Realization of the EGM96 Reference Frame

Mark Torrence
Raytheon ITSS
7701 Greenblelt Road
Greenbelt, MD 20770 USA

for the GSFC EGM96 analysis group

Abstract

The definition of the reference frame for EGM96 Earth gravity model is key to the development of the model. Satellite laser ranging (SLR) information is the fundamental component upon which the reference frame is realized. The realization process involved resolving an epoch difference between two SLR frames. Multiple tracking technologies were included in the realization through the utilization of local survey information, satellite dyanmics, and lastly, through simultaneous Earth orientation parameter (EOP) adjustment. The origin of the EGM96 frame realization agrees with the ITRF94 realization to about 1 cm and about 1.5 ± 0.4 ppb in scale.

Introduction

Following a brief background discussion of the EGM96 Earth geopotential solution, this paper shows the satellites used in the EGM96 solution [*Lemoine*, 1998]. Next is a discussion of the SLR sites that are used to define the fundamental reference frame definition for the EGM96 model and the methodology that was used to combine information from SLR sites that were in frames defined at different epochs. To complete the reference frame definition, the information from non-SLR technologies must be combined with the SLR information. For most of the the other tracking technologies, there were representative sites the were collocated within tens of meters of an SLR site. These sites will be briefly discussed. Then the paper will show a comparison of the recovered site positions and Earth orientation parameters (EOP) with IERS ITRF 94 frame and 90C04 EOP time series.

Background

The description of a gravitational potential model with a spherical harmonic series involves the geodetic coordinates at the point of computation. This requires the reference frames used in the development of the model and at the time of evaluation be consistent. The Earth Gravity Model EGM96 is a spherical harmonic geopotential model to degree 360 produced jointly by NASA, National Imagery and Mapping Agency (NIMA, formerly the DMA), and the Ohio State University.

Table 1. Summary of the EGM96 the 70x70 combination solution parameterization.

parameter	number
Geopotential to degree and order 70	5035
Tidal parameters	316
Station positions	1986
Earth orientation parameters	5079
TOPEX/Poseidon related biases	172
GEOSAT sea surface topography to 20x20	695
TOPEX/ERS-1 sea surface topography to 20x20	695

The model is a composite solution formed from an optimal combination of a complete degree and order 70 solution with a degree 360 model. The first 70x70 component is a combination solution derived from satellite laser ranging, DORIS, doppler, GPS, and satellite to satellite tracking data combined with surface gravity, and satellite altimeter data fromGEOSAT, ERS1, TOPEX. The degree 70 through 360 portion of EGM96 is derived from surface gravity data obtained from many worldwide sources, and altimeter-derived anomalies from both the GEOSAT GM period, and ERS-1. Table 1. summarizes the 70x70 combination solution type and number of parameters.

Satellites used in the EGM96 geopotential solution.

Tracking data to 41 satellites were used in the EGM96 gravity model solution, indcluding 20 optically tracked, and 18 SLR satellites. These satellites were choosen to be from a wide range altitude and inclination to sample the geopotential orbital perturbations over a variety of frequencies. Table 2 lists the satellites, orbits, and data.

Definition of the SLR Earth fixed reference frame.

The fundamental Earth fixed reference frame for the EGM96 gravity model solution is defined by fixing the latitude and longitude of the Greenbelt, Maryland, SLR site, and the latitude of the Haleakela, Hawaii, site at the position used in JGM–2 [*Nerem et al.,* 1994]. In the formation of the EGM96 solution, SLR information from two epoch had to be combined. The SLR data from 1993 through 1995 were analyzed in a frame that was not consistent with that of the earlier data. The frame used for the 1993 to 1995 SLR data was the TOPEX/Poseidon (T/P) precise orbit determination (POD) frame (CSR93L01 [*Boucher et al*., 1994]). This frame was not consistent in epoch date, position, or in time evolution with the JGM-2 frame. The T/P frame had an epoch of January 1, 1988, and a tectonic velocity model from CSR93L01, whereas the other JGM–2 SLR data were in a frame that had an epoch of July 1, 1987, and used the NUVEL NNR–1 tectonic motion model [*DeMets et al.,* 1990] for all sites. To combine the CSR93L01 normal equation with those from the JGM–2 frame, the *a priori* positions and tectonic velocities for the CSR93L01 frame were transformed to that of the JGM–2 frame with the following algorithm:

