Project 12399 TTW-NWO

Project Title:
Light-weight towers with stable platform for astronomical, meteorological and civil-engineering measurements.

Subject:
Measurements during a heavy and gusty storm with the 2 towers located on the KNMI (Royal Netherlands Meteorological Institute) test field in Cabauw. Comparison with shake experiments on the towers.

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1. Introduction

Measurements were carried out on two towers at a distance of 900m on the test field of the KNMI (Royal Netherlands Meteorological Institute) near the village of Cabauw. The towers are open light-weight framework constructions, transparent to the air for minimum influence on the local meteorological situation of temperature, wind and humidity, see Figures 2 and 4. The developed special geometric design and construction keeps the platform parallel to the ground under wind load, which gives the open towers the required stability for the measurements over large distances with directed optical beams.

2. Instrumental setup

A Large Aperture Scintillometer (LAS) measures the scintillation between the tops of the two towers. It consists of two 15cm aperture telescopes, which are precisely pointed to each other. The Transmitter is placed on the first tower, see Figures 2 and 3, the Receiver on the second tower, see Figures 4, 5 and 6.

The location of the Transmitter tower is called Wielsekade, the name of the nearby street along a small canal. The Receiver location is called RSS from Remote Sensing Site, a nearby place with many instruments. The eye safe light beam from a LED in the Transmitter has a wavelength of 850nm.

Wind and acceleration sensors are installed on the tops of the towers in addition to the LAS. Light-weight fast-response cups anemometers and wind vanes are mounted on both towers, see Figures 3 and 5. An ultrasonic anemometer is mounted in addition on the Receiver tower, see Figure 5. This instrument is able to measure both wind velocity and direction with even higher frequency.

The fast-response biaxial acceleration sensors are mounted on the central base platforms for instruments on top of the towers. Two sensors are installed on each tower. One axis of each sensor is placed in vertical direction. The other is in horizontal direction. The horizontal axes of the two sensors on a tower are placed perpendicular to each other. The accelerations in all three directions are measured in this way. The many cables of the sensors are seen on Figures 3, 5 and 6. The acceleration sensors itself are small and not clearly visible in the images.

3. Measurements

Continuous measurements are performed and the data stored on two computers in the Porto-Cabin, a work-room container on the RSS nearby the Receiver tower. One computer services the LAS and ultrasonic wind sensors, the second serves the cups plus vane wind sensors and the acceleration sensors.

A heavy gusty storm occurred in the evening of June 5, 2019, see for instance KNMI website page:
http://projects.knmi.nl/cabauw/insitu/index2.htm
-> observations -> cabauw -> special days (meteo) -> 20190605

The results of the measurements on the towers during the heaviest wind gusts are placed together in combinations of measurement curves from the wind sensors, the LAS signal and acceleration sensors to show the correlations between the different types of measurements.

Wind speeds measured by the cups anemometer and ultrasonic sensor on the Receiver tower at the RSS location are combined with the LAS measurements in Figure 1. The curves are from the minute with the strongest wind gusts at the RSS. Small differences are visible between the two wind curves because of different location of the wind devices at the tower, see Figure 5. The cups are higher located at the tower top compared to the ultrasonic sensor at the West side of the tower platform, what can make the ultrasonic windspeed measurements also slightly dependent on the wind direction. The measured maximum windspeed by the cups is 37 m/s and by the ultrasonic sensor 35 m/s, what can be explained by the slightly lower position of the ultrasonic sensor. Additional reasons for small differences between the wind curves are the shorter response time of the ultrasonic sensor and small time differences between the measurement registrations of cups and ultrasonic sensor because of the use of two different computers.

Remarkable: Not any disturbance is visible in the scintillation curve during this minute of extreme wind gusts. This proves that the two telescopes of Transmitter and Receiver remain precisely aligned during the heavy wind gusts.

The signals of the two bi-axial acceleration sensors on the RSS tower during the minute of strongest wind gusts are shown in Figure 7. The acceleration sensors detect some movement of the tower top during the heaviest wind gusts. The tower moves only small amounts in horizontal direction, calculations show less than 3mm in the heaviest wind gusts, see Table 1. There is no tilt because of the special tower geometry for parallel motion of the platform.

Figure 8 shows the period of 7 minutes around the strongest wind gusts with the signals of the two acceleration sensors and the wind velocity of the cups on the RSS Receiver tower in combination with the LAS signal, which is completely undisturbed during the whole period of 7 minutes. This longer registration shows clearly that the small horizontal movements are only present during the heavy wind gusts and that these horizontal movements do not at all disturb the LAS signal.

Figure 9 shows the same period of 7 minutes with the signals of the acceleration sensors and cups anemometer on the Wielsekade Transmitter tower in combination with the LAS signal. The heaviest wind gusts are 50 seconds later than at the RSS tower (maximum peaks 48.7 seconds from each other). This corresponds with the more northern location of the Wielsekade tower and the SW to SSW wind direction. The maximum wind velocity is 38 m/s. Not any influence on the LAS signal is notable during this heaviest wind gusts. The differences in length and direction of the heaviest wind gusts can be explained by the different landscape situations around the towers, see Figure 4 for the RSS tower standing completely free in the grass land and Figure 2 for the Wielsekade tower completely free to the South, but some trees and houses to the East and West sides.

The periods of 10 seconds with the heaviest wind gusts are shown in:
Figure 10 for the Wielsekade Transmitter tower
Figure 11 for the RSS Receiver tower.
The curves of the acceleration sensors have enough time resolution for calculation of the frequencies and amplitudes of the horizontal motions. The times are measured from the zero crossings of the three motion periods with largest amplitude. The maximum amplitude of the movements can be calculated by two times integration of the acceleration over the time. The results are in table 1.

