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Mobile Satellite Ranging

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Introduction

For more than a decade, dozens of laser ranging stations have been active throughout the globe monitoring the orbits of about 15 retroreflector-equipped artificial satellites. As has been reported by several publications, including Pearlman et al. [1975], McGunigal et al. [1975], and Masevitsch and Hamel [1975], the lasers are an operationally acceptable manner with which to closely monitor the orbital parameters of a wide variety of objects. Almost from the beginning, the possibility of establishing geodetic benchmarks by the use of laser satellite tracking was recognized, leading to a number of convincing demonstrations over selected baselines [Smith et al., 1978]. Even though these experiments were conducted at quasi-fixed locations, owing to the lack of truly mobile facilities, and used low level orbiting satellites, they showed great promise for the use of this technique over continental distances. With the relatively recent launch of the Lageos target into an unusually stable orbital configuration [Pearlman et al., 1976], and with the continuing development of improved techniques for laser ranging, we are now in a position to realize a much wider utilization of this geodetic application. One can expect the current emphasis being placed on the measurement of crustal motions (and on earth dynamics in general) to fuel an evolution in the field of satellite ranging, from the use of the versatile fixed station devices, which served so well until now, to the procurement of specialized, highly mobile instrumentation devoted to the global establishment of geodetic benchmarks.

The main thrust of the following article will be a brief review of the constraints which have limited satellite ranging hardware and an outline of the steps which are underway to improve the status of the equipment in this area. In addition, some suggestions will be presented for the utilization of newer instruments and for possible future R & D work in this area.

Current Status

Most of the three dozen laser ranging stations now in existence were designed as fixed observatories. A small subset, consisting of eight NASA stations and two French stations [McGunigal et al., 1978 and Gaignebet, 1978], was configured to be routinely transported between various locations. Several other satellite stations can also be classified as transportable [Pearlman et al., 1978; Wilson, 1978; and Hamel, 1978]; but, to this author's knowledge, they are not expected to move between various locals with any frequency. While none of these existing ranging units is considered "mobile", their operation at many different locations has demonstrated the geodetic benchmark capability and has provided a testbench for many operational concepts. The operating parameters which were used by these first generation transportable systems are summarized in Table 1. The two French systems generally represent the smallest and largest of the relevant parameters, while the NASA/Goddard system parameters lie somewhat between.

Each of the current stations is sufficiently versatile to permit ranging either the bright, very fast moving, low targets, or the much higher NTS2 satellite, which gives the weakest return of the current lot. Such flexibility, however, is not without cost. The current systems must routinely cope with over five orders of magnitude in target strength. Until very narrow pulse lasers recently became available, high accuracies dictated the use of high radar signals, sometimes

TABLE 1. A Summary Of The Operating Parameters For The Transportable Satellite Ranging Stations

	Smallest	Largest
Aperture	0.36 m (CNES I)	1.0 m (CNES II)
Energy per Pulse	0.25 J (Moblas II-VIII)	2 J (CNES II)
Firing Rate	0.5 PPS (CNES II)	3 PPS (Moblas)
Pulse Width	2 nsec (CNES II)	12 nsec (CNES I)
Signal Strength on Lageos	5 photoelectrons/shot	80 photoelectrons/shot
Single Shot Uncertainty	∿ 4 cm (RMS)	∿ 75 cm (RMS)
Size (critical components)	1 van approximately 2.3 x 3.5 x 12 m	3 vans approximately 2.3 x 3.5 x 12 m

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exceeding hundreds of photoelectrons per shot. Such signal strengths call for moderate aperture receivers and strong lasers. The energy in the output laser beam was sufficiently strong, in some instances, to warrant the use of active radar to monitor the airspace above stations. The lower but brighter objects, on the other hand, dictated fast track rates and frequent update of the orbital predictions. Furthermore, with multiple tracking tasks involved, considerable data handling capability was required. Lastly, and most telling, these multipurpose stations have been expensive to build and expensive to operate, predicating their use to cost-shared tracking programs, and preventing great utility in many of the specific areas of interest such as crustal dynamics.