Given the two frames JGM–2 ("*s*") and CSR93L01 ("*c*") with different epochs, epoch positions, and velocities, define the following:

$t_s^0 \neq t_c^0$	epoch
$\vec{X}_s(t_c^0) \neq \vec{X}_c(t_c^0)$	epoch station position
$\dot{\vec{X}}_s \neq \dot{\vec{X}}_c$	tectonic station velocity

then the station position at time t for the s frame is

$$\vec{X}_s(t) = \vec{X}_s(t_s^0) + (t - t_s^0)\dot{\vec{X}}_s$$

and for the c frame,

$$\vec{X}_c(t) = \vec{X}_c(t_c^0) + (t - t_c^0)\dot{\vec{X}}_c$$

Step 1. Transform the "c" frame to the "s" frame by applying the difference between the two different *a priori* values, using the SOLVE program [*Ullman*, 1992], to change the "right-hand side" of the normal equations set "c" *a priori* values to:

$$\vec{X}_s(t_c^0),\ \dot{\vec{X}}_s$$

This step changed the epoch position of the frame but not the epoch time.

Step 2. Use the normal equations created in the first step in the SOLVE program for the EGM96 solution, but:

a. The right-hand side of the normal equations from step 1 was not allowed to change to compensate for different *a priori* values of station and tectonic velocity.
b. The unchanged station normal equations from the preceding step were combined with the "s" frame normals.
c. The unchanged station tectonic velocity normal equations from step a. above were removed; i.e., the site velocity normals were not combined with the "s" frame site velocity normals.
d. The SLR positions were adjusted; the SLR site velocity parameters were not adjusted.

The result was SLR station positions in EGM96 at epoch with tectonic velocity.

Table 2. Satellites used in the EGM96 Earth geopotential solution.

Satellite	a (km)	e	incl	Data type	num obs	date, T/P Cycles
5BN–2	7462	.0060	90.0	optical	818	1960's
Ajisai	7870	.0011	50.0	**SLR**	256307	1986–1987
					53698	1993
Anna–1B	7501	.0080	50.1	optical	4043	1960's
ATS–6	41867	.0010	0.9	SST	cf GEOS–3 ATS	1960's
BE–B	7354	.0140	79.7	optical	1734	1960's
BE–C	7507	.0252	41.2	optical	7505	1960's
				SLR	64786	1979–1982
				Doppler	14106	1965
Courier–1B	7469	.0160	28.3	optical	2470	1960's
DI–C	7341	.0526	40.0	optical	2692	1960's
				SLR	7680	1971
				Doppler	24537	1967
DI–D	7622	.0842	39.5	optical	6032	1960's
				SLR	12160	1971
				Doppler	33483	1967
Echo–1RB	7966	.0120	47.2	optical	4468	1960's
EP/EUVE	6895	.0013	28.5	TDRSS	151426	1994
				GPS	169596	1992–1993
ERS–1	7154	.0022	98.5	**SLR**	37137	1992–1993
ETALON–1	25501	.0007	64.9	**SLR**	82918	1991
GEOSAT	7169	.0010	108.0	Doppler	555663	Nov., Dec. 1986 Jan. 1987
GEOS–1	8075	.0710	59.3	optical	60737	1960's
				SLR	114261	
GEOS–2	7711	.0310	105.8	optical	61431	1960's
				SLR	18641	1976-1977
GEOS–3	7226	.0010	114.9	SST ATS–6	27400	1975–1979
				SLR	16935	
				SLR	76662	1980
GFZ–1	6728	.0013	51.7	**SLR**	5548	1995
GPS/MET	7128	.0011	70.0	GPS	1046676	1995
Hilat	7178	.0045	82.0	Doppler	24858	1993
Injun–1	7316	.0080	66.8	optical	3264	1960's
LAGEOS	12273	.0048	109.9	**SLR**	650870	1980–1992
					86897	1993–1994
LAGEOS–2	12163	.0132	52.0	**SLR**	93194	1993–1994
Midas–4	9995	.0110	95.8	optical	31749	1960's
NOVA–1	7559	.0010	90.0	Doppler	71767	1984
OGO–2	7341	.0750	87.4	optical	1204	1960's
OSCAR–14	7448	.0030	89.2	Doppler	62227	1980
OSCAR–7	7440	.0020	89.2	optical	1851	1960's
OVI–2	8317	.0180	144.3	optical	962	1960's
Peole	7006	.0160	15.0	**SLR**	4315	1971
RADCAL	7193	.0105	89.5	Doppler	83930	1994
SEASAT	7171	.0010	108.0	**SLR**	13145	1978
				Doppler	123516	
Secor–5	8151	.0790	69.2	optical	721	1960's
SPOT–2	7208	.0020	98.7	DORIS	420458	1990–1992
Starlette	7331	.0211	49.8	**SLR**	184740	1984–1986
					54766	1993–1994
Stella	7173	.0013	98.6	**SLR**	21366	1993–1994
Telstar–1	9669	.2430	44.8	optical	3946	1960's
TOPEX/ Poseidon	7716	.0004	66.0	**SLR**	334031	cycles 11–84
				DORIS	4191617	cycles 11–84
				GPS	644026	10,14,15,17,18,19
Transit–4A	7322	.0080	66.8	optical	3831	1960's
Vanguard–2	8298	.1640	32.9	optical	1290	1960's
Vanguard–2RB	8496	.1830	32.9	optical	681	1960's

