Utilization of Galvanic Couples in Wireless Network for Salinity Deposition Sensing

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ABSTRACT Galvanic couples traditionally used for the evaluation of atmospheric corrosivity are constant monitoring sensors whose output correlates with the deposition of sea salt. This report provides the conversion methodology needed to monitor real-time airborne salinity. The methodology was validated by wireless observations made in two Japanese coastal areas, where a remarkable increase in salt deposition revealed rapid contamination. Additionally, the amount of deposition varied according to distance from the shore. Solar radiation reduced the sensor output and induced a sharp drop in the estimated deposition. These unexpected discrepancies were resolved by considering surface humidity, which was reduced by surface heating.

INDEX TERMS Galvanic couples, data analysis, wireless network, sea-salt deposition, rapid contamination, surface humidity, solar radiation.

I. INTRODUCTION
Monitoring the air-borne salinity and its deposition is important for insulators because deliquescence could reduce the insulation strength of electrical equipment. This need becomes stronger when storms are approaching and so-called rapid contamination is concerned. The galvanic couples developed to evaluate the corrosion environment are a promising tool for this purpose because they are designed to perform constant monitoring and to withstand being exposed outdoors [1]-[3]. As the sensor outputs are determined by the combination of the amount of sea salt deposition ($W_s$) and humidity, their back calculation enables to estimate $W_s$ values from the sensor observation [4]-[6]. That is to say, the overall framework of the study is to estimate $W_s$ values from the simultaneous measurements of humidity and galvanic sensing. The specific progress made herein is the establishment of data correlation methodology that is required to deal with field data. Its utility was validated for the field data obtained in two Japanese coastal areas.

A specific feature of a galvanic couple is its wireless measurement record over a year [7]. The robustness and passive measurement features of the galvanic couple are attractive for this type of measurement in the field. Wireless networking enables users to monitor the real-time situation through the data server, and also provide the latest analysis technology even during the period of observation.

To the authors’ knowledge, no traditional technique has realized real-time sensing for salinity in the gas phase. Traditional techniques usually require large and expensive systems and/or chemical laboratory analyses. For example, gauzes are used in an international standard to collect the salinity [8]. This is not a real-time monitoring because at least for a month of field exposure and time-consuming laboratory analysis such as titration or ion chromatography are required. A dummy insulator is installed in some Japanese substations to evaluate its $W_s$ [9]-[12]. However, literature pointed out that the data reliability would be eroded if the measurement is conducted frequently [10]; the dummy must be removed from the area and transferred to a steam chamber for the measurement. Recently, potentiometric chloride sensors adoptable for wireless sensing were reported to evaluate the salinity in soil [13], [14]. Its sensing postulates that redox reaction in soil phase takes place similar to the case in aqueous media.

II. PRINCIPLE OF THE ANALYSIS
The sensor used is a stripe-patterned layered Zn–Ag galvanic couple with an insulation sheet. Its output current is governed by the wetness of the sensor surface, which is determined by...
$W_v$ and relative humidity. Three-dimensional representation of such characteristic is depicted in Fig. 1 [3]. The $W_v$ value can be estimated by inserting the observed data set of the sensor output and humidity into this three-dimensional sensor characteristic. The present study estimated $W_v$ for all instantaneous data observed every 10 minutes, which contain outlier outputs that needed to be corrected.

The first outlier is raid surge typically observed in the rainfall period [3]. Its large value leads to an overestimation of the $W_v$ value. This study extracted these outliers using the automated judgment algorithm established previously by other authors [4]-[6]. The extracted outliers were multiplied by a correlation factor of 0.2 that was established for corrosion rate estimation [3].

Another outlier is the output affected by solar radiation. A preceding study reported that the output of a wetness sensor was reduced when the sensor was exposed to the sun in order to increase the surface temperature $T_S$ and reduce the surface humidity $\phi_S$ [15]. The present study then calculated saturated vapor pressure from the atmospheric temperature and humidly ($T_A$ and $\phi_A$) to estimate $\phi_S$, based on the $T_S$ measurement.

