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Wireless links for global positioning system receivers

Fabio Casciati and Lijun Wu*

Department of Structural Mechanics, University of Pavia, Via Ferrata 1, 27100 Pavia, Italy

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Abstract. Given an object, its positioning in the space is a main concern in structural monitoring and a required feedback in structural health monitoring, structural control and robotics. In addition, to make the sensor unit wireless is a crucial issue for advanced applications. This paper deals with the exploitation of wireless transmission technology to long-term monitoring GPS (Global Positioning System) receivers - like the Leica GMX 902 and the Leica GRX 1200-pro. These GPS receivers consist of five parts: antenna, receiver, user client computer, interface and power supply. The antenna is mounted on the object to be monitored and is connected with the receiver by a coaxial-cable through which the radio frequency signals are transmitted. The receiver unit acquires, tracks and demodulates the satellite signals and provides, through an interface which in this paper is made wireless, the resulting GPS raw data to the user client computer for being further processed by a suitable positioning algorithm. The power supply reaches the computer by a wired link, while the other modules rely on batteries re-charged by power harvesting devices. Two wireless transmission systems, the 24XStream and the CC1110, are applied to replace the cable transmission between the receiver and the user client computer which up to now was the only market offer. To verify the performance and the reliability of this wireless transmission system, some experiments are conducted. The results show a successful cable replacement.

Keywords: displacement sensors; global positioning system; transceiver; wireless technology

1. Introduction

In structural monitoring, structural health monitoring, structural control and robotics, a common core issue is to position objects and to measure movements. Two features are crucial: 1) No contact (Lanza di Scalea *et al.* 2006), wireless sensor units (Lynch and Loh 2006, Spencer and Yun 2010) should be preferred; 2) The accuracy must be consistent with the structural response amplitude.

For the class of structures requiring an accuracy of centimeters, global positioning systems (GPS) offer a valid solution (Kijewski-Correa, Kareem and Kochly 2006, Casciati and Fuggini 2009, Casciati and Fuggini 2011). Indeed, the GPS technology covers a large area and is suitable for high rise building or long span bridge monitoring, i.e., for the monitoring of constructions characterized by a large own period. It is worth noticing that here laboratory experiments are precluded since the GPS receivers must have open sky visibility. The receivers are therefore put in the roof of buildings, on the top of bridge antennas or along suspended cables. Thus it is evident that to have physical links between the receiver and the data acquisition (DAQ) unit is undesirable.

This paper deals with the application of wireless transmission technology to long-term monitoring

*Corresponding author, Master, E-mail: lijun.wu@unipv.it

GPS receivers - like the Leica GMX 902 and the Leica GRX 1200-pro. Only the GRX 1200-pro supports to work by battery power supply. In the former case, therefore, the power supply reaches the computer by a wired link, while the other module relies on batteries.

The receivers GMX 902 and GRX 1200-pro are briefly introduced in section 2, as well as the requirements for replacing the cable by a wireless connection. These are the design constraint necessary to produce the software managing the radio-frequency transceivers, i.e., the main contribution of this paper. Two wireless transceivers, the 24XStream, which provides a baud rate of UART at 9600 bit per second (MaxStream, Inc. 2006), and the CC1110, which supports a baud rate of UART at 115200 bit per second, are then described. The power consumption of the system is also analyzed. Some experiments based on the coupling of the GMX902 with the transceiver 24XStream are first executed to check the feasibility of substituting the wired communication cable between the GPS receiver and the computer. Due to some unsatisfactory outcomes, some experiments based on the GRX 1200-pro coupled with the transceiver CC1110 are finally executed to check the performance of this second wireless solution.

In the GPS system, there are 32 satellites all around the Earth which periodically broadcast their position information. A GPS receiver measures the distances from it to at least four satellites based on the corresponding signal propagation time: the relevant equations are obtained from the fact that the distances can be expressed on the basis of geometric relationships, the light speed being known. The unknowns in these equations are the position coordinates of the receiver (x, y, z) and the clock offset between the single GPS receiver and the GPS system. The four unknown quantities can be obtained by solving the system of the above four equations.

The GPS receiver system generally consists of six components: an antenna, a receiver, a processor, an input/output (I/O) interface connecting the last two with a control unit (a PC) and a power supplier (as shown in Fig. 1). It is worth noting that usually the receiver and the processor are integrated in a single block: thus one only sees five components. The satellite signal, which is at radio frequencies (RF), is received via the antenna and then is down converted into intermediate frequency (IF) before its sampling as a digital signal. The digital signals are correlated in the correlator with an internally generated replica of the satellite code in order to acquire, track and demodulate the GPS signals. The results of the correlation are delivered to the processor which extracts the GPS raw data, (such as pseudorange, integrated carrier phase, Doppler shift, satellite ephemeris), and controls the software signal tracking loops.

The GPS raw data are then processed by a positioning algorithm to obtain the position and the velocity of the receiver which are eventually displayed. A significant limitation in the applications is the spatial distribution of the receiver. As shown in Fig. 1, the connection between the receiver and the control display unit available on the market is of the wired type which causes inconveniences when this system is used for monitoring the roof of a building or the cables of a suspension bridge. Indeed, the final control display unit in such a long-term monitoring GPS system is a computer which is not conveniently located near-by the antenna, thus resulting in cables of the length of 80-100 m. Therefore, wireless connection is considered to be employed to replace this wire connection.

