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IV. RELATED RESULTS AND ACTIVITIES IN WESTERN PACIFIC VLBI NETWORK

IV.3 COLLOCATION AND LOCAL-TIE OF SPACE GEODETIC TECHNIQUES, VLBI, SLR, AND GPS IN CRL, TOKYO

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ABSTRACT

The global position of the station in the Communications Research Laboratory (CRL), Tokyo was determined independently by means of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Positioning System (GPS) techniques with a precision of several centimeters. Local-tie survey among ground markers and points on which the techniques are referenced in position have also been done. The coordinates from three results from various source of analysis are consistent within 7 cm peak to peak. The difference may include uncertainty in local-tie measurement (3 cm in maximum) and in coordinates transformation in a comparison process (2.5 cm in mean) as well as in the observations themselves especially in vertical component.

Keywords: VLBI, SLR, GPS, collocation, IERS

1. Introduction

Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) are the major space geodetic techniques for determining the relative station position over intercontinental distance with centimeter-level precision. Since the two techniques are independent in their observation principles, it is of interest to compare results from them to evaluate the accuracy of the measurements when they are collocated in the same place. Global Positioning System (GPS), another precise geodetic technique widely used for monitoring a local deformation, is also utilized as a means of local-tie between other space techniques in a collocation process.

There are three major stages in a collocation process to evaluate uncertainty of the station position of interest. The first is the observation and data processing by each technique. The uncertainty of the station position should be expressed by an internal error based on the observation and analysis model. The second, local-tie between each technique should be performed precisely enough within the internal observation error. The distance between the reference point of each

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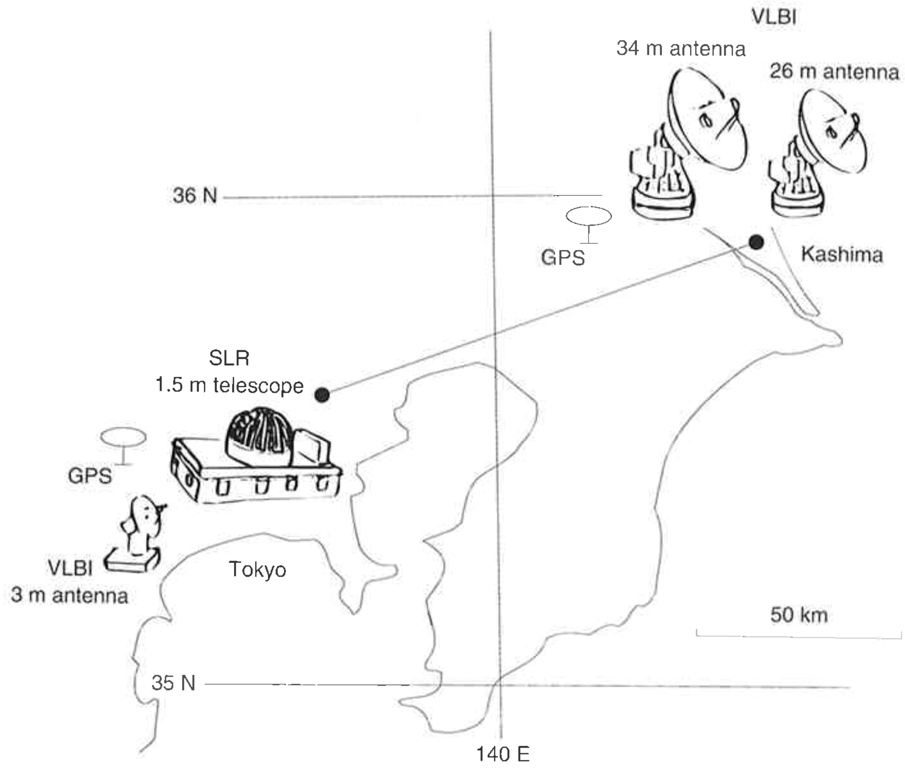

Fig. 1 The location of each technique in Tokyo and Kashima

techniques generally ranges from a few meters to several tens of km, and the goal of local survey accuracy within 1 cm would not be easy to get, especially in case that the reference point is covered by telescope or antenna structures. Finally in the third process, the coordinates transformation may be required depending on the difference of definition of each coordinate system. The transformation should be made in attention to the observation epoch and adopted plate motion model . The activities of collocation to establish an unified global coordinates have been organized by the International Earth Rotation Service (IERS) and the results have been annually reported as the IERS Terrestrial Reference Frame (ITRF)[1].