### III. EXPERIMENTAL PROCEDURES

The observation was initiated in February 2021. Two Japanese coastal areas, facing the Sagami and Sasebo bays, were selected as observation areas. The selection process of the observation area is described in the Appendix. The Zn–Ag couple sensor was manufactured in accordance with an industrial standard [16]. An example of the observation scene is depicted in Fig. 2. All sensors were oriented to face the south. Wireless 2.4 GHz local networks were established in each area to store the obtained data on the web server. The Sagami area, located in Yokosuka City, additionally measured solar radiation using a pyranometer, and $T_S$ using the T-type thermocouple. Salinity deposited on a dummy ceramic insulator was estimated from the surface conductivity of a dummy insulator—a traditional evaluation method in the electric industry [9]. The airborne salinity at the area was also numerically calculated based on the WRF model [17], [18]. The main features of these methods are compared in Table I; the areas where the methods were applied are included. The dummy measurement was conducted every eight hours to avoid the uncertainty pointed out in [10]. The numerical calculation used the meteorological record, since prediction of typhoon path is a challenging task. These two methods were only applied for the Sagami area. The Transmission towers were used for performing observation in the Sasebo area.

![FIGURE 1. Output characteristics of Zn-Ag-type ACM sensor as a function of sea salt amount and humidity [3]. Approximated surface constructed in [4]-[6] was used in the analysis.](image1)

![FIGURE 2. Example of an observation setup in the Sagami Bay area. Five series of dummy insulators next to the sensors were used to measure their surface conductivity.](image2)

| Method                  | Real-time operatability | Margin of data error | Areas applied          |
|------------------------|-------------------------|----------------------|------------------------|
| Galvanic sensing       | 10 min.                 | –55% - +120%         | Sagami and Sasebo areas|
| Insulator’s resistivity| 8 hours                 | –32% - +32%         | Sagami area only       |
| Meteorological calculation | 10 min. 110 min.  b) | –50% - +50%        | Sagami area only       |

a) Data scattering reported in [9].
b) Calculator used: HPE SGI 8600 with Intel Xeon Gold 6148 processor. Meteorological record was used to trace the typhoon path.

Data scattering reported in [17].
IV. RESULTS AND DISCUSSION

Rapid increases in galvanic current outputs from sub-μA to sub-mA were observed at the sensor installed in the Sagami coastal area when typhoon Miriane approached in August 2021 (Fig. 3). Records of the nearest meteorological observatory [19] show only slight rains because the typhoon did not hit the observation area itself. Instantaneous sensor outputs only observed in this rainy period were judged to be outliers, to prove that the automated judgment algorithm worked normally. Such data were coupled with the corresponding φA value to convert into Ws by plugging them into the sensor’s characteristic. The obtained Ws value showed a sudden surge from 0.01 to 1 g/m2 and a gradual decrease for approximately 10 days thereafter.

These temporal changes in salinity were compared to the one estimated from the dummy insulator in Fig. 4. This figure also shows the calculated airborne salinity. The three trends agreed with each other, suggesting the plausibility of the analyses. What is important herein is the fact that real-time value is only obtained from the galvanic output.

According to a chemical analysis conducted for sensors removed from the field, the error range was found to be 10±0.35 against the estimated value for Ws determined by the sensor output [4], [5]. Milder temporal changes were evaluated for the dummy than the ones from the galvanic sensor in Fig. 4. This may be attributed to the orientation of the measurement surface: the insulator’s ground-facing surface was used for the dummy measurement; whereas the
galvanic sensor was always directly exposed to rain, wind, and sun. Equivalent salt-deposition density is adopted for the salinity value in the dummy insulator to meet the standard [20]. This was calculated by adapting the measured surface conductivity in wet conditions to the conduction characteristic of NaCl, which is expressed as $\rho_{NaCl} = 6.2 \times 10^{-8}$. Here $p$ is concentration in g/L and $\sigma$ is the conductivity in S/m. On the other hand, $W_i$ values estimated from the galvanic sensor are secured by the chemical analyses results [4], [5]. The relationship between the conductivity and ion chromatography results for depoaread matters on sensors removed from the field provided a similar expression: $\rho_{NaCl} = 8.4 \times 10^{-12}$. The two equations are almost identical, allowing the direct comparison of the two vertical axes in Fig. 4.