Table 1. Frequency, maximum Acceleration and maximum Amplitude of the movement of the tower top for the Transmitter and Receiver tower in the two horizontal directions during the heaviest wind gusts, Red curve and Green curve of the two perpendicular horizontal directions of the two acceleration sensors.

Tower	**Sensor**	**Period time**	**Frequency**	**Acceleration**	**Amplitude**
Transmitter	Red curve	0.2136 sec	4.682 Hz	0.209 g	2.37 mm
Transmitter	Green curve	0.2136 sec	4.682 Hz	0.259 g	2.94 mm
Receiver	Red curve	0.2144 sec	4.664 Hz	0.232 g	2.65 mm
Receiver	Green curve	0.2139 sec	4.675 Hz	0.187 g	2.13 mm

The slightly lower frequency of the Receiver tower can be explained by more weight on top of the tower because of the ultrasonic wind sensor and a large electronic box for the LAS and the ultrasonic wind sensor. The frequency difference is near the precision of the measurements.

The occasional blue and black upward peaks in the graphs of the two bi-axial acceleration sensors indicate very short vertical pulses. The orientation of the sensors is such that an upward peak in the graph corresponds to a downward shock to the sensor.

These peaks can be explained by clapping of the upward rotatable floor grates between the storeys of the open towers. A wind gust lifts upward a floor grate, which falls downward at the moment of wind sinking down. It were the rotatable floor grates of the lowest storeys, which were not in the upward lock positions like in the higher-up storeys. Heavy wind gusts were also at the low levels with this storm. A second source for downward shocks could have been the falling of tree branches, which were found on the lower storeys of the towers after this storm. These falling tree branches did not give any damage to the towers or instruments. All the cables are well protected and no instruments are installed on the lower storeys.

The frequency spectra of the 1 minute and 7 minute LAS measurements do not show any influence of the tower motions in the region of the tower motion frequencies as measured by the acceleration sensors. This is an additional proof for the absence of any tilt on the tower platforms also during the heaviest wind gusts.

4. Comparison with shake experiments on the towers

The earlier shake experiments with the two towers gave already an indication for this tilt absence. Figure 12 shows the heaviest reached shakes by a person on top of the towers trying to give maximum impulse to the tower top for maximum movement of the tower top. The results of these experiments are in table 2. The reached accelerations and amplitudes in horizontal direction are about of the same value as during the wind gusts, the heaviest wind gusts of 38 m/s at the Transmitter tower and 37 m/s at the Receiver tower give slightly larger values than the shaking person. The slightly lower frequencies with the shake experiments can be explained by the addition of the weight of the person on top of the tower. The decline of the amplitude after the peak value is slower in the shake experiments than in the wind gusts. Reason is the effort of the person on top of the tower to move as much as possible.

Table 2. Measurements with heavy shaking person on top of tower. The available place on the top floors for the shaking person brought about that the largest swing for the Transmitter tower was in the direction of the horizontal axis of Sensor 1 with Red curve and for the Receiver tower the horizontal axis of Green Sensor 2.

Tower	Sensor	Period time	Frequency	Acceleration	Amplitude
Transmitter	Red curve	0.2154 sec	4.643 Hz	0.200 g	2.31 mm
Receiver	Green curve	0.2200 sec	4.545 Hz	0.215 g	2.59 mm

5. Conclusions

The horizontal motions in the heavy wind gusts are of the same size as during the shakes of a person on top of the tower. The motions in vertical direction remain very small in both cases.

These experiences demonstrate the avoidance of tilt by the special geometry of the framework. The counterforce of the tower structure against the wind force is built up by small pure horizontal motion of only a few mm during extreme storm.

The open light-weight towers are very suitable for location of the Large Aperture Scintillometers (LAS). The measurements are completely undisturbed even during heavy gusty storm with measured wind speeds up to 38 m/s (137 km/hour). The Transmitter and Receiver telescope remain precisely pointed to each other.
This is reached with open light-weight towers, which do not disturb the local meteorological situation of wind, temperature and humidity.

The realized construction of these towers is not only a demonstrator for meteorological measurements but also for astronomical applications. The seeing is not disturbed by the open tower construction, which is still stable enough to point precisely a telescope to a target.