Any laser contribution to a more aggressive attack on earth dynamics requires a system which is optimized solely for providing accurate benchmarks. Newer laser systems must be far more mobile than the current compliment. However, unlike the first generation units, these future systems need only concern themselves with obtaining accurate data on the Lageos satellite, which is the optimum target from which to infer crustal motions. This specialization is a significant advantage from the hardware standpoint for, while Lageos is weaker than most other satellites, it still provides a good signal from a moderately slow, highly predictable orbit. Bender et al. [1978] did propose, therefore, that a highly mobile ranging station be developed specifically for use on the Lageos satellite, taking advantage of low signal techniques, such as used for lunar ranging, and designed to respond to problems of crustal strain monitoring.

Mobile Station Design

The University of Texas McDonald Observatory has been working for the past nine months in cooperation with NASA and the Joint Institute for Laboratory Astrophysics to develop the required laser station. The basic design goals which have been chosen for this effort are the following:

1. The station will be highly mobile, able to be driven routinely from place to place in a time scale of less than a few days.
2. The station will be air transportable.
3. The station should range the Lageos target with a normal point accuracy better than 2 centimeters for a three-minute average. And,
4. The station must be eye-safe and present no hazard to overflying aircraft or ground-based observers.

This set of constraints, while relatively simple, leaves little flexibility in the choice of station parameters. There is so little flexibility, in fact, that until the availability of mode-locked laser systems, with pulsewidths of less than 1 nanosecond, the entire subset of requirements was impractical. In particular, the requirement for eye safety is very restrictive to the choice of system parameters. It is thought that the eye damage threshold for short pulse lasers at visible wavelengths is approximately 5×10^{-6} joules cm^{-2}, for a distended pupil [Taboada and Gibbons, 1978]. In other words, the system can transmit no more than 3.5 millijoules of energy on each laser shot provided that the beam is dispersed over a 30 cm transmitting aperture. It is easy to show that an appreciable size receiver is required before an average of even one photoelectron per shot is expected from the Lageos target, even if such an energy is transmitted with a beam divergence of only 10 arc seconds. When this fact is coupled with the desire to maintain a very compact instrument, several conclusions are immediately evident.

1. The transmitting and receiving functions of this station must be contained in a single aperture in order to prevent having to transport two moderately large, high quality telescopes. (The single aperture telescope should be a coude instrument to accommodate the connection to the laser light source.)
2. The transportable laser station will have to operate on the Lageos target with signal levels at or below one photoelectron per shot.
3. The system will have to operate with a relatively narrow beam divergence, requiring an excellent prediction and pointing system in order to acquire the target. And,
4. The system should employ a subnanosecond (mode-locked) laser.

It is also interesting to note that the use of a single aperture system which is restricted to a specific output density, implies a return signal proportional to the fourth power of the aperture. This puts a great premium on the packaging of the telescope, since 40 cm aperture optics will produce almost ten times the return of a 30 cm aperture instrument.

The design parameters chosen for the University of Texas station (TLRS) are shown in Table 2. Owing to the availability of high repetition rate lasers, the system operates well into the single photoelectron regime. Even so, the design is relatively conservative, with a predicted return of some 20 photoelectrons per minute at worst zenith distances using a conventional photomultiplier, and some three times higher with newer detectors which are now on the market. Single shot uncertainties from each detected photon from the Lageos target will be on the order of 5 to 7 cm. These parameters forecast a worst case ranging precision for a one minute normal point of approximately 2 cm, with the best case accuracy limited to about 1 cm by the atmospheric corrections [Gardner, 1977] and the measurement of system biases.

Figure 1 gives two views of the system as it is now being constructed. These drawings differ somewhat from previous presentations; but, with construction in progress on all major components, is likely to remain relatively accurate. The system has been sized such that it will load without disassembly through the side door of a Boeing 747 air freighter, thus permitting movement between continents on commercial airlines. The system is designed to be able to operate without site preparation on any relatively level, firm surface. Mount orientation will be determined by means of an electronic level and an azimuth marker, or by the observation of stellar sources. We rely on an automatic, internal calibration method not requiring outside targets. Sufficient computing capability is carried with the station such that daily communication with the home facility is not required. Among the other innovations being tested by this prototype is a mode-locked laser which transmits several narrow pulses on each shot, so as to save power and complexity of system. At present, the items pacing the construction of this unit include the delivery of the van, which will hold the major equipment, and the accurate telescope gearing. We expect the unit to be assembled in February of 1979, after which an extensive program of testing will begin.

