, it seemed that the spaceborne laser would probably have a greater potential accuracy than these other techniques for distances up to a thousand or more kilometers if the altitude and configuration of the satellite were carefully chosen.

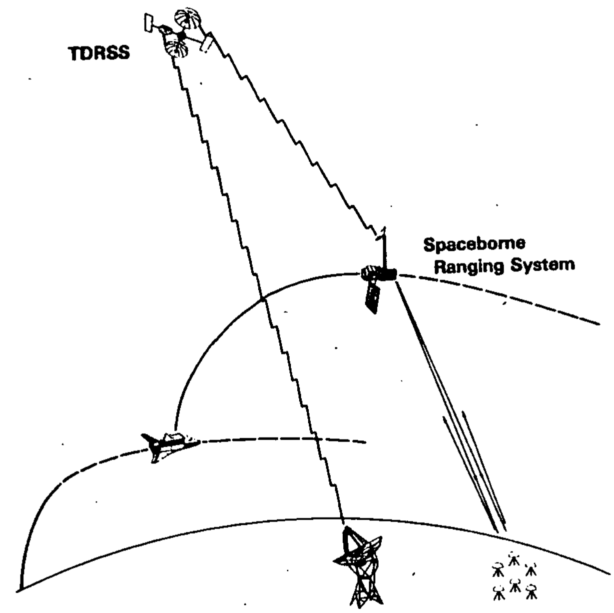

Fig. 1. Spaceborne ranging system: general concept.

In this paper a spaceborne laser ranging system is described and the results of performance simulations presented that show the capability of such a space mission in providing precision geodetic positions on a global, near real-time basis.

Spacecraft System

The Spaceborne Ranging System consists of an orbiting spacecraft carrying a pulsed laser distance measurement system that sequentially measures the distance to a number of retroreflector arrays on the ground. Figure 1 shows the general concept of the system. Launched by the Space Shuttle into a low altitude orbit the spacecraft is subsequently lifted into a higher orbit by its own propulsion system. Once in orbit the spacecraft ranges to the corner reflectors on the

Proc. of the 9th GEOP Conference, *An International Symposium on the Applications of Geodesy to Geodynamics, October 2-5, 1978.* Dept. of Geodetic Science Rept. No. 280, The Ohio State Univ., Columbus, Ohio 43210.

...rth's surface, as it passes overhead. The measurements are stored on the spacecraft and subsequently relayed to a high altitude relay satellite, the Tracking and Data Relay Satellite System, for re-transmission to a ground terminal. The measurement objective of the system is a relative position uncertainty in the locations of the reflectors of ± 1 cm precision or better for separations of reflectors as large as 1200 to 1500 km. The specifications of the spaceborne and ground reflector system are such that they should meet this measurement accuracy for a mission to be launched in the early to mid-1980's.

The proposed laser system (M.W. Fitzmaurice, private communication) would consist of a Nd YAG laser with a 200 picosecond pulse length and a repetition rate of 10 pulses/sec. The rms range uncertainty of a single pulse at 5 to 10 photo-electrons is expected to be 1 to 2 cm with a bias of a few millimeters.

The ground targets (P.O. Minott, private communication) will consist of a small corner cube array of retroreflectors mountable on a permanent pillar or a surveyors tripod. A design for these targets is shown in Figure 2. Eight corner cubes are mounted in a cone approximately 28 cm in diameter at the base and 20 cm high. Each retro-reflector consists of a glass prism, 73 mm in diameter and the proposed housing is constructed of aluminum or moulded plastic. Estimated weight of the reflector array is 3 to 5 kg. Details of the laser system and ground reflector system are shown in Table 1.

As the first reflector of a ground network comes into view of the spacecraft an acquisition procedure is initiated that is expected to take 10 to 15 seconds. The procedure consists of a search for the reflector based on a priori knowledge of the reflectors location and the position of the spacecraft. After the successful acquisition of the first reflector the laser makes 20 to 30 range measurements in a 2 to 3 second period and then swings on to the next reflector taking less than 0.5 seconds for this operation even for the most widely separated reflectors. The laser dwells 2 to 3 seconds on the second reflector making range measurements and then moves to the next. No acquisition time is expected to be necessary for the second and subsequent reflectors because the relative location of the spacecraft and the ground network will be updated from the corrected a priori positions obtained during the acquisition of the first reflector.