In addition, the power support cable could be another inconvenience: it is likely that nearby one of the receivers there is a connection to the power network, but it is also true that several receivers must be displayed and again several meters of electrical cables must be left in an aggressive environment. Also this cable should be replaced by a battery in order to increase the flexibility of the system and the battery must be coupled with a power harvesting device able to recharge it. Hence, this paper aims to replace the communication cable by a wireless transmission system

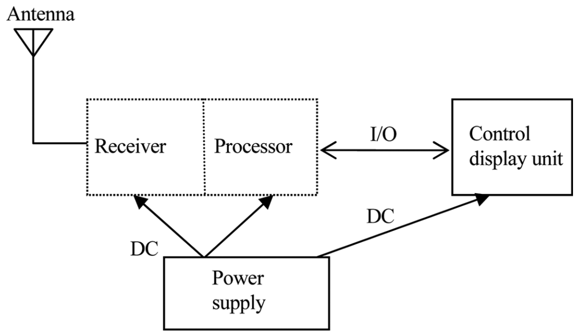


Fig. 1 Scheme of a GPS receiver

without the inconvenience of any power support cable. Such an improvement is possible since the signal between the receiver and the control display unit is in the digital form.

One wireless system, 24XStream, is firstly employed to replace the communication cable between a GPS receiver (Leica GMX 902) and the computer in order to examine the feasibility of a wireless communication replacement of the wired link. The urban communication range of the 24XStream is around 180m without considering the relay mode. This system works properly when the sample rate of the GPS receiver is up to 1Hz. But, since the capacity of serving as a wireless data link of the 24XStream is small, when the sample rate is increased, the data to be transmitted increase giving rise to improperly working situations, like the failure of the connection or a high data lose rate. Moreover, the power support cable of the GPS receiver could not be removed since the GPS receiver adopted, the GMX 902, can only work with its power support cable (Leica Geosystems AG 2007).

Therefore, another GPS receiver, the GRX 1200-pro, which is also produced by Leica and comes with a battery power support, is adopted. A different wireless transceiver was developed based on the integrated circuit CC1110 and the software was programmed in order to utilize this wireless transceiver into this second series of experiments. The line-of-sight communication range of the CC1110 is around 150 m.

2. Leica GPS receivers

As shown in Fig. 2, the Leica GPS receiver system includes: compact geodetic antenna (AX 1202), receiver (GMX 902 or GRX 1200-pro), computer and software (GPS or GNSS Spider and GNSS QC V2.0: GNSS means Global Navigation Satellite System).

2.1 The receiver and its interface with the computer

The Leica GRX1200-pro is a high-performance GNSS receiver, specially developed to monitor sensitive structures. It provides precise GPS dual frequency raw data (12 L1 + 12 L2 GPS, from 0.17 Hz up to 20 Hz), enabling precise data capture of fast moving objects. The data are logged into the Leica binary (LB2) raw data format and could be sent back to the computer by a RS232 compatible interface by which the receiver also receives commands from the software GPS/GNSS Spider which is installed on the computer. The RS232 interface supports a baud rate at 115200 bit/s. In this way,

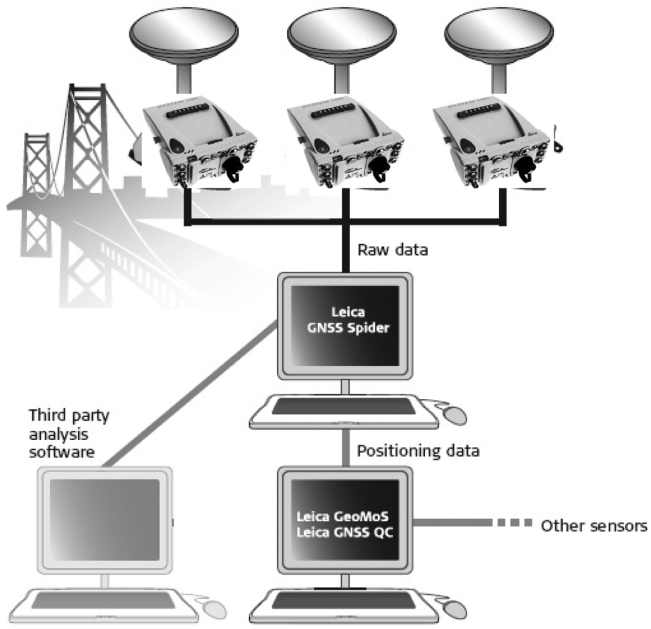


Fig. 2 The GPS receiver system for GRX 1200 (elaborated form (Leica Geosystems AG 2010)).

