TIGO and its Future Application for the ITRF

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Abstract

The Transportable Integrated Geodetic Observatory (TIGO) is a fundamental station for geodesy. All relevant sensors for space geodesy like VLBI radiotelescope, SLR telescope, GPS receiver and additional devices like time and frequency standards, a super conducting gravity meter, seismometer, meteorological sensors are collocated at one site. The local geometrical tie is provided by a local survey. A possible reoccupation of a previous TIGO site demands special considerations for the construction of a transportable observatory. The advantage of TIGO is its transportability, which allows to occupy sites in areas in the southern hemisphere and also to react in a flexible manner to changing situations concerning the geographical distribution of the contributors within the ITRF. The method of the largest empty circle allows to find new site candidates to achieve successively a homogeneous distribution.

1. TIGO - A Transportable Fundamental Station

The Transportable Integrated Geodetic Observatory (TIGO) was designed to serve the terrestrial reference frames at remote locations in the southern hemisphere outside Antarctica. TIGO was designed to function as a *fundamental station for geodesy*, which means to operate *permanently*, to employ *complementary* and *redundant* sensors *collocated* at one site. Hence TIGO consists of (1) a radiotelescope for geodetic VLBI, (2) an optical telescope for SLR, (3) a GPS receiver array to monitor permanently the regional stability of the site, (4) a super conducting gravity meter, (5) a broadspectrum seismometer, (6) meteorological sensors, (7) surveying instruments for the local tie.

The aspect of permanency and transportability appears to be contradictionary. But the distribution of ITRF sites is insatisfactory in the southern hemisphere due to the lack of resources and land surface. For the improvement of the global reference frame it is important to operate more collocated sensors as fundamental stations in the south. The transportability of TIGO has the advantage to (re)occupy more than just one site for periods longer than one year (to monitor annual phenomenas). A reoccupation after a couple of years can be seen as permanency synthesis.

For transportation all instruments will be housed in six standard containers. During the operation the containers are transformed to the operation rooms, workshops and power plant.

2. Distribution of Fundamental Stations

The key role in the generation of terrestrial reference frames like the ITRF is played by fundamental stations, which contain all important space geodetic techniques as such as VLBI, SLR, GPS and possibly DORIS at one site and which are operated on a long term

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basis emitting high quality data. The concept of fundamental stations allows the determination of the excentricity vectors between the geodetic reference points by the means of a local terrestrial survey. *It is the local survey which enables a combined solution of all geodetic space techniques resulting into the ITRF.* Therefore special care must be given in the process of construction of the space geodetic sensors in order to realize accessible reference points at the telescopes or antennas. The accuracy of the local survey should be one order of magnitude higher than the one achieved by (inter)continental baseline measurements with geodetic space techniques.

In 1998 the ITRF contained only a few sites which deserve the title of a fundamental station. These are *Wettzell* (Germany), *Matera* (Italy), *KeyStone* (Japan), *Greenbelt*, (U.S.A.).

In addition there are some quasi-fundamental stations, where the distances between the different instruments are larger than 1 km. This makes the local survey on the accuracy level better than that coming from the geodetic space techniques more difficult. However the results from these stations represent within a global reference frame the same region and are subject of almost the same geodynamic phenomena. The list of these stations consist of *Shanghai* (P.R.China), *Canberra-Tidbinbilla* (Australia), *Kokee Park-Maui* (Hawaii). An additional fundamental station at *Hartebeesthoek* (R.S.A.) will be created with the beginning of a permanent operation of MOBLAS-6.

These observatories represent the backbone of global geodetic reference frames. As many of ITRF sites have been selected due to national interests rather than under global network aspects, the site distribution is very inhomogeneous and adverse. For a *global* reference frame a more homogeneous site distribution is required in order to: (1) understand the system Earth and test global plate tectonic models, (2) avoid systematics in the determinations of satellite orbits, (3) provide globally the same level of accuracy of the reference frame.

Due to the limited resources to improve the distribution of fundamental stations on the globe, two requirements become obvious:

- need for additional fundamental stations,
- need for a method to locate new sites which will optimally homogenise a given point distribution.

