Experience with RTK-GPS system for monitoring wind and seismic effects on a tall building

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ABSTRACT: A dual-rover monitoring system using GPS to track displacements was installed on a tall building in 2000 and integrated with an existing vibration monitoring system. The original purpose of the system was to identify the slowly varying quasi-dynamic component of wind induced response in order to compare with seismic effects on the building. The system operated in real time, collecting data synchronous with acceleration signals, as well as off-line, through post processing of large raw data files. There were numerous technical problems with the system, partly due to the inherent limitations on capability for displacement resolution and the nature of the signal noise, leading to questions about the validity of the larger non-dynamic movements. Nevertheless, the system has been able to detect and resolved dynamic response to both wind and seismic effects. The paper described the practical implementation of the system, the problems encountered and some of the results.

1 INTRODUCTION: PERFORMANCE MONITORING OF STRUCTURES

Performance monitoring of as-built, full-scale structures has become increasingly popular due to developments in design philosophy, changes in performance requirements and developments in structural health monitoring (SHM). Performance is measured either as displacement or acceleration resulting from wind or seismic actions and design aims to provide adequate resistance against various degrees of failure.

Full-scale monitoring has been used to calibrate wind codes (Lam & Lam 1979, Littler & Ellis, 1990), to provide information about structural and foundation system performance that can be used for other designs and to provide indication of changes to structural state, including damage (Jeary et al., 2001, Stewart et al., 2005).

There has been long experience of performance monitoring of tall buildings, but generally long span bridges have been the subjects of the greatest advances in monitoring technology. They are mostly public owned, accessible, visible and high profile. Their designs have usually resulted from elaborate experimental and numerical simulation exercises and there is still much to be learnt about load and response mechanisms. They also have large maintenance requirements and performance monitoring via SHM systems is now seen as the way forward in assisting lifetime management of these major assets. Bridge SHM systems have become very elaborate (Wong, 2003, Le Diourion, 2005) and also provide opportunities to evaluate newly developed sensors and conduct research.

A major target for bridge monitoring is the motion of the deck structure, which for long span suspension bridges can be of the order of a metre. Vertical, lateral, torsional and even longitudinal response is driven by a combination of wind, traffic and thermal actions Brownjohn et al. 1994) and measurement of ‘static’ and ‘dynamic’ components provides information on structural and loading mechanisms. ‘Dynamic’ implies modal response while ‘static’ relates to non-modal response in the frequency range up to fundamental modes. For long span bridge, with first mode frequencies so far as low as 0.05Hz, recovery of displacements from accelerometers is prone to a range of errors. Primarily, broadband signal noise can result, after double integration, in large artificial low frequency displacements. This can be minimized with high specification DC (servo) accelerometers, noise free cables and highly stable signal conditioning but there is no way to avoid kinematic effects due to cross-coupling between motion in different direction. In particular, a DC accelerometer mounted horizontally to measure lateral vibrations will sense rotation such that a lateral mode involving swinging (variation of angle of attack with lateral deflection) will be unable to distinguish the lateral component of deflection. Hydraulic level sensors have been used to measure vertical deflection (Wong, 2003, List, 2004) but are not favoured. Faced with the difficulties of low frequency multi-component motion, an obvious solution is to use an optical system (Marecos et al., 1969). Apart from adaptations of surveying equipment, solutions have been available using light beams (Ahola & Tervaskanto, 1991) or image processing (Brownjohn et al., 1994). Optical systems are challenged by adverse weather and long lines of sight so the promise of GPS to provide absolute displacement signals unaffected by weather, electrical noise or complex kinematics has been welcomed by a number of bridge operators. So far, however, only a few experiences have been reported (Ashkenzia & Roberts, 1997, Nakamura, 2000, Guo et al., 2005, Wong et al., 2000, Kashima et al., 2001).

GPS units were temporarily installed on the deck and towers of Humber Bridge (Ashkenazi & Roberts, 1997), and they showed the same characteristic response obtained using optical systems a few years ealier (Brownjohn et al., 1994), thus demonstrating the capability of the system to track displacements.

For tall buildings the problems are more acute. While the frequencies are higher, the action-response patterns are more complex, movements are smaller then for a flexible long-span bridge, and optical systems are problematic due to lack of reliable line of sight, particular in built-up city areas. There is, however, as much demand for the ability to measure an absolute deflection. While accelerometers are completely capable to measure sway vibration response, they cannot detect changes in building tilt resulting from bending in wind or due to thermal effects, or even subtle shifts in foundation. The extent of quasi-static wind-induced building tilt is handled semi-empirically by loading codes and represents a large potential source of design error, while permanent set or tilt resulting from varying ground movement can be used as a measure of structural integrity. There have been a limited number of building studies (Li et al., 2004, Pagnini et al., 2002, Loyse et al., 1995) but so far the most promising would be the Chicago Experiment (Kijewski-Correa & Kareem, 2003) involving instrumentation of three Towers with GPS, accelerometers and anemometers.

A GPS system was installed on the 280m Republic Plaza office tower in Singapore (Figure 1) between November 2001 and January 2005 with the aim of providing direct measurement of building deflections to calibrate loading code predictions of the relative contributions of dynamic and quasi-static wind-induced deflections. The experiment was as much to test the capability of GPS to resolve the relatively small deflections expected as to characterize the loading and response.

Figure 1 View of completed building

2 BUILDING CONFIGURATION

A full description of the building is provided elsewhere (Brownjohn et al., 1998). In summary, the tower has a frame-tube structural system with an internal reinforced concrete core wall connected to a ring of 16 external steel columns by horizontal steel framing system at every floor, all supported by a deep caisson system, and with diagonal outriggers provided at only two floor levels. The fundamental natural frequency for the building was predicted by the architect to be 0.14Hz, and as well as meting local design requirements on resistance to design winds (up to 35m/sec gust at 10m height) and accidental eccentricity (equivalent to 1.5% of weight as a lateral force), a vibration serviceability requirement of 100mm/sec^2 maximum acceleration was used.

3 PEFORMANCE MONITORING

The building had been instrumented from 1996 using a set of four accelerometers, two at basement level, two at roof, and a pair of three-component anemometers perched just above the parapet on each corner of the building. Signals were continually digitized at 60Hz per channel before decimation at 8x into blocks of 4096 data samples. Mean and variance values for these 540-second blocks were saved and the raw time history also collected when trigger conditions of strong wind or strong acceleration were met. From these data it was possible to determine the correspondence of dynamic response with loading conditions, specifically wind and tremor excitation. The only other source of strong response was the roof-mounted crane used for window-cleaning.

