ITRF and Co-location Sites

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Abstract. The main focus of this position paper is to review the current status of the co-location sites, necessary for ITRF combination. The definition of a co-location site is given in terms of distance between geodetic markers or instrument reference points of different techniques and accuracy of the local ties connecting them. Distribution and quality of the current co-location site are summarized. Given the precision increase of the measurement of the space geodesy techniques and modelling, 1 mm precision or better should be the goal of all new local tie surveys. Moreover, SINEX files with full variance-covariance information is now mandatory.

1 Introduction

When combining TRF solutions of station coordinates provided by different techniques, it is essential to be able to connect these solutions. This could not be possible without having common observing sites of the various techniques. The common sites (co-locations) have different instruments and observing monuments for which differential coordinates (local ties) should be available for TRF combination purpose.

Co-location sites represent a key element of the ITRF combination, connecting the individual TRF networks together. Without co-locations an inter-technique combined TRF could not exist. A global homogeneous geographical distribution of co-locations is desired and the quality of local ties must be high.

2 Definition of a Co-location Site

A co-location site is defined by the fact that two or more space geodesy instruments are occupying or have occupied simultaneously or subsequently close locations which are very precisely surveyed in three dimensions, using classical or GPS surveys. We designate throughout this paper by "geodetic marker" or simply "marker" an unambiguous, fully defined reference point in space for which we estimate (refer) geodetic coordinates. The marker could be either:

- a well defined physical point anchored/settled in a geodetic monument (pillar, pole, etc.), or
- an instrument reference point (e.g. intersection of axes of SLR telescope or VLBI antenna, GPS/DORIS Antenna Reference Point)

There are at least two main criteria which could be considered for the definition of a co-location site:

1 **Inter-marker distance**: typical distance between geodetic markers in a co-location site is of the order of few hundred meters. One could impose a given "maximum" length of distance between markers for an ideal co-location site. Meanwhile the current reality of the available co-location sites (insufficient number and distribution) lead to consider distances up to 30 km (e.g. Tidbinbilla/Orroral complex site). Moreover, footprint network and repeated survey should be established for local site long-

term stability. In any case the accuracy of the local tie should be properly taken into account in TRF combination.

2 **Accuracy of the local tie**: the typical uncertainty (when available) of the currently available local ties for ITRF combination ranges between 1 to 3 mm (sometimes larger than 3 mm for imprecise ties)[1]. Given the precision increase of the measurement of the space geodesy techniques and modelling, 1 mm precision or better should be the goal of all new local tie surveys. Moreover, SINEX files with full variance-covariance information is now mandatory.

3 History and current status of Local Ties in Co-location Sites

The currently available local ties used in ITRF combinations were collected by the IERS ITRS-Product Center starting in the 1980's. They are from diverse sources and of various qualities, very often without variances.

3.1 Local Ties Usage in ITRF Combination

In ITRF combination, the local ties are used as observations, with proper variances.

The procedure adopted for ITRF2000 combination is to include local ties as independent solutions per site with full variance matrices using SINEX format. Unfortunately, local tie SINEX files were submitted to ITRS PC by only one group: The Australian Surveying and Land Information Group (AUSLIG) for all the Australian co-location sites. Consequently, the other local ties used in the ITRF2000 combination were first converted into a complete set of positions for each site, provided in SINEX format. This has been achieved by solving for the following system of observation equations (1):

$$\begin{pmatrix} \Delta x_s^{i,j} \\ \Delta y_s^{i,j} \\ \Delta z_s^{i,j} \end{pmatrix} = \begin{pmatrix} x^j - x^i \\ y^j - y^i \\ z^j - z^i \end{pmatrix} \qquad (1)$$

where $\left(\Delta x_s^{i,j}\right), \left(\Delta y_s^{i,j}\right), \left(\Delta z_s^{i,j}\right)$ are the geocentric components of the tie vector linking two *i* and *j*, of a given data set *s*. The standard deviations (SD) $\left(\sigma\Delta x_s^{i,j}, \sigma\Delta y_s^{i,j}, \sigma\Delta z_s^{i,j}\right)$ for each local tie vector are used to compute a diagonal variance matrix. If these SD are not available, they are computed by :

$$\sigma_{computed} = \sqrt{\sigma_1^2 + \sigma_2^2} \qquad (2)$$

where, $\sigma_1 = 3\,\text{mm}$, and $\sigma_2 = 10^{-6} \times \sqrt{\left(\Delta x_s^{i,j}\right)^2 + \left(\Delta x_s^{i,j}\right)^2 + \left(\Delta x_s^{i,j}\right)^2}$.