After the transformation of the 1993 SLR epoch frame to the 1987 epoch, the combination of the information from all the SLR satellites forced the reference frames for all of the SLR satellites to be identical.

Combination of SLR reference frame with other technologies.

For satellites tracked by non-SLR technologies, the connection to the SLR frame is achieved by one of three methods, in order of preference:

1. By use of local survey information relating the position of an SLR system with that of another technology.
2. Through orbital dynamics of a satellite that was tracked SLR and other technologies.
3. Through the common adjustment of EOP for all of the satellite data and fixing a longitude of a tracking site for that tracking system and satellite.

For the first frame tie method, the local survey distances between the SLR system and the other tracking technologies were used to link the frame from other technologies to the SLR by combining the adjustment of the other technology with the SLR site. Table 3 shows the local survey information that was used to link the Spot–2 DORIS frame with the LAGEOS SLR frame.

Table 3. Spot–2 DORIS and SLR local survey ties used in EGM96.

location	DORIS site	SLR site	ΔX (m)	ΔY (m)	ΔZ (m)
Huahine	4027	7061	–4.6635	8.8673	4.5090
Easter Island	4041	7061	–9.8646	3.5882	–5.1321
Arequipa	4046	7907	4.6540	–1.0900	3.8000

An example of the use of satellite dynamics to perform the frame tie is the simultaneous tracking of T/P by SLR, DORIS, and GPS. The constraint for the SLR position of Greenbelt and Hawaii defined the Earth-fixed frame for T/P. The T/P orbit dynamics, common to both tracking systems, constrained the locations of the T/P DORIS and GPS sites to be consistent with that of the SLR.

Another example of the "dynamics" defined frame tie is the SLR and Doppler tracking of SEASAT. Because the SLR and Doppler data both contributed to the estimation of the SEASAT state, the Doppler and SLR frames are linked together throught the SEASAT dynamics. The SEASAT satellite was key to tie of the modern Doppler tracking frame to the SLR frame, because SEASAT is the only satellite that was tracked by "historic" and "modern" doppler sites. Table 4 shows the local survey tie information used in EGM96 to tie the Doppler sites from SEASAT and GEOSAT together. The Doppler site at Thule, Greenland, brings the modern Doppler information (Hilat and Radcal) into the same frame as GEOSAT, and hence into the SLR frame through the common GEOSAT–SEASAT Doppler sites.

Table 4. SEASAT–GEOSAT Doppler receiver local survey ties used in EGM96.

Location	SEASAT site	GEOSAT site	ΔX (m)	ΔY (m)	ΔZ (m)
Brussels	21	547	34.03	13.66	–23.22
Ottowa	128	564	0.81	–1.25	–0.90
Calgary	30414	563	–0.01	–0.02	0.03

The third method of frame tieing was used for some of the Doppler-tracked satellites, for which there were no tracking systems that were collocated with SLR. Additionally, the systems either were not located at a Doppler site that was used by GEOSAT or SEASAT, or local survey information to link the different Doppler systems was neither available nor reliable. This forced the Doppler to SLR frame tie to be achieved only through the common EOP adjustment. To remove the rank deficiency in the adjustment of EOP, satellite sate, and tracking sites, a longitude of one of the Doppler tracking sites was held fixed. Although the common adjustment of EOP allows the frame tie to the SLR to be achieved, this frame tie weaker than the first two methods. An example of this type of constraint was the fixing of the longitude of Herndon, Virginia, for the Oscar satellite. To summarize the satellite frame connections to the EGM96 frame, Table 5 shows a list of the satellites used in the gravity model solution, the tracking technology used, and the frame tie utilized in the EGM96 estimation.

