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A Smart Real-Time Monitoring GNSS System for High-Rise Buildings | 全球卫星定位系统的高层结构智能实时监控

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Abstract | 摘要

This paper analyzes and develops a real-time GNSS monitoring system to evaluate the lateral and torsional displacement and wind-induced response of a high-rise building. The system is made up of four GNSS receivers located on the rooftop of high-rise building and an original software, which together define a local geodetic network. The data processing is based on the Gaussian adjustment methodology and its own imposed condition. Each monitored high-rise building has a unique mathematical model with its own conditioning. Thanks to these algorithms adapted to the project and a contrasting filter, we can correct blunders, avoid unstable GNSS systems and improve quality and reliability of displacement of the high-rise building being monitored. The real-time GNSS monitoring system provides interesting feedback information for structural engineers and architects regarding the position and other key data of high-rise buildings in real time, contributing to an effective risk management.

Keywords: Risk, Seismic, Structural Engineering, Structural Health Monitoring, Supertall, and Wind.

本文件的分析和开发了一种实时的全球导航卫星系统的监控系统来评价横向和扭转流离失所和风力引起的反应的高层建筑。 它由四个全球导航卫星系统接收机,它定义了本地的大地测量网,位于屋顶的高层建筑和原创的软件。数据处理是基于高斯分布的调整方法及其自己的所施加的条件的情况。 每个被监测的高层建筑有一种独特的数学模式有其自己的空调。 由于这些算法的适应项目和对比鲜明的过滤器: 我们可以纠正失误，避免不稳定的全球导航卫星系统的系统和改善产品的质量和可靠性的位移高-建筑到正在被监视。实时的全球导航卫星系统监控系统提供了一种有趣的反馈信息结构工程师和建筑师因为我们可以知道位置和其他关键数据的高-建筑的实时帮助我们有效的风险管理。

关键词：风险、地震、结构工程、结构健康监测、超高层建筑、风

Introduction

The control of the position of structures using GNSS techniques is a fact nowadays. Specifically, auscultation and the dynamic deformation behavior of engineering structures has been a subject of concern for engineers for many years. In this sense, the adoption of GPS technology for monitoring and auscultation of civil and architectural structures has already been validated in other preliminary research verifying its adoption as a standard technique. Earlier examples of this include the Calgary Tower, in Canada (Loves et al.1995) and the Humber suspension bridge, in the UK (Ashkenazi and Roberts, 1997).

The advancement of technology and communications has allowed the development of methods that provide these positions with millimeter accuracy. It is also becoming a research field of great academic interest (Van der Auweraer, H. and Peeters, B. 2003) with an understanding that tolerance levels, sometimes to high levels of accuracy, are a vital detail.

引言

现如今，利用全球卫星导航系统技术进行建筑结构定位已是普遍现象。具体来说，工程结构的探伤和动力变形行为，已经成为了工程师们多年来一直研究的两个主题。在此背景之下，运用GPS对土木建筑结构进行检测和探伤的技术，在其他前期研究中作为标准技术进行应用已经得到了证实。该技术应用的早期范例包括：加拿大的卡尔加里塔(Loves et al.1995)和英国的亨伯河吊桥(Ashkenazi, V. and Roberts, G. W. 1997)。

科技及通讯的进步促进了定位方法的发展，将建筑物定位误差控制在毫米级。这一领域正引起学术界的极大兴趣(Van der Auweraer, H. and Peeters, B. 2003)，它的公差水准有时候可以精确到毫米级，这一点至关重要。

因此，GPS技术的发展促使了一种全新改进型定位方法的出现，采用相位动态实时差分进行定位（RTK）。几项课题研究已经证明了GPS实时动态差分法的可行性，比如，对地处日本的一座塔(Tamura et al. 2002)的外在全面性能研究。另外一项

So, due to the evolution of GPS technology an improved method using differential positioning real-time kinematic (RTK) was developed. Several studies have demonstrated the feasibility of RTK-GPS such as the observed full-scale performance of a tower in Japan (Tamura et al. 2002). Another study with the same aim used full-scale measurement for the displacement of three tall buildings in downtown Chicago (USA). The wind-induced responses of the buildings were measured and compared to wind tunnel tests and finite element models by installing force balance accelerometers and a GPS receiver (Kilpatrick et al. 2003)

Some years ago the feasibility of a GPS method for measuring wind-induced responses and monitoring horizontal and torsional displacement and acceleration in high-rise buildings was verified (Park et al. 2008).

The authors Yi, T.H. Li, H.N and Gu, M. (2013) present an interesting review of current research and development activities in the field of high-rise structure health monitoring using the (GPS).

In Japan, wind engineering studies on the effect of typhoons in tall buildings through full-scale monitoring with accelerometers, anemometers and pressure sensors have been carried out (Li et al. 2014). There have been further preliminary studies undertaken about technical feasibility of GNSS observations, such as the research on the Yonghe Bridge in China; focus of this was to examine the GNSS technique in the deformation monitoring of the bridge tower and develop parametric models to assess the dynamic behavior of the bridge utilizing RTK-GPS measurements. Then, functions were transferred expressing the relationship between the displacements of the tower and the variations of temperature, humidity, wind speed with the use of robust fit regression models (Kaloop, M. R., and Li, H. 2014).

In accordance with the theme of CTBUH 2016 International Conference, this paper suggest that it is fundamental and essential within the scope of smart high-rise buildings to have an instantaneous determination of its precise position with high reliability. This is because smart buildings allow integrated and automated management and control.

The continuous assessment of the displacement of a high-rise building with GNSS facilitates the systematic and scientific analysis of its overall dynamic movement. This provides an interesting source of information which will be explored later.

This paper proposes to modify the software to calculate GNSS observations by introducing alternative mathematical and statistical algorithms in the scope of monitoring of structures.

In order to do this, the real-time monitoring system includes:

- Geometric inner constraints with the aim of giving more rigor to the results, we added an enforceable condition. According to the monitoring methodology of structures that we propose, each building has a unique mathematical model with its own inner constraints. Thanks to the algorithms adapted for the project we can correct errors, and improve the position and reliability of GNSS measurements.
- Control surface defined by GNSS receivers, instead of isolated points. The control surface does not need to conform to an existing flat surface on rooftop of the building, as it is always possible to project the structured to monitor on the control surface. It is not necessary that the non-fixed points, which the GNSS receivers are installed, are visible to each other.
- Local geodesic network on the structure to be monitored that improves the compensated network solution. At the same time, the system proposes new algorithms to process measurement uncertainty. It is precisely the treatment of data, adjustment and analysis of partial and final results that allows us to achieve a high level of security and effective risk management in real time.

All of these features help to make our system different from the current research and commercial software.

A case study that has allowed the validation of the model in the monitoring of two-dimensional surfaces is presented, and the current research is proposed to implement the conceptual model monitoring with three-dimensional surfaces, provided that there is displacement of the structure in the Z coordinate.

