Apparent and Real Local Movements of two Co-Located Permanent GPS Stations at Bogotá, Colombia

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Summary

Simultaneous observations from two co-located permanent GPS stations at Bogotá, Colombia, are analyzed with regard to local movements. The two years time series of daily estimates of the 192 m long baseline yields a linear change of the vector components of 7.4, –4.6 and –7.0 mm/yr in north, east and vertical direction respectively. In addition, the baseline height component shows systematic effects during periods of between some days and several weeks. For assessing the effects absolutely and for identifying the responsible station, observations from two distant permanent GPS stations are included in the analysis. The results prove that the relative movement is real and is caused by the building housing one of the stations. The offsets in the height estimates can be allocated to the other station. Its antenna is mounted on a concrete pad with bordering which seems to be flooded during periods of heavy rainfall. This leads most likely to multipath effects and to changes of the electrical properties of the antenna, and consequently to apparent positive height changes. Comparisons with precipitation data support this finding.

Zusammenfassung

Die simultanen Beobachtungen zweier benachbarter GPS-Permanentstationen in Bogotá, Kolumbien, werden hinsichtlich lokaler Bewegungen analysiert. Die zweijährige Zeitreihe täglicher Ausgleichungen der 192 m langen Basislinie zeigt lineare Änderungen des Vektors zwischen beiden Antennen von 7.4, –4.6 und –7.0 mm/Jahr in Nord-, Ost- und Höhenkomponente. Außerdem treten in der Höhe systematische Abweichungen während Perioden von einigen Tagen bis zu mehreren Wochen auf. Um die Bewegungen absolut zu erfassen und die verursachende Station zu identifizieren, werden Messungen zweier entfernter Permanentstationen einbezogen. Die Ergebnisse belegen, dass die Relativbewegung zwischen den beiden Stationen in Bogotá real ist und durch das Gebäude verursacht wird, auf dessen Dach eine der beiden Antennen montiert ist. Die systematischen Abweichungen in den Höhenergebnissen können der anderen Station zugeordnet werden, deren Antenne auf einem ebenerdigen Betonfundament mit Randeinfassung montiert ist. Dieses Fundament scheint bei starken Regenfällen überflutet zu werden. Dadurch werden Mehr-

wegeeffekte und Änderungen der elektrischen Eigenschaften der Antenne erzeugt, die zu scheinbaren positiven Höhenänderungen führen. Vergleiche mit Niederschlagsmengen unterstützen diese Aussage.

1 Introduction

A permanent Global Positioning System (GPS) station with the identification BOGT in the global network of the International GPS Service (IGS) was in operation at Bogotá, Colombia, since November 1994, but ceased its operation by the end of 1999. The latest realization of the International Terrestrial Reference Frame (ITRF2000) quotes for BOGT a vertical velocity of −27.2 mm/yr (Altamimi et al. 2002, http://lareg.ensg.ign.fr/ITRF). After a replacement of the receiver the station has been operating again since late May 2002. Actual analyses by the Scripps Institution of Oceanography (SIO) and the Jet Propulsion Laboratory (JPL) including also the new data up to early 2004 yield even slightly larger vertical velocities (http://sopac.ucsd.edu/cgi-bin/plotTimeSeriesServlet.cgi; http://sideshow.jpl.nasa.gov/mbh/all/BOGT.html). Tab. 1 summarizes the results from the three solutions, but does not include the standard deviations because these differ by one order of magnitude depending on the analysis strategy and are therefore no reliable indicator of accuracy.

Tab. 1: Velocity estimates of the permanent GPS station BOGT (mm/yr)

Solution	Data Span	North	East	Height
ITRF	1994.9 – 1999.9	13.4	2.1	−27.2
SIO	1994.9 – 2004.4	11.9	0.8	−28.2
JPL	1994.9 – 2004.2	12.9	0.4	−33.3

The reason for the obviously continuous subsidence of the area probably is that the city of Bogotá is situated in an extended sediment basin at about 2600 m altitude in the eastern cordillera of the Andes, surrounded by mountains rising to 3500 m. There are oceanic and continental sedimentary structures with a thickness of up to 3000 m, the main constituents being clays. In the area of the station there are also deposits of materials produced by fracturing and erosion processes, which form a soft and highly compressible layer complicating the construction of buildings.

