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The Development of the "Storm Tracker" and its Applications for Atmospheric High-resolution Upper-air Observations

Wei-Chun Hwang[1] Po-Hsiung Lin[1] and Hungjui Yu[1]

[1] Department of Atmospheric Sciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Raod, Taipei, Taiwan, 106.

Correspondence to Po-Hsiung Lin (polin@ntu.edu.tw)
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Abstract

In this study, we introduce a newly-developed upper-air observational instrument for atmospheric research. The "Storm Tracker" (or "NTU mini-Radiosonde"), is an ultra-lightweight (about 20g including battery), multi-channel simultaneous capable radiosonde designed by the Department of Atmospheric Sciences at National Taiwan University. Developed since 2016, the Storm Tracker aims to provide an alternative for observation of atmospheric vertical profiles with a high temporal resolution, especially lower-level atmosphere under severe weather such as extreme thunderstorms and tropical cyclones.

Two field experiments were conducted as trial runs in December 2017 and July 2018 at Wu-Chi, Taichung, Taiwan, to compare the Strom Tracker with the widely used Vaisala RS41 radiosonde. Among 53 co-launches of the Storm Tracker and Vaisala RS41 radiosondes, the raw measurements of pressure, wind speed, and wind direction are highly consistent between the Strom Tracker and Vaisala RS41. However, a significant daytime warm bias was found due to solar heating. A metal shield specifically for the Storm Tracker was thus installed and shows good mitigation for the warm biases.

With the much lower costs of the sondes and the simultaneous multi-channel receiver, the Storm Tracker system has been proved to be beneficial for high-frequency observational needs in atmospheric research.

1. Introduction

With a long history of development, the upper-air radiosonde has been one of the essential and the most reliable method to measure the atmosphere above us so far. Operational weather agencies worldwide share their daily to twice-a-day (00UTC and 12UTC) radiosonde observational data through WMO GTS (Global Telecommunication System) for synoptic weather analysis and numerical model forecast. According to the European Centre for Medium-Range Weather Forecasts (ECMWF), in 2017, there are about 818 upper-air radiosonde stations worldwide in addition to more than twelve radiosonde manufactures (Ingleby 2017). So far, most radiosonde manufacturers had participated in the field inter-comparison program hosted by World Meteorological Organization (WMO) throughout 1984–2010, and there were 11 different types of operational radiosondes processed in the recent inter-comparison experiment at Yangjiang, China in 2011 (Nash *et al*. 2011)

Among all different types of radiosondes, the mostly used Vaisala RS41 radiosonde weighs 110g, and the previous version RS92 weighs 280g. The Japan radiosonde from Meisei Corporation, iMS-100 weighs 38g only, which is so far the lightest operational radiosonde. However, for different purposes in different field campaigns, a large number of radiosondes are often necessary within a short period to acquire much higher temporal resolution data. For the atmospheric research community, most of these radiosondes on the market are often a burden regarding the research budget.

In this study, we introduce a newly-developed, smaller, lighter, and cheaper upper-air radiosonde system designed with the capability of simultaneously receiving multiple radiosondes, which is explicitly for high temporal resolution observations on mesoscale weather systems. This so-called Storm Tracker system, developed at the Department of Atmospheric Sciences at National Taiwan University, has been tested in several field experiments since 2016. In section 2, the configuration of the Storm Tracker system is

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described in detail. Two trial runs of preliminary comparisons between the Storm Tracker and Vaisala RS41 radiosonde are discussed in section 3. Section 4 concludes the current status of the Storm Tracker system and its applications in different field campaigns.

2. Configuration for Storm Tracker Upper-air Observation System

The Storm Tracker upper-air observation system consists of the upper-air radiosonde (the Storm Tracker) and the surface signal receiving unit (the Ground Receiver). The overall configuration is described in this section. Figure 1 shows the system block diagram of the Storm Tracker system.

a. The Storm Tracker radiosonde

The Storm Tracker radiosonde is packed with sensors and supporting hardware as shown in Figure 2. The main portion includes the ATMEGA328p microcontroller, the U-blox MAX7-Q GPS sensor, the Bosch BMP280 pressure sensor, the TE-Connectivity HTU21D temperature-humidity sensor, and the LoRa™ transmitter.

The central processor of the Storm Tracker is the Microchip ATMEGA328p microcontroller (Atmel Corporation, 2015) with a 2KB of ram and a 32KB of program memory, running at 3.3V with 8MHz clock speed to minimize the power consumption. The microcontroller processes all measurements from the sensors and sends them to the radio transmitter.

For the GPS module, the U-blox MAX-7Q is selected (U-Blox, 2014), and the pulse per second output is connected to the MCU for time synchronization. This GPS module provides the geolocation and speed as well as the direction of the Storm Tracker. Also, a chip antenna is chosen to minimize the weight and size, as well as an on-board signal amplifier and a filter to maximize the performance. The overall GPS module possesses an accuracy of 2.0 m for horizontal position and 0.1 m/s for velocity (U-Blox, 2014).

The pressure sensor on the Storm Tracker is Bosch BMP280, with an overall operation range from 1100 to 300 hPa and from –40 to 85℃, in addition to a typical accuracy of ±1hPa (Bosch Sensortec, 2018). This sensor has been applied to indoor navigation, where a precise pressure measurement is required.

For the sensor of temperature (T) and relative humidity (RH), we used the HTU21D, a digital relative humidity sensor with temperature output from the TE Connectivity. This sensor is chosen regarding its high accuracy (±0.3℃ in T and ±2% in RH), wide operational range (–40 to 125℃, 0–100%), the short response time (5 seconds), and cutting-edge energy-saving property (TE Connectivity, 2017). The HTU21D sensor is attached to a 3-cm arm as shown in Figure 2, to extend outside of the protection box to measure the environment. Table 1 briefly summarizes the operational ranges and typical accuracies of atmospheric measurements for Vaisala RS41-SGP radiosonde (VAISALA Corporation, 2017) and the Storm Tracker.

