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Design and Implementation of a Low-Cost Air Quality Network for the Aburra Valley Surrounding Mountains

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Abstract: The densest network for measuring air pollutant concentrations in Colombia is in Medellin, where most sensors are located in the heavily polluted lower parts of the valley. Measuring stations in the higher elevations on the mountains surrounding the valley are not available, which limits our understanding of the valley's pollutant dynamics and hinders the effectiveness of data assimilation studies using chemical transport models such as LOTOS-EUROS. To address this gap in measurements, we have designed a new network of low-cost sensors to be installed at altitudes above 2000 m.a.s.l. The network consists of custom-built, solar-powered, and remotely connected sensors. Locations were strategically selected using the LOTOS-EUROS model driven by diverse meteorology-simulated fields to explore the effects of the valley wind representation on the transport of pollutants. The sensors transmit collected data to internet gateways for posterior analysis. Various tests to verify the critical characteristics of the equipment, such as long-range transmission modeling and experiments with an R score of 0.96 for the best propagation model, energy power system autonomy, and sensor calibration procedures, besides case exposure to dust and water experiments, to ensure IP certifications. An inter-calibration procedure was performed to characterize the sensors against reference sensors and describe the observation error to provide acceptable ranges for the data assimilation algorithm (<10% nominal). The design, installation, testing, and implementation of this air quality network, oriented towards data assimilation over the Aburrá Valley, constitute an initial experience for the simulation capabilities toward the system's operative capabilities. Our solution approach adds value by removing the disadvantages of low-cost devices and offers a viable solution from a developing country's perspective, employing hardware explicitly designed for the situation.

Keywords: low-cost sensors; data assimilation; air quality; In-situ sensing; LOTOS-EUROS chemical transport model; low-cost air quality monitoring Systems (LCAQSs); SimpleSpace

1. Introduction

Medellín is the largest city in the Aburrá Valley, a region of Colombia composed of ten municipalities in the mountains, and it is the second most populous urban agglomeration and the third densest in the world [1,2] The valley follows the Medellín River for 60 km

and is 3 to 10 km wide. It is situated at an elevation of 1300–1750 m above sea level, with a height difference of up to 1800 m between the valley floor and the surrounding hills. The air quality in the valley deteriorates seasonally due to weather patterns and the transit of the Intertropical Convergence Zone (in March–April and October–November) [3]. During these times, the atmospheric boundary layer remains below the canyon's rim throughout the day, trapping all of the pollutants from the city in the lower atmosphere [1].

The air quality measurement network in the Aburrá Valley is managed by SIATA (https://siata.gov.co/ (accessed on 27 December 2022)), which is the institution in charge of the different early warning systems for the region. This network is one of the densest in terms of air quality measurements of the world, with a combination of low-cost and certified sensors that creates a complete spatial coverage of this complex orography with a deep-seated urban valley [4]. However, the valley receives and exports atmospheric pollutants from and to the surrounding regions, yet measuring stations to monitor these fluxes are not available.

Recent cases of low-cost sensors in valleys can be found in [5,6]. Some recent comparisons with different chemical transport models with low-cost sensors can be found in [4,7–10] showing constant research driven by the increase of air quality-related problems and availability of electronic technologies. On the other side of measuring, modeling studies using Chemical Transport Model CTM, such as the LOTOS-EUROS model, have shown that the Aburra Valley releases pollutants in daily cycles, which suggests the transport of contaminants to surrounding areas [11]. These pollutants are deposited in vulnerable natural areas, such as páramos, tropical rain forests, and tropical dry forests. Figure 1 shows simulation results for four different periods in 2016 using the LOTOS-EUROS model. The experiments were designed to illustrate overall regional flow and deposition patterns rather than assess the amount of deposited material. The boundaries of the ten municipalities in the Aburra Valley are shown in red. Rionegro was simulated as a source of pollutants equal in magnitude to those of Medellín (panel (b)) to explore the impact on air quality in Medellín. The simulation showed that contaminants from Rionegro can enter the Aburrá Valley in all seasons, with increased intrusion during June and December. Emissions may also travel southwest towards the Cartama Province, potentially affecting agricultural productivity.

The results highlight the need for regional air quality monitoring systems that allow atmospheric connections in constructing regional development plans. While the impact on natural ecosystems from this distant atmospheric transport has not been evaluated in Colombia, the ecosystem function alterations have been documented in Northern ecosystems [12]. These two possible impacts highlighted the need to understand atmospheric contaminants' fate, both primary and secondary, that originate in Medellín and the Aburrá Valley. Furthermore, this urban center may be a source of regional contaminants and a recipient because pollutants emitted in cities near the valley, e.g., Rionegro, could reach this area.

From those previous simulations, the interest in developing a measuring network study to corroborate previous CTM representation of the Valley and start collecting data in these allocations for a future operational Data Assimilation (DA) system started such as recent cases like in [13] for the estimation of emissions in urban environments and IoT based (Wifi protocol) for suburban environments [14]. DA is a mathematical technique that reconciles the mathematical modeling representation of reality with the measurement perspective through different approaches depending on the gaussian or not gaussian error background model and observations covariance error distribution.
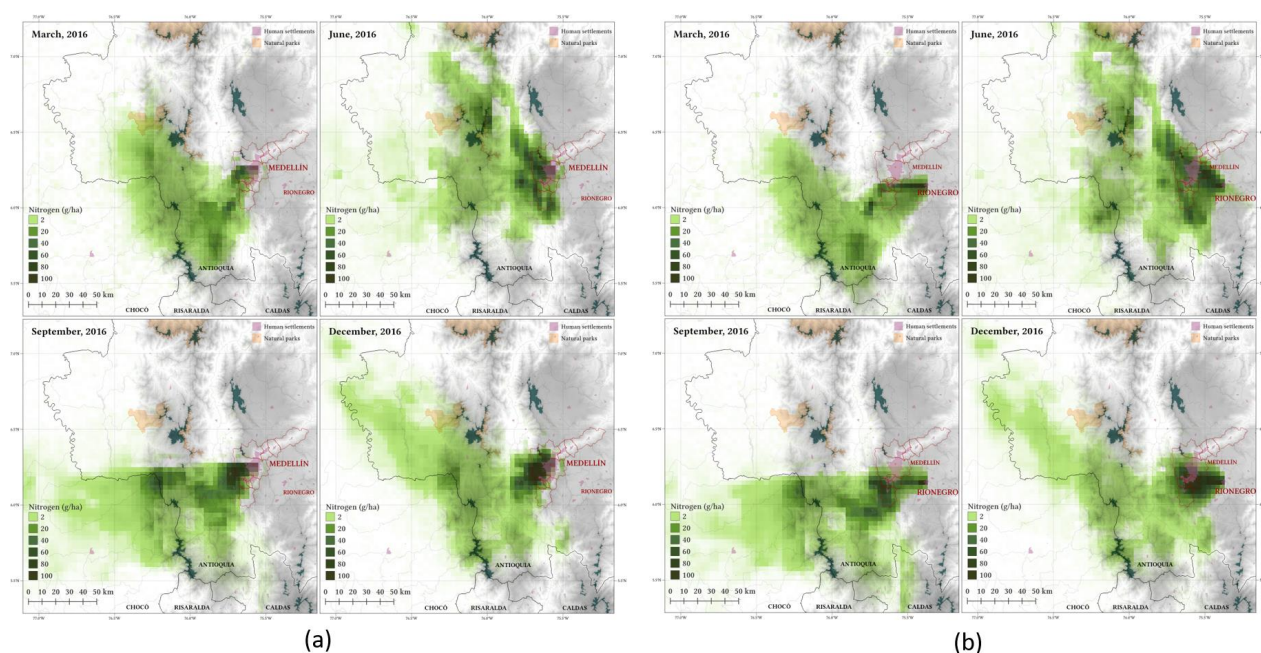
Figure 1. The figure shows two patterns for the hypothetical simulation for regional atmospheric pollutant transport. The panels in the image represent simulation results using the LOTOS-EUROS CTM for Medellín (**a**) and Rionegro (**b**) with a point source of nitrogen oxides equivalent to the emitted by the city in one day (1000 kg of nitrogen oxides/hour). These releases were over the background concentration (The background simulation was removed, which makes that the NO_2 was liberated from a specific point) during the hours of 06:00–20:00 on the third day of the simulation. The deposition was monitored from day 3 through day 9 (days 1 and 2 were used as model ramp-up time).