TIGO is an additional fundamental station, which has due to its transportability the ability to be placed on those sites, which contribute in an ideal way to the process of homogenisation of inhomogeneous networks.

3. Method of Densification of Inhomogeneous Cospherical Point Fields

Where should a new fundamental station be located? Besides geological, climatical, social and political arguments it exists also a strict geometrical approach to homogenise the unequal distribution.

The location which is most remote to a given point distribution is the optimal choice in the process of homogenisation (*'fill the gap'*). After including the most remote location to the point distribution the next most remote location can be defined. With infinite iterations of adding always the most remote location as new point it is possible to achieve a homogeneous point distribution (Hase, 1998).

This method can be applied to a spherical point distribution. In a first order approximation we assume that the existing fundamental stations are located on a sphere. If one is able to locate the most remote point from the other platforms, that would be the best candidate to setup a new site for the homogenisation process. With infinite iterations by adding always the most remote point (or a site being closely located to the most remote point in case it is in the ocean) the inhomogeneous site distribution converges to more homogenity.

In order to solve this problem mathematically, one has to find the largest empty circle, in which no existing observatory is situated. A circle is defined by three points. The center of the largest empty circle is the most remote location from the existing point distribution. Therefore the densification process can also be called the **method of the largest empty circle**.

In a 2-dimensional plane the Delaunay-triangulation provides the necessary information about which are the closest point neighbours to any given point. If the point distribution is cospherical, then the *normals of each Delaunay triangle* indicate the center of a circle which is also called the *Voronoi-vertex*. The geometrical dual to the Delaunay triangulation is the Voronoi-diagram, which contains the Voronoi-ridges marking the lines of maximum distance to the given point distribution (O'Rourke, 1994). Since the Voronoi-vertices identify the points of largest distance to the three surrounding given points, it is easy to find the most remote Voronoi-vertex among them which is the center of the largest empty circle.

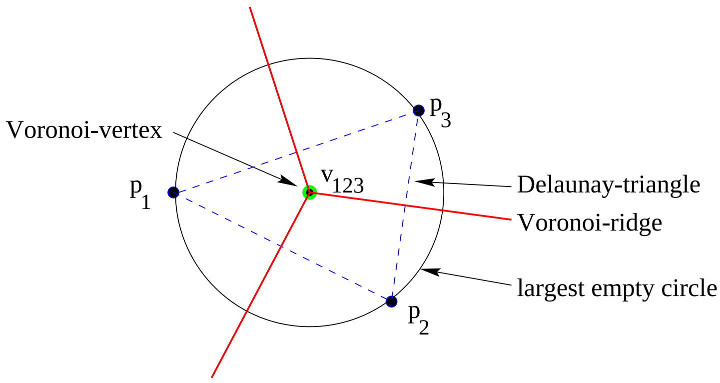

Figure 1. Delaunay-triangle $\overline{p_1p_2p_3}$ and Voronoi-vertex v_{123} in a plane. The Voronoi-ridges mark the lines of maximum distance from the given point distribution. On a sphere the Voronoi-vertex corresponds to the normal of a 3-dimensional Delaunay triangulation of a cospherical point distribution.

4. Proposed Sites for Fundamental Stations according to the Method of the Largest Empty Circle

The site selection according to the method of the largest empty circle considers geometrical aspects only. Other aspects regarding the use of TIGO needs to be considered: (1) partner institute in the hosting country for a joint operation of TIGO, (2) geophysical stability of the site, (3) climatic conditions of the site, (4) property of partner institute to build the platform for TIGO, (5) provided infrastructure by the partner institute, (6) educational level of operators.

For the proposal of possible locations for the fundamental station TIGO one has to consider the global distribution of existing fundamental stations. For the following computations a set of station coordinates given in table 1 had been used.