The Communications Research Laboratory (CRL) has developed geodetic VLBI system for the last two decades. It has performed more than seventy international and domestic VLBI experiments using 26 m and 34 m antennae at the Kashima Space Research Center, Ibaraki (KASHIMA), and also at Koganei, Tokyo using a 3 m mobile antenna[2]. Kashima has been established as one of the major sites in a global terrestrial reference frame[1]. Tokyo SLR station in Koganei (CRLLAS), one of the facilities in the Space Optical Communication Ground Station, started observation in February 1990 and obtained more than 350 passes in total for major geodetic satellites up to the height of 20,000 km[3]. Although the system is not in operation routinely but is acting as an engineering test bed for the research and development, the global position of the station was determined by CRL and IERS independently. The Tokyo SLR station has been collocated with mobile VLBI antenna since 1988 and has been connected to the Kashima VLBI station. The conventional local-tie surveys in Kashima and Koganei have been done, mainly by Geographical Survey Institute (GSI) using both the

Table 1 The station coordinates of Tokyo SLR station, Kashima 26 m and Kashima 34 m antenna in ITRF92[1] (Epoch: 1988.0, Unit: meter)

	X	Y	Z
Tokyo SLR (7308)	−3,942,020.077 +/−0.116	3,368,097.548 +/−0.112	3,702,191.136 +/−0.138
Kashima 26 m (1856)	−3,997,892.252 +/−0.007	3,276,581.252 +/−0.006	3,724,118.349 +/−0.010
Kashima 34 m (1857)	−3,997,649.233 +/−0.008	3,276,690.751 +/−0.007	3,724,278.957 +/−0.011

Table 2 The baseline vectors between Kashima 26 m and Koganei 3 m antenna obtained by VLBI (Epoch: 1988.0 and 1990.0, Unit: meter)

	X	Y	Z	Epoch
Kashima 26 m	55,814.886	91,750.862	−22,213.418	1988.0
Koganei 3 m	55,814.908 +/−0.020	91,750.843 +/−0.015	−22,213.436 +/−0.017	1990.0

Table 3 Coordinates of CRLLAS (Tokyo) in CSR91L01 geocentric coordinate system (Epoch 1983.0, Plate Motion Model: AM1-2, Unit: meter)

X	Y	Z
−3942019.882 +/−0.048	3368097.932 +/−0.056	3702191.126 +/−0.080

Electronic Distance Meter (EDM) and GPS methods. The GPS receivers have been also used for baseline determination between KASHIMA and CRLLAS. The location of each technique on the map is shown in Fig. 1.

2. Experiments and Data Analysis

2.1 VLBI

The Koganei 3 m mobile antenna was established in September 1988, conducting the first VLBI experiment with the Kashima 26 m antenna. It was then moved to a remote island and returned in 1992 to perform further experiments with a 26 m and a newly built 34 m antenna switching over in Kashima during the Metropolitan Diamond Cross (MDX) program[4][5]. The data sets used in our analysis are those from seven experiments during the period from September 1988 to July 1993.

We fixed the position of the Kashima 34 m antenna given by ITRF92[2] (See Table 1) where the relative coordinates between the 26 m and 34 m antennae were determined by GLB867[6]. The physical model depended on the software CALC version 7[7]. Atmospheric correction towards the zenith was done in offset and slope every 6 hours by applying a mapping function NMF[8]. Clock