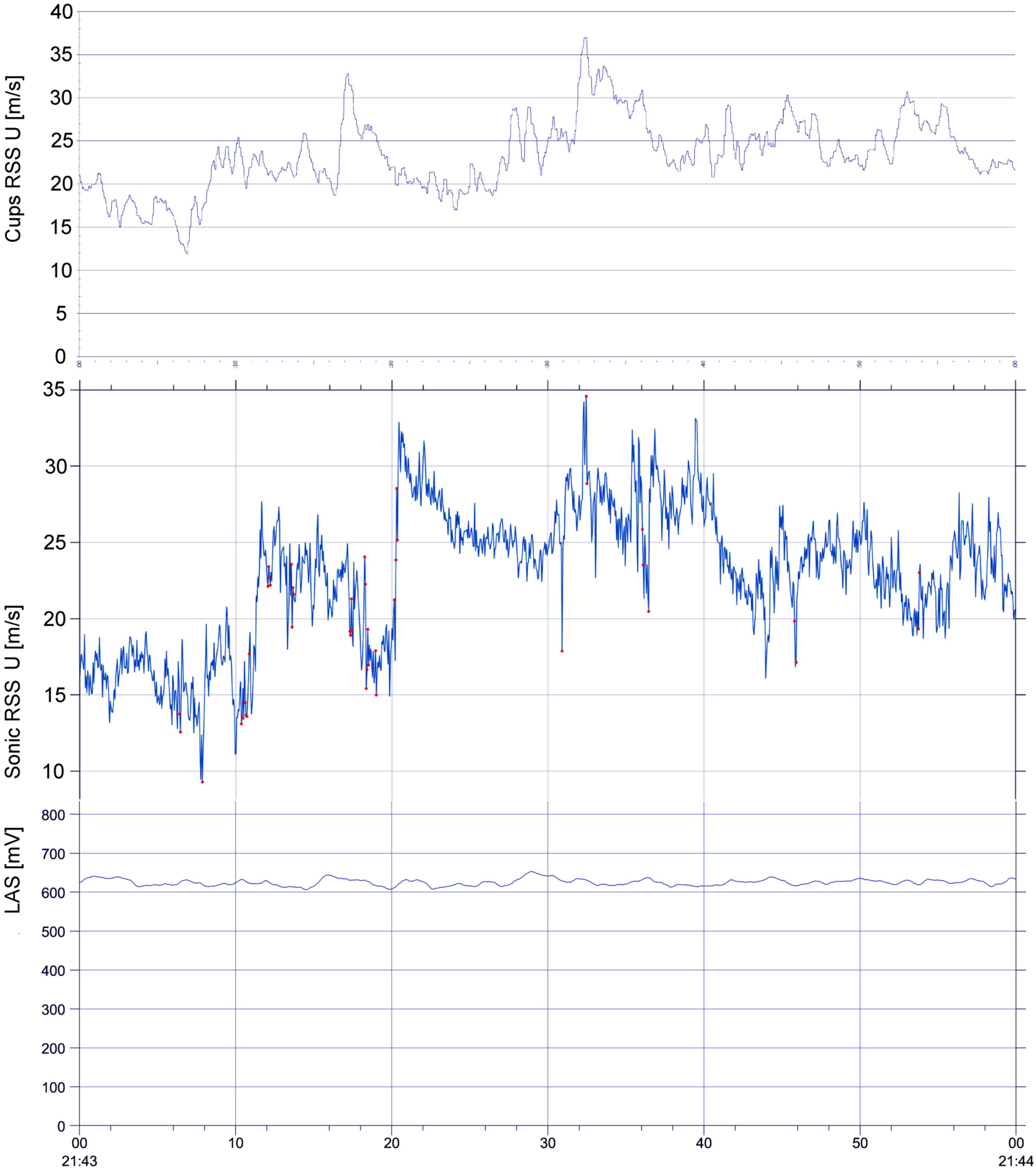


Figure 1. The minute of strongest gusts UTC time 21:43:00 till 21:44:00, local time 23:43:00 till 23:44:00 June 5, 2019 at the Remote Sensing Site (RSS) on the test field near the village Cabauw (KNMI).

Top: Wind velocity measured by light-weight fast-response cups anemometer at very top of tower, see Figure 5.

Middle: Sonic anemometer 2m lower than the cups at the side of the tower platform, see Figure 5 of top of tower. The Sonic anemometer has faster response than the cups but is slightly disturbed by rain drops indicated by the red points.

Bottom: Signal of the Large Aperture Scintillometer (LAS), two equal towers on 900m distance First tower with Transmitter at Wielsekade, see Figure 2, second tower at RSS with Receiver, see Figure 4. Maximum wind speeds: Cups on transmitter tower 38m/s. Cups on receiver tower 37m/s and Sonic 35m/s. The towers are so stable that the signal of the Large Aperture Scintillometer (LAS), see Figure 6, is not disturbed by the strong wind gusts because of the extreme tilt stability of the tower platforms. The fluctuating scintillation signal is very small because of night with clouds and wind mixing the air without temperature differences.

Figure 2. First tower with on top the Transmitter of the Large Aperture Scintillometer (LAS), the 15cm aperture telescope pointed in the right front direction exactly to the Receiver on the second tower on a distance of 900m. This photo is made before all the additional instruments were installed. It shows how the Transmitter is mounted on the top of the tower. The peak gives protection to the transmitter against lightning.

Figure 3. Top of the first tower with also the additional instruments installed. The LAS transmitter is seen from the backside pointed with his front lens towards the LAS Receiver. The cups anemometer and vane are seen on the nearest corner point of the tower top. The many visible cables are from the highly sensitive acceleration sensors. A second peak is mounted for lightning protection of the additional instruments.

Figure 4. Second tower with on top the LAS Receiver, like the Transmitter a 15cm aperture telescope, which is precisely pointed to the Transmitter on the first tower at the left side on 900m distance. Wind is measured by cups for velocity and vane for direction and also by a 3-D ultrasonic acoustic anemometer, which sticks outside the top platform and is shown in detail in Figure 5. It is able to measure very fast the wind speed and direction.