The proposed station locations aim to obtain data from sites linking the urban areas of the Aburrá Valley and the San Nicolás Valley to the East (e.g., Rionegro). The proposed sites attempt to cover the highest points along the slopes of the Aburrá Valley to monitor the contaminants dynamics of the Valley and thus understand the magnitude of these regional atmospheric interconnections sampling in the completest spatiotemporal possible resolution. The simulation presented in Figures A1 provides experimental justification for the proposed network configuration, offering stations to complement the SIATA stations network. SIATA stations will be used as reference and calibration stations to ensure the reliability of the data generated because it is the operational network for policy decisions in the metropolitan area. In these simulations, the LOTOS-EUROS CTM was used to simulate in a nested domain configuration to reach 1×1 km resolution for the particulate matter PM2.5 using two different meteorology input conditions (ECMWF and WRF), showing how the ECMWF meteorology drives the pollutants far away from the Valley and otherwise, for the WRF meteorology, the Valley traps the contaminants.

In terms of low-cost sensor and applications with CTM, the work in [4] shows the comparison between a certified air quality network and a DA experiment with the low-cost sensor network offering the benefit of using the combination of these two sources of information through DA schemes to balance the inaccuracy of these with the possibilities to drive a model with the right trend. In Figure 2, the comparisons of the three-dimensional snapshot of the model output over the valley and assimilated outputs of a low-cost sensor network inside the valley are depicted in transversal cuts.
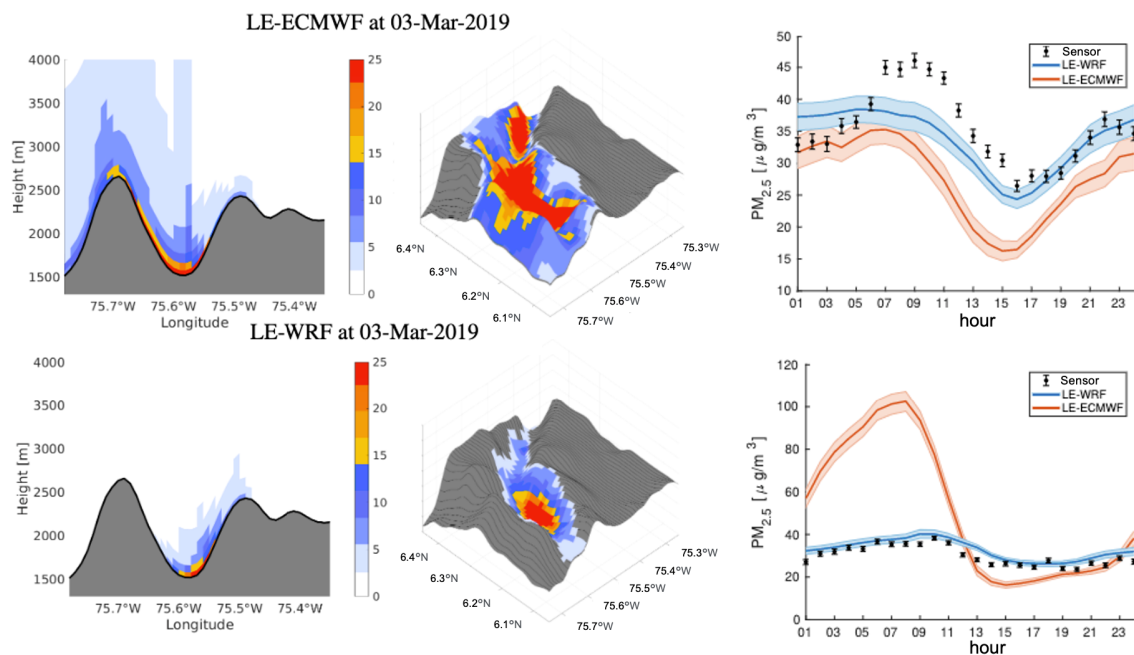
Figure 2. Transversal cut comparisons, three-dimensional snapshot of the model output over the valley and assimilated outputs of a low-cost sensor network inside the valley.

The development of technology for monitoring air quality based on the low-cost sensor is an increasing trend for small cities, harbors, and rural areas with increasing pollution-related problems [15–17]. Technology miniaturization lets new modular integration opportunities appear [18]. In this case, robust and rugged aerospace-inspired low-cost monitoring stations were deployed in strategic remote sites to detect the exchange of atmospheric contamination among regions. The proposed network, nested in a cyber-physical system [19], will integrate new and existing data into a framework for understanding regional dynamics, evaluating development scenarios, and supporting decision-making and citizen science [20] at the local and regional scales. A review of low-cost sensors for outdoor quality applications is [21] and includes useful information to understand the difference between the existent way to measure that the common sensor has.

In Section 2, Material and methods, the measurement unit Simple is presented with the different experimental procedures such as long-range tests, simulation power consumption, the irradiance simulation experiment, and the network consideration are explained. In Section 3, the results of the different experimental methodologies for the instrument and the implementation of the network are presented, followed by the discussion section around the usability of this kind of data from low-cost devices in conjunction with DA techniques as a way to circumvent the necessity of expensive infrastructure by using DA making the observation and modeling worlds to talk to improve the representation of the different pollutants over a region.

2. Materials and Methods

2.1. Description of the Network

At the mentioned heights around the valley, measurements for the different proposes are necessary with the chemical model comparison. Those points were selected because they are city-representative locations and can be accessed by hill walking routes. Therefore, the nodes are considered energy autonomous and remotely connected.