Table 4 The geodetic reference points and ground markers in Koganei, Tokyo

No.	Name	Mnem-onic	Type	Status	Description	Year set	North	East	Height
1	SLR AXIS	S	AXIS	Permanent[1)]	1.5 m telescope Az-El intersection point	1988–		See text	
2	VLBI AXIS '88	V88	AXIS	Settable[3)]	1988 Sep. occupation of 3 m VLBI antenna Az-El intersection point	1988.9–10		See text	
3	VLBI AXIS '92	V	AXIS	Settable[3)]	1992 Mar.-occupation of 3 m VLBI antenna Az-El intersection point	1992.3–		See text	
4	TERY_E	T	POLE	Permanent[1)]	Terrestrial target on the building eastward from telescope	1989–	0.000	0.000	0.000
5	TERY_W	TW	POLE	Permanent[1)]	Terrestrial target on the ground westward from telescope	1989–	14.902	−100.358	−8.068
6	PRESTAR	P	MRK	Tentative alive[4)]	Marker on the roof top of the Maser building (used as PRESTAR GPS receiver)	1989–	−356.883	−135.925	−4.631
7	GSI plate	G	PLAT-E	Permanent[1)]	The plate GSI set on the no. 3 building in 1975	1975–	−381.497	−54.552	3.343
8	AOA	A	ANT	Settable[3)]	AOA receiver for GPS time comparison set on the pole on the no. 3 building	1989–		–	
9	SLR NE	SNE	GRD	Permanent[1)]	Ground base at optical center north east in 1992	1992–	66.556	18.623	−10.851
10	SLR SE	SSE	GRD	Permanent[1)]	Ground base optical center southeast in 1992	1992–	−40.658	5.398	−11.759
11	SLR SW	SSW	GRD	Permanent[1)]	Ground base optical center southwest in 1992	1992–	−31.319	−64.864	−10.353
12	TEMP NE	–	TMP	Tentative obsolete[5)]	Ground marker at optical center northeast in 1990	1990–90		–	
13	TEMP N1	–	TMP	Tentative obsolete[5)]	Transit ground marker at optical center north in 1990	1990–90		–	

1) The point is (would be) permanent
2) It is used for tentative azimuth reference
3) Position would be changed at every set up. but not changed during in operation
4) The point is tentative but still be used as survey
5) The point is tentative and already obsolete

Table 4 The geodetic reference points and ground markers in Koganei, Tokyo—continued

No.	Name	Mnem-onic	Type	Status	Description	Year set	North	East	Height
14	TEMP N2	–	TMP	Tentative obsolete[5)]	Transit ground marker at optical center north in 1992	1992–92		–	
15	TEMP SE1	–	TMP	Tentative obsolete[5)]	Ground marker at optical center southeast in 1989	1989–89		–	
16	TEMP SE2	–	TMP	Tentative obsolete[5)]	Ground marker at optical center southeast in 1990	1990–90		–	
17	TEMP SW1	–	TMP	Tentative obsolete[5)]	Ground marker at optical center southwest in 1989	1989–89		–	
18	TEMP SW2	–	TMP	Tentative obsolete[5)]	Ground marker at optical center southwest in 1990	1990–90		–	
19	VLBI N	VN	GRD	Permanent[1)]	Ground base at 3 m antenna north in 1992	1992–	−319.802	−157.142	−11.423
20	VLBI S	VS	GRD	Permanent[1)]	Ground base at 3 m antenna south in 1992	1992–	−361.970	−153.047	−11.224
21	TEMP VLBI	–	MRK	Tentative alive[4)]	Marker on the 3 m antenna base	1990–	−345.582	−151.732	−10.969
22	TEMP 4B1	–	TEMP	Tentative obsolete[5)]	Transit marker on the top of no. 4 building in 1989	1989–89		–	
23	TEMP 4B2	–	TEMP	Tentative obsolete[5)]	Transit marker on the top of no. 4 building in 1990	1990–90		–	
24	NTT	–	AZM	Azimuth ref[2)]	The lightning rod on the NTT tower for the azimuth reference at point P	1988–		–	
25	TANASHI	–	AZM	Azimuth ref[2)]	The lightning rod on the Tanashi tower for the azimuth reference at point T	1988–		–	
26	No. 3 build.	–	AZM	Tentative azm. ref.	The lightning rod on the no. 3 building of CRL	1988–		–	

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Table 4 The geodetic reference points and ground markers in Koganei, Tokyo—continued

