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High precision leveling supporting the International Comparison of Absolute Gravimeters

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Abstract

The local gravity field strongly dependents on the vertical terrain deformation. 1 cm displacement implies about3µGalchangeintheverticalgravityacceleration.Theprecisionofabsoluteandrelativegravimetrynowadaysis within 1 µGal. High precision leveling is a method indispensable to monitor the benchmark and terrainstability in the BIPM (Bureau International des PoidsetMesures). Associated with the ICAG (InternationalComparisonofAbsoluteGravimeters),repeatedlevelingmeasurementswerecarriedoutinthepastdecades.

In the begining of the century, a strategy was outlined that the ICAG should be upgraded as a metrological KeyComparison of the CIPM (Comité International des PoidsetMesures) under the MRA (Mutual RecognitionArrangement) recognised officially by the designated governmental organizations. The BIPM Site B was thenconstructed and completed in Spring 2001. The pillar is 4×6×1.5 m^3 in dimension and more than 80 tons inweight. Such a huge new built concrete body would produce the local deformation due to its sinking or tilting.This in turn influences the local gravity field. Rigorous levelling measurements were performed by BRGM(Bureau de RecherchesGéologiquesetMinières, France) since 2001 and repeated together with the 4-yearICAGs of 2001, 2005 and 2009. The ICAG2009 was characterised by being the first CIPM Key Comparison andsupporting the BIPM watt balance (WB) project, the pillar of which was built in Spring 2009. The IGN (InstitutGéographique National, France) was hence invited to participate in the leveling. The latter measured also thelinkbetweentheBIPMlocalnetandtheexternalstationsoftheFrenchnationalheightreferencesystemIGN69.

Keywords: Precisionleveling,NGF,IGN69,heightandheightreferencesystem

Introduction

Intheabsoluteandrelativegravimetrypractices,ameasuredpointisdefinedatacertaindistanceverticallyabove the ground benchmark. The free air gravity acceleration is a linear function of the altitude. The coefficientis about 3 µGal/cm. The stability of a local gravity field strongly dependents on the vertical terrain deformation.At present, the precision of state-of-the-art of the absolute and relative gravimetry nowadays approaches 1 µGal[3,4]. For most of the geoscience applications, permanent gravity stations are installed in stable locations. As thebase of the ICAG (International Comparison of Absolute Gravimeters) and a starting gravity point of certaingeoscienceorganisations,thestabilityoftheBIPM (BureauInternationaldesPoidsetMesures)localgravityfield is important. High precision leveling is an effective method to monitor the variation in height of the gravitystations.Associatedwith theICAGin thepastdecades,irregularlevelingmeasurementswereperformed.

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High precision and repeated leveling measurements have been organized since 2001. Then a long-term programofpushingtheICAGtowardsametrologicalKeyComparison(KC)oftheCIPM(ComitéInternationaldesPoidsetMesures) was initiated [1]. The result of a KC under the convention of the MRA (Mutual RecognitionArrangement)isrecognisedofficially bythedesignatedgovernmentalorganizations[2]. Asapartoftheconstruction of the Pavillon du Mail (PM in Figure 2.1), a new gravity laboratory was built which is a half-buried hall,where the Site B comprises 7 stations (Figure 2.2.1). It was completed in Spring 2001, six monthsbefore the ICAG2001. The 7 stations are B, B1, B2, B3, B4, B5 and B6 over the same concrete pillar. B5 and B6were installed afterwards in 2004. The pillar is 4×6×1.5 m^3 in dimension and more than 80 tones in weight. Sucha huge new-built concrete body would produce the local deformation due to its sinking or tilting before its finalstabilisation. In addition, the whole building of the Pavillon du Mail, constructed in 2000, may also suffer aperiodofthesettlementandstabilisation.Thesein turn mayaffectthelocalgravity field.

It order to monitor the possible instabilities, rigorous levelling measurements were performed by BRGM (Bureaude RecherchesGéologiquesetMinières, France) since 2001 associated with the ICAGs held in 2001, 2005 and2009. The ICAG2009 was characterised by being the first CIPM KC and supporting the new BIPM watt balance(WB) project. The WB laboratory locates in the basement of the Building Observatoire (OBS in Figure 2.1) ofwhich the gravity and WB pillars were built in Spring 2009. The IGN (InstitutGéographique National, France),official organization that established and maintains the French national height reference system IGN69, washence invited to participate in the enforced leveling program. The IGN measured also the link between the BIPMlocalnet and the externalIGN69 stations.