The power for Storm Tracker comes from one typical AAA battery with a converter, and this minimizes the total weight. The radio transmitter is powered by LoRa™, which is the long-range, low-power wide-area network technology (Augustin *et al*., 2016). The radio frequency used by Storm Tracker ranges from 432MHz to 436.5MHz, the configuration for LoRa™ is 7 for spreading factor and 4/5 for code rate with 125kHz channel bandwidth. To extend the battery life, transmit power is set to 18 dB with 1 Hz of transmission frequency.

As for the enclosure, we use thick paper with anti-water coating for the Storm Tracker board enclosure. For the external sensors, to mitigate the solar radiation warm bias found during the trial runs in 2017, we design a 1-mm tinplate metal shield to cover the temperature and humidity sensors to prevent direct solar radiation. The whole design of Storm Tracker as shown in Figure 3 is then sent to a local printed circuit board (PCB) assembly factory for

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production. With the help from the local factory, the final cost of each unit is about 26 US dollars, only about one-tenth of the price of a regular Vaisala RS41 radiosonde.

And since the Storm Tracker only weighs about 20g including battery, it can be easily carried by a constant volume foil balloon for constant-height flight, or pilot rubber balloon for regular upper-air observation. Figure 4 shows a typical Storm Tracker launch with a pilot rubber balloon, and Table 2 summarizes the Storm Tracker properties.

b. The Ground Receiver

To receive the radio signal from the Storm Tracker, a micro-computer module is specifically designed to process the data. We use MT7688 SoC (System on Chip) as the core, which runs the OpenWRT operating system at 588MHz with 128MB of ram and 32MB of internal flash (MediaTek, 2016). The SoC connects to an ATMEGA328p (Atmel Corporation, 2015) for interfacing with RF (Radio Frequency) modules. Furthermore, a built-in web server uses Node.JS to save and display measured data on the web-page user interface (UI). All data is recorded into an SD memory card and can also be downloaded from the UI. To be portable and easily used in the field, an external USB power supply or DC jack can provide the power for the whole system. Figure 5 shows a complete set of Storm Tracker Ground Receiver installed in a 3D-printed box (9cm*2cm*5cm) with the supporting equipment. The Ground Receiver is finally connected to an omnidirectional antenna with 6dB gain and dual-band (144 & 433MHz) frequencies. A typical setup of the Ground Receiver in the field is shown in Figure 6.

The most powerful feature of the Storm Tracker system based on the design of the Ground Receiver is the ability to receive data from up to 10 radiosondes simultaneously, which provides the opportunity of upper-air observations with extremely high temporal/spatial resolution. In a word, one can launch up to 10 Storm Trackers at once from multiple locations

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with only one system; or launch a series of Storm Trackers in a short period say an hour, 30 minutes, or even 10 minutes depending on the manpower.

To accomplish this goal with a single-channel transceiver on the Storm Tracker, time-divided multi-access (TDMA) was implemented into the Storm Tracker system. Since each Storm Tracker only takes about 76ms for data transmission, the system splits every second into 10-time slots, and each Storm Tracker transmits the data on the different time slots pre-assigned by the user. Therefore, the Ground Receiver is constantly scanning ten different frequencies per second and tracking up to 10 Storm Trackers at the same time. If the Storm Trackers were in the air at the same time and the data were received simultaneously, each Storm Tracker still takes up the different frequencies from 432 to 436.5 MHz to prevent any interference.

A newer version of the Ground Receiver is currently underway, which is powered by Raspberry Pi SBC (Single Board Computer) and a unique in-house designed LoRa™ gateway, which can receive 8-channel simultaneously. In the future, this new design with TDMA could monitor 80 Storm Trackers at the same time.

3. The intercomparison between the Storm Tracker and Vaisala RS41-SGP

Two trial field experiments were conducted to examine the actual performance of the Storm Tracker system. In these trial runs, the Storm Tracker was launched attaching to a Vaisala RS41-SGP radiosonde for intercomparison of the measurements as shown in Figure 7. The first trial run was conducted for four days in December 2017 at Wu-Chi, Taichung, Taiwan, and in total 28 flights of Strom Tracker and Vaisala RS41 were launched.

The raw data from both radiosondes were processed and linearly interpolated according to the same heights, which then separated into daytime (8 ~18LST) and nighttime (18 ~ 8 LST). Since the radiosondes were only launched when the sky is clear without clouds, the average

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vertical profile from the Vaisala RS41 shows a clear signature of subsidence and an overall dry atmosphere (Figure 8).

The results of the intercomparison are shown in Figure 9. According to the temperature difference in Figure 9, the temperature sensor had experienced significant solar heating during the daytime, which also caused the solar radiation dry bias. During the daytime, the mean warm bias is 5.68℃, and the dry bias is 6.42%. Nevertheless, during the nighttime, both temperature and humidity show good agreements between the Storm Tracker and Vaisala RS41, with the mean differences of 0.35℃ and 1.75%. The vertical profiles of the differences during daytime and nighttime are shown in Figure 10, which also shows the apparent heating and drying over the whole atmosphere during the daytime.

On the other hand, in Figure 9 the differences in measurements such as the pressure and winds are not mainly affected by solar heating, which shows a relatively good agreement between the Storm Tracker and Vaisala RS41. The mean difference for the measurements of pressure is 1.69hPa (0.75hPa) below 0℃ (above 0℃), which lies within the error of the sensor according to Table 1. And since the GPS systems in both the Storm Tracker and Vaisala RS41 track almost the same satellites, the mean errors for wind measurements are insignificant with that of wind speed of 0.09m/s, and -0.15 degrees for wind direction.

Since the results from the trial run in 2017 show that the solar radiation is an important factor affecting the temperature and moisture measurements, we installed a thin metal shell (i.e. the "hat") around the temperature/humidity sensor as shown in Figure 3 to prevent the direct solar heating in the second trial run conducted in July 2018. In the second run, every launch includes a Vaisala RS41 attached with two Storm Trackers, one is with the hat and one is not. Similar to the first run, in the second run, the data from 19 co-launches under the clear sky were collected. As shown in Figure 11, the average vertical profile shows an overall dry

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atmosphere with slight subsidence above 850hPa. The maximum height of the measurements is lower in the second run than that in the first run due to the different batteries used in 2018.