The equation system (1) needs of course initial coordinates for one point per tie vector set *s*, which are taken from ITRF solutions. The local tie information should be completely independent of the geocentric site coordinates.

The ITRF Report 4 on local ties (Altamimi, 2001), available at: http://lareg.ensg.ign.fr/ITRF/ITRF2000/ITRF2000.TIE-prob, summarizes local tie problems in co-location sites as a result from the ITRF2000 analysis:

[1] Note that within a co-location site, several geodetic markers per techniques are often present. Therefore the accuracy of local ties between pair of markers may vary from one vector to another depending on the quality of the available survey.

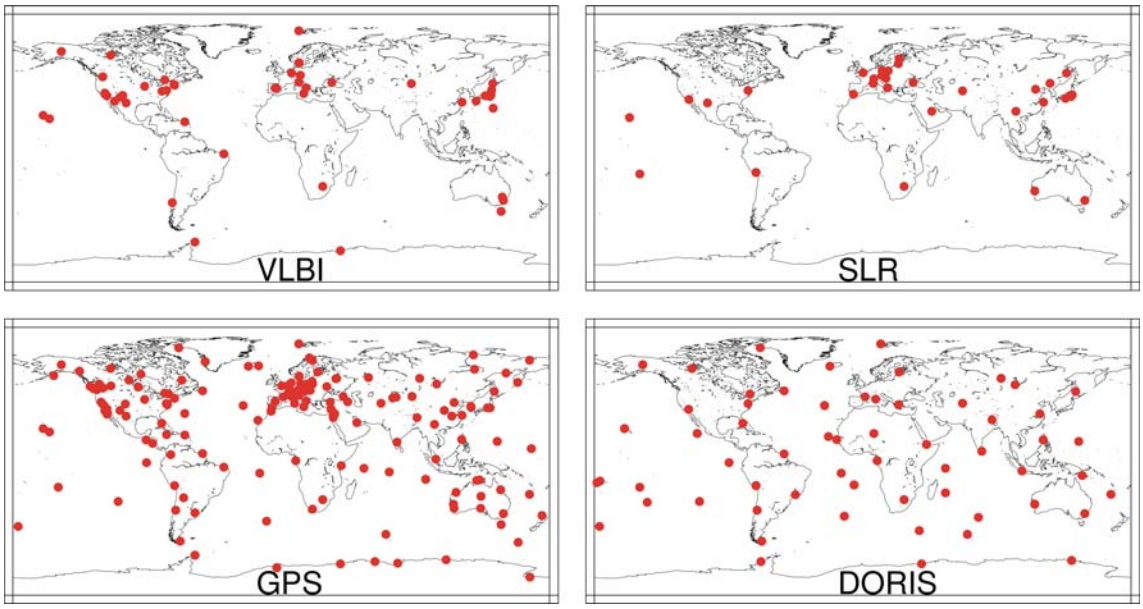
- ITRF2000 contains 101 sites having 2 (72 sites), 3 (25 sites) or 4 (6 sites) collocated techniques
- the number, distribution and quality of the ITRF2000 co-locations were insufficient and old SLR-VLBI mobile co-locations are now obsolete
- 200 local tie vectors were included in the combination
- 38 local tie vectors were missing, 25 of which are highly important
- 20 vectors were declared as dubious: post fit residuals ≥ 1 cm.