For the current project, the species of interest will be particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), and ozone (O_3), in addition to the standard meteorological variables of relative humidity, temperature, wind magnitude, and speed even though other compounds, such as ammonia and isoprene may be of interest for future development. The

proposed location of the measuring stations is presented in Figure 3. These locations are primarily selected for coverage of remote sites not covered by the SIATA network but that may provide data to detect the transport of contaminants in and out of the Aburrá Valley. Because of the urban growth trends described earlier, there will be an emphasis on stations that may provide data to understand the atmospheric interconnections between the Aburrá Valley and the San Nicolás Valley (see Figure 2).
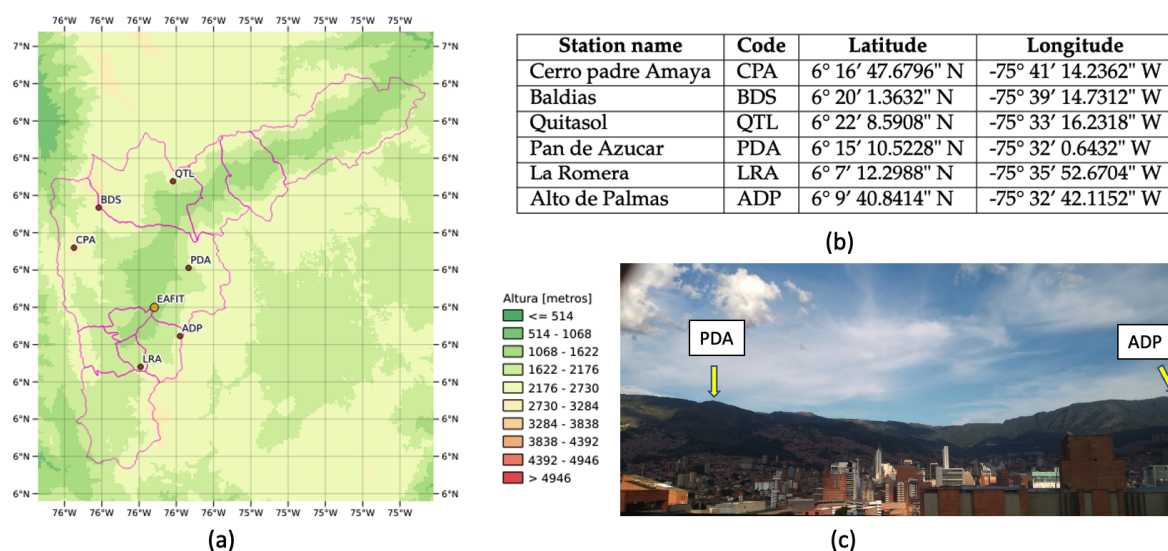

Station name	Code	Latitude	Longitude
Cerro padre Amaya	CPA	6° 16′ 47.6796″ N	-75° 41′ 14.2362″ W
Baldias	BDS	6° 20′ 1.3632″ N	-75° 39′ 14.7312″ W
Quitasol	QTL	6° 22′ 8.5908″ N	-75° 33′ 16.2318″ W
Pan de Azucar	PDA	6° 15′ 10.5228″ N	-75° 32′ 0.6432″ W
La Romera	LRA	6° 7′ 12.2988″ N	-75° 35′ 52.6704″ W
Alto de Palmas	ADP	6° 9′ 40.8414″ N	-75° 32′ 42.1152″ W

(b)

(a)

(c)

Figure 3. (**a**) Locations selected for the air quality network disposition around the surrounding mountains. The red cross is located at the point of view in the right direction from the arrow of the (**c**) photo. (**b**) table with the code and station coordinates. (**c**) The landscape of Medellín with the image of the east mountains of the valley and the disposition of two stations over the urban areas of this deep-seated valley.

Figure A1 shows a panel with the argument about the need to have a measurement point in the high levels of the Aburrá Valley from a perspective of a previous DA scenario Figure 4. The first graphic shows the LOTOS-EUROS simulation output for the Aburrá Valley with circles and stars from the validation network with the same color bar magnitude of the simulation from the model. Circles and stars refer to stations located in high positions and bottom positions inside the valley, respectively. This comparison shows an underestimation of the model concerning the measurements from the validation network. The following image shows the LOTOS-EUROS model assimilated with the $PM_{2.5}$ high-density network. It is crucial to notice how almost all stations from this assimilation network are located below the 2000 m.a.s.l. With this result, a discussion supports the need to measure more information in the high altitudes of this valley. An example to support this affirmation is seen for the star station that is possible to see in the right part above the valley (yellow circle), for which the value in both situations for the model was underestimated, not presenting a proper update of the analysis for this area suggesting increase the number of observations.

2.2. Low-Cost Sensor Hardware Architecture

The module used to develop this network is called Simple-4. This device's electronic architecture evolved from the Simple-3 architecture created in 2018 and the previous before (Simple-3, Simple-2, Simple-1, Simple-0) [22,23]. The Simple Missions represent projects based on the CanSat development (A CanSat is a standard pico-satellite form factor soda can satellite), with a cylindrical array structure, a mass of approximately 250 grams, and a volume of approximately 330 cubic centimeters. While originally designed for deployment aboard rockets or weather balloons, the CanSat-inspired design results in rugged, modular,

robust, non-invasive measuring devices that are highly efficient in their communication approaches and energy use.
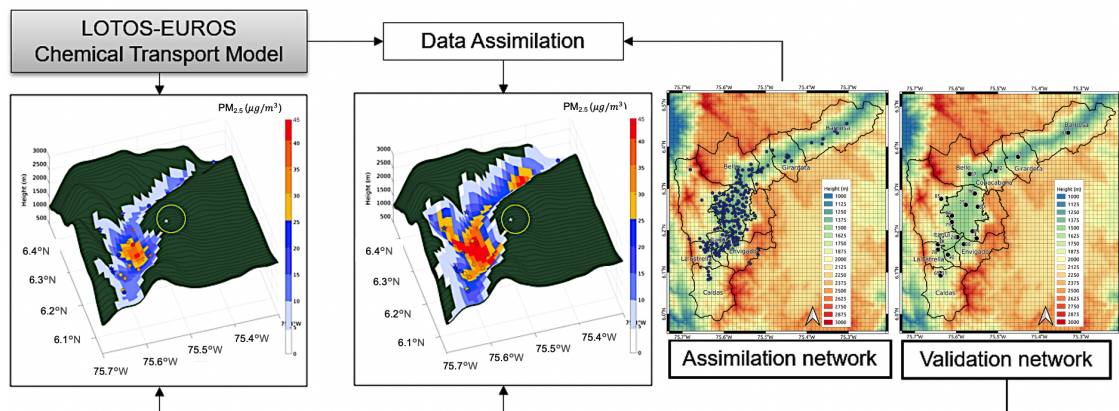

Figure 4. Data assimilation system with new measurements in the high part of the valley complementing the SIATA network.

The subsequent developments to this module facilitated the use of different communications modules and protocols, increased the number of sensors in the payload, and improved the energy system, which consists of an independent board from the previous payload subsystem. The attributes of the modules make them for deployment as remote measuring stations. Figure 5 shows the Simple-4 diagram schematic system.