Figure 12 shows the histograms for the comparison between the Storm Tracker w/wo the hat. The results of the pressure and winds measurements show almost no difference between the Strom Trackers w/wo the hat, however, during the daytime the mean temperature warm bias drops from 2.47℃ to 2.18℃ by adding the hat. The standard deviation also drops from 1.2℃ to 0.86℃. Likewise, the mean dry bias for humidity drops from 2.37% drier to 1.27% drier with the hat, which is within the sensor accuracy range as shown in Table 1. And the standard deviation decreases from 4.74% to 4.08%. These results show that the reflective metal shield does help to prevent direct solar heating when the Storm Tracker is in the air.

However, the installation of the metal shield causes a further warm bias when there is no solar heating. During the nighttime, even the biases lie within the accuracy range of the sensor, the mean warm bias increases from 0.13℃ without the hat to 1.17℃ with the hat, and the standard deviation increases from 0.36℃ to 0.54℃. The mean humidity bias, on the other hand, drops from 6.11% for Strom Tracker without the hat to 2.11% Strom Tracker with the hat, but the standard deviation slightly increases from 2.67% to 2.87%. During the nighttime, the results show that the metal shield further induces a warm bias, which may be the main cause of the dry bias in the moisture measurement.

On average, even though the mean warm bias increases from 1.24℃ to 1.66℃ if the hat is added, the standard deviation decreases from 1.45℃ to 0.87℃. Moreover, the mean humidity bias improves from 2.10% to 0.50% with the hat, and the standard deviation also drops from 5.69% to 3.88% with the hat. It is shown that the metal shield installation does prevent the solar radiation heating effects during the daytime even it also introduces an additional warming effect during the night.

These results can also be seen in the vertical profiles according to Figure 13. As shown in Figure 13, overall the variances of measurements are lowered by adding the metal shield onto the temperature/humidity sensor. Moreover, Table 3 lists all the statistics for the second intercomparison run between the Storm Tracker w/wo the hat and Vaisala RS41. Even though the metal shield causes a slight warm bias during the nighttime, it mitigates the solar radiation heating effects and the solar radiation dry bias during the daytime when most of the mesoscale convective rainfall occurs. For such events in Taiwan, it is worthwhile to apply these new instruments to acquire much higher resolution data especially for afternoon thunderstorms triggered by daytime solar heating.

4. Applications in the field campaigns and the concluding remarks

In 2018, during the Taipei Summer Storm Experiment (TASSE), hourly launches (8 ~16LST) of Storm Trackers were conducted among several sites in the Taipei Basin. These data were used to study the urban atmospheric boundary layer variation and the prevailing environment of thunderstorm convection in the afternoon. Figure 14 shows the Strom Tracker paths launched from June 27 to July 3, 2018, during the TASSE. This campaign is a good example to use the Storm Tracker for vertical profiles with high temporal resolution up to every hour at multiple launch sites. The Storm Tracker is a good alternative with a much lower cost and capability for multiple simultaneous observations.

Another campaign during typhoon Talim on September 13, 2017, was conducted with two Storm Trackers to see if the observations inside the tropical cyclones are possible. Figure 15 shows the flight path and the altitude of the Strom Tracker which uses the larger CR123 battery to extend the lifetime. The flight path shows that the Strom Trackers can be carried and observe at a constant altitude and following the outlying wind direction of the typhoon.

Although the signal was lost eventually, this launch shows the potential of Strom Tracker to conduct drift sound experiments in the future, and even for more kinds of observational needs.

Although the Strom Tracker system is incorporated with the new low-cost sensors, we show that it can accomplish decent performance compared with Vaisala RS41 radiosonde with a significant cost reduction. Moreover, with the capability of tracking multi-tracker simultaneously and incorporating LoRa™ technology, it enables future missions to deploy a large number of radiosondes to collect higher temporal/spatial resolution data.

These trial runs show that the Storm Tracker radiosondes still have issues regarding temperature and moisture measurements, but the current configuration with a thin metal shield does help with the daytime biases. More experiments to compare the measurements between the Storm Tracker and Vaisala RS41 are underway, in addition to the intercomparison among different individual instruments such as radiometer. More importantly, with more intercomparison data, the objective correction algorithms are currently developed and tested for better data quality control.

Data availability

All field measurement data from our Storm Tracker and Vaisala RS-41-SGP could be accessed through FTP by request.

Authors contribution

Mr. Hwang makes the PCB, program coding and document draft. Dr. Lin supports all funding of this study and coordinated field tests. Dr. Yu joins the discussion of data intercomparion.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

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Caption List

Table 1. List of the operational ranges and typical accuracies of basic atmospheric measurements for Vaisala RS41-SGP radiosonde (VAISALA Corporation 2017) and the Storm Tracker.

Table 2. Characteristics of Storm Tracker.

Table 3. Temperature and Humidity Error (Storm Tracker – Vaisala RS41-SGP) Statistics for the second intercomparison experiment in July 2018 at Wu-Chi.

Figure 1. System block diagram for the Storm Tracker system, including Storm Tracker (left) and Receiver (right). The part number for the chipset is indicated in the box, and the arrow indicated the dataflow.

Figure 2. Photo of a PCB assembled Storm Tracker product from the PCBA, in addition to a reference (ruler in centimeters) and a AAA battery. The diameter of the Storm Tracker is 58.1mm x 50.2mm (height x width, including sensor arm). The GPS antenna and GPS module are located on the top right of Storm Tracker, along with the power switching on the top left. The RF module is located on the bottom, and the red wire is the quarter-wave antenna. The extended arm hosts the temperature and humidity sensor, and the pins on the bottom are for programming and debug purposes. Lastly, in the middle are the microcontroller and pressure sensor.

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Figure 3. A Storm Tracker with the enclosure and the metal shield. The enclosure is composed of paper, and the hole on the top (bottom) is for connecting to the balloon (passing of the antenna). The metal shield is attached to the PCB board with hot glue.

Figure 4. A Storm Tracker (without enclosure) launched with a pilot rubber balloon during a field campaign.

Figure 5. Photo of a Storm Tracker Ground Receiver. On the right are the GPS module and RF module to receive the signal, along with the USB and DC power jack for power input and the console access. In the middle is the central processor, which handles data recording and hosts the website. On the left is the SD card for storage. On the top are the indicator LEDs, which show the current status of the receiver and the received data channels.