3.2 Current Situation

The sites where stations of the 4 major techniques are currently operating (i.e. over the past 5 years) are illustrated in Figure 1. VLBI and SLR networks each include less than 50 sites. DORIS network is more homogeneous and includes 56 sites. Finally IGS GPS network is containing more than 300 permanent sites (actually 362 IGS stations, at the time of writing). Note on the other hand that there are far more than 1000 continuously and permanently observing GPS stations around the world due to regional denser networks whereas the IGS maintains a global focus. This huge number of GPS permanent stations is deployed thanks to, mainly, GPS easy use and low cost, compared to the other techniques. This GPS particularity, coupled with its high precision reached now thanks to IGS in particular, is of great interest to IERS and IAG IGGOS project, since it allows strengthening somehow the current situation of IERS co-location sites. In short, we should have a GPS permanent station at each VLBI and SLR sites (DORIS/GPS co-location sites are already numerous and well distributed), thus leading to reinforce the connection between these three techniques. On the other hand, GPS permanent stations collocated with SLR and/or VLBI should become IGS core stations and be analyzed by IGS ACs regularly.

The quality and distribution of the recently operating collocated stations are presently questionable and deserve more attention for improvement. Figure 2 shows the co-location sites (approximately 72 sites) where at least two of the 4 techniques (VLBI, SLR, GPS and DORIS) have been recently operating (for the past 5 years). While 58 sites are hosting 2 observing techniques, only 12 sites are having 3 techniques (with inhomogeneous distribution over the globe) and, more dramatically, only 2 sites with the 4 techniques. Moreover, as results from the combination analysis developed below, there are 8 sites where the local ties are inconsistent with space geodesy estimates and 8 sites with missing ties. The current status and distribution of co-locations, taken by pair of techniques, are as follows (based on the available information at the ITRS Product Center):

- SLR and VLBI observing stations are poorly distributed;
- VLBI session observing networks are very sparse and not all connectable n terms of common stations, over periods less than a year.
- For the upcoming IERS Combination Pilot Project, the number of VLBI co-locations with other techniques (1) may not be sufficient in a weekly basis and (2) are not the same from one week to another. This may lead to a weak connection of the VLBI network to the other techniques.
- The current number of SLR-VLBI co-location sites does not exceed 6;
- Almost all active VLBI and SLR stations are collocated with GPS, but there are still 6 SLR sites not collocated with GPS
- Only 8 VLBI-DORIS co-locations exist and they are not well distributed
- Only 7 SLR-DORIS co-locations exist and they are not well distributed: 5 in the southern hemisphere and 2 in the northern hemisphere



- There are about 30 well distributed GPS-DORIS co-locations
- The current available local ties are values at different (mostly unknown) epochs and they are thus considered as static, i.e. without time variation. For future improvement of the combination results, it is important to consider time variations of the local ties. This implies organizing repeated (yearly!) surveys at the co-location sites.

With some international cooperation via national surveying agencies, the situation of missing and inconsistent ties could be easily improved. Meanwhile, the long term maintenance of co-location sites and their distribution need more attention. The urgent action is to envisage new design of ITRF Core Co-location Sites (ICCS), the indispensable "ITRF Pillars", with global coverage, stable and solid monumentation, regularly/repeatedly surveyed and geophysically monitored. For instance, extensive description and specifications to reinforce and secure the IGS Reference Stations were recently formulated by Ray (2003), which could be extended and adapted to the ICCS.