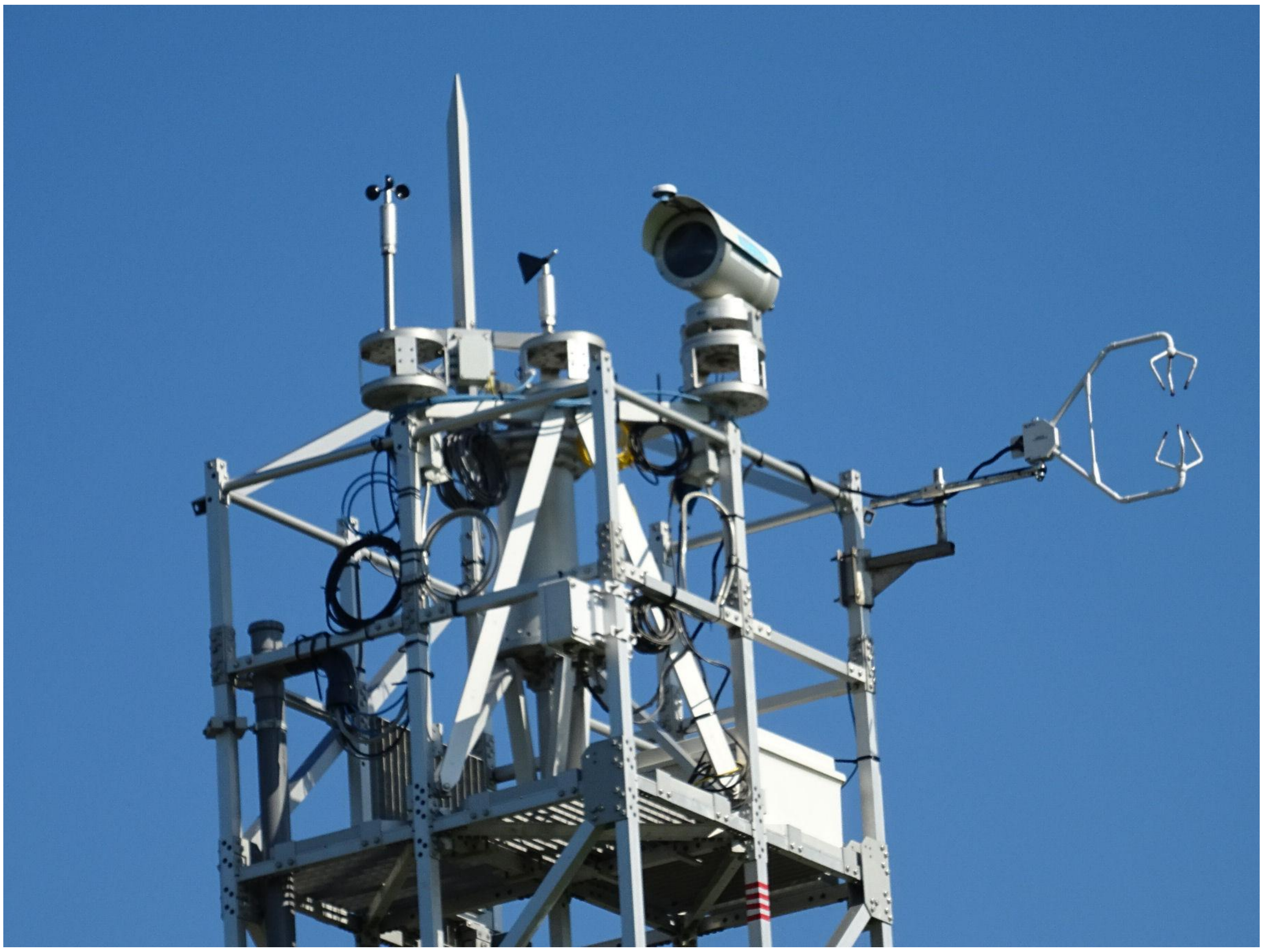


Figure 5. Top of second tower. The ultrasonic anemometer sticks outside the platform at the right side. The wind cups and vane are on the backside of the tower platform at a higher level like the peak for lightning protection able to protect the whole top platform with the acceleration sensors and cables.

Figure 6. Close-up of the LAS Receiver and the four base platforms for instruments on the second tower.

