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# Heliocentric Potential (HCP) Prediction Model for Nowscast of Aviation Radiation Dose

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It is well known that the space radiation dose over the polar route should be carefully considered especially when the space weather shows sudden disturbances such as CME and flares. The National Meteorological Satellite Center (NMSC) and Korea Astronomy and Space Science Institute (KASI) recently established a basis for a space radiation service for the public by developing a space radiation prediction model and heliocentric potential (HCP) prediction model. The HCP value is used as a critical input value of the CARI-6 and CARI-6M programs, which estimate the aviation route dose. The CARI-6/6M is the most widely used and confidential program that is officially provided by the U.S. Federal Aviation Administration (FAA). The HCP value is given one month late in the FAA official webpage, making it difficult to obtain real-time information on the aviation route dose. In order to overcome this limitation regarding time delay, we developed a HCP prediction model based on the sunspot number variation. In this paper, we focus on the purpose and process of our HCP prediction model development. Finally, we find the highest correlation coefficient of 0.9 between the monthly sunspot number and the HCP value with an eight month time shift.

**Keywords**: space radiation, CARI-6/6M, Heliocentric Potential (HCP)

## 1. INTRODUCTION

Air safety is tied to the phenomenon of ionizing radiation from space weather, primarily from galactic cosmic rays but also from solar energetic particles. The origins of space radiation on the Earth are galactic cosmic rays (GCRs) from deep space, solar energetic particles (SEP) from the Sun, and energetic protons in the Earth's inner radiation belt. Space radiation is ionizing radiation that ionizes the incident energetic particles in the atmosphere by interaction with atmospheric neutral atoms and produces secondary particles causing space radiation. Low energy particles are generally cut off by the Earth's geomagnetic field, but relatively higher energy particles (higher than a few tens of MeV) can penetrate the atmosphere. Recently, with national airline companies in Korea operating polar routes since 2006, the stakeholders, the public, and the space weather service providers and customers have started to pay greater attention to monitoring and prediction of aviation radiation dose. Various efforts to keep pace with these trends have been conducted throughout the world. As part of these efforts, in-flight measurement experiments of the space radiation were performed in 2009 in Korea for the safety of flight crews and passengers (Hwang et al. 2010). Furthermore, the development of a national space radiation estimation and/or prediction program is strongly required and is being carried out in sequence and smoothly (Hwang & Shin 2013, Hwang et al. 2014). A global framework for addressing radiation issues in the space weather environment has been constructed but more must be done at international and national levels (Tobiska et al. 2015).

CARI-6/6M is the most widely used space radiation

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estimation program. As it takes time to utilize our own developed radiation program, as the first step, we select CARI-6M for the public aviation service (Copeland 2013). CARI-6M uses the heliocentric potential (HCP) as a critical input parameter. The HCP value is related with neutron counts observed at a ground neutron monitor. In this paper, we report the purpose and progress of designing the HCP model for nowcast of the space radiation in the aircraft altitude. To date, there was no attempt to predict the HCP itself, but a study was carried out to predict the cosmic ray intensity based on the sunspot number (Lantos 2005).

## 2. HCP PREDICTION MODEL

### 2.1 CARI-6/6M and HCP

CARI-6/6M is a program that calculates the cumulative effective dose of aircrew and passengers during a flight, developed at the US Federal Aviation Administration (FAA) in recognition of the cosmic radiation exposure. This program has provided the route dose since 1958 at aircraft altitude and the official website is http://www.faa.gov/data_research/research/med_humanfacs/aeromedical/radiobiology/cari6m/. This website only provides the execution file in the form of a MS-DOS based program. Although freely distributed, this program is limited in that it only works on a 32bit processor. In principle, CARI-6 assumes the shortest route (a geodesic) between the origin and destination airports and it makes a great circle route. In the case of CARI-6M, the user enters a route consisting of waypoints (geographic coordinates and altitudes are required) and the program assumes the shortest route between each successive pair of waypoints. After the user enters the route and altitude, CARI-6M calculates time taking-off and landing to a new waypoint with duration time at that position. CARI-6M calculates the radiation dose received during any change in altitude. The latest version of CARI-6M was distributed on December 3, 2001. Table 1 summarizes the differences between CARI-6 and CARI-6M. Both programs calculate the radiation dose depending on the altitude, latitude, longitude, solar activity, and related change in the Earth's magnetic field.