SimpleVital—On-Board Data Handling (OB&DH). The OB&DH manages, stores, and sends information from the other electronic subsystems to the ground segment through the communication subsystem. This board contains an 8-bit microcontroller that communicates employing standard protocols such as Serial, I2C (Inter-Integrated Circuit), and SPI (Serial Peripheral Interface) to peripheral units such as GPS (Global Positioning System), IMU (Inertial Measurement Unit), barometer, and temperature and communicates with the subsystems of EPS, Payload, and COMM (Communications). Furthermore, this subsystem is responsible for formatting the data for storage in SD memory. This four-layer PCB design promotes the integration of more components per area.

SimplePower—Energy Power Subsystem (EPS). EPS regulates the power of satellite subsystems. In this module, the charge is stored in a battery bank with 20,000 [mAh]. This battery supplies between 3 and 4.2 volts, raised to 5 volts, to be distributed to other subsystems and a stage for overcharge protection. Additionally, this subsystem controls the power supplied by the solar cells (solar array interfaces) through a DET (Direct Energy Transfer) architecture; this enables the extension of the operation time of the module thanks to the additional power already available in the batteries.

SimplePollution—Payload Subsystem. This subsystem is composed of a sensor (MICS-6814) that measures the concentration of gases such as CO (Carbon monoxide), NO_2 (Nitrogen dioxide), C_2H_6OH (Ethanol), H_2 (Hydrogen), NH_3 (Ammonia), CH_4 (Methane), C_3H_8 (Propane), and C_4H_{10} (Iso-butane), in addition to this two SPEC ™sensors for measuring NO_2 and O_3 thermodynamic variables such as relative humidity and temperature.

SimpleCOMM—Communications Subsystems. Notably, the Simple-4 design features three different types of radios (LoRa Tx/Rx @ 915 MHz, Dorji Tx/Rx @ 434 MHz, and Radiometrix Tx/Rx @ 434 MHz). Besides, it incorporates Wi-Fi technology. In terms of communication having different radio possibilities allows greater autonomy and modularity in the network and the capabilities to support long, medium, and low-range transmissions. Two references were used, a 144 MHz Very High Frequency (VHF) and 434 Ultra High Frequency (UHF). Both frequencies used Narrow Band FM (NBFM) and Audio Frequency Shift Keying (AFSK) modulation at a 1200 baud velocity using the AX.25 (Amateur X.25) protocol, supporting the use of an Automatic Packet Reporting System (APRS) packets

for real-time digital communications, thus permitting Tx/Rx coverage. Communication links generated between the Simple-4 CanSat pico-satellites and the gateway station ensured a minimum vertical line of sight communication range of 300 m without multipath propagation, rain fade, and attenuation for vegetation phenomena.
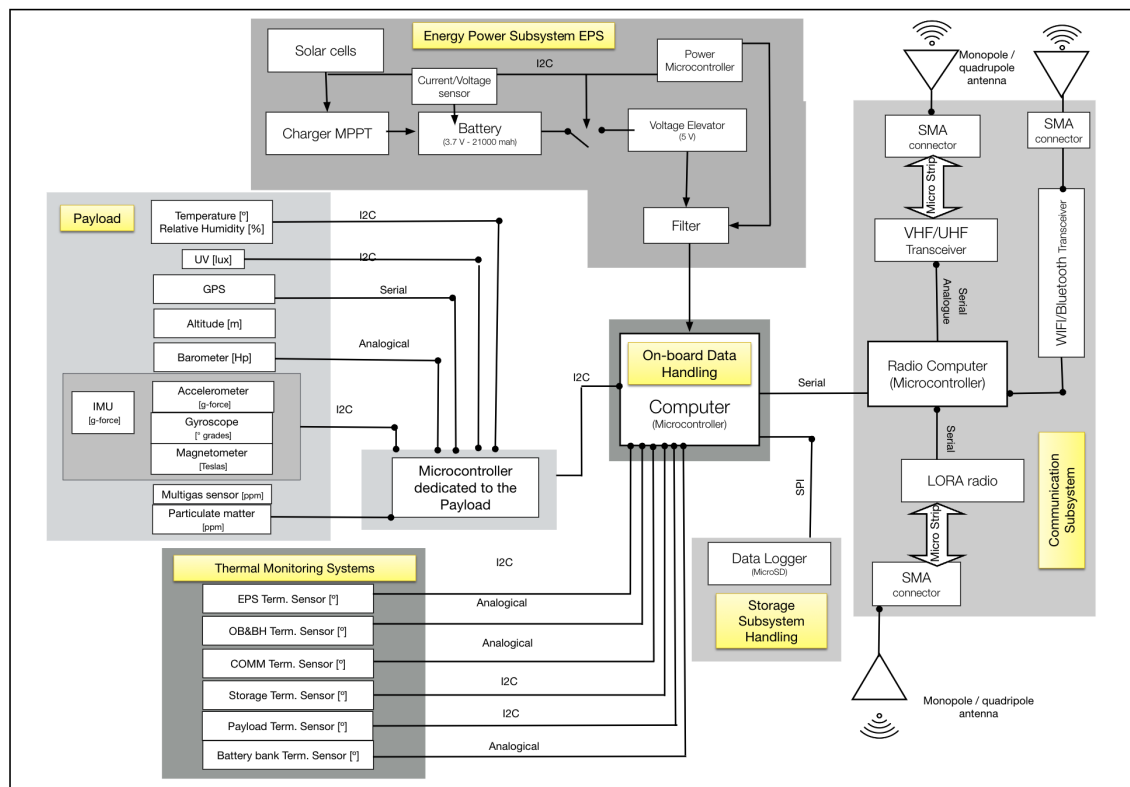

Figure 5. Flowchart with the various subsystems that comprise the Simple-4 partial centralized architecture. The Energy Power Supply (EPS) subsystem with the MPPT module controls the charge and discharge cycles of the battery and the load consumption. A dedicated microcontroller collects the payload information and, once the data is preprocessed, is delivered to the OB&DH to command the communication subsystem. The other secondary system is the thermal monitoring system, a transversal support system conformed by the different thermal sensors in each PCB layer.

2.3. Experimental Procedures

For the calibration and validation experiment with the unit, experimental activities with the measurement device were reproduced to ensure the reproducibility of the measure. Long-range transmission experiments were developed at the end of 2020 to study different radios to decide correctly about the new component. Solar irradiance simulated values were analyzed to estimate the charge and discharge cycles for specific periods. Controlled dust and moisture IP analysis test were performed to certify the enclosure protection for the electronics.