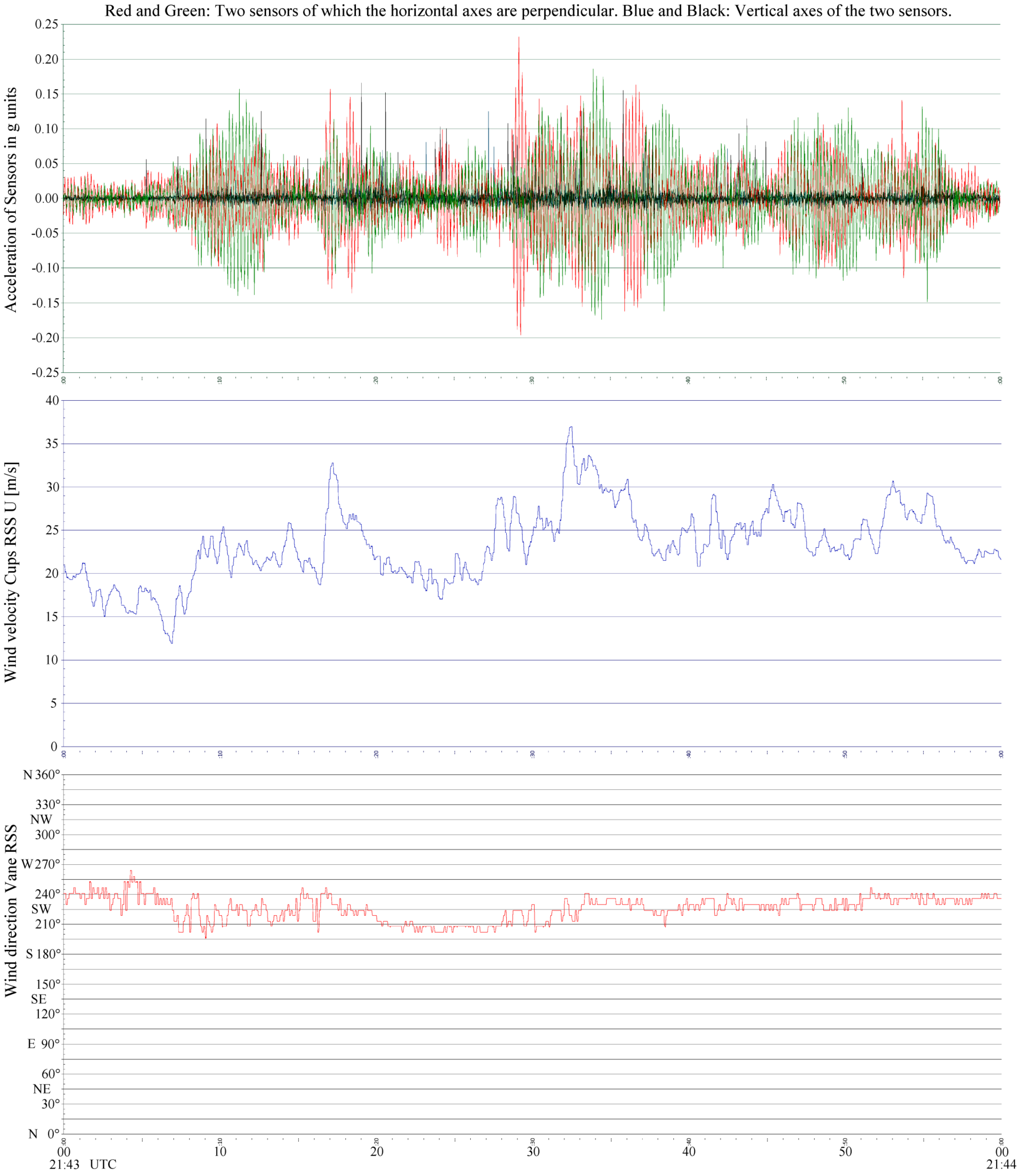


Figure 7. The acceleration measurements on the RSS tower during the same minute of Figure 1.

Top: Signals of two bi-axial acceleration sensors installed on top of tower. Orientations of the sensors are with one axis horizontal and the other vertical. The two horizontal axes are perpendicular to each other, the vertical parallel. Colors of acceleration curves: Red and Green horizontal, Blue and Black vertical axis.

The towers move only small amounts in horizontal direction, calculations show less than 3 mm in the heaviest wind gusts, the Transmitter and Receiver telescopes remain precisely pointed to each other, consequently not any disturbance of the scintillation signal of the LAS, also not during the heaviest wind gusts, see Figure 1.

Middle: Wind velocity measured by cups anemometer at top of tower, the same curve as on top of Figure 1.

Bottom: Wind direction measured by vane at top of tower, see Figure 4 and 5 of total and top of tower.