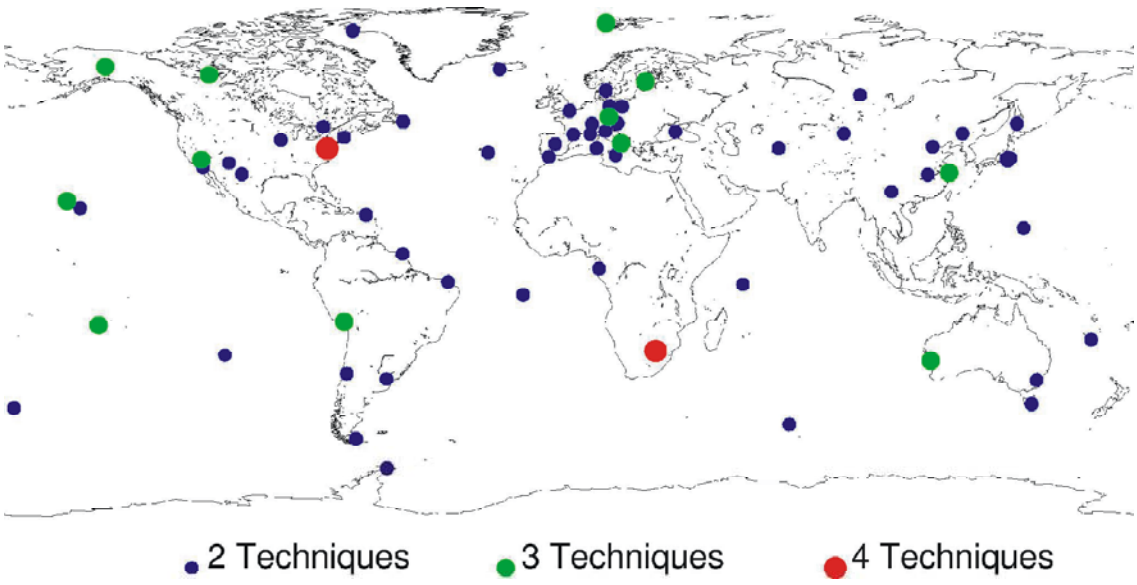


Figure 2: Current co-locations of space geodetic techniques (Since 1999)

3.3 New Local Ties Evaluation

After the ITRF2000 report 4 on local ties, it seems necessary to evaluate the current situation of the available local ties. A global combination test was then performed based on the following time series data:

- VLBI: 24h-session SINEX files over 1990-2003, provided by Goddard Space Flight Center (GSFC) VLBI Group, using the terrestrial reference frame of gsfd001 (IVS, 2003),
- SLR: weekly solutions over 1993-2003, provide by the Italian Space Agency (ASI), (Luceri, 2003),
- GPS: Official IGS weekly combined solutions over 1999-2003 (Ferland, 2003)
- DORIS: IGN-JPL weekly solutions over 1993-2003 (Willis, 2003).

As results of this combination tests, Tables A1 and A2 in the appendix list the missing and inconsistent (dubious) tie vectors. Table A2 lists differences, in geocentric and local frame, larger than one centimeter (2 cm in case of DORIS ties to the other techniques) between the available local tie values and space geodesy estimates as results from the multi-technique test combination. Concerning Table A2 it is possible to identify which point is most dubious when at least 3 systems are present, as for example 12734/Matera VLBI 40424/Kauai GPS.

3.4 Priority list of Problematic Sites

Based on ITRF2000 analysis and the combination test presented here, Table A3 of the appendix lists the priority sites to be (re)-surveyed. The site selection is based on the following criteria:

- Missing ties
- Critically inconsistent (dubious) ties: differences larger than 1 cm for VLBI/SLR/GPS and 2 cm for DORIS sites, see table A2 of the appendix
- Co-location sites after an Earthquake

4 Recommendations

Some important recommendations related to local surveys and co-location sites were already addressed during the IERS Workshop in Munich 2002 (Altamimi et al, 2002). These recommendations are reproduced, emphasized and augmented below.

Recommendation 1: In order to improve co-location sites distribution and observing networks:

- International effort is needed to improve VLBI-SLR co-locations by installing new SLR systems (e.g. SLR2000) at all VLBI sites. These are very critical for the long term TRF scale maintenance.
- IVS is urged to schedule repeated Global-TRF observing sessions;
- IDS is asked to consider installing DORIS beacons at all SLR and VLBI sites, starting with sites collocated with GPS in order to augment the number/distribution of the 4-technique “primary” sites.

Recommendation 2: The Working Group on Local Ties is asked to organize repeated (yearly !) local surveys at all available co-location sites. Per-site local tie components (at the survey epoch) and their time variations should be provided in SINEX format with full variance-covariance matrix. The priority list of sites (re-)surveys should be organized as follows:

- start with sites where local ties are missing and critically dubious, e.g. Shanghai
- after Earthquakes, e.g. Arequipa, Fairbanks
- Sites for which full SINEX files are not available, so that ultimately all co-location sites should have local ties expressed in SINEX format. It might be possible that full SINEX files can be computed for surveys performed in the past (if the necessary information is still available or can be recomputed).