Table 1 Some parameters of the receiver GRX 1200-pro

No. of channels	12 L1 + 12 L2
Code and Phase Measurement Precision (irrespective whether AS off/on)	Carrier phase on L1 / L2 0.2 mm rms / 0.2 mm rms Code (pseudorange) on L1 / L2 2 cm rms / 2 cm rms
Accuracy (rms) with post processing	Static (phase), choke ring antenna, long lines, long observation time: Horizontal: 3 mm + 0.5 ppm, Vertical: 6 mm + 0.5 ppm
Position update rate Selectable	0.05 sec (20 Hz) to 60 secs (0.17 Hz)
Data capacity (1 GB)	1152h GPS L1 + L2 data logging at 1s rate 17600h GPS L1+L2 data logging at 15s rate

Note: if the standard deviation of positioning result is a mm+b ppm, the distance from the rover to the reference station is D (km). Then, the positioning accuracy is: $\sigma_D = \pm\sqrt{a^2 + b^2 \times D^2}$, unit: mm

the receiver is combined with the Leica GPS/GNSS Spider which manages the coordinates calculation and the raw data storage, and with the Leica GNSS QC monitoring software which manages the analysis of the movement. Removable and robust industrial grade compact flash cards up to 8 GB are used for logging data. Table 1 lists some parameters of the GRX 1200-pro (Leica Geosystems AG 2008). In the available device, the compact flash card is 32 M Bytes, which is sufficient for around 41 recording hours (according to Table 1). The data rate could be calculated as 2071bps when the data logging rate is 1s (the data rate will be 40 kbps when the logging rate is 0.05 s).

GMX 902 GG, which is also produced by the Leica company, possesses similar features as the GRX 1200-pro. But it provides precise GPS/GLONASS dual frequency raw data (14 L1+14 L2 GPS, 12 L1 + 12 L2 GLONASS, up to 20 Hz), and there is not the battery power supply option.

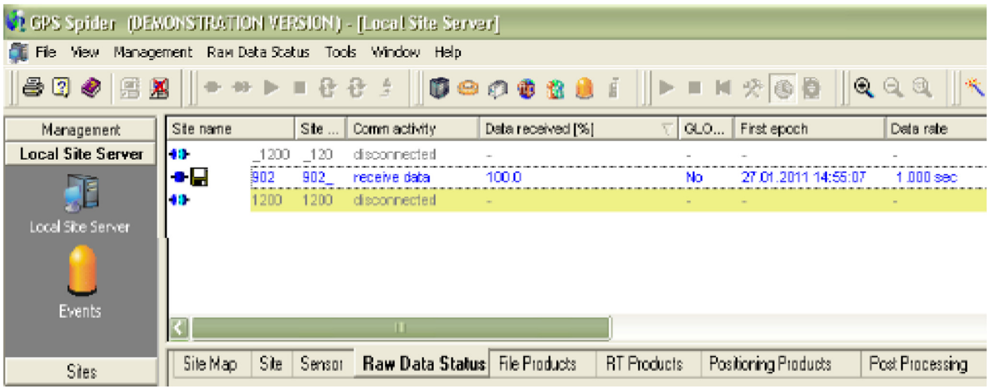


Fig. 3 The local site server interface of the software GPS Spider

2.2 Server and software

The computer acts as a server on which two software products, Leica GNSS Spider and GNSS QC V 2.0, are installed. Leica GNSS Spider manages single and multiple receivers and provides file products service (automatic RAW, RINEX, Compact RINEX data management, data compression, quality control and FTP service) for standard continuously operating reference station (CORS) applications. Continuously streamed raw data can be archived by the GNSS Spider software instead of, or in addition to, downloading the files that were internally logged). The validation of the raw data, for quality and completeness, can be performed automatically (see Fig. 3). It also offers positioning services which include real-time or post-processing. Real-time processing is ideal for solving short and medium baselines between stations and monitoring rapid changes of reference station positions. Post-processing is appropriate for longer baselines between reference stations and detecting slower long term station movements.

By the GNSS Spider software, one can also read the details of the signal such as which or how many satellites are tracked and their navigation information. The achieved data are also accessible in the computer. By the GNSS QC V2.0, one can assess the quality of the tracked satellites signals and the quality of the positioning result (Leica Geosystems AG 2010).

3. Wireless transmitting systems

The goal is to move from Fig. 1 to Fig. 4. Two wireless transceivers, the 24XStream and the CC1110, are employed toward this cable replacement.

3.1 24XStream

The 24XStream RF Module is a drop-in wireless data solution that transfers a standard asynchronous serial data stream (according to the Universal Asynchronous Receiver/Transmitter (UART) protocol) over-the-air between devices (Fig. 5). The module was engineered to integrators with an easy-to-use wireless solution that yields reliable, long range and low cost wireless links. Besides, the signal from the 24XStream is at complementary-metal oxide-semiconductor (CMOS)