Figure 6. A typical setup of the ground receiver in the field, with the 433Mhz antenna in the middle, and the receiver, GPS antenna and power bank at the bottom black box.

Figure 7. A photo of the intercomparison launch setup. The Strom Tracker is attached to the side of a Vaisala RS41 radiosonde with double side tape.

Figure 8. The skew-T-log-P diagram of the average vertical profile measured by Vaisala RS41 radiosondes during the intercomparison run in December 2017 at Wu-Chi. The thick red line indicated the dew point and the thick blue line indicated the temperature profile.

Figure 9. Histograms of the differences between the Vaisala RS41 radiosonde and the Storm Tracker separated by daytime and nighttime during the first intercomparison run in 2017 at Wu

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Chi. The blue histograms show the data during the nighttime, and the red histograms show the data during the daytime.

Figure 10. The vertical profiles for temperature and humidity differences during both the daytime and nighttime in the first intercomparison run. The lines indicated the mean, and the one standard deviation ranges are shaded. The red color indicates daytime data, and blue color indicates nighttime data.

Figure 11. Similar to Figure 8 except for the second intercomparison run in July 2018 at Wu-Chi.

Figure 12. Similar to Figure 9 except for the differences between the both configurations and the Vaisala RS41 radiosondes during the second intercomparison run. The blue histograms show the data for Storm Tracker with the hat, and the red histograms show the data for Strom Tracker w/o the hat.

Figure 13. Similar to Figure 10 except for the differences between the Storm Trackers with and without the metal shield.

Figure 14. Picture of the tracks of the Storm Trackers launched during 27 Jun–3 Jul, 2018 in the TASSE-2018 field campaign. The launching sites include Chidu, Banqiao and Shezi. Credit to Google Earth Pro for providing the satellite image.

Figure 15. Three balloon tracks during Typhoon Talim (top) and the height profile of the Strom Tracker 0 (bottom). The launching site is located on campus of the National Taiwan University.

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The maximum range of the Storm Tracker from the site is 132km, in which the Storm Tracker could maintain at about 6200m height. Credit to Google Earth Pro for providing the satellite image.

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Tables

Table 1. List of the operational ranges and typical accuracies of basic atmospheric measurements for Vaisala RS41-SGP radiosonde (VAISALA Corporation 2017) and the Storm Tracker.

Spec	Vaisala RS41-SGP	Storm Tracker
P Range	sfc. - 3 hPa	1100 - 300 hPa
P Accu.	1.0 hPa (>100 hPa)	1 hPa (0 - 65 ℃)
		1.7 hPa (-20 - 0 ℃)
T Range	-90 - +60 ℃	-40 - +125 ℃
T Accu.	0.3 ℃ (<16 km)	0.3 ℃
	0.4 ℃ (>16 km)	
RH Range	0 - 100 %	0 - 100 %
RH Accu.	4%	2%
Horizontal WIND SPEED Accu.	0.15 m/s	0.1 m/s
		(Hor. Accu.: 2.5 m)

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Table 2. Characteristics of Storm Tracker.

Characteristic	**Storm Tracker**
Sensors	Temperature, Humidity, Pressure, GPS location, Wind Speed
Frequency	432 MHz to 436.5 MHz
Channels	Ten simultaneous Channels
Time Resolution	1s (1Hz)
Power	1x AAA Battery
Battery Life	2 - 4 Hours
Weight	20g with 1x AAA Battery
Dimension	58.1 mm x 50.2mm x 30mm

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380 **Table 3. Temperature and Humidity Error (Storm Tracker – Vaisala RS41-SGP)**

381 **Statistics for the second intercomparison experiment in July 2018 at Wu-Chi.**

	Temperature Error (℃)		Humidity Error (%)	
	W/o Hat	With Hat	W/o Hat	With Hat
Night Time	0.13±0.36	1.17±0.54	6.11±2.67	2.11±2.87
Day Time	2.47±1.20	2.18±0.86	-2.37±4.74	-1.27±4.08
Total	1.24±1.45	1.66±0.87	2.10±5.69	0.50±3.88

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384 **Figures**

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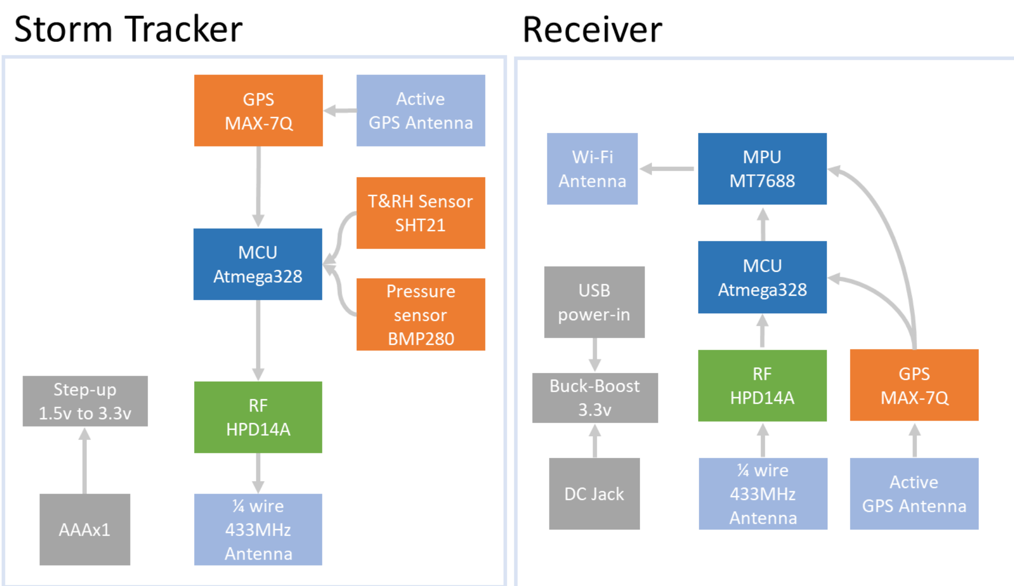