Program Expectations

Although the University of Texas transportable station is, in many respects, a prototype, it is expected to be able to play a significant role in crustal dynamics studies. Modelling studies by Bender and Goad [1978] indicate that a site occupation of less than a week should be sufficient to accurately determine any location relative to other Lageos observatories. Even presuming longer stays during an initial campaign and moderate weather statistics, it is obvious that large numbers of sites are possible, provided that the logistics of each move are kept reasonable. Bender and Goad claim that the accuracy of each determination should be on the order of 4-5 cm, presuming reasonable monitoring by other stations and will improve measurably over the next few years as additional studies are completed on the satellite's orbit. Scaler baselines to specific nearby fixed laser stations also observing the same target may be somewhat better determined. It is expected that the sites would be revisited on a bi-annual schedule so as to maintain their status as fundamental benchmarks. If some of these sites are shared with systems sensitive to "inertial" reference frames, such as lunar ranging or VLBI, one could monitor long-term crustal motions in a fixed coordinate system.

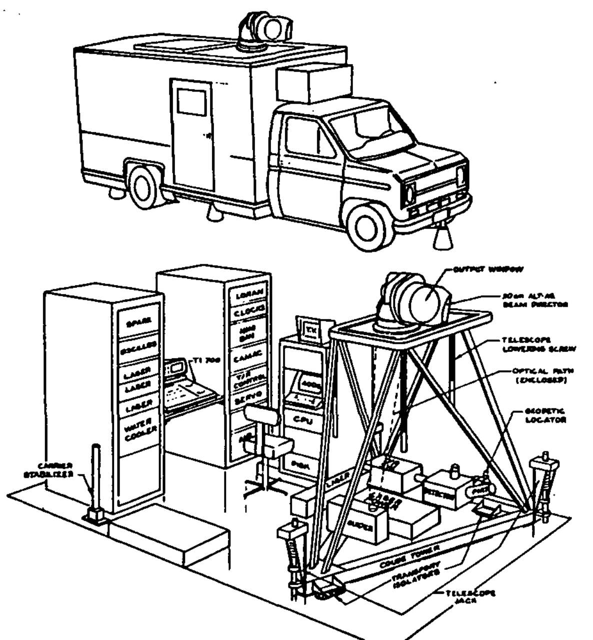

Fig. 1. An artist's representation of the exterior and interior of the highly transportable laser ranging system.

Since the use of this station, even if only partially successful, represents a large increment in the global capability for establishing high accuracy benchmarks, there are a large number of potential programs which could be chosen. It is hoped that conferences such as GEOP can be instrumental in setting priorities in this area. Since this station will enjoy a temporary advantage in mobility, it is the personal opinion of this author that it should concentrate on those relatively uncharted plate boundaries which have reasonably suitable weather statistics. (Poor weather areas, like the Aleutians, would, by necessity, need to be done by radio techniques.) Programs along the poorly known fault zones could not only take advantage of the station's relative transportability, but also its ability to monitor the character of the strain field around each benchmark by using the system as a very powerful, pulsed geodimeter. In the latter application, single, disposable one-inch retroreflectors would be permanently placed on distant mountain tops around each occupied benchmark. These lines would be monitored by the so-called "ratio" method, first conceived by Robertson [1972], and could greatly increase the impact of this station at remote sites. Provided that the ratio method proves accurate to a few parts in 10^7, as has been indicated by preliminary NGS work around McDonald Observatory [Carter, 1978], and to the extent that this method would be applicable over the much longer lines which would be accessible by this pulsed system, this added facility could prove very useful in "uncharted" areas, especially since the horizontal monitoring could be done at very little additional cost.