On any particular pass of the spacecraft over the network, the spaceborne ranging system will range to a given reflector three times, each for a 2 to 3 second period; once at low to medium elevation on the approach, once at high elevation and once at medium to low elevation on the way out. For a thousand kilometer altitude orbit a pass of the satellite over the network will last about 10 minutes which indicates that about 50 reflector arrays could be surveyed on every pass over the region assuming a 2 to 3 second dwell time and a

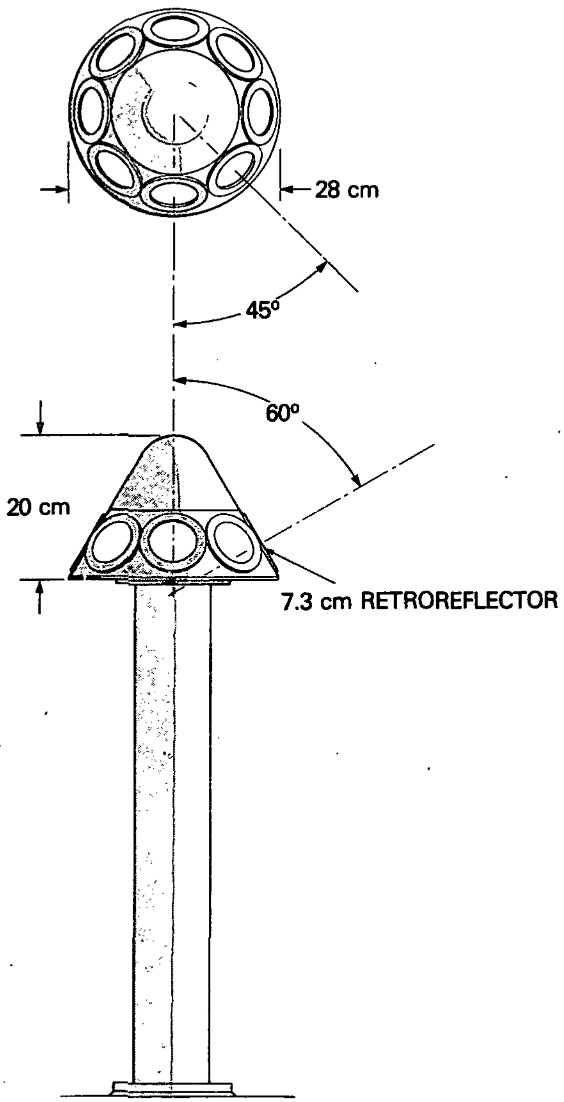

Fig. 2. Ground reflector array.

TABLE 1. System Specifications

Laser

Nd YAG
0.2 nanosecond pulse width
10 pulses/sec
1-2 cm rms uncertainty (single pulse) at 5-10 photo electrons
Lifetime - 5 x 10^6 pulses
Beam divergence - 10 arcseconds

Pointing

2-3 arcsecond accuracy

Retroreflectors

Number - 8
Size - cone, 28 cm diameter base, 20 cm high
Weight - approx. 3 to 5 kg
Materials - glass prisms, 73 mm diameter
housing - moulded plastic or aluminum
Initial acquisition - 15 seconds
Stay time - 2-3 seconds
Transfer time - 0.5 seconds (max) between reflectors

few tenths of a second transfer time between reflectors. The lowest elevation at which measurements are expected to be made is about 20 degrees due to uncertainties in being able to account accurately for atmospheric refraction. Figure 3 shows the sequence of events as the system passes over a network.

Simulated Survey

A simulation has been performed of a survey of the State of California by the Spaceborne Ranging System (W.D. Kahn and T.S. Englar, private communication). In the simulation approximately 150 corner cube arrays are distributed over California at a separation of about 50 km. Using the system described in the previous section, the simulation estimates the accuracy and precision with which the relative positions of the reflector arrays can be obtained in the presence of noise and bias on the laser system, perturbations of the spacecraft motion and errors in the refraction calculations.

The orbit of the satellite is assumed to be circular at 1000 km altitude and 50 degree inclination to the equator. A medium inclination orbit was chosen because it provides ground tracks across California in almost orthogonal directions (southwest to northeast and northwest to southeast) and thus provides a strong geometric distribution of range measurements. In contrast, a polar orbit provides only north to south or south to north tracks and these provide strong geodetic ties in the north-south direction but only weak control in the east-west direction.

The simulation has been conducted for a six-day observation period assuming 50% cloud cover that effectively reduces the number of successfully observed tracks over the area from 18 to 9. The data on these tracks is simulated at an effective rate of 10 pulses/sec. with a noise of 2 cm and a bias of 0.3 cm. The effect of errors in the gravity field on the motion of the satellite were accounted for in the simulation by adopting the GEM 10 covariance model out to degree and order 22. GEM 10 is a model of the gravity field derived from satellite tracking and surface gravity data (Lerch et al., 1977). The effects of solar radiation pressure and air drag on the satellite were assumed to be in error by a constant percentage in the estimation of their effect on the solution. The effect of atmospheric refraction was estimated through a two parameter (pressure and temperature) model developed by Gardner (1977). In this model the temperature and pressure are assumed known at a limited number of locations in the region and are used to develop an atmospheric model of the whole region from which the temperature and pressure at each of the reflectors can be estimated.