**Table 1.** Comparison between CARI-6 and CARI-6M

| Program | Characteristics | Inputs |
|---|---|---|
| CARI-6 | calculation of one radiation exposure dose between departure and arrival airport assuming great circle | 1. departure and arrival airports<br>2. flight altitude<br>3. HCP |
| CARI-6M | calculation of summed radiation exposure dose of several intervals between departure and destination airport by dividing route depending on waypoints up to a maximum of 1,000 points | |

CARI-6/6M calculates the route dose and effective dose rate by using particle transport codes of LUIN99 and LUIN2000 code, and the atmosphere model of US standard air 1976 (U.S. COESA 1976). A desired route selected according to the International Civil Aviation Organization (ICAO) airport code is the input of CARI-6/6M. Users can easily obtain the route dose if they enter the specific flight information, that is, the flight date, departure, and destination airports and waypoints' latitude and longitude, and the Heliocentric Potential (HCP) value.

The critical limitation of this program is one of the important input parameters, the HCP value. The HCP value is provided at the FAA official website (http://www.faa.gov/data_research/research/med_humanfacs/aeromedical/radiobiology/heliocentric/). But the HCP values are available from the web one or two months late, thus making it impossible to nowcast, let alone forecast, the aviation radiation dose. In this paper we try to solve this shortcoming by predicting the HCP value. We found that the key is in the relationship between the HCP value and the sunspot number.

The Heliocentric Potential is the result of a steady-state solution to the diffusion equation of cosmic rays through the solar wind. The counting rate of any high-latitude, ground-level neutron monitor can be used to determine this potential, which will return cosmic ray spectra in real time. These spectra are routinely used to determine the radiation dose rate to which air crew are exposed during the precise hours of a flight, including the effects of quick decreases and Forbush decreases. Further, it has been used to calculate the radiation dose rate to air crew during an energetic solar particle event, as the cosmic ray background before the event must be determined. An alternate approach is to use the deceleration potential, which assumes a significant time-dependence of cosmic rays through the heliosphere. However, the theory behind it does not account for the behavior of ground-level neutron monitors (O'Brien 1971, O'Brien et al. 2005).

### 2.2 Correlation Analysis

It is well known that cosmic ray incidents in the Earth's atmosphere are influenced by the solar activity cycle of eleven years. The solar activity rises and falls with a period of about eleven years. The number of sunspots indicates the level of such solar activity. Emissions of matter and electromagnetic fields from the Sun increase during high solar activity, making it harder for galactic cosmic rays to reach the Earth's surface. Cosmic ray intensity becomes lower when the solar activity becomes higher. In general the cosmic rays are anti-correlated with the solar activity (Tiwari et al. 2011). One of the indicators representing the intensity of the solar activity is the HCP value. The HCP is a physical quantity associated with the number of neutrons detected on the ground. It can be derived from the neutron counts observed by a neutron monitor. Fig. 1 shows the relationship between the neutron counts and the HCP values; the neutron counts are measured at the Apatity Cosmic Ray Station of the Russian Polar Research Institute (Taylor 2004). The blue line indicates the neutron counts at the Apatity GLM station and the red line indicates the monthly HCP values in megavolts (MV). This shows a clear anti-correlation relationship between the two quantities. Generally, the higher the HCP value is, the higher the sunspot number is and the lower the neutron counts are.

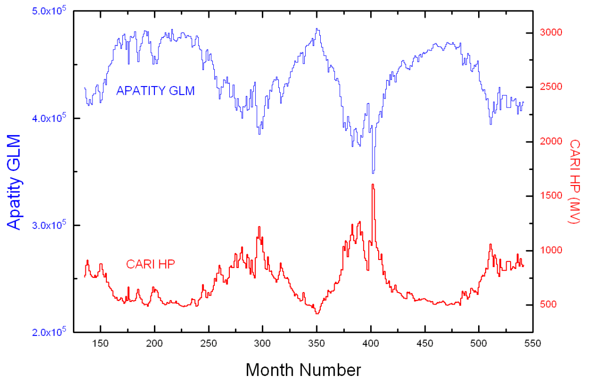

**Fig. 1.** Relationship between HCP values (red) and Apatity GLM neutron count rate (blue) (from Taylor 2004).

As shown in Table 1, CARI-6/6M uses the monthly average HCP values provided by the FAA as the critical input parameter. However, it is impossible to calculate the aviation radiation dose during the flight on an individual basis because an individual cannot obtain the current HCP value. The HCP values are put on the FAA website one month late. Therefore, in order to calculate the current radiation dose at one point or to determine the future dose value, the HCP prediction must be a priority. Fig. 2(a) shows the relationship between the HCP values and the monthly sunspot number provided by the Sunspot Index and Long-term Solar Observations (SILSO) website (http://sidc.oma.be/silso/datafiles). As the HCP value is only provided monthly, in order to investigate the one-to-one correspondence we used the monthly averaged sunspot numbers. As shown in Fig. 2(a), there is a very clear correlation between the two quantities with a slight time difference. In other words, as the number of sunspots increases and the solar activity becomes stronger, the HCP values are likely to increase. We thereupon conceived the idea that we would be able to obtain a more accurate correlation by simply changing the time difference between the two quantities. Fig. 2(b) shows the variation of the Spearman correlation coefficient depending on the time shift (Press et al. 1992). The Spearman correlation is also known as a rank-order correlation coefficient, which shows a minor change or monotonic degree between the two physical quantities. It is somewhat different from the commonly used Pearson correlation coefficient representing a simple linear relationship between the two quantities. The Spearman correlation coefficient also has the advantage that it is not largely influenced by the type of data distribution because the coefficients are calculated based on rank of the data rather than using the actual data itself. As shown in Fig. 2(b), the current HCP value has the highest relevance to the sunspot number prior to eight months with a correlation coefficient of about 0.9. That is, after the sunspot number started to increase, eight months later the HCP also starts to increase associated with the increasing sunspot number. This result can be very helpful in that if we know the current