This real-time monitoring system has been awarded the third position in the

相同主题的研究是对坐落在美国芝加哥市中心的三座高层建筑进行全尺寸测量，以确定这些建筑物的位移。通过安装平衡加速器和GPS接收器测出建筑物风振响应的结果，并与风洞试验及有限元模型分析结果进行对比。

有一种GPS的应用方法是测量高层建筑的风振响应及监测水平、扭转位移和加速度，这种方法的可行性在若干年前就已经得到了证实。

在应用全球定位系统对高层结构进行健康监测的领域中，作者Yi,T.H.;Li,H.N.和Gu,M.(Yi et al. 2013)针对目前的研究和开发活动，提出了一个有趣的观点。

日本已经应用加速度计、风速计和压力传感器等，针对台风对高层建筑的影响进行全面的监测，以此来开展风工程研究(Li et al. 2014)。关于GNSS（全球定位导航系统）观测技术的可行性问题，已有更进一步的初步研究，例如，对中国永和大桥的研究。该研究的重点在于检验GNSS技术在监测桥塔变形的应用，并开发参数化模型，对使用RTK-GPS（GPS实时动态差分法）测量永和塔桥动力性能进行评估；然后，使用稳健拟合回归模型建立转移函数，表示塔的位移和温度、湿度、风速变化之间的关系。

本文建议，对高层智能建筑而言，实时获得其精确位置和高可靠度是基础性的，也是必要的，这也正与世界高层都市建筑学会（CTBUH）2016年国际会议的主旨一致。因为，智能建筑允许管理和控制实现全局化和自动化。

使用全球卫星导航系统（GNSS）对高层建筑的位移进行连续评估监测，有利于系统地、科学地分析其整体的动态运动。这种方法提供了一个有趣的信息来源，下文将会对其进行探讨。

在结构监控这一范畴内，本文建议引入替代数学和统计学算法对处理计算全球卫星导航系统（GNSS）观测数据的软件进行修正。

为达到上述目的，实时监控系统实现了：

- 几何内部约束。为使结果更精确，我们增加了一个可行性条件。根据结构监控方法，我们建议每一栋建筑要有一个带有其内部约束的数学模型。因为项目所采用的算法，我们能修正误差，改善GNSS设备的位置和可靠性。
- 全球卫星导航系统（GNSS）接收器定义的控制面而非孤立的控制点。因为总能将结构投影到控制面上的监控器，所以控制面并不需要与建筑物屋顶的水平面相适应。安装全球卫星导

regional phase, of the European Satellite Navigation Competition 2015, supported by the European GNSS Agency (GSA), the European Space Agency (ESA), the German Aerospace Center (DLR), and the German Federal Ministry of Transport and Digital Infrastructure (BMWi) in association with the Federal Ministry for Economic Affairs and Energy (BMWi).

Technical Aspects

The technological improvements in GNSS techniques, the progress of computer data processing, and the development of Internet and mobile telephony, has allowed us to upgrade and advance the Gaussian methodology applied to control the dynamics of building structures in real time. This is due to algorithms for calculating, and controlling especially strict interpretation based on analysis and least squares adjustment of satellite surveys measurements.

What makes our system different from the others, is not the GNSS techniques, but is the methodology of calculation, interpretation and control of the results, with the design of original software.

In general terms, the system strictly determines the position (coordinates x and yY) of the non-fixed points of this local geodetic network observed with VRS-RTK techniques and the instantaneous and simultaneous precision of each antenna at any time, with high accuracy and reliability.

To achieve robust results of the instantaneous position of each structure, a proper conditioning must be designed to be part of the proposed algebraic system. We add to the observation equation some unique condition equations for each structure.

Continuing with the applied method, we defined the deformation experienced by the network in the monitored structure as a vector which will be the result of the differences in the position of the measuring points of the network in different GNSS measurement campaigns:

$$d = x_2 - x_1$$

being

$d = x_2 - x_1$ = displacement

x_1 = UTM - ETRS89 at epoch 1

x_2 = UTM - ETRS89 at epoch 2

航系统接收器的非固定点也不需要彼此通视。

- 结构与监控器之间的局部测量网络，改善补偿网络方法。同时，该系统建议了处理测量不确定性的新的算法。其精确的数据、修正和局部、最终的结果分析使得我们能够获得高水平的安全性和实时、有效的危机管理。

上述特征使得我们的系统与现有的研究、商业软件不同。

一个验证该模型监控二维表面有效性的案例研究已经呈现出来，而且，最新研究指出，如果结构有Z向位移，建议采用三维表面的概念模型监控。

2015年，在欧洲导航局、欧洲太空局、德国太空中心、德国联邦交通和数字基础设施部、德国联邦经济与能源部支持下举办的欧洲卫星导航竞赛中，实时监控系统获得了区域第三名的成绩。

技术方面

全球卫星导航系统（GNSS）的完善，计算机数据处理的进步，以及因特网、移动通讯的发展使得我们已经能够实时更新和改进应用于控制结构动态相应的高斯算法。这归功于在卫星勘察测量的分析和最小平方校正，在此基础上的算法来用于计算、控制，特别是严谨的阐述。

使我们系统有别于其他系统的原因不在于全球卫星导航系统（GNSS）技术，而在于原始软件的设计，这让该系统的计算、阐述和控制结果方法与众不同。

概括地说，该系统严格确定采用虚拟参考站—实时动态差分法（VRS–RTK），高度精确和可靠地获得局部测量网络的非固定点位置（x、y轴坐标），以及每一个天线任意时间的实时精度。

为了获得每一个结构的瞬时精确结果，须要为其设计一个适当的调节，使之成为拟议代数系统的一部分。我们为每一栋建筑在观测方程中加入了独特的条件方程。

作为该应用方法的继续，我们将被监控结构网络的结构变形定义为向量d。该向量d的定义是，用不同的GNSS系统测量方法时，对该网络测量点测出的不同位置结果的差值：

$$d = x_2 - x_1$$

being

$d = x_2 - x_1$ = displacement

x_1 = UTM - ETRS89 at epoch 1

x_2= UTM - ETRS89 at epoch 2

这个微分表达式既不受固定坐标或参考点影响，也不受可能影响该点位的误差影响。

基于对观测模型特定情况下的序列解法，以及假定的额外变量或参数方程，我们建立了一个整体校正数学模型，表达式为：

$$\begin{pmatrix} {A_{d1}}^T \cdot P_1 \cdot A_{d1} & A_{d2}^T \\ A_{d2} & 0 \end{pmatrix} \begin{pmatrix} x \\ -\lambda_2 \end{pmatrix} = \begin{pmatrix} {A_{d1}}^T \cdot P_1 \cdot K_{d1} \\ K_{d2} \end{pmatrix}$$

另外，对于所监测结构的变形d，我们的表达式如下：

$$\begin{pmatrix} {A_{d1}}^T \cdot P_1 \cdot A_{d1} & A_{d2}^T \\ A_{d2} & 0 \end{pmatrix} \begin{pmatrix} d \\ -\lambda_2 \end{pmatrix} = \begin{pmatrix} {A_{d1}}^T \cdot P_1 \cdot K_{d1} \\ K_{d2} \end{pmatrix}$$

being

A_{d1} = 设计矩阵

P_{d1} = 权矩阵

A_{d2} = 几何内部约束矩阵

$d = x_2 - x_1$ = 位移

λ_2 = 拉格朗日乘子

从上面的表达式中，我们从整体数学模型的结果中得到未知向量d，以此确定屋面非固定点的位移。

一般而言，我们可以假定一座建筑物中的一块板是具有无穷大刚度的刚性隔板，所以，在太空塔屋面上定义的四边形网络非固定点的变形应为零。因此，我们可以使用从上面四边形中得到的方程式来定义该数学模型的几何内部约束。

所以，向量d是在初始调整数学模型中计算出来的，也与设计矩阵A_d2中规定的内部约束相符合。自从所有提出的条件都能被满足，它就展示了能监测结构运动的物理事实的信心。

为了在被监测建筑物中构建一个局部大地网，可以通过外部可靠性定义网络阈值灵敏度或准确性，这对于研究这种方法和全球卫星导航系统（GNSS）技术的准确性，是至关重要的。这也有助于建立错误检测，来避免全球卫星导航系统的不稳定性，因为，由实时全球卫星定位系统技术得到的坐标并不十分精确，短时间的误差会在0.2~3厘米之间波动。

由于局部大地网实施的优势性，一旦系统已经确定了非固定点的位置，我们可以运用标准多元化分析来获得计算位移置信区域的组合可靠性，以便我们在任何时间里，对每根天线都能获得瞬时、同时准确的信息。透过精度可以了解：误差曲面，同时性和各GNSS系统接收器的独立可靠性。错误的时间间隔是通过测定非固定点来确定的，非常可靠。

This expression, being differential, has the advantage of not being influenced by the coordinates of the fixed or reference point nor by errors that may affect that point.