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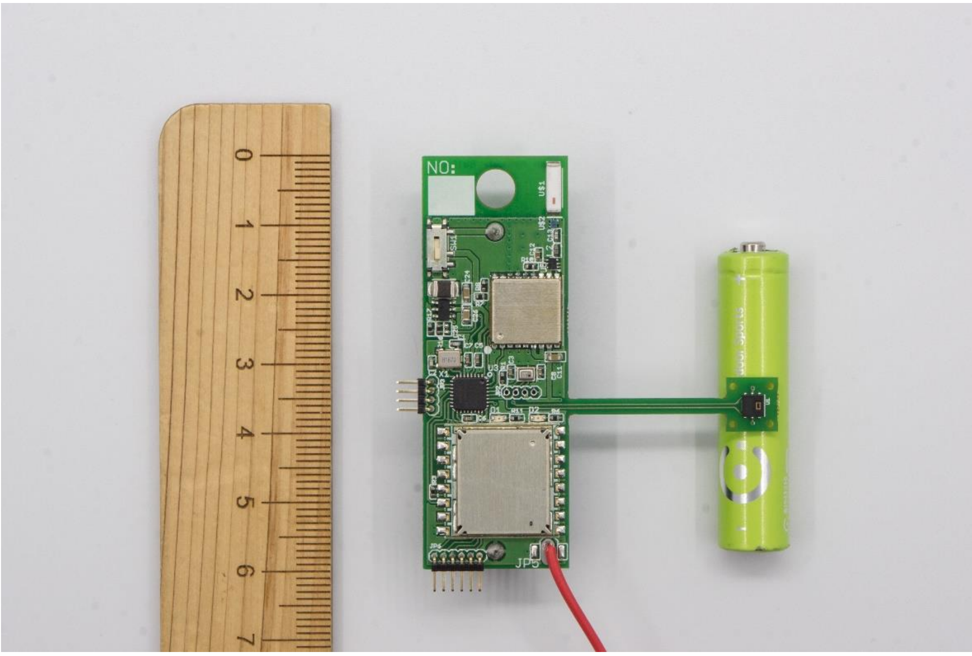

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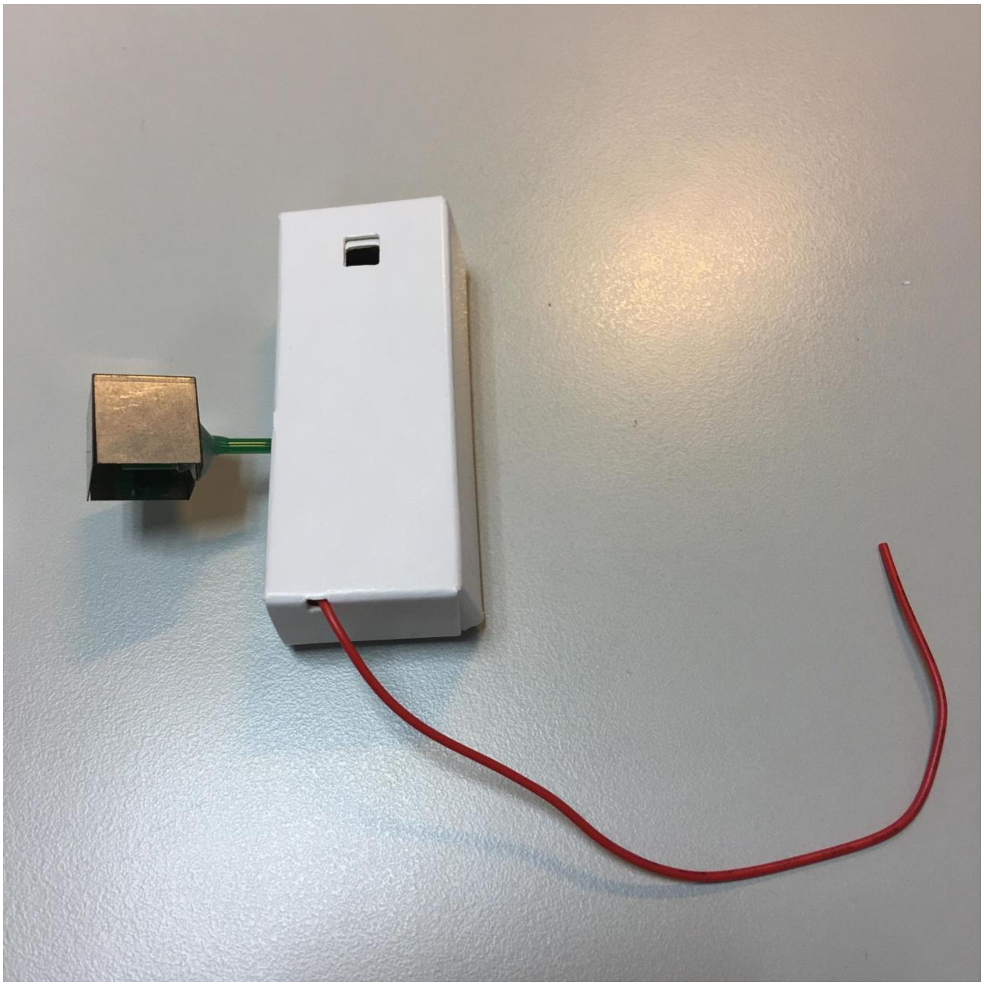

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Figure 6. A typical setup of the ground receiver in the field, with the 433Mhz antenna in the middle, and the receiver, GPS antenna and power bank at the bottom black box.