In February 2000 the Deutsches Geodätisches Forschungsinstitut (DGFI) in collaboration with the Instituto Geográfico Agustín Codazzi (IGAC) installed another permanent GPS station BOGA on the roof of IGAC's eight floors office building in less than 200 m distance from BOGT. The observations collected by BOGA are at DGFI included in the routine processing of the IGS densification network of South America. Previous episodic GPS measurements at the BOGA marker as well as spirit levelling between BOGA and BOGT indicated that the IGAC building might experience an even larger subsidence than BOGT and also a relative horizontal movement. Therefore, in absence of BOGT data an analysis of the first year of observations acquired at BOGA since its establishment was done by processing the 656 km long baseline to the nearest permanent station at Cartagena (Kaniuth et al. 2002a). The results clearly indicated a tilted movement of BOGA towards north-north-west. This finding was supported by the fact that the pointer of the spherical mass of a 29 m long pendulum in the entrance hall of the building was at that time displaced by 18 cm. The recent availability of simultaneous observations from the two co-located stations BOGA and BOGT allows to study in detail any local movements occurring at the site. Therefore, we analyze in this study all data acquired between May 2002 and June 2004.

2 GPS Data Analysis

2.1 Local Baseline

The GPS data processing is done with the Bernese software system version 4.2 (Hugentobler et al. 2001), the principal strategy of which is the so-called double difference approach: Instead of the original phase observations the differences between measurements at two stations to two satellites are processed. This approach eliminates the satellite and receiver clock errors. The satellite orbits determined by the IGS are kept fixed in all adjustments.

In case of the local baseline BOGA-BOGT there is no need for estimating tropospheric path delay corrections from the GPS data nor for eliminating the ionosphere by creating the ionosphere free linear phase combination L3. Instead, the L1 and L2 phase measurements can be analyzed, because the ionosphere affects both stations likewise and the effect cancels in the double difference processing. The same holds for the troposphere, where a prediction based on standard meteorological conditions is sufficient, which accounts for the approximate height difference between both antennas. The L1 and L2 phase ambiguities can be completely resolved on this short baseline.

Tab. 2 documents the observations available between day 151, 2002 and day 180, 2004. Unfortunately, there

Tab. 2: Number of common observation days and gaps at BOGA and BOGT

Period [Year, Day of Year]	Obs.	Gaps
2002,151 – 2002,365	202	13
2003, 43 – 2004, 51	365	9
2004, 87 – 2004,180	85	9