In the following discussions, we first in chapter II outline the structure of the BIPM gravity-leveling network anddescribe the stations. We then introduce the organization of the leveling measurement and the relation betweenthe BIPM local net and the French national height stations. Special attention is given to the evolution of theFrench height reference systems because of the complexity of the somehow co-existing references in France. Inchapter III, we report the final results of the leveling missions 2001, 2005 and 2009. By comparing the resultsobtained over the last decade, we investigate the stability ofthe BIPM gravity-leveling stations. We concludethat the existing and the new-built stations are stable for the purposes of the ICAGs and the WB project.However,itissuggested torepeatlevelingmeasurementsatleastonemoretimefortheWBsite.

Thisisthefirsttime,thedetailedandcompletelevelingdataandresultsarepublished.After32years'organizingandholdingthepreviouseightICAGs,theBIPMhasdecidedtohandovertheKCICAG2013toother MRA designated organizations. This paper serves then as a technical and historical document of thepreviouslevelingtasksassociatedwiththe sofarICAGs.

I. TheBIPMgravity-levellingnetwork

2.1 Thegravity-levellingstations

In the BIPM yard, there are four individual levelling stations: two old national levelling points PBK3-360 and361 and two new stations PBK3-360a and 361-I established in the 2009 mission by IGN [5-9], cf. Figure 2.1 andTable3.1.1.Asillustrated,thereare18levelledgravitystations:A,A1,A2,B,B1,B2,B3,B4,B5,B6, C1,C2, W1, W2, W11, W14, W15 and W18. C1 and C2 are the out-door stations used as a short calibration baseline fortherelativegravimeters. Allother stations are indoor.

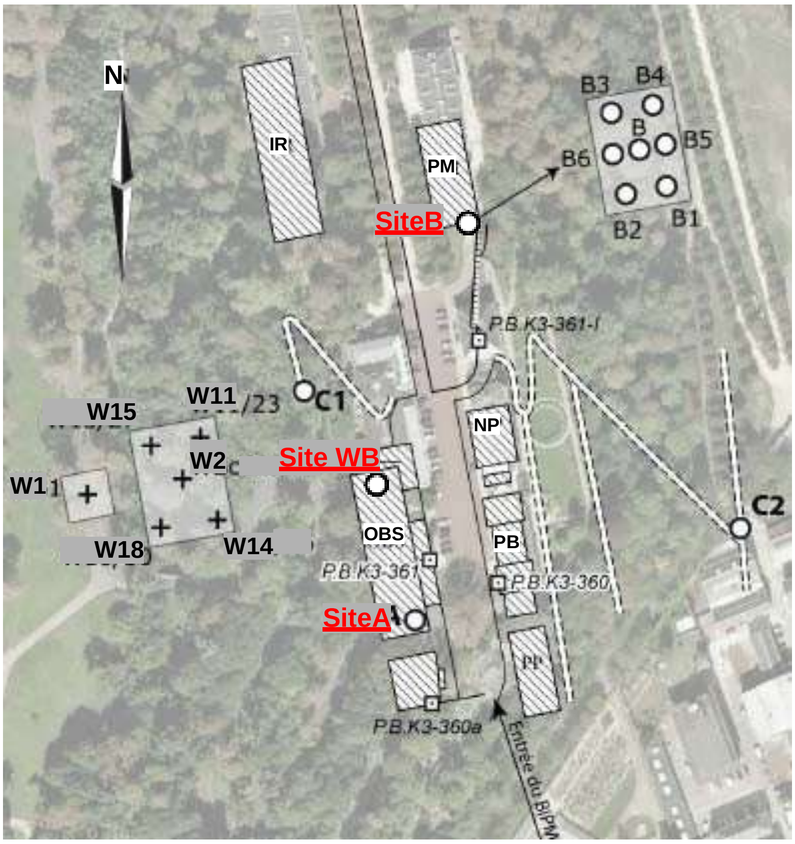


Figure2.1 Thegravity-levellingstationsofBIPM.
There are 4 leveling stations: the PBK3-360a and 361-I are the new stations established in the 2009 mission by IGN and the IGN PBK3-360and 361 are the already existed stations and both are the 4th order stations and have their heights in the ancient and new French heightsystems:theNGF andtheIGN69.