The repeated computation of the largest empty circle on a global sphere with adding one new site in each step is given in the following subsections. The fundamental stations listed in table 1 had been used as the initial site distribution. The Voronoi-diagrams

Table 1. Averaged coordinates of fundamental stations based on the ITRF96. After reduction to a unit sphere they have been used for the *largest empty circle* computation to find the best new locations for fundamental stations within the ITRF.

Name	Longitude [°]	Latitude [°]	Höhe [m]
Wettzell	12.878	49.145	662.996
Matera	16.704	40.649	534.371
Hartebeesthoek	27.697	-25.888	1486.177
Shanghai	121.255	31.122	15.656
Tokyo	139.489	35.710	122.447
Canberra/Tidb.	148.962	-35.517	934.191
Kokee Park	-159.665	22.126	1167.349
Greenbelt	-76.827	39.022	14.505

below indicate the sites of fundamental stations with (blue) stars while the centers of the three largest empty circles are marked with a (green) circle and the ordering number. The Voronoi-ridges as lines of maximum distance from two neighbouring sites are marked with (red) continous lines. The table to each plot lists the geographical location of the Voronoi-vertices and the radius of the largest empty circle as baseline to the closest sites.

The results of this analysis give a first clue for sites in the southern hemisphere, which deserve a fundamental station for the improvement of the distribution in the global network. The final decision about the abroad sites for TIGO has to consider the other above mentioned and not computable aspects as well.

4.1. Computation of the 1st Proposed Site

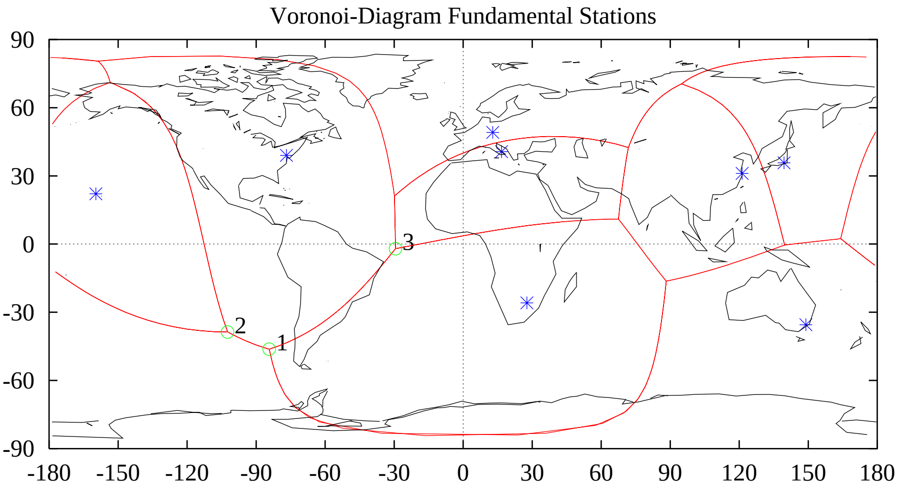

Figure 2. Voronoi-diagram with fundamental stations. The numbered Voronoi-vertices label the order of the largest empty circle (1=largest, 2= second largest, 3 = third largest empty circle). There is a lack of fundamental stations in the southamerican-pacific area. As first proposed site the close by town of Valdivia in the south of Chile was selected in the first step.

Table 2. Coordinates of the Voronoi-vertices and baseline radii of their cocircle (Fig. 2).

vertex	longitude [°]	latitude [°]	baseline radius [km]
1	-84.295	-46.276	8648.410
2	-102.360	-38.654	8280.435
3	-29.389	-2.019	6349.454
4	88.310	-16.316	6076.100
5	67.505	11.028	5732.164
6	-158.712	80.498	5437.311
7	-153.364	71.160	5320.694
8	-29.861	21.200	4752.523
9	94.938	70.516	4588.110
10	71.847	42.462	4429.093
11	164.131	2.352	4391.572
12	139.744	-0.423	3936.786

The largest empty circle has a baseline radius of 8648 km and covers almost a complete hemisphere of which most of the area is in the southern hemisphere. This fact emphasizes the lack of a fundamental station in the southamerican-pacific area. Since the center point of the largest empty circle is in the ocean the town of **Valdivia** in the south of Chile was in the subsequent computations chosen as a suitable first proposed site.