3. Results

3.1. Hardware Development

The simple-4 device is made up of 5 Printed Circuit Boards PCBs, each one of them housing a subsystem. The first is one 4-layer PCB called SimpleVital, which corresponds to the Command On Board & Data Handling (CB&DH) subsystem. The second is a three 2-layer PCBs called SimplePayload (Gases/Pollution), the third one the SimplePower (Energy Power Supply (EPS)), the fourth is the SimpleBattery (Battery bank), and the last the SimpleCOMM (Communications Subsystems (COMM)). All those are shown in Figure 6.
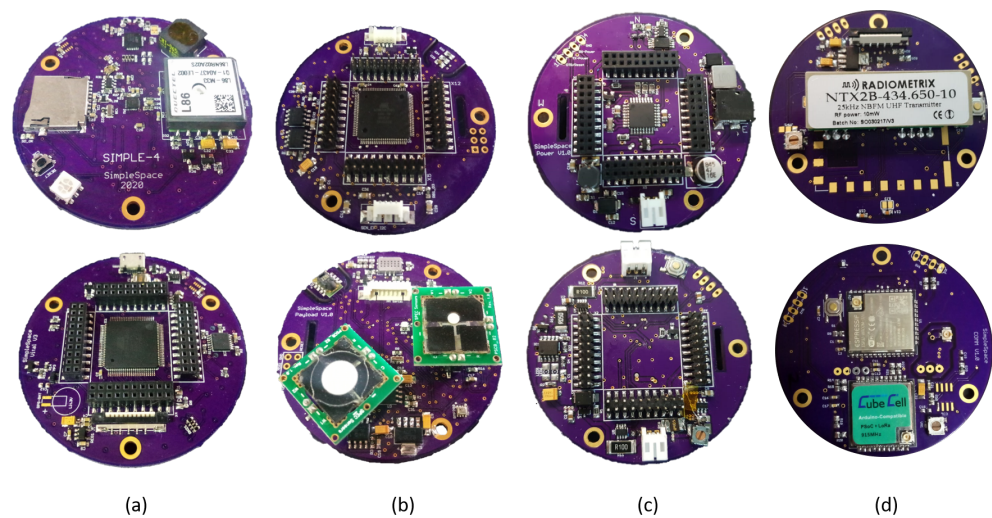
Figure 6. (**a**) SimpleVital (Command On Board & Data Handling (CB&DH)), (**b**) SimplePayload (Gases/Pollution), (**c**) SimplePower (Energy Power Supply (EPS)), (**d**) SimpleCOMM (Communications Subsystems (COMM).

The information transmitted (TX) from the Simple units is received in a gateway (RX) that uploads the information to the cloud service. Different long-range tests were developed in the Aburra Valley intending to guarantee the success of the network communication challenges as the abrupt terrain as well as possible obstacles, assuring the maximum distance of 18 km from the (TX) location in Bello (Baldias) to the gateway node (RX) in Universidad EAFIT.

3.2. Long Range Tests

The communication nodes of this network were programmed under the OTAA and ABP registration protocols necessary for secure communication with The Things Network. The nodes established contact with the web server through the configured gateway in the Universidad EAFIT for different distances in Table 1. An incremental distance test was carried out to understand the system's operation under a variable factor in the node antenna (Figure 7). In this process, two antenna types were used in two configurations, centered and not centered in frequency, to determine the type of antenna with the best performance. The measurement of the intensity of the signal was compared against the theoretical electromagnetic signals propagation models.

The EPS subsystem of the Simple-4 module was tested to ensure the power operation's durability and stability. Different current and voltage sensors distributed before the load and the battery packets worked to understand the unit's behaviour for the other climatological conditions with low irradiance values are shown in Figure 8. The solar cells used for the station are 10 Watts polycrystalline cells with efficiency values of 12%.
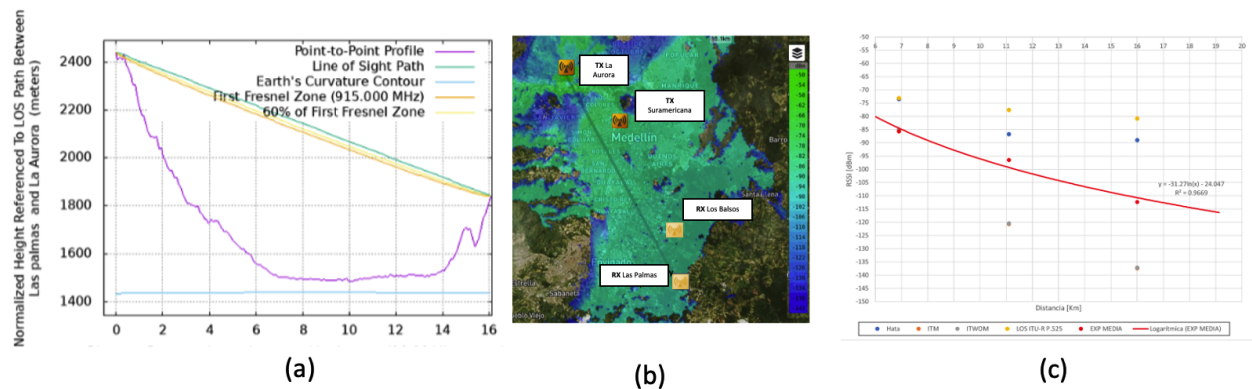
Figure 7. (**a**) Vertical cut and Fresnel distance. (**b**) Spatial intensity over the Aburra Valley and (**c**) model generated from the different signal intensities and experimental locations.

Table 1. Locations selected for the long-range transmission test. This gradual increase of successful experiments assures us of the long-range and stable communication link possible with the modules.

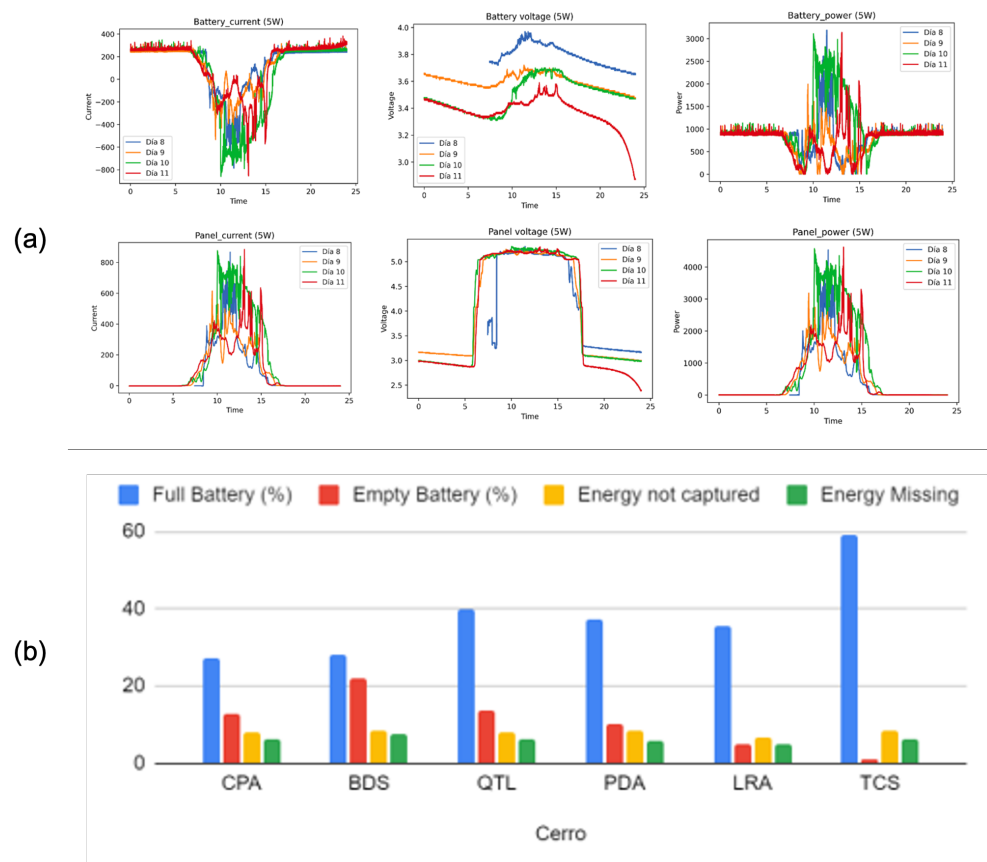| Test	Location TX (Latitude/Longitude)	Name	Location RX (Latitude/Longitude)	Name	Distance (m)
1	6°15′10.9″ N/75°34′52.1″ W	Suramericana, Medellin	6°11′33.0″ N/75°34′03.1 W	Los Balsos, Medellin	6910
2	6°16′51.5″ N/75°36′50.1″ W	La Aurora, Medellin	6°11′33.0″ N/75°34′03.1 W	Los Balsos, Medellin	11,015
3	6°16′51.5″ N/75°36′50.1″ W	La Aurora, Medellin	6°09 ′13.2″ N/75°32′41.7 W	Alto las Palmas, Envigado	15,998