2.2 Descriptionofthegravity-levelingstations

2.2.1 TheBand WBsites

The new building, the Pavillon du Mail, was constructed in 2000. This enabled the extension of the gravity-leveling net by creating a number of new stations for the comparisons. The foundation for the new site B(composed ofthe stations B, B1, B2, B3, B4 and added in 2004 B5, B6) is a concrete block with a mass of morethan 80 tones with the dimensions 6.0 m in length, 4.0 m in width and 1.5 m in depth. The top surface of thefoundation is leveled to the floor to minimize the non homogeneity of the gravity field. This construction differsfrom that of the pillars of sites A and A2 in the Observatoire building. The two pillars on A site (A and A2) havea height of about 2.4 m above floor level in the basement and would rise the problem of instability. To improveisolation from micro-seismic vibrations, the new foundation is installed on pads of an elastic material insertedbetween its lower surface and the bottom of the hole in the concrete basement. No metal reinforcing bars wereusedintheconstructionofthisfoundation.Figure2.2.1showsthepositionsofthestationsonthesite Bpillar.

The Site of the WB laboratory is a renovated ancient laboratory located in the basement of the Observatoirebuilding (OBS in Figure 2.1). There are in total two leveled gravity stations (W1 and W2 with permanentbenchmarks on the ground) and 4 leveling stations (W11, W14, W15 and W18 without permanent benchmarks).The W1 is in the gravimeter pillar of which the top surface is about 7 cm lower than surrounding ground surface,cf.Figure2.2.2.Thetopsurfaceofthegravitypillarisabout1.54m²and thatoftheWBisabout4.0×2.45m².

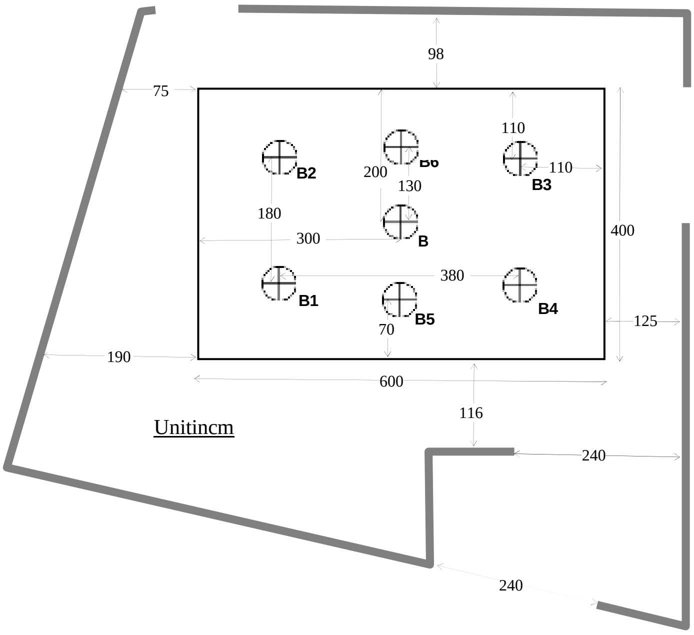


Figure2.2.1 ThegravimetrylaboratoryandtheSiteBpillarbuiltinSpring2001.Therearethe7gravity-levelingstationsonthepillar:B,B1-B6ofwhichtheB5andB6were installedin2004(dimensionsincm).Thestationlocationsaresymmetric totheBstation