Figure 2 shows a hypothetical program which could be conducted with a combination of these capabilities in the complex Central American re-

TABLE 2. Design Parameters For The Highly Transportable Lageos Ranging Station

Aperture	0.30 m (common trans./receive apert.)
Energy per Pulse	3.5 mj @ 5322 Å
Firing Rate	10 PPS nominal
Beam Divergence	20 arc sec (nominal)
Pulse Width	100 psec
Nominal Signal Strength	0.06 photoelectrons/shot
Single Shot Uncertainty	$\pm$ 7 cms (RMS)
Size Critical Pkg.	Two single chassis vehicles, 2.4 m (width) x 2.97 (height) x 6.5 (length)

gion, where the North American, Caribbean and Cocos plates intersect. This example is shown to indicate the scale at which the two methods might be applied and to show how the powerful combination of capabilities could monitor crustal strain in logistically difficult areas. The eight occupied sites are located near paved roads at selected plate locations. The eight would find the overall character of the motions, act as base sites for horizontal ranging into the inaccessible regions, and set scale for the ratioed lines. All of the horizontal lines outside of Guatemala terminate near unimproved roads for the one-time retro deployment, while inside Guatemala the proximity and inaccessibility would warrant a short helicopter campaign. Needless to say, however, the many possible facets of this system warrant a great deal of testing before we dare plan for any ambitious program. Specific recommendations must await a later time when the results of preliminary tests of the station capability are available.

Future Expectations

The design of the TLRS has been extremely cautious, permitting the staff to bring into operation as few new concepts as possible during the early operations. A number of improvements which might be added to this or subsequent stations with little effort are: 1) two color ranging so as to permit some additional atmospheric information; 2) the addition of advanced detectors which have both higher quantum efficiency as well as lower pulse jitter; 3) the addition of a computer-readable TV guide system so as to permit fully automatic mount modelling; and, 4) the addition of software to permit on-site orbital updates so that the system may, in fact, bootstrap its orbital predictions without requiring frequent updates from larger analysis centers. In addition, we certainly expect much effort at other institutions, particularly Goddard Space Flight Center, to optimize the packaging for such systems, and to improve the ranging accuracy [McGunigal, 1978].

Recently, Wilson and several other authors [1978] attempted to determine the limitations on the compaction of portable laser systems. The major thrust of these discussions was that the higher cross sections of the lower satellite targets, such as Starlette, makes it possible to