No.	Name	Mne-monic	Type	Status	Description	Year set	North	East	Height
27	KSP build.	KS1	POLE	Permanent[1]	Pole for GPS/geodetic measurement on the KSP building	1994–	30.468	−102.107	0.131
28	KSP NE	KS2	POLE	Permanent[1]	Pole for GPS/geodetic measurement northeast around 11 m antenna	1994–	75.403	−63.981	−8.348
29	KSP N	KS3	GRD	Permanent[1]	Ground base in north of 11 m antenna	1994–	85.609	−106.297	−9.843
30	KSP W	KS4	GRD	Permanent[1]	Ground base in west of 11 m antenna	1994–	49.144	−122.330	−9.981
31	GSI POLE	GP1	POLE	Permanent[1]	5 m tall pole for GPS measurement for GSI	1994–	16.920	−113.265	−3.860
32	TEMP P	–	MRK	Tentative alive[4]	Marker 3 m off north of PRESTAR point	1992–		–	
33	TEMP T	–	MRK	Tentative alive[4]	Marker 2 m off north of Tery_E point	1992–		–	
34	AZM PLATE	AZM	GRD	Permanent[1]	Ground base for azimuth reference at north-east of ground field	1995–	The local coordinate origin on no. 4.		

1) The point is (would be) permanent
2) It is used for tentative azimuth reference
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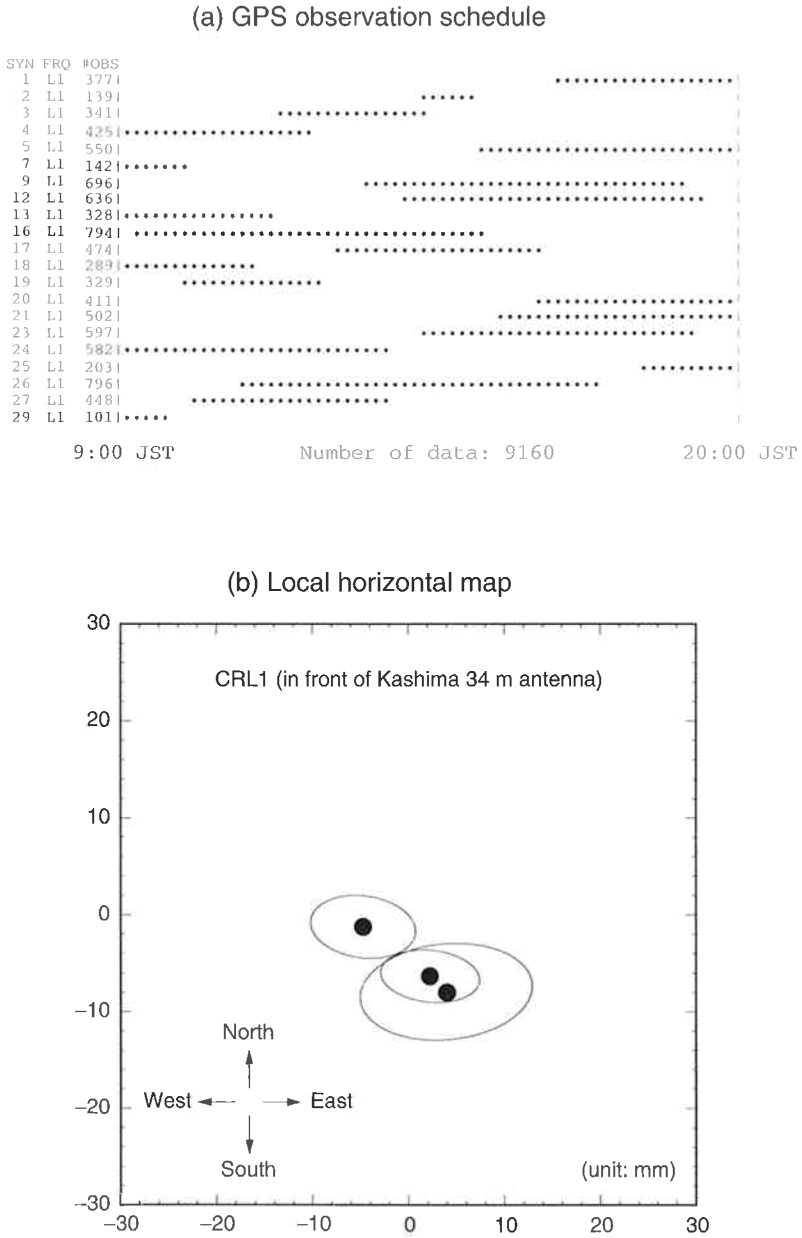

Fig. 2 (a) The schedule of GPS observation and (b) the example of horizontal repeatability in Kashima GPS site

offset and rate was estimated every 2 hours. No ionospheric correction was made since 3 m portable station was capable of receiving only X band frequency. The Kashima-Koganei baseline vectors in epoch 1988.0 and 1990.0 derived from VLBI are listed in Table 2.

