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Evaluating the Public Value of Improving Early Detection Accuracy of Cumulonimbus Using a Geostationary Satellite in South Korea

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ABSTRACT

The Cheollian Satellite 2A called Geo-Kompsat-2A is a geostationary meteorological satellite operated by Korea Meteorological Administration for weather and space-weather observation purposes. This article seeks to evaluate the public value arising from improving the accuracy of early detection of cumulonimbus using Geo-Kompsat-2A. To this end, an economic technique called contingent valuation (CV) is adopted taking a three step approach. In step 1, a CV questionnaire was prepared for deriving the willingness to pay (WTP) for the improvement. In step 2, a nationwide survey of 1000 households was conducted using the CV questionnaire and employing person-to-person interviews with household visits. In step 3, the average WTP was estimated. The yearly household average WTP was KRW 2143 (USD 1.91), securing statistical significance. Adjusting this value to suit the entire population of South Korea produces a yearly public value of KRW 44.1 billion (USD 39.3 million). Although it is not easy to accurately evaluate the costs involved in the improvement, the results of conducting a pilot cost-benefit analysis suggest that the improvement secures social desirability.

1. Introduction

The Cheollian Satellite 2A called Geo-Kompsat-2A (GK-2A) is a geostationary meteorological satellite launched by South Korea at 36,000 km above the equator for weather and space-weather observation purposes. It was launched on December 5, 2018, went through satellite orbit transition, completed the orbit test to secure data quality for six months, and began satellite data service on July 25, 2019. Since the mission period of GK-2A is 10 years, it will be operated until 2028 and replaced by a subsequent geostationary meteorological satellite. The next-generation meteorological imager mounted on the GK-2A produces basic cloud images every 10 min in the full-disk area and every 2 min in East Asia and the Korean Peninsula on a total of 16 channels of infrared wavelengths to visible wavelengths.

The Korea Meteorological Administration (KMA) uses satellite data from these 16 channels on the next-generation weather payload of GK-2A to develop algorithms for various meteorological outputs and uses these outputs to provide various meteorological satellite information such as torrential rains, typhoons, fogs, forest fires, and yellow dust. In particular, since the mid-1990s, the intensity and frequency of torrential rains in South Korea have been increasing due to the influence of abnormal weather. As a result, damage to industries such as tourism as well as natural disasters such as landslides and flooding occur frequently [1]. In response, the KMA has developed a technology for the early detection and prediction of torrential rains using the GK-2A and is utilizing this for weather forecasting.

Cumulonimbus is a kind of cloud created vertically by strong convections when atmospheric temperature is unstable because of a surface adiabatic heating or an advection of warm air mass. These strong convections get stronger with the latent heating released when water vapor condenses into water droplets in cloud as well as the vertical atmospheric instability of background air. The cumulonimbus typically grows up to the tropopause, resembling an anvil, and has a very short lifespan of about an hour. Cumulonimbus is associated with severe weather events such as heavy torrential downpours, lightning, hail, and floods for a short time. It is difficult to provide the early prediction of a convective cloud which will

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Abbreviations

GK-2A	Geo-Kompsat-2A
KMA	Korea meteorological administration
CV	Contingent valuation
WTP	Willingness to pay
cdf	cumulative distribution function
SB	Single bounded
1.5B	One-and-one-half bounded
CI	confidence intervals
PV	present value

grow into a cumulonimbus among small cumulus cells within a storm due to the short-lived characteristics of cumulonimbus, but human and economic losses caused by severe weather from cumulonimbus are large and widespread.

The convective cloud cells within a small-scale storm rapidly grow up in the developed cumulonimbus, causing a severe thunderstorm which is always accompanied by heavy torrential downpours, thunder, and lightning. Therefore, the early detection of cumulonimbus is quite important to prevent weather disasters derived from severe storms. In addition, object-oriented diagnostic technology that monitors and diagnoses convective clouds and convective cloud cluster cells based on weather satellite data to detect cumulonimbus accompanied by thunderstorms is called rapid development thunderstorm technology. The KMA uses the rapid development thunderstorm technology of applying regression analysis and machine learning techniques to the data of four infrared channels (3.9, 8.7, 10.5, and 12.3 μm), two water vapor channels (6.3 and 7.3 μm), and the forecast data from the United Kingdom climate model, and performs the early detection and prediction of cumulonimbus [2].