Table 2 shows the accuracy and precision of the baselines obtainable between reflectors over various distances and summarizes the error models and assumptions made in the simulation. The accuracy is the estimated total error in the baseline; the precision is the ability to repeat the measurement. Thus the noise in the precision is approximately 1.44 times that of the accuracy while the systematic errors are generally smaller in the precision than the accuracy because of the correlations.

The general trend in Table 2 is for all the error sources to increase as the intersite distance increases. The gravity model error dominates the accuracy while the solar radiation pressure and drag effects on the orbit are negligible in both the accuracy and precision and over all distances. The noise level in the

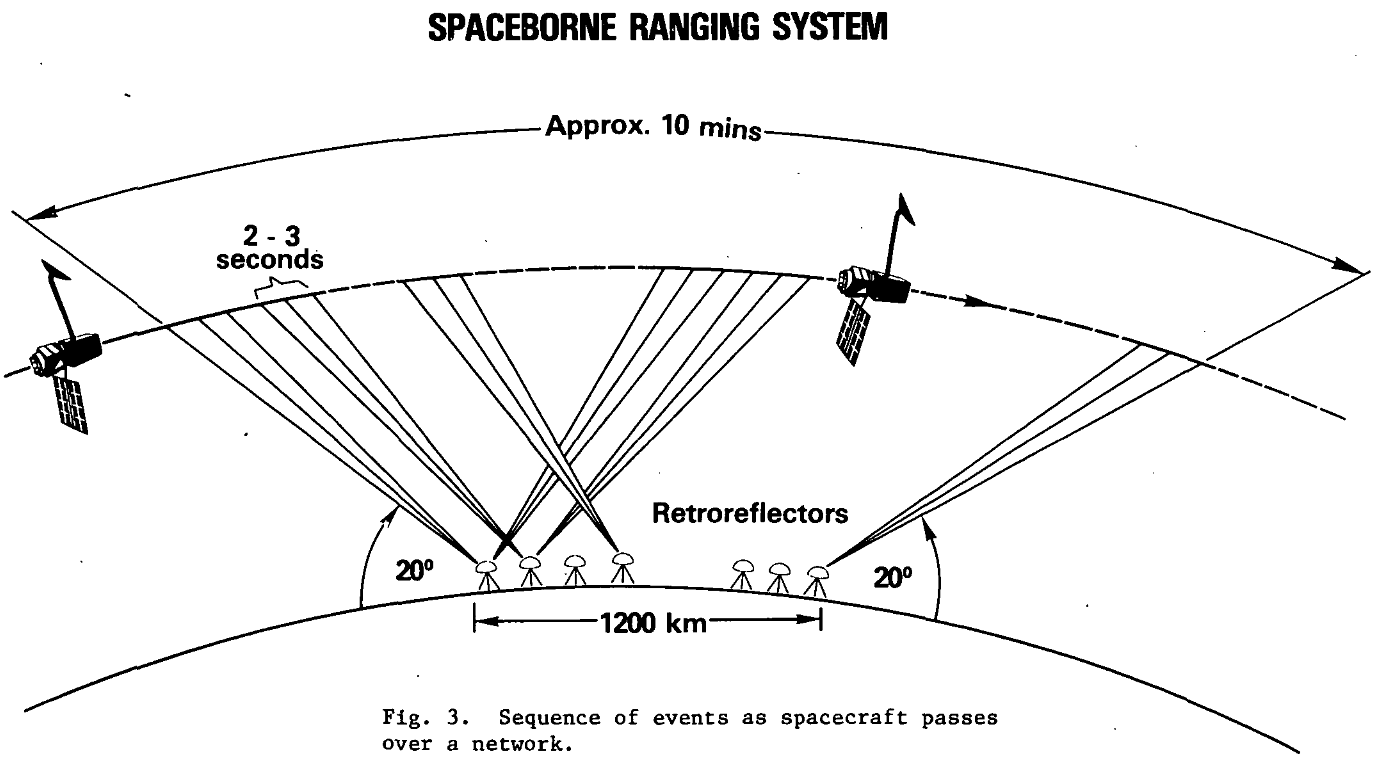

Fig. 3. Sequence of events as spacecraft passes over a network.

precision is larger than in the accuracy but the gravity contribution is significantly reduced in the precision columns showing that a large segment of the gravity error is of a systematic nature that is repeated from one simulation (or observation) to the next. The atmospheric refraction is larger in the precision than the accuracy showing that much of this error has the property of noise. Similarly the laser system bias behaves like noise in the precision columns because the bias on one track is assumed independent of any other track.