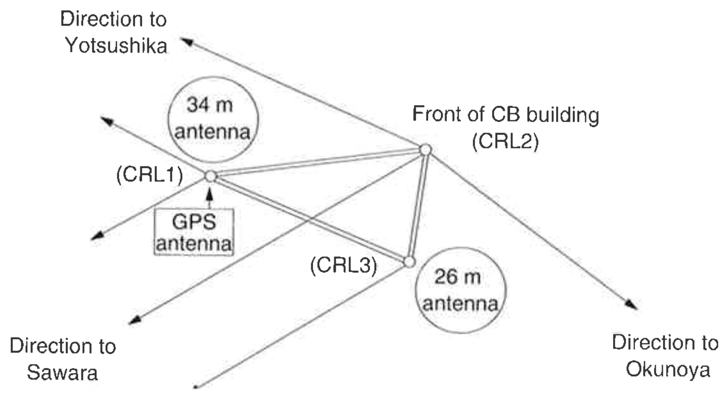

Fig. 3 The schematic survey map in Kashima (CRL1, 2 and 3 are the ground markers)

2.2 SLR

The data sets used in the analysis were 19,554 LAGEOS passes in total (including 38 passes in CRLLAS) obtained by 35 SLR tracking stations during a period from September to November 1990 when ETALON tracking campaign was organized in the global SLR network. Data analysis has been made using University of Texas Orbit Processor and Application (UTOPIA) software[9]. The TEG50 geopotential model and CSR Earth Orientation Parameter were used in the analysis. The global position of the Tokyo SLR station in CSR91L01 coordinate system is listed in Table 3. The coordinates are based upon the reference epoch 1983.0 being evolved by plate motion model AM1-2.

The same data were also analyzed in the ITRF92 reference frame by the IERS. The results are reported in ITRF92 which has 11 to 14 cm formal error in each component in Table 1. We have found that it is due to the range bias of 30 cm included in the initial released data and to be corrected in the later release.

2.3 GPS

The CRL owns three commercial geodetic receivers (Ashtech XII-P), capable of C/A code, L1/L2 carrier, and P-code measurement. We have participated in the "GPS JAPAN '93" campaign locating them in the vicinity of the Koganei SLR telescope building, the Kashima 34 m, and the Inubo Radio Observatory, respectively. The schedule and the position repeatability obtained during the campaign is shown in Fig. 2.

Data analysis was made by using an on-site modification version of the Bernese GPS software ver. 3.4 running on a HP workstation. In the analysis, we used the broadcast orbital elements and Kashima coordinates fixed as the ITRF92 site. A cyclic slip elimination was done manually and ionospheric excess path was corrected by L1/L2 frequency.

3. Local-Tie Survey

The origin of VLBI-antenna/SLR-telescope and ground marker has been surveyed by the CRL and GSI, respectively where the origin is defined as at the intersection of two orthogonal rotating axes.