The operation of satellites can create various economic effects such as inducement of other sectors' production, value-added, and employment [3,4]. For example, Yi et al. [5] investigated perceptions using a public survey to evaluate the impacts of the Korean Astronaut Program on the national economy. Clark et al. [6] reviewed various studies that analyzed the economic effects of investment in space. In particular, George [7] analyzed the economic effects of the commercial space industry using input−output analysis. The economic effect itself has some implications, but it does not mean value. Thus, it has limited use in cost-benefit analysis.

On the other hand, since the economic value related to the operation of satellites is an important factor to be put into cost-benefit analysis, research to estimate this has been continuously conducted in the literature [8,9]. For example, Eom and Hong [10] estimated the economic benefits arising from receiving information from the operation of environmental satellites using contingent valuation (CV). Yi et al. [5] used revenues from public lectures, media, and textbooks for assessing the economic value ensuing from the Korean Astronaut Program. Park et al. [11] investigated the economic value of developing satellite in South Korea and attempted cost-benefit analysis. Liu et al. [12] evaluated the economic value ensuing from on-orbit servicing of satellites using real option pricing.

Nordhaus [13] emphasized the economic value generated by weather and climate information. From this point of view, Macauley [14] stressed that information obtained from satellites has significant economic value. In line with the ideas reported in the former studies mentioned above, this article intends to empirically evaluate the public value arising from improving the accuracy of the early detection of cumulonimbus using the GK-2A. In particular, so far as the authors know, the paper is the first trial to evaluate the economic value that satellites contribute by improving the prediction accuracy of certain meteorological phenomena.

More specifically, as a method for estimating public value, a CV that can obtain household's willingness to pay (WTP) is applied. Data on the WTP are collected by selecting 1000 households from South Korea and conducting a CV survey of them. After the data are analyzed through economic and statistical models, the results and implications will be described. There are three sections in the later part of this article. The materials and methods are shown in the next section. The penultimate section presents the Results and discussion. The last section contains Conclusions.

2. Materials and methods

2.1. Method: CV

As stated above, in this study, CV is employed for evaluating the public WTP to improve the accuracy of the early detection of cumulonimbus using GK-2A. CV is a useful technique in eliciting WTP for consuming a non-market good [15−17]. The application of CV demands a survey of potential consumers to derive WTP responses. When applying the research methodology using surveys, it is always an issue whether reliability and validity of the methodology are secured or not [18]. In this respect, whether CV holds the reliability and validity or not is also an important issue. Overall, the literature supports the reliability and validity of CV to some extent if the survey is properly conducted [19−21]. Of course, further research is still needed on this topic.

When empirically applying CV, three steps are usually required. In the first step, a CV questionnaire is prepared. At this point, the most important task is to clearly define the good to be evaluated. Data obtained using poorly prepared questionnaires are meaningless and cannot be used for further analysis. In the second step, a CV survey is conducted. Even if the questionnaire is properly prepared, the collected data can be distorted if sampling and field surveys are not scientifically conducted. In the third step, the necessary information is deduced by applying economic and statistical theories to the collected data and analyzing them. Each step adopted in this study will be described in more detail below.

2.2. Step 1: preparation of the CV questionnaire

There are usually three parts in a CV questionnaire. The first part describes the good of concern and then poses some questions about the perception of respondents to this. In the questionnaire used in this study, cumulonimbus was first explained to the respondents. In this process, color photos related to cumulonimbus were used. Afterward, the respondents were asked if they had heard of cumulonimbus before receiving the questionnaire. In addition, they were asked whether they had suffered damage from lightning strikes or torrential rains over the past three years. The main purpose of the first part is to help the interviewees enter the hypothetical market gradually, before asking them about WTP. The description of cumulonimbus presented to the respondents during the survey is as follows:

> "*In recent years, localized torrential rains accompanied by lightning have been increasing in South Korea, increasing the risk of lightning accidents as well as damage caused by heavy rain. Cumulonimbus is highly developed vertical cloud, causing heavy rain with thunder and lightning. Especially in summer, it develops rapidly for a short time, causing dangerous weather such as*

torrential rain, lightning, and hail. Therefore, early detection of cumulonimbus is very important to prevent damage caused by torrential rains accompanied by lightning."