Table 5. EGM96 satellite and tracking system frame definition.

Satellite	Tracking Type	Frame tie utilized
Ajisai	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
BE–C	Laser Doppler	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI fix λ of APL, MD (41111)
D1–C	Laser Doppler	fixed Earth Orientation fix λ of APL, MD (41112 same site as D1–D)
D1–D	Laser Doppler	fixed Earth Orientation fix λ of APL, MD (41112 same site as D1–C)
ERS–1	Laser	SLR frame same as T/P
ETALON–1	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
EUVE	TDRSS GPS	site positions unadjusted Earth Orientation and site positions unadjusted
GEOS–1	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
GEOS–2	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
GEOS–3	Laser SST Doppler	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI dynamic tie to the SLR
GEOSAT	Doppler	Doppler tracking sites at Brussels, Ottowa, and Calgary tied to SEASAT sites (Table 7.3.5–2)
GFZ–1	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
GPS/MET	GPS	site 55020898 common with T/P and EUVE
HILAT	Doppler	15 Doppler sites in common with GEOSAT
LAGEOS	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
LAGEOS–2	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
NOVA–1	Doppler	fix λ of 3711
optical (all)	optical	optical frame: fixed Earth Orientation
OSCAR–14	Doppler	fix λ of 60407
Peole	Laser Doppler	fixed Earth Orientation
RADCAL	Doppler	Doppler site at Thule, Greenland (35508) tied to the Thule GEOSAT site (557)
SEASAT	Laser Doppler	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI satellite dynamics constrain the Doppler sites to the SLR frame
Spot–2	DORIS	DORIS systems at Easter Island, Huahine, and Arequipa, Peru, are tied to the SLR systems at those sites (Table 7.4.3–3)
Starlette	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
Stella	Laser	SLR frame: fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI
TOPEX/Poseidon	Laser DORIS GPS	SLR frame at epoch 930101, fix ϕ and λ of Greenbelt, MD, and ϕ of Haleakala , HI satellite dynamics tie the T/P DORIS sites to the SLR frame five GPS sites fixed

Comparison of the EGM96 reference frame to ITRF94.

Earth orientation parameter comparison.

EGM96 included solution for EOP. The X and Y position of the pole (in milliarcseconds), the recovered values for A1–UTC in seconds, and the excess length of day in milliseconds, calculated by forming a simple forward difference in the recovered A1–UTC series are shown in Figure 1. The increased density of plotted values in 1993 and 1994 reflects the different EOP adjustment intervals in that time span. EOP were adjusted in 5-day intervals from 1980 through 1993, and 1-day intervals thereafter. These adjustment intervals for EOP were chosen to correspond to the same intervals of the *a priori* series: the IERS 90C04 time series [*IERS*, 1990].