From the observations it became clear that response to regional earthquake, occurring at distances of up to 3000km, were the most significant vibration source. The strongest roof level acceleration response, reaching +/-56mm/sec^2, resulted from the June 2000 magnitude 8 earthquake. This response exceeded even that caused by the 2004 Boxing Day earthquake, also epicentred in the Sumatran subduction zone. Compared to these levels, the maximum acceleration due to wind was +/-16mm/sec^2. Based on experimentally obtained mode shapes and construction material weights provided by the contractor, it has been possible to estimate the corresponding peak base shears; these come to 0.88MN for the tremor and 0.38MN for wind.

Compared to the 711MN dead weight of the building these are insignificant, but the data lead to a question about the performance of lower rise buildings responding more heavily to seismic loads. Republic Plaza has relatively low response since it responds primarily in second mode (around 0.7Hz) that has a lower participation factor than first mode (around 0.19Hz) and it is expected that typical residential structures of around 30 storeys would be more vulnerable, particularly those on soft soil or reclaimed land sites.

For tall buildings of this class, there is still a risk, given the sequence of tremors beginning in late 2004, that larger seismic motions could result, yet design only caters for wind load, and this is based on an archaic British design code (CP3). This code is based on an equivalent static load due to a 3-second gust, and it is generally believed that resulting lateral loads govern tall building design in Singapore.

The monitoring exercise provided a means to check this belief, using a more rational design approach (e.g. the new Australian code AS1170.2) which is based on a mean wind speed with a dynamic amplification factor, typically at least 2, that accounts for turbulence, peak factor and resonance. Calculations for Republic Plaza showed that the base shear, and hence the lateral deflection, should comprise up to 50% from static effect of mean wind and at least 50% from background and resonant contributions. The accelerometer-based system could only detect accelerations so the 'static' contribution could not be measured. Despite the widespread use of the static+dynamic load approach, there have (apparently) been less than a handful of exercises to validate it at full-scale and the Republic Plaza exercise provided an opportunity to investigate the nature of the dynamic amplification factor from direct measurement of total displacement.

4 RECOVERY OF AND DYNAMIC DISPLACEMENTS FROM ACCELEROMETER SIGNALS

To begin, recovery of displacements from accelerometer signals was investigated. The double-integration approach to recover displacements is subject to contamination by noise at very low frequencies which translates to high displacements. Experimentation with high pass filtering in the baseline correction process applied to tremor response data has shown that using a cut-off frequency of 0.02Hz or higher the lowest frequency components show the expected rigid body motion of the building; Figure 2 shows time series of double-integrated accelerations resulting from a very distance tremor with a little mode 1 vibration response superposed on the roof level response (upper plot) compared to basement response (lower plot). Using lower frequencies generate random artifices (such as in the first part of the upper plot of Figure 2) and since the time taken for build up to peak wind levels even in sudden severe storms was observed to be much longer than 50 seconds, this method cannot be relied on to recover quasi-static response to wind.

An alternative method based on acceleration signals assumes that deflection is accompanied by rotation which would be evident as a shift in mean acceleration of the DC accelerometers. For example if the building behaves as a perfect cantilever with a point load at the tip, the rotation α is related to deflection δ by $\delta = 2h\alpha/3$ where h is height and g is acceleration due to gravity.

Since the accelerometers operate down to 0Hz (DC), a rotation of the accelerometer by a small angle α is sensed as a (mean) static acceleration $\ddot{x} = g \cdot \alpha$. Using a typical wind profile and an experimentally validate finite element model, then $\delta = 0.84h\alpha = 0.84h\,\ddot{x}/g$, a result that cold be used to infer the static drift; a 1mm/sec^2 shift in mean acceleration can be interpreted as an improbably large static deflection of 24mm. Displacement recovered this way is termed pseudo-displacement.

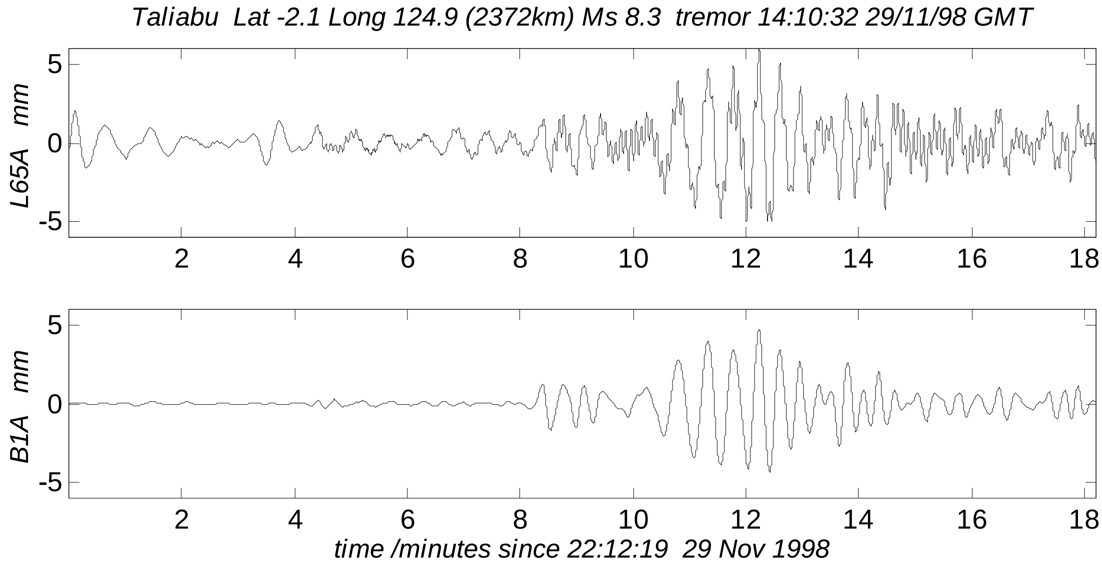

Figure 2 Double integration of tremor acceleration signal

This works if there is no temperature dependent bias in the instrument system so thermal correction factors have been applied to the signals. There remains a temperature dependence which cannot easily be corrected for and given the issues of noise and thermal drift, this method appears to be unreliable. Hence, having observed the performance of GPS at Humber[7,11], a system was designed and installed at Republic Plaza.