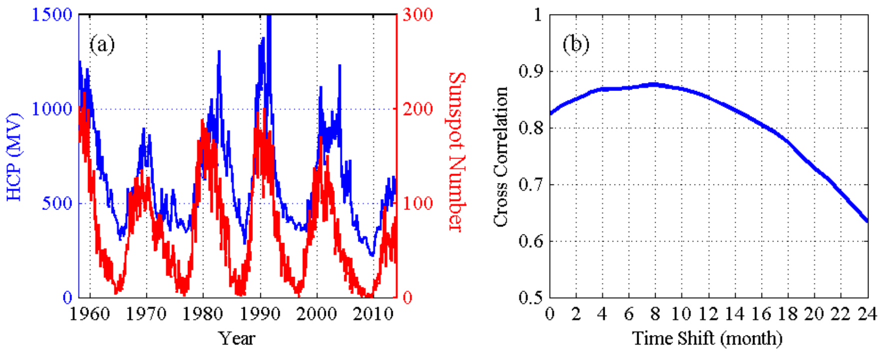

**Fig. 2.** (a) Relationship between HCP (blue) and monthly sunspot number (red), (b) correlation coefficients between HCP values and monthly sunspot number depending on the time shift .

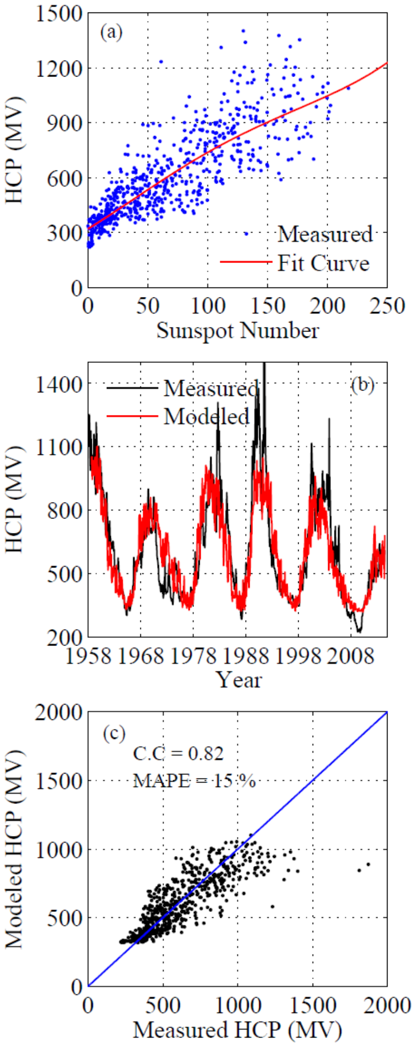

**Fig. 3.** (a) Monthly HCP values (blue) during 1958-2014 and fitting curve (red), (b) measured HCP values (black) and predicted HCP values (red), (c) correlation coefficients and mean absolute percentage error (MAPE) between measured HCP and modeled HCP values.

sunspot number, we can then obtain the future HCP value after eight months.

### 2.3 HCP prediction model

Based on the relationship between the monthly sunspot number and the HCP value in section 2.2, we derived the following functional form. This functional form is referred to as the HCP prediction model hereafter.

$$\text{HCP (MV)} = \exp\left(c_n S^n + c_{n-1} S^{n-1} + \ldots + c_0 S^0\right)$$

Here S is the average monthly sunspot number prior to eight months, and we obtain the constants of $n = 3$, $c_3 = 8.9605 \times 10^{-8}$, $c_2 = -5.1220 \times 10^{-5}$, $c_1 = 0.0126 \times 10$, and $c_0 = 5.7658$. Fig. 3(a) shows the measured HCP values (blue) and the fitting curve (red) depending on the sunspot number observed from 1958 to 2014. A comparison between the HCP prediction model and the observed HCP value is presented in Fig. 3(b). As a result, the modeled HCP values generally show very good agreement with the measured HCP values except for the HCP being very high in the region above 1100 MV. This inconsistent high HCP region is distributed in a large scattered area in Fig. 3(a). The accuracy of eight months' prediction is approximately 15% of the Mean Absolute Percentage Error (MAPE) in Fig. 3(c) and the correlation coefficient (C.C.) is still relatively high at 0.82.