In the second part of the questionnaire, three main contents are dealt with. The first is a description of the good to be assessed. Second, an explanation related to eliciting WTP is presented. Third, the WTP is asked. The first content in the questionnaire was explained as follows:

"*Assuming that the Cheollian Satellite 2A is not currently installed and that no technology has been developed to utilize it, please read the following description and answer the questions. Following the launch of the geostationary satellite, Cheollian 2A, into space, the government has been obtaining various weather-related information since July 2019, especially the early detection of cumulonimbus improving the accuracy of forecasting dangerous weather. This will allow forecasting at least 30 minutes to 2 hours before a dangerous weather event occurs. In short, the government intends to improve the early detection accuracy of cumulonimbus from 64.8% as of 2020 to 70.0% by 2024 using the Cheollian Satellite 2A. The value of 70% corresponds to the 94% early detection accuracy of cumulonimbus of developed countries such as the United States and Europe. This is expected to have various positive effects. However, in order to achieve that improvement goal, it is necessary to continuously invest money for operating the geostationary satellite and developing the technology for utilizing weather-related information obtained from the satellite.*"

In addition, the various positive effects arising from improving the accuracy of the early detection of cumulonimbus were explained through a visual infographic, outlined follows:

- by allowing an early warning to be issued, human casualties can be prevented through evacuation,
- by enabling warnings to be issued and securing waiting time, damage to various assets such as infrastructure can be reduced, and
- data for improving the early detection technology for dangerous weather can be provided to researchers.

The payment vehicle, which have three factors: relevance to the good to be assessed and familiarity with people, and unboundedness to daily spending, must be determined for inducing WTP responses. Expenses related to the installation and operation of GK-2A are fully supported by the national budget, and the main source of the budget is national tax levied on people in South Korea. Since income tax is the most popular national tax to them, it was adopted as the payment vehicle. The explanation presented in the questionnaire regarding the elicitation of WTP is as follows.

"*To improve the accuracy of early detection of cumulonimbus by utilizing a geostationary satellite costs a considerable amount of money. If many people pay for this, the accuracy of early detection of cumulonimbus can be improved. However, if they don't pay, it can't be improved. In this survey, we would like to find out how much your household would be willing to pay for improving the accuracy of early detection of cumulonimbus. If your household accepts the payment of the cost, the cost will be covered through an additional income tax that your household will have to pay once a year for the next five years. Could you please answer the following questions carefully, bearing in mind that your household's income is fixed at a certain level and should be distributed for various purposes (food, clothing, housing, etc.)? There are many other projects that the government has to fund besides improving the accuracy of early detection of cumulonimbus.*"

There are two main types of questions about WTP: open- and closed-ended questions. Since data obtained through the open-ended questioning method have the characteristics of point data, this has the advantage of being quite convenient to handle statistically. However, it is not preferred in the literature because it is difficult for respondents to respond. Moreover, it can lead to strategic behaviors that mean that respondents' responses exceed their true WTP [22].

On the other hand, the use of a closed-ended questioning method that asks whether to pay a specific amount or not is convenient for respondents to respond; however, it makes the task of analyzing the data more complicated for researchers. The closed-ended questioning method is more widely used in empirical CV studies because it is incentive-compatible. Moreover, the employment of closed-ended questioning method as a guide was suggested by Arrow et al. [23]. Therefore, in this study, a closed-ended questioning method was used.

The payment unit and the payment period must be determined before confirming the WTP question. As a unit of payment, one of the individuals and households is usually adopted. From a theoretical point of view, there is no essential difference in the analysis results regardless of whether an individual or a household is used. However, from an empirical point of view, the analysis results may vary depending on which individual or household is used.

Furthermore, if an individual is used as a payment unit, this raises two issues. First, whether or not middle or high school students participate in the survey. Second, whether retired people are invited to the survey or not. In this regard, Korea Development Institute [24] presents a guideline of using households instead of individuals. This study followed the guideline. The payment period was also set at once a year for the next five years in accordance with the guidelines presented in Korea Development Institute [24]. The annual payment was supported in Egan et al. [25]. The basic question used to elicit WTP was offered as:

"*Would your household accept the payment of an additional X Korean won in income tax once a year over the next five years for improving the accuracy of early detection of cumulonimbus that causes lightning and torrential rains using the Cheollian Satellite 2A*?"