Based on the method of Sequential Solution for a particular case of observation model, and in assuming the additional of functions of variables or parameters, we established an adjustment to the overall mathematical model (a firm mathematical model) for which the expression is

$$\begin{pmatrix} A_{d1}^{T} \cdot P_1 \cdot A_{d1} & A_{d2}^{T} \\ A_{d2} & 0 \end{pmatrix} \begin{pmatrix} x \\ -\lambda_2 \end{pmatrix} = \begin{pmatrix} A_{d1}^{T} \cdot P_1 \cdot K_{d1} \\ K_{d2} \end{pmatrix}$$

In particular, for the deformation $\mathbf{d}$ of the structure that we have to monitor, we obtain this expression:

$$\begin{pmatrix} A_{d1}^{T} \cdot P_1 \cdot A_{d1} & A_{d2}^{T} \\ A_{d2} & 0 \end{pmatrix} \begin{pmatrix} d \\ -\lambda_2 \end{pmatrix} = \begin{pmatrix} A_{d1}^{T} \cdot P_1 \cdot K_{d1} \\ K_{d2} \end{pmatrix}$$

being

A_{d1} = design matrix

P_{d1} = weight matrix

A_{d2} = matrix used to incorporate geometric inner constraints

$d = x_2 - x_1$ = displacement

λ_2=Lagrange multiplier

From the preceding expression, we know the displacement of the non-fixed points on the rooftop according to unknown vector $\mathbf{d}$ from the result of the overall mathematical model.

It can be stated that in general a slab in a building is assumed to be a rigid diaphragm with infinite stiffness, so the deformation of the quadrilateral which is defined by the non-fixed points of the network situated on the rooftop of Torre Espacio, is null. Therefore it is possible to use equations from this quadrilateral to define the geometric inner constraints of the mathematical model.

So the calculated vector $\mathbf{d}$ comes from the initial adjustment mathematical model and complies with the inner constraints which are laid down by the design matrix A_{d2}. This reflects the physical reality of the movement of the structure to be monitored with confidence since at all times the imposed conditions are met.

Implementing a local geodesic network on the building to be monitored can define a threshold sensitivity or accuracy of the network by external reliability, which is essential to study the accuracy of the methodology and GNSS techniques used. It will also help in establishing a Blunder Detection Test to avoid instability in the GNSS system as the coordinates obtained with real-time GNSS techniques have an accuracy which can vary between 0.2 and 3 cm in a short time.

Due to the advantages of the implementation of the local geodesic network, once the system has determined the position of the non-fixed points, we can apply standard multivariate analysis to obtain the composed reliability of confidence regions of calculated displacement. In this way we obtain the instantaneous and simultaneous accuracy of each antenna at any given time understanding by accuracy the error surface and simultaneously the individual reliability of each GNSS receiver. The error intervals are known through the determination of the non-fixed points with a 0.99 reliability.

What Advantages Does it Provide?

Global Navigation Satellite Systems have revolutionized the science of positioning and Earth measurement. One part of that revolution is accuracy; another part is speed and simplicity. A third part is cost (Strang, 2012). The developed system focuses on one major advantage of GNSS: accuracy. Due to prior testing of GNSS observations the integrity of the system improves. Another added advantage is that it can correct the mistakes in the position of the GNSS antennas.

GNSS coordinates in real time have an accuracy that can vary between 0.2 and 3 cm in a short time. The proposed system allows instant quality control of precision, corrects errors of GNSS coordinates to Gaussian algorithms, and determines the accuracy and reliability of the errors that could not be corrected.

The advantages of the proposed system:

- Motion control, with more accuracy and reliability, facilitates scientific and systematic analysis of the overall dynamics of high-rise building and other structures, that can be an important source of information which that can be extrapolated to new projects. Since it is possible to study the lateral and torsional displacement and wind-induced response in real time, a cost saving in the design process can be obtained.
- The key data for applications connected with wind and earthquake engineering such as accelerations, damping or displacements can be calculated through the realtime monitoring system because it detects any movement in the horizontal plane

提供的优势有哪些?

全球卫星导航系统GNSS革新了科学定位和大地测量。这种革新第一准确无误，第二快速简单。第三是成本（Strang, 2012）。所开发系统研究GNSS的一个主要优点是：精度。由于之前测试GNSS观测系统的完整性得到改善。所以另一个优势是，它可以纠正GNSS天线的错误位置。

GNSS实时坐标的精度可以在很短的时间内改变0.2至3厘米。而该系统提供了即时质量控制精确性、纠正GNSS的错误坐标而用高斯算法，并确定该错误无法纠正的精度和可靠性。

该系统的优点：

- 具有更高精度和可靠性的运动控制，有利于科学和系统地分析高层建筑和其他结构的整体动力响应，它可以作为一个重要的信息来源外推到新的项，因为它使研究实时横向和扭转位移以及风振响应成为可能，并且在设计过程中也节约成本。
- 与风工程和地震工程，如加速度，阻尼或位移相关应用的关键数据可以通过实时监测系统计算得到，因为它能检测每个天线在任何时间任何移动的水平面中定义的坐标x和坐标Y。因此，实时监控系统引入了一种在位移计算中，可靠性、准确性和精度性的改进方法。

有时，对结构位移了解到亚厘米级精度十分必要。因此，滤波器、从属几何、定位间隔以及天线几何位置也要与项目的这个需求相适应。

因此，GNSS加速度是由三个连续点t−Dt,t,t+Dt的数值微分位移值计算得到的。由公式（1）得到t时刻的w(t):

$$w(t) = \frac{1}{2} \cdot \left(\frac{x_t + \Delta_t - x_t}{\Delta t} + \frac{x_t - x_{t-\Delta t}}{\Delta t} \right) \quad (1)$$

另一方面，高层建筑的位移由X轴和Y轴的水平位移以及扭转位移组成。为了测量扭转位移，可以用四根实时监控系统里的两根GNSS天线。定义GNSS1坐标为（X1，Y1），GNSS2坐标为（X2，Y2）。GNSS1和GNSS2之间的X轴位移微分ΔX(t)以及Y轴位移微分ΔY(t)可以一段时间进行测量。

时间t的扭转位移θ(t)可使用公式（2）计算，坐标值如下：

$$\theta(t) = \mathrm{arctg}\left(\frac{\Delta Y(t)}{\Delta X(t)}\right) = \left(\frac{Y_2(t) - Y_1(t)}{X_2(t) - X_1(t)}\right) \quad (2)$$

defined by the coordinates x and y of each antenna at any time. So, the real-time monitoring system introduces an improvement in reliability, accuracy and precision in the calculation of displacements.

Sometimes it is necessary to know the displacement of a structure with a sub-centimeter level of accuracy, therefore the filter, the dependent geometric, the positioning interval and the geometrical location antennas are also adapted to this requirement of the project.