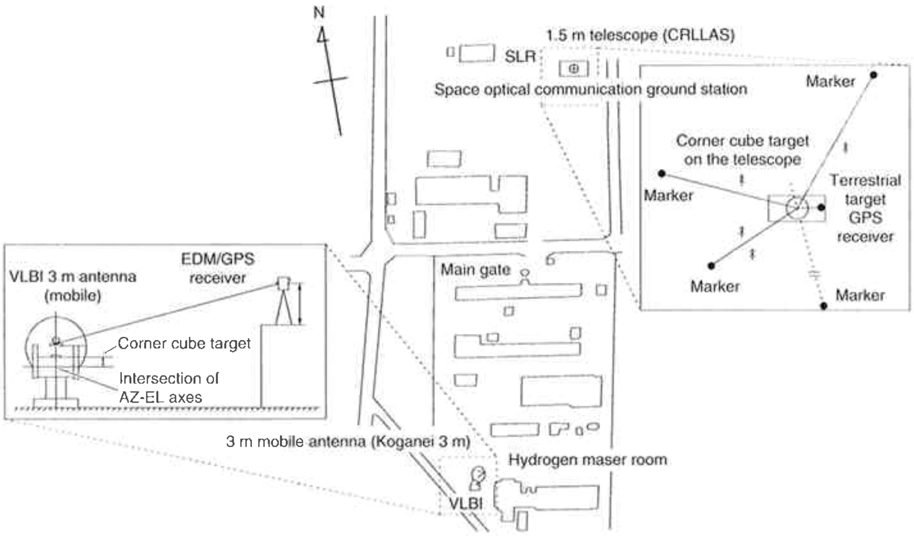

Fig. 4 The location of SLR, VLBI and GPS in CRL Koganei, Tokyo

In the Kashima Research Center, there are three major geodetic markers and measurements of the relative position with respect to 26 m and 34 m VLBI antennae have been done by GSI[10]. The schematic survey map is shown in Fig. 3.

In Koganei, such surveys with respect to 3 m VLBI antenna and 1.5 m SLR telescope have been done many times since 1988 by CRL and GSI. Figure 4 shows the map of local tie in Koganei and Table 4 lists all the geodetic reference points and ground markers in Koganei. The SLR telescope is located 500 north of the VLBI antenna. We made local-tie measurement between them by GPS receiver and by conventional EDM method. The major local-tie vectors between reference points are listed in Table 5. It should be pointed out that the discrepancy between the CRL and GSI results are 3 cm peak to peak and should be examined by further survey.

4. Comparison

4.1 Comparison between VLBI and SLR: Results of Transformation from ITRF92 to CSR91L01 Coordinates

Using the position of Kashima by ITRF92 and position of CRLLAS by CSR91L01 described in 2.2, we made a coordinate adjustment. Figure 5 illustrates the comparison process between VLBI and SLR coordinates each of which has different definition. It aims to minimize the error for the difference of the plate motion model used in each solution. First, we prepare the two sets of coordinates for collocation sites, one set from ITRF92 and another for CSR91L01. Second, the epochs of station position for both system are moved to the common observation epoch (1990.0) by the adopted plate motion model namely nnr-NUVEL-1 for ITRF92 and AM1-2 for CSR91L01. Third, adding the local-tie information given by J. Ray et al. 1991[11], the transformation matrix (offset, rotation and scale) between two systems is calculated by least square method. Then we apply

