The Relationship of Laser Ranging to other Space Techniques

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Each of the different space geodetic technologies has certain strong properties, as well as capabilities which overlap with the others at varying levels of viability. GPS networks clearly exceed that of the other methods in local and regional station positioning detail, VLBI uniquely defines accurate Earth orientation in an inertial frame, and the DORIS and PRARE systems provide wide coverage for regular and reliable orbit definition. The purity of the range measurements from the SLR/LLR instruments allows accurate definition of Earth scale, and we must meet the challenge of harnessing the strong properties of each space technique to produce results which exceed the sum of the contributing parts. Many of the technologies have progressed to the stage at which they provide fertile opportunities for independent interpretation of Earth motions: station velocity vectors, geocenter variation parameters, and Earth orientation series. However, in order to directly combine the results of the alternative methods it is first necessary to establish compatibility between reference frames. Broad measures of comparison and compatibility include the offset or slope of Earth polar motion series, the positions and speeds of rotation poles for continental networks, an index of horizontal motion defined through the tectonic time scale, and assessments of Earth scale measured through the universal gravitational constant. The motions of individual stations and more localized networks can be usefully monitored and the measurements combined with less concern for the global frame. Models of Earth structure can be improved through tidal and loading observations, and evidence for nonsteady horizontal or vertical motion can be found in well-instrumented regions, with resulting implications for seismic risk. The International Laser Ranging Service will provide the structure to discipline the SLR/LLR analysis and will also coordinate with the services representing the other space techniques. Our discussion will address the need for these groups to agree on an adopted reference system based on a few fiducial stations in order to optimize the combination of observations from a variety of sources.

Introduction

Although the title of this talk is “The Relationship of Laser Ranging to other Space Techniques”, the goal of our effort is “The Combination of Laser Ranging with other Techniques”. In order to produce results which exceed the sum of the contributing parts we must first establish compatibility between reference frames in position and velocity. This will help us to monitor Earth motions of interest for broad geophysical interpretation. For example, geocenter variation has implications for Earth/ocean/climate dynamics, Earth orientation series for Earth/ocean/climate dynamics, and station velocity fields for tectonics and reference frame improvement. The different properties of the space geodetic technologies suggest that GPS is most useful for local and regional station positioning, VLBI to define Earth orientation in an inertial system, DORIS and PRARE for their wide coverage for orbit determination, and SLR for Earth scale definition. In order to meet the goal of establishing compatibility between reference frames in position and velocity, we must define the domains of stable velocity fields. We must then consider measurement differences within technologies, between technologies, and with the geophysical model (NUVEL-1A).The velocity field properties which we can monitor include the positions and speeds of rotation poles for continental networks, and the index of horizontal motion defining the tectonic time scale.

The space geodetic networks which have been established to maintain the terrestrial and celestial reference frame are crucial to research in global geodynamics. The Fiducial Laboratories for an International Natural Science Network (FLINN) are a mix of technologies whose capabilities can be balanced with careful consideration of the strengths and weaknesses of each system. The stations have been established to detect and monitor tectonic plate motion, crustal deformation, Earth rotation and polar motion. Post-glacial rebound and land subsidence are also important applications of the network, which can support ground-based geodetic surveys, and atmospheric and ionospheric studies.

SLR, VLBI and GPS systems have been shown to agree at the level of a few centimeters in position and a few mm./year in horizontal velocity if a transformation is applied to align and scale the reference systems (Ray et al., 1991). This suggests that a combined solution of all space geodetic measurement types would provide the best reference frame for rigorous kinematics. In Smith et al., 1995, velocity fields defined by the GPS systems were combined to extend global coverage from long histories of VLBI and SLR observations. In recent years the SLR network has grown more slowly than the burgeoning GPS network and the regularly deployed DORIS instruments. The addition of the stations of the Very Long Baseline Array to the VLBI network has extended the scope of the application of quasar observations. The solution presented here is a refinement of that given by Smith et al. 1996a, in which a preliminary DORIS velocity model was first incorporated.