In this way, the GNSS accelerations are computed by numerically differentiating displacement values of three consecutive points of t - Dt, t, t + Dt using equation (1) to obtain w(t) at time t.

$$w(t) = \frac{1}{2} \cdot \left(\frac{x_t + \Delta_t - x_t}{\Delta t} + \frac{x_t - x_{t-\Delta t}}{\Delta t} \right) \quad (1)$$

On the other hand, high-rise building displacements consist of horizontal displacement of X-axis and Y-axis as well as torsional displacement. In order to measure torsional displacement we can use two antennas of the four that are available in the real-time monitoring system. We denote $GNSS_1$ coordinates as (X1, Y1) and $GNSS_2$ coordinates as (X2, Y2). The X-axis displacement differential $\Delta X(t)$ and Y-axis displacement differential $\Delta Y(t)$ between $GNSS_1$ and $GNSS_2$ were measured for a period of time.

The torsional displacement θ(t) at time t can be computed using equation (2) and these coordinate values:

$$\theta(t) = \mathrm{arctg}\left(\frac{\Delta Y(t)}{\Delta X(t)}\right) = \left(\frac{Y_2(t) - Y_1(t)}{X_2(t) - X_1(t)}\right) \quad (2)$$

- Construction of high-rise buildings can be economically attractive only if the structural engineers can have a comprehensive understanding of the structural behaviors of various systems on the one hand and the practical sense of the construction problems on the other (Khan, 1965). The continuous assessment of the displacement of the building enables verification that meets the structural assumptions calculated for the project, which provide an additional useful feedback for the structural engineers. Abnormal or unexpected structural responses during the phases of construction or once the building is in use can help detect current and future problems. It can also result an improvement in maintenance of the structure's life.
- For improving risk management against natural phenomena, for example, it is recommended that the position data of a building after an earthquake or typhoon is used to verify the stability of the structure and its return to its original position. In this way the real-time monitoring system provides an additional safety item for the building.
- The system we have developed allows the integration of other information such as the acceleration of gravity, wind direction and speed, and so it models the dynamics of the structure with different variables and detects possible correlations between them. GNSS receivers provide big data that can help us to detect large mechanical and structural failures, modeling the position of the building or structure with positional variables.
- Monitoring and remote monitoring of the proposed system continuously keeps the customer informed of the status of the work in real time with high accuracy and reliability and sends automatic alerts of potential dangers.
- An added advantage is that the cost of the system is minimal when compared to its advantages and the value of any structure. In the case of Torre Espacio, the cost of implementation of the real-time monitoring system has been 0.08% of the price of construction of the building.

Torre Espacio, Case Study

The experimental validation of the proposed methodology was performed on one of the tallest towers in Madrid. A working prototype already exists for Torre Espacio, Madrid, Spain (Figure 1).

In the case of Torre Espacio, our costumer (OHL's R+D) wanted to install a security system with GNSS technology that would allow us to know Torre Espacio's position at any time. Once a preset threshold is

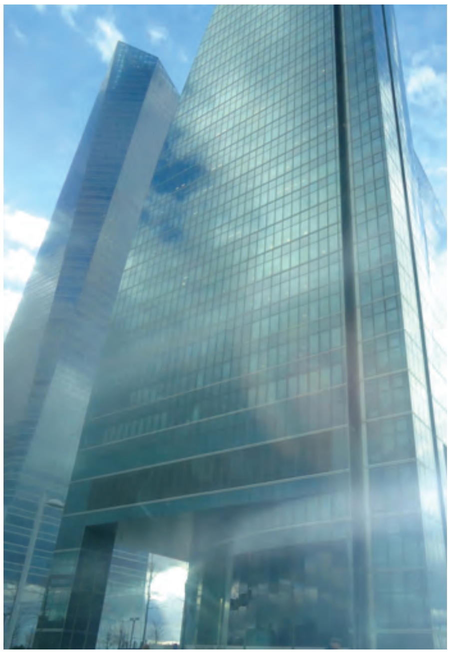

Figure 1. Torre Espacio, located on Paseo de la Castellana in Madrid, Spain (Source: Nieves Quesada).
图1. Torre Espacio，位于西班牙马德里的Paseo de la Castellana（来源：尼夫斯克）。

- 只有当结构工程师对各种各样系统的结构行为有了全面的了解，或者对建筑实际问题拥有全面的经验感知，高层建筑施工才能在经济收益上具有吸引力（Khan，1965）。建筑物位移的连续评估验证了在项目中计算中满足结构假设，这为结构工程师提供额外的有用的反馈信息。施工阶段或建筑物使用过程中的异常或意外的结构响应，可以帮助检测当前和未来的问题。它也可以使结构使用周期维护得到改善。
- 以改善自然现象风险管理为例，建议使用地震或台风后的建筑物位置数据来验证结构的稳定性，并将其恢复到原来位置。这样以来，实时监控系统给建筑物提供了额外的安全项目。
- 我们开发的系统允许集成如重力加速度，风向和速度的其他信息，用来模拟不同变量的结构动力响应，并检测它们之间可能的相关性。GNSS接收机提供的大数据可以帮助我们检测大型机械和结构故障，模拟位置变量下的建筑物和结构的位置。
- 该系统的监测和远程监控以高准确度和可靠度不断提供客户及时了解结构工作状态，并自动发送潜在危险警告。
- 另一个优点是，与任何结构及其优势相比，该系统的成本是最小的。例如太空塔，实现了实时监控系统成本是建筑成本的0.08%。