Similar analysis was also conducted for the sensor outputs observed for transmission towers in the Sasebo area. Fig. 5 shows the typical $W_s$ analysis results obtained when another typhoon, Chanthu, approached the area in September 2021. The results obtained at that time confirmed distance dependence. That is, the $W_s$ value during the typhoon decreased by one tenth when changing the distance from 1.6 to 5.0 km. Another interesting finding was the fact that the $W_s$ value obtained for normal sensor output and for outlier output showed continuous temporal changes. This result is considered to bring a certain degree of validity to the data correction for outliers related to rainfall. Note that data correction for solar radiation effect was not conducted for the above-mentioned results, since $T_s$ measurement was not performed.

Fig. 6 shows an example of the correction against solar radiation effect, for the data observed in the Sagami area, where the $T_s$ measurement was performed. The sensor output showed a decrease during the daylight period. A remarkable feature was observed on October 27th when the sensor output suddenly decreased after the rainfall stopped and $T_s$ was raised. The $W_s$ obtained without the correction also showed a reduction by one twentieth to emerge rapid dip. To resolve the dip, the correction was performed by using $\phi_s$ instead of $\phi_s$ to obtain $W_s$, for data observed when $T_s$ was higher than $T_A$. The average wind speed was 4 m/s during the period in Fig. 6 and no strong winds were observed. Therefore, corrected $W_s$ changes are preferable from the perspective of climatic phenomenon. Data scattering still remained in the corrected $W_s$ trend, but the direction of sophistication in analysis was confirmed from the figure.

V. CONCLUSION
Galvanic couples traditionally used for corrosion sensors were taken on a subject for salt-deposition meter for their ability of continuous monitoring. Wireless field measurements in two Japanese coastal areas facing the Sagami and Sasebo bays validated its utility at least for the analysis of rapid contamination. That is, rapid increases in galvanic current outputs observed when a typhoon approached were successfully converted to the amount of sea salt-deposition to show a surge from about 0.01 to 1 g/m². The trend of the estimated salinity matched the results obtained using the conventional instrument, as well as the ones obtained for airborne salinity calculations. Solar radiation reduced the sensor output and induced a sharp drop in estimated deposition value. Surface temperature measurement was confirmed to correct such data scattering by calculating the surface humidity.

APPENDIX
This section describes the selection of the observation area. The Sagami Bay area is first selected to realize easy access and maintenance activities because the area is located in our yard. Contrary, the observation in transmission towers was to confirm how the sensor works in an environment where salinity decreases according to the distance from the shore. Five Japanese coastal areas were subjected to assess their salt-deposition to show a surge from about 0.01 to 1 g/m². The results obtained at that time confirmed distance dependence. That is, the $W_s$ value during the typhoon decreased by one tenth when changing the distance from 1.6 to 5.0 km. Another interesting finding was the fact that the $W_s$ value obtained for normal sensor output and for outlier output showed continuous temporal changes. This result is considered to bring a certain degree of validity to the data correction for outliers related to rainfall. Note that data correction for solar radiation effect was not conducted for the above-mentioned results, since $T_s$ measurement was not performed.

FIGURE 6. (a) Temporal changes in galvanic outputs and atmospheric humidity observed at the Sagami area in October 2021. The designations of the symbols are the same as in Fig. 3 (a). (b) Solar irradiance measured at the area, as well as the daylight duration measured at the nearest observatory. (c) The changes in atmospheric and surface temperature. The sea salt amount $W_s$ estimated with and without correlation of the solar effect is respectively represented by open triangles and solid circles in (d).
because it affects the maintenance frequency of the sensor. The assessed results were as follows:

- **Area A**: Significant change in salinity was expected to show the distance dependence. Concern has been raised that the knowledge gained could be limited because the area faces a local bay.
- **Area B**: The most significant change in salinity and resultant distance dependence from the shore was expected. Long-distance dependence cannot be evaluated because the area is located on a peninsula. Frequent maintenance was required because of the severe corrosion environment.
- **Area C**: Significant change in salinity was expected to show the distance dependence. The appropriate corrosion severity predicted that the galvanic sensor works normally. This is the Sasebo area that finally passed the assessment.
- **Area D**: Corrosion severity was expected to be appropriate, but milder than Area C. The distance dependence of salinity was also expected to be mild. The advantages of Area C were highlighted.
- **Area E**: Very mild decrease in salinity is expected along with the distance from the shore.

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