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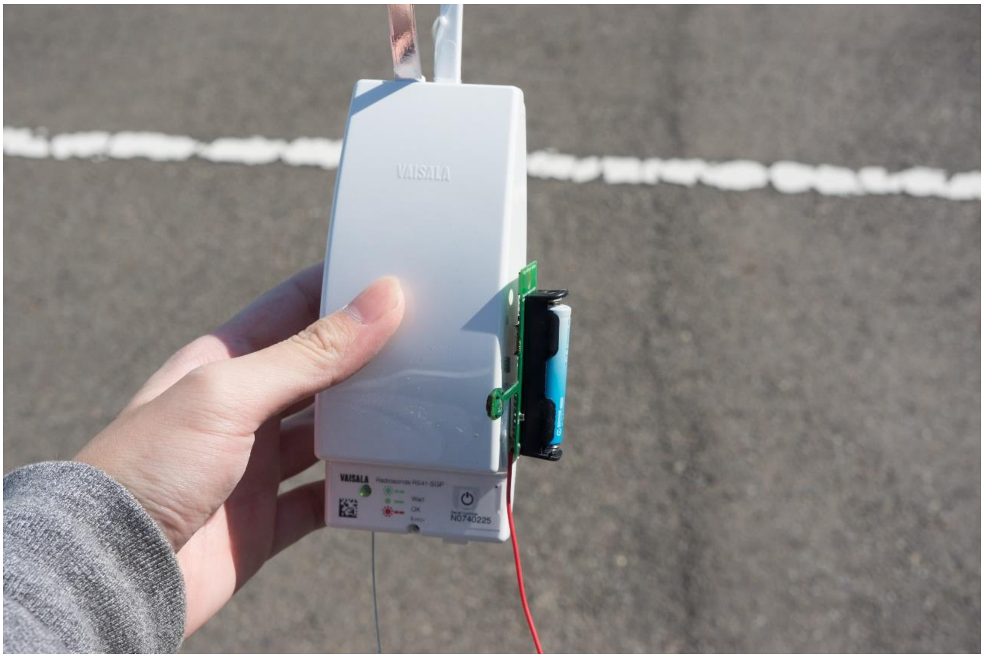

Figure 7. A photo of the intercomparison launch setup. The Strom Tracker is attached to the side of a Vaisala RS41 radiosonde with double side tape.

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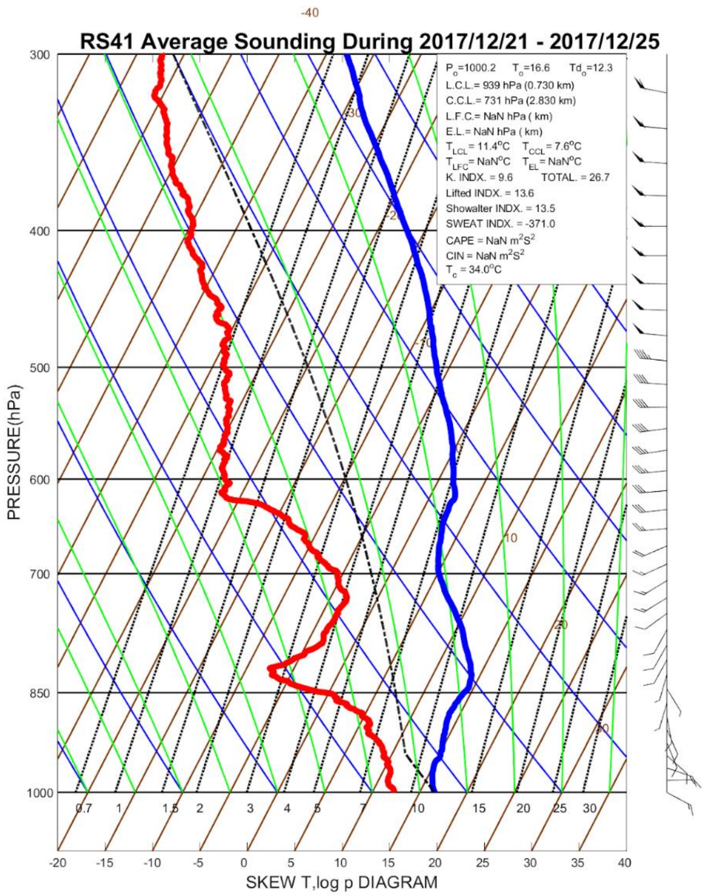

Figure 8. The skew-T-log-P diagram of the average vertical profile measured by Vaisala RS41 radiosondes during the intercomparison run in December 2017 at Wu-Chi. The thick red line indicated the dew point and the thick blue line indicated the temperature profile.

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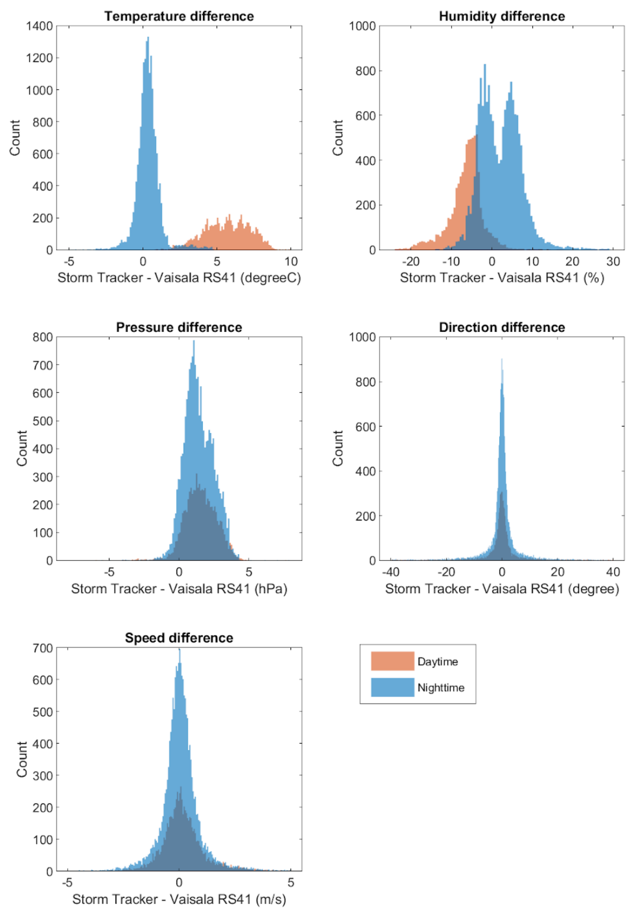

Figure 9. Histograms of the differences between the Vaisala RS41 radiosonde and the Storm Tracker separated by daytime and nighttime during the first intercomparison run in 2017 at Wu Chi. The blue histograms show the data during the nighttime, and the red histograms show the data during the daytime.