Characteristic variables concerning the respondent are collected from the third part of the questionnaire. For example, it contains questions about the respondent's age, gender, education level, household income level, and household members. In addition, the interviewees are demanded to report their residence address and mobile phone number at the end of the questionnaire. This was required for a verification process in which a supervisor belonging to the survey company directly called the respondent's cell phone after the survey was completed to ensure that each respondent had responded to the survey properly.

2.3. Step 2: implementation of the CV survey

The implementation of the CV survey is largely composed of two processes. The first process is to create a sample. In this study, a professional survey company was requested to extract the sample. This is because the authors do not have expertise in sampling. The company has know-how in professional sampling. The company has been conducting more than 20 CV surveys every year. Thus, the authors think that scientific sampling was carried out. Regarding

the sample size, Arrow et al. [23] proposed 1000, which was supported by Korea Development Institute [24]. This research also used a sample size of 1000.

South Korea has a total of seventeen provinces. Sampling only sixteen provinces, excluding an island province with relatively small population, is suggested by Korea Development Institute [24]. Reflecting this suggestion, the size of each strata based on the 2015 census data was assigned to the 16 provinces nationwide, and random sampling was performed within each strata. In other words, stratified random sampling was performed.

The second process is to administer a survey to the sample using the CV questionnaire. For this, it is necessary to determine the survey method. In other words, one method must be selected among postal surveys, telephone surveys, Internet surveys, and person-to-person individual interview surveys. Arrow et al. [23] recommended the conduction of the fourth method. Korea Development Institute [24] also presented the use of the method as a guideline for applying CV. Consequently, this research employed a person-to-person individual interview survey. However, rather than the authors conducting the questionnaire survey directly, the survey was performed by the survey company with skilled interviewers trained by the company's supervisor. After sufficiently reviewing the initial versions of the questionnaire with the supervisor, the contents of the questionnaire were confirmed.

The survey was conducted during the month of May 2021. In consideration of the COVID-19 Pandemic situation, a person-to-person interview was conducted between an interviewer and an interviewee while taking sufficient social distancing measures. Respondents were able to respond without much difficulty thanks to the questionnaires, with the aid of colored graphics, and explanations from the interviewer. These findings are based on the comments of interviewers. The supervisor then called the respondent to verify whether they had responded sincerely. If it was concluded that a particular respondent lacked sincerity in completing a questionnaire, the response was removed from the data set and a further survey was implemented to secure 1000 observations.

2.4. Step 3: analysis of the CV data

This research applied a closed-ended questioning method to eliciting WTP response, as mentioned earlier. Several versions of closed-ended questioning methods suggested in the literature. The most widely applied one is the single-bounded (SB) model given in Hanemann [26]. However, this model may suffer from a problem of low statistical efficiency because of considering only one question response. For the sake of overcoming the problem, a one-and-one-half-bounded (1.5B) model was proposed by Cooper et al. [27]. This research intends to apply this model among the various closed-ended questioning methods.

When employing the 1.5B model, the two bid amounts are first determined in advance. One is a higher bid amount and the other is a lower bid amount. Approximately half of the respondents are first offered a lower bid amount and asked for their intention to pay for it. The other half of respondents first offered the higher bid amount and asked for their intention to pay for it. Thus, those who respond “yes” to the lower bid presented first or “no” to the higher bid amount presented first are asked for their intention to pay additional higher and lower bid amounts, respectively.

In fact, with regard to additional questions, the occurrence of bias or dissatisfaction with procedural invariance is often pointed out as a limitation of the 1.5B model [28]. Therefore, the results from estimating the SB model as well as the 1.5B model will be presented and compared in this research. The SB model uses only one response to first question. The models including covariates such as income and age will be also considered. Let the WTP and the presented bid amount be T and O, respectively. Moreover, let $G_T(\cdot)$ and τ be a cumulative distribution function (cdf) of T and a parameter vector of $G_T(\cdot)$, respectively. In both the 1.5B model and the SB model, the probability of answering “yes” and “no” to O is derived as follows, respectively.