Satellite Laser Ranging Systems

Laser systems are among the most accurate means of satellite tracking and the precision of existing SLR measurements is better than a centimeter for the latest instruments. The process of forming laser normal points, a type of compressed data, eliminates spurious observational noise in the current measurements and can reduce the precision as measured by the noise level to a few millimeters. Systematic errors which are not eliminated in the normal point computation process must be carefully calibrated. Electronic errors, non-linearities in the tracking electronics as a function of signal strength, and errors in the distance to the calibration targets can now be reduced to give ranging systems of sub-centimeter absolute accuracy (Degnan, 1993) with further improvements in tracking hardware in progress.

Very Long Baseline Interferometry

The primary VLBI observable for geodetic studies is described by Ma (1976) as the measured time interval between the arrival of a radio signal at one VLBI antenna and its arrival at another VLBI antenna. This interval is the delay and its time derivative is the delay rate. The delay is found by cross-correlating the two signals and determining the point of maximum correlation. From a sufficient set of these data as a function of time the positions of the antennae and the observed radio sources can be determined. The time tag of the signal is recorded in terms of a local clock, so variations in the local clock's behavior must be modeled. As the VLBI antennae rotate with respect to each other (from Earth rotation) the projected baseline in the direction of the source changes with time, introducing the delay rate observable. The signals recorded by each moving antenna are Doppler shifted, and these effects must be modeled to properly determine the delay observable.

The Global Positioning System

The use of signals transmitted by the GPS constellation of high Earth-orbiting satellites is the technique of choice for regional surveys, due to the precision of its phase measurements and the low instrument costs. The large and expanding global network of stations enables the reference frame errors to be limited to a few parts per billion, which leads to centimeter accuracies over inter-continental distances and much higher accuracy in regional networks. The primary sources of GPS error are signal multipathing, atmospheric modelling error and uncertainty in the definition of the antenna phase center, all of which affect the system accuracy at the millimeter level

Doppler Orbitography and Radio Positioning Integrated by Satellite

DORIS provides measurement by a space-borne receiver of the Doppler shift of radio signals transmitted from a ground network of a large number of orbit-devoted beacons (Labrune et al., 1986). The DORIS system has several elements: a space segment, ground based beacons, and a control center. The space segment consists of a range rate measurement receiver with an ultrastable temperature controlled crystal oscillator, an omnidirectional antenna, and a data recording and transmitting facility. The ground-based beacons are designed to operate in a controlled environment having two transmitters and an ultrastable oscillator all linked with an antenna and three meteorological sensors. The beacons and space-borne receiver operate continuously and the data are stored in the telemetry memory of the space segment for transmission to the control center in Toulouse, France. Commands are also sent via the space segment, and there is a remote loading link providing instructions for the beacons to process.

Geomagnetic Time Scale Revisions

SLR-defined global and regional kinematic velocity models have suggested that the relative velocities of stations on the stable interiors of tectonic plates are about five percent slower than those expected from the NUVEL-1 geophysical model (Smith et al., 1990). This observation supports the recent revision of the Potassium/Argon-defined paleomagnetic time scale based on astro-geochronology. On the other hand VLBI analyses do not support the SLR model's agreement with NUVEL-1A (Demets et al., 1994) which is based on the revised time scale. For example, Heki (1996) considers it premature to adopt NUVEL-1A for the standard terrestrial system without verifying it in the geodetic time window. The differences between the SLR and VLBI results could be caused by the choice of stations to represent stable plate interiors, or alternatively, the assumption of uniform motion over the differing observation spans for the chosen stations could be questioned. The inclusion of contemporary measurements in geophysical models will be considerably simplified when the causes of these disagreements between space technologies have been identified.

Error Estimates for Motion Models

Argus and Gordon (1996) have established that the geodetic VLBI results of Ma et al (1994) do not demonstrate significant velocities between sites in the stable interior of a plate, and bound the speeds of the best intraplate sites at 2 mm/year. They do not question the assumption of plate rigidity which allows the theory of plate tectonics to make precise predictions, and find that the accuracy of the space geodetic measurements is better than the marine geophysical data used to estimate plate velocities over geological time. The error budget associated with the VLBI velocity solution was suspected to be too small, and this could be due to a faulty assumption of uniform motion during the data measurement interval, or to the influence of unmodeled error, in particular in the estimates of delay due to water vapor in the troposphere.