5 GLOBAL POSITIONING SYSTEM

The acceleration and wind recording system was upgraded in 2001 to include a dual-rover displacement tracking system using real time kinematic (RTK) differential GPS. Data sample rate was changed to 8Hz.

For a single receiver (rover) as with a personal satellite navigation system, estimates of location are subject to errors that depend on modification to signal transit time due to atmospheric and other effects. If a fixed base or reference (base) station is used nearby, given the known fixed location, the 'differential' errors can be identified and used to adjust the rover position estimate. When the errors are transmitted from base station to rover and incorporated in rover position estimates in real time, position fixes accurate to the order of a centimeter or better are possible, at real-time rates of 10Hz or more. Real time operation uses software embedded in the receivers, whereas by saving original signal transmission times as 'raw data' for each receiver, subsequent post-processing can merge the base station

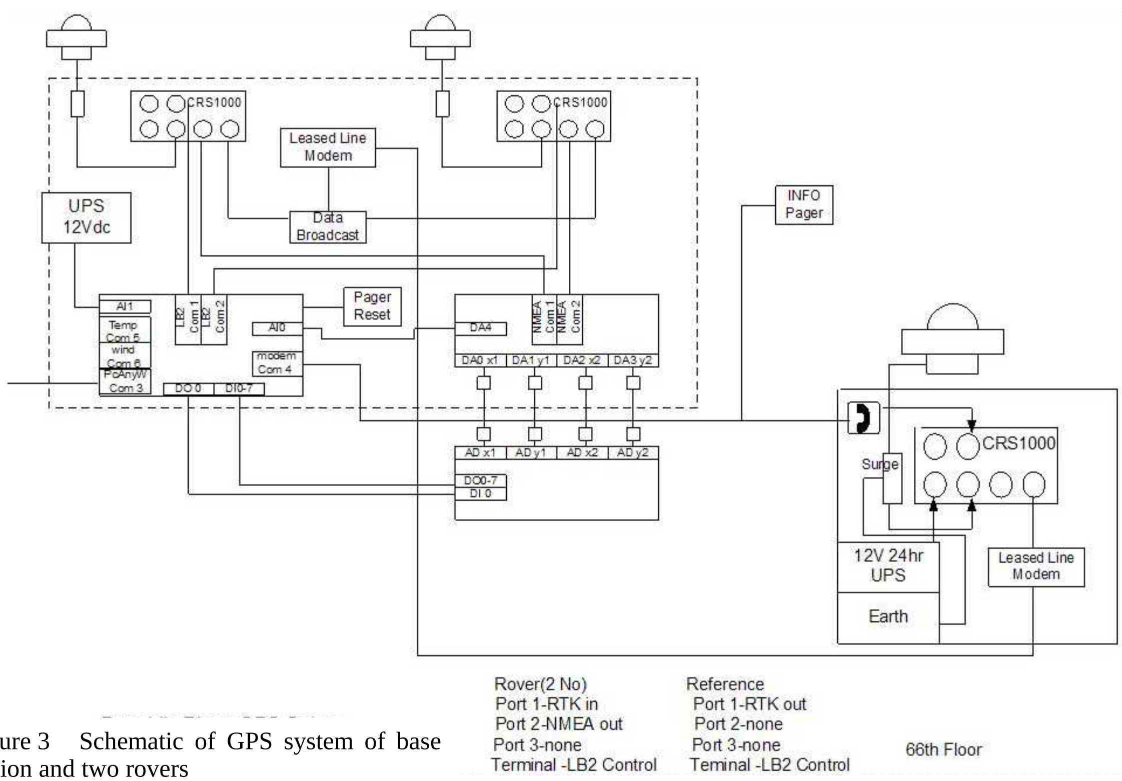

Figure 3 Schematic of GPS system of base station and two rovers

and rover data sets to provide position fixes taking advantage of more sophisticated off-line processing and virtual base stations, potentially providing more accurate data.

5.1 *GPS configuration*

The system at Republic Plaza as shown in Figure 3 and was designed to operate in both RTK and off-line post-processing modes. The system comprised Leica SR530 receivers for base station and rover, using standard geodetic antennae.

The base station antenna was mounted on the roof of Diethelm headquarters in Singapore (Figure 4), rover antennae were mounted on slender, rigid poles at each corner of the open roof top of the Republic Plaza (Figure 5). RTK corrections generated by the fixed base station at 1Hz data rate were transmitted by permanent leased line to both rovers, which generated corrected solutions as 1Hz. Leica 'raw data' files were continuously acquired into ring buffers and these were saved on trigger command for each significant event. The data save process involved retrieval of the base station data files over a separate dial-up line, during which time new trigger conditions were not recognized. For a single isolated trigger event, data files spanning 30 minutes either side would be stored in the host computer at Republic Plaza for each of the three rovers, for subsequent post-processing.

As well as saving the raw data files, the corrected solutions for each rover were continuously output as NMEA format ASCII data. Since the data recorder PC used a primitive data acquisition programming environment, synchronization of ASCII input with analog signals was impossible and it was necessary to install digital to analog converter units to interface with the existing analog recorder.

The 1Hz data rate was chosen as it was expected that displacement levels corresponding even to significant seismic response in building second mode would not reach the best estimate of GPS resolution of about 3mm and even at 1Hz there were considerable overheads in transmitting the raw data over phone lines. The post-processing technique used was also semi-manual restricting the amount of data that could readily be processed.

The antenna configuration at Republic Plaza (Figure 5) was not ideal; it was not possible to use larger, more expensive and more accurate choke ring antennae and the low level mounting was intended to reduce likelihood of lightning strikes.

5.2 *Validation*

The initial GPS data appeared very noisy and not to correlate with other signals, hence it was difficult to believe what the data represented. In fact validating the GPS data was a major issue, as the signals were, in principle, subject to various forms of error such as multi-path, cycle-slip, random noise and systematic noise. Also, the total movement of the building was expected to be of the order of +/-0.1m as a combination of all loads. Direct evidence of correct functioning of the system was obtained first by physically moving the antenna during a recording and secondly by studying the signal during strong winds generating first mode deflections at least 5mm amplitude.