Recommendation 3: The IERS Directing Board is asked to consider establishing Associated Analysis Centers for Local Ties survey and analysis, analogous to the existing Analysis Centers of space geodesy techniques.

Recommendation 4: For the long term maintenance of co-location sites and thus the ITRF global stability, the urgent action is to envisage new design of ITRF Core Co-location Sites (ICCS), the indispensable "ITRF Pillars", with global coverage, stable and solid monumentation, regularly/repeatedly surveyed and geophysically monitored.

Recommendation 5: The technique services (IGS, IVS, ILRS, IDS) should try to detect and assess the size of systematic biases that may be present in their solutions.

References

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Appendix

Table A1: Currently Missing Ties: Not available at ITRS PC (October 2003)

DOMES	Name	Techniques involved
12329	YUZHNO-SAKHALINSK	GPS-DORIS
12337	SIMEIS KATZIVELY	SLR-VLBI
12725	CAGLIARI	GPS (CAGZ)-SLR
14201	WETTZELL	VLBI TIGO-SLR/GPS
21602	WUHAN	SLR-GPS
21605	SHANGHAI	GPS-SLR/VLBI
21609	KUNMING	SLR-GPS
21612	URUMQI	VLBI-SLR/GPS
21729	USUDA	GPS-VLBI
30314	SUTHERLAND	GPS SUTM - SLR
40419	KODIAK	Mobile VLBI-GPS
40424	KAUAI	DORIS-GPS
40445	MAUI	GPS-SLR
40499	RICHMOND	VLBI-SLR/GPS
41609	CACHOEIRA PAULISTA	GPS-DORIS
41705	SANTIAGO	SLR-GPS
41719	CONCEPCION	TIGO points (Imprecise tie (+/- 2cm))

Table A2: Inconsistent local ties as results from a multi-technique test combination (October 2003): Differences with space geodesy estimates larger than 1 cm for VLBI-GPS-SLR ties and 2 cm in case of DORIS ties to the other techniques.