The errors which restrict the interpretation of geodetic results from alternative space techniques are caused by a variety of modeling problems, and the satellite-based methods of SLR, GPS, and DORIS all require accurate orbits to produce full precision. The velocity models developed from SLR measurements have until recently used only LAGEOS I observations in the kinematic solution. Observations from the other retro-reflector carrying satellites have contributed to improved gravity field definition but until recently the stability of the LAGEOS I orbit and the concentration of tracking observations from a network of accurate stations could not be matched by any other satellite target. In October 1992, LAGEOS II was launched and presented an independent method for determining Earth parameters for orientation, scale and surface deformation. The time span of LAGEOS II measurements now extends to almost five years and this is long enough to provide reliable estimates of motion at the stronger stations in the Global Laser Network. Smith et al., 1996b show that the difference in the results from the two satellites provides an objective estimate of any geodetic parameter which is affected by orbit modeling error, and the combination solution incorporating data from the two satellites provides a significant improvement to that from a single satellite.

Analysis Method

Robbins et al. (1993) describe a technique to combine horizontal tectonic velocities from different technologies within a uniquely defined kinematic reference frame. It allows the combination to be free of aliasing from vertical velocities and does not need any local survey information to connect the different technologies at sites with measurements from multiple technologies. The method has been extended in our analysis to use velocity information from other sources, as the computation basis lies in the geodesic distances and rates. Estimates of tectonic motion derived from combining different technologies will reduce the overall systematic errors as each technology has different, and largely independent, error sources.

Attempts to mix SLR, VLBI and GPS information at the velocity field level have revealed discrepancies which could have several causes. Torrence et al., 1994 combined relative geodesic rate information from independent SLR, VLBI and GPS solutions to yield estimates of the motion of all of the sites within a single reference frame. When the derived relative rates were compared to the relative rates from geological models some differences among the technologies were seen. Incompatible definitions of the fixed reference stations for each technique, inequitable data intervals for stations experiencing non-uniform motion, as well as errors in station position and velocity due to errors in the individual instruments would all distort the mixed solution.

Rotation Poles from Space Geodesy

The global site coverage realized by combining space technologies has been exploited by computing poles of rotation based on the site motions from a solution combining SLR, VLBI, GPS and DORIS velocities. The velocity models were derived from the submissions to the IERS

1996 Annual Report GSFC 96 L 01 (SLR), GSFC 96 R 01 (VLBI), JPL 96 P 02 (GPS), supplemented by the DORIS solution GRGS 97 D 02. The choice of stations to represent the motion at stable locations occupied by more than one technique was based on the uncertainty assigned to the velocity by the contributing analysis group. The combination solution comprised of measurements from 19 SLR stations, 47 VLBI stations, 20 GPS stations and 17 DORIS stations. The North American plate was represented by 36 velocity measurements, Eurasia by 30, Africa 7, Australia 6, Pacific 8, Nazca 2, South America 4 and Antarctica 10.

The relative poles of rotation determined from the space geodesy combination solution for plates, which have a common boundary, are listed in Table 1. The table also provides the differences between the estimated model parameters and the rotation poles given by DeMets et al. 1994 for NUVEL-1A. The agreement between the results from space geodesy and those from the geophysical model is generally within the uncertainty of the combination solution, with the exception of the motions associated with the Nazca plate, which shows a significantly slower angular velocity than that given by NUVEl-1A. The Easter Island station strongly influences the definition of Nazca plate motion, as well as the speed correlation comparison with NUVEL-1A, as its motion with respect to neighboring stations on the Pacific plate is the largest of all plate pairs. The motion of the Easter island station is slower than that given by NUVEL-1A for each independent measurement by SLR, GPS and DORIS. We must therefore question the validity of the choice of this station as representative of a stable plate interior, or alternatively consider that the NUVEL-1A model for the behavior of the Nazca Plate should be re-addressed.