Figure 4 Base station antenna

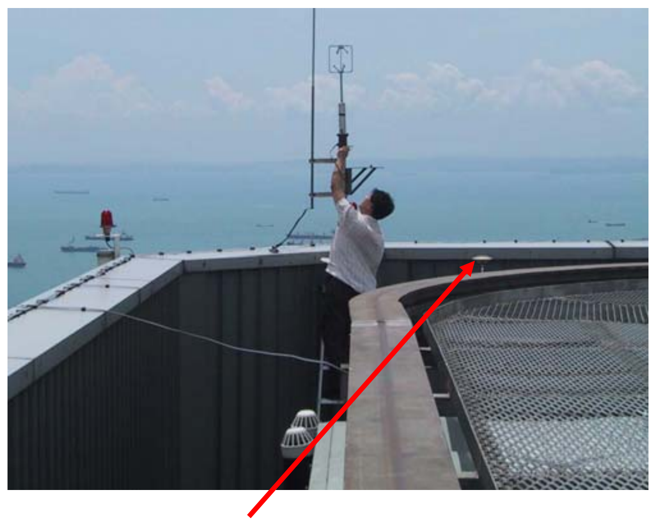

Figure 5 Rover 1 antenna flush with parapet

Figure 6 shows the movement of the antenna in relation to the building configuration and direction, in a cycle of -220mm, +440mm then -220mm along the mounting beam. Figure 7 shows the recorded RTK signal. The first frame of data is corrupted by a periodic over-ranging of the system (at varying intervals of approximately 30 minutes) that appears in many of the earlier data and was never explained.

Due to the orientation of the beam, the antenna moved +173mm, -346mm, +173mm in east direction, at the same time -135mm, +270mm then -135mm in north direction. The magnitudes shown in channel 13 (west rover -2, eastings) and channel 14 (west rover -2, northings) correspond, but the sign for the east direct is revered.

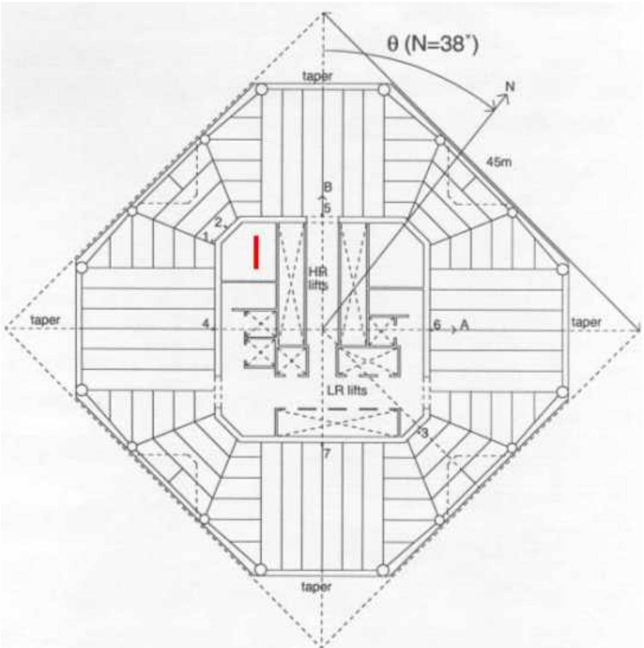

Figure 6 Experiment moving antenna +/-200m along red line

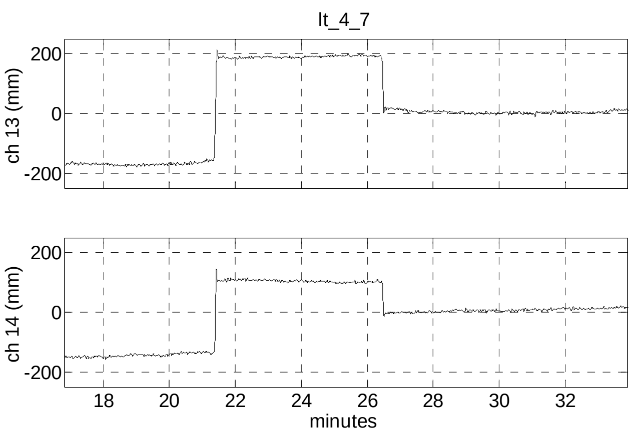

Figure 7 Recorded RTK signals fro experiment

Only raw data sets for more interesting events were post-processed; Figures 8 shows results for two of the 'best' data sets; best in terms of clear signals and lack of sudden anomalous shifts. The raw data were able to provide information about confidence limits on each data point together with a wealth of other information, including details of satellite availability but there were significant problems using it, specifically, it was not straightforward to synchronise the data with the analog recordings except by sliding one or other data set along the time axis to account for different start times. Because of the various practical difficulties with the raw data it was decided to first check that RTK and post-processed solutions concur and then rely on RTK for most purposes, with post-processing to be applied in collaboration exercises for occasional (special) events and to employ more accurate software.