$$\Pr(\text{"yes"}) = \Pr(T \geq O) = 1 - G_T(O;\tau) \tag{1}$$

$$\Pr(\text{"no"}) = \Pr(T < O) = G_T(O;\tau) \tag{2}$$

$G_T(\cdot)$ is determined as a logistic function in this study according to the practice in the literature, and the relationship between O and τ is assumed to be linear. In other words, the argument of $G_T(\cdot)$ becomes $\tau_0 - \tau_1 T$. One more thing to consider is that those who responded “no” to the lower bid amount fall under one of three cases. The first case concerns negative WTP. The second case is related to zero WTP. The third case refers to WTP ranging from 0 to the lower bid. In this regard, two difficulties arise. First, how to identify negative WTP and how to deal with it is identified. Negative WTP means compensation should occur, not payment, but it is difficult to actually compensate, and it does not seem reasonable to have a negative WTP for improving the accuracy of the early detection of cumulonimbus. Therefore, in this study, negative WTP will be treated as zero WTP without separately identifying it.

Second, how to analyze zero WTP. Usually, zero WTP response means true zero WTP or protest bid. The first should be included in the data set, but the second can be removed from the data set. Since the protest bid responses can be seen as a meaningful response and it may be better to maintain a conservative perspective, they are also handled as zero WTP in this research. That is, the authors deal with both a protest bid as well as a true zero WTP as a zero WTP. However, since zero WTP is point data and positive WTP is interval data, some consideration is needed to deal with these in one composition. In this regard, the spike model proposed by Kriström [29] is applied here. The spike model is useful for analyzing the three cases simultaneously in one framework [30].

3. Results and discussion

3.1. Summary of the CV survey results

Table 1 summarizes the bid amounts presented in the survey and the interviewees' responses to them. In order to determine the bid amounts, the following three steps were performed. First, data on WTP were obtained by asking the WTP in an open-ended question through a focus group survey of 50 people. Second, a distribution was derived by listing only positive data among the data obtained in order. Third, seven sets of bid amounts were selected within the range of the remaining values after trimming 15% from both sides of the distribution. That is, the finally determined sets of bid amounts in Korean won are (1000, 3000), (2000, 4000), (3000, 6000), (4000, 8000), (6000, 10,000), (8000, 12,000), and (10,000, 15,000). The two elements in each set indicate the lower and higher bids, respectively. A total of 1000 interviewees were allocated to seven groups with approximately similar number of people. Each set of bids was assigned to each group.

The upper part of Table 1 shows the case where a lower bid is presented first. If a “yes” response is observed to this bid, a higher bid is additionally presented. If “yes” is responded to the additional bid, the responses are recorded as “yes-yes,” and if “no” is answered, the responses are recorded as “yes-no.” On the other hand, if “no” is responded when a lower bid is presented first, a follow-up question concerning if the interviewee's WTP is larger than zero. At this time, if “yes” is answered, the responses are

Table 1
Number of observations for each set of bids in the sample.

Bids[a]		Number of answers				
First	Second	"yes-yes"	"yes-no"	"no-yes"	"no-no"	Totals
1000	3000	25	15	1	31	72
2000	4000	11	17	3	41	72
3000	6000	6	14	10	41	71
4000	8000	6	13	9	43	71
6000	10,000	2	1	14	54	71
8000	12,000	3	4	11	53	71
10,000	15,000	3	7	12	50	72
	Totals	56	71	60	313	500
First	Second	"yes"	"no-yes"	"no-no-yes"	"no-no-no"	Totals
3000	1000	14	10	3	44	71
4000	2000	12	14	3	43	72
6000	3000	9	13	3	47	72
8000	4000	4	4	10	53	71
10,000	6000	5	4	16	46	71
12,000	8000	3	2	7	59	71
15,000	10,000	6	5	8	53	72
	Totals	53	52	50	345	500

Note:
[a] They are expressed in Korean won (USD 1.0 = KRW 1122 at the time of the survey).

recorded as "no-yes," and if "no" is responded, the responses are recorded as "no-no." Thus, the "no-no" implies a zero WTP.

The lower part of Table 1 suggests a case where the interviewee faces a higher bid first. If "yes" is stated to the bid, there is no need for additional questions. However, if "no" is responded to the higher bid, a lower bid will be additionally presented. If "yes" is stated to the lower bid, "no-yes" response is observed. When "no" is answered to the lower bid, a follow-up question regarding if the interviewee's WTP is larger than zero is asked. At this time, if "yes" is answered, the responses are recorded as "no-no-yes," and if "no" is responded, the responses are recorded as "no-no-no." Thus, the "no-no-no" response represents a zero WTP.