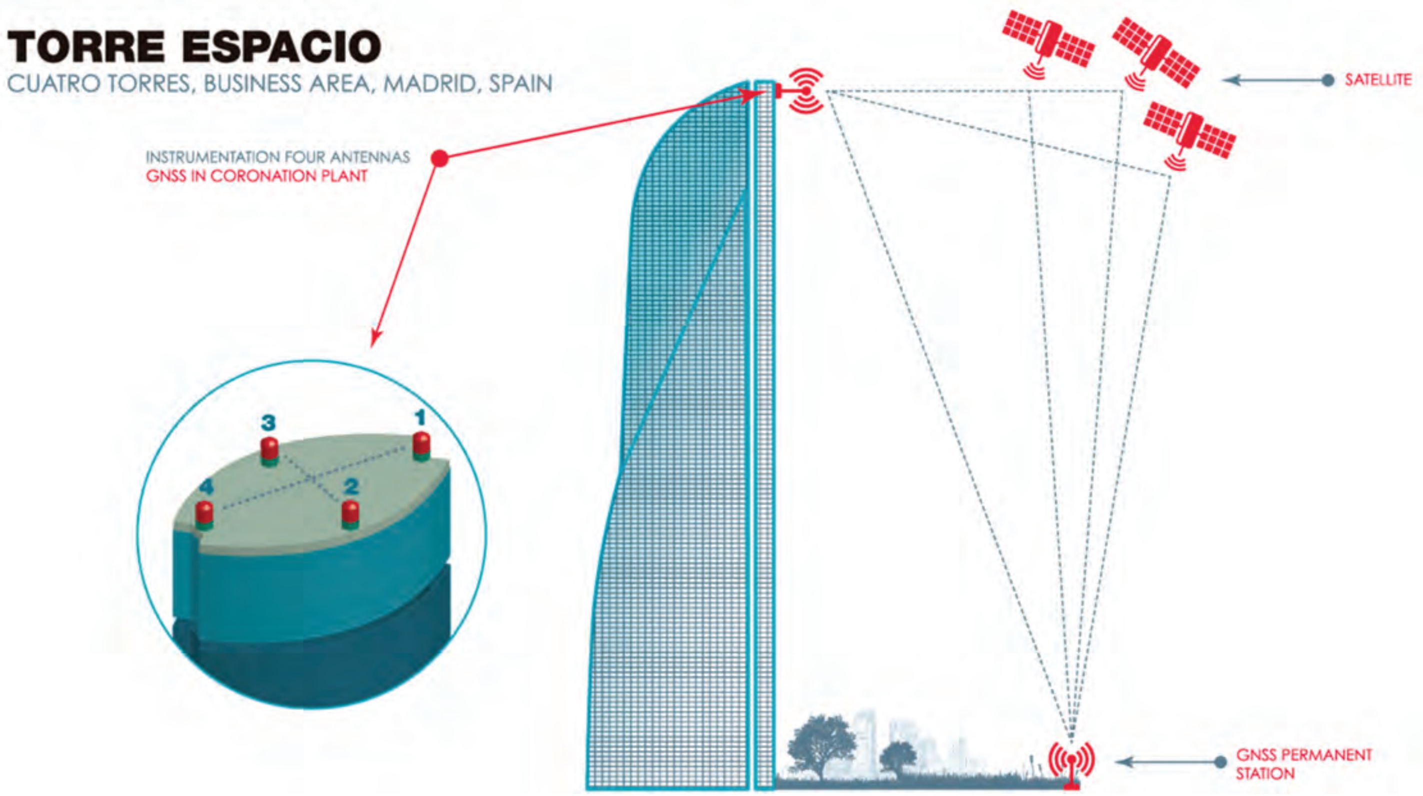

Figure 2. The real-time monitoring system has been installed on Torre Espacio (Source: Nieves Quesada Olmo, María Jesús Jiménez Martínez, and Mercedes Farjas Abadía)
图2. 实时监控系统已安装在Torre Espacio（来源：Nieves Quesada Olmo, María Jesús Jiménez Martínez, Mercedes Farjas Abadía）

exceeded the system will send an alarm (via SMS and email) to the user. The methodology proposed by the authors, had as its priority an aim to improve the monitoring system established previously at the tower, consisting of theodolites fixed to position on the upper floors and accelerometers. The approach was challenged to keep the order of accuracy of traditional monitoring while improv response times and maintenance costs.

The real-time monitoring Ssystem which has been installed on the rooftop the Torre Espacio is composed of a quadrilateral control surface limited by a local geodetic network with four GNSS receivers (Figure 2). The system strictly determines the position of non-fixed points of this local geodetic network, through the instantaneous and simultaneous precision of each antenna at any time with high accuracy and reliability, but not considered as isolated vertices of a network, as a rigid figure through modeling algorithms implemented in both processing and calculation methodology.

In the case of Torre Espacio, the adjusted overall mathematical model reduces the maximum error, with a 0.99 reliability, from 0.0165m to 0.0100m; this is a 40% reduction.

The physical location of the four GNSS antennas is indicated in figure 3. In

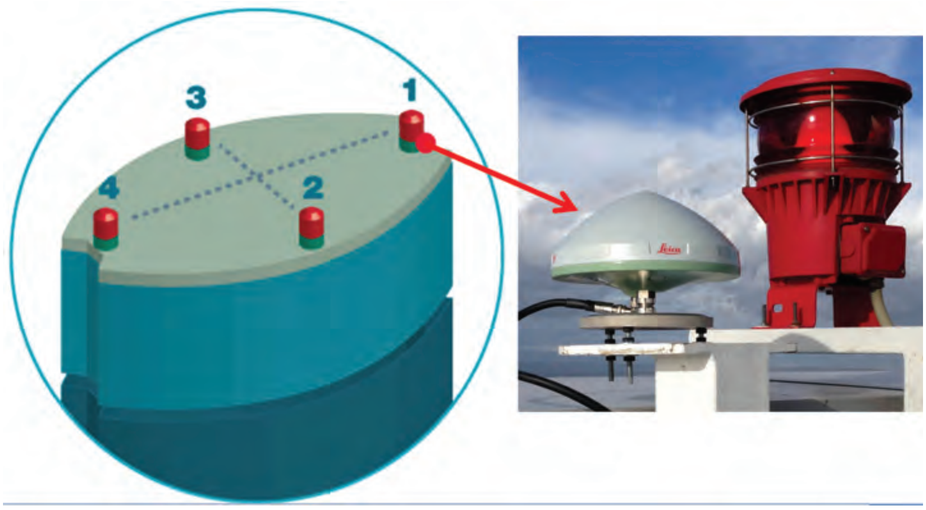

Figure 3. The real-time monitoring system is composed of a local geodetic network with four GNSS receivers, located on the rooftop of the structure to be monitored (Source: Nieves Quesada).
图3. 实时监控系统由当地的大地测量网与四个GNSS 的接收器组成，位于屋顶的结构将受监控（来源：尼夫斯克）。

案例研究：太空塔建筑

所提方法的实验验证是在马德里最高塔之一进行的。已经存在的工作原型是西班牙马德里的太空塔（图1）。

以太空塔为例，客户（OHL´s R+D）想利用GNSS技术安装一个安全系统，这允许我们任何时候监控太空塔的位置，一旦超过预设阈值系统将（通过短信和电子邮件）给用户发出警报。作者提出的方法，旨在优先提高先前建立在塔上的由定位在楼上的经纬仪和加速度计组成的监测系统的性能。该方法挑战性地保持了传统监测精度的次序，以提高时间响应和维护成本。

已经在太空塔这个高层建筑屋面上安装的实时监控系统由一个四面形控制面构成，该四边形控制面由四个GNSS接收器组成的局部大地网构成（图2）。系统严格确定了局部大地网非固定点的位置，每个天线在每时每刻都保持瞬时、同时的高精度性和可靠性，并且运用处理和计算方法把它作为一个整体刚体进行建模分析，而不是孤立的个体。