Figure 8. (**a**) Current, Voltage, and Power (Watts) before the battery and before the load measure for four days, (**b**) Energy supply simulation for the percentage of full, empty, not captured, and missing energy at the different point locations in the mountains around Medellín.

3.3. Energy Power Supply Simulation Experiment

The European Commission's Joint Research Centre (JRC) developed the PVGIS European power calculation tool (https://ec.europa.eu/jrc/en/pvgis (accessed on 27 December 2022)). PVGIS uses data from meteorological models and satellite imagery to estimate the solar radiation that a PV system would receive at a given location, considering the local weather conditions, solar panel orientation and tilt, and other factors taken in account in Table 2. In this study, we used PVGIS and other tools to estimate the power needed to select the solar array for a simple module based on the nominal values of battery charge and discharge information we measured. Our energy simulation experiments showed that the stations on the valley's west side had higher solar power availability due to higher radiance values from a meteorological model.

To conduct our experiments, we used PVGIS to input the location, panel type, and battery information for our PV system and estimate the energy production and performance of the system. We also collected and analyzed data from other sources, such as meteorological models and satellite imagery, to better understand the factors contributing to higher solar power availability. Our experiments showed that the valley's west side had higher solar power availability due to higher radiance values from a meteorological model. This finding has important implications for policy and practice, as it suggests that PV systems located on the valley's west side may be more efficient and effective at generating energy. There are, however, some limitations to our study. For example, the results are based on data from a specific location and may not be generalizable to other regions.

Table 2. Parameters used to simulate the energy charge and discharge system.

Parameter	Power
Maximun installed photovoltaic power	6 W
Battery capacity [Wh]	38.85 Wh (3 Batteries de 3500 mAh * 3.7 V)
Daily consumption [Wh]	(3.7 * 0.35 * 24 = 31.08 Wh)
Batteries [3000 mAh]	66.6 Wh
Discharge cut limit	20%

The annual charge and discharge cycles for the selected points in the valley with a 10-watt panel configuration are depicted in the information presented. The graphic also includes simulations for four additional energy states: a fully charged battery, an empty battery, energy that was not captured, and missing energy simulation. This information helps understand the performance of the battery array and load in different locations and under various conditions. Analyzing the data makes it possible to identify patterns and trends that can inform future design decisions and optimization efforts.

3.4. Case Development and Disposition

The unit's design focused on protecting the internal electronics while maximizing the available volume without sacrificing structural integrity. To facilitate this, the case was carefully designed to meet these goals. One notable feature of the case is the transparent dome on the top, which allows light to reach the UV sensor and enables the user to monitor the device's health through light signals emitted from the top PCB layer (Figure 9). The GPS antenna is also positioned to have direct sky-sight, a crucial requirement for optimal connectivity. Overall, carefully considering design elements has resulted in a unit that balances functionality and durability.
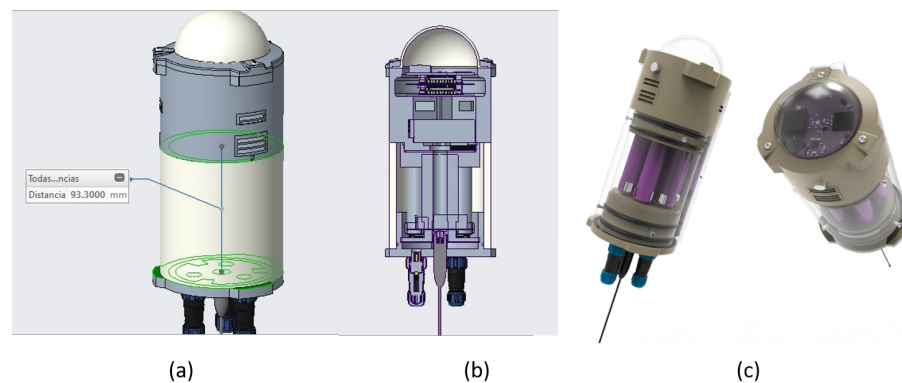
(a) (b) (c)

Figure 9. (**a**) The case developed for the measurement device, (**b**) Transversal cut to see the inside disposition of the elements and the different chambers specially designed to orientate the air mass flux through the payload bay where the gas sensors are located, and (**c**) Render visualization of the case to appreciate the translucid top dome and the lateral airflow channels.

The lateral airflow ducts allow the air in the chamber to reach the gas sensors. Controlled installations of the case to dust and moisture drastic changes were submitted to ensure an IP degree for the electronics case.

3.5. Experimental Calibration Results

We conducted different tests to ensure the module's long-term performance and reliability. A thermal camera was used to monitor the electronic PCB during complete operation cycles. This enabled us to detect deviations from the nominal operating temperature, as shown in Figure 10a. By identifying components that were not functioning properly, we were able to take proactive measures to prevent future malfunctions and energy losses.

Additionally, this testing allowed us to identify any potential issues before they become serious problems, helping to ensure the longevity and effectiveness of the module. By regularly monitoring the temperature of the PCB and its components, we were able to catch any abnormalities early on and take corrective action to maintain the overall efficiency and reliability of the system. Overall, this testing was critical in ensuring the long-term capabilities of the module and safeguarding against costly and inconvenient malfunctions. On another side, Figure 10b,c show some images of the integrity tests performed in the chamber for the IP5X IP6X evaluation. These tests are essential to satisfy the long term requirement for the hardware because bring the oportunity to expose to drastic conditions the equipment because the location sites surrounding the valley are not supposed to be visited frequently.

The Figure 11 shows the time series comparison between the Vaisala AQT400 unit and the module developed for this project for the Ozone, NOx gasses and humidity, temperature from two sensors. The data from the module overestimated the Vaisala value, and once the calibration algorithm is applied, the corrected value is also depicted.