## 3. APPLICATION TO SPACE WEATHER SERVICES

The National Meteorological Satellite Center (NMSC) and Korea Astronomy and Space Science Institute

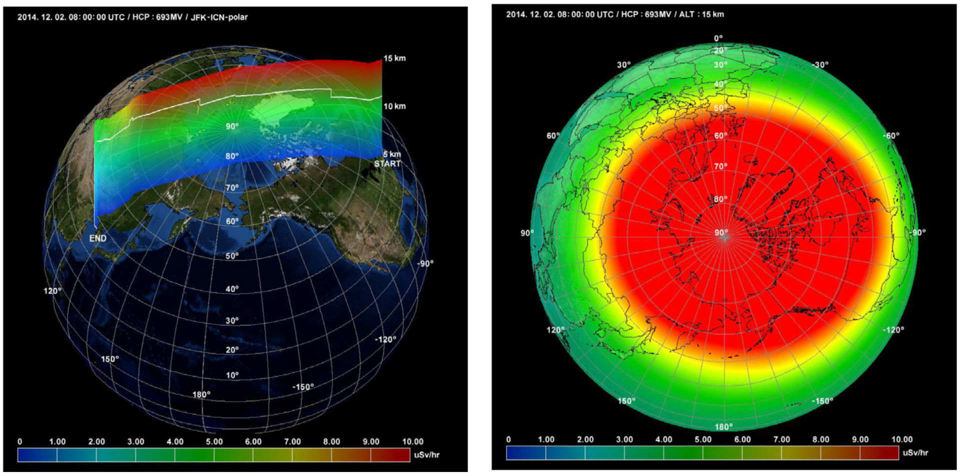

**Fig. 4.** (Left) Nowcast of effective dose rate for the JFK-ICN polar route using newly developed HCP prediction model, (right) the global map of effective dose rate at 693 MV of the HCP value at 15 km altitude on 2 December 2014.

(KASI) have collaborated in developing a national space radiation prediction model and an HCP prediction model for providing the input of CARI-6/6M. The results of this paper are one of the outcomes of this collaborative work for the space weather public services and to support air navigation service in the near future. The newly developed HCP prediction model enables real-time operation of the daily prediction of the effective dose rate. This also would be very useful for dispatchers' decision-making for polar routes. Fig. 4 shows the effective dose rate of the polar route (JFK-ICN) at the altitudes of 5, 10, and 15 km and the global map of the effective dose rate when the HCP value is 693 MV at altitude of 15 km on 2 December 2014. As shown in Fig. 4, it is clear that as the altitude becomes higher and the aircraft gets closer to the North Pole, the effective dose rate becomes significantly higher. The maximum dose rate is 10 μSv/hr, represented as red in the color bar at both panels. The visualization and software installation of this global map of space radiation over the North Pole are performed by InSpace Co., Ltd. As our HCP prediction is based on the monthly averaged sunspot number, a simple interpolation method is applied for the smaller time unit.

## 4. SUMMARY

In this paper, we reported on why and how we developed a HCP prediction model. The HCP value is the critical input parameter of the CARI-6 and CARI-6M programs, which are commonly used as the aviation route dose estimation program. The execution file of CARI-6/6M is simply provided at the FAA official website. This HCP value is given one month late at the webpage, thus making it impossible to obtain real-time information on the aviation route dose, let alone forecast the route dose. In order to overcome this critical limitation in preparation of the space weather service, we developed a HCP prediction model based on the relationship between the sunspot number and the HCP value. We found that the highest correlation coefficient is obtained with eight months' time shift between the aforementioned two quantities. In order words, the current HCP value has the highest relevance to the sunspot number prior to eight months with a Spearman correlation coefficient of about 0.9. That is, after the sunspot number starts to increase, eight months later, the HCP also starts to increase associated with that increasing sunspot number. Then, if we know the current sunspot number, we can obtain the future HCP value ahead eight months. Of course, inconsistency still exists between the modeled and the measured HCP values, and this inconsistency becomes significant when the solar activity increases near the solar maximum period. The accuracy of the eight months' prediction is approximately 15% of the Mean Absolute Percentage Error (MAPE).

A monitoring and estimation program of space radiation is strongly required for the health and safety of flight attendants and passengers from the perspective of the public space weather service. As the first step for such a public space weather service, we developed a simple HCP prediction model based on using the monthly sunspot number. This model will be very useful for real-time space weather operation. The present efforts for basic research and applications are ultimately for a space weather public service and to support air navigation service in Korea.

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