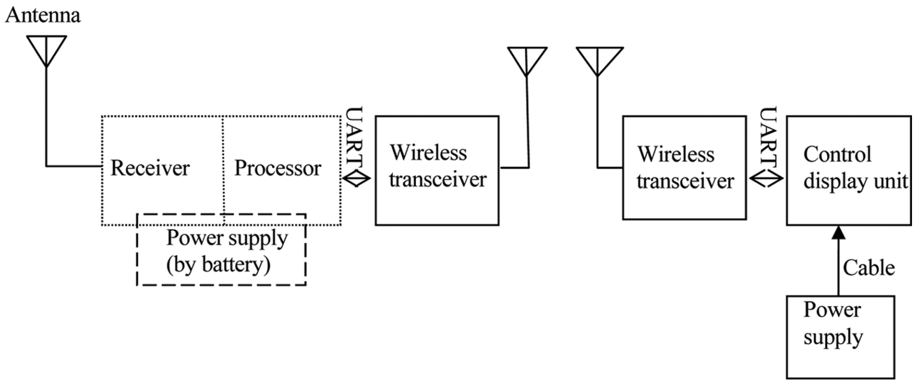


Fig. 4 The objective of wireless connection GPS system

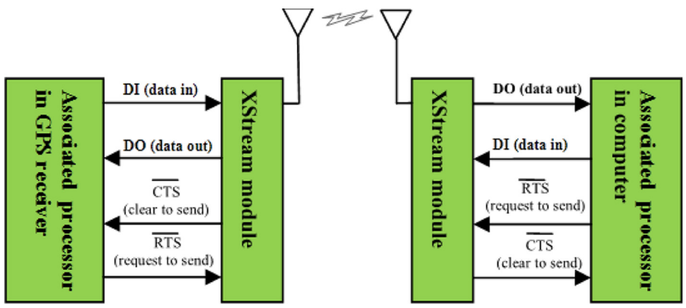


Fig. 5 24XStream wireless links

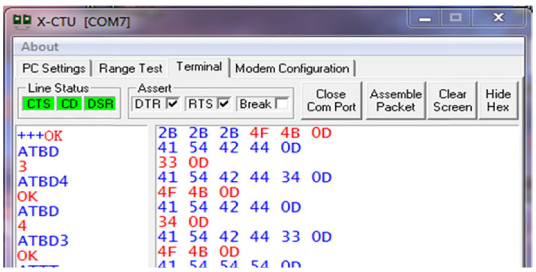


Fig. 6 X-CTU display window

compatible voltage (in which logic "1" is at -3 V, logic "0" is at 3 V) while the signal from the computer interface is at recommended- standard (RS) 232 compatible voltage (in which logic "1" is at -15 V, logic "0" is at 15 V). Therefore, one protocol transceiver Integrate Circuit (IC), MAC3161, is employed to enable the communication.

The module parameters of the 24XStream, like the baud rate of RS 232 or the address of the wireless module, can be modified or read by the software X-CTU (Fig. 6) which is designed to interact with the firmware files found on Digi's RF products and to provide a simple-to-use graphical user interface to them (Digi International 2008). The module must firstly enter into Command Mode with the intention of modifying the parameter by sending a 3-character command

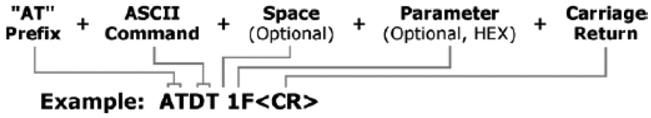


Fig. 7 Syntax for sending AT commands

sequence "+++" in "Terminal" tab of X-CTU. The AT commands[1] could be sent according to the syntax shown in Fig. 7, where the DT is the address command and the following parameter is the new address allocated to the wireless module. As a different example, the baud rate can be configured to be 9600 bit/s by typing "ATBD3 <Enter>", where BD is the interface data rate command and 3 is the parameter of the baud rate which correspond to 9600 bit/s.

3.2 The performance of the 24XStream

Table 2 lists some specifications of the 24XStream RF module. It supports a 9600 bps data rate within 180 meters. A variety of network topologies could be realized based on the 24XStream: peer-to-peer, point-to-multipoint, and point-to-point. At the mean time, it offers the Hopping Channel Command by which different sub-networks could have different hopping channel numbers and they can communicate in parallel. In addition, the 24XStream could be configured as a repeater through which the signal received will be passed and the communication range can be increased. In this way, all these features enable the 24XStream as adequate to be adopted for building a flexible network.

After the power on step, the 24XStream initializes itself and then enters the normal operation processes: idle, receive, transmit, sleep or command. That module can only be in one mode at any moment and this means that it can either receive or transmit at one time, namely it works in simplex mode. When it is used to replace the RS232 connection between the Leica receiver and the computer, the wireless channel is occupied by the data from the GPS receiver to the computer, and therefore it cannot carry the command from the computer to the receiver. This prevents the system from working correctly. The 24XStream introduces a streaming limit configuration (so called TT Command) which is specified by the transmitting module as the maximum number of bytes that the transmitting module can send in one transmission event. This avoids the indefinite occupation of the

Table 2 Specifications for the 24XStream RF Module (with 9600 bps throughput data rate)

Urban range	Up to 180 m
Supply voltage	5 V DC
Receive/Transmit/Power down current	80 mA/150 mA/<26 uA
Frequency range	2.4000-2.4835 GHz
Spread spectrum	Frequency Hopping, Wide band FM modulator
Network topology	Peer-to-Peer, Point-to-Multipoint, Point-to-Point
Channel capacity	7 hop sequences share 25 frequencies
Serial data interface	CMOS UART

[1]A AT command line is a string of characters sent from a DTE (Data Terminal Equipment) to the DCE (Data Communications Equipment) while the DCE is in command state. Command lines have a prefix, a body and a terminator. The prefix consists of the ASCII characters AT or at. The body consists of printable ASCII characters. Space characters other than <Carriage Return>, and <Back Space> are ignored. <CR> is command terminator. Characters preceding the AT prefix are ignored.

channel and therefore it simulates the duplex mode of RS 232.