The inter-calibration procedure validated the performance of the sensor under investigation. The sensor was compared with reference sensors to determine observation error and accuracy. Results showed error margins within 10% of nominal, considered acceptable for use in the data assimilation algorithm. The inter-calibration contributed to the robustness of the study's findings by ensuring the reliability of the sensor data.
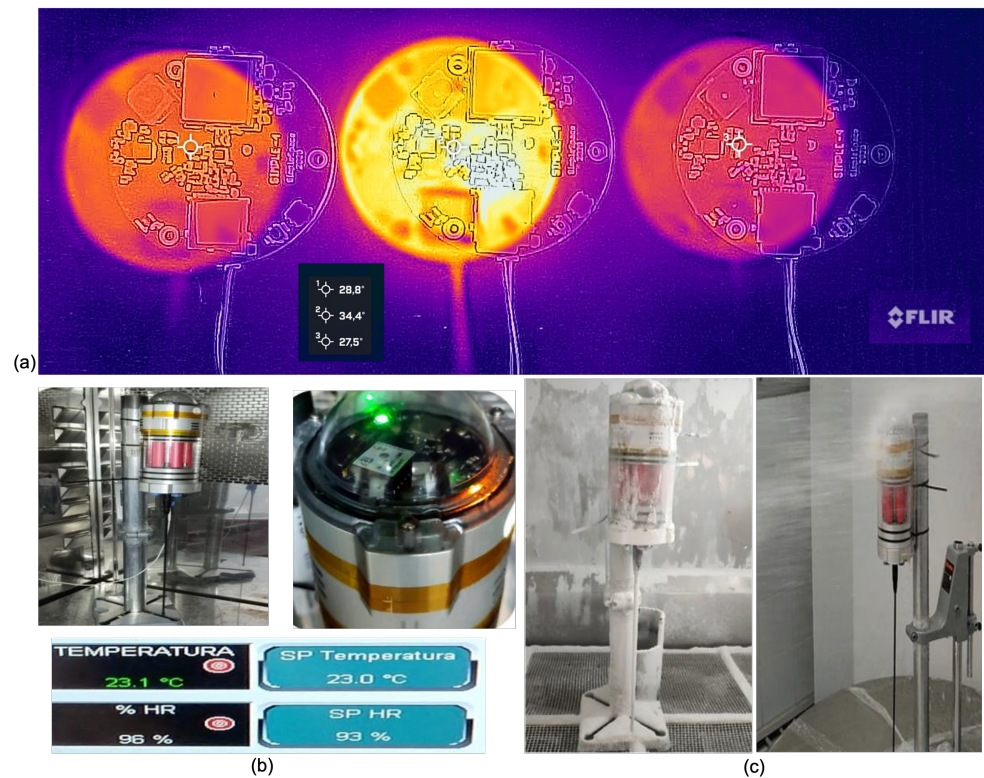
Figure 10. (**a**) Infrared thermal images under operations for different operation routines of the module. IP5X IP6X test for the device. (**b**) Temperature and Humidity stationary chamber test. (**c**) dust and wind tests.
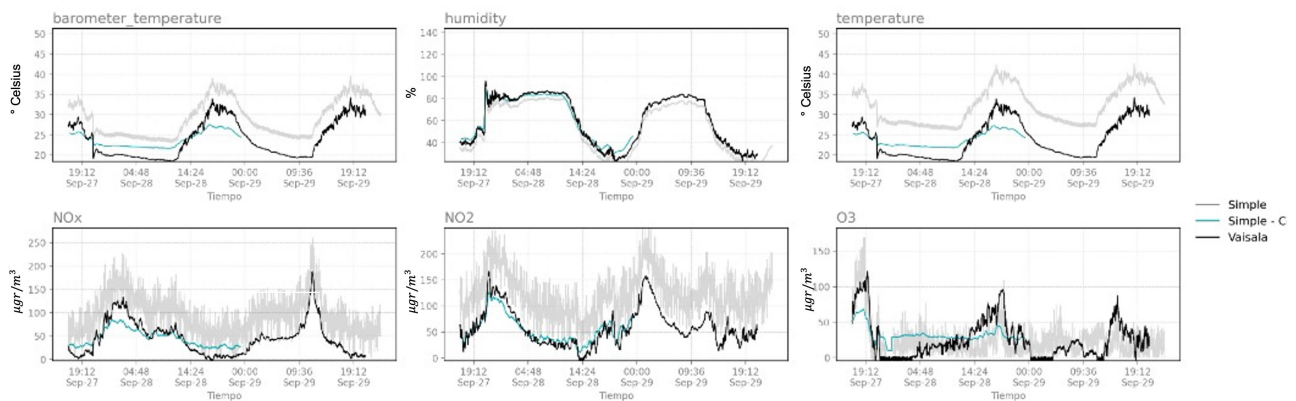

Figure 11. Qualitative comparison of the device with the Vaisala AQT400 ®calibrated equipment.

4. Discussion

The previous modeling of atmospheric composition dynamics in the Aburrá Valley showed inconsistencies in concentration and deposition fields based on the meteorology input to the CTM. Accurate meteorology suggests a reduced simulated concentration from the previous ECMWF meteorology used for this valley. Although emissions and meteorology are relevant dynamics in these models, the detailed emissions inventories contain high uncertainty, so the developments of a DA system like this oriented to emission estimations bring a region a capability.

Air quality data at the top of the Valley's surrounding mountains are nonexistent, and the hypothesis of the chemical transport from the valley still needs to be explored experimentally. In Figure 11 the measurement unit's first deployment campaign in the valley's surrounding mountains is shown. A comparison of the particulate sensor (pm10)

of the device against two sensors one inside the valley (Est 295) and the other outside (Est 152) is shown in the right image. This low-cost sensor ground base measurement could be a feasible solution to increase data availability from non-connected areas. It will be validated if evidence corroborates these contradictions in these difficult-to-reach areas.

Air quality modeling and monitoring are crucial for understanding the sources and distribution of pollution. Incorporating additional spatial and temporal information into model simulations can improve predictions. However, the lack of monitoring in certain areas and the dependence of particulate matter simulation impact on meteorological modeling accuracy pose challenges for fully understanding air pollution. These findings underscore the need for continued research in this field (Figure 12).