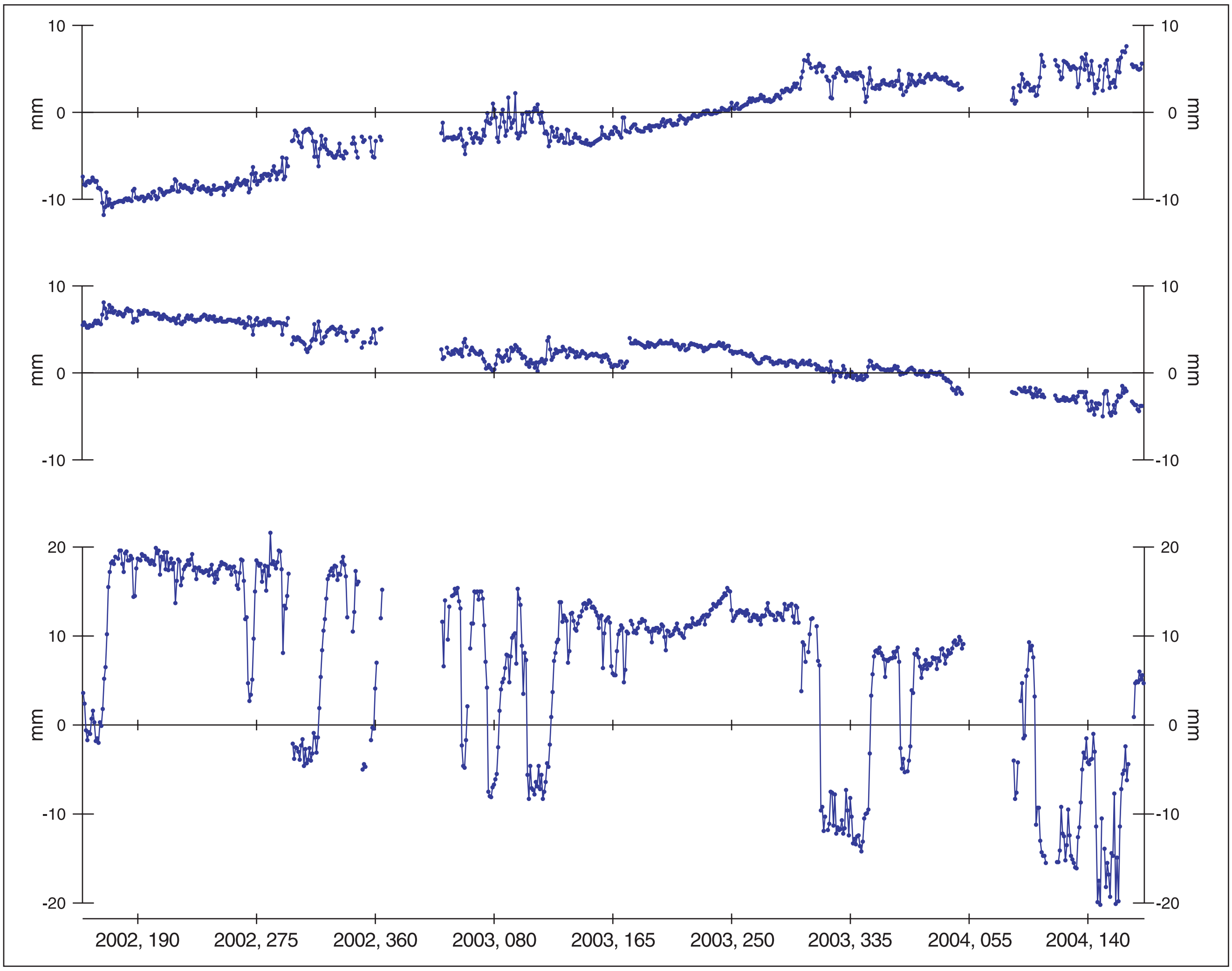

Fig. 1: Daily L1 estimates BOGA–BOGT during the period 2002, day 151 – 2004, day 180: north (top), east (middle) and vertical (bottom) component (approximate values subtracted)

are two longer interruptions and in addition some gaps of single days. Thus, in total 652 days of observations are available. Daily baseline adjustments, separately for L1 and L2, are performed, constraining one station to its coordinates in the ITRF2000 system. Fig. 1 displays the time series of daily L1 estimates of the ellipsoidal coordinate differences BOGA-BOGT with respect to approximate values.

It is evident that

- there is a clear trend in all three baseline components,
- several negative systematic offsets appear in the vertical component during periods of a few days and several weeks.

The small discontinuity showing up in the east component is probably due to an exchange of the BOGT antenna on June 23, 2003. The L2 series look very similar, and also the short period height offsets show up likewise. In order to assess the effects quantitatively, adjustments of the L1 and L2 time series are performed. These solve for mean ellipsoidal coordinate differences at epoch 2003.5, linear relative velocities and constant height offsets for the identified biased periods. Considering the length of the time series and the gaps in it, we do not solve for annual variations. According to Blewitt and Lavallée (2002) this could corrupt the linear velocity estimates as long as the time series extends not at least over 2.5 years. Tab. 3 gives the estimated linear velocities from the L1 and L2 adjustments and shows also the root mean square agreements of the daily estimates with the solution, which is in case of the horizontal components surprisingly better for L2 than for L1. Tab. 4 gives some examples of estimated height offsets, again for both L1 and L2. These offsets result from the time series adjustment; thus, they are relative to the mean height difference and the linear trend.

So far we can state that the building housing the BOGA station moves with respect to BOGT about 7.4 mm/yr

Tab. 3: Linear velocity of BOGA relative to BOGT

Component	RMS [mm]		Velocity [mm/yr]	
	L1	L2	L1	L2
North	1.5	1.2	7.7 ± 0.10	7.1 ± 0.08
East	1.1	0.9	–4.6 ± 0.07	–4.6 ± 0.06
Height	2.8	2.9	–6.9 ± 0.23	–7.0 ± 0.24