Tie Vector		dX	dY	dZ	dE	dN	dUP	CODE	CODE	Techniques	Site Name
FROM	TO	cm									
10317M003	10317S002	0.2	2.7	-1.1	2.6	-0.9	-0.9	NYA1	SPIA	GPS-DORIS	NY-ALESUND
10503S011	10503S014	-0.5	-0.2	-0.9	0.0	0.1	-1.0	METS	7806	GPS-SLR	METSAHOVI
12349M002	12349S001	-1.8	-2.1	-1.5	1.9	0.8	-2.4	KSTU	KRAB	GPS-DORIS	KRASNOYARSK
12334S006	12334M001	4.7	-4.8	-0.9	-6.3	0.9	-2.6	KIT3	KIUB	GPS-DORIS	KITAB
12717S001	12717M003	-0.7	0.4	0.9	0.5	1.1	0.0	7547	NOTO	VLBI-GPS	NOTO
12734M004	12734S005	0.8	-1.0	-0.3	-1.2	-0.6	0.2	7541	7243	SLR-VLBI	MATERA
12734M008	12734S005	0.8	-1.0	-0.3	-1.2	-0.6	0.1	MATE	7243	GPS-VLBI	MATERA
12734S001	12734S005	0.8	-0.9	-0.9	-1.1	-1.0	-0.2	7939	7243	SLR-VLBI	MATERA
13402M004	13402S007	-2.2	1.1	-1.9	0.9	-0.1	-3.0	SFER	7824	GPS-SLR	SAN FERNANDO
13420M001	13420S001	-1.5	0.2	-0.1	0.1	0.9	-1.2	YEBE	7333	GPS-VLBI	YEBES
14106S011	14106M003	2.2	2.1	3.2	1.5	-0.1	4.1	7841	POTS	SLR-GPS	POTSDAM
21601S004	21601M001	0.8	-1.0	-2.7	-0.3	-1.3	-2.7	7249	BJFS	SLR-GPS	BEIJING
21605S001	21605S009	-2.4	1.3	1.9	1.4	0.5	3.0	7837	7227	SLR-VLBI	SHANGHAI
39801S005	39801M001	7.0	3.4	0.5	-3.8	1.0	6.6	SEY1	MAHB	GPS-DORIS	MAHE ISLAND
40127M003	40127M004	-0.1	0.3	-1.0	-0.2	-0.3	-1.0	YELL	7296	GPS-MVLBI	YELLOWKNIFE
40405S005	40405S019	4.0	3.3	-0.4	2.1	2.4	-4.1	GOMA	1515	DORIS-VLBI	GOLDSTONE
40405S019	40405S035	0.9	0.2	2.6	0.7	2.4	1.0	1515	GOLA	VLBI-DORIS	GOLDSTONE
40405S019	40405S037	-3.5	-3.8	0.5	-1.4	-2.5	4.3	1515	GOMB	VLBI-DORIS	GOLDSTONE
40408M001	40408S004	1.9	2.9	-1.3	-1.4	2.3	-2.5	FAIR	FAIA	GPS-DORIS	FAIRBANKS
40424M004	40424S001	3.0	-1.3	3.3	2.3	4.0	-0.9	KOKB	1311	GPS-VLBI	KAUAI
40424M004	40424S007	3.1	-1.2	3.1	2.2	3.8	-1.1	KOKB	7298	GPS-VLBI	KAUAI
40424M004	40424S008	2.6	-1.6	3.2	2.4	3.6	-0.5	KOKB	KOKA	GPS-DORIS	KAUAI
40442M006	40442S017	-0.4	-0.7	1.0	-0.2	0.4	1.2	7080	7613	SLR-VLBI	FORT DAVIS
40442M012	40442S017	-0.4	-0.9	0.4	-0.2	-0.2	1.1	MDO1	7613	GPS-VLBI	FORT DAVIS
40456M001	40456S001	-1.0	0.9	-0.9	-1.2	-0.4	-1.0	PIE1	7234	GPS-VLBI	PIETOWN
40499M002	40499S001	0.2	0.9	-1.1	0.4	-0.6	-1.2	7295	7219	SLR-VLBI	RICHMOND
41507S005	41507M004	-2.5	1.8	1.9	-1.6	-0.9	-3.1	RIPB	RIOG	DORIS-GPS	RIO GRANDE
50103M108	50103S007	2.7	-1.0	1.6	-0.5	-0.3	-3.2	TIDB	7843	GPS-SLR	TIDBINBILLA
50103M108	50103S202	3.1	-1.1	1.6	-0.6	-0.6	-3.5	TIDB	ORRB	GPS-DORIS	TIDBINBILLA

Table A3: Priority list of co-location sites to be (re)-surveyed

DOMES	Name	VLBI	SLR	GPS	DORIS	Missing	Inconsistent
12329	YUZHNO-SAKHALINSK			x	x	x	
12337	SIMEIS KATZIVELY	x	x			x	
12334	KITAB			x	x		x
12349	KRASNOYARSK			x	x		x
12711	NOTO	x	x	x			x
12734	MATERA	x	x	x			x
13402	San Fernando		x	x			x
14106	POTSDAM		x	x			x
21601	BEIJING		x	x			x
21602	WUHAN		x	x		x	
21605	SHANGHAI	x	x	x		x	x
21609	KUNMING		x	x		x	
21612	URUMQI	x	x	x		x	
21729	USUDA	x		x		x	
39801	MAHE ISLAND			x	x		x
40405	GOLDSTONE	x	x	x	x		x
40408	FAIRBANKS	x		x	x	EQ	
40424	KAUAI	x		x	x		x
40442	FORT DAVIS	x	x	x			x
40446	PIE TOWN	x		x			x
40445	MAUI	x		x		x	
42202	AREQUIPA		x	x	x	EQ	