The next steps of iterations point to locations near **Ascension**, **Cocos Island** and **Pitcairn Island**, which have been successively included. These steps are not illustrated here. With these sites included a much more homogeneous distribution of fundamental stations could be achieved (Fig. 3).

4.2. Computation of the 5th Proposed Site

After the inclusion of the additional four sites the next recommended sites are located in either antarctic or arctic regions.

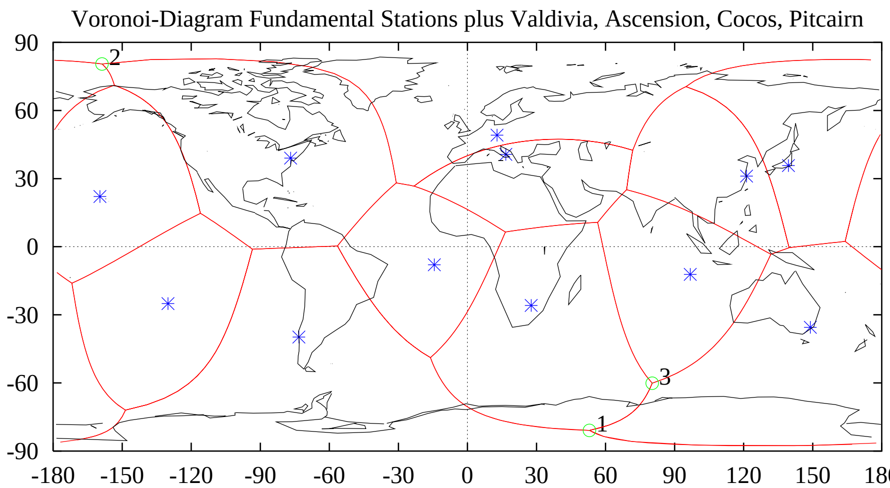

Figure 3. Voronoi-diagram with fundamental station with respect to four additional sites in Valdivia, Ascension, Cocos Island and Pitcairn Island. In this configuration the recommended sites are located in antarctic or arctic regions.

Table 3. Coordinates of the Voronoi-vertices and baseline radii of their cocircle with respect to four additional sites in Valdivia, Ascension, Cocos Island and Pitcairn Island (Fig. 3).

vertex	longitude [°]	latitude [°]	baseline radius [km]
1	52.964	-80.901	5999.380
2	-158.713	80.499	5437.318
3	80.292	-60.083	5341.655
4	-153.364	71.160	5320.694
5	-148.574	-71.997	5208.071
6	56.585	10.709	4987.213
7	69.151	25.092	4980.047
8	-56.485	0.332	4651.939
9	-93.404	-1.062	4644.672
10	94.938	70.517	4588.103
11	-115.973	14.714	4567.480
12	-16.083	-48.828	4464.338
13	71.847	42.463	4429.093
14	164.131	2.353	4391.573
15	-171.801	-16.080	4350.850
16	-30.907	28.080	4294.909
17	139.744	-0.424	3936.793
18	131.828	-3.324	3913.007
19	-23.212	26.693	3901.791
20	16.522	6.471	3728.283

From table 3 it can be seen that the baseline radius of the largest empty circle is about 6000 km without and about 5000 km with occupations in the arctic regions. The map of figure 3 shows with the above mentioned four additional points already a much more homogeneous site distribution in comparision with original situation at present shown in figure 2.

5. Conclusion

The *method of the largest empty circle* is an optimal approach to identify the most important sites for the homogenisation of a given point distribution. It can be applied to any kind of networks. In a network of fundamental stations this method indicates the largest gaps and the best locations for new foundations of fundamental stations. If this method would be applied to define locations for any new station the distribution of existing observatories in a global network would converge to homogenity. Under this aspect TIGO is the ideal tool for the densification of the ITRF. If the network configuration changes over time, TIGO could be again positioned at the most useful site to densify the ITRF optimally.

References

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