The wireless data rate of 24XStream (9600 bps) is not enough to promptly transmit the data from the Leica receiver back to the computer while many satellites are tracked in the receiver. Since the GPS receiver will continuously send data to the 24XStream transmitter by UART, there will be more and more data stored on the 24XStream waiting to be sent out by wireless. These queuing data could cause data loss due to overflowing, therefore the baud rate between the receiver and the connected wireless module should be lower than the data rate of wireless link, such as 4800 bps (Casciati and Wu 2011).

3.3 CC1110

Another wireless transmission system, the CC1110, is employed in this contribution to link the GRX 1200-pro receiver: the baud rate cannot be set, but the wireless transceiver is now compatible with the receiver properties. Since the CC1110 wireless module accesses the link by a frequency division multiplexing (FDM) technology (Casciati *et al.* 2009), different modules can transmit signal using different frequency channels at the same time and the communication of several GPS receivers to the computer are ensured.

CC1110 is a low-power radio frequency system-on-chip (SoC) with microcontrol unit (MCU), memory and transceiver. It has up to 32 kB of in-system programmable flash memory and up to 4 kB of RAM, programmable data rate up to 500 k Baud and programmable output power up to +10 dBm (decibel mW). The frequency range adopted in the present application is one of the ISM frequency: 433 MHz. CC1110 supports the use of DMA (direct memory access) for both receiver and transmitter proceedings which minimizes the requirement of CPU intervention. This spares the CPU from transmit and receive process and enables power saving. Besides, CC1110 supports easily constructing the wireless communications since it has flexible support for packet oriented systems, on-chip support for sync word detection, address check, flexible packet length, and automatic CRC handling.

Fig. 8 is the block diagram of the wireless GPS system. The signal from the GPS receiver is transmited to the wireless transceiver CC1110 through a UART-RS232 bridge, SP3223, which converts the RS232 signal into UART signal and vice versa. On the computer side, there is another transceiver CC1110 connected with the computer by a USB-UART bridge. Hence, the CC1110 transceivers communicate with the computer and the GPS receiver through UART. The CC1110 is programmed to achieve wireless communication between computer and GPS receiver. When data are received by Radio, they will be transferred to DMA UART transmit buffer, in which they will be transmitted to the computer or GPS receiver by the bridges when the UART transmit DMA is started, as illustrated in Fig. 9(a). When data is received by CC1110 through UART, they will be saved in the UART receive buffer and then will be transmitted packet by packet through radio. The

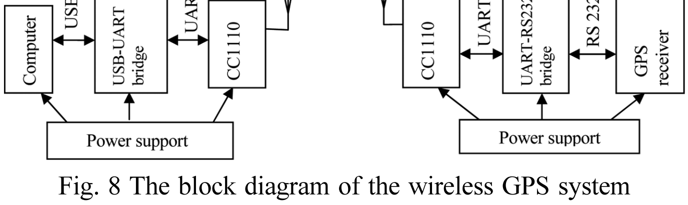
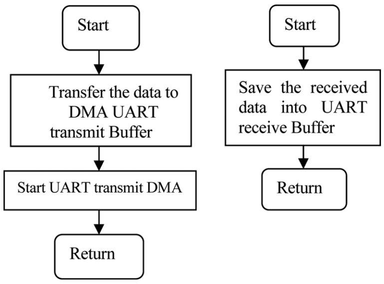


Fig. 8 The block diagram of the wireless GPS system



(a) (b)

Fig. 9 (a) Radio receive interrupt service routine (ISR) and (b) UART receive ISR