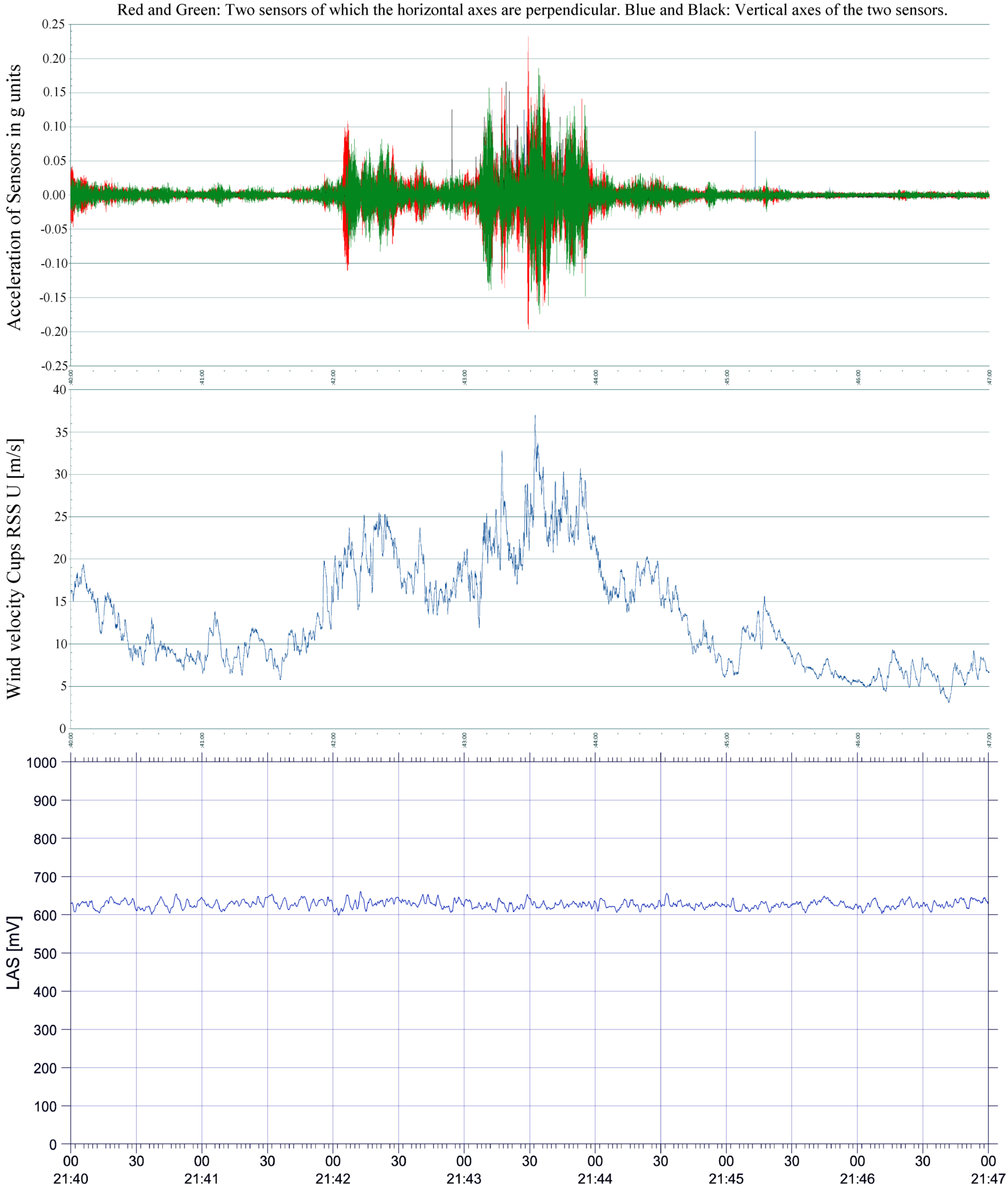


Figure 8. 7 minutes around the strongest gusts UTC time 21:40:00 till 21:47:00, June 5, 2019

Top: Signals of the two bi-axial acceleration sensors installed on top of the Receiver tower at the RSS site. Orientations of the two sensors as described in Figure 7 and with same colors: Red and Green horizontal, Blue and Black vertical axis. The acceleration curves cannot clearly be separated anymore on this more compact time scale.

Middle: Wind velocity measured by light-weight fast-response cups anemometer at top of RSS tower.

Bottom: Signal of the Large Aperture Scintillometer (LAS) undisturbed during the whole period of gusts. No influence of the small horizontal translations of the tower top, see also Figure 7.