The simulation perspective gives some ideas for this kind of network to verify the predicted removal dynamics corroborating from the observation point of view through DA and validation activities. DA activities have been reviewed for this region in [24] analyzing the state-of-the-art and the subsequent state applicable to the Tropical Andes region. DA has been applied in the Aburrá valley since 2019 [25] for a high-resolution experiment assimilating particulate matter observations with the LOTOS-EUROS CTM using an ensemble-based technique. From this first DA experiment, the urgent need to expand the data sources on atmospheric pollutants concentrations were identified to improve the performance models at local and regional scales. Low-cost sensors are gaining importance through the years for managing air pollution in the cities [26]. Therefore more and more electronic technology of this kind is gaining respect and complementing operative air quality networks. Problems like calibration have been reviewed recently, and methodologies such as [27] can be applied to assess the network's data through calibration models or specific tools designed for the evaluation of low-cost gas sensors [28]. Also, the correction of hysteresis developed in [29] must be considered further for oxidative-based sensors. Data assimilation onto the LOTOS-EUROS CTM demonstrated how, with low-cost sensors and data assimilation techniques, a system for air quality monitoring could add value to the low-cost budget for instrumentation. Understanding the dynamic of the several gasses that escape from the valley is essential. This rural network has diverse logistic and engineering design challenges to comply with the objectives successfully.
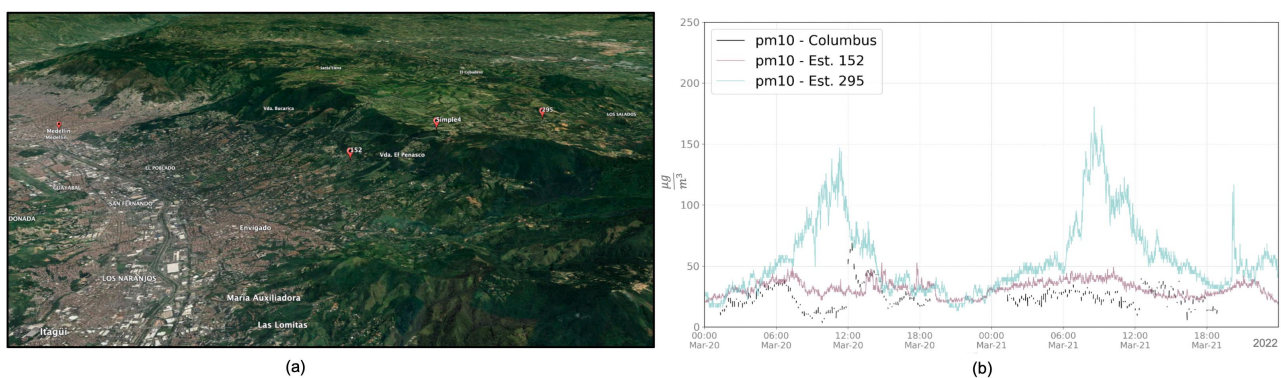

(a)

(b)

Figure 12. (**a**) Locations of a Simple 4 compared with two sensors of the Ciudadanos network at two altitudes. (**b**) PM10 concentrations. Interesting to see how the mountains can "contain" the contamination; it is clear these days that the concentration is greater within the valley and, on the other side, also greater than that recorded by the device. At the altitude of the module in the Columbus, that more wooded corridor of the slopes of the eastern mountains of the Aburrá Valley can also be seen.

5. Conclusions

This study has presented the implementation of a low-cost sensor network for air quality measurement in the Aburrá Valley region. The network is designed to complement the existing air quality network in the area based on various considerations and experiments to test the hardware equipment. The telemetry signal was analyzed using four radio propaga-

tion models and field measurements, allowing a more comprehensive understanding of the network's behavior and signal behavior in the region with this topography. Simulations of energy charge and discharge cycles were used to determine the optimal configuration of solar cells and batteries, and additional studies were conducted on the IP degree of the system. This study demonstrated the utility of PVGIS for estimating the potential energy production of PV systems for a low-cost autonomous air quality sensor. Our results suggested that the valley's west side may be optimal for PV systems due to higher solar power availability. However, further research is needed to confirm and expand upon these findings because in this part of the paper we had simulated radiances for the past from PVGIS but not yet measured values in the installation points; nevertheless, the simulated values gave a useful design input. Extra research is needed in intercomparison procedures with models and other meteorological and air quality sensors. Implementing this alternative network in a tropical region at high altitudes will provide valuable empirical data for data assimilation purposes. In addition to this project, we hope to deploy similar sensors in remote, natural ecosystems in Colombia, leveraging the network's long-range transmission capabilities and energy independence to monitor the influx of urban contaminants from a distance. The network's geolocation and other data provided may also be helpful in data assimilation experiments seeking to increase spatiotemporal frequency. By expanding the network to other such regions in the future, we can leverage its capabilities to more effectively monitor the influx of urban contaminants and improve our understanding of the impacts of such contaminants on the environment.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

OB & DH	On Board and Data Handling
EPS	Energy Power Subsystem
COMM	Communication Subsystem
MPPT	Maximum Power Point Tracker
PCB	Printed Circuit Board
CTM	Chemical Transport Model
DA	Data Assimilation
LE	LOTOS-EUROS
WRF	Weather Research and Forecast

ECMWF   European Centre for Medium-Range Weather Forecasts
LCAQS   low-cost air quality monitoring Systems
RX   Reception
TX   Transmission
I2C   Inter-Integrated Circuit
PVGIS   Photovoltaic Geographical Information System
PV   Photovoltaic
IoT   Internet Of Things
APRS   Automatic Packet Reporting System
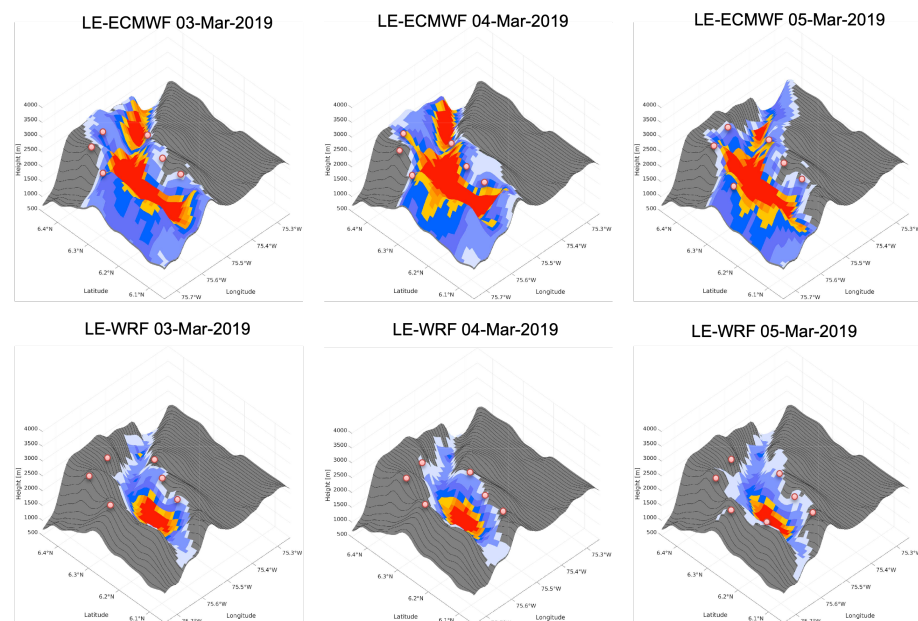
Appendix A

Figure A1. Different meteorology field input (ECMWF and WRF) the LOTOS-EUROS CTM simulating particulate matter 2.5 for the contingency period of the 3, 4, and 5 of March 2019. The red dots are the station network's location. There is a noticeable difference in the particulate matter concentration fields that, in one situation, respect the other and is trapped by the valley structure.

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