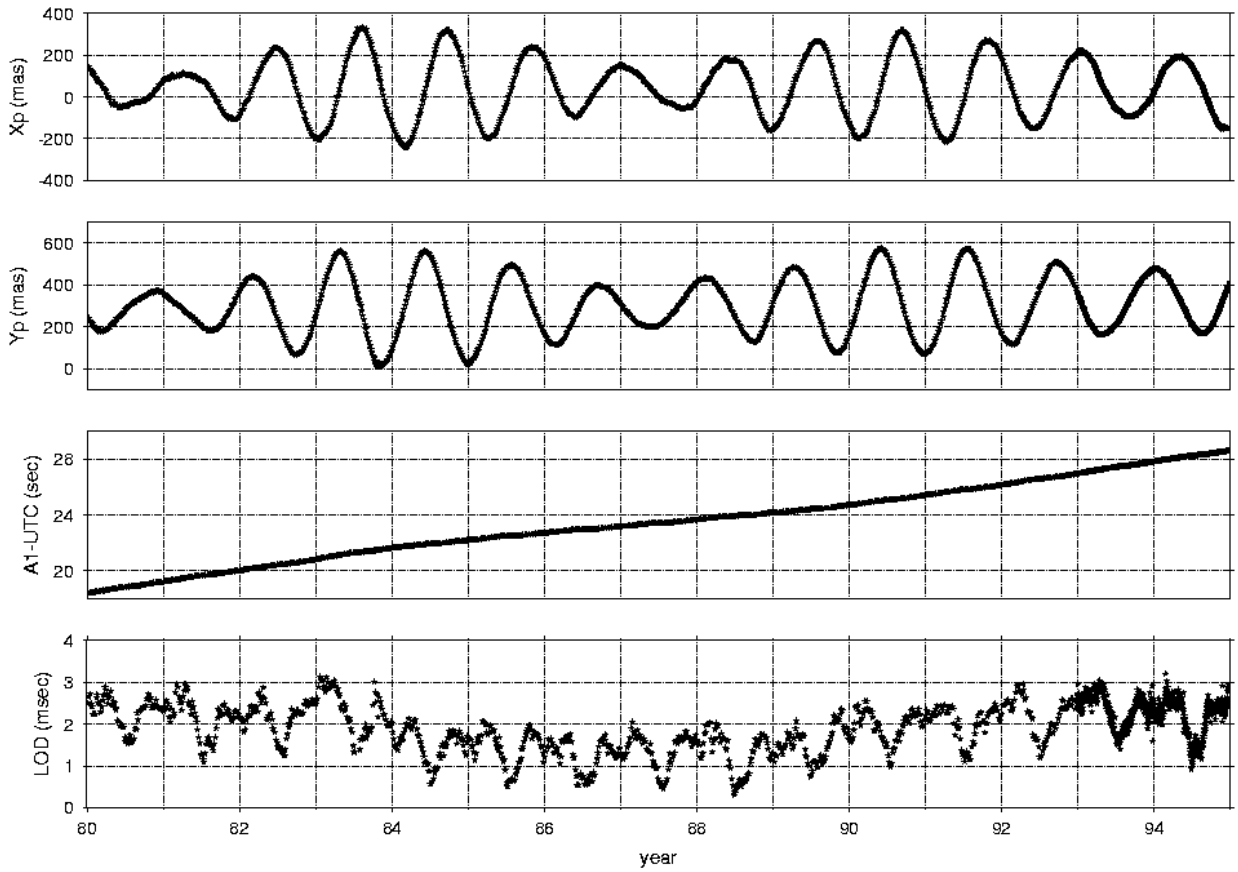

Figure 1. X-pole, Y-pole, A1–UTC, and Length of Day for EGM96.

The EOP solution differences from the *a priori* IERS 90C04 time series are shown in Figure 2. The recovered X-pole position in the EGM96 solution was offset by 6 mas bias from the *a priori* series 90C04, which has been removed from the top frame of 2. The larger scatter in the differences for 1980 through the middle of 1983, particularly evident in the X- and Y-pole plots, results from the poorer quality SLR data from that time period. The SLR systems of the early 1980's were generally second generation, having noise of a few cm, and the number of systems worldwide was less than those deployed currently. Beginning in the middle of 1983, the SLR systems began a major upgrade resulting in data with increased precision and reduced systematic errors. Prior to the launch of T/P in 1992, the SLR systems were further upgraded to have precision of a few mm. Coupled with lengthened tracking schedules that allowed more data to be acquired, these better quality data allowed more frequent adjustment of the EOP in 1993 and 1994 within the EGM96 solution. The somewhat larger scatter shown in the figure for 1993 and 1994, when compared to 1990 through 1992, is due to the 5x more frequent adjustment interval. As the data used in the estimation have both better spatial and temporal coverage, and increased precision, the 1-day adjustment differences display a scatter that is a bit less than expected from the increased adjustment frequency. The slight slope apparent in the Y-pole plot is secular drift in the Y-pole position caused by the effect of the Laurentide postglacial rebound [*Peltier*, 1997].