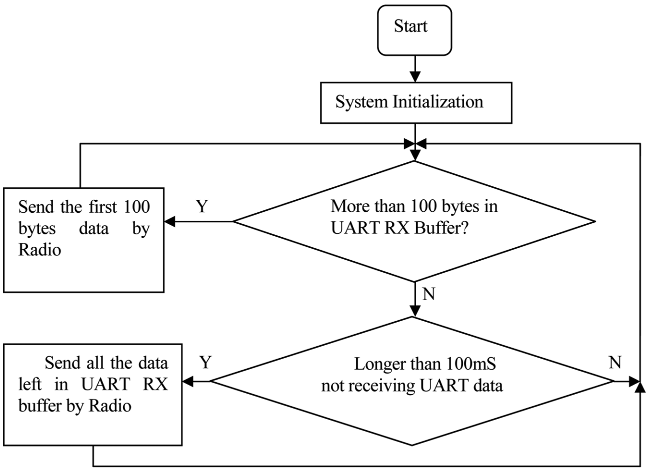


Fig. 10 Main loop

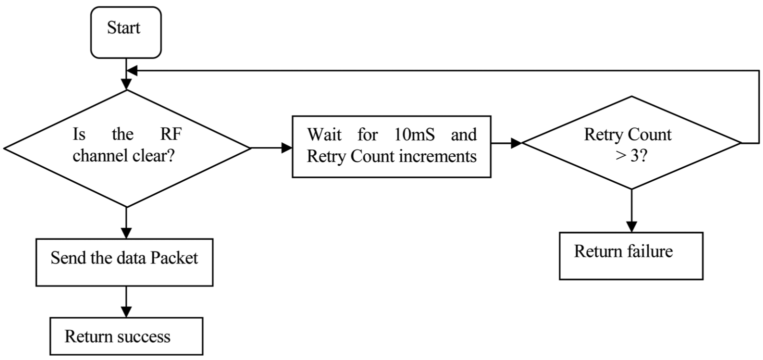


Fig. 11 Radio send

packet will be constructed and sent when more than 100 bytes are in the buffer or there is not data received during 100 ms, as shown in Figs 9(b) and 10. When transmitting the data packet through radio, it must be assured that the radio frequency channel is clear in order to avoid conflict and interference. In our case, three times check will be executed, as shown in Fig. 11. In this way, the computer and the GPS receiver communicate each with the other.

Table 3 The power consumption of GRX 1200 pro receiver system

	GRX 1200+GNSS	AX 1202	Total
Voltage	12 V	4.5-18 V DC	--
Current	Non specified	50 mA maximum	--
Power	3.6-4 W	0.25-1 W	3.85-5 W

Table 4 The power consumption of the wireless transceiver using the CC1110 hardware

	Voltage	Current	Power consumption
CC1110	3.0 V	20.5(RX)/33.3(TX) mA	61.5/100 mW
SP3223	3.0 V	1 mA	3 mW

3.4 Power consumption of GRX1200 and CC1110

Inside the GRX1200, there is an interface for the battery: GEB171, which is a rechargeable 8000 mAh/12 V NiCd battery (8000 mAh/12 V means the battery could work 1 hour if it works in the nomianl voltage (12 V) and the discharge current is 8000 mA). The power consumption of GRX 1200 and its antenna AX 1202 are shown in Table 3. The system could work around 25 hours with the battery (Leica Geosystems AG 2007). The work time of the battery must therefore be extended by adopting an energy harvesting module able to recharge the battery. Normally, the receiver is installed on open sky location in order to capture signals from enough satellites which ensure taking advantage of solar energy or wind energy, In some cases, as in the cables of suspended bridges, the vibration energy of the monitored structure could also be collected to recharge the battery (Casciati and Rossi 2007).

The power consumption (Texas Instruments 2007) of the wireless transceiver and the UART module are shown in Table 4. The capacity of a common AAA size Battery is 1175 mAh/1.5 V, two of which allow the wireless transceiver and interface adapter work in nearly 34.6 hours.

4. Experiments

Some experiments are reported in this section in order to confirm the feasibility and to validate the two wireless links for the Leica system. Experiments are based on both the 24XStream module and the CC1110. The feasibility and capacity of wireless link are examined. As one knows, comparing to outdoor environment, the wireless signal suffers serious multipath effect and deep attenuation under indoor scene which is adopted in these experiments. But for GPS receiver, the antenna is installed on the roof of a three-storey building since indoor GPS signal is poor.

In the first experiment, one 24XStream is connected with the GPS receiver and a second module with the computer, the baud rate being 9600 b/s. The data logged rate in the GPS receiver is 1 Hz and the wireless module works without streaming limit. The software GNSS Spider is configured to archive the data received by the computer. During the monitoring time, one can also read the data received percent (Fig. 3), the tracking progress (Fig. 12) and the real time positioning result (Fig. 13) in GNSS Spider. Then the completeness of archived data is examined by GNSS QC 2.0. Fig. 14 gives the quality report which includes the file details, station details and session summary among other items. The document passed the quality check, thus showing the feasibility of the wireless