In summary, 658 of the total 1000 respondents (=313 + 345) revealed zero WTP, while only the remaining 342 respondents reported positive WTP. 109 respondents (=56 + 53) had a greater WTP than the higher bid. 123 respondents (=71 + 52) had a distribution of WTP between the lower and higher bid amounts. 110 respondents (=60 + 50) had WTP greater than 0 but less than the lower bid. There are two groups of interviewees. A lower bid is presented to one group first and a higher bid is offered to the other group first. Each group is again divided into four subgroups: (i) WTP of zero; (ii) WTP ranging from zero to the lower bid; (iii) WTP of greater than the lower bid and less than the higher bid; (iv) WTP of greater than the higher bid. Therefore, the total respondents are composed of a total of eight subgroups.

3.2. Results of evaluating the public value

The results from estimating the 1.5B model are contained in the second column of Table 2. Statistical significance is secured for the coefficient for the bid amount as well as the constant term. The coefficient for the presented bid amount was estimated to be negative, which is reasonable. This is because an increase in presented bid lowers the acceptance of the payment of the bid. The spike, implying the probability of having a WTP of zero, was estimated as 0.6574, which is almost the same as 65.8%, the proportion of respondents with a WTP of zero. It is likewise statistically significant. Consequently, the spike model applied in this study produces reasonable results.

One of the most important objectives of conducting CV research is to obtain the average WTP. When the spike model is applied, the formula for average WTP becomes to be $(1/\tau_1)\ln[1+\exp(\tau_0)]$. Substituting the results of the 1.5B model into the formula, the household average WTP is estimated as KRW 2143 (USD 1.91) per annum. This estimate holds statistical significance. As described above, this study also intends to present the results of estimating the SB model. The third column of Table 2 contains the results. If there is a large difference between the two results, it suggests that a response effect arise in the 1.5B model. If the response effect is large, the estimation results of the SB model should be used instead of those of the 1.5B model. However, if the two results do not differ significantly, the response effect is insignificant and thus there will be no problem in utilizing the results of the 1.5B model.

At first glance, the estimates for constant term, coefficient for the presented bid amount, and spike do not show much difference between the two models. The average WTP estimates for the 1.5B model and the SB model are KRW 2143 (USD 1.91) and KRW 2455 (USD 2.19), respectively. The latter is 14.6% larger than the former. Although there seems to be a difference between the two, it is difficult to strictly test whether there is a structural difference between the two results derived from the same sample, not from two independent samples. Therefore, as a simple approach, an overlap test is applied here using the confidence intervals (CI) for average WTP estimate.

Table 2 also presents the 95% CI derived from the two models using the technique presented in Krinsky and Robb [31]. The null hypothesis for the overlap test is that the two estimates do not differ. Looking at the 95% CIs, the CI for the average WTP from the 1.5B model and that from the SB model overlap each other. Therefore, the hypothesis is not rejected at the 5% level. In other words, the data used in this study do not appear to suffer seriously from the response effect. Therefore, for convenience, this study will develop a subsequent discussion based on the 1.5B model.

3.3. Discussion of the results

The above-described results will be discussed from four perspectives. First, by expanding the estimated average WTP to the entire population, the value for the entire nation is obtained. One crucial thing to consider in the expansion is whether the population is well represented by the sample. In this regard, in this study, the authors' sampling was not made arbitrarily and was entrusted

Table 2
Estimation results of the models.

Variables	One-and-one-half-bounded model		Single-bounded model	
	Coefficient estimates	*t*-values	Coefficient estimates	*t*-values
Constant	−0.6516	−9.80#	−0.6597	−9.92#
Bid amount[a]	−0.1958	−16.22#	−0.1698	−13.17#
Spike	0.6574	43.89#	0.6592	44.12#
Annual mean willingness to pay per household	KRW 2143 (USD 1.91)	13.62#	KRW 2455 (USD 2.19)	11.71#
95% confidence interval[b]	KRW 1861 to 2484 (USD 1.66 to 2.21)		KRW 2110 to 2923 (USD 1.88 to 2.61)	
Wald statistics (*p*-values)[c]	185.62# (0.000)		137.22# (0.000)	
Log-likelihood	−1008.61		−841.53	
Sample size	1000		1000	

Notes:
# indicates that the estimate holds statistical significance at the 5% level.
[a] The unit is 1000 Korean won (USD 1.0 = KRW 1122 at the time of the survey).
[b] This is derived by the use of the technique presented in Krinsky and Robb [31].
[c] The null hypothesis is that the model is mis-specified.

to an experienced polling company. Thus, the authors think that the sample used in this research represents the population well with the help of the scientific sampling.