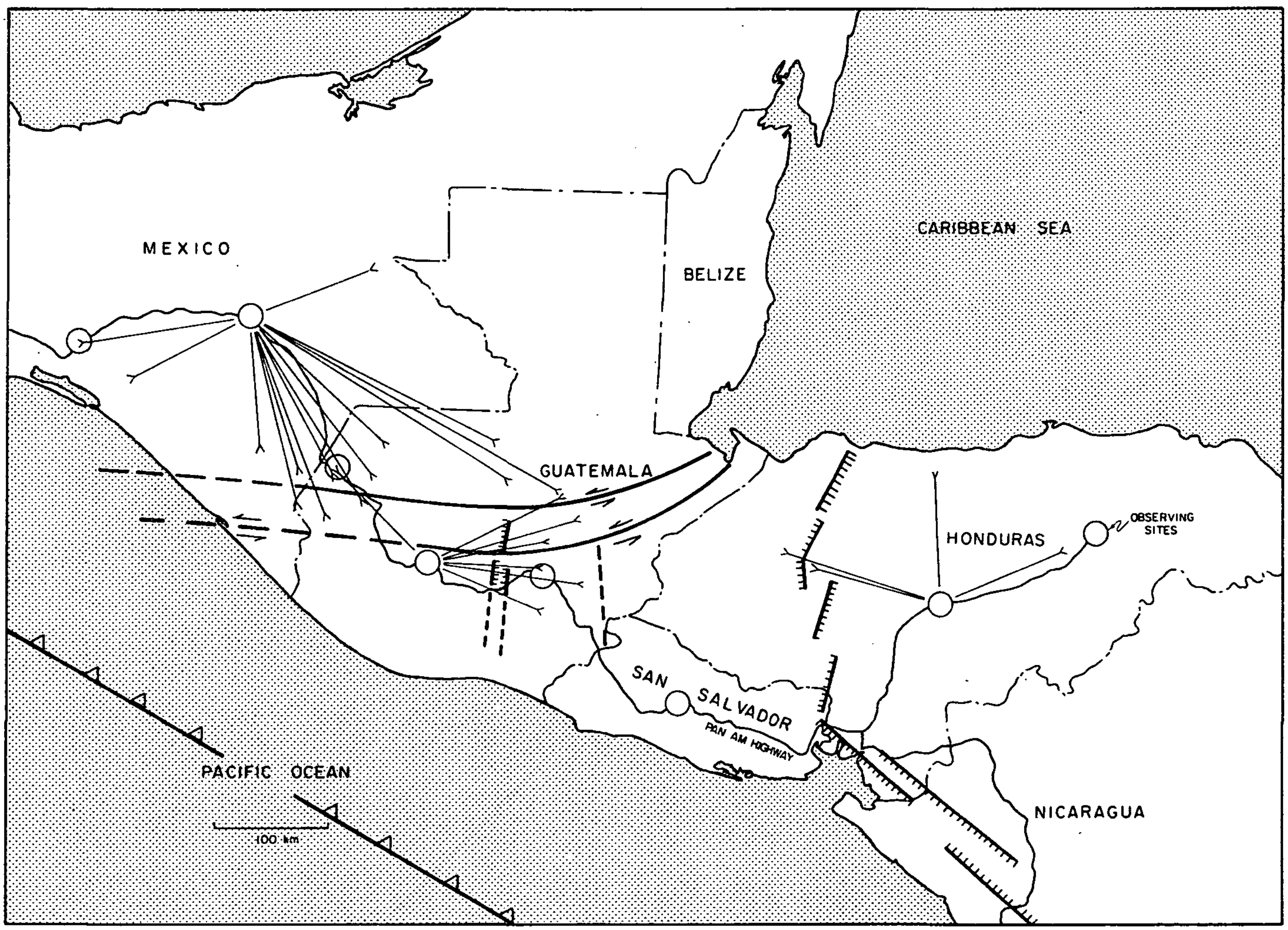

Fig. 2. A possible TLRS campaign for regional strain analysis illustrating the station's ability to use both satellite observing and long baseline terrestrial ranging in a combined program.

package a geodetic laser system small enough to be transported by a single jeeplike vehicle. Since it uses lower satellites the smaller system would only be practical for measuring the shorter (<1000 Km) baselines. However, the system could, of course, also act as a long baseline horizontal geodimeter and might reduce the cost of large operational tracking deployments such as required for the Seasat instrument. In those areas where the horizontal "ratio" method permits the measurement of a large number of unoccupied baselines for little cost, it would be unnecessary to use more highly mobile systems to permit the occupied measurement of these terrestrial lines, particularly if the smaller systems were unable to track the Lageos target which would provide the best overall control. On the other hand, there are many areas where horizontal work does not appear practical -- many which would be more easily studied by a system significantly more mobile than the TLRS. Thus, the success or failure of the concepts to be tested by the TLRS will certainly have a marked impression in the development and possible deployment of more advanced laser ground systems. Most certainly, the degree of success by totally different techniques will also play a major role in these developments.

In summary, it should be clear that the wide application of laser satellite ranging to the field of crustal dynamics is promising, but untried. Systems development in this area is, and will remain for at least a year or two, in a high state of flux. It seems likely that this method can be an important contributor to many problems in this area, but the exact nature which this interaction will take is not clear at this time. The recent technological advances have opened up new avenues which we have only recently started to explore. It is clear, furthermore, that a large number of other possibilities including space borne lasers [Smith, 1978], extra-galactic radio receivers [MacDoran, 1978], and satellite based radio systems [Counselman and Shapiro, 1978] are also available. If we are to properly adjust to the discoveries of the next one to two years with intelligent approaches to the acquisition of meaningful geophysical data, we must, for the moment, retain a flexible, responsive approach, as free from inertia as possible.

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