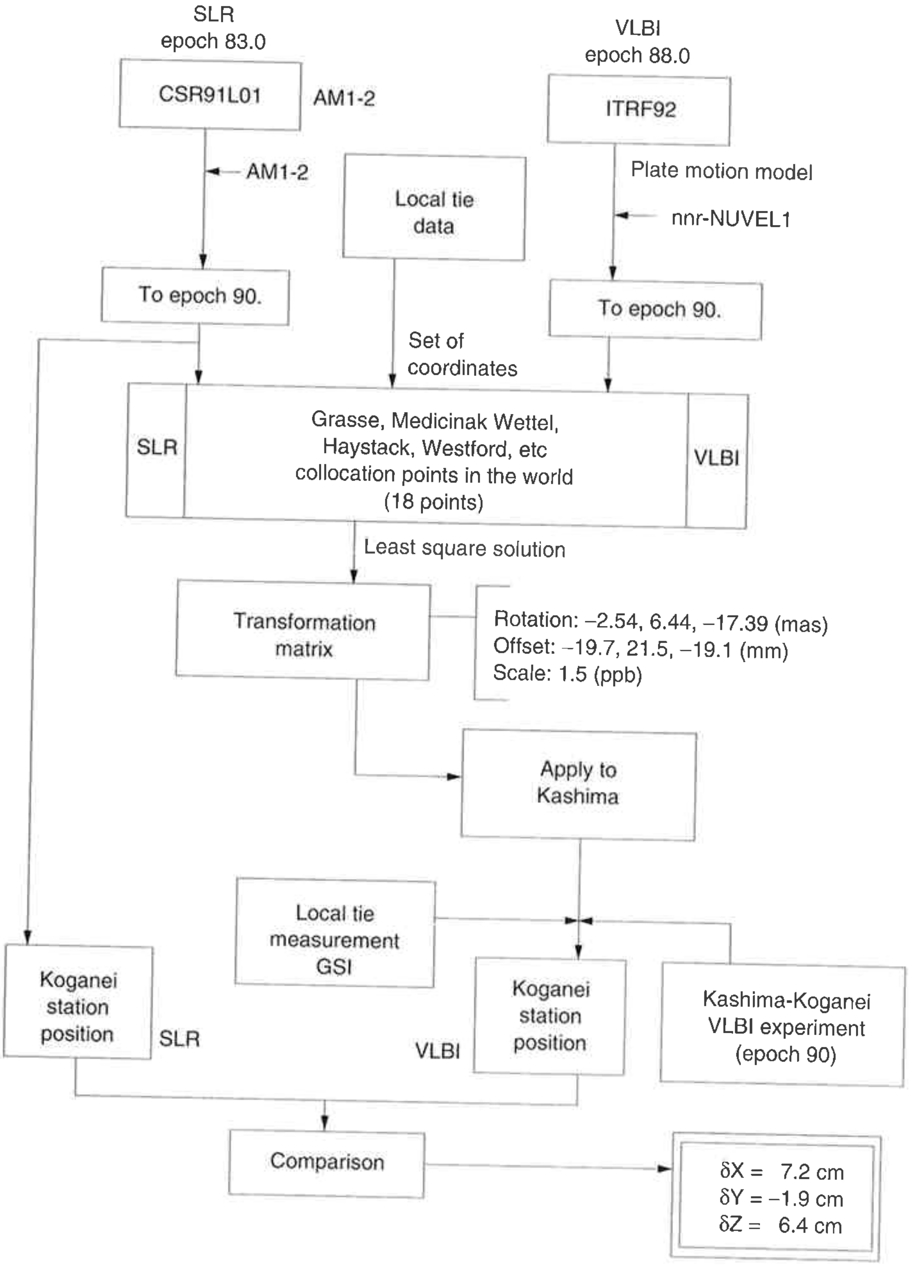

Fig. 5 Flow diagram of comparison process between SLR and VLBI in custom coordinates

it to the Kashima station to produce the position equivalent to one by CSR91L01 at epoch of 1990.0. Finally, Kashima-Koganei baseline vector in epoch 1990.0 and local-tie vector in Koganei are added for final comparison. Note the effect of the transformation for Kashima-Koganei and local-tie vectors

Table 5 The relative vectors for local-tie between major reference points in geocentric coordinate system (Unit: meter)

Vector	X	Y	Z
Kashima 34 m to Kashima 26 m	−243.019	−109.493	−160.607
Kashima-GPS to Kashima 34 m	−39.895	−64.923	44.260
Koganei 3 m to CRLLAS (SLR)	57.220	−234.522	286.214
CRLLAS (SLR) to Koganei-GPS	−8.771	−7.458	−1.030

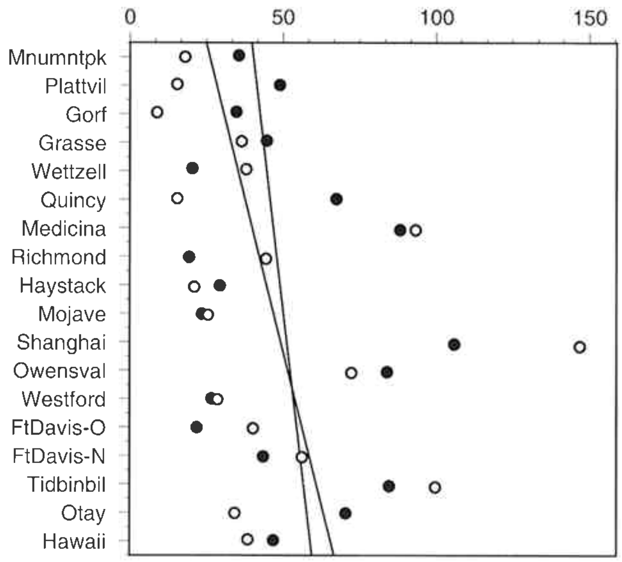

Fig. 6 Residuals after adjustment of VLBI and SLR coordinates for the collocation sites. (Black dots: Results from custom adjustment in this paper, White dots: Results from J. Ray et al.[11], Unit: mm)

are negligible here. The difference of coordinates between SLR and VLBI at Tokyo SLR station are 7.2, −1.9 and 6.4 cm, respectively, in geocentric component.