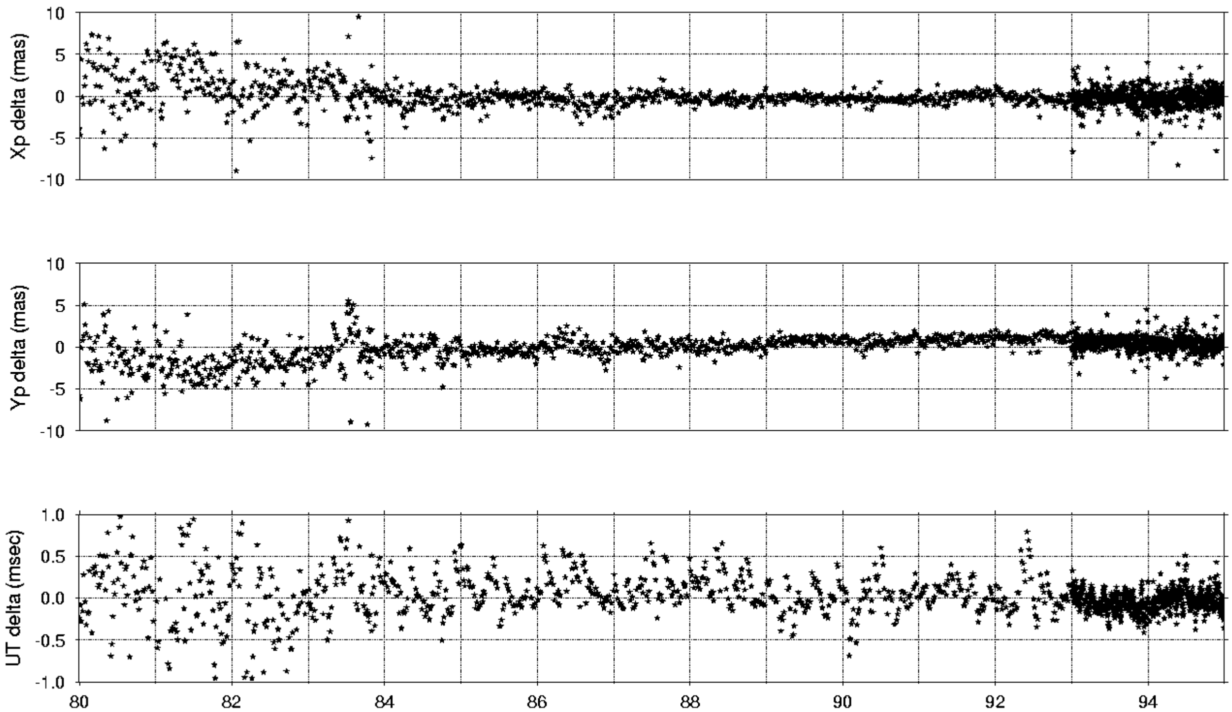

Figure 2. Difference of EGM96 EOP solution with the IERS 90C04 time series. A 6 mas bias has been removed from the delta Xp values.

Tracking site comparison.

In EGM96, the global frame is defined by the network of the SLR stations. This frame will have multiple realizations depending on the number and distribution of the stations included in the definition of the transformation. A comparison of the EGM96 frame with the International Terrestrial Reference Frame 1994 (ITRF94) frame was performed by using a seven-parameter similarity transformation between the two frames. There were three criteria for computation of this transformation: 1. the total position residual after application of the transformation be less than 10 cm, 2. no duplicate stations be used at the same tracking site, and 3. uncertainty estimates on the station coordinates from both the IERS solution and the EGM96 solution were used to perform a weighted least-squares adjustment. Twenty-four stations satisfy these criteria. Multiple solutions were done using the base set of 24 stations, and permutations of this base set, omitting selected stations. A list of the EGM96 coordinates for the 24 base stations, along with their formal uncertainties, is provided in Table 6. To make the uncertainties commensurate with the ITRF94 values, the formal uncertainties were scaled by a factor of 0.5 for all the stations, except for the Greenbelt, MD, site. The latitude and longitude of this station were fixed in the comprehensive combination low degree geopotential solution, resulting in unrealistically small uncertainties. Therefore, an uncertainty of 0.5 cm was used for each of this site's Cartesian position components. In all cases, the comparisons used coordinates mapped to the epoch January 1, 1993. The EGM96 SLR station coordinates have an epoch July 1, 1986, and so were mapped to epoch January 1, 1993 using the tectonic motion model SL7.1 [*Smith*, 1991]. This velocity field should be used for mapping any of the station coordinates from EGM96 to an epoch other than July 1, 1986. Table 7 shows the result of the similarity transformation.