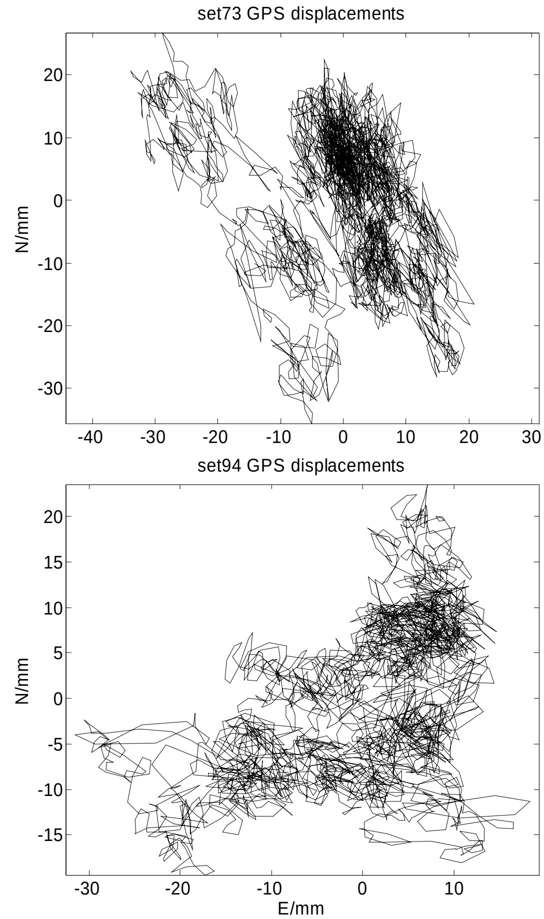

Figure 8 Building movements from raw data post-processing

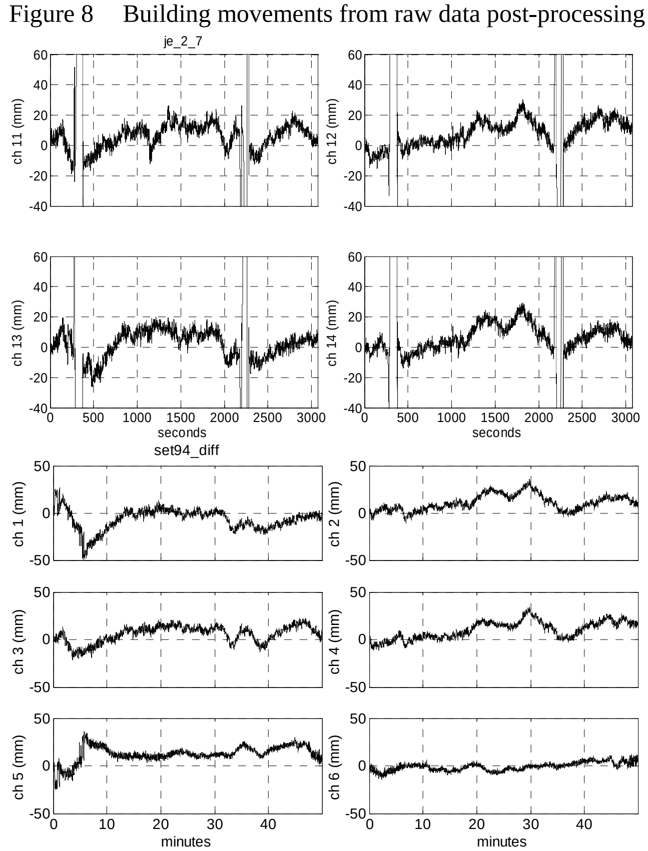

Figure 9 Comparison of RTK and post-processed GPS solutions: Top: RTK data Je_2_7 Bottom: Post-processed set 94. Last row is difference of post-processed signals

Data set 94 and the concurrently acquired analog set JE, are compared in Figure 9. Although the sequence of the sensors is slightly shifted, and apart from the periodic dropout, the signals match well enough for RTK to be used. Note that there are differences between the northings and easting between the two rovers; due to the fixed relative position, the only difference for a real signal should be due to rotation which is expected to be negligible. Hence the difference between the two signals provides one indication of possible errors.

Figure 9 also shows, in the bottom row, for the raw data, that these differences are of the same order as the building deflections that the system is attempting to recover.

Figure 10 shows response during what appears to be the windiest day of 2003. The building anemometers had failed but recorders elsewhere in Singapore had logged an unusually high (for Singapore) 30-minute mean wind speed over 20mph. There is a clear component of displacement at mode 1 frequency, also evident in the time series.

5.3 *Continuous acquisition and further validation*

From December 2003, in addition to capture of triggered data files with 8Hz sample rate, continuous acquisition of a subset of six data channels (two level 65 acceleration and four GPS) at 1Hz was in operation, so that acceleration data were provided at the same rate as GPS. Only the response in the first mode and the quasi-static response are useful hence 1Hz is adequate to resolve these.

Figure 11 shows one period during March 2004 when a storm excited relatively strong dynamic response. The enhanced dynamic response, in mode 1, is clear in the acceleration signals, which show sudden increase in mean level of A-direction signal.

There is a clear correlation between temperature and mean level. These storms are associated with noticeable temperature drops as winds pick up and dynamic acceleration increases. There is, however, a lag before the accelerometer cools and the first row of Figure 10 shows accelerations after correction for thermal bias so instrument effects seem an unlikely explanation. On the other hand, if the shifts in mean acceleration are interpreted as pseudo-accelerations, the 2mm rise corresponds to a 50mm deflection, but it is always in the same direction, whatever the wind. The GPS displacement signal in this case is likely to be more reliable. The RTK data shown (channels 5 and 6) are corroborated by the second rover and appear to indicate a steady drift of the building with a kind of ratcheting, together with dynamic response.

6 GPS RECORDING OF GROUND MOTION DURING 2004 BOXING DAY EARTHQUAKE

The final result for the system before it was permanently shutdown in early 2005 was to provide a record of the response during the Boxing Day (26th December) 2004 magnitude 9.0 earthquake.