针对太空塔的例子来说，整体数学模型的调整把测量误差由0.0165米降到0.0100米，相当于降低了40%，在高可靠性前提下最大化降低了误差。

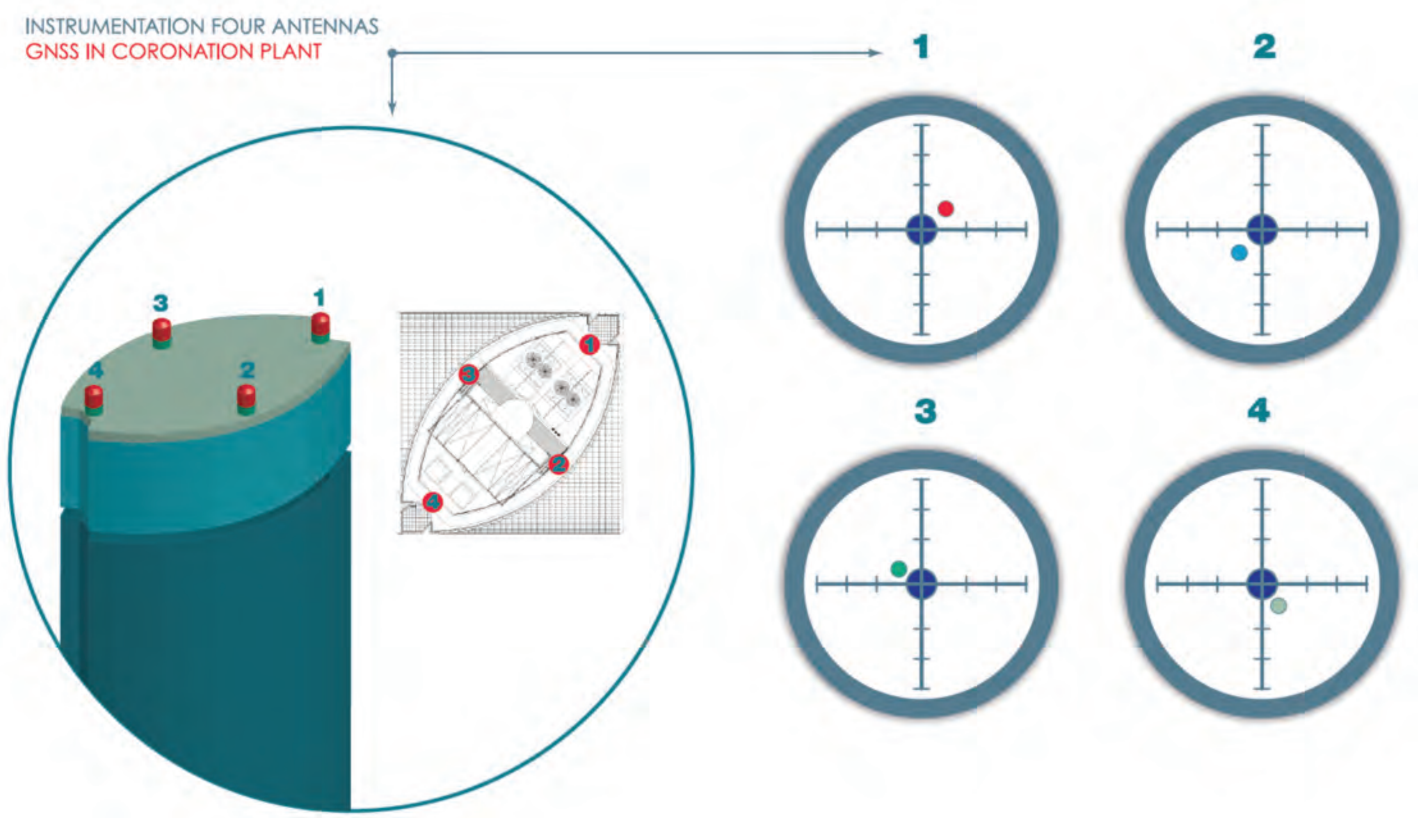

Figure 4. The real-time monitoring system develops mathematical algorithms to allow us to reduce position errors of each antenna at any time (Source: Nieves Quesada Olmo, María Jesús Jiménez Martínez, and Mercedes Farjas Abadía)
图4. 实时监控系统开发的数学算法使我们能够在任何时间降低每个天线的位置错误（来源：Nieves Quesada Olmo, María Jesús Jiménez Martínez, Mercedes Farjas Abadía）

principle it would be enough to utilize a line defined by two GNSS antennas in order to define a torsional and translation response of the rooftop, but the secure option is constituted by a quadrangle that keeps its shape.

The observational data of antennas can be configured remotely, and then they can record positions at intervals of sub-second time if necessary.

A Graphical User Interface has been designed, and there is also an App which implements all the algebraic and statistical algorithms used in the real-time monitoring system (Figure 4 and 5).

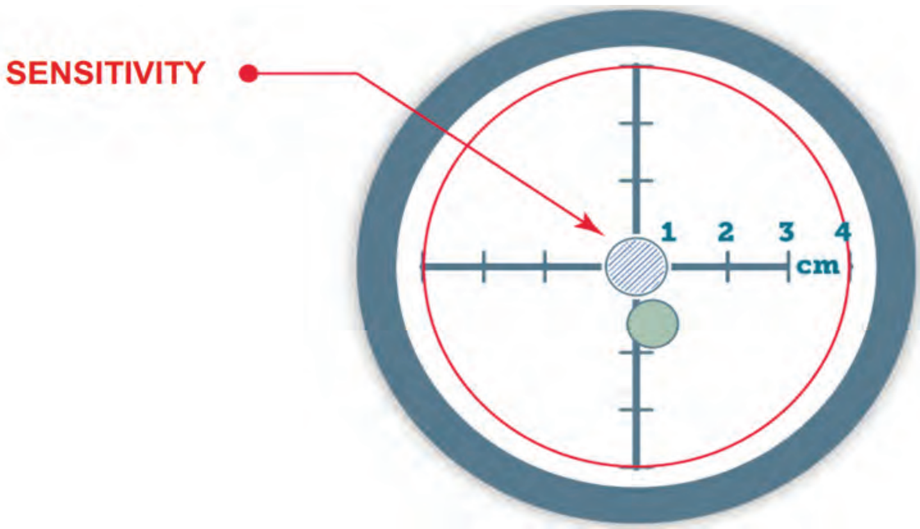

Figure 5. This is the Graphical User Interface (GUI) of the developed system (Source: Nieves Quesada Olmo, María Jesús Jiménez Martínez, and Mercedes Farjas Abadía)
图5. 这是该软件的图形化用户界面(GUI)的开发系统（来源：Nieves Quesada Olmo, María Jesús Jiménez Martínez, Mercedes Farjas Abadía）

四个GNSS天线的物理位置如图3所指。原则上，由两个GNSS天线确定的直线本足以测定屋面的扭转和平移相应，但组成四边形并保持形状才是最稳妥的办法。

天线的观测数据可以远程配置，然后，如果必要，它们可以记录亚秒级时间间隔范围内的位置变化。

系统的图形用户界面已经设计出来，而且手机应用程序也已开发，同时也实现了原本用在实时监控系统中的所有代数和统计算法（图4、5）。

主要特征

该系统明显优于其他已存在系统的独特方法特征包括：

1. 在结构实时监测系统开始应用之前，我们就对GNSS系统应用和初始调整数学模型的精确性进行了研究。这样，我们可以通过一个准确的阈值来定义和认识该网络的灵敏度。如果低于这个值，我们就不能确定由该网络数据表示的建筑物变形是否准确。系统的统计程序由几个互补的方法组成。简而言之，巴尔达型检验（Baarda Test）适用于从外部可靠性获得位移数据，而广义F检验