The result from straightforward comparison with ITRF92 CRLLAS coordinates versus ITRF92 Kashima (using number from Table 1, Table 2 and Table 5) are 6.9, −4.4 and −0.9 cm respectively which shows the comparable difference with the results given above.

Figure 6 shows the residuals after adjustment of VLBI and SLR coordinates. The black dots are from our results and the open dots come from J. Ray et al. 1991[11]. The stations are arranged by the distance between the VLBI and SLR sites in ascending order. The straight lines, which all the data fits, explain a dependence of distance of the two techniques. Weighted rms of residuals are 2.5 cm in both analyses. However, some stations (Medicina, Shanghai, OwensVally, and Tidbinbilla) have large residuals and must be studied more carefully in the local-tie measurement.

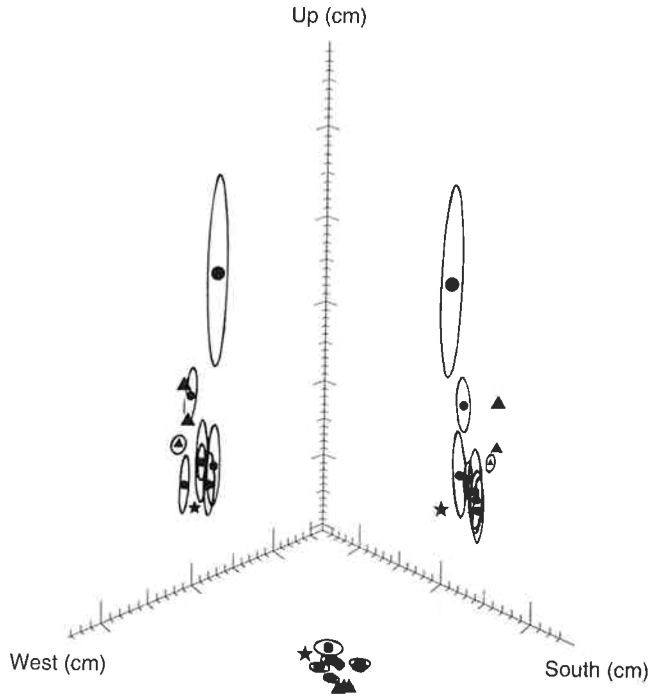

Fig. 7 The coordinates projection to local geodetic coordinate by VLBI, SLR and GPS. Error ellipsoids shows 1 sigma for VLBI, 3 sigma for GPS. No ellipsoid for SLR plot here due to large formal error in ITRF92.

4.2 Results of IERS Coordinates Comparison using ITRF92 Coordinates (3 Techniques Comparison)

Using ITRF92 coordinates at Kashima and Koganei and local-tie information all consistent in Epoch 88.0, we obtained the comparison of VLBI, SLR and GPS coordinates. Figure 7 shows the Koganei 1.5 m telescope position in a local coordinates determined by three techniques. The error ellipses are given by each technique except SLR where ITRF92 solution has a large error. The scatters of 20 cm peak to peak in vertical component are seen in VLBI possibly caused by non-ionospheric correction in VLBI. The repeatability of GPS observation is as good as 1 cm in horizontal and 3 cm in vertical, but the results might include a systematic error due to atmosphere because the campaign was performed within a short time. The mean of VLBI position, if we exclude point which has the largest error ellipsoid, will coincide with GPS and SLR within 5 cm.

The difference would include errors in local-tie measurement and coordinates transformation in a comparison process as well as errors in SLR/VLBI observation themselves.

5. Conclusion

The activities of collocation study in CRL are presented. The coordinates from three results from various source of analysis are coincident to within 7 cm peak to peak. The difference may include uncertainties in local-tie measurements (3 cm in maximum) and in coordinates transformation in a comparison process (2.5 cm in mean) as well as in the observations themselves, especially in vertical component.

To improve collocation accuracy, we should increase the number of SLR observations in Tokyo to put the range bias correctly and should increase the VLBI observations in Tokyo to determine the relative station motion. We should also improve the accuracy of local-tie survey not only for Tokyo but for the other collocation points in the world. They should contribute to the reference frame accuracy better than 1 cm.

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