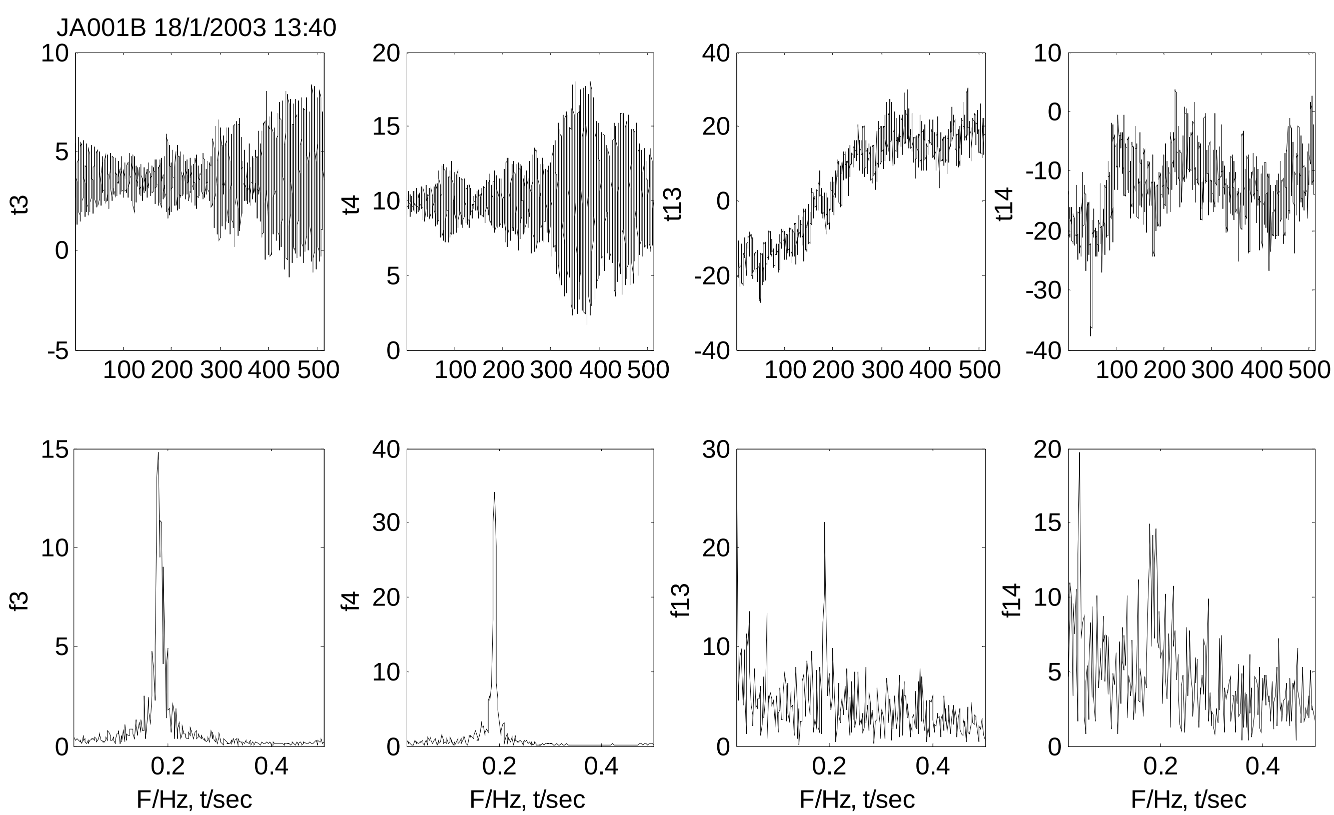

Figure 10 Acceleration and GPS time series and FFT for on windy day

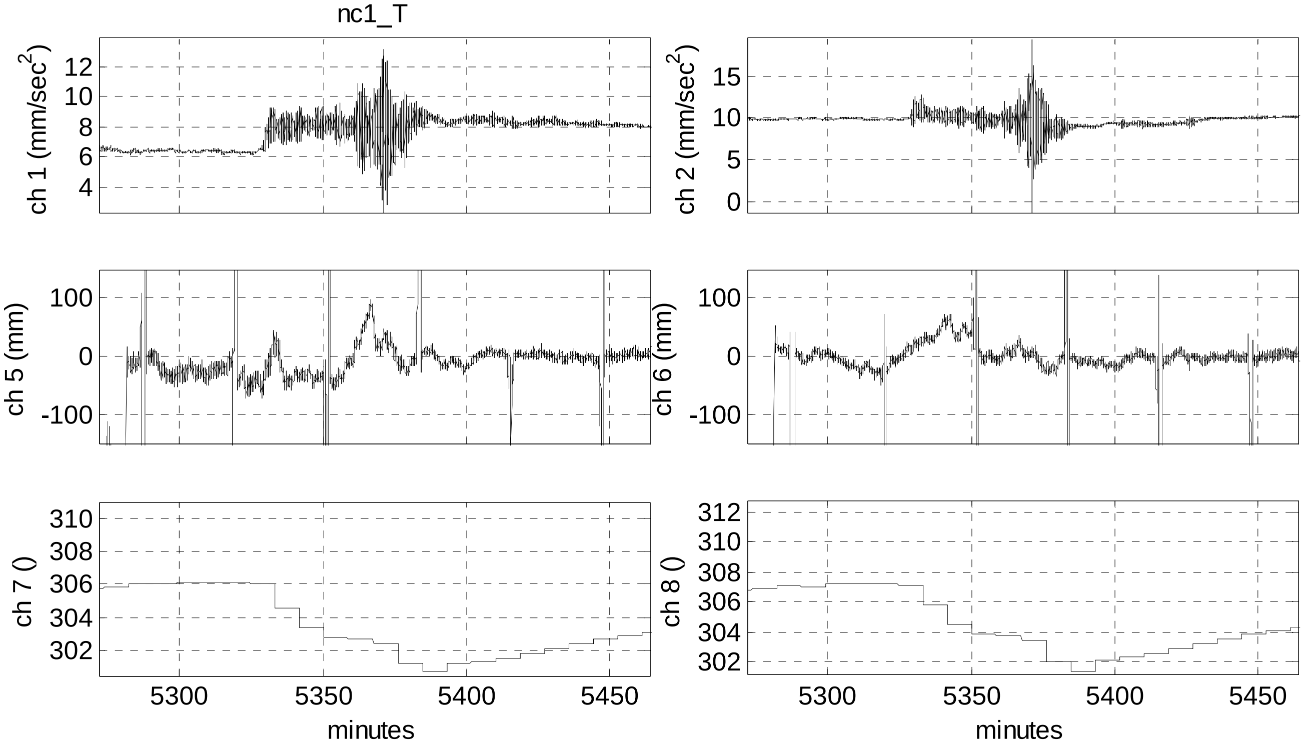

Figure 11 Acceleration, GPS and temperature (degrees Kelvin) signals during storm

Acceleration, RTK and raw GPS signals were recorded and show some notable features. The response spectrum of the earthquake is unusually strong at lower frequencies; peaking below 0.7Hz and peak accelerations, displacements and base shears were all less than for the closer Bengkulu quake of 2004.

Figure 12 shows a sample of displacements from GPS and double-integrated accelerometer signals. Since GPS provides signals relative to the base station, the accelerometer-derived signals are the values relative to basement, also rotated to the GPS axes. The signals are band-passed in the range 0.1Hz-0.3Hz. The correspondence is very clear.

Figure 13 shows untreated post-processed signals, in the global XYZ Cartesian system (which is a frame of reference rotated w.r.t East/North/Vertical). Z is North and Y is approximately vertical. The variance errors are also plotted; they are relatively low during the 'strong motion' part of the signal but values are as large as the signal itself. Figure 14 is the spectrogram showing time-frequency variation. The enduring first mode response is clear, there is also some signal up to 0.08Hz.

7 CONCLUSIONS ON PERFORMANCE OF GPS

Even after ten years of monitoring there are still mysteries about the building performance. For example the static deflections due to temperature have still not been determined and present a problem as temperature affects the instrumentation as well as the structure movements.