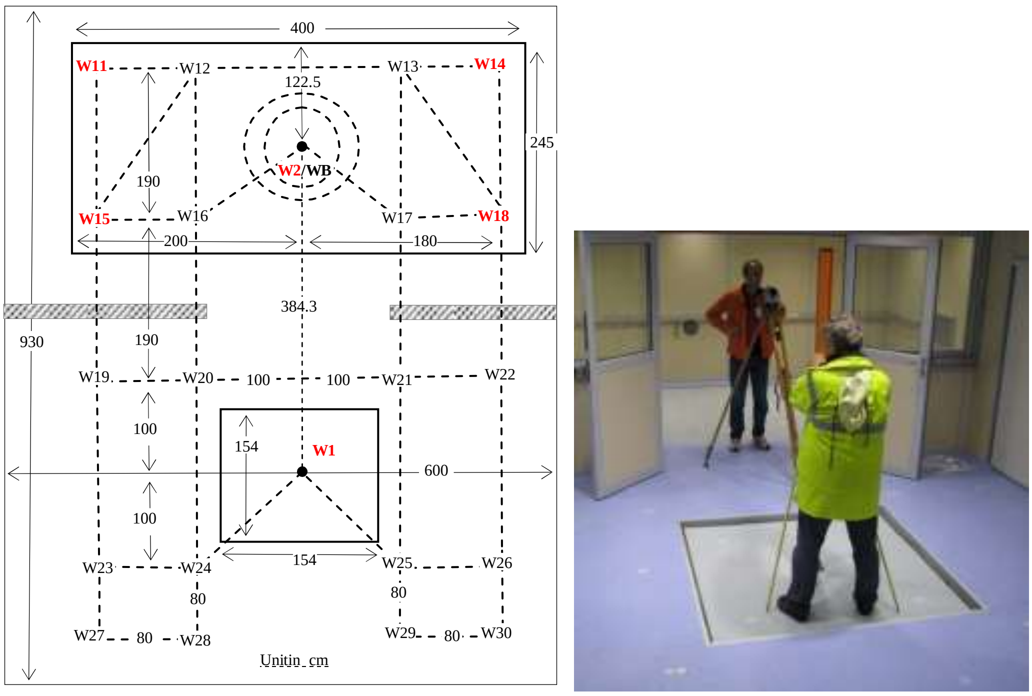


Figure 2.2.2 Site WB and the gravity-stations of which 6 are leveled (W1, W2, W11, W14, W15 and W18). The top surface of the pillar W1is7cmlowerthan surrounding groundsurface(dimensionsincm).AlevelingbetweenW1andW2 isundertaking

2.2.2 Descriptionofthestations

There are two kinds of benchmarks on the indoor and outdoor gravity-leveling stations cf. Figure 2.2.3. The out-door benchmarks made off bronze are buried in the top surfaces of the pillars of C1 and C2. The reference pointis defined on the cross centre on the top surface of the benchmark. As for the indoor stations, a disk of 1 cm inheight and 40 cm in diameter for B, B1, B2, B3 and B4 and of 45 cm for B5 and B6 are installed. The disk isgluedtothegroundsurfaceandatthecentreisahole of5cmindiameter.Thenacovercoversthehole.Bothethediskandthesmallcoveraremadefromaluminum.Thereferencepointisdefinedasthecrossinthecentreonthetop surfaceof thecover whichis1mmhigherthan thetopsurfaceof thedisk.

Figure2.2.3 Twokindsofbenchmarksontheindoor(leftB1)andtheoutdoor(rightC2)gravitystations

TheoldnationallevellingpointsPBK3-360and361arethein-wallpoints,SeeFigures2.2.4and3.2.1.ThepointPBK3-361isverystable and isusedasthe startingpoint since 2001.

Figure 2.2.4 The NGF-Lallemand leveling point on the wall of the Nouveau Pavillon building of BIPM and is numbered P.B.K3-360 with itsvalue66.0612minIGN69.Thelastmeasurementvisitwasin1968bytheIGN.Thisis theback-uppoint.

II. Theprecisionlevellingbetweenin2001,2005and2009

Repeated precision leveling measurements were carried out three times during the duration of 10 years in 2001,2005and2009.Theheightresultswerenotcomputedbasedonthesameheightreferencesystems. Inthissection, we first investigate the stability of the leveling stations at BIPM and then quickly review the heightreference systems in France. We then convert all the results into the current French height system and finallymake a comparison of the results to investigate if there were significant terrain deformations during the lastdecades.