The origins of the EGM96 and ITRF94 frames coincide to within 1 cm, and there is a change scale of about 1.5 ± 0.4 ppb between EGM96 and ITRF94. The rotations are robust being virtually unaffected by the number of stations selected for the transformation. The rotations about Xp and Yp are most likely directly related to the constraints that were used to solve for the SLR station coordinates in the EGM96 solution—namely, that both the latitude and longitude of Greenbelt, as well as the latitude of Haleakala (Maui, Hawaii) were fixed at the JGM–2 values. These rotations are seen in the comparison of the EGM96 polar motion series to the *a priori* IERS series 90C04 (see Figure 2), where a constant offset of about 6 mas is observed in the X position of the Earth’s rotation pole.

Table 6. Sites used in similarity transformation from EGM96 to ITRF94 at epoch January 1, 1993.

Location	CDP site #	X (m)	Formal σ	Y (m)	Formal σ	Z (m)	Formal σ
McDonald, TX	7080	–1330021.108	± 0.012	–5328401.810	±0.010	3236480.850	±0.009
Yarragadee, Australia	7090	–2389006.647	0.010	5043329.383	0.008	–3078525.015	0.011
Easter Island	7097	–1884984.202	0.035	–5357608.164	0.027	–2892853.365	0.026
Greenbelt, MD	7105	1130719.648	0.001	–4831350.615	0.005	3994106.481	0.004
Quincy, CA	7109	–2517234.830	0.009	–4198556.117	0.010	4076569.741	0.007
Monument Peak, CA	7110	–2386278.155	0.009	–4802354.156	0.009	3444881.584	0.007
Platteville, CO	7112	–1240678.276	0.022	–4720463.372	0.022	4094480.628	0.015
Mazatlan, Mexico	7122	–1660089.477	0.015	–5619100.327	0.012	2511637.936	0.013
Huahine	7123	–5345867.168	0.024	–2958246.908	0.030	–1824623.998	0.026
Mt. Haleakala, HI	7210	–5466006.579	0.007	–2404427.473	0.013	2242187.825	0.002
Goldstone, CA	7265	–2356475.774	0.040	–4646618.236	0.034	3668424.777	0.031
Arequipa, Peru	7403	1942807.808	0.015	–5804069.781	0.008	–1796915.575	0.010
Askites, Greece	7510	4353444.996	0.043	2082666.210	0.049	4156506.597	0.035
Melengiclick, Turkey	7580	4247620.580	0.057	2778638.882	0.062	3851607.444	0.046
Yigilca, Turkey	7587	4117362.098	0.057	2517076.757	0.058	4157678.991	0.048
Grasse, France	7835	4581691.838	0.011	556159.287	0.013	4389359.298	0.013
Shanghai, China	7837	–2831087.645	0.045	4676203.467	0.043	3275172.908	0.040
Graz, Austria	7839	4194426.774	0.013	1162693.812	0.013	4647246.486	0.013
Herstmonceux, England	7840	4033463.906	0.010	23662.265	0.011	4924305.001	0.011
Orroral Valley, Australia	7843	–4446476.946	0.019	2678127.190	0.021	–3696251.318	0.017
Cabo San Lucas, Mexico	7882	–1997242.085	0.072	–5528041.089	0.061	2468355.427	0.062
Ensenada, Mexico	7883	–2406126.993	0.072	–4898368.198	0.067	3290336.760	0.051
Matera, Italy	7939	4641965.147	0.012	1393069.826	0.012	4133262.160	0.013
Wettzell, Germany	8834	4075577.118	0.021	931785.238	0.022	4801583.424	0.017

Table 7. Transformation parameters from EGM96 to ITRF94.