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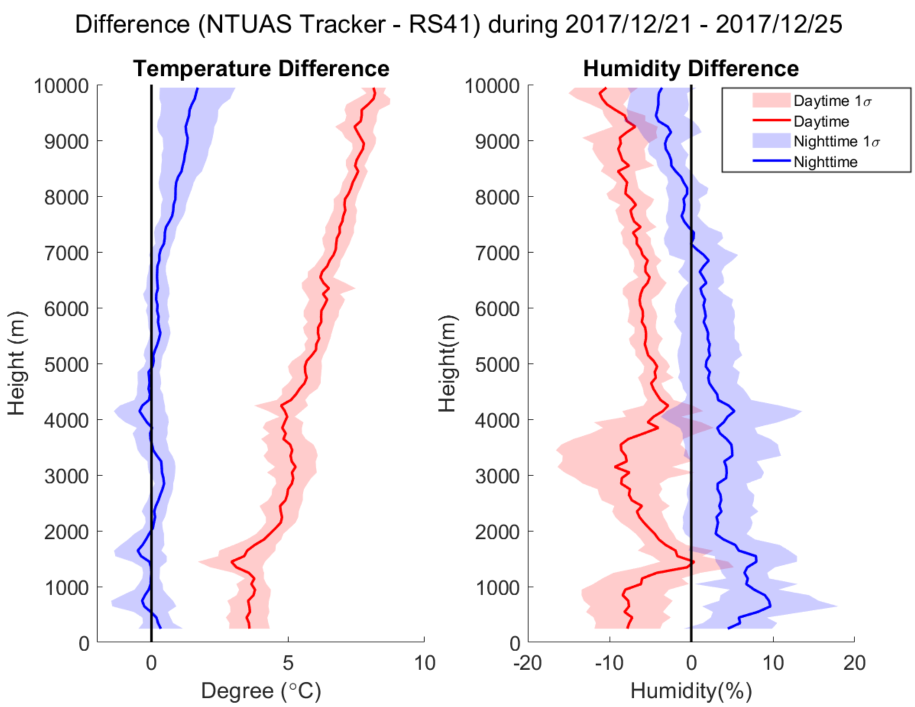

Figure 10. The vertical profiles for temperature and humidity differences during both the daytime and nighttime in the first intercomparison run. The lines indicated the mean, and the one standard deviation ranges are shaded. The red color indicates daytime data, and blue color indicates nighttime data.

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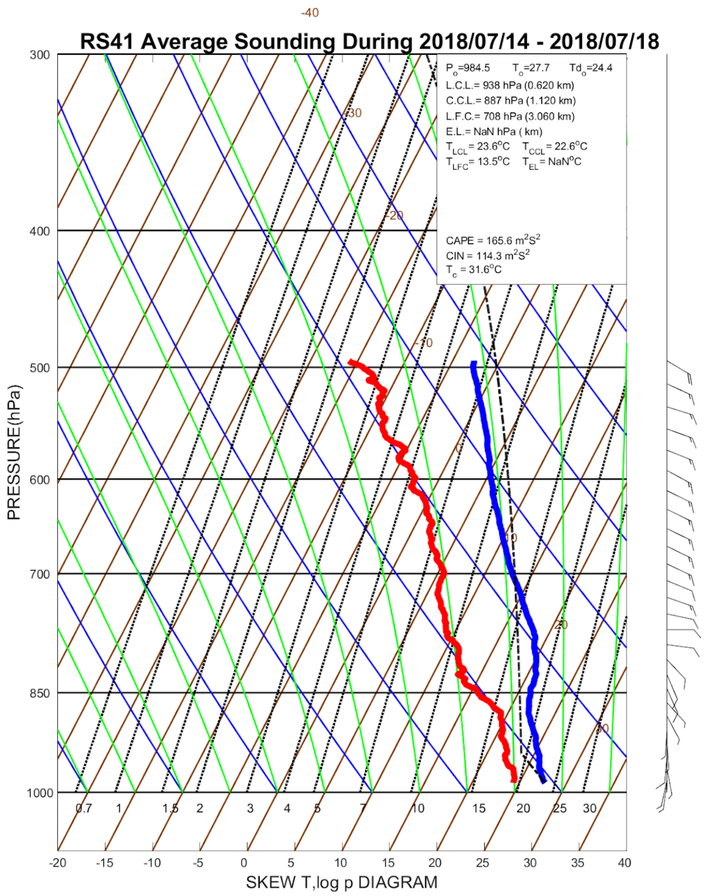

Figure 11. Similar to Figure 8 except for the second intercomparison run in July 2018 at Wu-Chi.

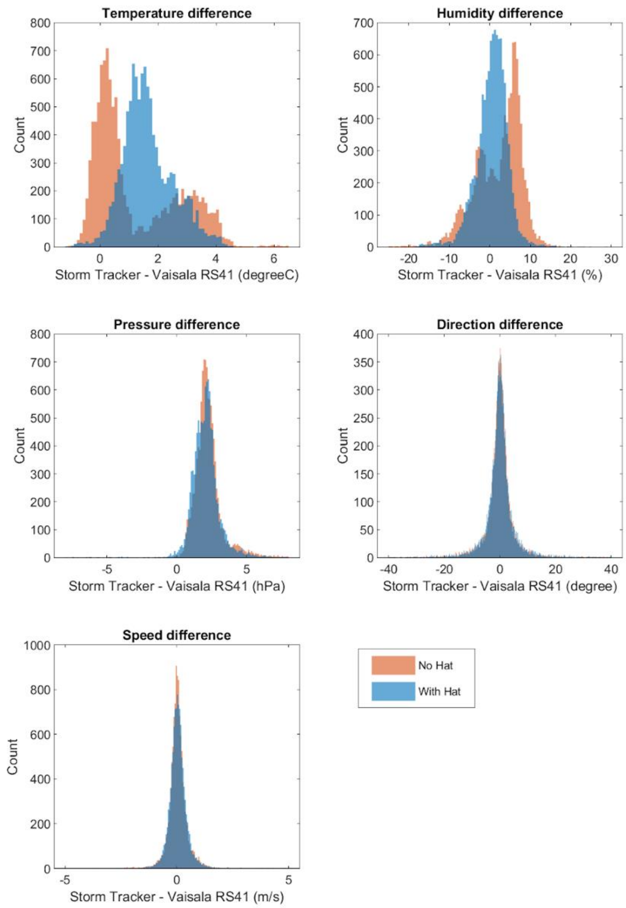

Figure 12. Similar to Figure 9 except for the differences between the both configurations and the Vaisala RS41 radiosondes during the second intercomparison run. The blue histograms show the data for Storm Tracker with the hat, and the red histograms show the data for Strom Tracker w/o the hat.