The GPS data show no daily cycle and the pseudo displacements do not appear to be reliable given the strong correlation with temperature even after applying the given correction factor. The way the building responds to mean and slowly varying winds is still not clear; so far there is not an obvious pattern, and even a suggestion of highly non-linear behaviour.

The GPS did not quite live up to the high expectations; it was technically challenging to integrate the signals into the (rather archaic) existing logger, there were problems with unreliability for various reasons (communication issues from rover to base station, system overheating, antenna destruction, unusual application). For the periods of uninterrupted RTK signals, the signal appeared to be very noisy with non-random behaviour difficult to interpret as building movements. Nevertheless, during sudden strong wind and seismic events with sustained large first-mode amplitude, there were clear and systematic GPS displacement signals of quasi-static movement or dynamic response. These indications alone are enough to indicate that for (rare) building dynamic response exceeding 10mm/sec^2 amplitude GPS should be able to identify both static and dynamic response. This includes response to large earthquakes, although only the relative motion of the building can be captured.

Since the difficulty is to capture the very low frequency signals, it seems that a different approach should be to use a static (rather than dynamic) GPS solution with sample rate of 1 per minute and integrate this with accelerometer data.

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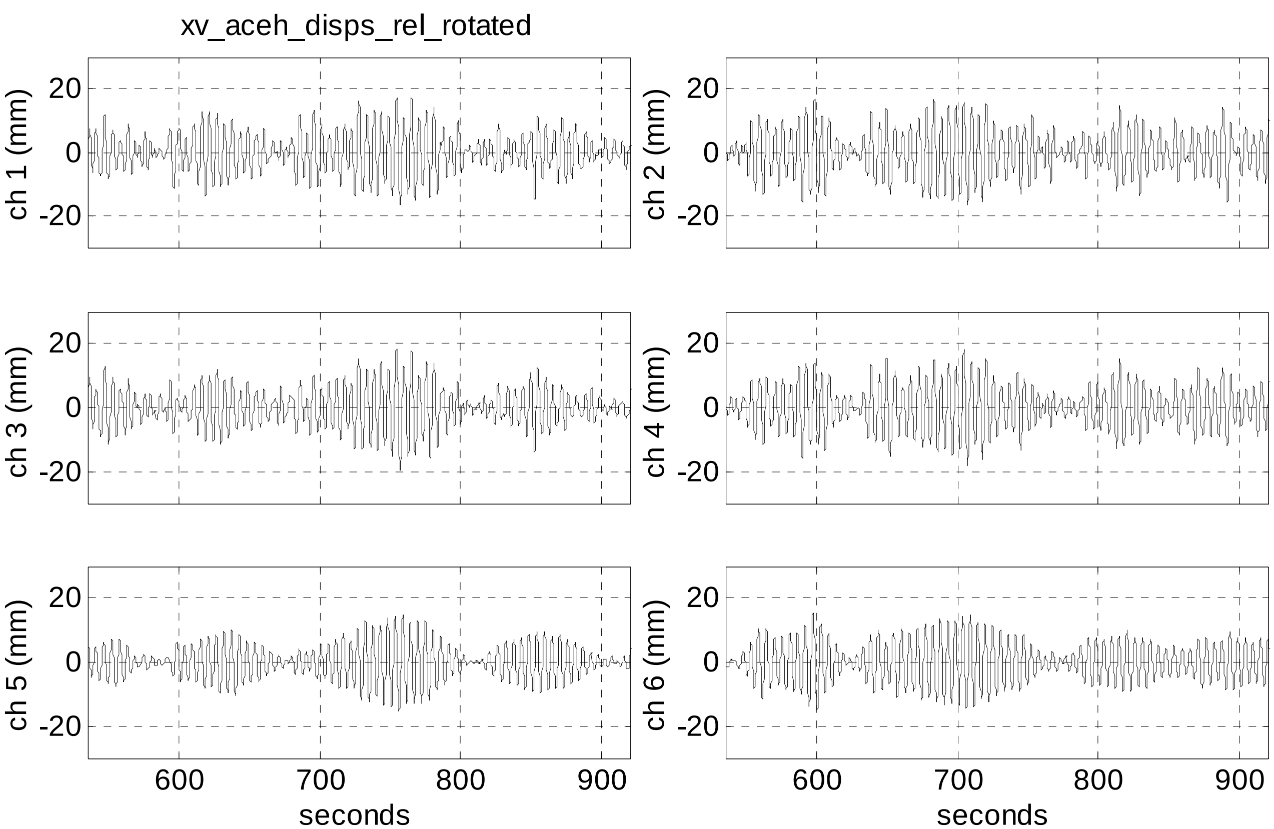

Figure 12 Narrow-band (0.1-0.3Hz) filtered displacement signals during Boxing Day 2004 earthquake: Ch1/2 are rover 1, ch3/4 are rover 2, ch1/3 are eastings, ch2/4 are northings. Ch5/6 are difference or roof and basement accelerometer signals rotated to north/east axes.