Comparison of Rotation Pole Fields

The determination of relative motions between six plates can be established with enough accuracy to discriminate results between the different space techniques. The plates are those of North America, Europe, Pacific, Africa, Australia and Nazca. If we consider the relative rotation poles with respect to the North American plate, significant differences are found with NUVEL-1A at the Nazca plate, with a discrepancy of 22 degrees in latitude, at the European plate, with 7 degrees in longitude, and at the Australian plate, with 3 degrees in longitude.

Table 2 shows the pole rotation values for the European plate relative to the North American plate, together with the formal error of the pole position and rotation rate, and the differences with NUVEL-1A pole values. It is noted that the resolution of the combination solution is about the same as NUVEL-1A, and there are significant differences in pole positions of the combination solution compared with NUVEL-1A. The limited consensus among techniques suggests that the alignment of the reference frames for the individual methods is a necessary requirement for combining the results.

Time Scale Ratio Comparisons

In Figure 1, the correlation between the geophysical NUVEL-1A and the SLR solution is seen to agree with the geophysical model within its error estimate. Table 3 gives the equivalent correlation estimates for the solutions from the other three space technologies, and also from the same selection of stations on stable plate interiors in the ITRF96 system (Sillard et al., 1998). Bearing in mind that NUVEL-1 was faster than NUVEL-1A, we find that, in the independent solutions, VLBI-determined rates are faster than those from SLR as expected, and that VLBI rates match NUVEL-1 and SLR rates match NUVEL-1A. However, when we consider the results from ITRF96, it appears that although the VLBI-determined rates are still faster than SLR, in this case VLBI rates match NUVEL-1A, and SLR rates are even slower than NUVEL1A. Perhaps there is an indication here that Heki's misgivings that the NUVEL-1A model's adoption in the reference system definition should be carefully considered.

Differences between fields that may lead to such discrepancies include the inadequate definition of stable plate interiors, intrinsic measurement differences, intraplate tectonics and unsteady motion at certain locations. In order to define a reference frame for the optimal combination of technologies, we need agreement at a few fiducial stations (e.g. Greenbelt and Hawaii). We must then adopt a model of stable blocks, which are regionally and temporally homogeneous within blocks, and then we can be assured that the site kinematics resulting from a combined solution will provide a firm framework for a rigorous interpretation of current and future regional observing campaigns.

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Plate pair	latitude	long.	rate	Errors			Diff.	with	NUVEL
	deg N	deg E	deg/ba	deg N	deg E	deg/ba	deg N	deg E	deg/ba
Euras-N.Ame	69	132	220	2	5	10	7	-4	6
Africa-N.Ame	83	150	224	6	54	25	4	112	-14
Pacific-N.Ame	-51	103	771	1	2	12	-3	1	22
S.Ame-N.Ame	-10	130	184	5	3	52	5	8	38
Africa-Eurasia	16	-55	58	23	32	19	-5	-35	-65
Austr-Eurasia	12	45	657	1	1	13	-3	5	-31
Austr-Africa	10	49	666	1	2	29	-2	-1	34
S.Ame-Africa	-58	128	301	9	11	35	3	-13	-9
Antar-Africa	-29	138	100	16	20	33	-24	-3	-27
Pacific-Austr	-61	-175	1079	1	2	13	-2	2	5
Antar-Austr	-14	-137	681	2	1	16	-2	4	32
Nazca-Pacific	60	-86	1252	3	3	33	4	3	-108
Antar-Pacific	62	-86	873	1	3	31	-2	-3	3
S.Ame-Nazca	-61	98	595	8	8	47	-6	12	-130
Antar-Nazca	-56	93	381	12	6	46	-17	9	-140
Antar-S.Ame	70	-64	220	14	12	32	-16	-24	-43

