MITSUBISHI-B project

Title:

Multi-objective optimization for best early prediction of extreme weather events

Industrial Partner: Information Technology R&D Center of Mitsubishi Electric Corp.

Mitsubishi Electric is one of the world's leading names in the manufacture and sales of electrical and electronic products and systems used in a broad range of fields and applications. As a global, leading green company, we are applying our technologies to contribute to society and daily life around the world. The Information Technology R&D Center is actively creating new business through our basic research and development in the fields of information technology, media intelligence, electro-optics microwave and communication technologies. We are also searching out technologies that enable us to be the leader, and are working to renew existing business through the fruits of our R&D in the field of IT.

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Project Description:

1. Motivation for the project

~ Early prediction of extreme weather events is vital ~

Climate change and global warming has increased extreme weather events. This includes, for example, heavy rains, tornados, and more. Concretely, you know the tragic heavy rain disaster in New York this September [1], and the big landslide caused by heavy rain in Atami this July [2]. Such disasters make the early prediction of weather events vital for disaster mitigation [3]. The mathematical problem to be solved here is related to this scientific field. The goal of this project is multi-objective optimization [9] on locations of meteorological sensing instruments for the best early prediction of extreme weather events. This will be explained in more detail in the following

2. Toward the early prediction of heavy rain

~ Sensing of water vapor and wind is effective ~

As many people know, we can predict heavy rain after the appearance of the cumulonimbus.

However, for the purpose of disaster mitigation one needs to be able to make this prediction before the appearance of the cumulonimbus. For this early prediction, accurate and wide-area meteorological sensing within a certain time interval is necessary of course.

Especially, the "distributions of the water vapor and wind in the atmosphere" are very important, since these often become the signs for the cumulonimbus and eventually heavy rain [3].

2.1. The attractive meteorological sensor "LiDAR"

For the sensing of the water vapor and wind, the "LiDAR (Light Detection And Ranging)" is an attractive instrument, and its deployment has recently grown. This instrument (LiDAR) transmits a laser light to the atmosphere, and detects the light that is scattered (reflected) by the aerosols (particles) drifting in the air. The distribution of the water vapor and wind can be measured (visualized) by analyzing the received light [3-5] (see Fig. 1). The detection of light scattered by the aerosols is similar to what one observes when one illuminates a search light at midnight; in that case, you can see the path of the light in the air [6], and your eyes are exactly detecting the scattered light by the aerosols.

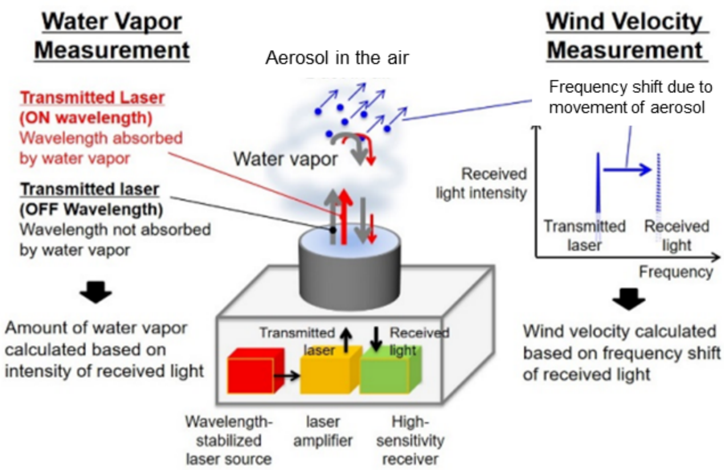

Fig. 1. Measurement principle using LiDAR[3].

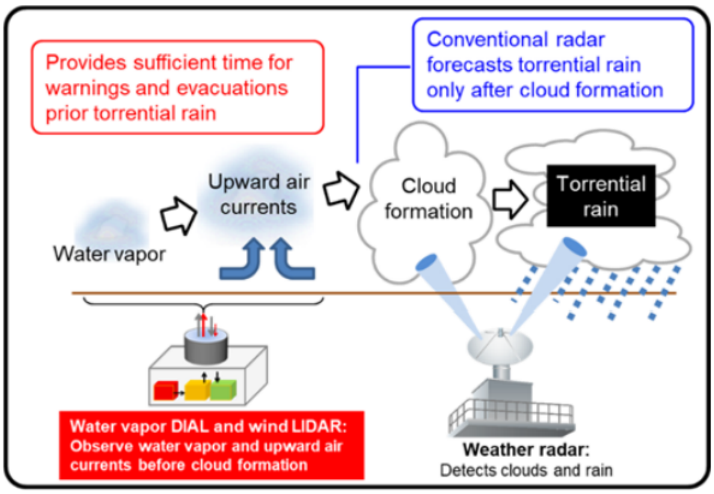

Fig. 2. LiDAR system for early weather predictions[3].