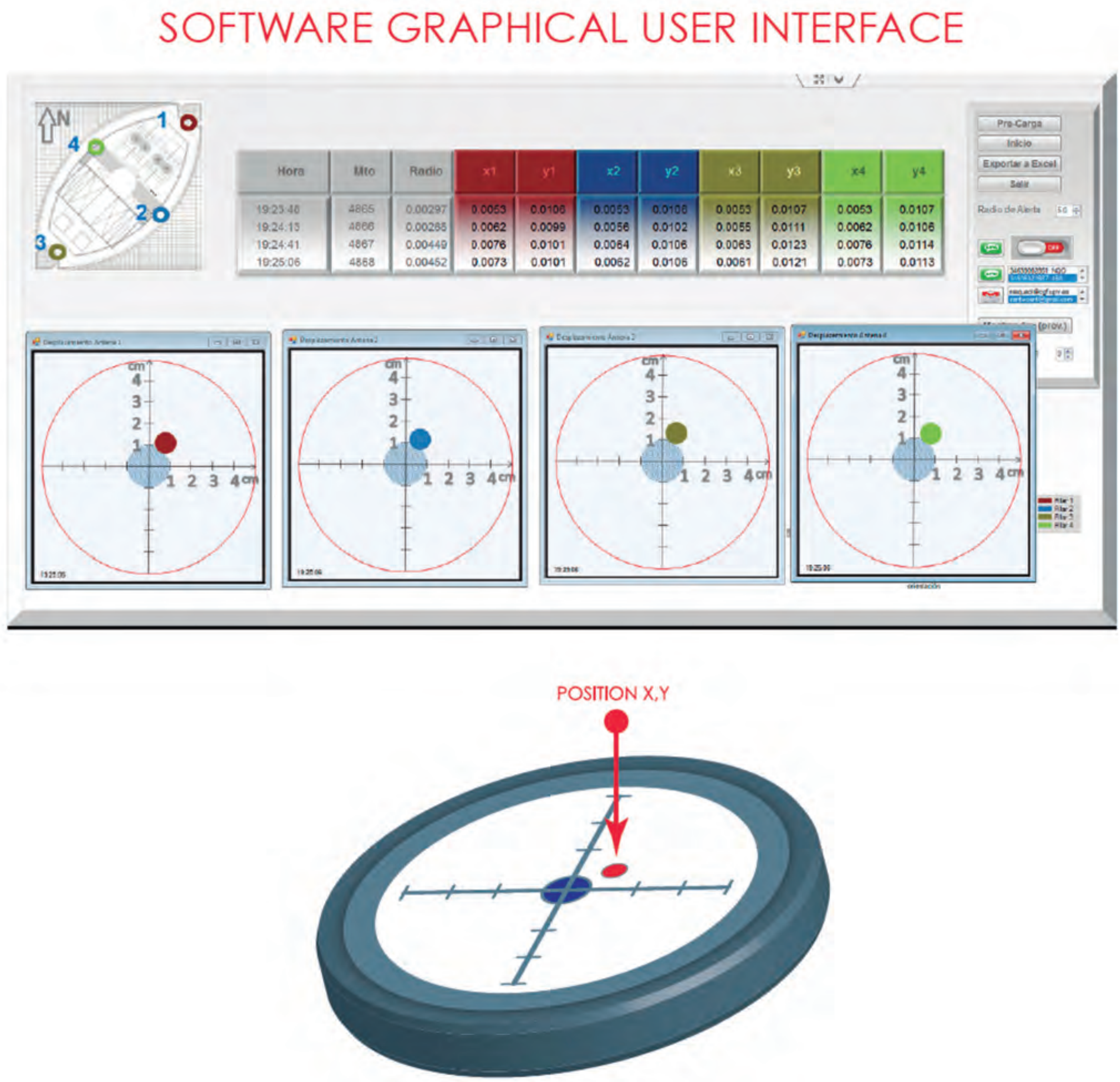

Figure 6. The sensitivity of the network is established through an accuracy threshold; below this figure we cannot be certain about the building deformation indicated by the network data (Source: Nieves Quesada Olmo, María Jesús Jiménez Martínez, and Mercedes Farjas Abadía)
图6. 网络的灵敏度是通过精确的阈值建立的，低于这一数字，我们不能确定根据网络数据指示的建筑变形（来源：Nieves Quesada Olmo, María Jesús Jiménez Martínez, Mercedes Farjas Abadía）

What are the Key Features?

The unique methodological characteristics of this system, compared to the others in existence can be summed up by the following:

1. Before implementing the real-time monitoring system in the structure, the accuracy of GNSS implementation and initial adjustment mathematical model is studied. In this way we can define and understand the sensitivity of the network through an accuracy threshold., bBelow this figure we cannot be certain about the building deformation indicated by the network data. The statistical procedure consists of several complementary methods. In short, the Baarda Test was applied to obtain displacements from the external reliability and the generalized F-test was applied to obtain displacements by least squares adjustment of the observational data (Figure 6).

2. GNSS technology can be an unstable system in real time, as in a short period of time it can vary its accuracy between 2mm and 3cm. In order to avoid this instability our real-time monitoring system provides a contrasting filter that selects GNSS observations to reach the precision required by the project. Once the system has been installed on the

（F-test）适用于通过观测数据的最小二乘平差获得位移数据（图6）。

2. GNSS技术系统不能保证实时稳定，比如，在很短的时间周期内，它的精度会在2毫米到3厘米之间变化。为了避免这种不稳定性，，我们的实时监控系统提供了一个对比滤波器对GNSS观测进行筛选，以此达到精确性要求。一旦建筑物中已安装了此系统，由GNSS接收器构成的局部大地网就能够让我们连续不断地比较GNSS系统瞬时的测量质量，也可以处理没有通过滤波器筛选的观测值信息：错误检测实验。

3. 为了获得可靠的结果，该系统还引入了计算算法和统计方法。这使我们能

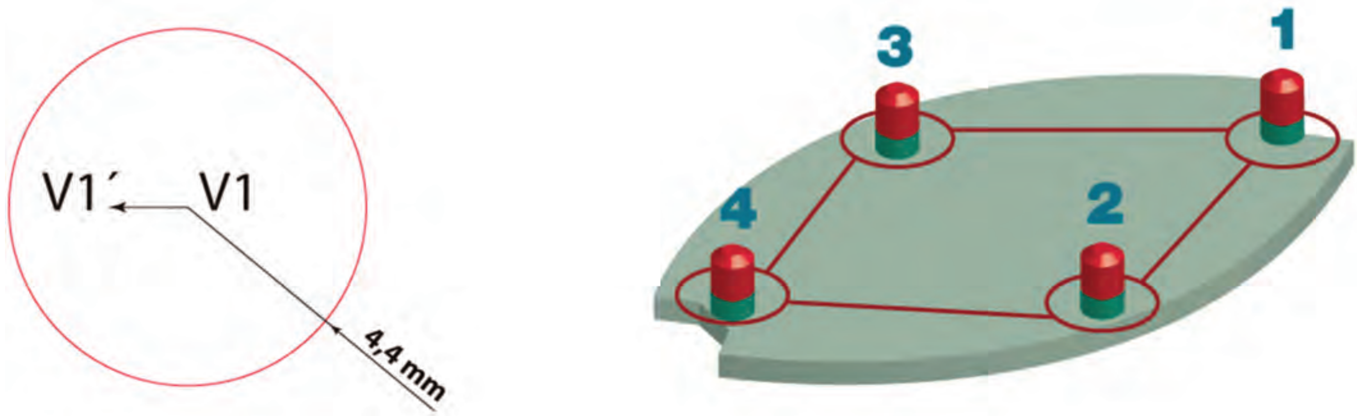

Figure 7. The system determines the position (coordinates X and Y) of the vertices and calculates instantaneously and simultaneously the accuracy of each antenna at any time. The error intervals can be known and the vertices determined with a 0.99 reliability (Source: Nieves Quesada Olmo, María Jesús Jiménez Martínez, and Mercedes Farjas Abadía)

图7. 该系统确定的位置坐标(X和Y)的顶点数和计算出任意时间每个天线瞬时和同时的准确性。错误的时间间隔可以被发现，以0.99的可靠性确定顶点（来源：Nieves Quesada Olmo, María Jesús Jiménez Martínez, Mercedes Farjas Abadía）