The conclusions to be drawn from Table 2 are that a survey of the complete State of California can be accomplished with a precision of 1 cm and an accuracy of 3 cm in about 6 days. Making an allowance for an increase in our knowledge of the gravity field over the next several years suggests an overall accuracy in the mid 1980's of 1 cm as a reasonable objective.

After the gravity field and data noise, the largest source of error is the atmospheric refraction. Alternative ways of making the refraction correction are presently being considered. One possibility is that the laser system operate in two colors separated enough in frequency that the total atmospheric refraction can be derived from the delay between the two pulses. This is technically difficult but might be possible in the next few years. Another possibility is to limit the observations to greater than 30 degrees elevation. This reduces the refraction error by about 40% but decreases the amount of data thereby increasing the noise contribution in the analysis. At the present time, with the noise on the data a larger contribution to the total error than the expected atmospheric refraction it seems that restricting the elevation may not be desirable.

Although no mention has been made so far of the ability to measure relative height changes the Spaceborne Ranging System does have this capability. At this stage it appears that all error sources affect the vertical more than the horizontal (baseline) but that similar accuracies can be achieved in height if the network is constrained at three perimeter reflectors. That is, the system could measure changes of height within the network but not of the whole network itself or of possible rotations of the network. This aspect is continuing to be investigated.

Applications in Geophysics

Perhaps the single most important application of a spaceborne ranging system is in its potential for monitoring crustal motions in seismic zones. The capability of providing high accuracy geodetic measurements in a very short period of time, i.e., a geodetic snapshot, could have significant impact on our ability to study pre- and post-seismic motions. With this system it would be possible to establish in a region such as California, a network of reflector systems that could be monitored routinely and would provide warning of any motion at the centimeter level. Monitoring of an active

TABLE 2. CALIFORNIA SIMULATION: BASELINES

	ACCURACY							PRECISION						
DISTANCE (km)	NOISE (cm)	GRAVITY (cm)	ATM. REFR (cm)	MEAS BIAS (cm)	SOL.RAD PRESS (cm)	DRAG (cm)	RSS (cm)	NOISE (cm)	GRAVITY (cm)	ATM. REFR (cm)	MEAS BIAS (cm)	SOL.RAD PRESS (cm)	DRAG (cm)	RSS (cm)
150	.18	.54	.10	.01	.00	.00	.58	.25	.10	.14	.01	.00	.00	.30
300	.20	1.06	.12	.01	.00	.00	1.09	.28	.19	.17	.02	.00	.00	.38
600	.24	1.65	.16	.02	.01	.00	1.68	.34	.24	.23	.04	.01	.00	.48
900	.27	2.21	.18	.03	.01	.00	2.23	.38	.33	.26	.05	.01	.00	.57
1300	.31	3.09	.25	.05	.02	.00	3.11	.44	.49	.35	.07	.03	.00	.75

Assumptions:

- Orbit
  - Mean Altitude: 1000 km
  - Inclination: 50°
- Observation Period: 6 days
- Cloud Cover: 50%
- No. Retroreflectors: 150 @ 50 km spacing
- Measurement Noise: ± 2cm single pulse, 10 pulses/sec
- Measurement Bias: 0.3 cm
- Gravity Uncertainty: Gem 10 covariances (ℓ,m=22)
- Atmospheric Error Model: 2 parameter
  - Pressure Noise: ± 1.0 mbar
  - Bias: 0.33 mbar
  - Temp. Noise: ± 1.4°C
- Radiation Pressure: 33% error
- Atmospheric Drag: 22% error

region might be accomplished by regular surveying of the area every three months, say, until such time as evidence of motion is detected and then increasing the frequency of the re-surveys down to once per week, and perhaps even more frequently. The major advantage of the spaceborne system is that it can monitor a large enough region that it can identify a sub-area within the survey network of potential activity that can then be monitored more accuractely by ground based methods.

In principle, the separation of ground reflector systems can be as close as a few hundred meters but in reality it would seem that the most advantageous separation is likely to be greater than 20 km where the accuracy of the space system appears to start to become superior. In this respect, it should be remembered that the reflector systems can be located in almost any kind of terrain and not necessarily at the most accessible locations and that line of sight visibility between reflectors is not a requirement, in contrast to ground based surveying.