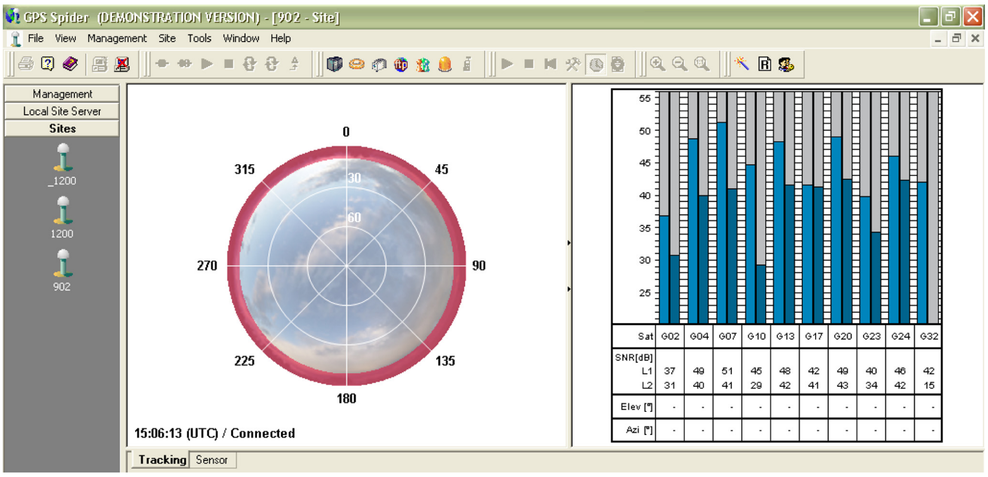


Fig. 12 The real-time tracking result of the GPS receiver

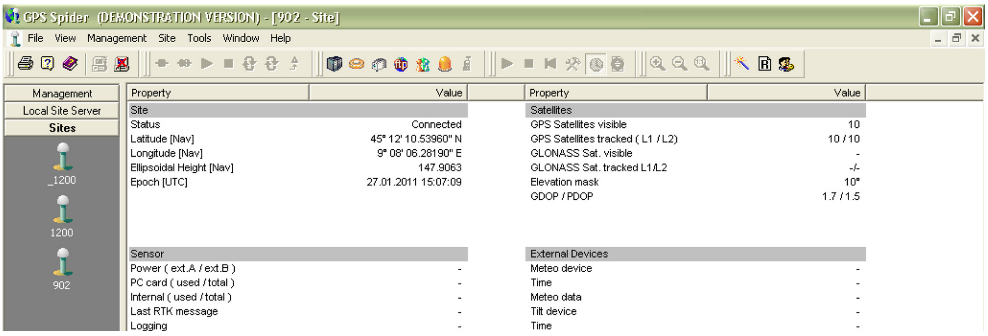


Fig. 13 The real time tracking and positioning results of the GPS receiver

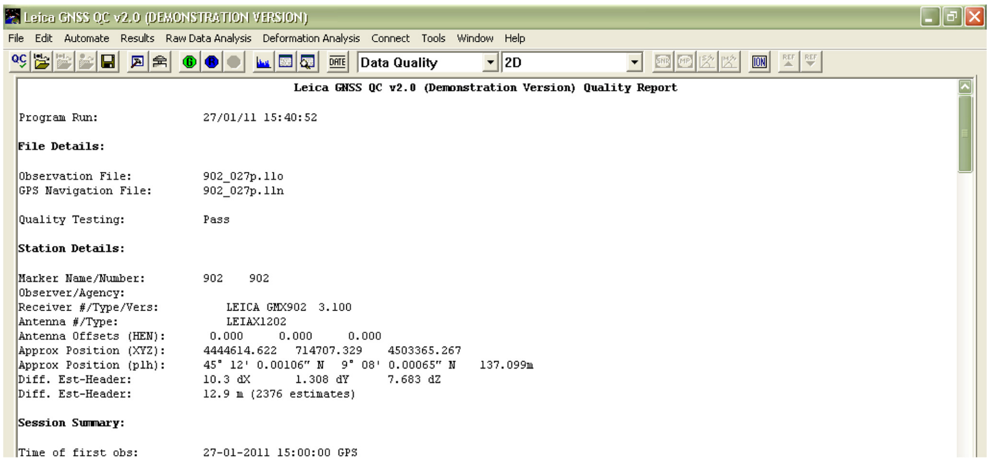


Fig. 14 The quality check report from GNSS QC V2.0

link. But when the logged rate is set to 0.5s, the data needed to be transmitted is increasing. Hence, the data could not be transmitted back to the computer properly.

The CC1110 is then introduced and a further experiment in which the logged rate of GPS receiver

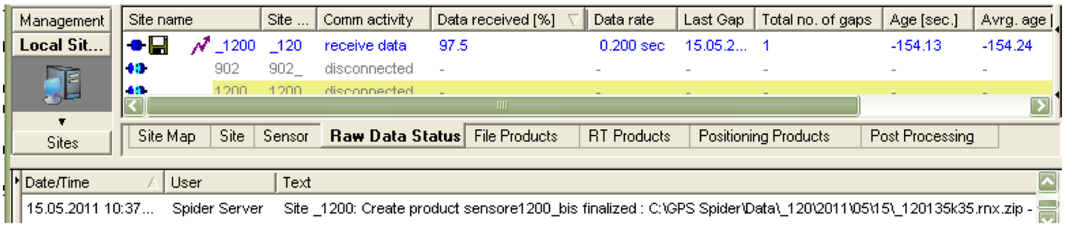
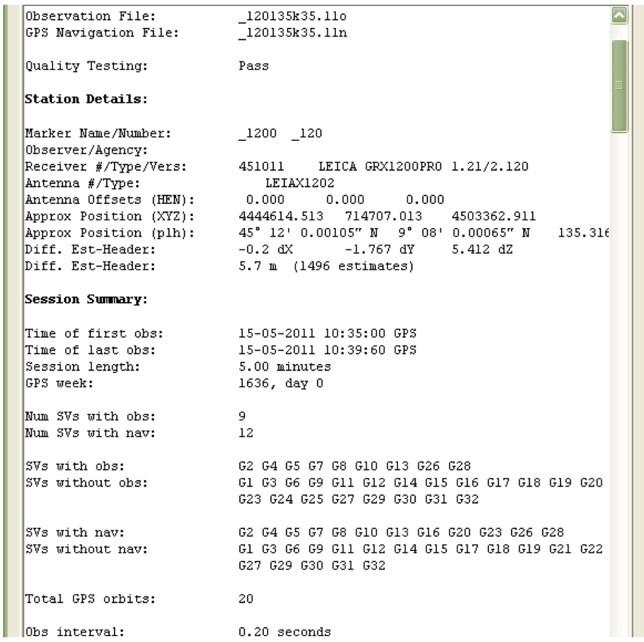