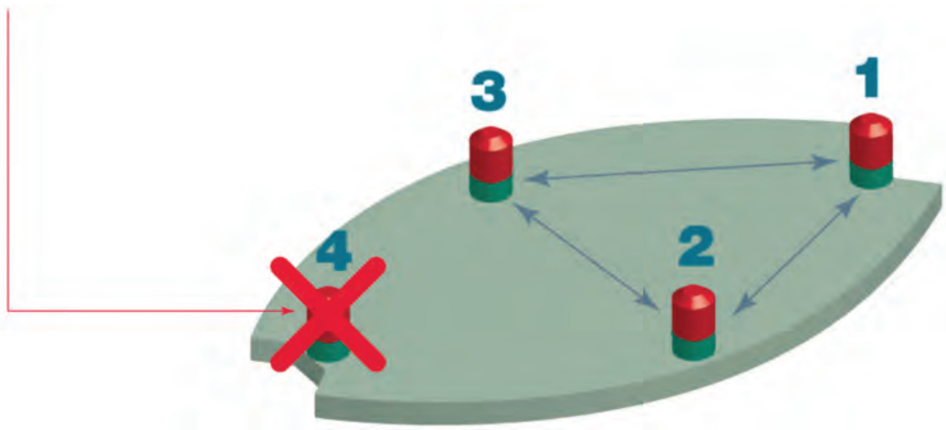

Figure 8. If the system detects that one or more of the receivers are abnormal, it warns the user and dispenses with the receiver in the calculation of the adjusted position of the network (Source: Nieves Quesada Olmo, María Jesús Jiménez Martínez, and Mercedes Farjas Abadía)

图8. 如果系统检测到某个或更多的接收器是不正常的，它将警告用户并根据计算调整后的网络位置分配接收器（来源：Nieves Quesada Olmo, María Jesús Jiménez Martínez, Mercedes Farjas Abadía）

building, the local geodesic network, consisting of GNSS receivers, allows us to compare the instantaneous quality of GNSS measurements continuously and can dispose of observables that do not pass the filter: the Blunders Detection Test.

3. The system also introduces calculation algorithms and statistical methods in order to obtain reliable results. This enables us to define a structural deformation model on which to make successful decisions. These algorithms must be adapted to the structure that needs to be controlled so that each building has a unique mathematical model with its own inner constraints. In this way it creates a tailor-made system. Thanks to these algorithms, adapted for each individual project, we can correct errors, and improve the position and reliability of GNSS measurements.

4. Once GNSS observation filtered and their mistakes reduced by the Blunders Detection Test, the system determines the position (coordinates X and Y) of the vertices and calculates instantaneously and the accuracy of each antenna at any time.By understanding the accuracy,: the error surface and simultaneously the individual reliability of each GNSS receiver, the error intervals can be established and the vertices determined with a 0.99 reliability (Figure 7).

5. Each structure will have a set of GNSS receivers that form a local geodetic network. The consistency of the quadrilateral's shape and its displacement makes possible the detection of any problems in the antennas. If the system detects that one or more of the receivers are abnormal, it warns the user and

够定义一个结构变形模型来帮助我们做出正确分析和决定。这些算法必须适用于需要测控的结构中，以便每一座建筑物都能拥有独立的、包含自己内部约束的数学模型。因为这些算法都与每个单独的项目相适应，所以，我们能够纠正其中的错误，且提高GNSS系统测量的精度和可靠度。

4. 只要错误检测试验过滤掉了GNSS观测系统的糟粕部分，减少了错误，该系统就可以确定各个顶点的二维 坐标（x，y），并在任何时间瞬时 且同时计算每个天线的精度。我们 所说的精度是：误差曲面，每个GNSS接收器的实时可靠性，建立误差时间间隔，以及基本可靠的确定顶点位置（图7）。

5. 每个结构都将会有一套从局部大地网引出的GNSS接收器。四边形的形状以及它的位移都保持一致，这让监测各个天线中存在的所有问题变得可能。如果系统检测到一个或者多个接收器不正常，它就会警告用户，并且在计算网络的平差后位置时自动隔离这个接收器 （图8）。

6. 为了提高数据的有用性，开发的系统能够暂时减少阈值范围内的测量，这个阈值是由用户定义，由特定的位移等级发起。仅会让观测时的准确性和可靠性发生变化。

7. 鹰图公司的软件也可以安装在任何移动设备上。它已经开发出一款手机自用软件，使我们了解由实时监控系统计算的同一控制参数。

结论

- 全球卫星导航系统（GNSS）已经彻底改变了定位科学和地球测量学。

dispenses with the receiver in the calculation of the adjusted position of the network (Figure 8).

6. In order to improve the usefulness of the data, the developed system is able to temporarily decrease the measurement under the threshold defined by the user, initiated by some specified level of displacement. It would only affect that the accuracy and reliability at the time of observation will change.

7. Intergraph's software can also be installed on any mobile telephone. An own App has been developed which allows us to know same control parameters calculated by the real-time monitoring system

Conclusion

- Global Navigation Satellite Systems (GNSS) have revolutionized the science of positioning and Earth measurement. One part of that revolution is accuracy, another part is speed and simplicity. The feasibility of GNSS techniques for monitoring of high-rise buildings has been verified through previous diverse studies.
- To achieve robust results for the instantaneous position of each structure, the real-time monitoring system introduces calculation algorithms and statistical methods which must be adapted to the high-rise building to be monitored so that each building has a unique mathematical model with its own inner constraints. In this way it creates a tailor-made system, implemented in an original software package.
- So, the real-time monitoring system introduces an improvement in reliability, accuracy and precision in the calculations of displacements and positioning of the high-rise building being monitored.
- The key data for applications in wind and earthquakes can also be calculated through the real-time monitoring system because it detects any movement in the horizontal plane defined by the coordinates x and y of each antenna at any time.
- Motion control, with more accuracy and reliability, facilitates scientific analysis of the overall dynamics of high-rise buildings. Since it is possible to study the lateral and torsional displacement and wind-induced response, this allows us to achieve a high level of security and effective risk management in real time.
- The real-time monitoring system can be used to improve risk management for natural phenomena. For example, after an earthquake or typhoon it can be used to verify the stability of the structure. It provides an additional safety item for the building.
- It is fundamental and essential within the scope of these smart high-rise buildings to have an instantaneous determination of its precise position with high reliability. This is because smart buildings allow integrated and automated management and control.
- This prototype can be installed on any new high-rise building or similar structure. In the case of Torre Espacio, the cost of implementation of the real-time monitoring system was 0.08% of the price of construction of the building.

改革的其中一部分便是测量定位的精度，另一部分则是快速性和简洁性。应用GNSS系统监测高层建筑的可行性已在之前的各个研究中得到证实。

- 为了可靠地获得各个结构的瞬时位置，实时监测系统引入了计算算法和统计方法，这些算法和方法必须适用于被监测的高层建筑，以便每一座建筑物都能拥有属于自己的、包含自己内部约束的数学模型。实时监测系统通过这种方式创建了一个为每个建筑物量身定做的系统，并通过原软件包启用。
- 因此，实时监控系统提高了计算被监测高层建筑位移和定位的可靠性，准确性和精度。
- 与风工程和地震工程相关应用的关键数据可以通过实时监测系统计算得到，因为它能检测每个天线在任何时间任何移动的水平面中定义的坐标x和坐标Y。
- 具有更高精度和可靠性的运动控制，这便于对高层建筑的整体运动进行科学的分析，因为我们可以研究这些建筑的横向及扭转位移，以及风振响应。使我们能够在实时条件下实现高水平安全管理和有效风险管理。
- 实时监测系统可以用于改善对自然环境的风险管理。例如，在地震或台风发生后，该系统可以用来检验该结构的稳定性。它为建筑物提供了额外的安全保障。
- 对它们的精确位置和高可靠性进行瞬时判定，这对于智能高层建筑而言是最基本的，也是最重要的。因为智能建筑允许集成和自动化的管理与控制。
- 该样本可以安装应用在任何新建的高层建筑或相似结构中。以太空塔为例，使用实时监控系统的成本仅占建筑物施工总价的0.08%。

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