The LiDAR instruments can measure the water vapor and wind "remotely" from the ground. This is a very big advantage compared to "in-situ" humidity and wind sensors [7-8] especially for the measurement in the high-altitude regions. Furthermore, the LiDAR can work especially well in clear sky conditions before the appearance of the cumulonimbus and can catch the sign of that. This is also a significant advantage compared to the electro-magnetic wave RADAR (RAdio Detection And Ranging) which works only after the appearance of clouds and rain (see, Fig. 2). How the LiDAR contributes to the early prediction of heavy rain is roughly shown in Fig. 2. Note again that what is important is the detection of the first signs before the appearance of the cumulonimbus. This project focuses on how to improve this early detection of water vapor that might lead to catastrophic rain events.

2.2. "The sky is the limit"

The LiDAR is an attractive meteorological instrument. But unfortunately, it also has some weaknesses. In investigating these weaknesses, one English phrase comes to mind: “The sky is the limit.” This phrase means “no limitation in your future”, or “your possibilities are unlimited.” This phrase was recently used by Shohei Otani, the two-way major-league baseball player, and is true for all of you. This is also true for the LiDAR instruments in another meaning. For example, what happens when the sky is very clear? (see, Fig. 1) In this case, the aerosol loading is very low and therefore there is only a low scattering signal from the atmosphere. If there is no signal, the LiDAR data cannot be used. Similar issues arise when it is foggy: The laser light from the LiDAR cannot pass through the atmosphere and cannot reach to the measurement volume. This also leads to limitations of the LiDAR performance. Therefore, the LiDAR measurement performance is always affected and limited by the atmospheric conditions in the sky. The atmospheric conditions here include the visibility (aerosol loading) and more, and they highly depend on the locations and altitudes. For example, the aerosol loading is high at the ground (which is good for the LiDAR measurement), and it is low at the higher altitudes. It is also high in urban areas and low in the countryside.

3. What is the best meteorological sensing?

One can improve the performance of the LiDAR instrument in different ways: one strategy is the deployment of higher grade instruments (i.e., with high-grade laser components, Fig. 3(a)). However, this comes with a higher cost. Alternatively, one can also use multiple sensors with low specification (Fig. 3(b)), but this also increases the deployment cost. This means that there is an optimization problem for the number of instruments and locations to obtain the best measurements while also considering the deployment cost.

(a) (b)

Fig. 3. High-grade (a) and low-grade (b) LiDARs [10].

4. The Project

In this project students will use a mathematical approach to develop an optimization strategy for the number and location of instruments, to get the best early prediction of the extreme weather events.

4.1. What we can provide before solving the problem

We can give you the atmospheric conditions in three dimensional meshes which depends on the location and altitudes. The importance of the measurement for the weather prediction depends on the location of the atmospheric mesh in the three-dimensional space. This is defined as the "measurement score", which can be obtained with the knowledge of simple meteorology. Formulas of the score have not yet been reported in the literature, but we can provide examples of the score (simple formulas with exponential functions). If the students in the project team have some knowledge of meteorology, they might also work on the score formula to be more accurate and to fit more realistic situations.

An example of an atmospheric mesh and measurement scores is depicted in Fig. 4. The area size of 70 km × 30 km is roughly equal to the area of Tokyo. The terrain can be expressed with a formula as schematically shown in the figure, but real terrain models for specific areas can be used if you like.