3.1 Verificationofthestabilityofthelevelingstationsandthestartingvalues

The BRGM performed the leveling measurement in Aug. 2009 and the IGN did in Nov.–Dec. 2009. Theinstruments used were Leica Wild Nak2 automatic level (serial number 456924)and Zeiss Dini 10 (Figure 3.2.1)respectively. Before the mission 2009, the IGN made an investigation in the existing national leveling stationslocated between 200m to 2 km to check the stabilities of all related stations since the last measurementsperformed in the 60s' oflast century, see Table 3.1.1 and Figure 3.1.1. An iteration of pre-adjustment wascarried out to take out the unstable stations. A known station is considered stable if the difference of the heightsbetween the known and the new value is, according to the French regulations, less than 0.7 mm×(1+*n*) for thefirst order and 1.0 mm×(1+*n*) for other orders. Here the *n* is the number of intermediate measuring points alongthe leveling line. Only the stable stations will be used as starting values. In total 10 stations were measured andfour of them (*italic* letters in Table 3.1.1) were stable, including the P.B.K3-361 which was used as the startingpointbyBRGMsince2001.Forthisparticularpoint,asgiveninTable3.1.1,thedifferencebetweentheprevious measurement in 1968 and the new one is only 2.2 mm, which can be considered as height variationduring the 41 years or simply the measurement errors. While that of the P.B.K3-360 is 6.6 mm. In addition, threenewstationswereestablishedandtwoofthemarein BIPM:P.B.K3-360aandP.B.K3-361-I(Figure2.1).

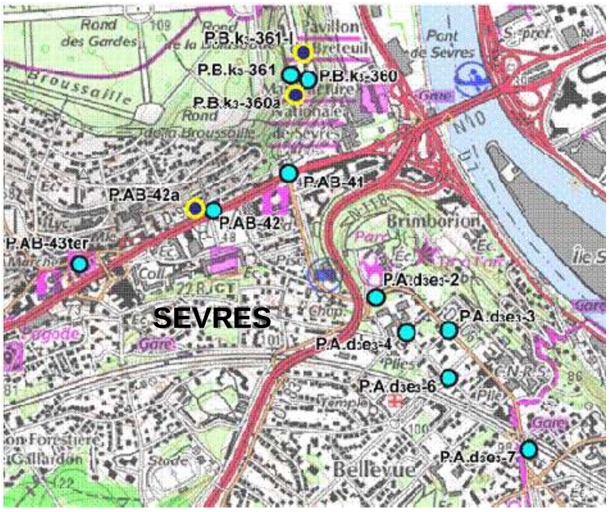


Figure3.1.1 Theinvestigatednationallevellingstationswithin2kmfromtheBIPMinthe IGN2009mission

Table3.1.1 Thenear-bynationallevelingstationsandtheheightsmeasuredindifferentperiods. H_{2009}istheresultsobtainedintheIGN2009 mission,H_{old}istheresultoftheexistingIGN69stations.Theitalic valuesarethestartingvaluesfor the computation of the IGN 2009 mission and the *P.B.K3-361* is the starting point of the BRGM leveling missions in 2001, 2005 and2009

Stn	*Latitude* ° ′ ″	*Longitude* ° ′ ″	*order*	*Year*	H_{old} /m	H_{2009} /m	$H_{old}-H_{2009}$ /m
P.A.D3E3-7	213 47	4849 02	3	1968	*99.0252*	*99.0230*	*0.0022*
P.A.D3E3-6	213 34	4849 15	3	1968	*90.1337*	*90.1344*	*-0.0007*
P.A.D3E3-4	213 28	4849 19	3	1968	87.1684	87.1542	0.0142
P.A.D3E3-3	213 35	4849 20	3	1968	88.0659	88.0595	0.0064
P.A.D3E3-2	213 23	4849 23	3	1968	*77.9886*	*77.9878*	*0.0008*
P.AB-41	213 10	4849 36	2	1968	39.0762	39.0601	0.0161
P.AB-42	212 58	4849 32	2	1968	45.8741	45.8523	0.0218
P.AB–42a	212 58	4849 32	2	2009	–	45.8491	–
P.AB–43ter	212 37	4849 26	2	1985	49.7330	49.7217	0.0113
P.B.K3–360	213 12	4849 45	4	1968	66.0678	66.0612	0.0066
P.B.K3–360a	213 11	4849 44	4	2009	–	65.4921	–
P.B.K3-361	213 11	4849 46	**4**	**1968**	***66.4536***	***66.4558***	***-0.0022***
P.B.K3–361-I	213 12	4849 48	4	2009	–	62.7857	–
						Mean:0.0077	
						Std:±0.0080	

3.2 TheFrenchheightreferencesystemsandtheirinterrelation

Special attention is paid to the evolution of the French national height reference systems. They are somehow co-exist and used by different organizations in France. Users may be confused by the complexity and errors arelikelytooccuras inthe ICAG 2005heightanalysis earlier[2].