Fig. 15 The raw data status of GRX 1200-pro (by GNSS SPIDER software)


```
Observation File:          _120135k35.11o
GPS Navigation File:       _120135k35.11n

Quality Testing:           Pass

Station Details:

Marker Name/Number:        _1200  _120
Observer/Agency:
Receiver #/Type/Vers:      451011     LEICA GRX1200PRO 1.21/2.120
Antenna #/Type:                LEIAX1202
Antenna Offsets (HEN):      0.000      0.000      0.000
Approx Position (XYZ):     4444614.513   714707.013    4503362.911
Approx Position (plh):     45° 12' 0.00105" N   9° 08' 0.00065" N    135.316
Diff. Est-Header:          -0.2 dX       -1.767 dY      5.412 dZ
Diff. Est-Header:          5.7 m  (1496 estimates)

Session Summary:

Time of first obs:         15-05-2011 10:35:00 GPS
Time of last obs:          15-05-2011 10:39:60 GPS
Session length:            5.00 minutes
GPS week:                  1636, day 0

Num SVs with obs:          9
Num SVs with nav:          12

SVs with obs:              G2 G4 G5 G7 G8 G10 G13 G26 G28
SVs without obs:           G1 G3 G6 G9 G11 G12 G14 G15 G16 G17 G18 G19 G20
                           G23 G24 G25 G27 G29 G30 G31 G32

SVs with nav:              G2 G4 G5 G7 G8 G10 G13 G16 G20 G23 G26 G28
SVs without nav:           G1 G3 G6 G9 G11 G12 G14 G15 G17 G18 G19 G21 G22
                           G27 G29 G30 G31 G32

Total GPS orbits:          20

Obs interval:              0.20 seconds
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Fig. 16 The quality check report (by GNSS QC V2.0)

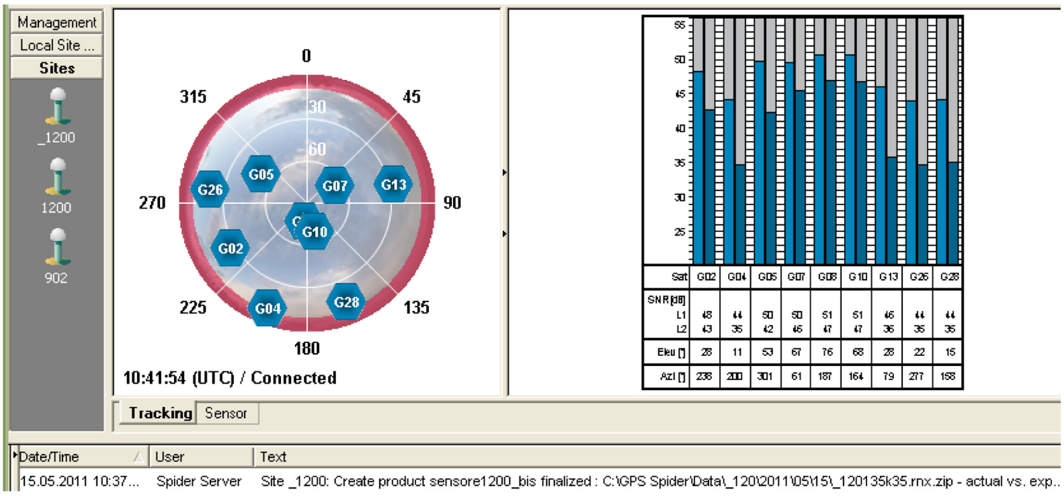

Fig. 17 The real-time tracked satellites (by GNSS Spider)

is 0.2s is carried out. Please, note that GPS receivers are used today in monitoring structure of very high own period and hence a sample rate is 5 Hz is enough to monitor the vibration of the structure. Fig. 15 is the raw data status of the receiver, by which one can see that the wireless UART works properly. Since there is a receive gap at the beginning, the data received rate is close to 100% but not 100%. Then the archived data is sent to the quality check of GNSS QC V2.0, which shows how the data are satisfactorily transmitted (Fig. 16). Fig. 17 shows the real-time tracked satellites.

6. Conclusions

Some experiments are carried out after replacement of the cable within GPS receiver and computer. The results show that this replacement is feasible. Two types of wireless module, the 24XStream and the CC1110 were utilized for the cable replacement. The 24XStream works properly when the logged rate of the GPS receiver is down to 1s, while the CC1110 supports logged rate of the GPS receiver down to 0.2s. The power consumptions of the receiver GRX 1200-pro and of the transceiver CC1110 are also analyzed. According to the analyzed results, the system should work nearly 25 hours as alimented by battery.

This paper contributes to overcome an inconvenience met when one wishes to adopt GPS receivers in structural monitoring: the cable link from the antenna to the storage/processing computer realized by thick cable of tens meters length. In particular, it is shown that the link between the block antenna-receiver and the computer can be successfully replaced by a wireless connection under indoor environment even though the wireless signal is affected by multipath and deep attenuation. In addition, outdoor wireless connection will be implemented in order to examine its robustness.

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