Tab. 4: Examples of estimated height offsets BOGA-BOGT

Period [Year, Days]	L1 [mm]	L2 [mm]
2002, 151 – 167	–16.4 ± 0.7	–15.1 ± 0.7
2002, 301 – 321	–17.1 ± 0.6	–18.5 ± 0.6
2003, 104 – 121	–17.0 ± 0.7	–15.8 ± 0.7
2003, 314 – 349	–18.3 ± 0.5	–17.1 ± 0.5
2004, 103 – 135	–17.6 ± 0.6	–17.1 ± 0.6

towards north, 4.6 mm/yr towards west and –7.0 mm/yr vertically (Tab. 3). As regards the short period height offsets, the daily baseline adjustments do not show any details as to the evolution of these effects. Therefore, we perform for some relevant periods adjustments in two hours intervals. Fig. 2 displays such a high resolution height difference time series over five days. This example shows the transition phase from unbiased to biased height estimates. The other analyzed periods look very similar. It seems as if the phenomenon is caused by any environmental changes at either of the antennas. However, at this stage we cannot identify the responsible station. Therefore, we extend the analysis to distant GPS stations.

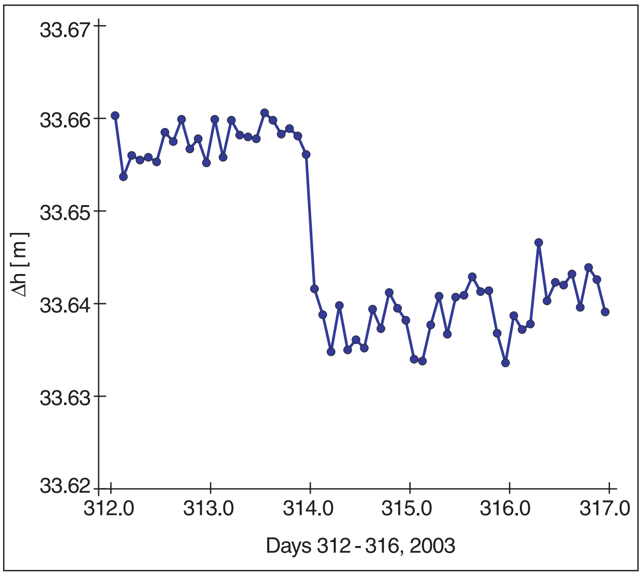

Fig. 2: Two-hourly L1+L2 height difference estimates BOGA-BOGT during days 312–316, 2003

2.2 Regional Baselines

Including longer baselines is a means to gain further insight into the local phenomenon occurring in Bogotá and to identify the responsible station, provided the noise level of the daily height difference estimates on these baselines is well below the effect to be investigated. The selection of proper stations is not as easy as e.g. in Europe, because the network of permanent GPS stations in South America is still sparse. The requirement, that the selected stations should be with high accuracy represented in the ITRF2000 reduces the candidates to a very few, and the distances to Bogotá will already be in the order of 2000 km. We exclude Arequipa (AREQ) because this station experienced more than half a meter displacement due to heavy earthquakes in June/July 2001 (Kaniuth et al. 2002b), and its new position and velocity is not yet very well determined. Therefore, we select Kourou (KOUR), 2347 km east of Bogotá, and Galapagos (GALA), 1893 km west-south-west of Bogotá. GALA has been replaced by a new station GLPS at the same site in early 2003.

We process the baselines between these stations and BOGA as well as BOGT during several periods where the anomalous height effects at Bogotá occur. The main differences to the analysis of the local baseline are, that the ionosphere free linear phase combination L3 is processed instead of L1 and L2, and that the tropospheric delays are estimated for each station from the GPS data without introducing any prediction. The Niell (1996) mapping function is applied in all these adjustments.

Fig. 3 displays the results from processing the baselines between KOUR and GLPS and the two Bogotá stations BOGA and BOGT during a 30 days period. We show the ellipsoidal height differences BOGA-BOGT from the L1+L2 solutions of the local baseline and the L3 adjustments of the regional baselines. The Fig. covers a transition phase from a biased to an unbiased period at Bogotá. There is no obvious explanation for the effect that the L3 solution seems to recover earlier from the anomalous offset than the L1+L2 solution. However, this phenomenon appears in all analyzed periods. The mean values of the height estimates during the biased and unbiased periods are summarized in Tab. 5, which documents also the results for another 30 days time span one and a half years earlier. In both examples the mean values exclude the