The first leveling network was designed and measured under the direction of AdrienBourdalouë from 1857 to1864. The second one was the so called NGF-Lallemand (NivellementGénéral de la France or French generalleveling in English) by Charles Lallemand started in 1884 based on the macrograph recording of Marseille fromthe 1 Feb. 1885 to 1 Jan. 1897. The orthometric height system with theoretical gravity correction was adopted.The NGF was largely used in France for about a century. The BRGM performed the leveling measurements in2001, 2005 and 2009 and the height results were given in the NGF. The starting value used by BRGM was thatmarkedonthebenchmark:66.12m,asillustratedinFigure3.2.1.From1962to1969,theIGNupgradedthe

NGF network by converting it to the normal height system using measured gravity values. The new system isnamed NGF-IGN 1969 or

IGN69. The leveling measured and computed

.

by IGN in 2009 is given in the IGN69.TheIGN69 is30to60 cmover theNGF inFranceand is about33cmin the Parisregion

Figure 3.2.1 The NGF leveling point on the wall of the Observatoire building of BIPM and its value 66.12m in the NGF served as thestarting value of the height measurement before the RGC2009. The same point in the new IGN system is numbered P.B.K3-361 with itsvalue 66.4558m in IGN69. The difference between the two systems is: IGN69-NGF=+0.3358m. The levelling instrument used by IGN wastheZeissDini10

3.3 Therepeatedheightmeasurementresultsbetween2001and2009

Since the ICAG2001, the precision leveling has been carried out by BRGM. Only the inner-stations in BIPMwere leveled without linking them to the external leveling stations. The starting point and starting value are asillustrated in Figure 3.2.1. The NGF-Lallemand leveling point is installed on the façade wall of the Observatoirebuilding of BIPM and its value is 66.12m in NGF served as the starting value of the height measurement beforetheRGC2009.Thesamepointinthe IGNsystem isnumberedP.B.K3-361withitsnormalheight value66.4558m inIGN69.The difference betweenthe twosystems onthis point is: IGN69-NGF=0.3358m,notingthat the orthometric height in NGF is rounded off to cm. A back up point is shown in Figure 2.2.4 numbered asP.B.K3-360 andthenormalheightis66.0612minIGN69.

Table 3.3.1 gives the height results of the repeated measurements performed by BRGM in 2001, 2005 and 2009as well as the differences between the heights during the 10 years. The difference between 2001 and 2005 is onlyabout +1 mm, within the measurement uncertainty. However, the heights of 2009 are 3 to 5 mm lower than thoseof 2005 and 2 to 3 mm lower than those of 2001. At present, we have no exact explanation for this heightchanges. Because the discrepancies are either all positive or all negative, the major part comes likely from thechangeoftheheightdifferencebetweenthepillar Bandthestartingpoint:P.B.K3-361.Mostprobably,therewas a subsidence of the pillar B because P.B.K3-361 is installed in a wall built in 1878 and considered stable bythe IGN investigation, 2.2 mm different from the last measurement in 1968. We can almost exclude the usualcauses of the deformation: such as the influences of the seasonal variations of temperature and humidity on thewall and foundation of the Observatory. However it was mentioned that, the benchmark of P.B.K3-361 waspainted during a façade renovation of the Observatory before 2001. The thickness of the extra material wouldmakethe2001startingvaluehigherthanthetrue.Thecoatinglayer,ascanbeseenevennowsome millimetersin thick, was removed later. This would make the 2005 starting value lower than that of the 2001's andcompensate the subsidence of pillar B during 2001 to 2005. Unfortunately, we have not exact information now toallow a reliable conclusion. Nevertheless, 3 mm implies a change of 0.9 μGal in gravity which is lower than therepeatability of the gravimetry measurement between the ICAGs due to the measurement uncertainties betweenthe site A and site B.On the other side, the in-door stations on the pillar site B can be considered as stable withrespecttoeachother,onlyvariationsof1mmwithintheuncertaintyoftheleveling measurements.Therefore,the observed height changes should not disturb the relative and absolute gravity difference results on the B sitewhich was the major location performing the ICAGs. An exception is the difference of the −18 mm of 2009-2005forthestationC2.AsseeninFigure2.1,C2isfar fromthemainpartofthenetandabout20meterlower than the station B. The access is difficult especially whenit rains. This was the case of the measurements of2009. The fact that the C2 pillar was built in the soil surrounding by the huge trees made it unstable. From theTable 3.1.1, even some 2nd order stations have changed about 2 cm. The back up leveling point P.B.K3-360 wasnotusedfor the BRGM measurements.