If the sample properly represents the population, the public value corresponding to the entire nation is computed as the multiplication of the average WTP per household by the size of the population. That is, the value of the annual public value can be obtained by multiplying KRW 2143 (USD 1.91) by 20,573,060, which is the total number of households in 2021 [32]. In conclusion, the annual public value of improving the accuracy of the early detection of cumulonimbus using the GK-2A amounts to KRW 44.1 billion (USD 39.3 million).

Second, because the previously presented estimation results do not contain covariates, the estimation of the models with covariates is also tried to examine the effect of several variables on the likelihood of stating "yes" to the presented bid. Table 3 contains seven variables to be used as covariates in this study, such as education level, income level, gender, age, prior knowledge, weather information-related behavior, and number of recreational activities. In other words, the definition and basic statistics of each variable are described in Table 3. The results from estimating the covariate-inclusion model are given in Table 4. The covariate falls into the parentheses of $G_T(\cdot)$ in equations (1) and (2).

There is little difference in the sign of each variable for the two models. Thus, the authors intend to analyze the estimated coefficient based on the 1.5B model. The positive sign of the coefficient means that as the value of each variable increases, the possibility of answering "yes" to the offered bid amount increases. The estimated coefficients for Education, Income, Knowledge, Frequency, and Activity variables are positive and statistically significant. These imply that respondents with higher education level, respondents with higher income level, respondents who recognized cumulonimbus before the survey, respondents who check weather information more frequently, and respondents with frequent outdoor activities are more likely to answer "yes" to a provided bid than other respondents. The coefficients for Gender and Age variables were not statistically significant.

Third, since this study has estimated a kind of benefit, it can be used as a basis for evaluating the social feasibility of GK-2A's service of improving the early detection of cumulonimbus if the benefits can be compared to related costs. However, it is not easy to separate only the costs related to the improvement from the development, installation, and operation costs of GK-2A. Therefore, this research seeks to evaluate the cost of the improvement schematically. There are a total of 23 technologies used in GK-2A. One of these is cumulonimbus detection technology. In view of this, the cost related to improving the early detection of cumulonimbus is assumed to be 1/23 of the total cost of developing, installing, and operating the GK-2A.

If 4.5%, the official social discount rate announced by the Korea Ministry of Strategy and Finance, is applied to the annual cost obtained in this way, the present value (PV) of the costs related to the improvement is KRW 114.36 billion by the end of 2020. This study found that the annual public value of KRW 44.1 billion occurs for five years from 2021. The PV value of the public value is worth KRW 190.28 billion by the end of 2020. The net PV value is KRW 75.92 billion, exceeding 0, and the benefit/cost ratio is 1.66, exceeding 1.0. In addition, the internal rate of return is computed as 17.3%. This is greater than 4.5%.

Thus, GK-2A's service of improving the early detection of cumulonimbus secures economic feasibility. Although it is needed to examine the economic feasibility of the improvement through more rigorous estimation of related costs in the future, through the pilot cost-benefit analysis above, we have confirmed that GK-2A's

Table 3
Information about some variables in the model.

Variables	Definitions	Mean	Standard deviation
Education	Dummy for interviewee has more than twelve years' education (0 = no; 1 = yes)	0.61	0.49
Income	Dummy for interviewee household's monthly income per family member being higher than KRW 3.36 million (USD 2.99 thousand) (0 = no; 1 = yes)	0.39	0.49
Gender	The interviewee's gender (0 = male; 1 = female)	0.50	0.50
Age	Interviewee's age	48.10	9.77
Knowledge	Dummy for the interviewee recognizing the cumulonimbus before the survey (0 = no; 1 = yes)	0.16	0.37
Frequency	Frequency of interviewee checking the weather information (0 = not checked; 1 = only checked when necessary; 2 = once a week; 3 = once in 2 or 3 days; 4 = once a day; 5 = at least twice a day)	3.37	1.40
Activity	The average number of monthly outdoors activities (sports, travel, picnic, etc.) of interviewee before the outbreak of COVID-19.	2.48	1.57

Table 4
Estimation results of the spike models with covariates.