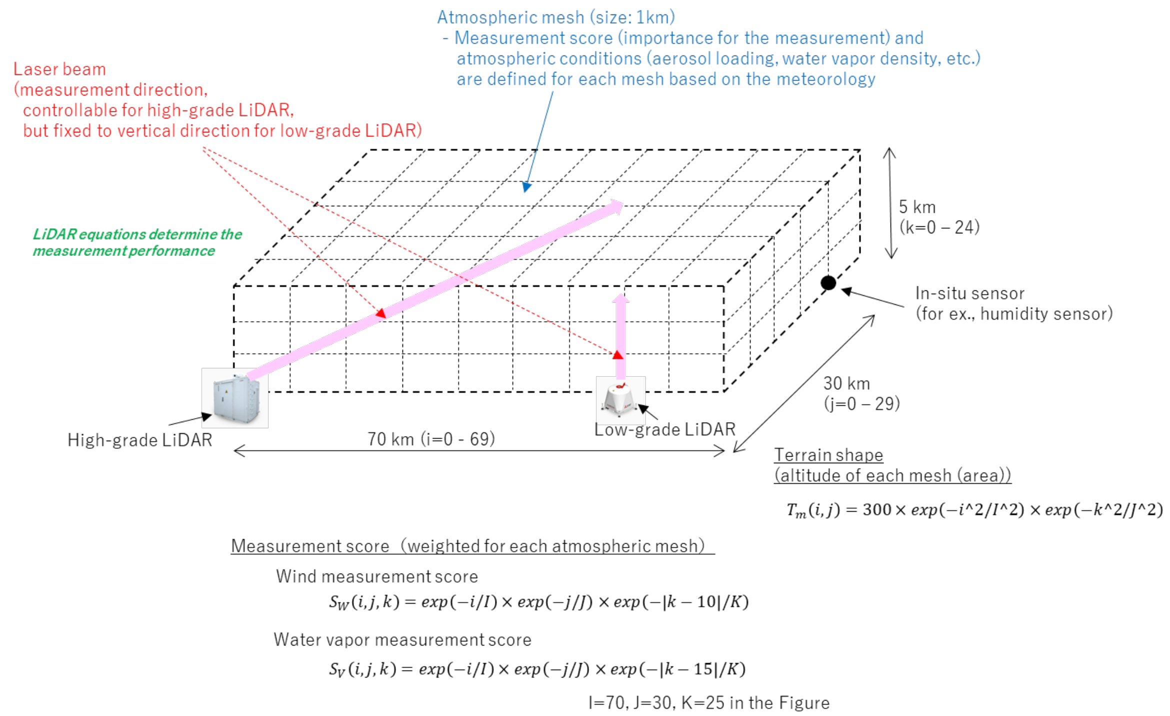

Fig. 4. Example of atmospheric mesh and measurement scores.
(The pictures of LiDARs are the ones in [10])

Examples of scores are also shown in Figs. 4 and 5. Generally speaking, measurements at the ground are very easy with in-situ wind sensors and humidity sensors, but the importance of the measurement at the ground level is not so high from the view point of meteorology. This means that the “measurement score” is low at the ground level. On the other hand, measurements at high altitude (especially around the height of 1 ~ 3 km) have a high “measurement score”, since this is important for the early prediction of heavy rain. The measurements at high altitudes are impossible with in-situ sensors, but are possible with LiDAR (i.e., a remote sensor). Measurements in mountainous regions with living areas have also high “measurement scores”.

Accumulated measurement score (high: better)

$$S_M = \sum_{i,j,k} Q_W(i,j,k) + Q_V(i,j,k)$$

$$Q_W(i,j,k) = \begin{cases} 0 \ if \ not \ measured \\ S_W(i,j,k) \ if \ measured \end{cases}$$

$$Q_V(i,j,k) = \begin{cases} 0 \ if \ not \ measured \\ S_V(i,j,k) \ if \ measured \end{cases}$$

Larger number of measurable meshes and larger measurement score of the meshes contribute to the better accumulated measurement score.

Higher value of S_M means the best measurement performance.

Cost score (low: better)

$$S_I = \alpha \cdot N_{LL} + \beta \cdot N_{LS} + \gamma \cdot N_P$$

N_{LL}: Number of High-grade LiDARs; N_{LS}: Number of low-grade LiDARs; N_P: Number of in-situ sensors

α, β, γ: Relative cost of each sensor ($\alpha >> \beta >> \gamma$, rough image: α=100, β=10, γ=1)

Measurement specification (ability)
High-grade LiDAR > Low-grade LiDAR > In-situ sensor
However, Larger number of High-grade LiDAR means large cost score (i.e., worse).

Minimizing of S_I means the best deployment cost.

Fig. 5. Examples for measurement and cost scores

The “cost score” is defined by considering the financial cost of each instrument as shown in Fig. 5. The in-situ sensors (for example, a humidity sensor) are also available in addition to the LiDAR as cheaper instruments. It should be noted again that the in-situ sensors can measure the wind and humidity only at the ground and cannot measure them at high altitudes. The LiDARs (especially, high grade one) can measure them remotely even though they make the cost score large (i.e., worse).

Further, we also give you the specification of the LiDAR instruments and the equation to derive their measurement performance named "LiDAR equation". You can calculate the measurement performance of water vapor and wind by using the above-mentioned LiDAR equation and the atmospheric conditions.

Formulas and parameters shown in Figs. 4 and 5 are just examples and are expected to be improved during the project.

4.2. What should be optimized

The students will perform a multi-objective optimization [9] on (i) where we should place the

LiDAR instruments, (ii) how many instruments we should use for each type of the instruments. The goal is to maximize the measurement score S_M and to minimize the cost score S_I.

Recommended interests, skills, and knowledge

The ideal students for this project have an interest in the social issue of climate change, natural science, and mathematics. Knowledge of the following items is necessary.

- Basic knowledge of optimization
- Programing skill (MATLAB or Python)

Knowledges on the following items will be helpful.

- Topology, Bayesian inference, meteorology

We highly recommend that students read the references [4-5] before starting this project. The equations (10) – (16) in [5] are what we call the set of LiDAR equations. The example of the atmospheric parameters has been shown in Fig. 7 in [4]. At the beginning of the project we will give additional lectures about the LiDAR instrument and how to derive the LiDAR equation, if necessary.

References

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[4] M. Imaki, K. Hirosawa, T. Yanagisawa, S. Kameyama, and H. Kuze, “Wavelength selection and measurement error theoretical analysis on ground-based coherent differential absorption lidar using 1.53 μm wavelength for simultaneous vertical profiling of water vapor density and wind speed,” Applied Optics, 59(8), 2238-2247 (2020).

[5] M. Imaki, H. Tanaka, K. Hirosawa, T. Yanagisawa, and S. Kameyama, “Demonstration of the 1.53-μm coherent DIAL for simultaneous profiling of water vapor density and wind speed,” Optics Express, 28(18), 27078-27096 (2020).

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[9] https://en.wikipedia.org/wiki/Multi-objective_optimization

[10] http://www.mitsubishielectric.co.jp/lidar/products/index.html#DopplerLidarSystems