Table 3.3.1 Repeated leveling measurement results during 10 years by BRGM with the inter-comparisons(HeightsaregiveninNGFreferencesystem)

Station	*H*in NGF/m			Differenceof*H*/m		
	2001	2005	2009	2005-2001	2009-2005	2009-2001
A	65.938	65.939	65.937	0.001	-0.002	-0.001
A1		65.941				
A2	65.956	65.957		0.001		
B	56.327	56.329	56.324	0.002	-0.005	-0.003
B1	56.341	56.342	56.338	0.001	-0.004	-0.003
B2	56.339	56.34	56.337	0.001	-0.003	-0.002
B3	56.334	56.335	56.332	0.001	-0.003	-0.002
B4	56.329	56.33	56.326	0.001	-0.004	-0.003
B5		56.329	56.326		-0.003	
B6		56.335	56.331		-0.004	
C1		76.457	76.459		0.002	
C2		37.64	37.622		-0.018	
W1/13			62.77			

W2/14			62.838			

Table 3.3.2 Repeated leveling measurement results by BRGM and that of the IGN 2009 mission(HeightsaregivenintheIGN69referencesystem)

	*H*byBRGMinIGN69 /m			*H*byIGN /m	BRGM−IGN /m
Station	**2001**	**2005**	**2009**	**2009**	**2009**
A	66.2738	66.2748	66.2728	66.2722	0.0006
A1		66.2768			
A2	66.2918	66.2928			
B	56.6628	56.6648	56.6598	56.6584	0.0014
B1	56.6768	56.6778	56.6738	56.6723	0.0015
B2	56.6748	56.6758	56.6728	56.6705	0.0023
B3	56.6698	56.6708	56.6678	56.6654	0.0024
B4	56.6648	56.6658	56.6618	56.6597	0.0021
B5		56.6648	56.6618	56.6592	0.0026
B6		56.6708	56.6668	56.6649	0.0019
C1		76.7928	76.7948	76.7956	-0.0008
C2		37.9758	37.9578	37.9535	0.0043
W1/13			63.1058	63.1079	-0.0021
W2/14			63.1738	63.1770	-0.0032
W11/23				63.1749	
W14/26				63.1737	
W15/27				63.1767	
W18/30				63.1737	

Preparing the RGC2009, we realized that the significant difference of nearly 30 cm between the NGF and theIGN69. We then invited the IGN, official responsible of the height reference system in France, to make aninvestigation in the starting point and the corresponding values used for the earlier ICAGs/RGCs. The task wasfulfilled in Dec. 2009 [5]. Some 13 national graded points within a 2 kilometer diameter zone around BIPM werecarefullyinvestigatedand4stablepoints,includingthepointP.B.K3-361,wereselectedasthestartingpointsof the adjustment of the IGN leveling measurements. Table 3.3.2 lists all the height results given by missions ofBRGM and IGN in the IGN69 reference system. Here the orthometric height values in NGF have been convertedto the normal heights in IGN69 system, by adding the constant offset of 0.3358m computed from the heightvalues of the only IGN-BRGM-common-point P.B.K3-361. The last column of the table gives the differences ofthe two sets of the results. As seen, on the 8 common stations of the sites A and B, the heights of the BRGM areconstantly about 2 mm higher than IGN's. However for the difference on the two WB stations, BRGM's arelower than that of IGN's by 2.5 mm. This would be caused by the measurement methods. The WB site is locatedin the basement of the Observatoire. The accessibility is rather difficult. BRGM performed a leveling profilethrough the stairs which are narrow and deep. But IGN performed a direct profile going through a little windowof the basement. The latter seems a less disturbed operation. The difference of the height measurements foroutdoorpointC2is4.3 mmthatmaybe causedbythe difficultconditionasdiscussed above.