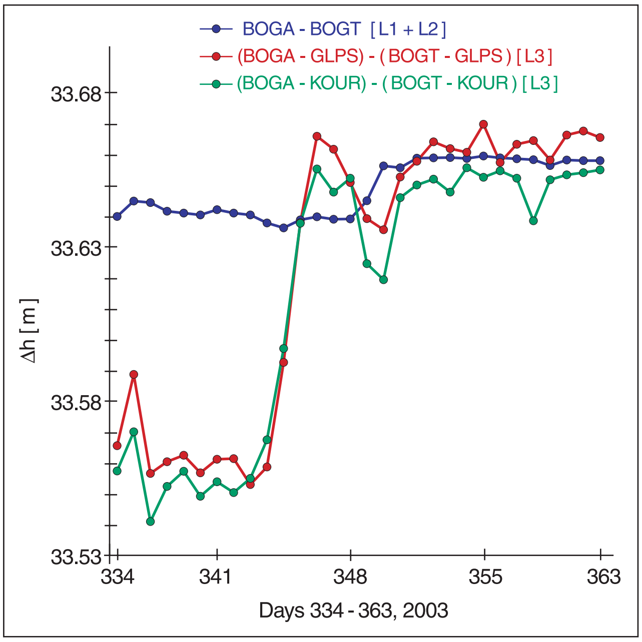

Fig. 3: Ellipsoidal height differences BOGA-BOGT derived from the local and the regional baselines during days 334–363, 2003

Tab. 5: Mean ellipsoidal heights (m) of BOGA and BOGT during biased and unbiased periods (* = biased period)

Period [Year, Days]	Reference Station	Ellipsoidal Height [m]	
		BOGA	BOGT
2002, 151 – 162*	KOUR	2610.517 ± 0.003	2576.954 ± 0.003
	GALA	2610.519 ± 0.002	2576.942 ± 0.003
2002, 164 – 180	KOUR	2610.516 ± 0.003	2576.856 ± 0.004
	GALA	2610.525 ± 0.003	2576.862 ± 0.004
2003, 334 – 344*	KOUR	2610.454 ± 0.003	2576.898 ± 0.004
	GLPS	2610.454 ± 0.002	2576.892 ± 0.003
2003, 351 – 363	KOUR	2610.455 ± 0.004	2576.793 ± 0.003
	GLPS	2610.454 ± 0.001	2576.791 ± 0.002

transition days between biased and unbiased periods. The heights refer to the World Geodetic System 1984 (WGS84) ellipsoid. The reference stations are constrained to their ITRF2000 positions. Therefore, the absolute values of the BOGA and BOGT heights may slightly depend on the selected reference station. The quoted standard deviations are derived from the scatter of the daily solutions. The height changes of both stations in Bogotá during one and a half year demonstrate the dramatic subsidence of more than 3 cm/year. Whereas there are no systematic variations of the BOGA height estimates during each of the two 30 days periods, the station BOGT experiences apparent height jumps of about 9 to 10 cm. The results will be discussed further in the next chapter, but the following can already be stated:

- The station BOGT is responsible for the offsets appearing in the time series of height difference estimates BOGA-BOGT.
- As found in section 2.1 these offsets do not exceed 2 cm if the local baseline is processed with L1 or L2.
- The offsets in the height estimates of BOGT increase tremendously by approximately a factor of four or five when long baselines are processed with L3 and tropospheric delays are estimated.

3 Discussion of Results

The apparent height changes of Station BOGT are similar to the effect occurring when a radome is mounted on or removed from an antenna. The height estimates change only by some mm if L1 or L2 are processed, but up to one order of magnitude more if L3 is processed and tropospheric delays are estimated (Kaniuth and Huber 2003). Therefore, we look closer at the troposphere estimates on the longer baselines. Fig. 4 shows the mean differences between the 12 daily zenith delay estimates of BOGA and BOGT for the same 30 days period as in Fig. 3. As the height difference between both antennas is about 33.6 m, the deeper-seated station BOGT should yield slightly larger zenith delays, and all values in Fig. 4 should be negative. However, exactly the opposite appears in the first part of Fig. 4, which represents a period of height offsets at BOGT: Apparently the higher station BOGA experiences larger tropospheric delays than BOGT. According to a rule of thumb, which claims a relation of about three between height and zenith delay errors, the systematic differences in the order of 20 to 25 mm between the troposphere estimates during biased and unbiased periods account almost completely for the apparent height changes of BOGT. Note in particular the nicely corresponding variation of both parameters on days 349 and 350, 2003.