Variables[a]	One-and-one-half-bounded model		Single-bounded model	
	Coefficient estimates	*t*-values	Coefficient estimates	*t*-values
Constant	−1.4717	−2.86*	−1.4211	−2.74*
Education	0.2724	1.65*	0.2636	1.58
Income	0.3121	2.26*	0.2909	2.09*
Gender	0.0956	0.70	0.0765	0.56
Age	−0.0037	−0.46	−0.0040	−0.50
Knowledge	0.3452	1.98*	0.3431	1.95*
Frequency	0.0966	2.02*	0.0904	1.87*
Activity	0.1059	2.44*	0.1062	2.43*
Bid amount[b]	−0.1998	−16.31*	−0.1738	−13.24*
Spike	0.6614	43.48*	0.6637	43.78*
Annual mean willingness to pay per household	KRW 2069 (USD 1.84)	13.56*	KRW 2358 (USD 2.10)	11.69*
95% CI[c]	KRW 1803 to 2393 (USD 1.61 to 2.13)		KRW 2007 to 2818 (USD 1.79 to 2.51)	
Wald statistics (*p*-values)[d]	183.76* (0.000)		136.55* (0.000)	
Log-likelihood	−992.03		−826.08	
Sample size	1000		1000	

Notes:
* indicates that the estimate holds statistical significance at the 10% level.
[a] They are described in Table 3.
[b] The unit is 1000 Korean won (USD 1.0 = KRW 1122 at the time of the survey).
[c] This is derived by the use of the technique presented in Krinsky and Robb [31].
[d] The null hypothesis is that the model is mis-specified.

service of improving the early detection of cumulonimbus secures social profitability. The service needs to be carried out continuously and reliably. Since the lifespan of the GK-2A is expected to end by 2030, it will be necessary to consider launching subsequent geostationary satellite development.

Fourth, if the comparison of the results from this study for South Korea with those for other countries can present interesting implications. Unfortunately, however, international comparison work could not be conducted because no suitable prior research could be found to carry out this comparison. If related studies are additionally conducted in various ways in the future, various implications can be derived through studies comparing the results. Alternatively, applying a benefit transfer technique that adjusts research results for one country to another country using appropriate factors such as income level and purchasing power parity will reduce the need for conducting empirical studies that cost a lot of time and money.

4. Conclusions

This article tried to assess the public value arising from improving the accuracy of the early detection of cumulonimbus using a geostationary satellite by applying CV. For this purpose, a survey of 1000 South Korean people was conducted to collect data, models well-established in the literature were employed, and some quantitative results were presented. In particular, it was the first trial evaluating the value that the public placed on the role of a geostationary satellite related to improving the predictive accuracy of a specific meteorological phenomenon. At least, this article attempted to contribute to related literature by confirming that CV can be usefully employed to determine whether the public value will exceed the cost of installing and operating the geostationary satellite.

Since the installation and operation of geostationary satellites involve considerable costs, and in South Korea, all of these costs are covered through national taxes, evaluating the public value will have important policy implications. For example, the results can be utilized as an important basis in securing a budget for the stable operation of GK-2A by 2028. In addition, it can be used as a useful basis in various policy-making processes, such as making decisions on whether to push for a new geostationary satellite to be operated from 2029 after GK-2A, and calculating social benefits that may arise from it.

Credit author statement

Ju-Hee Kim: Data curation, Writing- Original draft preparation, Formal analysis, Validation.
Hancheol Lim: Formal analysis, Investigation, Project administration, Visualization.
Jinho Shin: Validation, Investigation, Project administration, Software, Visualization.
Seung-Hoon Yoo: Conceptualization, Methodology, Writing-Reviewing and Editing, Supervision, Funding acquisition.

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Institutional review board statement

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the survey was approved by Institutional Review Board at Seoul National University of Science & Technology for exemption from deliberation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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