Table1: Relative Plate Rotation Poles from Space Geodesy compared to NUVEL-1A

CASE	latitude	longitude	rate	pole	position	rotation	rate
				sigma	delta	sigma	delta
	(degrees)	(degrees)	(deg/ba)	(deg.)	(deg)	(deg./ba)	(deg/ba)
NUVEL-1A	51	-112	234	5	0	10	0
COMB	54	-105	239	5	8	9	5
SLR	53	-107	237	10	6	14	2
VLBI	51	-112	233	12	<1	20	-1
GPS	52	-104	236	6	8	10	2
DORIS	43	-100	267	25	13	47	23

Table 2: European Plate Rotation Poles from Four Technologies compared with NUVEL-1A.

	Independent	Fields	ITRF96	
	ratio	error	ratio	error
SLR	99%	2%	96%	1%
VLBI	105	1	100	1
GPS	94	1	97	.5
DORIS	81	3	98	2

Table 3: Time Scale Ratios with Nuvel-1A from Four Technologies and Two Sources.

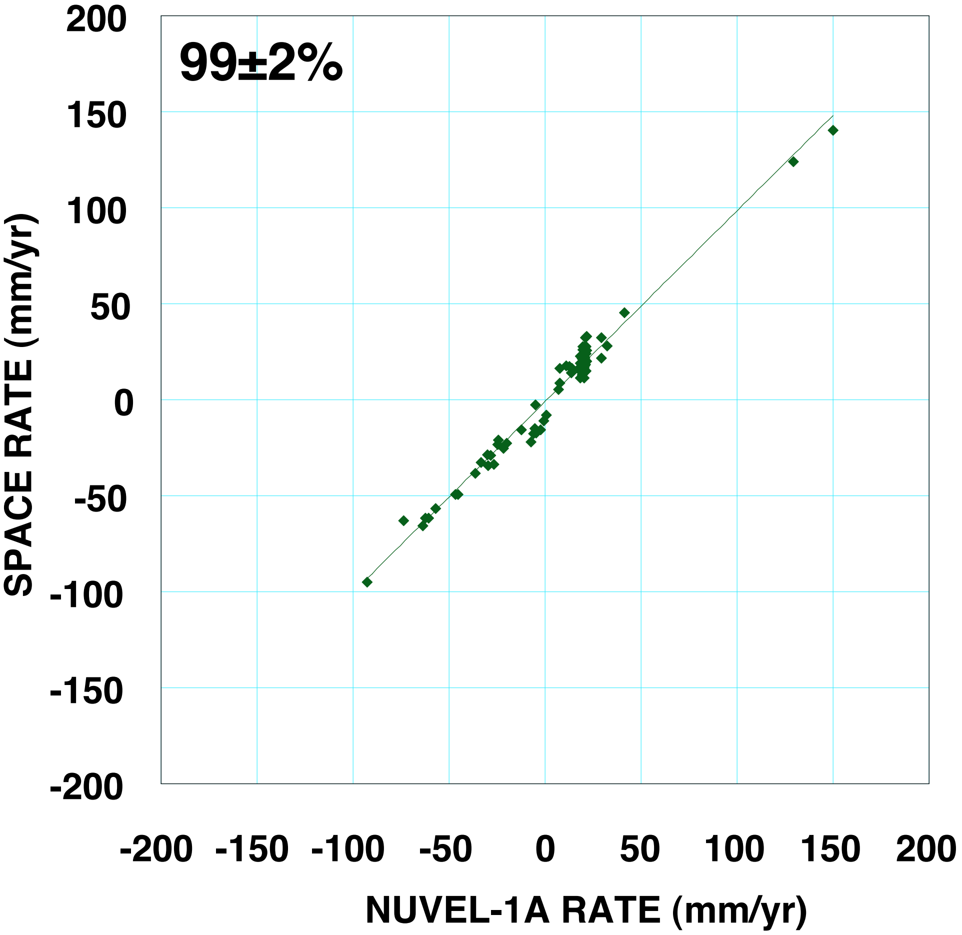

Figure 1: The correlation between the geophysical NUVEL-1A and the SLR-determined velocity model