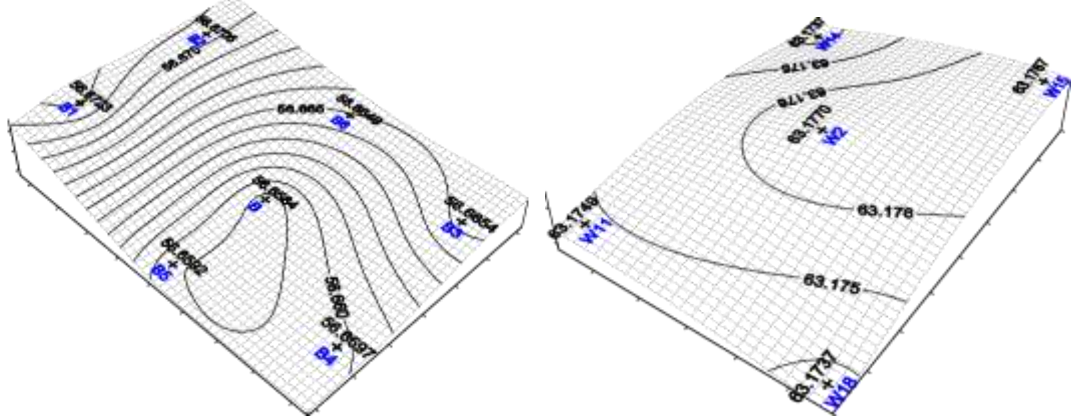
3.4 **ThereliefofthesurfacesofthepillarBandthepillarWB**

The top surfaces of the pillars of the sites B and WB are 4×6 m² and 2.5×4 m² respectively. It is interesting topoint out that the surface of the WB pillar seems smoother than that of B pillar, see Figure 3.3.1. The maximumdifferences in heights are for B pillar B1-B=1.39 cm while for WB pillar W2-W14=0.33 cm, noting also that theWB pillar is smaller than the B pillar. By Figure 3.3.1, the contour map of B site illustrates a 'valley' from B tothe mid-point of B4-B5.We cannot exclude the possibility that the B4 corner sunk about 1 cm, i.e. the pillarsloped down from the B1-B2 edge towards the corner of B4 after its construction. From the Table 3.3.1, theheight variations of 2009-2005 and 2009-2001 are −5 mm and −3 mm at the B station and that of B4 are −4 mmand −3 mm. However, from the same table, the B4 in 2001 was already lower 10 mm than B2 and 12 mm thanB1.Thisslopingwouldhappeneitherjustafteritsconstructionbeforethelevelingmeasurementin2001ordueto the construction fault. Table 3.3.1 is based on the measurements of the BGRM and Figure 3.3.1 is base on thatoftheIGN.

VI. Conclusions

Associated with the ICAGs, precision levelling missions were organised to check the stability in the gravity-levelling stations at the BIPM. To monitor the possible deformation of the site B located in the building Pavilliondu Mail constructed in 2000, rigorous levelling measurements have being carried out since 2001. To bettersupport the first ICAG2009 as a CIPM Key Comparison and the BIPM watt balance project of which the pillarswerebuiltin2009,bothBRGMandIGNperformedthelevelling2009.Duringthe2009mission,theBIPMlocalstationswerelinkedtotheFrenchnationallevellingstationsoutsideofBIPM.Themeasurementuncertaintyisabout2mm.

Carefulcomparisonsweremadebetweentheseresults.Itisconcludedthatbetween2001and2009nodeformations in height significantly beyond the repeatability of the gravity measurements (about 2 µGal) havebeen confirmed on the B and A sites, which were occupied by the absolute gravimeters during the ICAGs. It istherefore expected that the WB site be stable for the watt balance performance althoughit is suggestedtoperformat least onemorelevelling measurements when possible.



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