One of the more interesting possibilities that this system could make possible is the "capture" of a very large earthquake, say magnitude 7.5 and above. By suitably instrumenting with reflectors a number of regions of the world which historically have had large earthquakes and regularly monitoring these regions over many years, we could eventually expect to observe the geodetic development, occurrence, and relaxation after a major shock. Such an experiment is impossible at the present time because of the magnitude of the task but a spaceborne system of the kind described could probably simultaneously monitor about ten areas the size of California distributed around the globe. The limitations to such an extensive activity are primarily with the weather, which might limit the choices of location of some reflectors, and to the lifetime of the laser. If we consider monitoring 10 regions around the world, each containing 100 reflectors and we plan 10 complete surveys of each area per year, then we have 10^4 site determinations per year, which is probably the limit that can be expected from a single laser unit. Thus, for a 2 or 3 year mission lifetime the spacecraft must contain a multiple laser system.

Another area in which this system could be of potential assistance is in routine geodetic surveying. Although the accuracy of a centimeter or two may not always be required, a large area the size of the United States could be surveyed in a matter of weeks with the main problem being the deployment of the reflector array.

Many other applications of the system have been suggested including subsidence monitoring (Kahn and Vonbun, 1977), volcano monitoring, measuring the changing thickness of the ice caps etc., and these have been discussed in the report (University of Texas, 1978) of a Workshop on the Spaceborne Laser held at the University of Texas, Austin.

Conclusion

The general concept of a spaceborne ranging system has been described that would have a geodetic capability of $\pm$ 1 cm in relative positioning of a network of ground reflectors separated from 20 to 1200 km, or more. Such a system appears technically feasible for launch in the early to mid-1980's and could have a major impact on our ability to observe the precursory geodetic motions believed to occur before large earthquakes. Indeed, established on a global scale, with survey areas around all major seismic zones the spaceborne system could provide the first real probability for "capturing" a magnitude 7.5, and above, earthquake.

Simulations of a survey of a large area indicate that the largest error sources in the recovered reflector positions are the gravity field and atmospheric refraction, the latter being smaller but less well understood and itself liable to error. The technological consideration that presently poses the greatest challenge appears to be the development of a laser system that can operate for two or more years in a spacecraft and provide the order of 2×10^7 pulses. In the timescale proposed for the spaceborne laser this development appears realizable.

As in the case for all optical systems, a consideration in its operation is the weather. In the simulations that have been performed a 50% cloud cover has not significantly affected the quality of the results but has extended the time over which data must be collected, e.g., from 3 days to 6 days. For general surveying work, however, where there is little or no time restriction for acquiring the data, it is probable that weather may be a minor consideration.

Acknowledgements. The author would like to thank Drs. M.W. Fitzmaurice and P.O. Minott for providing information on the spaceborne laser and the ground reflector system, and Mr. W.D. Kahn and Dr. T.S. Englar for allowing me to make use of their simulation studies. In addition, I would like to thank Dr. F.O. Vonbun, Dr. H.H. Plotkin and Mr. D. Premo who have played a major part in developing the concept of the spaceborne ranging system.

References

Castle, R.O., J.N. Alt, J.C. Savage and E.I. Balazs, Elevation changes preceding the San Fernando earthquake of February 9, 1971, Geology, 2, 61-66, 1974.

Gardner, C.S., Comparison between the refraction covariance model and ray tracing, Radio Research Laboratory Publication No. 486, College of Engineering, University of Illinois, Urbana, Illinois, 1977.

Kahn, W.D. and F.O. Vonbun, Detectability of land subsidence from space, Proceedings of the Second International Symposium on Land Subsidence, International Association of Hydrological Sciences, 1977.

Mueller, I.I., B.H.W. van Gelder and M. Kumar, Error analysis for the proposed close grid geodynamic satellite measurement system (CLOGEOS), Department of Geodetic Science, Report No. 230, Ohio State University, 1975.

Scholz, C.H., L.R. Sykes and Y.P. Aggarwal, Earthquake prediction: A physical basis, Science, 181, 803-810, 1973.

Smithsonian Astrophysical Observatory, Staff, Study of a close-grid geodynamic measurement system, Smithsonian Astrophysical Observatory, Reports in Geoastronomy, No. 5, 1977.

University of Texas, Report of spaceborne geodynamics ranging system workshop, Dept. of Aerospace Engineering, University of Texas, Austin, 1978.

Vonbun, F.O., W.D. Kahn, P.D. Argentiero and D.W. Koch, Spaceborne earth applications ranging system (SPEAR), J. Spacecraft and Rockets, 14, 492-495, 1977.