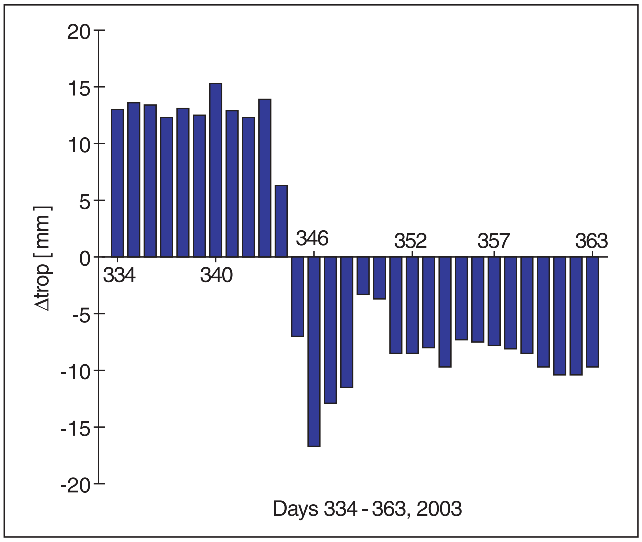

Fig. 4: Daily mean zenith tropospheric delay differences BOGA–BOGT during days 334–363, 2003

This phenomenon can only be explained by changes of the electrical properties of the BOGT antenna leading to an increase of the estimated height, which is compensated by a decrease of the zenith delay estimates. This physical effect is not reflected in the mathematical correlations resulting from the adjustment, which remain unchanged. Similar effects show up when a GPS antenna or its radome is covered by snow (see Scherneck et al. 2003). In case of BOGT we approach an explanation by looking at the antenna set-ups. Whereas the BOGA antenna is mounted on a pillar on the roof of an eight floors building, the BOGT antenna is fixed to a concrete pad in grassy environment. This pad is protected against damaging by a concrete border which is slightly higher than the top of the choke ring antenna (Fig. 5).

During the past years occasionally visitors of the site reported that they found the concrete pad flooded. Obviously some drain holes are jammed and prevent a rapid water flow-off after heavy rainfall. Unfortunately, we

Fig. 5: Antenna set-up at the BOGT station

have had access to precipitation data of Bogotá only since April 2004. Fig. 6 shows the recorded daily precipitation during the period from April 10 to May 20, days 101 to 141, 2004. As can be seen, the accumulated precipitation during four consecutive days between April 21 and 24 reached as much as 12 cm. Comparing the precipitation with the time series of estimated height differences BOGA-BOGT indicates the correlation with the second last negative offset shown in Fig. 1. This leads us to conclude that flooding of the concrete pad indeed changes the electrical properties of the antenna in such a way that apparent positive height variations result. These reach up to 10 cm if tropospheric delays are estimated simultaneously with the station position, and the troposphere parameters will be biased accordingly.

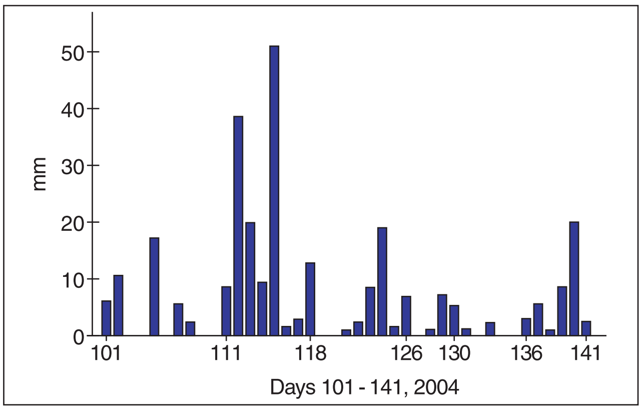

Fig. 6: Daily precipitation at Bogotá during days 101–141, 2004

4 Concluding Remarks

The horizontal motion and the subsidence of the station BOGT is determined by the global IGS analysis centers. The apparent height variations of BOGT will not show up in these operational analyses as clearly as in this study, because they will to a large extent vanish undetected in weekly solutions. However, as these height offsets are systematically positive, they will most likely affect the linear velocity estimates, as long as they are not identified and properly modelled. Raising the antenna set-up or taking care of an efficient draining of the concrete pad could immediately solve the problems.

As regards the building which houses the BOGA station, its estimated additional local movement relative to BOGT is real. It should be monitored further with high accuracy and reliability, not only for preserving its capability to serve as a reference station for local and regional surveys, but also, and even more importantly, to timely identify any risks for the building and the people working in it.

Acknowledgement

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