	T1 (ΔX) (mm)	T2 (ΔY) (mm)	T3 (ΔZ) (mm)	D (scale) (ppb)	R3 (Z–rot) (mas)	R2 (Y–rot) (mas)	R1 (X–rot) (mas)
24 stations used							
Solution	1.43	3.62	–2.48	1.47	–7.59	6.19	0.14
Standard deviation	2.58	2.42	2.55	0.36	0.10	0.10	0.10
22 stations used: Base set without 7882 and 7883							
Solution	1.49	3.66	–2.46	1.47	–7.59	6.20	0.14
Standard deviation	2.58	2.42	2.56	0.36	0.10	0.10	0.10
21 stations used: Base set without 7882, 7883, and 7837							
Solution	1.35	4.29	–2.05	1.52	–7.59	6.18	0.12
Standard deviation	2.60	2.44	2.58	0.36	0.10	0.10	0.10
18 stations used: Base set without 7510, 7580,7587, 7882, 7883, and 7837							
Solution	0.93	4.42	–2.35	1.52	–7.61	6.18	0.12
Standard deviation	2.62	2.46	2.62	0.37	0.10	0.10	0.10

Table 8. Correlations between the similarity transformation parameters for base set of 24 SLR stations.

	Δx	Δy	Δz	scale	z-rot	y-rot	x-rot
Δx	1.0	–0.065	–0.053	0.022	0.282	0.493	0.139
Δy		1.0	0.068	0.268	–0.114	–0.053	–0.422
Δz			1.0	–0.497	0.052	–0.057	–0.421
scale				1.0	–0.053	0.043	0.081
z-rot					1.0	–0.077	0.175
y-rot						1.0	0.158
x-rot							1.0

The correlations between the similarity transformation parameters for the case of 24 SLR stations is shown in Table 8. The highest correlations for these parameters are 0.4. The residual RMS difference in position for all 24 stations after the transformation is applied is 28.5 mm in X, 28.2 mm in Y, and 20.5 mm in Z.

Summary

The definition of the reference frame for EGM96was key to the development of the model. Satellite laser ranging (SLR) information is the key fundamental component upon which the reference frame is realized. The origins of the EGM96 and ITRF94 frames agree to within 1 cm, about 1.5 ± 0.4 ppb in scale. SLR provides the connection of the geopotential to an Earth centered frame. No other satellite tracking technology has the fundamental unambiguous geometric strength to provide this Earth coordinate frame definition.

References:

Boucher, C., Z. Altamimi, and L. Duhem, Results and Analysis of the ITRF93*, IERS Technical Note 18*, Observatoire de Paris, October, 1994.

Boucher, C., Z. Altamimi, M. Feissel, and P.Sillard, Results and Analysis of the ITRF94*, IERS Technical Note 20,* Observatoire de Paris, March, 1996.

DeMets, C., R.G. Gordon, D.F. Argus, and S. Stein, Current Plate Motions, *Geophys J. Intl.,* 101 425-478, 1990.

IERS Annual Report for 1989, International Earth Rotation Service (IERS), Observatoire de Paris, July 1990.

Lemoine, F. G., S.C. Kenyon, J.K. Factor, R.G. Trimmer, N.K. Pavlis, C.M.Cox, S.M. Klosko, S.B. Luthcke, M.H. Torrence, Y.M.Wang, R.G. Williamson, E.C. Pavlis, R.H. Rapp, and T.R. Olson, “The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96”, NASA/TP-1998-206861, July, 1998.

Nerem, R.S., F.J. Lerch, J.A. Marshall, E.C. Pavlis, B.H. Putney, B.D. Tapley, R.J. Eanes, J.C. Ries, B.E. Schutz, C.K. Shum, M.M. Watkins, S.M. Klosko, J.C. Chan, S.B. Luthcke, G.B. Patel, N.K. Pavlis, R.G. Williamson, R.H. Rapp, R. Biancle, and F. Nouel, Gravity Model Development for TOPEX/POSEIDON: Joint Gravity Models 1 and 2, *J. Geophys. Res*., 24421–24447, 1994.

Peltier, W.R., and X. Jiang, Glacial isostatic adjustment and Earth rotation: Refined constraints on the viscosity of the deepest mantle, *J. Geophys. Res., 101*, 3269–3290, 1997.

Smith, D.E., R. Kolenkiewicz, P.J. Dunn, M.H. Torrence, J.W. Robbins, S.M. Klosko, R.G. Williamson, E.C. Pavlis, "LAGEOS Geodetic Analysis--SL7.1", NASA TM 104549, September, 1991.

Ullman, R.E., SOLVE Program Mathematical Formulation, Hughes STX Report HSTX/G&G–9201, NASA Contract NAS–5–29393/503, January, 1992.