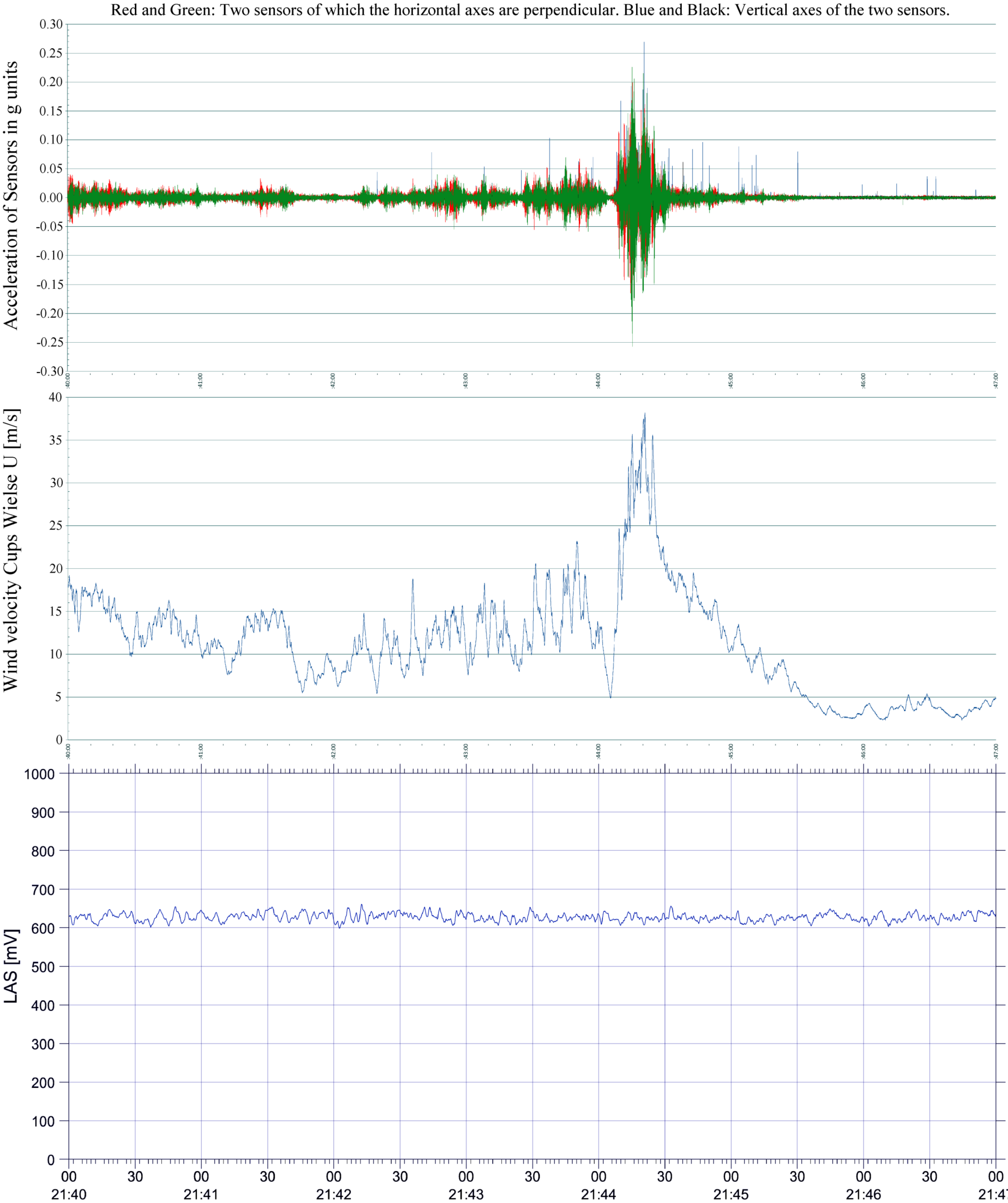


Figure 9. The same 7 minutes around the strongest gusts as in Figure 8 with the signals of the acceleration sensors and of the cups anemometer on the Transmitter tower at the Wielsekade on the Cabauw test field.
Top: Signals of the two bi-axial acceleration sensors installed on top of tower. Orientations of the two sensors as described in Figure 7 and with same colors: Red and Green horizontal, Blue and Black vertical axis. The acceleration curves cannot clearly be separated on this more compact time scale as in Figure 8.
Middle: Wind velocity measured by light-weight fast-response cups anemometer at top of Transmitter tower.
Bottom: Same curve as in Figure 8, the signal of LAS undisturbed during the whole period of gusts. Also no influence of the small horizontal translations of the Transmitter tower top, see also Figures 7 and 8.

Figure 10. The acceleration measurements on the Transmitter tower during the10 seconds with the strongest gusts UTC time 21:44:14 till 21:44:24, local time 23:44:14 till 23:44:24.

Top: Signals of two bi-axial acceleration sensors installed on top of tower. Orientations of sensors as in Figure 7 and same colors: Red and Green horizontal, Blue and Black vertical axis.

The acceleration curves show the shape of the horizontal motions on this expanded time scale. The tower moves only in horizontal direction less than 3 mm, see the calculations and measurement comments. Not any disturbance of the scintillation signal of the LAS, see Figure 9.

Middle: Wind velocity measured by light-weight fast-response cups anemometer at top of Transmitter tower.

Bottom: Wind direction measured by vane at top of Transmitter tower.

See Figure 3 for top of Transmitter tower with cups anemometer and wind direction vane.

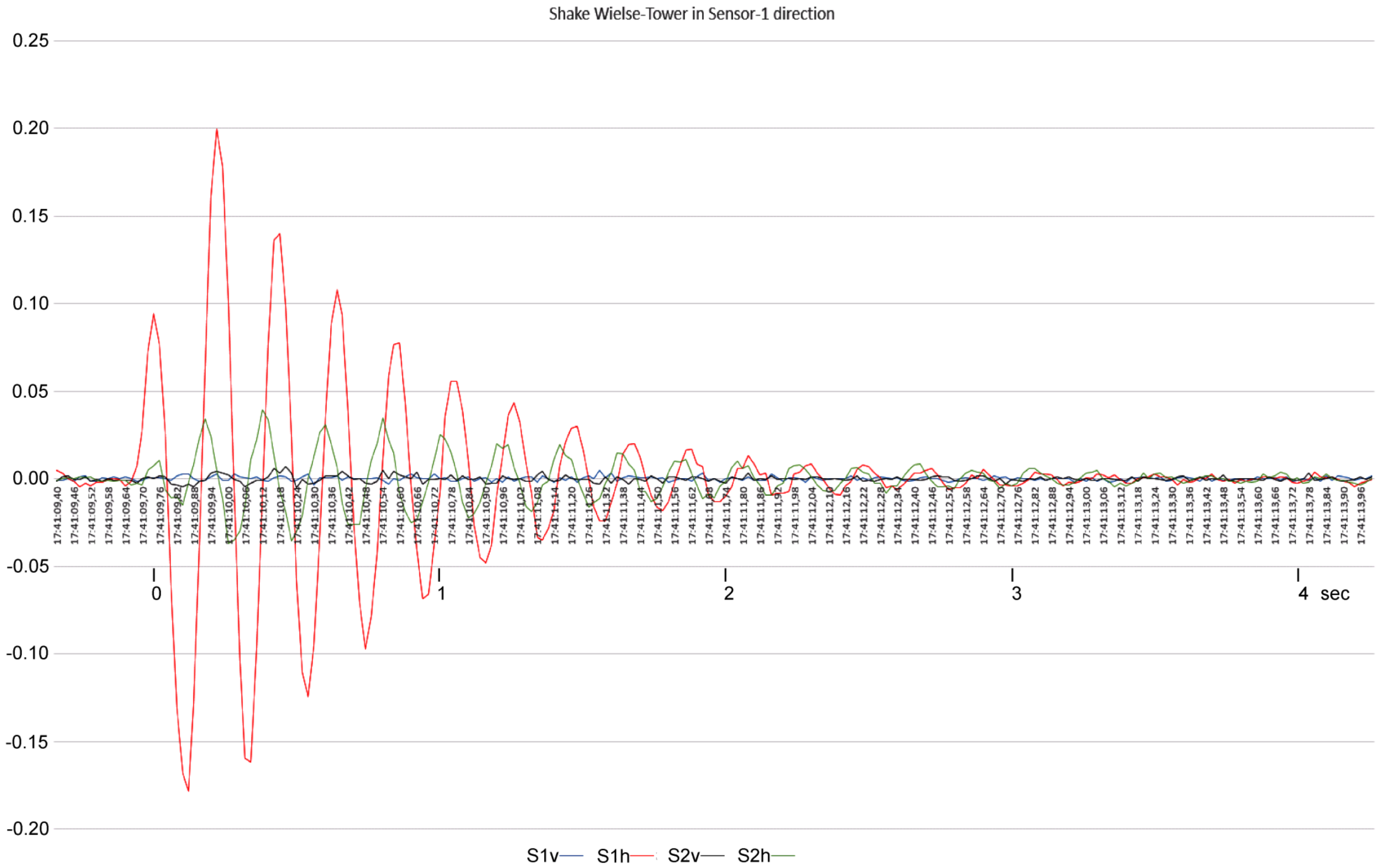
Figure 11. The acceleration measurements on the Receiver tower during the10 seconds with the strongest gusts UTC time 21:43:27 till 21:43:37, hence 47 seconds earlier than at Transmitter tower on 900m distance.