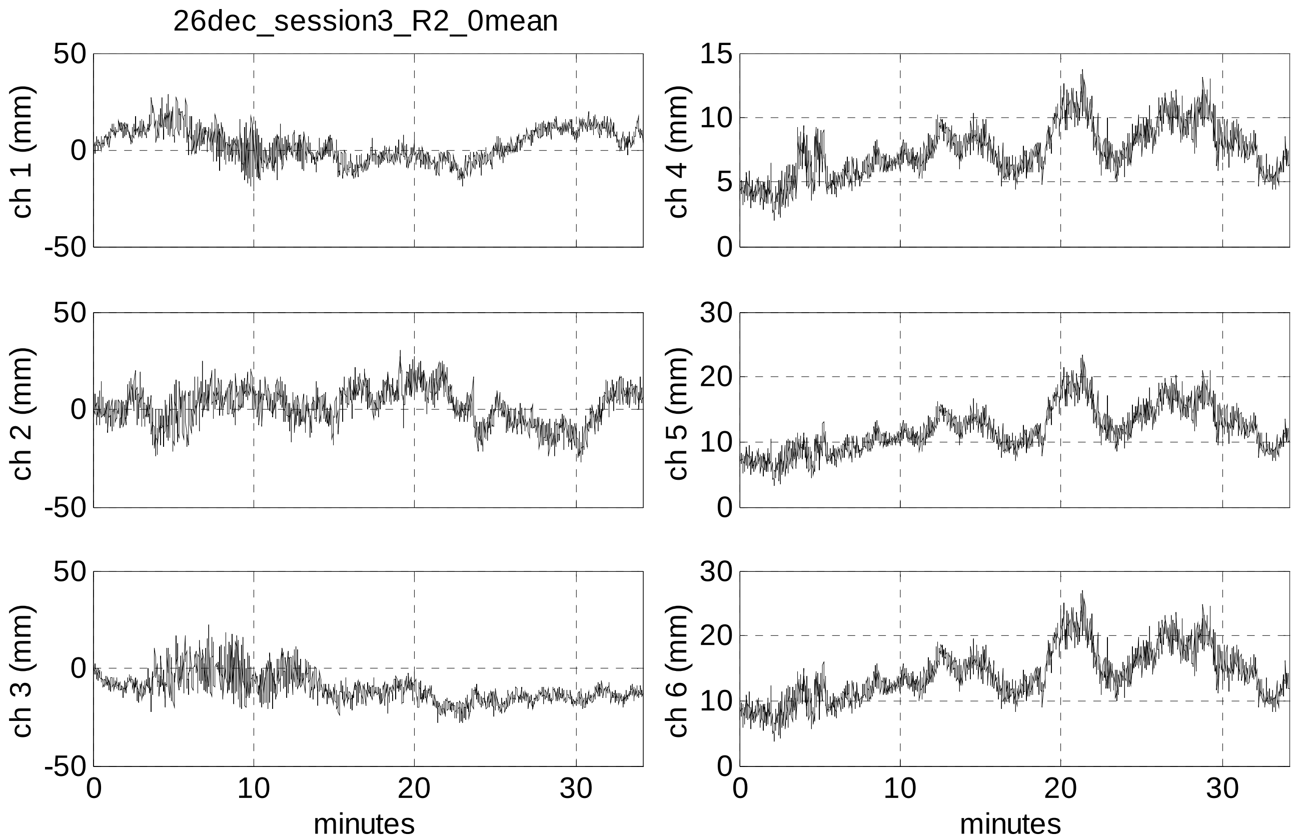

Figure 13 Post-processed rover 2 data in Cartesian global co-ordinates, ch4-6 are variance

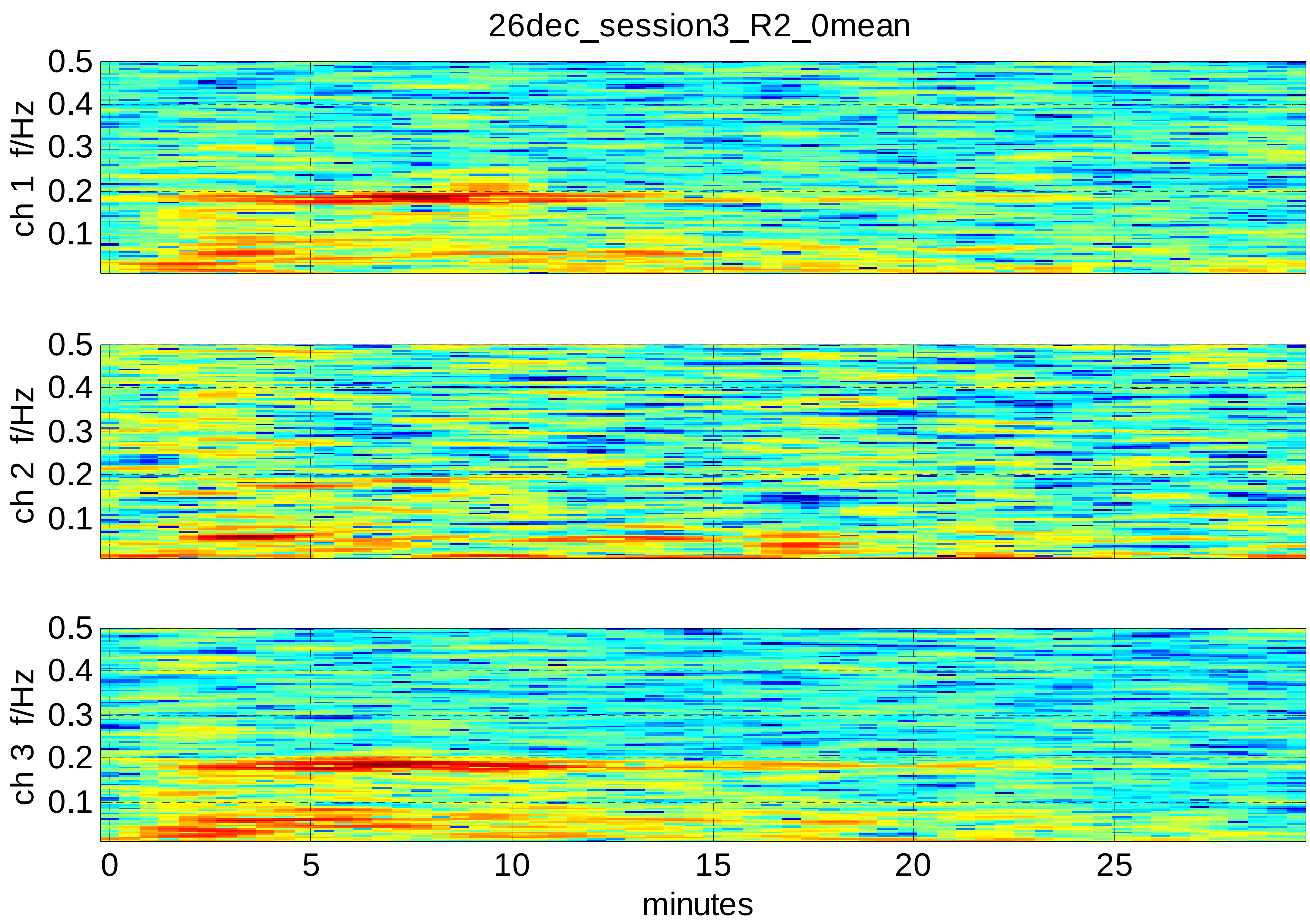

Figure 14 Time frequency plot (spectrogram) of rover 2 signal