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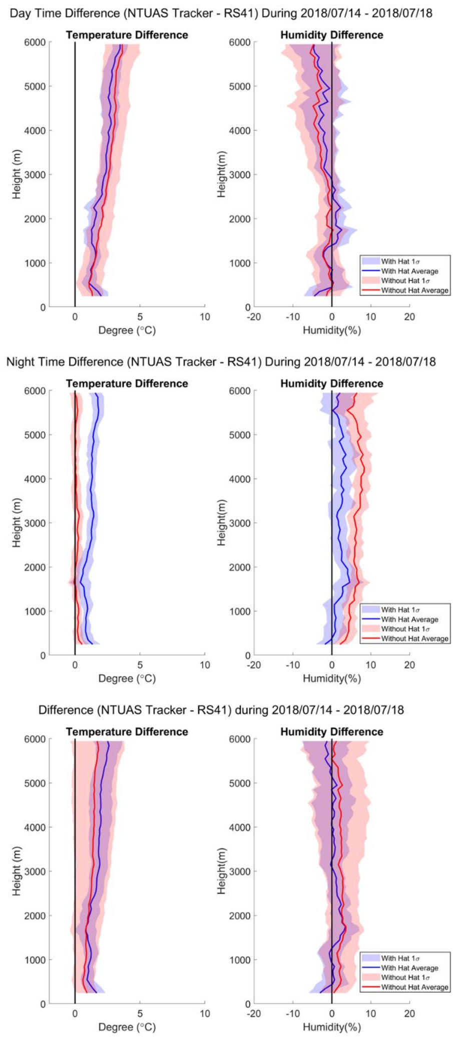

Figure 13. Similar to Figure 10 except for the differences between the Storm Trackers with and without the metal shield.

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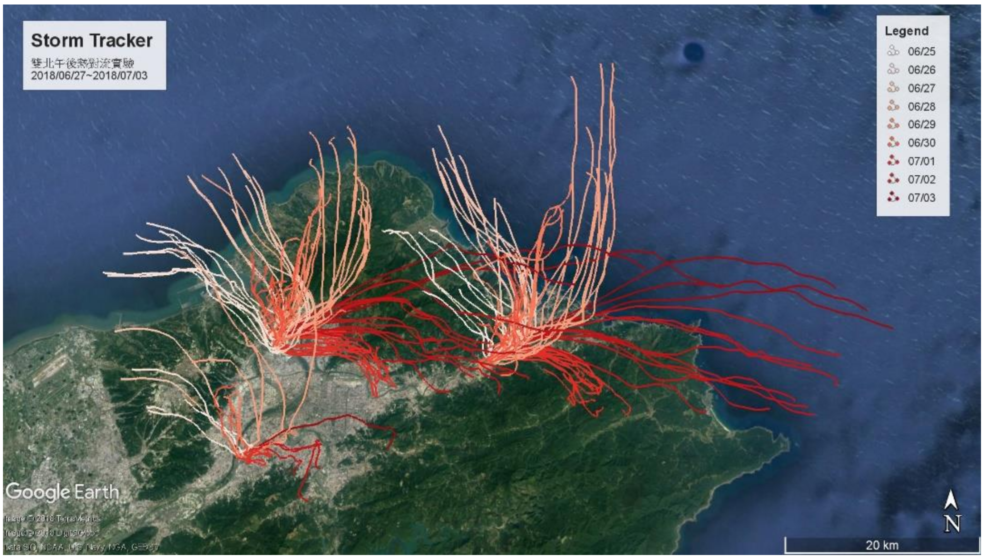

Figure 14. Picture of the tracks of the Storm Trackers launched during 27 Jun–3 Jul, 2018 in the TASSE-2018 field campaign. The launching sites include Chidu, Banqiao and Shezi. Credit to © Google Earth Pro for providing the satellite image.

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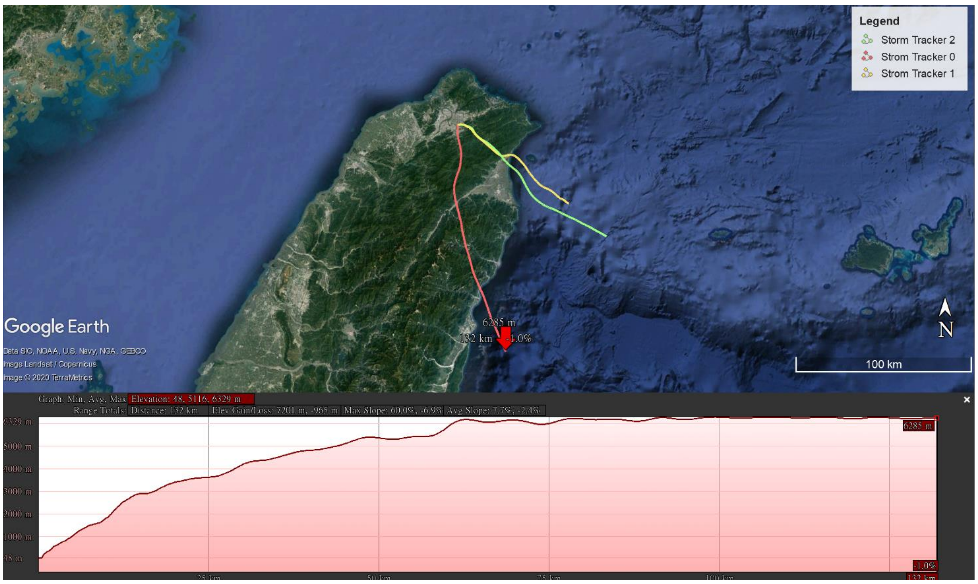

Figure 15. Three balloon tracks during Typhoon Talim (top) and the height profile of the Strom Tracker 0 (bottom). The launching site is located on campus of the National Taiwan University. The maximum range of the Storm Tracker from the site is 132km, in which the Storm Tracker could maintain at about 6200m height. Credit to © Google Earth Pro for providing the satellite image.