Top: Signals of two bi-axial acceleration sensors installed on top of tower. Orientations of sensors as in Figure 7 and same colors: Red and Green horizontal, Blue and Black vertical axis.

The acceleration curves show the shape of the horizontal motions on this expanded time scale. The tower moves only in horizontal direction less than 3 mm, see the calculations and measurement comments. Not any disturbance of the scintillation signal of the LAS, see Figure 8.

Middle: Wind velocity measured by light-weight fast-response cups anemometer at top of Receiver tower.

Bottom: Wind direction measured by vane at top of Receiver tower, see Figure 5 for cups and vane on top.



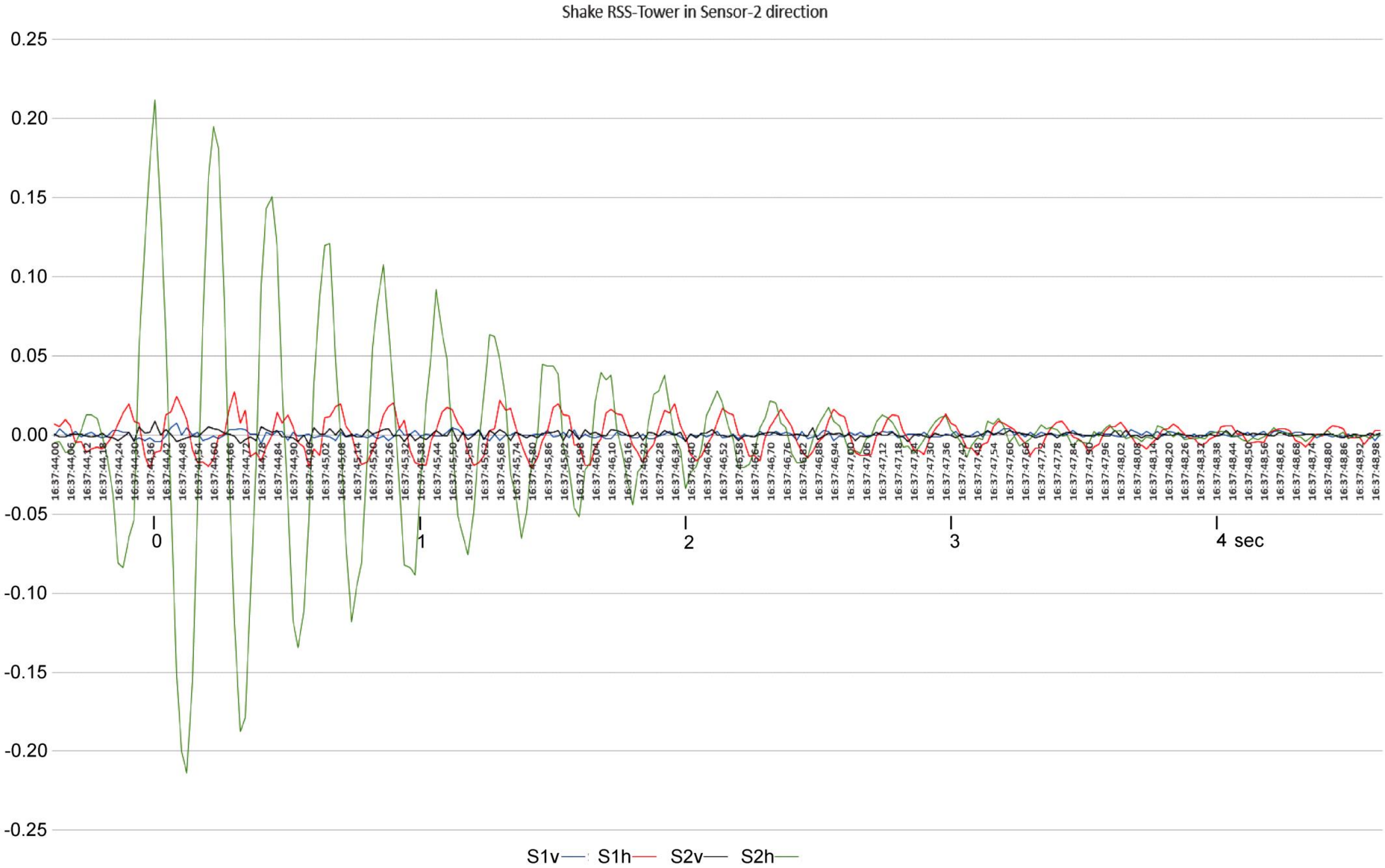


Figure 12. Person on top of tower shaking as strong as being able. Registration of the acceleration sensors. Top: Transmitter Tower Wielsekade. Bottom: receiver Tower RSS.
Horizontal axis: Time in seconds. Vertical axis: Accelerations of Sensors in g units.
Red S1h and Green S2h: Two sensors of which the horizontal axes are perpendicular.
Blue S1v and Black S2v: The vertical axes of the two sensors. No vertical motions, only noise in the signals.
The horizontal motions are about of the same amplitude as the motions during the heaviest wind gusts.